NISTIR 6284

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1999 PROGRAM PLAN

Electronics and Electrical Engineering Laboratory

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Electronics and Electrical Engineering Laboratory

February 1999

NIST

EEEL SEEKS YOUR COMMENTS

The Electronics and Electrical Engineering Laboratory (EEEL) reviews its plans regularly to keep them focused on the most important measurement needs of the U.S. electronics, electrical-equipment, and electric-power industries. Comments on this plan are invited and should be sent to the following address:

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U.S. DEPARTMENT OF COMMERCE
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Abstract

This program plan provides a detailed description of the important work that the Electronics and Electrical Engineering Laboratory at the National Institute of Standards and Technology is undertaking to provide measurement capability for U.S. industry. This measurement capability underlies the development, manufacturing, marketing, and after-sales support of new products in industry. The services provided by this program further U.S. economic growth and strengthen U.S. competitiveness in international markets.

The Electronics and Electrical Engineering Laboratory focuses on measurement capability needed especially by the electronics industry, the electric-power industry, and the electrical-equipment industry. This measurement capability also serves government, educational institutions, and the public broadly, either as users of that capability or as customers for the products and services of the supported industries.

Keywords

commercialization of technology; economic growth: electrical-equipment industry; electric-power industry; electronics industry; international competitiveness; measurement capability; metrology

Ordering

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PREFACE

This document is part of a set of planning documents developed by the Electronics and Electrical Engineering Laboratory (EEEL). These planning documents cover five principal subjects, listed here in the order in which they are employed in EEEL's planning process: (1) assessments of industry's measurement needs, (2) strategic plan for responding; (3) program plan for realizing the goals of the strategic plan through specific technical efforts (this document); (4) technical accomplishments resulting from completed work; and (5) economic impact evaluations of those accomplishments.

This program plan is composed of an overview followed by descriptions of the twelve programs that EEEL addresses. The overview describes the mission, customers, deliverables, resources, structure, and other basic dimensions of the overall EEEL effort in support of U.S. industry. Additional details on these subjects are included in the strategic plan referred to above. Each of the twelve programs described in the program plan, such as "semiconductors" or "optoelectronics", is responsive to the measurement needs of a selected field of technology. Most of these fields of technology are associated with specific product categories in industry. Other programs, such as "electromagnetic compatibility" and "national electrical standards", are cross-cutting in nature because they support many product categories. Each program is broken down into projects. The projects may run for a few years or for many years, depending on their complexity and other factors. The projects are described in detail. Project descriptions include objectives, background information, resources, the specific tasks addressed, and the milestones required to complete these tasks. These descriptions look both forward and backward in time in order to set the current work in context.

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OVERVIEW

OVERVIEW

EEEL's mission is to promote U.S. economic growth by providing measurement capability of high economic impact focused primarily on the critical needs of the U.S. electronics and electrical industries, and their customers and suppliers.

This measurement capability promotes economic growth by improving the *competitiveness* of U.S. industries. This capability is part of the national infrastructure that helps attract and retain businesses and jobs in the United States. EEEL focuses on measurement capability that U.S. industries need but cannot provide for themselves, for technical, economic, or other reasons. In particular, EEEL provides the fundamental basis for all electrical measurements conducted in the United States.

CUSTOMERS

Because of EEEL's primary focus on U.S. industry and its competitiveness, most of EEEL's customers are from industry. When EEEL last completed a comprehensive analysis of its customer base, about 72 percent of EEEL's customers were from U.S. industry. About 50 percent of the industrial customers were large businesses with over 500 employees, 38 percent were small businesses with 20 to 500 employees, and 12 percent were small businesses with fewer than 20 employees. About 20 percent of the Fortune 500 companies were included in EEEL's customers.[1]

EEEL's customers also include: other government agencies (Federal, state, and local); educational institutions; the research community, whether located in industry, government agencies, educational institutions, or non-profit organizations broadly; and, indirectly, the general public through services to the organizations already named. The measurement capability and other services that EEEL provides to Federal, state, and local agencies help them to fulfill their many responsibilities in areas such as defense, energy, transportation, communications, health, safety, environment, and law enforcement. The characteristics of EEEL's primary industry customers -- the electronics industry, the electric-power industry, and the electrical-equipment industry -- are discussed below.

Electronics Industry

Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.7 million people, as shown in Table 1. The electronics industry, the automotive industry, and the chemical industry are the three largest in shipments, each with over $300 billion of product per year.[2]

Table 1: LARGEST U.S. MANUFACTURING INDUSTRIES (1995)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[2(a)]	382	1,750
Automotive[2(b)]	340	937
Chemical[2(c)]	338	839
Petroleum Refining[2(d)]	131	70
Aerospace[2(e)]	95	483

The electronics industry produces a broad spectrum of products. This spectrum is outlined in Table 2, using a condensed version of the structure employed by the industry itself through the Electronic Industries Alliance.[3] In addition, electronic products are built into the products of many other industries, including, for example, virtually all manufacturing equipment, motor vehicles, and aerospace products. Thus, the electronics industry exerts extraordinary influence on the performance of every other U.S. industry.

While the U.S. electronics industry is a strong one, it is battling for market share in increasingly competitive international markets. There are several indicators of the intensity of this competition. Those indicators suggest an improving situation. U.S. shipments increased from 1995 to 1996 by 8 percent in nominal terms. Employment increased, too, by 3 percent.[4] Trade, for which we have more recent data, showed an improvement, too. The balance of trade for 1997 remained unfavorable, but was improved over 1996. Specifically, for the nine broad categories of electronic products shown in Table 2, the balance of trade for 1997 was positive for six categories and negative for three categories, an improvement of one category relative to 1996.[5]

Table 2: ELECTRONIC PRODUCTS

Electron Tubes
Passive Components
Solid-State Components
Consumer Products
- television and other video
- audio
- mobile
- home information
- media

Telecommunications
- commercial, industrial, military
- broadcast, studio, and related
- telephone and telegraph

Defense Communications
- search and detection
- navigation and guidance

Computers and Peripherals
- computers
- storage
- input/output
- terminals

Industrial Electronics
- controls
- processing
- industrial process display and control instrumentation
- test and measuring equipment

Electromedical Electronics

Electric-Power Industry

The U.S. electric-power industry is composed of the electric utilities, both private and public, and the independent suppliers of electricity. This industry is one of the largest industries in the United States. Electricity sales are $215 billion per year (1997), and the industry employs 404 thousand people (1997).[6] If the sales of the electric-power industry are compared with the shipments of the manufacturing industries in Table 1, those sales fall between the third largest (chemical) and fourth largest (petroleum refining).

At present the electric-power industry is undergoing major changes as it encounters deregulation and domestic competition for the first time. These changes are giving rise to new measurement needs.[7] An example of these changes is the emergence of transmission systems as common carriers, shared by multiple and competing suppliers.

Electricity plays an essential role in the manufacture of the vast majority of products. In fact, about 1.3 percent of the value of the products of all manufacturing industries in the United States is attributable to the cost of the electricity used in making them.[8]

Electrical-Equipment Industry

The U.S. electrical-equipment industry is smaller than the U.S. electronics industry and the U.S. electric-power industry but is still quite large. EEEL has not estimated its size recently but expects it to be the better part of $100 billion per year in 1999.[9]

The products of the electrical-equipment industry are outlined in Table 3, where they are arranged by the basic services that they provide. Included in this outline, among other products, are all of the electrical products used by the electric-power industry. Automobiles, too, rely heavily on electrical equipment, accounting for perhaps 14 percent, by dollar value, of all electrical equipment shipped in the United States.[10]

Like the electronics industry, the electrical-equipment industry is also struggling against strong competitors in many market segments. This competition manifests itself both in small-scale products, such as tiny electric motors, and in large-scale products, such as electric-power generation and transmission equipment.

Table 3: ELECTRICAL PRODUCTS

Electrical Supply Equipment
- generation
  - generators
- transfer
  - transformers
  - insulation
  - wire
  - wiring devices
- control
  - switchgear
  - relays and controls
- storage
  - storage batteries
  - primary batteries

Electrical Conversion Equipment
- motion
  - motors
- light
  - lighting devices
- heat
  - electrodes and spark elements
- electrolytic action
  - electrolytic elements

Competitiveness

There are many factors that bear on the competitiveness of these industries: social, economic, and technical. Among the technical factors is the need for improved measurement capability. NIST has been a major force in this area and will continue to be. NIST's assistance has been strongly demanded by industry in many areas. An example is the additional measurement capability that industry needs to meet conformity requirements, such as electromagnetic compatibility, in order to gain market access.

Simply stated, both the electronics industry and the electrical-equipment industry are outstripping the measurement capability required for international competitiveness. Affected are important factors such as product performance, price, quality, compatibility, time to market, and the implementation of new management strategies like concurrent engineering and just-in-time manufacturing.

Similarly the electric-power industry needs new measurement capability to stream-line its generation and delivery methods for electricity to cope with intensifying domestic competition and to realize the aims of deregulation.

DELIVERABLES

EEEL provides three major classes of deliverables. They are listed in Table 4 and are discussed below. EEEL provides measurement capability needed to support the efforts of U.S. industry to improve its competitiveness. EEEL engages in technology development and fundamental research, and EEEL makes the findings available to industry. Each of these categories of deliverables is discussed further below.

Table 4: DELIVERABLES

Measurement Capability
- absolute accuracy
- reproducibility
- materials reference data

Technology Development

Fundamental Research

Measurement Capability

EEEL focuses the largest part of its resources on the development and delivery of measurement capability for two principal reasons:

> Measurement capability has very high impact on U.S. industry because measurement capability supports manufacturers in addressing so many of the challenges that they face in realizing competitive products in the marketplace. A detailed discussion of the dependence of

competitiveness on measurement capability is provided in Chapter 1 of *Measurements for Competitiveness in Electronics*.[11]

NIST bears the official imprimatur of the U.S. Government as the lead agency for measurements.

EEEL focuses on developing measurement capability that is beyond the reach of the broad range of individual companies. Thus, EEEL does not develop measurement capability that companies can provide for themselves. Companies seek NIST's help for several reasons:

The companies need NIST's special technical capability for measurement development.

The companies need NIST's acknowledged impartiality for diagnosing a measurement problem affecting the industry broadly or for achieving adoption of a solution across the industry.

The companies cannot develop measurement capability needed by the industry broadly because they cannot individually capture the returns of the cost of development.

Industry's quality standards require that key measurements be traceable to the national measurement reference standards that NIST maintains. This is a requirement of growing importance in export markets.

The reasons for NIST's involvement are reviewed in greater detail in Chapter 2 of *Measurements for Competitiveness in Electronics*.

Within the area of measurement capability, EEEL places its highest priority on delivering absolute accuracy. This emphasis reflects NIST's unique role as *the* national reference laboratory for measurements. Support for absolute accuracy may require a documented measurement method, a special measurement device, a reference standard to assure the accuracy of the measurement method, and a means of delivery such as a measurement assurance program or a calibration service.

EEEL places its second highest priority on delivering reproducible measurement capability. Reproducible measurement capability provides consistent measurements but does not by itself assure high absolute accuracy.

EEEL also develops reference data on the measured electronic properties of materials. EEEL undertakes this work if NIST's special measurement skills are needed for development, or if NIST's evaluation and imprimatur are needed for wide acceptance. However, when these special conditions do not apply, EEEL prefers to provide industry with measurement capability that industry can use to develop its own data, maximizing EEEL's leverage.

Technology Development

EEEL regularly engages in technology development that directly supports its measurement mission. For example, as part of developing or delivering new measurement capability, EEEL may find it necessary to build a special instrument or an integrated circuit that embodies the new capability. EEEL transfers the technology realized in that instrument or circuit to the private sector, along with the associated measurement capability. Industry may modify the technology for incorporation in commercial products. Also, EEEL sometimes develops technology used for analyzing measured data.

Examples include test strategies for complex electronic systems and expert-systems analyses for semiconductor process lines.

EEEL engages in only limited technology development that extends beyond its measurement mission. EEEL limits the fraction of its resources so applied to about 10 percent of the total. For a technology-development project to be undertaken, it must offer unusually high impact. Also, there must be specials reasons for EEEL to be the performer. For example, the project may have arisen from a fortuitous discovery at NIST, or it may require facilities or capabilities available only at NIST.

There are important reasons why EEEL limits the technology development that it undertakes outside of its measurement mission:

> EEEL generally finds that measurement development has the highest impact among the deliverables that it can provide.
>
> EEEL's funding level is far short of that required to meet all of the principal measurement needs of the U.S. electronics, electric-power, and electrical equipment industries. Therefore, any technology development undertaken outside of the measurement mission reduces the level of measurement support that EEEL can provide to U.S. industry.
>
> Other programs exist to fund technology development, and some have considerable resources. Thus, the additional resources that EEEL could provide would not, in themselves, be significant.

Electronic data exchange is an example of a major technology-development project to which EEEL and other parts of NIST are contributing. This is a national effort. The national goal is the development of methods for codifying information to support multiple industrial needs. An important application is specifying products for manufacturing. EEEL's contributes objectivity to the broader effort focused on developing improvements in the infrastructure used for marketing electronic products. Even though this project is not focused on measurement development, EEEL's role has a measurement character: EEEL will develop methods for testing proposed schemes for data exchange.

Fundamental Research

EEEL defines fundamental research by the nature of the work conducted, not by the reason for undertaking it:[12]

> Fundamental research is the pursuit of the discovery or the understanding of the fundamental phenomena of nature.

EEEL conducts considerable fundamental research as an integral part of many of its measurement-development projects. This is not surprising, since new measurement capability is generally developed at the leading edges of science and technology. Further, EEEL endeavors to maintain a fundamental-research effort in every broad program area. Such research is an important means of nucleating pathbreaking measurement capability. For example, EEEL laid the bases for the present Josephson voltage standard with two successful theoretical inquiries: one on the interactions of series arrays of Josephson junctions, and the other on chaos in Josephson junctions.

Most of the fundamental-research projects that EEEL pursues are focused on topics likely to have outcomes benefitting measurement development for U.S. industry. That is, EEEL conducts *directed fundamental research*. EEEL does not bound the amount of directed fundamental research that it conducts to support its measurement mission. The amount conducted is determined by the needs of the individual projects pursued. For a given project, that amount may be 80 percent of project resources or next to nothing.

EEEL conducts some fundamental research that is not focused on immediate measurement needs. The criteria for identifying suitable projects are similar to those for technology development: unusual opportunity for high impact, and some special reason for EEEL to be the performer. Examples include EEEL's work on determining values for the fundamental physical constants, such as the fine-structure constant and the gyromagnetic ratio of the proton.

Table 5: MEANS OF DELIVERY

Communications	**FY 1998**
publications	230
software requests	297
talks	228
consultations	2000
visits	250
visitors	375
meetings	
contributors	41
attendees	3000
Joint Activities	
standards organizations	
staff participating	45
memberships	80
professional societies	
memberships	140
cooperative research	150
consortia (incl. forming)	6
guest workers	89
Paid Services	
custom measurement development	
other agency contracts	105
cooperative research and development agreements	11
standard reference materials	
types available	22
number sold	236
calibration service customers	300
training	
courses	9
attendees	300

MEANS OF DELIVERY

EEEL provides its deliverables by three principal means, as shown in Table 5: communications, joint activities, and paid services. FY 1998 levels of activity are shown in the table. These means of delivery involve regular interactions with industry, government agencies, and educational institutions. The interactions are essential to planning as well as to delivery. Over recent years, the levels of activity associated with the various means of delivery have varied up and down but generally not with distinct trends. Staff members are operating at capacity in terms of the number of technology-transfer activities that they can handle.

RESOURCES

EEEL's funding and staff resources for FY 1998, the most recently completed year, are shown in Table 6. EEEL's funding is shown in two major categories: (1) the funds expended *in EEEL*, and (2) the funds expended *outside EEEL*. This second category represents the funds that EEEL transfers to other NIST laboratories for work supportive of its programs. For the funds expended in EEEL, the "NIST Funding" is provided by the Congress directly to NIST. The "Other Agency Funding" is transferred to NIST by other Federal agencies for the development of

Table 6: FY 1998 RESOURCES

Funds (in EEEL)	$millions	percent
NIST Funding	36.0	74
Other Agency Funding	8.4	17
Other Funding	4.6	9
total	49.0	100
Funds (outside EEEL)	7.5	
Staff	number	percent
paid		
full-time permanent	271	65
other	27	7
total paid	298	72
unpaid		
guest researchers	51	12
other non-employees	67	16
total unpaid	117	28
total	415	100

measurement capability supporting their programs. The "Other Funding" comes from multiple sources, including calibrations services provided to EEEL's customers. The funds expended outside EEEL but inside NIST are a combination of funds provided by the Congress directly to NIST and funds provided by other Federal agencies.

PLANNING

EEEL's planning process includes five principal steps. Each step is reflected in one of the five types of published documents shown in Table 7. Also included there are the publication intervals and time horizons currently applicable to those documents.

Table 7: PUBLISHED PLANNING DOCUMENTS

Document	**Publication Interval** (years)	**Typical Time Horizon** (years)
needs assessments	varies	10 forward
strategic plan	1	5 forward
program plan	1	3 backward, 2 forward
technical accomplishments	1	1 backward
impact studies	varies	10-20 backward

The needs assessments identify the principal measurement capability for which industry needs NIST's assistance. The electronics industry was examined in *Measurements for Competitiveness in Electronics* in 1993. Since then EEEL has expanded upon this analysis by conducting a number of additional assessments that maintain a current picture of the key needs for the electronics industry. The electrical-power industry was examined in *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation* in 1997.[13] Both studies were prepared by EEEL in consultation with U.S. industry and other NIST laboratories.

The strategic plan describes the overall directions of EEEL's programs in response to industry's needs and describes the most important planned outputs. The program plan (this document) implements the strategic directions with specific program objectives and planned tasks. The program plan also describes completed tasks extending backward typically three years. The technical-accomplishments document describes selected accomplishments for the most recently completed year in a form suitable for the general reader. The impact studies translate selected accomplishments into economic and other terms and provide perspective helpful in planning new work.

Table 8 provides more information about the two types of planning documents published at varying intervals: the measurement needs assessments and the impact studies. In addition, two key activities that support assessing measurement needs are broken out separately: surveys of industry's measurement needs conducted by EEEL, and reviews of the measurement needs assessments by industry. Table 8 shows the documents published in FY 1993 through FY 1998 and, also, the documents contemplated for publication in FY 1999. A full list of all of the documents referenced in Table 8 is contained in the endnote.[14]

As indicated in the key at the bottom of the Table 8, the assessments are marked "a". The review is marked "r" in the table. Reviews may be conducted before or after the publication of the assessment for a given technical field. If conducted afterward, the reviews contribute to the next assessment for the named technical field. The surveys are marked "s" in the table. They may employ a written questionnaire, telephone calls, or visits to gather information from industry's technical and managerial personnel. The impact studies are marked "i" in the table. Impact studies are sponsored by EEEL or the NIST Program Office and are conducted with the assistance of external economists and industry experts to determine how completed work has affected industry.

EEEL employs other mechanisms to gather information important for planning. These mechanisms may or may not result in published documents. Among them are individual contacts with industry representatives by all staff members, round-robin measurement intercomparisons, informal customer surveys, and workshops. EEEL and other laboratories at NIST also participate in the development of industry "roadmaps" that lay out long-range plans for technical progress and improved competitiveness in specific industries. The roadmaps have implications for needed measurement support from NIST but address the specific needs to varying degrees. Examples of roadmaps important for the electronics industry are these: (1) *The National Technology Roadmap for Semiconductors* (1997), under the auspices of the Semiconductor Industry Association, which describes specific measurement needs;[15] (2) the *Optoelectronic Technology Roadmap: Conclusions and Recommendations* (October 1996), under the auspices of the Optoelectronics Industry Development Association (OIDA), which identifies the need for improved measurement capability;[16] (3) the *National Electronics Manufacturing Technology Roadmaps* (December 1996), under the auspices of the National Electronics Manufacturing Initiative (NEMI), which identifies specific measurement needs, and a new issue is planned for publication in FY 1999;[17] and (4) the *Optical Disk Storage Roadmap* (June 1996), under the auspices of the National Storage Industry Consortium (NSIC) in collaboration with OIDA, which addresses industry directions but not yet associated measurement needs;[18] and (5) *Metrology for Optoelectronics, An OIDA Workshop Report* (October 1998), which addresses specific measurement needs.[19]

Table 8: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

Fields	Fiscal Year						
	'93	'94	'95	'96	'97	'98	'99
semiconductors	a,s	.	.	a,s	.		a,i
magnetics	a	.	.	.	.	.	.
superconductors	a	i	.	.	.	.	.
optoelectronics	a,r	.	.	.	.	.	i
low frequency	.	.	.	.	.	.	.
radio frequency	a	.	.	.	.		i
computers	.	.	.	.	.	.	.
video	r,a	.	.	.	.	.	.
power	.	.	i	.	a	.	.
Cross-Cutting Fields							
national electrical standards	.	.	.	.	.	.	i
electromagnetic compatibility	r,a	.	r	.	s	a	.
electronic data exchange	.	.	.	.	.	.	.

a = assessment of industry's measurement needs
r = review of measurement needs assessment
s = survey of industry's measurement needs
i = impact study

ORGANIZATION OF THIS PROGRAM PLAN

The fields of technology that EEEL presently addresses, or plans to address in future years, are shown in Table 9. They provide the basis for the organization of this program plan. Each field of technology is associated with a responsive EEEL program of the same name. This structure has the advantage that it is readily accessible to the three supported industries and thus facilitates communication with EEEL's customers.

Almost all of these fields are seeing rapid advances in technology, in either product technology or manufacturing technology, or both. They are all the subject of current or foreseeable intense competitive pressures. They are increasingly interdependent technologies; success in any one of them is generally tied to success in one or more of the others. Because of this interdependency, it is not possible to create entirely separable fields to describe these technologies and the products made from them. The arrangement in Table 9, however, has been found workable. In this scheme, products are generally associated with the first applicable field on the list, as described in the following several paragraphs.

Four *materials* fields of technology lead the list. They are semiconductors, magnetics, superconductors, and optoelectronics. They focus on measurement support provided for those materials and for discrete components and integrated components that are most conveniently classified by the key material from which they are made.

Two *frequency-based* fields of technology follow. They are low frequency and radio frequency. They focus on measurement support for materials, discrete components, integrated components, and equipment that are most conveniently classified by the frequency region employed.

The computer field of technology provides a location for measurement support for equipment and systems important to computers and their peripherals and beyond the measurement support provided for materials and components under other fields.

The video field of technology focuses on measurement support for integrated components, equipment, and systems that are specific to video and that are beyond the broadly applicable component technologies addressed in earlier entries in the table.

The power field of technology focuses on measurement support for materials, equipment, and systems of principal interest to the electric-power industry and the electrical-equipment industry but also to other industries, such as the automotive industry.

Table 9: FIELDS SERVED (PRESENT AND FUTURE)

Fields	
semiconductors	
silicon	present
compound semiconductors	present
magnetics	
magnetic information storage	present
magnetie sensing	present
power materials	future
superconductors	
low temperature	present
high temperature	present
optoelectronics	
lasers	present
optical-fiber communications	present
optical-fiber sensors	present
optical information storage	present
optical signal processing	future
optical computing	future
low frequency	
alternating current	present
direct current	present
radio frequency	
signal processing	present
computing	present
transmission	present
computers	future
video	
vision (cameras)	future
signal processing	present
transmission	present
information storage	present
display	present
power	
generation	future
transmission	present
control	present
storage	future
conversion	present
Cross-Cutting Fields	
national electrical standards	present
electromagnetic compatibility	present
electronic data exchange	present

Finally, three cross-cutting fields are shown. The first of these is national electrical standards. This field focuses on measurement reference standards for the most fundamental dc (direct-current or zero-frequency) quantities, such as dc voltage, dc current, and dc resistance. These standards enable achieving high levels of absolute accuracy in measuring these quantities. They also provide reference values used to support the measurement of related ac (alternating-current or above-zero-frequency) quantities up to very high frequencies. In this way, the national electrical standards support the products of virtually all other fields of technology in the table. These national electrical standards underpin the national measurement system for electrical quantities. These standards also support U.S. participation in the determination of international electrical standards.

The second cross-cutting field is electromagnetic compatibility. It addresses the measurement support required to achieve two related purposes: reduced unwanted emissions of electromagnetic energy from electronic and electrical products; and increased immunity of products to incoming electromagnetic energy. By so doing, this field supports the products associated with virtually every other field in the table.

The third and final cross-cutting field is electronic data exchange. It focuses on test methods for the evaluation of data systems intended to support the development and manufacture of the products of virtually all other fields of technology in the table. For example, the automated product descriptions that are a part of electronic data exchange support the manufacturing of electronic and electrical products.

EEEL provides some measurement support for all of the fields of technology marked "present" in Table 9. EEEL sees a need to provide support for the several fields marked "future" in the table but lacks the resources to launch significant programs.

EEEL collaborates with other NIST laboratories in providing needed support so that their special skills in related technologies, such as chemistry and mechanical engineering, can be brought into the service of the electronics, electrical-equipment, and electric-power industries. As with any industry, these industries require a broader diversity of support than any one NIST laboratory can provide. As a result EEEL engages in many collaborative activities with other NIST laboratories. The number of such collaborations typically falls between 30 and 60 per year.

The pages that follow describe EEEL's program plan in detail. The program plan is arranged by the programs that correspond one-for-one to the fields of technology shown in Table 9. Each program is composed of a number of projects. The projects are the fundamental building blocks of this program plan. A full list of all of the projects is provided in Table 11 on page 15. Also, within the plan, the page introducing each program indicates any changes in the project structure of that program for 1999.

Descriptions of the projects begin on page 21. The descriptions cover objectives, background information, resources, the specific tasks addressed, the milestones required to complete these tasks, and accomplishments. These descriptions look both forward and backward in time in order to set the current work in context.

ORGANIZATION OF EEEL

EEEL's programs are implemented through the two offices and five divisions that comprise EEEL's organizational structure. A crosswalk from the programs to the organizational units principally conducting them is shown Table 10. The table indicates that a given organizational unit may support the programs associated with more than one field of technology. For example, the Electricity Division supports the programs associated with five fields of technology directly. In addition, a given program may be supported by more than one Division. That relationship is not shown in the table.

The five divisions in EEEL manage programs conducted within their own organizational units. The two offices matrix manage programs conducted across the NIST Laboratories.

Table 10: CROSSWALK BETWEEN EEEL'S PROGRAMS AND PRINCIPAL CONDUCTING ORGANIZATIONS

PROGRAMS: FIELDS OF TECHNOLOGY	ORGANIZATIONS: OFFICES AND DIVISIONS
Semiconductors	Semiconductor Electronics Division Office of Microelectronics Programs
Magnetics	Electromagnetic Technology Division
Superconductors	Electromagnetic Technology Division
Optoelectronics	Optoelectronics Division
Low Frequency	Electricity Division
Radio Frequency	Radio-Frequency Technology Division
Video	Electricity Division
Power	Electricity Division
National Electrical Standards	Electricity Division
Electromagnetic Compatibility	Radio-Frequency Technology Division
Electronic Data Exchange	Electricity Division
Law Enforcement	Office of Law Enforcement Standards

The first of the two offices is the Office of Microelectronics Programs (OMP). It manages the NIST-wide National Semiconductor Metrology Program (NSMP), which is a focused, matrix-managed effort addressing those measurement needs that the industry has identified in its *National Technology Roadmap for Semiconductors*. This office and the program it manages are NIST funded. NSMP projects are conducted within EEEL and four other NIST Laboratories: the Chemical Science and Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, and the Physics Laboratory.

The second of the two offices is the Office of Law Enforcement Standards. It manages a NIST-wide program in support of the criminal-justice community and also conducts some of the work of the program. This program is funded entirely by three other Federal agencies: the National Institute of Justice of the U.S. Department of Justice, the National Highway Traffic Safety Administration of the U.S. Department of Transportation, and the Office of Management and Budget of the Executive Office of the President. The program is conducted both within NIST and outside of NIST. Within NIST, EEEL and five other NIST laboratories participate: the Building and Fire Research Laboratory, the Chemical Science and Technology Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, and the Materials Science and Engineering Laboratory. Outside of NIST, the participants include Government agencies and research laboratories, universities, and companies. International collaborations are also employed.

Table 12 on page 15 associates every project in this program plan with the EEEL organization conducting it, including all five divisions and the two offices.

Table 11: EEEL PROGRAMS AND THEIR PROJECTS

PROGRAMS	PROJECTS
SEMICONDUCTORS	NIST-Wide Semiconductor Programs Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Metrology for Simulation and Computer-Aided Design Metrology for Process and Tool Control Gate Dielectric and Interconnect Reliability Metrology Micro-Electro-Mechanical Systems (MEMS) Plasma Chemistry - Plasma Processing
MAGNETICS	Magnetic Recording Technology Magnetic Instruments and Materials Characterization Nanoprobe Imaging for Magnetic Technology
SUPERCONDUCTORS	Superconductor Interfaces and Electrical Transport High Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
OPTOELECTRONICS	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
LOW FREQUENCY	AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems
RADIO FREQUENCY	High-Speed Microelectronics Metrology Nonlinear Device Characterization Power, Voltage, and Impedance Standards and Measurements Network Analysis and Measurement Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems Electromagnetic Properties of Materials
VIDEO	Video Technology
POWER	Dielectrics Research Metrology for Electric Power Systems
NATIONAL ELECTRICAL STANDARDS	Ohm and Farad Realization and Dissemination Quantum Voltage and Current
ELECTROMAGNETIC COMPATIBILITY	Standard EM Fields and Transfer Probe Standards Emission and Immunity Metrology
ELECTRONIC DATA EXCHANGE	Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

Table 12: EEEL ORGANIZATIONS AND THEIR PROJECTS

ORGANIZATIONS: OFFICES AND DIVISIONS	PROJECTS
SEMICONDUCTOR ELECTRONICS DIVISION	Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Metrology for Simulation and Computer-Aided Design Metrology for Process and Tool Control Gate Dielectric and Interconnect Reliability Metrology Micro-Electro-Mechanical Systems (MEMS)
OFFICE OF MICROELECTRONICS PROGRAMS	NIST-Wide Semiconductor Programs
ELECTRICITY DIVISION	Plasma Chemistry - Plasma Processing AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems Video Technology Dielectrics Research Metrology for Electric Power Systems Ohm and Farad Realization and Dissemination Quantum Voltage and Current Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
RADIO-FREQUENCY TECHNOLOGY DIVISION	High Speed Microelectronics Metrology Nonlinear Device Characterization Power, Voltage, and Impedance Standards and Measurements Network Analysis and Measurement Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems Electromagnetic Properties of Materials Standard Electromagnetic Fields and Transfer Probe Standards Emission and Immunity Metrology
ELECTROMAGNETIC TECHNOLOGY DIVISION	Magnetic Recording Metrology Magnetic Instruments and Materials Characterization Nanoprobe Imaging for Magnetic Technology Superconductor Interfaces and Electrical Transport High-Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
OPTOELECTRONICS DIVISION	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

ENDNOTES

1. EEEL's most recent analysis of the composition of its customer base was conducted in 1991 and reflected the preceding five-year period.

2. All shipments figures in the table are *product data* in current dollars. Product data reflect all products classified in the named industry and sold by all industries. Employment figures are industry data. Industry data reflect all products and services sold by establishments in the named industry, whether or not the products are classified in that industry. There is some overlap in the products listed in the table. Some electronic products are included in the automotive and aerospace industries. This overlap arises because there is no set of codes in the Standard Industrial Classification (SIC) System, on which all of the figures in the table are based, that is devoted exclusively to the electronics industry. The superscripts in the table refer to the notes that follow: (a) *1998 Electronic Market Data Book*, Electronic Industries Alliance, pp. 1-1 (1998). The data associated with (b), (c), (d), (e) come from the International Trade Administration of the U.S. Department of Commerce and are published in the *Statistical Abstract of the United States 1998*, CD-COMP-ABSTR97 (March 1998): (b) the figures shown reflect both the motor-vehicle bodies (Table No. 1462) and supporting parts industries (Table No. 1439); (c) Table No. 1416; (d) Table No. 1428; and (e) Table No. 1463.

3. *1998 Electronic Market Data Book*, Electronic Industries Alliance, p. 1-4 (1998).

4. *1998 Electronic Market Data Book*, Electronic Industries Alliance, p. 1-1 (1998).

5. *1997 Electronic Market Data Book*, Electronic Industries Alliance, pp. 2-3 (1997). The balance of trade for 1996 is positive for electron tubes, telecommunications, defense communications, industrial electronics, and electromedical equipment. The balance is negative for passive components, solid-state products, consumer products, and computers and peripherals. Together electron tubes, solid-state products, and passive components comprise the category electronic components which is negative overall.

6. Data provided by the Edison Electric Institute, October 30, 1998.

7. Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

8. *Statistical Yearbook of the Electric Utility Industry 1995*, Edison Electric Institute, p. 82 (1997). The value of 1.3 percent was calculated for 1994.

9. The last estimate of the size of this industry made by EEEL for the year 1990, $48 billion, *Measurements for Competitiveness in Electronics,* National Institute of Standards and Technology, Report No. NISTIR 4583, p. 38 (1993). The definition used for the electrical-equipment industry, in terms of SIC codes, was developed at NIST but was influenced by the products of interest to the members of the National Electrical Manufacturers Association. The definition excludes products which employ electrical components for practical applications. For example, excluded are household appliances, transportation equipment, and manufacturing equipment. Most of these excluded products are as much the products of other industries. Further, the excluded products are difficult to bound because electricity is used so widely. Also, excluded from the definition are electronic products. For the most part, they are the products that apply electricity in electrical form rather than as motion, light, heat, or electrolytic action.

10. *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583, from the data for 1990 in Table 13 on p. 38 (April 1993).

11. *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583 (April 1993).

12. Some definitions of fundamental research exclude any research undertaken with a view to achieving practical benefits from its successful completion. That is, they add the notion of lack of specific purpose, or for the purpose of advancing knowledge only, to the definition, even if the nature of the work is unaffected by this addition.

13. Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

14. All documents referenced in Table 8 are shown below. They cover the period FY 1993 to FY 1999. Years shown in the left column are fiscal years.

Semiconductors

1993	a	Chapter 4, "Semiconductors", *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 4583 (April 1993).
1993	s	"$Hg_{1-x}C_xTe$ Characterization Measurements: Current Practice and Future Needs", *Semiconductor Science and Technology*, Vol. 8, pp. 753-776 (1993).
1996	a	*Semiconductor Characterization: Present Status and Future Needs*, W. Murray Bullis, David G. Seiler, and Alain C. Diebold, ed., published by the American Institute of Physics (1996). Reporting on the *International Workshop on Semiconductor Characterization: Present Status and Future Needs*, a workshop on measurement needs conducted on January 30-February 2, 1995 in Gaithersburg, MD, sponsored by the Advanced Research Projects Agency, SEMATECH, the National Institute of Standards and Technology, and other organizations.
	s	*Survey of Optical Characterization Methods for Materials, Processing, and Manufacturing in the Semiconductor Industry*, National Institute of Standards and Technology Special Publication 400-98 (November 1995).
1999	a	*International Conference on Characterization and Metrology for ULSI Technology*, a conference on measurement needs to be held on March 23-27, 1998, in Gaithersburg, MD, sponsored by the National Institute of Standards and Technology, SEMATECH, the Semiconductor Research Cooperative, the Semiconductor Equipment and Materials Institute, and the American Vacuum Society's Manufacturing Science and Technology Division. Proceedings should be published in 1999.
1999	i	Economic impact study of power-device modeling, underway.

Magnetics

1993	a	Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.

Superconductors

1993 a Chapter 6, "Superconductors", *Measurements for Competitiveness in Electronics*, First Edition.

1994 i Robert L. Peterson, "An Analysis of the Impact on U.S. Industry of the NIST/Boulder Superconductivity Programs: An Interim Study", Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 5012 (November 1993).

Optoelectronics: Lasers

1993 a Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 8, "Lasers", *Measurements for Competitiveness in Electronics*, First Edition.

1999 i Economic impact study of laser and fiber-optic power calibrations services.

Optoelectronics: Optical-Fiber Communications

1993 a Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 9, "Optical-Fiber Communications", *Measurements for Competitiveness in Electronics*, First Edition.

Optoelectronics: Optical-Fiber Sensors

1993 a Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.

1993 r Industry review: Chapter 10, "Optical-Fiber Sensors", *Measurements for Competitiveness in Electronics*, First Edition.

Radio Frequency

1993 a Chapter 7, "Microwaves", *Measurements for Competitiveness in Electronics*, First Edition.

1999 i Economic impact study of near-field antenna measurements, underway.

Video

1993 r Industry review of draft of Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.

1993 a Chapter 11, "Video", *Measurements for Competitiveness in Electronics*, First Edition.

Power

1995 i Albert N. Link, *An Evaluation of the Economic Impacts Associated with the NIST Power and Energy Calibration Services*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 5565 (January, 1995).

1997 a Gerald J. FitzPatrick, James K. Olthoff, and Ronald M. Powell, *Measurement Support for the U.S. Electric-Power Industry in the Era of Deregulation*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 6007 (May 1997).

National Electrical Standards

1999 i Economic impact study of the Josephson voltage standard.

Electromagnetic Compatibility

1993 r Industry review of draft of Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.

1993 a Chapter 12, "Electromagnetic Compatibility", *Measurements for Competitiveness in Electronics*, First Edition.

1995 r Industry review of *EMI/EMC Metrology Challenges for Industry - A Workshop on Measurements, Standards, Calibrations, and Accreditation*, Boulder, Colorado (January 25-26, 1995).

1997 s Ramon C. Baird and Motohisa Kanda, *Electromagnetic Compatibility: Results of a Limited Survey*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 5049 (July 1997).

1998 a *EMI/EMC Metrology Challenges for Industry: A Workshop on Measurements, Standards, Calibrations, and Accreditation*, Report No. NISTIR 5068 (November 1997).

15. *The National Technology Roadmap for Semiconductors*, Semiconductor Industry Association (1997).

16. *Optoelectronic Technology Roadmap: Conclusions and Recommendations*, Optoelectronics Industry Development Association, p. 6 (October 1996).

17. *National Electronics Manufacturing Technology Roadmaps*, National Electronics Manufacturing Initiative, Inc. (December 1996).

18. *Optical Disk Storage Roadmap*, National Storage Industry Consortium in collaboration with the Optoelectronics Industry Development Association (June 1997).

19. *Metrology for Optoelectronics: An OIDA Workshop Report*, Optoelectronics Industry Development Association (October 1998).

SEMICONDUCTORS

* This project combines the former "Dielectric Reliability Metrology" and "Interconnect Reliability Metrology" projects.

Office of Microelectronics Programs

Office Director: Robert I. Scace
Robert Scace retired in December 1998, and Stephen Knight is serving as Acting Director.

Staff-Years: 4 professionals (2 physicists, 1 physical chemist, 1 secretary)

Funding Sources: NIST

Objective: Develop and execute NIST's National Semiconductor Metrology Program (NSMP); apply NIST-wide technical resources regardless of organizational location to deliver solutions to highest priority metrological problems of the semiconductor industry. Provide formal liaison to SEMATECH, International SEMATECH and the Semiconductor Research Corporation.

Background: NIST has developed metrology for the semiconductor industry for over 40 years in EEEL and its predecessors. Twelve years ago, the breadth of technology then applied in semiconductor manufacturing clearly transcended EEEL's technical scope. New appropriated funds were sought, and first obtained in 1991. The Semiconductor Industry Association (SIA) took the initiative in defining and gaining Administration support for the National Semiconductor Metrology Program, established in early 1994. The needs are identified in the current *National Technology Roadmap for Semiconductors*, the third in a series of needs documents developed with strong industry participation led by the SIA. The technical program is confined by agreement to mainstream digital silicon complementary metal oxide-semiconductor (CMOS) technology.

Current Tasks (Listed below are NSMP-funded tasks in other NIST organizations. NSMP-funded tasks within EEEL's domain are described elsewhere in this document):

1. Dimensional Metrology at the Nanometer Level

FY 1996 Completed installation and initial optimization of both the field-emission scanning electron microscope (FESEM) and the proximal probe microscope (PPM); Provided first-order feedback to the manufacturers of both of these instruments regarding the functioning of the combined instrumentation system.

FY 1997 Optimized the current PPM for operation in the FESEM in collaboration with the manufacturer; Performed combined FESEM/PPM scans of the SEM sharpness standard and RM 8090, SEM magnification artifact; Presented and published the first papers on the combined tools.

FY 1998 Incorporated design improvements in the PPM, improving its performance in the combined FESEM/PPM instrument; Imaged RM 2090, SEM magnification standard.

FY 1999 Use the combined FESEM/PPM in the determination of the measurement uncertainty of SEM standards and production wafer samples; Initiate study of PPM tip stability and suppression of tip wear during measurements; Incorporate a tuning-fork sensor into the PPM and upgrade stage design of

	the combined FESEM/PPM to enable optimal measurements from both instruments during simultaneous operation.
FY 2000	Investigate new probes and probe materials such as nanotubes into the PPM by adapting methods devised for attaching probe tips onto tuning fork sensors to these novel probes; Extend current capabilities of the combined FESEM/PPM to enable in-vacuum investigations of PPM/electrical correlation; Continue to refine the measurement uncertainty of the SEM standards.

2. Nanometer Scale Metrology with Atomic Force Microscopy

FY 1996	Completed initial characterization of the Calibrated Atomic Force Microscope (C-AFM) performance for pitch, height and width measurements; Completed initial measurements of silicon single atom step height measurements.
FY 1997	Installed new z-stage in the C-AFM and reevaluated all motion errors in the system to further reduce uncertainties; Received samples for first C-AFM pitch measurements from an external customer; Completed new round of measurements on silicon single atom step samples having reduced uncertainty and improved agreement with the lattice constant value.
FY 1998	Completed top width measurements on several preferentially etched silicon samples for the linewidth measurement comparison; Completed first report of test pitch measurements with the C-AFM for an external customer, and explored the use of such samples as pitch/height standards.
FY 1999	Perform first measurements of step height for external customer; Perform more pitch measurements for external customers; Perform new round of linewidth measurements with tip characterization for method intercomparison; Evaluate sharp alternative tips, particularly carbon nanotubes, as probes in the C-AFM; Continue evaluation of possible sample types for SRM 2089; Perform preliminary evaluation of square-wave type samples for possible roughness standards.
FY 2000	Perform additional pitch and height measurements for external customers; Upgrade C-AFM scanner with a new z-stage and a new x-y stage to further increase scan range and reduce motion errors; Begin measurements on samples for initial release of SRM 2089; Complete second major round of linewidth measurements with tip characterization for method intercomparison; Complete evaluation of sharp alternative tips, particularly carbon nanotubes, asprobes in the C-AFM; Complete evaluation of square-wave type samples for possible roughness standards.

3. Linewidth Correlation

FY 1998	Completed "preliminary" C-AFM and SEM measurements, including correction for probe-specimen interactions, of a SIMOX linewidth specimen.
FY 1999	Perform an improved intercomparison of AFM, SEM, and electrical critical dimension results on a linewidth specimen, this intercomparison to include improved measurement and analysis techniques as learned from the preliminary measurements; Report preliminary results at SPIE Microlithography meeting.
FY 2000	Intercomparisons on new samples; Incorporate any necessary revisions to edge models into software and make the software available to SEMATECH (and other interested parties).

4. Optical CD and Overlay Metrology

FY 1996	Stewart platform strut joint patent approved, licensed to industry; UV linewidth and overlay microscope programming commenced for fully automated instrument control and data acquisition; Major components of overlay system assembled and tested; Optical system performance demonstrated on industrially supplied 8" wafer overlay targets.
FY 1997	Aligned interferometers and qualified overlay metrology system; Manufactured prototype microcone alignment artifacts and measured with the overlay system; Wrote computer code for calibrating SRM 2800 on pitch standard UV Microscope.
FY 1998	Completed programming of UV microscope hardware control system; Performed preliminary measurements of SRM 2800 and develop software for the calibration of SRM 2800; Designed and procured prototype two-dimensional grid artifacts, microscale and macro 6" grid; Developed automated focus algorithms and control hardware for the overlay tool; Investigated and determined best method for edge detection for linewidth and overlay target structures; Designed prototype conventional overlay standards (design photomask and CAD files, established wafer processing and overlay target levels).
FY 1999	Complete UV microscope program for linewidth calibrations; Design and procure overlay SRM prototypes based on preceding measurements; Calibrate SRM 2800 pitch standard; Procure and calibrate 6" photomask linewidth SRM; Measure the microgrids on the 6" two-dimensional grids; Establish measurement sequence and begin quantitative verification of that sequence on the 6" two-dimensional grids; Improve edge detection and focus algorithms to optimize repeatability and accuracy; Install new vibration isolation and thermal stability systems on the overlay tool.
FY 2000	Calibrate conventional overlay standard artifacts as SRMs; Make calibrated 6" two-dimensional grids and microscale grid photomasks available; Develop self-calibration methods and apply methodology to overlay optical system and data acquisition systems; Verify and make modeling results available for transmission and reflection mode optical microscope modeling.

5. High Accuracy Two Dimensional Measurements

FY 1995	Developed and tested control system for Moore Model M48 coordinate measuring machine; Began characterization of system accuracy for measurement of large (up to 750 mm x 750 mm) grid plates; Developed and tested positioning system for small grid measuring machine (M4).
FY 1996	First commercial calibrations of large grid plates made on NIST M48 coordinate measuring machine; Typical accuracy for 500 mm x 500 mm grid is 0.40 μm; Completed development of small 200 mm x 200 mm measuring machine (M4); Began characterization of geometric errors and development of error map; Developed robust edge-finding algorithms for system, and began study of methods divergence problems for grid mark edge finding.
FY 1997	Finished characterization of M4, including comparisons in one dimension measurements with the NIST Line Scale Interferometer, the most common traceability path for semiconductor length measurements; Continued development of instruments and began design of industry interlaboratory tests of length measurement capabilities; Continued study of calibration algorithms

for grid calibration, including partial closure methods which calibrate the test grid and machine geometry using multiple measurements of a grid in multiple positions and orientations.

FY 1998 Finished a study of the Least Average Deviation algorithm for robust edge detection; Drafted research paper ready for submission and presentation (probably to SPIE); Made the first attempt to measure machine straightness by rotating a grid plate; Measurements of the machine error to check results were started.

FY 1999 Begin a study of the Least Median of Squares method for edge fitting; The self-calibration method developed under the 1998 SBIR grant will be tested with data from the grid measuring machine; Study the effects of fixturing on the calibration of grid plates; model the plate as it is fixtured on our machines and transform to the undeformed state in response to industry needs for califbration data for an undeformed plate; Analysis will be tested by measurements on a commercial phase stepping flatness interferometer.

FY 2000 Upgrade the accuracy of the grid measuring machine (M4) substantially; Design a metrology frame and fixturing system which will decouple the stage errors from the measurement system (This approach has had great success on research machine, although it is not generally available in commercial instruments).

FY 2001 Test and characterize the newly upgraded grid measurement system.

6. Radiometric Metrology for Deep Ultraviolet Lithography

FY 1995 Developed method for calibrating discharge lamps used for ultraviolet photoresist stabilization; Continued work with commercial partner to improve accuracy of ultraviolet probes.

FY 1996 Upgraded refractometer to enable high-accuracy refractive-index measurements and began measurements for SEMATECH/Lincoln Labs near 193 nm; Began development of dielectric barrier discharge source as potential ultraviolet/deep ultraviolet standard.

FY 1997 Performed high-accuracy measurements of the refractive index of optical materials and their temperature coefficients near 193 nm for SEMATECH/Lincoln Labs; Built up new refractive-index-measurement apparatus based on interferometry, capable of improved accuracy.

FY 1998 Measured the index of refraction, its dispersion, and its temperature dependence to high accuracy (index 7 ppm) near 193 nm of several grades of fused silica and calcium fluoride, using a goniometric refractometer; Communicated these results to the lithography industry for design of the 193 nm stepper optics.

FY 1999 Measure the index of refraction to 1 ppm, as well as its dispersion, and its temperature dependence near 193 nm of fused silica and calcium fluoride, using a newly-built interferometric refractometer; Extend these measurements to wavelengths near 157 nm for calcium fluoride to enable design of future-generation 157 nm steppers; Explore excimer-irradiation induced damage in detectors as a means of identifying stable UV semiconductor photodiodes for irradiance measurements at 193 nm and 157 nm.

FY 2000 Continue making accurate measurements of the index of refraction, its dispersion, and its temperature dependence to high accuracy (index 1ppm) near 193 nm and 157 nm of fused silica and calcium fluoride as needed by the lithography industry; Explore the relation between the refractive index and the grown-in and excimer-radiation-exposure-induced defects in these materials; (These measurements will be coupled with an exploratory program of defect characterization in these materials by spectroscopic and other techniques.); Continuation of material properties characterization and detector development to address the various radiometric needs in the lithography industry.

7. Fundamental Process Control Metrology for Gases

FY 1995	Developed prototype calibration system for partial pressure residual gas analyzers (RGAs); Developed primary and transfer flow standards for inert gases (10 to 1000 sccm); Published comparative evaluation of thermal mass flow controllers.
FY 1996	Developed model for residual gas analyzers that qualitatively describes commercial RGA performance in high pressure operation (0.001 to 0.1 Pa); Developed primary and transfer flow standards for inert gases (0.1 to 10 sccm); Conducted initial on-site flow proficiency tests with four mass flow controllers manufacturers (5 to 1000 sccm).
FY 1997	Developed a methodology to optimize commercial RGAs for semiconductor process control; Performed flow proficiency tests with gas handling suppliers to the semiconductor industry; Developed primary flow standards with uncertainties less than 0.05% (1 to 1000 sccm).
FY 1998	Designed in situ RGA calibration system, obtained performance data for closed-ion-source (CIS) RGAs. Designed and assembled in situ flow standard for use with process gases (e.g., WF_6).
FY 1999	Calibrate RGAs with reactive process gases, develop RGA gas sampling system for semiconductor process tool; Test *in situ* flow calibration techniques with reactive process gases.
FY 2000	Incorporate calibrated RGAs into tungsten deposition process control loop; Calibrate and evaluate performance of acoustic flowmeter with process gases.

8. Low Concentration Humidity Standards

FY 1995	Demonstrated quantitative capability of optical cavity ring-down spectroscopy (CRDS) for trace contaminant measurement; Completed construction of prototype low frost-point moisture generator.
FY 1996	Began intercomparison, in cooperation with LFPG (low-frost-point-moisture-generator) SEMI, of low moisture concentration measurement instruments and transfer standards in the 1 -100 parts-per-million range; Demonstrated quantitative measurements of contaminants in gases below 1 ppm using CRDS.
FY 1997	In cooperation with SEMI, continued intercomparison for moisture concentration in the 1 - 100 ppm range, and began evaluation of permeation-tube-based working standards in the 10 - 100 parts-per-billion range; Demonstrated capability to deliver parts-per-million down to parts-per-billion levels of humidity using the LFPG; Made absolute ppb-level measurements of LFPG output moisture concentration using a quantitative optical absorption technique.
FY 1998	Demonstrated quantitative measurements of LFPG output using a prototype commercial hygrometer based on modulation spectroscopy; Continued intercomparisons of low moisture working standards.

FY 1999 Demonstrate quantitative measurements of LFPG output using CRDS; Continue intercomparisons of low moisture working standards; Measure the vapor pressure of water ice between -70°C and -100°C using CRDS.

FY 2000 Improve LFPG by extending lower temperature range down to -120°C, allowing measurements down to ~140 ppt water vapor in air; experimentally determine enhancement factor for water and vapor/gas mixtures between -70°C and -100°C.

9. Plasma and CVD Process Measurements

FY 1995 Demonstrated utility of radio frequency (rf) measurements to monitor polymer build-up in plasma reactors; Modified Gaseous Electronics Conference (GEC) rf Reference Cell to accept inductively coupled plasma source; Measured/published spatial distribution of carbon-fluorine (CF) radicals in carbon tetrafluoride/oxygen/argon plasmas.

FY 1996 Performed critical review of available electron collision data for carbon tetrafluoride (CF_4) and trifluoromethane (CHF_3) and constructed World Wide Web-based database; Transferred rf electrical measurement techniques (hardware and software) to a specialty gas supplier and began investigation of electrical properties of nitrogen trifluoride (NF_3) discharges; Measured electron density and energy distribution functions in the inductively coupled plasma source for wide range of gases and plasma conditions; Measured first time-resolved optical emission spectra of rf biased electrode sheaths in inductively coupled plasma reactor.

FY 1997 Measured light emission from and the density of CF_2 radicals in O_2/CF_4 and C_2F_6 chamber cleaning plasmas using optical emission and planar laser induced fluorescence, respectively; Developed new non-intrusive technique for measuring ion current at wafers exposed to high-density plasmas which may be suitable for use as an ion-current sensor in industrial reactors; Measured effect of coil geometry and termination on plasma uniformity in inductively-coupled GEC Cells; Compared new diagnostic (plasma oscillation probe) for measuring plasma electron densities with Langmuir probe measurements; Measured degree of molecular dissociation in gas mixtures with argon in inductively-coupled GEC Cell; Extended electron interaction database to include dichloro-difluoromethane (CCl_2F_2) perfluoroethane ($C_2F_{6)}$.

FY 1998 Measured CF_2 densities in chamber cleaning plasma using planar laser induced fluorescence and correlated densities with electrical parameters; Developed a new model of ion dynamics in the plasma sheath region accounting for time variation of the ion current and compared with experiment; Developed tomography code to measure plasma uniformity in high-density etching reactors; Measured absolute, mass resolved ion fluxes and energies in the inductively-coupled GEC cell; Extended electron interaction database to include C_3F_8.

FY 1999 Perform measurement of CF_2 radical densities in inductively-coupled GEC cell using planar laser induced fluorescence; Develop high accuracy model of ion dynamics in plasma sheath; Develop IR laser absorption spectroscopy and tera-hertz spectroscopy as plasma diagnostics to measure density and temperature of plasma species; Study optical emission and ion flux in pulsed plasmas; Extend electron interaction database to include Cl_2 and SF_6.

10. Metrology for Contamination-Free Manufacturing

FY 1996	Completed first tests of numerical model for nucleation and transport of contaminant particles in a rotating disk CVD reactor; Completed fabrication of the reference rotating disk reactor to be used for model validation.
FY 1997	Developed particle contaminant models for prototypical perfectly-stirred and plug flow reactor configurations; Silicon hydride physical/chemical property database established on World Wide Web.
FY 1998	Began in situ temperature measurements in reference rotating disk chemical vapor deposition (CVD) reactor as initial stage in determining parameter regimes that are susceptible to particle formation during thin film growth; Modified rotating disk reactor contaminant model to simulate injected particles which will be used to test experimental particle measurement capabilities during FY 1999.
FY 1999	Complete numerical/experimental temperature comparisons in reference rotating disk CVD reactor; Demonstrate particle measurement capabilities (and compare with model results) using injected particles with known characteristics; Complete addition of thermochemical data on silicon oxyhydrides to existing database on the World Wide Web.
FY 2000	Perform experimental measurements of gas-phase generated contaminants in reference rotating disk CVD reactor; Modify rotating disk reactor contaminant model as necessary in order to accurately simulate experimental conditions.

11. Temperature Measurement for Rapid Thermal Processing (RTP)

FY 1998	Characterized the Test Bed temperature measurement chamber with different reflective shields; Obtained results for comparison of thin-film thermocouples (TFTCs) and radiation thermometers (RTs) to within 5° C; Characterized optical light pipe RTs against blackbodies to within 0.25° C; Developed test method for determining Seebeck coefficient of thin-film thermocouples on NIST TFTC test wafers; Tested Pt/Pd and Rh/Pt TFTCs on NIST TFTC test wafers.
FY 1999	Achieve goal of 2° C accuracy for *in-situ* calibration of RT to meet NTRS requirement; Develop Monte Carlo (MC) modeling for understanding effects of temperature and property non-uniformity in the Test Bed chamber; Develop improved thin-film calibration procedure to obtain +/- 1K calibration uncertainty; Demonstrate thin-film thermocouple technology on production RTP tools for use up to 1200 K; Develop RT measurements to match thin-film performance up to 1200 K.
FY 2000	Develop family of MC models for describing RT performance in production-type RTP chambers; Develop family of light pipe RT models to explain calibration and in-tool behaviors; Demonstrate in-tool RT calibration method using miniature blackbodies; Characterize TFTCs for durability, stability, and repeatability in simulated industrial RTP environments for temperatures up to 1300 K; Investigate performance of thin-film materials including Pt, Pd, Rh, Ir, and Ru; Develop RT measurement methods to match TFTC performance up to 1300 K.

12. Particle Measurements in Support of the Semiconductor Industry

FY 1996	In collaboration with SEMATECH and VLSI Standards, Inc., selected commercially available monosize particles for the calibration of scanning surface inspection systems.
FY 1997	Fabricated and performed initial characterization of three monosize dispersions of polystyrene spheres in the 90 nm to 220 nm size range and developed improved model for the measurement system.
FY 1998	Completed the characterization of three monosize dispersions of polystyrene spheres with sizes of 92 nm, 127 nm, and 218 nm; these are to be used for calibrating scanning surface inspection systems.
FY 1999	Deposit monosize calibration spheres on wafers for use by Physics Laboratory for testing light scattering model; Complete report describing the measurement of nominal 73 nm polystyrene spheres; Complete report on the performance of electrospray for generating monosize particles over the size range from 30 nm to 100 nm.
FY 2000	Develop the capability of generating and depositing monosize particles with diameters as small as 30 nm.

13. Optical Scattering for Wafer Surface Metrology

FY 1996	With a commercial partner, developed reference wafers to calibrate fab line haze meters; Developed methodology for characterizing microroughness-induced optical scatter instrumentation.
FY 1997	Characterized polarization of light scattered from different scattering sources on silicon wafers; Invented tool for improving particle detection limits on rough surfaces; Developed software, to be available via the World Wide Web, to enable manufacturers and users of light-scattering wafer inspection systems to determine the response functions of their instruments.
FY 1998	Investigated polarized light scattering properties of etched vias on wafers; Developed theory for polarized light scattering from defects and roughness in dielectric layers; Characterized polarization of light scattered by a correlated roughness SiO_2 layer on silicon; Constructed scanning polarized optical scatter instrument for inspection of silicon wafers.
FY 1999	Characterize polarization of light scattered by particles on silicon wafers, demonstrating capability for particle sizing; Characterize light scattering from defects and roughness in dielectric films; Demonstrate scanning polarized optical scatter instrument capabilities for analyzing discrete defects on silicon wafers; Model polarized light scattering from defects and etched vias using finite-element methods; Extend software to include a suite of programs for analyzing response of inspection systems to scattering from different sources.
FY 2000	Extend goniometric optical scatter instrument for measurements in the deep ultraviolet to characterize wafers and optical elements; Construct next-generation polarized optical scatter instrument using polarization spatial filtering.

14. Chemical Characterization of Thin Films and Particle Contaminants

FY 1997	Collaborated with MIT Lincoln Labs to characterize advanced processing technologies being developed for silicon-on-insulator CMOS devices; Developed and tested high-resolution, high-vacuum goniometer for

	synchrotron grazing incidence x-ray photoelectron spectrometry; Installed and validated field emission scanning electron microscope with x-ray analyzer; Developed digital-image visibility standard for electron microscopy; Determined x-ray spectroscopy signal-to-noise requirements for automated X-ray analysis of particles.
FY 1998	Determined accuracy of electron microprobe analysis of thin film composition; Characterized prototype standard TiN thin films on silicon; Developed a method for improved elemental analysis of particles in the scanning electron microscope; Developed electron diffraction analysis software for the compound analysis and identification of thin films; Collaborated with MIT Lincoln labs to optimize and characterize processing parameters for advanced titanium silicide thin films.
FY 1999	Apply grazing incidence x-ray photoelectron spectroscopy to characterize oxygen on silicon; Perform interdisciplinary study to characterize the accuracy of composition and thickness measurements of dielectric thin films; Characterize the reaction of oxygen atoms with hydrogen-passivated silicon surfaces.

15. Wafer and Chuck Flatness

FY 1996	Completed 300 mm flatness interferometer and made initial chuck distortion measurements; Initiated commercialization activities on thickness interferometer; Scaled up lap to 300 mm, demonstrated rapid silicon polishing process and potential for chem-mechanical process (CMP) applications.
FY 1997	Demonstrated principle of use of Rapidly Renewable Lap (RRL) technology for CMP of sheet oxide, copper and tungsten. Licensed RRL technology to U.S. company; Demonstrated full procedure for phase shifting 300 mm aperture flatness interferometer; Let contract to U.S. company to build 300 mm aperture IR interferometer, based on NIST developed technology, for wafer thickness, thickness variation and bow.
FY 1998	Evaluated application of RRL to photomask blank polishing and repolishing; Installed IR interferometer; Worked with manufacturer to refine the design and construction of XCALIBIR – the NIST x-ray Optics Calibration Interferometer designed for nm uncertainty of flats, spherical and mildly aspheric optical surfaces.
FY 1999	Install and perform initial measurements using XCALIBIR.
FY 2000	Measure extreme ultraviolet (EUV) optics using XCALIBIR; Provide calibration measurements for thickness and flatness for 300 mm wafers, as required by industry.

16. Thin Film Profile Measurement Methods and Reference Materials

FY 1995	Introduced SRM 2137 as first boron implant in silicon standard; Organized profilometry round-robin for Secondary Ion Mass Spectrometry (SIMS) crater depth measurements.
FY 1996	Developed neutron activation analysis protocol for arsenic in silicon; Began developing methods for ultra-shallow profiling using SIMS.
FY 1997	Completed certification measurements of arsenic implant SRM for SIMS; Developed molecular primary ion beam source for SIMS to improve depth resolution; Demonstrated interlaboratory agreement to better than 3% by SIMS in boron implant dose calibration using NIST SRM 2137 as reference.

FY 1998	Investigated delta-doped boron in silicon as prototype depth resolution reference material; Improved output current and stability of polyatomic ion source; Began feasibility study to measure phosphorus implant dose in silicon by radiochemical neutron activation analysis.
FY 1999	Apply polyatomic ion source to depth-profiling of ultra-shallow boron implants in silicon and collaborate with SEMATECH on comparisons; Establish precision of arsenic implant dose measurements using SIMS in collaboration with a commercial collaborator; Arrange to produce phosphorus-implant-in-silicon reference material and make certification measurements for dose.
FY 2000	Produce SIMS depth resolution reference material; Issue phosphorus implant reference material; Apply advanced cluster ion sputter source for depth resolution improvement.

17. Interconnect Materials and Reliability Metrology

FY 1996	Tested polysilicon in sample microelectromechanical systems (MEMS) devices. Explored the use of micromechanical resonators for determining the elastic constants of metal thin films and determined excessively careful specimen preparation to avoid out-of-plane bowing of the freed films would be required.
FY 1997	Measured mechanical properties of metals for low-cost solder bumps; Performed analysis on backscatter Kikuchi diffraction patterns from narrow Cu conductors which had undergone stress voiding; Observed that grain boundary triple junctions that favor rapid stress void growth may not necessarily favor rapid electromigration void growth.
FY 1998	Measured local microstructures in stress-voided interconnects, and local chemistries in blanket films; Measured thermal conductivity in thin film lines using microscale test structures; Assisted outside company in assembling and demonstrating their piezo-actuated microtensile tester, based on NIST's design.
FY 1999	Determine effects of stress voiding on electromigration in narrow aluminum-alloy interconnects; Demonstrate measurement technique for tensile testing of few- and sub-μm-width copper and aluminum interconnect traces using atomic force microscope-type devices to apply and measure the tensile force and the resulting displacement.
FY 2000	Correlate morphology and microstructure of damascene copper interconnect lines supplied by SEMATECH with processing variables; Explore use of advanced microscope technology, SEM and/or AFM, as the experimental environment for thin film tensile testing, to allow observation and testing of sub-μm-width specimens.

18. Experimental Micromechanics by e-Beam Moiré

FY 1996	Extended electron beam moiré measurements to biaxial displacements; Applied technique to measurement of thermal deformation of conductive adhesives.
FY 1997	Measured local stresses and strains in flip-chip on glass structures.
FY 1998	Investigated the feasibility of using the atomic force microscope to make moiré gratings with smaller pitches than possible by electron-beam lithography; Demonstrated the use of electron beam moiré to quantify the

	effect of underfill and solder-mask on the thermomechanical deformations in a flip-chip on organic interconnect structure.
FY 1999	Evaluate new methods for making moiré gratings and demonstrate feasibility; Evaluate improvements, resulting from design changes, in the thermomechanical deformations in a flip-chip on organic interconnect structure.
FY 2000	Implement new method for making a grating with the goal of sub-25 nm pitches; Apply electron beam moiré to measure displacements at suspected interfacial flaws identified by thermal microscopy.

19. Hygrothermal Expansion of Polymer Thin Films

FY 1996	Demonstrated capacitance cell measurement method for out-of-plane coefficient of thermal expansion (CTE) of polymer thin films; Using near infrared spectroscopy, concluded that moisture absorbed from a humid environment by unfilled polyimide and epoxy molding resin is molecularly dispersed.
FY 1997	Provided data on hygroscopic out-of-plane expansion of thin polymer films used in electronic packaging; Worked with standards-setting bodies to consider adopting capacitance cell technique for measuring expansion of thin films.
FY 1998	The newly developed capacitance cell was used to perform measurements on 0.5 mm <0001> oriented single crystal Al_2O_3 samples to obtain its coefficient of thermal expansion (CTE); Results were in excellent agreement with literature values; Developed experimental protocols which reduced the systematic and temperature-dependent relative uncertainties in the thickness from 100 μm/m to 1 μm/m; Demonstrated validity of the data reduction technique for a humid environment.
FY 1999	Complete a capacitance cell modification that will allow CTE measurements of conducting films, as well as measurements on silicon; Work with the Institute for Interconnecting and Packaging Electronic Circuits (IPC) to put forth the capacitance cell as a standard test method; Identify industry's high priority out-of-plane data needs for high density interconnect substrate materials and provide these data to the Center for Information and Numerical Data Synthesis and Analysis (CINDAS); Instrument manufacturers, material suppliers and testing laboratories interested in adopting this technology will be identified and contacted to enhance the industry exposure of this capacitance cell technique).
FY 2000	Conclude the work on the capacitance cell, and in the years beyond 2000 work will be continued with material suppliers and testing laboratories to broaden industrial acceptance of this capacitance cell technology; Correlation between out-of-plane CTE and in-plane CTE for polymer thin films will be examined in terms of the molecular orientation.

20. Solderability Measurements for Microelectronics

FY 1996	Research showing errors present in the interpretation of dynamic and nonisothermal wetting balance tests was published in ASME Journal of Electronic Packaging; Results were incorporated in new standard tests proposed by the Institute for Interconnecting and Packaging Electronic Circuits (IPC) Solderability Committee.

FY 1997	Co-invented a new method to enhance manufacturability and allow improved performance and new temperature ranges for step soldering for die attach and flip chip applications.
FY 1998	Provided leadership of the Materials Task Group work with the National Center for Manufacturing Science (NCMS) Consortium on High-Temperature Fatigue Resistant Solders on phase diagram analyses for solder melting ranges and establishing other critical properties of solder alloys for high temperature die attach and harsh automotive applications.
FY 1999	Determine mechanism that causes failure in through-hole soldering of lead-free solders, working in collaboration with U.S. companies.
FY 2000	Integrate a quartz crystal microbalance into the NIST electrochemical test apparatus to determine the effect of oxide films on solderability and solder/substrate reactivity; This microbalance will allow the amount of each constituent in the oxide film to be determined by means of the electric charge passed and the mass change associated with its electrochemical reduction.

Metrology for Nanoelectronics

Project Leader: Joseph G. Pellegrino

Staff-Years: 4.5 Professionals, 1.0 Technician

Funding Sources: NIST (100%)

Objective: Provide technological leadership to semiconductor and equipment manufacturers by developing and evaluating the methods, tools, and artifacts needed to improve the state of the art in compound-semiconductor growth and nanometrology (measurements on a scale of 10 to 100 nm). Provide measurements of growth and structural parameters in addition to fabrication properties required for the reliable manufacture of nanostructure devices. Develop research materials and methods to improve measurement standards.

Background: The yield and reliability of nanostructure devices (having feature sizes between 10 and 100 nm) critically depend on the quality of the materials and processes that are used to manufacture them. Industry needs NIST to provide the methodology, both experimental and theoretical, to evaluate and improve these materials and processes at resolutions on the order of 10 nm. Improved materials growth, evaluation techniques, and models are needed by the compound-semiconductor industry to manufacture useful and reliable devices based on advanced quantum phenomena. There is a great need for standard reference artifacts to reduce measurement ambiguities and uncertainties.

Current Tasks:

1. Develop an in-situ metrology effort for the real-time, in-situ characterization of advanced III-V epilayers

FY 1994 Designed state-of-the-art molecular beam epitaxy (MBE) facility to specifically address real-time, in-situ measurement of growth parameters critical to improved performance of lattice-matched, thickness-dependent, compositionally controlled heterostructures; Designed a unique state-of-the-art x-ray detector in order to implement, for the first time, x-ray fluorescence as an in-situ compositional probe during MBE growth.

FY 1995 Designed equipment and software for in-situ optical reflectometry; Designed multiple-wavelength reflectometer to improve thickness resolution to 5 nm level.

FY 1996 Used in-situ x-ray fluorescence capability in MBE growth chamber to measure and control composition and possibly thickness of MBE layers; Equipped MBE with in-situ ellipsometer for measuring thickness, composition, and roughness of MBE layers; Initiated plans to implement pyrometric interferometry as an in-situ optical probe to measure temperature.

FY 1997 Correlated x-ray fluorescence probe measurements with RHEED (reflection high-energy electron diffraction) measurements of the composition in InGaAs heterostructures; Implemented an in-situ ellipsometry capability for measuring composition and thickness in real time during growth.

FY 1998 Developed an in-situ method for the optical determination of sample temperature during growth.

FY 1999 Implement a capability for performing accurate Hall measurements of mobility and doping density of III-V material in order to conduct round-robin measurements among GaAs manufacturers; Utilize in-situ reflectance probe to correlate temperature variations occurring during growth with device performance parameters.

FY 2000 Explore requirements for performing multi-probe, real-time, in-situ feedback control; Provide data and real-time measurement methods for controlling the thickness and composition of layered structures during their growth by epitaxial deposition. (*1998 EEEL Strategic Plan*)

2. Develop a measurement infrastructure pertinent to the interface characterization of advanced III-V heterostructures

FY 1993 Characterized interface roughness in low-order aluminum arsenide/gallium arsenide superlattices and determined the influence of the gallium arsenide buffer layer thickness on the subsequent superlattice interface quality; Obtained smoother interfaces in samples with buffer layers with a thickness 250 nm and greater; Using high-resolution x-ray diffraction, showed that the quality of the superlattice interfaces is markedly affected by the growth technique; Also found interfaces were sharper in a migration-enhanced epitaxy sample than in an equivalent superlattice sample grown by the interrupted-growth technique.

FY 1994 Measured anisotropic strain and tilt along orthogonal directions in indium aluminum arsenide/indium phosphide heterostructures used in optoelectronic devices; Used the x-ray standing-wave technique to learn that the buried indium arsenide strained layer in Pseudomorphic High Electron Mobility Transistors (PHEMTs) is only 76% coherent. (Collaboration with Materials Science and Engineering Laboratory)

FY 1995 Correlated roughness properties of MBE-grown aluminum arsenide/gallium arsenide superlattices with carrier mobility in the associated modulation-doped field-effect transistor (MODFET) channel layers; Demonstrated that interface roughness is a function of the growth temperature and that room temperature x-ray diffraction spectra of the roughness can be related to the measured electron mobility in the channel.

FY 1996 Studied interface and structural properties with x-ray diffraction and x-ray standing-wave techniques to optimize layer quality. (Collaboration with Materials Science and Engineering Laboratory)

FY 1997 Used the x-ray standing wave technique to examine bond length contractions in the InGaAs on the GaAs heterostructure system.

FY 1998 Measured the influence of the interface quality on the performance of InGaAs-based MODFET devices using x-ray, optical, and magneto-transport techniques.

FY 1999 Use in-situ spectroscopic ellipsometry to study oxide desorption from GaAs, InAs, and InP surfaces.

FY 2000 Explore the use of curvilinear crystals to focus x-rays during MBE growth; Discuss with industry the feasibility of an in-situ x-ray reflectivity technique to provide real-time thickness and composition data.

3. Develop and address measurement issues pertaining to nanostructure characterization and fabrication

FY 1991	Generated nm-scale patterns on hydrogen-passivated Si by using scanning tunneling microscope (STM) techniques; STM-patterned oxide serves as a mask for selective-area GaAs heteroepitaxy on silicon, an essential step in mating GaAs and silicon device technologies. (Collaboration with Manufacturing Engineering Laboratory)
FY 1992	Grew high-quality GaAs samples for the quantum-Hall resistance standard. (Collaboration with Electricity Division)
FY 1993	Studied nm-scale oxides patterned by means of scanning tunneling microscopy and showed they are readily generated in an air ambient, easily imaged by scanning electron microscopy and other microprobe techniques, capable of surviving realistic processing environments, and useful as masks for etching and selective area growths. (Collaboration with MEL)
FY 1994	Designed a new series of superlattice structures to increase the confinement of the optically produced carriers and obtain stronger exciton peaks. (Collaboration with the University of Iowa)
FY 1995	Continued scanning tunneling microscopy effort (Collaboration with MEL) and made contributions to single electron transistor effort (Collaboration with Division 811); Fabricated "shadow masks" in MBE for use in growing vertically interdigitated optical switches. The interdigitated sample has been metallized and shows proper diode behavior. Characterized sample by photoreflectance while optically biased. Data indicate an upshift of the quantum well energy, as predicted. (Collaboration with the University of Iowa)
FY 1996	Installed focused-ion-beam (FIB) lithography system in MBE chamber for patterning III-V and possibly silicon wafers; Assisted optimization of STM system for measuring nanostructures; Grew specialized heterostructures for electronic and optoelectronic devices. (Collaboration with University of Iowa and others)
FY 1997	Used FIB to direct write on "two-dimensional" electron gas (two dimension electron gas) materials of InGaAs/GaAs heterostructures to produce confinement of the electrons at the nano-scale. The FIB-processed "laterally in-plane gated field-effect transistors (FETs)" demonstrated very good current-voltage and transfer characteristics at room temperature. Overall characteristics are similar to that of silicon depletion-mode MOSFETs.
FY 1998	Utilized FIB lithography to develop research artifacts for improved standards to advance processing metrology.
FY 1999	Integrate FIB and MBE technology to develop research artifacts for improved standards to advance processing metrology.
FY 2000	Investigate the use of FIB technology to fabricate lateral permeable base transistors (PBT); Explore the potential of PBT as a replacement in vacuum tube applications, such as the $100M music industry.

Optical Characterization Metrology

Project Leader: Paul M. Amirtharaj

Staff-Years: 2 Professionals

Funding Sources: NIST (100%)

Objective: Develop and implement advanced and robust optical probes needed by the semiconductor industry. Apply infrared absorption and photoluminescence (PL) for impurity analyses of silicon and advancement of 300 mm wafer technology. Advance and optimize modulation spectroscopy for the study of compound semiconductor materials and microstructures. Collaborate with Nanoelectronics Project and compound-semiconductor-based industries to advance optical in-situ probes. Develop needed spectroscopic measurement methodology, develop standard reference materials, and compile published data to improve device modeling.

Background: Manufacturers of electronic components for a wide variety of applications, extending from digital circuitry for computers to light emitters for optical communication, need reliable analytical methods and well-established standards for characterizing the behavior of elemental and compound semiconductor materials. The continual reduction in feature size set forth in the National Technology Roadmap for Semiconductors (NTRS) for increased packing density and the complex device structures that use 10 to 100 layers place stringent demands on current analytical probes. Further device advances can be commercially realized only with the enhanced yield possible with dependable and specialized characterization. Optical probes are powerful and attractive in analytical applications. They are contactless and nondestructive, compatible with any transparent gas, capable of remote sensing, and compatible with hostile environments and, hence, useful for on-line analyses in semiconductor fabrication facilities and for in-situ probing during growth and processing.

Current Tasks:

1. Develop metrology to identify and quantify impurities in silicon

FY 1988 Assisted American Society for Testing and Materials (ASTM), a voluntary standards organization in the U.S., through its Subcommittee F1.06 in a pilot study on the determination of trace impurities in silicon by photoluminescence; Determined the conversion coefficient for infrared measurement of oxygen in silicon. Wrote two new standard test methods adopted by ASTM: Method F 1188, Interstitial Atomic Oxygen Content of Silicon by Infrared Absorption, and Method F 1189, Using Computer-Assisted Infrared Spectrophotometry to Measure the Interstitial Oxygen Content of Silicon Slices Polished on Both Sides.

FY 1989 Published archival summary and extended report of analysis of International Round-Robin-on-Oxygen conversion-factor for infrared measurements.

FY 1990	Developed fully automated analytical procedure to study oxygen in double-side-polished silicon wafers.
FY 1991	Completed installation and testing of high resolution and high-stability Fourier transform interferometers for impurity analysis in silicon.
FY 1992	Completed oxygen-in-silicon Standard Reference Material (SRM) production methodology.
FY 1993	Completed certification and related measurements for 100 sets of SRM 2551 for Interstitial Oxygen in Silicon. Analysis of data indicates an uncertainty of certification, relative to the master calibration set, of better than 0.17% (2σ). SRMs are required by integrated circuit manufacturers to determine oxygen concentrations.
FY 1994	Demonstrated the use of Fourier transform infrared (FTIR) absorption for measurement of boron and phosphorous in high-purity silicon at densities of less than 10^{12} per cubic cm.
FY 1995	Applied the above capability for Defense Production Act-Title III high-purity silicon materials qualifications. NIST was requested to provide this assay of dopants by the Department of Defense.
FY 1996	Applied spectroscopic and photoconductive probes to investigate the origin of persistent-photoconductivity and/or slow traps in integrated circuit grade silicon.
FY 1997	Applied FTIR spectroscopy to determine the densities of technologically important impurities in silicon, especially integrated circuit grade wafers.
FY 1998	Applied FTIR methodology for characterizing 300 mm silicon wafer materials for emerging integrated-circuit fabrication; Applied technique to study impurities including concentration of interstitial and precipitated oxygen in collaboration with I300I/SEMATECH.
FY 1999	Develop reflection mode FTIR measurement methodology to determine oxygen concentration on low-resistivity silicon wafers for emerging IC fabrication. One of five high-priority NTRS metrology challenges.
FY 2000	Develop infrared ellipsometry to improve accuracy of optical constants measurements.

2. Develop and apply nondestructive optical probes of the electronic behavior of technologically important semiconductor materials and device structures

FY 1990	Developed and published "A Software Program for Aiding the Analysis of Ellipsometric Measurements, Simple Spectroscopic Models" as NIST Special Publication 400-84.
FY 1991	Completed building and testing a state-of-the-art spectroscopic ellipsometer with near monolayer sensitivity; Applied instrument to study real-time oxidation of the gallium arsenide surface.
FY 1992	Provided optical characterization of silicon carbide for x-ray mask application and cadmium zinc telluride substrates for infrared materials growth.
FY 1993	Achieved a critical advance in the quantitative understanding of the optical properties of the silicon dioxide/silicon interface region by conducting accurate spectroscopic-ellipsometry measurements and by developing an analysis that, for the first time, comprehensively accounted for strain and microroughness. This was a necessary step in the development of thin ($d < 10$ nm) silicon dioxide/silicon SRMs.

FY 1994	Advanced the state of the art of photoreflectance spectroscopy for semiconductor analyses through the use of double-modulation and multiple-pump beams. Detailed analysis of complex laser structures was now possible.
FY 1995	Completed one-of-a-kind selective-excitation system operable in the 350 to 1100 nm range and initiated comprehensive defect and impurity analyses in gallium nitride.
FY 1996	Completed automation of the selective excitation system, with capability from the ultraviolet to the infrared region of the optical spectrum, for high-resolution optical spectroscopy. Used system to investigate gallium nitride and related materials; Applied spectroscopic ellipsometry for the optical analyses of ultra thin semiconductor and insulator layers.
FY 1997	Conducted selective-excitation spectroscopy and analysis of dopants, including magnesium and silicon in gallium nitride.
FY 1998	Completed photoluminescence study of SiGe quantum structure grown with H-surfactant assisted growth to optimize growth conditions for Si-based optoelectronic devices.
FY 1998-2000	Collaborate with Nanoelectronics Project and compound-semiconductor based industries to advance optical in-situ probes.
FY 1998-2000	Develop modulation spectroscopy and photoluminescence techniques to obtain accurate measurements of the bandgap of AlGaAs epitaxial layers; Correlate measurements with other analytical techniques and participate in NIST effort to produce an AlGaAs alloy composition standard.

3. Provide coordination and leadership to industry in optical characterization and related activity

FY 1989	Organized and hosted the International Conference on Narrow-Gap Semiconductors and Related Materials in Gaithersburg, MD, June 1989.
FY 1990	Edited and published Proceedings of the International Conference on Narrow Gap Semiconductors.
FY 1991	Developed detailed questionnaire on optical characterization techniques needed by the industry; Presented invited tutorial talk, "Optical Characterization of Electronic Materials," at two-day symposium, Microanalysis of Electronics, organized by ASM International and NIST Office of Microelectronics Programs.
FY 1992	Distributed to major semiconductor companies a questionnaire regarding the use of optical characterization techniques for materials and device analysis by the semiconductor industry.
FY 1993	Wrote chapter on "Optical Properties of Semiconductors" for the *Handbook of Optics*, second edition, for the Optical Society of America and McGraw Hili; Provided review of all important optical properties and techniques for measuring them; Second mailing of optical characterization survey sent out.
FY 1994	Presented an invited review entitled "Optical Properties and Characterization Methods for HgCdTe" at the 1993 U.S. HgCdTe Workshop that emphasized industrial applications for semiconductors. Mercury cadmium telluride (HgCdTe) is a material used to make detectors for infrared light. Carried out analysis of optical characterization survey results.
FY 1995	Organized and conducted the Workshop on Planning for Compound Semiconductor Technology, attended by 60 participants and 6 invited speakers, with a panel discussion. Participants agreed on consensus-based planning to help the North American segment remain competitive.

FY 1996	Presented invited paper entitled "Double Modulation Photoreflectance" at the Symposium on Diagnostic Techniques for Semiconductor Materials Processing, Materials Research Society Fall Meeting, November 1995; Published Proceedings of the International Workshop on Semiconductor Characterization by the American Institute of Physics Press; Published and distributed to industry NIST Special Publication 400-98 containing results of the Optical Characterization Survey.
FY 1997	Contributed chapter on optical properties to book on properties of narrow-gap II-VI semiconductors, "Optical Properties of MCT {mercury cadmium telluride}," in Narrow Gap II-VI Compounds for Optoelectronic and Electromagnetic Applications published by Chapman-Hall, United Kingdom.
FY 1998	Presented an invited seminar on the optical analyses of interstitial and precipitated oxygen in 300 mm silicon wafers.
FY 1999	Contact silicon materials suppliers and IC fabrication companies and examine standards needs beyond SRM 2551 including oxygen in conducting wafers.
FY 2000	Organize meeting of IC industry representatives to build consensus regarding measurement methodolgy and standards for oxygen in conducting IC silicon wafers.

4. Compile near-edge fundamental parameters for III-V binary semiconductors

FY 1996	Initiated the Standard Reference Data (SRD) Project entitled, "Near Band-Edge Fundamental Parameters for III-V Binary Semiconductors."
FY 1997	Completed review of published literature.
FY 1998	Compiled parameter values.
FY 1999	Prepare manuscript detailing result of the review to date for publication in the *Journal of Physical and Chemical Reference Data*; Coordinate with the Office of Standard Reference Data the dissemination of data through the World Wide Web and other appropriate venues.

Scanning-Probe Microscope Metrology

Project Leader: Joseph J. Kopanski

Staff-Years: 4.4 Professionals

Funding Sources: NIST and OMP (100%)

Objective: Provide technological leadership to semiconductor and equipment manufacturers and other government agencies by developing and evaluating the methods, tools, and artifacts needed to apply scanning-probe microscopes and other electrical characterization to semiconductor materials and processes; provide silicon and compound-semiconductor manufacturers with advanced scanning-probe electrical metrology techniques and models to improve device performance and reliability.

Background: The reduction in feature sizes to near 100 nm predicted by the goals of the semiconductor industry for the early 21st century requires new and improved measurement methods to characterize materials and processes to the required 10 nm resolution scale. Industry needs NIST to provide the methodology, both experimental and theoretical, to evaluate and improve materials and processes by implementing scanning-probe microscope-based and traditional electrical techniques. Measurements of the dopant density, lifetime, and mobility of charge carriers in wafers and thin layers are essential for materials and process qualification. The National Technology Roadmap for Semiconductors has challenged NIST with responsibility for developing the technology needed to determine the dopant distribution across a processed silicon wafer to a resolution of 20 nm. Scanning capacitance microscopy is being developed as a new tool to achieve this goal.

Current Tasks:

1. Develop scanning-probe microscopy and models for dopant profiling

FY 1989 Demonstrated two-dimensional mapping of silicon resistivity striations with resolution of 40 μm by high-density four-probe structures.

FY 1990 Demonstrated and verified high-spatial-resolution resistivity mapping with ion-implanted test structures and theoretical modeling; Showed that lateral resistivity variations over dimensions as small as 45 μm can be mapped, which has important application to gallium arsenide and mercury cadmium telluride materials.

FY 1991 Applied fine-scale resistivity mapping technique to specimens of mercury cadmium telluride; Showed that nonuniformity patterns are correlated with the type of crystal growth, LPE (liquid-phase epitaxy) or SSR (solid-state recrystallization).

FY 1992 Prepared detailed specifications for a scanning tunneling/atomic force microscope for scanning capacitance microscopy (SCM); the microscope is one of the first to be made with a large sample stage, compatible with semiconductor wafers with diameters to 250 mm. Began development of the capacitance-sensitive circuit and theoretical modeling of the SCM measurement.

FY 1993 Designed, constructed, and tested an SCM for nanoscale (10 to 100 nm) profiling of semiconductor junctions; the design is the first to take advantage of incorporating a commercial atomic force microscope (AFM).

FY 1994 Obtained capacitance-voltage curves with the SCM as a function of probe position. Implemented tapping-mode capability on SCM to reduce damage to probe and specimen and give improved reproducibility and signal-to-noise ratio. Developed three-dimensional collocation code to solve Poisson's equation for SCM.

FY 1995 Demonstrated a new mode of scanning capacitance microscopy: imaging the high-frequency capacitance directly. This enables imaging of metal lines on an insulating substrate for overlay metrology. Produced two-dimensional (2D) images of dopant profiles from cross-sectioned silicon wafers with better than 30 nm resolution; Modeled the probe-ambient-insulator region with commercial code, which solves Laplace's equation in three dimensions (3D); Combined solutions with those from 3D collocation code for semiconductor region to obtain total solution of electric potential; Computed capacitance as a function of bias voltage for uniformly doped silicon wafer.

FY 1996 Established reliable techniques to obtain SCM data of carrier profiles; Applied SCM method to overlay metrology; Obtained solutions in 2D and 3D for the charge density in doped silicon wafers and simulate SCM data; Developed useful, simple methodology to relate SCM data to dopant profiles.

FY 1997 Interacted strongly with equipment and user community to transfer NIST technology; Validated SCM model and methodology from measurements on well-known samples provided by industry; Used developed code to produce model database; Investigated ways of including dopant gradient effect; Implemented data conversion methodology in a user-friendly and 2D format; Developed tapping-mode SCM for overlay measurements; Identified SRMs needed to support industry use of SCM measurement standards.

FY 1998 Improved spatial resolution and accuracy of SCM 2D dopant profile measurement by including the effects of the dopant gradient; Refined the SCM "wafer-to-profile" measurement methodology; Transferred the NIST SCM models and image conversion routines to industrial users.

FY 1999 Implement dual bias SCM image mode for p-n junctions; Add features to SCM image interpretation software; Develop improved understanding of the effect of SCM sample surface preparation to improve the accuracy and repeatability of extracted carrier profiles; Relate 2D carrier profiles measured with SCM to {semiconductor} technology computer-aided design (TCAD) simulations of dopant profiles fabricated with the same conditions; Complete assessment of inversion algorithm used to extract dopant profiles from scanning capacitance data with material having known profiles supplied by industry. (*1998 MSL Strategic Plan*)

FY 2000 Continue refinement of SCM model/measurement formalism to keep pace with the TCAD 2D dopant profiling spatial resolution (<10 nm) and accuracy goals; Compare SCM measurements of ultra-shallow junction technologies, such as BF_2 ion implants, with corresponding TCAD simulations; Calibrate TCAD simulators using SCM measured carrier profiles.

2. Develop scanning-probe microscopes (SPM) and models for semiconductor and device electrical characterization. (New task)

FY 1998	Investigated measurement of optically stimulated capacitance transients with SPMs for development of a microscope sensitive to semiconductor lifetime; Investigated the ac impedance measurement techniques and models necessary to implement an ac version of nano-spreading resistance.
FY 1999	Refine optically pumped SCM for carrier lifetime measurements, investigate alternate SPM-based approaches for lifetime measurement; Begin development of models to make SPM-based lifetime measurements quantitative; Apply intermittent-contact-SCM to dielectric layer characterization and lithographic overlay applications; Develop SPM measurement techniques and surface preparation for compound semiconductors.
FY 2000	Investigate potential 3-D dopant profiling techniques such as the Scanning Microwave Microscope.

3. Utilize conventional electrical characterization technique in support of scanning probe microscopes.

FY 1998	Continued development of the photo-Hall effect measurement; Used existing deep-level transient spectroscopy (DLTS) techniques to characterize slow time constant optical effect in silicon wafers used for resistivity SRM; Maintained proficiency in SEM model codes.
FY 1999	Use conventional electrical measurements to improve understanding of scanning probe-based optically pumped capacitance-voltage (C-V) and ac impedance measurements; Relate C-V measurements of oxides on silicon made with a calibrated mercury probe to SCM measurements of the same material.
FY 2000	Apply existing expertise in electrical characterization to support SPM-based characterization efforts; Perform electrical characterization of advanced materials supplied by collaborators at NIST and from industry.

Thin-Film Process Metrology

Project Leader: James R. Ehrstein

Staff-Years: 3.2 Professionals, 2.0 Technicians

Funding Sources: NIST (100%)

Objective: Develop new and improved measurements, models, data and reference materials, and mechanisms for traceability to NIST to enable better and more accurate measurements of select critical silicon-technology thin-film process parameters.

Background: Fabrication of thin films of various types is a fundamental building block in semiconductor device fabrication. The rapid, continuing requirements for ever thinner films place increasingly stringent requirements on the composition and structure of those films. This, in turn, places increasingly stringent requirements on the metrology tools and procedures used for process development and process monitoring. The drive in the industry is toward establishing in-situ process-monitoring capabilities for all major process steps. Yet as layers and structures are refined and shrunk, improved in-line, at-line, and off-line capabilities will also be necessary to verify the relations between material parameters resulting from the process steps and the parameters being monitored in situ. Current focus is on dielectric layers, particularly the ultra-thin dielectric layers used for transistor gate structures. The National Technology Roadmap for Semiconductors identifies robust gate dielectrics with 2 nm thickness as a specific near-term on-chip materials issue and gate dielectrics with sub 1 nm oxide-equivalent thickness as an issue that will impact the ability to achieve the 15-year goals of the Roadmap. NIST work will provide the metrology support required for the controlled processing of these films in the semiconductor manufacturing environment.

Current Tasks:

1. Establish traceability to NIST for measurements of critical dielectric layers of silicon

FY 1988	Certified and released the first Standard Reference Materials (SRMs) for thickness of silicon dioxide, at thicknesses from 50 nm to 200 nm.
FY 1989	Developed computer code and released documentation for ellipsometric analysis of thickness of dielectric layers and interface region.
FY 1992	Developed and certified SRMs for 14 nm and 25 nm silicon dioxide thickness.
FY 1994	Developed and certified 10 nm silicon dioxide thickness SRMs; Completed intercomparison with nine select laboratories for measurements of 10 nm oxides; Demonstrated interlaboratory repeatability consistent with industrial requirements. National Technology Roadmap for Semiconductors reaffirms critical nature of ultrathin gate oxide fabrication control.
FY 1995	Developed cooperative program with commercial source of reference materials to establish traceability to NIST for thin oxide materials.

FY 1996	Initiated Cooperative Research and Development Agreement (CRADA) experiments to establish traceability of ellipsometer-based Reference Materials.
FY 1997	Completed CRADA experiments and analysis to demonstrate traceability to NIST within 0.1 nm for single-wavelength ellipsometry measurements of oxide films between 4.5 nm and 100 nm; Organized workshop for industry experts in the optical characterization of thin dielectric films to focus on issues of standards and traceability for future generations of very thin films.
FY 1998	Conducted workshop on thin dielectric films and began to implement workshop recommendations for improving traceability to NIST; Evaluated requirements to reduce uncertainty of NIST ellipsometry measurements in order to keep pace with NTRS requirements.
FY 1999	Implement ellipsometry laboratory improvements to establish spectroscopic capability and reduce the uncertainty of NIST ellipsometry measurements; Prototype and evaluate NTRM measurement exchange with one or two laboratories for silicon dioxide films as thin as 2 nm.
FY 2000	Formalize NTRM program for next-generation silicon dioxide films; Prototype and evaluate NTRM measurement exchange with one or two laboratories for silicon nitride films or gate stacks, as appropriate.

2. Develop knowledge base of relation between silicon/dielectric layer interface properties and the determination of dielectric layer thickness and structure; apply knowledge to understanding the relation between electrical and optical determination of layer thickness

FY 1994	Used spectral ellipsometry measurements to validate interface model used for single-wavelength oxide Reference Material certification. The National Technology Roadmap for Semiconductors affirms the need to understand and control the surface on which gate oxide is grown.
FY 1995	Established capability for "Weak Localization" measurement technique to extract quantitative measure of electronic roughness at layer-interface.
FY 1996	Extended this technique to the quantitative measurement of interface roughness in typical silicon metal oxide-semiconductor field-effect transistor (MOSFET) test structures.
FY 1997	Began to develop understanding of optical, physical, and electrical determinations of dielectric layer thickness, structure, and interface with comparison analysis of SiO_2 film by spectroscopic ellipsometry, x-ray, and neutron reflectivity.
FY 1998	Established state-of-the-art ultra-low noise electrical measurement capability and began implementation and evaluation of sophisticated electrical models for the interpretation of film thickness with emphasis on nanometer-scale SiO_2 films.
FY 1999	Apply electrical methods to determine the thicknesses of very thin dielectric films with emphasis on silicon-dioxide and oxynitrides; Correlate results with ellipsometric and physical determinations of thickness in order to identify preferred electrical models and algorithms for thickness determination and to improve agreement between electrical and optical thickness scales for reference material.
FY 2000	Extend optical, electrical, and physical characterization comparisons of layer and interface structure to oxide/nitride stacks and suitable high-K dielectric materials.

3. Develop high-accuracy database for optical constants of silicon and its dielectric layers at elevated temperatures used for integrated circuit processing

FY 1995	Contracted for design and fabrication of customized vacuum chamber with in-situ ellipsometry and high-temperature film growth capability. The National Technology Roadmap for Semiconductors asserts the need for in-situ metrology of film thickness and gate dielectric composition.
FY 1996	Installed test chamber at NIST; Began test and evaluation of chamber.
FY 1997	Completed test of chamber and instrumentation, and developed control and analysis software.
FY 1998	Completed test of fast-scanning spectroscopic ellipsometer; Implemented and calibrated high temperature wafer heater.
FY 1999	Develop and evaluate suitable silicon surface preparation chemistry and measure optical constants of silicon at high temperatures.
FY 2000	Measure optical constants of other critical films of silicon at elevated temperatures.

4. Develop improved optical models and reference data for spectroscopic ellipsometry analysis of ultra-thin gate stacks and ultra-high K materials projected for use as dielectrics for CMOS gates (and related IC applications)

FY 1998	Began expansion of NIST code for ellipsometric analysis and modeling for use in SEMATECH Gate Dielectric Metrology project.
FY 1999	Begin determination of best optical models for available oxide/nitride films in conjunction with analytical and physical analyses; Determine range of optical constants for available films of contending high-K dielectric materials from various processes.
FY 2000	Begin determination of best dispersion models for high-K materials in thickness range appropriate for gate dielectrics; Determine suitability of optical index values obtainable from state of the art high-K dielectric films for reference data purposes.

Metrology for Simulation and Computer-Aided Design

Project Leader: Allen R. Hefner

Staff-Years: 3.8 Professionals

Funding Sources: NIST and OMP (86%), Other Government Agencies (14%)

Objective: Facilitate the efficient and reliable application of semiconductor computer-aided design (CAD) tools by: developing metrology necessary for providing model data, developing methods for simulator model validation, and providing simulation capability benchmarks; develop additional models and techniques necessary for advanced device, process, package, and system simulation; and support and participate in national and international standards and industry organizations.

Background: The project addresses needs at the boundary between model and simulator development and the application of computer-aided-design tools. The National Technology Roadmap for Semiconductor identifies modeling and simulation as cross-cutting technologies, and the availability of calibrated and easy-to-use technology computer-aided-design tools for device, process, and circuit simulation as areas requiring development and support to achieve the 15-year goals of the Roadmap. The Roadmap also states that using accurate computer models shortens time scales, lowers costs, and increases quality of each technology area. Advanced device electrical and thermal characterization procedures and validation of models used in computer-aided-design tools have not kept pace with the application of the new device types and processes. This project's goals are to develop methods and procedures and to support an industry infrastructure for establishing model accuracies.

Current Tasks:

1. Develop metrology for Micro-Electro-Mechanical Systems (MEMS) and package thermal simulations

FY 1997 Developed validation procedure for compact package models for use in computational fluid dynamics simulations in natural convection environment; Provided demonstration for multiple-package, highly confined, highly interacting system.

FY 1998 Developed methodology and program to convert CMOS-based MEMS layout structure files (CIF format) into analog hardware description language circuit simulation files (MAST format) for electro-thermal MEMS simulations.

FY 1999 Develop and fabricate test structures for extraction of physical parameters of MEMS devices to be used for calibration and validation of CIF-to-MAST electro-thermal simulation methodology; Characterize the capabilities of the convective heat transfer facility calibrating heat flux gages and the gas phase conduction facility for applications to critical technologies. (*1998 MSL Strategic Plan*).

FY 2000 Apply CIF-to-MAST electro-thermal simulation methodology for optimization of NIST MEMS-based flow rate sensor.

2. Develop metrology for integrated system simulation capability

FY 1997 Developed required electrical measurement techniques to support integrated system simulation capability for U.S. Navy's Power Electronic Building Block Program's modules and chips and also the Partnership for a New Generation Vehicle electric vehicle propulsion systems; Developed module thermal model for inclusion in system simulation programs.

FY 1998 Developed metrology for integrated package and circuit board electrical interconnect simulation and validation; Developed metrology and simulation methodology for Insulated Gate Bipolar Transistor (IGBT) power device reliability.

FY 1999 Develop varied characteristic impedance Time Domain Reflectometry for improved interconnect characterization; Measure avalanche sustaining reliability of different commercial IGBT types including punch through and non-punch through, large area and paralleled die modules, and various speed-up technologies; Develop high-speed transient infrared thermal metrology and apply to identification of avalanche sustaining filaments.

FY 2000 Apply varied characteristic impedance TDR metrology to characterization of advance micro-processor voltage regulator interconnect technology.

3. Develop models and validation metrology for circuit simulation

FY 1997 Began draft of IEEE-recommended practice standard for Insulated Gate Bipolar Transistor (IGBT) model validation and completed the draft of IEEE-recommended practice standard for microelectronic MOSFET model validation procedures; Applied model validation procedures to IGBT component libraries provided in commercial simulator software, and recommended improvements for commercial version of NIST IGBT model.

FY 1998 Investigated tools for improving analog-hardware-description language model development productivity; Completed draft of IEEE standard for micro-electronic MOSFET circuit simulator model validation; Transferred NIST VDMOSFET model and enhanced IGBT model to system simulator software vendors; Developed test method for validating power device models for soft switching applications.

FY 1999 Form balloting committee for micro-electronic MOSFET model validation standard; Apply soft switching model validation procedures to IGBT component libraries provided in PSPICE and Saber™, and develop enhancements in the NIST IGBT model for soft switching applications.

FY 2000 Complete draft of IGBT model validation standard; Apply micro-electronic MOSFET model validation standard to models provided in commercial software tools.

4. Develop physics, validation metrology, and benchmarks for device simulation

FY 1996 Determined suitability of aluminum gallium arsenide mobility models in commercial device simulators.

FY 1997 Investigated with industry partners methods for measuring mobilities in aluminum gallium arsenide and other compound semiconductor devices;

	Investigated influence of the mobility models on device simulation; Investigated with industry partners methods of implementing aluminum gallium arsenide mobility models into device simulation programs.
FY 1998	Investigated the development of benchmarks for determining suitability of effective intrinsic carrier concentration and mobility models in device simulators for compound semiconductor devices.
FY 1999	Investigate procedures for implementing NIST AlGaAs effective intrinsic carrier concentration and mobility models into commercial device simulators; Investigate suitability of new tools for rapid prototyping of semiconductor device physics.
FY 2000	Use simulator that accounts for quantum mechanical tunneling to calibrate and benchmark simulators for ultra-thin layered structures.

5. Develop metrology for calibration and benchmarking of process simulation parameters

FY 1997	Configured computer-aided design systems to run SUPREM4 process simulation program.
FY 1998	Used University of Texas-MARLOW to calculate two-dimensional boron implant profiles at mask edge for comparison with Scanning Capacitance Microscope (SCM) measurements.
FY 1999	Use University of Texas-MARLOW and TSUPREM4 to calculate two-dimensional boron implant and anneal profiles for comparison with SCM measurements; Investigate use of SCM to calibrate process simulator implant and anneal models.
FY 2000	Investigate the use of SCM to calibrate and validate UT-MARLOW and TSUPREM4 models for two-dimensional BF_2 implant and anneal damage enhanced diffusion.

Metrology for Process and Tool Control

Project Leader: Michael W. Cresswell

Staff-Years: 2.5 Professionals, 0.2 Guest Scientist, 1.4 Technician

Funding Sources: NIST and OMP (84%), Other Government Agencies (16%)

Objective: Develop test-structure-based electrical metrology methods and related reference materials with primary emphasis on overlay and linewidth metrology and calibration; contribute to standards groups supporting the development of a litho-metrology infrastructure for the semiconductor industry.

Background: Successive generations of integrated circuits are characterized by the widths of the narrowest lines that are replicated during the wafer-fabrication process. Control of gate length is a key factor driving device performance and yield. Overlay control is necessary for yield maintenance and economically viable manufacturing. Metrology for monitoring these parameters has been identified in the National Technology Roadmap for Semiconductors as a central requirement for maintaining fabrication-process control. The requirements of linewidth and overlay metrology are increasing as the complexity and density of integrated circuits increase from one generation to the next. Critical dimension (CD) and overlay tool manufacturers and users are expressing concern that current instrument technology may not have the capability to perform at the sub-quarter-micrometer level. However, electrical test structures have a measurement reproducibility that conforms with future projected error budgets and may be suitable as a low-cost means of reference-material certification to support the extension of current instrument technology to meet the requirements of the roadmap out-years.

Current Tasks:

1. Develop metrology for electrically-measured feature linewidth

FY 1988	Documented and extended statistical model and error analysis for characterizing the performance of a submicrometer lithography based on electrical test structure measurements.
FY 1989	Demonstrated lithography-process diagnosis using rule-based analysis of spatial linewidth variations extracted from multiple design-rule structures replicated in polysilicon on 100 mm wafers.
FY 1990	Developed and demonstrated guidelines for characterizing electron-beam pattern-generator linewidth control by extracting electrical linewidth measurements from electrical test structures.
FY 1991	Compared measurements extracted from scanning electron microscope measurements and measurements using electrical cross-bridge structures having design linewidths to 0.3 μm.
FY 1992	Applied principles of empirical tap-width correction to linewidth extraction from cross-bridge test structures having bridge lengths shorter than 10 μm.

FY 1993	Demonstrated static measurement precision of 1 nm for lines with 350 nm design linewidths.
FY 1994	Compared measurements of lines having drawn widths from 0.35 µm to 1.5 µm by a range of metrological techniques including optical, electrical, and scanning electron microscopy.
FY 1995	Showed agreement to within 10 nm for several materials for electrical linewidth and the NIST Molecular Measurement Machine (M^3) when operating in scanning-tunneling-microscope mode. Optical and electrical linewidth measurement differences are on the order of 100 nm. (collaboration with MEL)
FY 1996	Developed first electrical linewidth test structures with atomically-planar sidewall vertical features having known sidewall slopes in monocrystalline material; Tested to identify origins of critical dimension metrology methods divergence.
FY 1997	Developed electrical test structures having features with atomically-planar vertical sidewalls, which will enable co-calibration by transmission-optical, electrical, scanning-probe, and scanning electron-microscope metrology.
FY 1998	Fabricated and evaluated CD artifacts having features with known sidewall slopes patterned in silicon-on-insulator material; Began comparison of properties of BESOI- and SIMOX-based prototype CD reference photronics-materials; Began development of application of electrical test structures to CD measurements (known as ECD) techniques to on-reticle metrology.
FY 1999	Investigate utility of substrate biasing on electrical testing to reduce uncertainties of physical CD certification; Fabricate ECD artifacts in highly degenerate single-crystal silicon to reduce uncertainty of physical CD estimates.
FY 2000	Develop process for certifying linewidths of single-crystal CD reference materials with HRTEM imaging.
FY 2001	Provide technical and traceability support for commercial production of a Linewidth Standard for accurate calibration of metrology tools to support the 100 nm generation of lithography for integrated circuits. (*1998 EEEL Strategic Plan*)

2. Develop metrology for electrical overlay and registration

FY 1991	Demonstrated novel electrical test-structure based on the linear voltage-dividing potentiometer for the determination of accuracy and precision of feature placement by primary-pattern-generator systems; Demonstrated sub-15 nm electrical metrology with commercially-available test equipment.
FY 1992	Introduced voltage taps extending across the current-carrying bridge for feature-placement metrology, thereby substantially eliminating process-induced shifts resulting from asymmetrical inside-corner rounding.
FY 1993	Demonstrated the dynamic precision of electrical overlay test structures to be 1.5 nm, and their uncertainty less than 10 nm, by comparing electrical measurements with those made by the NIST Line-Scale Interferometer. (collaboration with MEL)
FY 1994	Developed and obtained patents for improved optical overlay-instrument calibration substrates and for electrical certification of graduated scales.
FY 1995	Designed, fabricated, and electrically tested substrates at multiple sites co-inspected by the NIST Line-Scale Interferometer. (collaboration with MEL)

FY 1996	Presented paper at SEMATECH to invited industry audience on new hybrid optical-electrical test structure to facilitate pixel-calibration of optical overlay systems; Initiated a consortium with industry to evaluate new overlay-metrology methods; Developed plan to implement mix-and-match overlay metrology for 193 nm lithography system.
FY 1997	Incorporated electrical edge-detectors into the design of hybrid optical-electrical test structures to enable fabrication of artifacts for estimation of process-specific wafer-induced shift; Developed a wafer-fabrication process for fabrication of structures for tool-induced shift estimation.
FY 1998	Fabricated prototype structures for estimation of tool-induced and process-specific wafer-induced shift; Began evaluation of suitability of large-area wafer-grade micro-machined silicon to provide reference grids for precision-metrology tool control; Began evaluation of scanning-capacitance for process-induced shift estimation.
FY 1999	Fabricate and evaluate prototype overlay reference artifacts in SOI films using MEMS (micro-electro-mechanical systems) processes; Investigate electron-diffraction imaging for certification of overlay artifacts.
FY 2000	Design and fabricate edge detectors for extraction of overlay and certifying overlay reference materials.

3. Contribute to development of x-ray lithography mask and metrology infrastructure

FY 1992	Led development of consensus among eight DoD industry contractors for mask-support ring dimensional standards for DARPA x-ray lithography based on finite-element analysis of residual distortion for beam-line applications.
FY 1993	Extended capability of mask-support ring dimensional standard for point-source systems.
FY 1994	Drafted initial international voluntary standard for x-ray mask configurations and chaired video-conference between U.S.-industry representatives and a Japanese task force on convergence between North American and Japanese standards.
FY 1995	Prepared revisions to draft of U.S. standard and obtained concurrence with the Japanese on almost all major points previously under contention.
FY 1996	Developed further agreement between U.S. industry and Japan on final draft of new international voluntary x-ray mask standard.
FY 1997	Submitted revised draft of the x-ray mask standard agreed to, in principle, by both Japanese and American companies to SEMI balloting process.
FY 1998	Continued to provide consultation to international x-ray community on standard non-circular masks.
FY 1999	Prepare draft of international standard for both circular and square format x-ray masks that conform with both Japanese and U.S. requirements.
FY 2000	Orchestrate adoption of standard by the international community.

Gate Dielectric and Interconnect Reliability Metrology

[This project combines the former "Dielectric Reliability Metrology" and "Interconnect Reliability Metrology" projects.]

Project Leader: John S. Suehle

Staff-Years: 3.2 Professionals, 2.0 Graduate Research Fellow

Funding Sources: NIST and OMP (62%), Other Government Agencies (38%)

Objective: Provide domestic semiconductor manufacturers with improved test structures, test methods, models, and novel sensor-based metrology for improving device reliability and monitoring tool performance and manufacturing processes.

Background: The domestic semiconductor industry is aggressively scaling gate oxides in microelectronic devices to achieve higher chip performance and packing density. Reduced time-to-market, new oxide processes, and advanced metallizations require fast and effective reliability characterization techniques. Physically correct models and tests to predict reliability of thin oxides and interconnects under dc and ac operating conditions are needed. As the semiconductor industry rapidly builds capacity to meet worldwide demand for their products, national standards are required to characterize dielectric integrity and interconnects for plant-plant and vendor-customer evaluation. Finally, it has been recognized by the National Technology Roadmap for Semiconductors that reliability and novel in-situ process sensors are required to manufacture competitive, cost-effective semiconductor products and improve manufacturing process and tool control.

Current Tasks:

1. Develop dielectric reliability standards and metrology methods

FY 1995 Revised and had approved by committee ballot two new Joint Electron Device Engineering Council (JEDEC) standards: “General Guidelines for Designing Test Structures for the Wafer-Level Testing of Thin Dielectrics” and “Addendum on Test Criteria for the Wafer-Level Testing of Thin Dielectrics.” The first standard has been approved by JEDEC Council. Awaiting Council approval on second standard.
Demonstrated differences of electric field and temperature dependence of time dependent dielectric breakdown (TDDB) for bimodal failure distributions; Performed TDDB characterization of 9 to 22 nm thick oxides with unipolar and bipolar pulsed bias stress over wide range of temperature and electric field.

FY 1996 Coordinated joint JEDEC-ASTM (American Society for Testing and Materials) working group to develop standard voltage ramp gate oxide integrity tests; Studied charge-trapping characteristics of thin oxides when subjected to dc or pulsed voltage stress.

FY 1997 Continued nine-laboratory round robins to evaluate new ASTM-JEDEC V-ramp Test for ultra-thin oxides; Developed new model to extract long-term

	TDDB acceleration parameters from highly accelerated Q_{bd} tests; Technique reduces test time by over 1 order of magnitude and can be used in a production environment; Showed that electrically active defects are not produced and responsible for breakdown during long-term low-electric field aging; Utilized Fowler-Nordheim tunneling technique to monitor latent, electrically inactive defects that are produced in gates oxides during low-electric field stress.
FY 1998	Developed improved lifetime model for gate oxides less than 5 nm thick and operating in the direct tunneling regime under either time invariant or varying voltages operating under dc and ac conditions; Worked with ASTM and JEDEC to modify and produce new standard gate oxide integrity test procedures that will be effective in characterizing ultra-thin gate oxides having thicknesses down to 2 nm.
FY 1999	Conduct study using electron spin resonance (ESR) to investigate the role of oxygen vacancy defects in the aging and breakdown in ultra-thin SiO_2 films; Perform electrical and reliability characterization of alternative gate dielectrics including Al_2O_3, Si_3N_4, and TA_2O_5; Lead a JEDEC and ASTM effort in conducting interlaboratory experiments to evaluate new gate oxide integrity test for ultrathin dielectrics. (*1998 MSL Strategic Plan*)
FY 2000	Investigate use of nano-probe oxidation technique as an in-situ metrology tool for characterizing the quality of ultra-thin gate dielectrics.
FY 2001	Develop improved measurements for making thinner insulating layers in transistors in integrated circuits, and for identifying better insulating materials, with thicknesses down to at least 2 nm. (*1998 EEEL Strategic Plan*)

2. Develop micro-hotplate gas sensor

FY 1995	Designed a new micro-hotplate chip, NIST21, and had it fabricated by an outside source. The devices have tungsten metallization for improved heater stability and reliability.
FY 1996	Demonstrated four-element gas sensor array for compositional gas analysis with CSTL.
FY 1997	Demonstrated chemical sensor prototype in industrial application to monitor manufacturing process of titanium matrix composites.
FY 1998	Completed development of multi-element chemical sensor array that incorporates several different metal-oxide sensing films; Collaborated with MIT Lincoln Laboratories to produce micro-chemical sensor arrays in Lincoln's advanced CMOS process. These devices will incorporate planarized top contacts via damascene plugs.
FY 1999	Demonstrate multi-element chemical sensor array on MOSIS chip with integrated control circuitry.
FY 2000	Complete characterization of custom micro-chemical sensor arrays provided by Lincoln Laboratories.

3. Develop electromigration standards and metrology methods

FY 1995	Documented the use of Matthiessen's rule for determining aluminum film thickness and line cross-sectional area from electrical resistance measurements.

FY 1996	Completed first phase of interlaboratory experiment to assess reproducibility of aluminum film thickness measurements; initial results show good agreement.
FY 1997	Continued plans for selective thermal conductivity measurements of silicon dioxide thin films and modeling experiments to improve characterization; Continued an inter-laboratory experiment to verify the reproducibility of thickness measurements of thin metal film using Matthiessen's rule.
FY 1998	Deferred electromigration testing to establish degree of correlation between t_{50} values and crystallographic measures determined by NIST/Materials Science and Engineering Laboratory's Reliability Divisionr because of a lack of test parts.
FY 1999	Evaluate, in collaboration with workers at SEMATECH, the use of electrical method to determine the geometry of copper interconnect lines.
FY 2000	Complete draft of a JEDEC test method procedure for measuring the electrical thickness of metal films and the area of interconnect lines.

4. Develop improved temperature coefficient of resistance (TCR) metrology
[Task began in FY 1990; completed in FY 1996; information included for completeness.]

FY 1995	Documented the results of the JEDEC inter-laboratory experiment for TCR, joule heating, linewidth, and hot-chuck measurements; Authored revised bias and precision section for JEDEC standard JESD33 (Standard Method for Measuring and Using the TCR to Determine the Temperature of a Metallization Line) for JEDEC.
FY 1996	Revised standard JESD33 distributed by JEDEC; News release announcing revised standard prepared by NIST. Task completed.

5. Promote Building-in Reliability (BIR) infrastructure development

FY 1995	Prepared three papers to promote a more rapid transition from a testing-in-reliability to a building-in-reliability approach in the semiconductor industry.
FY 1996	Worked with members in the semiconductor industry to develop plans and to organize a seminar on building-in reliability (BIR) for customers of semiconductor vendors.
FY 1997	Provided leadership to U.S. industry in the area of BIR; Served as editor of e-mail newsletter for BIR newly formed Special Interest Team; Published invited paper on BIR in *Microelectronics and Reliability* with industrial co-authors; Made plans for other seminars and papers with industrial colleagues.
FY 1998	Served as editor of newsletter; Spearheaded efforts to develop industry consensus definition of BIR; Collaborated with industry representatives in development of papers addressing significant BIR issues. Task completed.

Micro-Electro-Mechanical Systems (MEMS)

Project Leader: Michael Gaitan

Staff-Years: 1.5 Professionals, 1.7 Guest Scientists, 0.5 Graduate Research Fellow, 0.2 Faculty Hire

Funding Sources: NIST, Other Government Agencies

Objective: Provide domestic industry with MEMS-based test structures and test methods for characterizing the thermo-electro-mechanical properties of thin films used in ICs and MEMS manufacturing, work with IC and MEMS foundries to develop infrastructure for improved accessibility of MEMS manufacturing, and research and develop novel metrology applications of MEMS technology.

Background: The emerging technology of Micro-Electro-Mechanical Systems (MEMS) utilizes mechanical structures, fabricated in an integrated-circuit-based process, to miniaturize mechanical elements and integrate them within the ICs. Applications for this technology include pressure sensors, inertial sensors, gas and fluid regulation and control, process control, optical switching, and mass data storage. Market studies forecast a worldwide market of nearly $10 billion by the year 2000, enabling almost $100 billion in new or improved systems. Domestic industrial needs for MEMS manufacturing include the development of standardized characterization techniques for thin-film electro-mechanical properties. Such MEMS-based test structures also have applications for critical needs identified in the National Technology Roadmap for Semiconductors. These needs include the characterization of thin-film thermo-mechanical properties in ICs, measurement of electrical properties of thin films in the 2 GHz to 10 GHz frequency bands, and sensors for in-situ semiconductor fabrication process monitoring and control. Meeting these objectives will enable industry to manufacture competitive, cost-effective products, and improve manufacturing processes, device performance, and device reliability.

Current Tasks:

1. Develop electro-mechanical test structures/promote MEMS infrastructure

FY 1992 Designed test structures to determine design rules needed for design and fabrication of complementary metal-oxide semiconductor (CMOS)-compatible MEMS devices.

FY 1993 Submitted a design library to University of Southern California/Information Sciences Metal Oxide Semiconductor Informational Services (MOSIS) of CMOS-compatible MEMS devices and test structures. MOSIS announced its official support of CMOS compatible MEMS as a result of this effort.

FY 1994 Designed a set of test chips in collaboration with the Massachusetts Institute of Technology, Case Western Reserve University, and the University of California at Berkeley, and fabricated through the Microelectronics Center/North Carolina MUMPs service that contained electro-mechanical test structures. A test chip was also designed in collaboration with others at NIST.

FY 1995 Procured and installed an optical profilometer interferometric microscope system for measurement of deflections of the electro-mechanical test structures; Began deflection measurements of the MEMS test structures.

FY 1996 Worked with the NIST MEMS Strategic Planning Committee to hold a Strategic Planning Workshop in November 1995 in an effort to determine whether there is a need for a NIST-wide MEMS program; Completed characterizations of cantilever and fixed beam MEMS test structures; Competence proposal submitted and review held.

FY 1997 Continued work on MEMS-based test structure development. Developed a model that describes the fixed-fixed (attached at both ends) beam deflection data. Worked with MOSIS and the MEMS technical community to correct run-to-run uniformity problems with the open design rule and to attempt a CMOS foundry-compatible process through alternative technologies. Organized and held the first MEMS Test Structure Workshop at Transducers 97; Organized a second MEMS Test Structure Workshop at Society for Optical Instrumentation Engineers (SPIE) MEMS Conference; Developed a white paper on MEMS-based test structures for CMOS and submitted a proposal to NIST Office of Microelectronic Programs for this work.

FY 1998 Demonstrated the concept of using MEMS-based test structures in CMOS technology to characterize the thermo-electro-mechanical properties of thin films in ICs; Continued work on the development of standardized MEMS test structures for the MEMS community and continued work with MOSIS and industry to correct run-to-run uniformity problems with the open design rule and to attempt CMOS foundry-compatible process through alternative technologies.

FY 1999 Begin development of MEMS-based test structures to measure mechanical strain in multi-layer thin-films; Continue to work with the MEMS community to develop standardization of MEMS test structures and test methods; Participate in strain measurement round-robin experiment; Work with the MOSIS service to develop infrastructure to support accessibility of CMOS MEMS fabrication; Complete the development of tetramethylammonium hydroxide (TMAH) silicon micromachining etching for CMOS MEMS and develop methods to deposit and pattern stress compensation films on CMOS ICs.

FY 2000 Continue development of MEMS-based test structures to measure mechanical strain in multi-layer thin-films; Continue to work with the MEMS community to develop standardization of MEMS test structures and test methods; Continue development of methods to deposit and pattern stress compensation films on CMOS ICs.

2. Develop thermal flat-panel display

FY 1991 Initiated a program to develop a CMOS-based thermal flat-panel display; Demonstrated the concept of fabricating micro-heating elements through a commercial CMOS process; Designed, fabricated through MOSIS, performed silicon micromachining on CMOS chips, and tested the elements for applications as infrared emitters or pixels in a thermal flat-panel display.

FY 1992 Demonstrated the concept of using micro-heating elements as pixels in a small size thermal (infrared) flat-panel display; Designed, fabricated, and tested a 4 x 4 infrared pixel array for application as a thermal flat-panel display.

FY 1993 Designed, fabricated, and tested a 16 x 16 infrared pixel array; Interfaced the array to a computer and a video interface; Collected thermal images of the output of the display; Designed 64 x 64 and 128 x 128 infrared (IR) pixel array thermal flat-panel displays.

FY 1994 Completed the demonstration of concept of using micro-heating elements, fabricated in a commercial foundry process, to fabricate thermal flat-panel displays; Fabricated 64 x 64 and 128 x 128 infrared pixel array thermal flat-panel displays; Completed testing of 64 x 64 and 128 x 128 infrared pixel arrays.

FY 1995 Initiated a 3-year program to build prototype thermal flat-panel displays. (Collaboration with industrial partner)

FY 1996 Worked with industrial partner to design, fabricate, and test 64 x 64 pixel array prototype thermal display to be inserted in optical projection system for the first phase field demonstration; Initiated work to design and fabricate 128 x 128 pixel array prototype thermal display for the second phase of the task.

FY 1997 Completed second-generation design for a 64 x 64 pixel array thermal display, submitted the design for fabrication, and tested the fabricated array for operation; Completed designs of 128 x 128 pixel array prototype thermal display IC to be inserted in the optical projection system.

FY 1998 Completed a working demonstration 128 x 128 pixel array thermal display unit with projection optics in collaboration with industrial partner.

FY 1999 Transition thermal flat-panel display technology from 2.0 μm to 1.2 μm CMOS fabrication; Work with industrial partner to design and fabricate microheating elements and control electronics in the 1.2 μm CMOS fabrication technology; Fully characterize the operation of these elements and circuits.

FY 2000 Transition thermal flat-panel display technology from 1.2 μm to 0.6 μm CMOS fabrication; Work with industrial partner to design and fabricate microheating elements and control electronics in the 0.6 μm CMOS fabrication technology; Fully characterize the operation of these elements and circuits.

3. Develop microwave power sensor

FY 1991 Began development of a CMOS equivalent to the multijunction thermal converter fabricated in the Semiconductor Process Laboratory (collaboration with the Electricity and Electromagnetic Fields Divisions); Initial designs sent to the MOSIS service for fabrication.

FY 1992 Fabricated improved designs of thermal converter elements and tested ac/dc conversion accuracy to 1 MHz with conversion error under 200 parts per million.

FY 1993 Initiated a program to develop a high-precision low-cost RF and microwave power sensor to 10 GHz. Fabricated transmission lines and power sensors. Began the Cooperative Research and Development Agreement (CRADA) with industrial partner.

FY 1994 Demonstrated the concept of fabricating silicon micromachined microwave transmission lines in CMOS technology; Tested the transmission line elements to 20 GHz and demonstrated the benefits of silicon micromachining to reduce the attenuation of the lines.

FY 1995	Demonstrated the concept of fabricating silicon micromachined power sensors and coupling these devices to the CMOS transmission lines; Tested the CMOS silicon micromachined microwave power sensors to 20 GHz.
FY 1996	Developed a working prototype microwave power meter in collaboration with industrial partner; Incorporated the transmission line elements and the microwave power sensors with circuits on an IC chip and tested and characterized the elements and circuit performance.
FY 1997	Began work on characterization of polysilicon load element and investigation of techniques to control its stability for accurate power measurement in May; Assembled computers and controller boards for the characterization experiment. Software to run the test is currently being developed.
FY 1998	Continued work on characterization of polysilicon load element and investigation of techniques to control its stability for accurate power measurement; Continued to Develop and characterize antenna structures and passive resonant filters in collaboration with industrial partner.
FY 1999	Complete characterization of the polysilicon load element and investigation of techniques to control its stability for accurate power measurement; Work with industrial partner to continue development of on-clip passive resonant filters, antennas, and digital and analog circuits; Integrate power sensor element with coplanar transmission lines, passive resonant filters, and antennas and characterize performance.
FY 2000	Work with industrial partner to complete a working demonstration microwave power sensor unit; Interface with on-chip circuitry and laptop computer.

Plasma Chemistry - Plasma Processing

Project Leader: James K. Olthoff

Staff-Years: 1.5 professionals

Funding Sources: STRS, OMP, AND OSRD (100%)

Objective: To aid the semiconductor industry in the characterization of discharges used in plasma processing. Specifically by investigating 1) the chemical composition of capacitively- and inductively-coupled rf plasmas, 2) the performance of ion energy analyzers for use as plasma diagnostics, 3) the effect of ion-molecule collisions on the ions striking surfaces exposed to the plasma, and 4) fundamental collision data required for analysis of plasma processing data.

Background: The Electricity Division's work in plasma processing began in 1989 as an outgrowth of NIST's work in gaseous dielectrics. Initial work involved the evaluation of a mass spectrometer with an ion energy analyzer as a plasma diagnostic for SEMATECH. Subsequent research has been supported primarily by the EEEL Office of Microelectronics Programs under the National Semiconductor Metrology Program, and has emphasized the characterization of diagnostic devices and validation of theoretical models. In the past 10 years NIST has become a leader in the development of "reference" discharges for use in these studies, including GEC rf Reference Cells with capacitively- and inductively-coupled sources, and a Townsend discharge cell. Application of a wide range of diagnostic measurements, (electrical, mass spectrometric, ion energy analysis, optical emission and laser-induced fluorescence) to these well-characterized discharges, allows the accumulation of baseline plasma data necessary to confirm the performance of both the measurement techniques and the predictive models used to describe the discharge. More recently, NIST has led the world in providing standard reference data on electron interactions with gases used by the semiconductor industry. This project is partially funded by the Office of Standard Reference Data.

Current Tasks:

1. Application of mass spectrometric, ion energy diagnostics to discharges

FY 1989	Interacted with SEMATECH concerning need for characterization and calibration of a mass spectrometer/ion energy analyzer and a Langmuir probe.
FY 1990	Fabricated and brought to full operation GEC rf reference cell with optical, mass spectrometric, and electrical diagnostics.
FY 1991	Characterized mass spectrometer/energy analyzer for use as a real time diagnostic in rf production reactors; Sent results to SEMATECH for publication as a SEMATECH report.
FY 1992	Installed improved mass spectrometer/ion energy analyzer system to GEC Cell; Measured ion energy distributions in argon, argon/oxygen, and argon/helium mixtures and correlated with electrical and optical measurements.

FY 1993	Measured effects of trace impurities, such as oxygen or water, on electrical characteristics of argon discharges.
FY 1994	Performed comprehensive studies (including mass spectrometric, ion energies, optical emission, and electrical) of rf discharges in hydrogen and argon/hydrogen; Performed preliminary ion energy measurements in dc Townsend discharges.
FY 1995	Edited special journal issue dedicated to research performed on GEC rf Reference Cells; Constructed new inductively coupled GEC rf cell.
FY 1996	Completed investigation of rf discharges in SF_6; Completed investigation of ion energy diagnostic measurements for dc Townsend discharges in argon, helium, oxygen, nitrogen, CHF_3, and SF_6.
FY 1997	Measured gas decomposition in inductively coupled argon plasmas containing O_2, N_2, SF_6, and Cl_2.
FY 1998	Measured ion flux and energies in inductively coupled plasmas.
FY 1999	Extend mass spectrometric diagnostics to rf plasmas in the presence of silicon wafers and transfer technique to industry.
FY 2000	Develop method to measure time resolved ion energy distributions in pulsed plasmas.

2. Compilation and analysis of fundamental data for the semiconductor industry

FY 1995	Initiated investigation of known electron impact cross sections for CF_4 and CHF_3.
FY 1996	Completed electron-impact investigation for CF_4 and CHF_3; Published comprehensive paper and made summary data publicly available on World-Wide Web; Measured electron attachment to CCl_2F_2 molecules.
FY 1997	Investigated electron impact cross sections for CCl_2F_2, C_2F_6, and C_3F_8; Prepared papers on CCl_2F_2 and C_2F_6 and the summary data were made available on the World Wide Web.
FY 1998	Reviewed electron-impact cross sections for C_3F_8 and Cl_2. Measured total scattering cross section for Cl_2. (*1998 MSL Strategic Plan*)
FY 1999	Measure electron attachment cross sections for excited species using crossed beam method; Review cross sections for SF_6.
FY 2000	Measure electron attachment cross sections for radical species generated in plasma processing gases.

MAGNETICS

Magnetic Recording Metrology

Project Leader: David P. Pappas

Staff-Years: 4.0 Professionals, 1.0 Guest Researcher, 0.25 Undergraduate Student

Funding Sources: NIST (STRS-44%, Competence-18%), ATP (11%), Other Agency (27%)

Objective: Develop measurement methods and standards required by the magnetic data storage industry to further the development of ultra-high density magnetic recording, the performance of advanced heads, and nanoscale magnetic recording techniques.

Background: Magnetic data storage is one of the key industries driving the revolution in information technologies. Information systems, for both commercial and military applications, requiring terabytes of data storage and gigabyte transfer rates, are envisioned in the next 10 to 20 years. To achieve these storage densities and transfer rates, the size of magnetic bits and sensors needs to be reduced to submicrometer dimensions and the sensors and write elements need to work at very high frequencies. To enable these technological developments, new measurement methods and standards are needed. These include methods to measure domain structure of submicrometer magnetic devices, methods to accurately simulate read head and magnetoresistive random access memory components, and standards for magnetic imaging and high frequency thin-film permeability. Techniques based on scanned-probe microscopies need to be developed to address specific issues in magnetic recording.

Current Tasks:

1. Develop magnetic imaging reference standards (MIRS) heads

FY 1995	Fabricated first magnetic imaging reference samples for magnetic force microscopy calibration.
FY 1996	Samples distributed for magnetic force microscopy, SEMPA (scanning electron microscopy with polarization analysis), and Lorentz characterization.
FY 1997	Began magnetic media survivability studies using magnetic imaging standards; Prepared imaging Standards; Prepared imaging standards for general distribution.
FY 1998	Developed ability to record bit patterns; Tested uncoated media for writing MIRS patterns; Tested heads for bit size compatibility with Magnetic Force Microscopy. (*1998 MSL Strategic Plan*)
FY 1999	Fabricate MIRS samples and correlate magnetic properties using SEMPA and Low Velocity Read/Write Test Stand. Collaboration with Physics Laboratory. (*1998 MSL Strategic Plan; 1999 Budget Narrative*)

2. Develop hard disk drive metrology capability (Competence)

FY 1995 - 1997	Built proto-type Low Velocity Read/Write Test Stand; Recorded and imaged bits using commercial heads and magnetic force microscope, respectively.

FY 1998 Built Low Velocity Read/Write Test Stand including: Environmentally controlled enclosure, 5 axis motorized, computer controlled heated/cooled stage. Dual view video monitor. (*1998 MSL Strategic Plan*)

FY 1999 - 2000 Use LVR/W test stand to perform strip line measurements of high frequency media erasure characteristics; High temperature magnetic media bit stability and write tests; Advanced write head metrology development. (*1999 Budget Narrative; 1998 MSL Strategic Plan*)

3. Develop advanced scanned probe microscopy metrology for magnetic data storage industry (ATP)

FY 1998 Developed chemical-mechanical methods to measure efficacy of novel magnetic disc lubricants; Developed chemically modified tips for atomic force microscopy; Developed methods for imaging hydrophobic and hydrophilic surfaces with AFM; Developed low temperature atomic force microscope; Installed electron beam deposition system for evaporation of magnetic materials on piezo-electric scanning probe tips.

FY 1999 - 2000 Nanometer scale tribology of magnetic storage media lubricants will be conducted to image the local lubrication coverage; Compare lubrication coverage of different lubes on various surfaces and compare to actual media performance as measured on a spin stand; Install rotating sample holder with mask in e-beam system to prepare uniformly coated magnetic force microscope tips.

4. Develop in-situ metrology for magnetic thin film analysis

FY 1998 Assembled vacuum characterization/deposition system with low energy electron diffraction, angle resolved Auger, magneto-optic Kerr rotation and susceptibility system and spatially resolved spin polarized secondary electron spectroscopy; Measured spin reorientation transitions in rare-earth/transition-metal structures; Measured magnetization vs. temperature scaling for rare earth surfaces and compared to the bulk scaling. (*1998 MSL Strategic Plan*)

FY 1999 Develop metrology for the storage industry including in-situ magnetostriction measurements of thin films via susceptibility and surface-sensitive, spin-resolved secondary electron spectroscopy; Develop in-situ, absolute moment metrology techniques applicable to thin films. (*1998 MSL Strategic Plan*)

5. Develop magnetic film reference samples for hard disk drive industry

FY 1998 Conducted round robin interlaboratory comparison of nine different magnetic thin film samples including 12 labs from industry, academia, and national laboratories with four common metrology tools; Sputter-deposited single crystal nickel films on diamond as potential reference material; Set up e-beam deposition system and configured for making magnetic thin film samples.

FY 1999- 2000 Fabrication of samples will be continued. Preliminary feedback from industry reveals interest in consensus standards in the short term. Proceed with development of consensus standard for B-H loopers, vibrating sample, SQUID, and alternating gradient field magnetometers. Long-range development and focus will be to generate traceable magnetic thin film reference samples. (*1999 Budget Narrative*)

Magnetic Instruments and Materials Characterization

Project Leader: Ron B. Goldfarb

Staff-Years: 4.7 Professionals, 1.3 NRC Postdocs, 1.0 Guest Researcher, 0.5 Graduate Student

Funding Sources: NIST (STRS 46%, Competence 14%), ATP (13%), Other Agency (27%)

Objective: Develop instruments, measurement protocols, and theoretical models to characterize the magnetic properties of films, particles, and bulk solids as functions of magnetic field strength, field history, temperature, and time. Develop, promote, and transfer to industry magnetic metrology for applications in magneto-optics, magnetic data storage, magneto-chemistry, power conversion, and high frequency electromagnetics.

Background: Researchers, developers, producers, and users of magnetic materials need tools for the accurate determination of magnetic properties and the analytical interpretation of data. Industries supported include: manufacturers of inductive recording heads, magnetoresistive read-back heads, thin-film and particulate recording media, and magnetoresistive magnetic memories; producers of microwave materials; companies researching magnetoresistive sensors; superconductor wire manufacturers, and magnetic-particle researchers in medicine. The Project provides measurement services, often in the form of collaborations, to laboratories that do not have magnetic measurement and analysis capability.

Current Tasks:

1. Develop new magnetic measurement instruments and techniques

FY 1997 Developed background subtraction and sample-change techniques in reciprocating-sample method of magnetization measurements; Improved sensitivity and reduced noise in vibrating-sample magnetometer; Developed pulsed-field apparatus for magneto-optics.

FY 1998 Built Kerr effect magnetometer to measure remanent magnetization in magnetic recording media after exposure to pulsed fields; Added high field and variable frequency capability to induction-field (B-H) looper; Installed new alternating gradient magnetometer (AGM); Suggested software improvements to magnetometer manufacturers; Improved speed and accuracy of vibrating sample magnetometer (VSM). (*1998 MSL Strategic Plan*)

FY 1999 Improve magnetometer techniques used in magnetic recording industry: alternating gradient magnetometer (AGM), induction-field (B-H) looper, vibrating-sample magnetometer (VSM). (*1998 MSL Strategic Plan*)

2. Develop methods to measure magnetic relaxation in recorded bits approaching the superparamagnetic limit of magnetic recording

FY 1997 Developed capability to deposit quality hard disk media; Developed VSM technique to simulate thermal decay of bit transitions and extract fundamental energy barrier to thermal erasure; Developed magnetometer techniques to measure thermal decay and switching volumes of hard magnetic media at various temperatures. (*1998 MSL Strategic Plan*)

FY 1998 Studied time and temperature dependence of magnetic viscosity using different magnetometers; Used Kerr microscopy to measure viscosity at nanosecond time scales; Developed capability to measure viscosity continuously from nanoseconds to seconds; Developed capability for measuring viscosity using scanned magnetic head and correlated with magnetometer measurements; Deposited high coercivity CoCrTa media for viscosity studies; Developed self-consistent magnetometer technique to study thermal relaxation in media. (*1998 MSL Strategic Plan*)

FY 1999 Develop ability to make patterned media and measure thermal stability as a function of lithographically defined bit size; Determine possibilities for magnetoresistive measurement of thermal decay in longitudinal media; Develop higher amplitude pulsed magnetic field sources; Determine sensitivity of non-thermal switching speeds to bulk properties; Study spatial structure of magnetic domains in media as a function of switching speed; Determine role of spin waves in assisting reversal process in media. (*1998 MSL Strategic Plan; 1999 Budget Narrative*)

FY 2000 Observe switching in media using inductive and optical time-resolved methods; Measure write-head field rise times using inductive techniques. (*1998 MSL Strategic Plan*)

3. Develop time-resolved magneto-optic Kerr-effect metrology for dynamical magnetic domain imaging of nanoscopic magneto-electronic devices

FY 1997 Demonstrated sub-picosecond time-resolved magnetic characterization using second-harmonic magneto-optic phenomena in the far-field; Characterized dynamical response of thin-film magnetic recording head materials at frequencies above 100 MHz; Collaborated with National Storage Industry Consortium (NSIC) on fundamental limits of magnetic recording; Began to correlate SH-MOKE results with neutron and x-ray measurements of surface/interface magnetic properties in Permalloy; Investigated diagnostic uses for SH-MOKE in electromigration, surface oxidation, and interface diffusion; Developed inductive method to measure magnetic relaxation times in magnetic films; Compared surface dynamics measured with time-resolved SH-MOKE and bulk dynamics measured inductively; Performed dynamical measurements on FeTaN films; Designed and fabricated reference coplanar waveguides for comparing switching speeds of different materials. (1998 MSL Strategic Plan)

FY 1998 Compared time-resolved SH-MOKE and with inductive method; Designed new coplanar waveguides for delivery of field pulses; Automated date acquisition; Determined role of spin-wave generation in precessional damping; Studied uniformity of switching in thin-film head materials with Kerr microscopy; Studied role of inhomogeneity in anisotropy on damping of precession; Collaborated with NSIC on limits of magnetic recording; Imaged narrow NiFe stripe domain patterns after switching by high speed pulses; Extended dynamical measurements to different film thicknesses and shapes; Demonstrated performance of SH-MOKE at small spot sizes (2-4 µm); Measured SH-MOKE in FeAlN and FeTaN in addition to NiFe; Optimized substrates for SH-MOKE; Modeled magnetization dynamics with Landau-

	Lifshitz phenomemology; Developed new method to control precessional dynamics in Ni-Fe films using two field pulses. (*1998 MSL Strategic Plan*)
FY 1999	Continue optical and inductive studies of high speed magnetic response; Benchmark switching speeds in alternative head materials; Extend techniques to higher coercivity materials; Continue short-time thermal decay studies; Extend resolution of SH-MOKE technique to micrometer scales or smaller; Continue studies of fundamental origins of precessional damping and fundamental processes in thermal decay of magnetization; Continue collaboration with NSIC; Study spatial dependence of dynamic response in soft magnetic films; Compare surface and bulk magnetodynamics by simultaneous MOKE and SH-MOKE measurements; Compare experiments on coherently controlled damping with theoretical models. (*1998 MSL Strategic Plan; 1999 Budget Narrative*)
FY 2000	Use SH-MOKE to measure magnetodynamics in ferromagnetic-antiferromagnetic exchange-biased interfaces for giant magnetoresistive (GMR) devices; Develop probe techniques to extend time-resolved magneto-optics to sub-micrometer dimensions. (*1998 MSL Strategic Plan*)

4. Measure interfacial magnetostriction in multilayer magnetic films (New task)

FY 1998	Constructed apparatus to measure surface and interface magnetostriction; Developed microwave structures for fast pulse delivery; Demonstrated spot MOKE system for measurement of bulk magnetostriction in soft ferromagnetic films; Measured interface magnetostriction in Cu/NiFe.Cu and Ta/NiFe/Ta trilayers using SH-MOKE and compared with bulk data. (*1998 MSL Strategic Plan*)
FY 1999	Perform surface magnetostriction measurement using SH-MOKE and bulk magnetostriction using MOKE; Test microstructural origins of magnetostriction; Correlate dynamical and magnetostriction measurements to determine role of magnetostriction in magnetodynamics. (*1998 MSL Strategic Plan*)
FY 2000	Extend surface magnetostriction measurements to study effect of local stress variations on magnetic properties; Perform time-resolved magnetostriction measurement using time-resolved magnetoresistance. (*1998 MSL Strategic Plan*)

5. Develop methods to characterize sub-micrometer magnetoresistive devices for use in recording heads, magnetoresistive random access memory (MRAM), and sensors.

FY 1997	Compared effects of high pulsed currents and elevated temperatures on magnetoresistive response of films; Measured and characterized low frequency noise in spin-valves in collaboration with magnetic recording companies; Measured size and magnetostatic effects in spin-valves designed for use in recording heads and MRAM; Performed detailed comparisons of spin-valve performance with magnetic models. (*1998 MSL Strategic Plan*)
FY 1998	Designed circuits to measure high-speed response of sub-micrometer GMR devices and tunnel junction devices to be used in recording heads and MRAM; Measured high speed response of devices used in DARPA program; Fabricated magnetic tunnel junction arrays and optimized for sensor applications; Fabricated arrays on flexible substrates; Developed low-noise test apparatus to quantify ultimate performance of GMR sensors; Fabricated

	magnetic nanostructures for characterization of advanced media and read head concepts; Studied effects of oxidation of tunnel junction barriers; Measured SH-MOKE in NiFe/$A1_20_3$ tunnel junctions as function of thickness. (*1998 MSL Strategic Plan*)
FY 1999	Complete high-speed measurements for DARPA MRAM program. Apply high-speed metrology to submicrometer GMR devices for use in recording applications. Complete low noise measurement system and measure GMR sensor response down to 10 pT/$\sqrt{}$Hz. Characterize magnetic properties of sub-100 nm structures including isolated switching properties and cluster interactions; Optimize GMR arrays for imaging and metrology applications. (*1998 MSL Strategic Plan*)

6. Conduct fundamental studies of practical magnetic materials and new materials of current interest

FY 1997	Measured magnetic properties of nanoparticles and molecules of iron, iron oxides, and ferritin.
FY 1998	Measured ac losses of Nb_3Sn multifilamentary superconductors for fusion and high energy physics applications; Advised manufacturer about flux jumps in certain wires; Measured exchange coupling in ferromagnetic-antiferromagnetic bilayers; Measured magnetic particles of iron carbides and oxides in collaboration with other laboratories.
FY 1999	Provided consultation and measurements on ac loss behavior of superconductors for fusion energy and high energy physics projects, including contributions to benchmark interlaboratory comparisons; Measure magnetic properties of nanoparticles.

Nanoprobe Imaging for Magnetic Technology

Project Leader: John Moreland

Staff-Years: 1.0 Professionals, 1.0 Guest Researcher

Funding Sources: NIST (STRS-30%, Competence-40%), ATP (15%), Other Agency (15%)

Objective: Develop scanned probe microscopy (SPM) in support of the magnetic storage industry and work with industry to understand and relate SPM images to magnetic and electronic properties of media and devices that affect the performance and manufacture of current technologies as well as the direction of future developments in the recording industry.

Background: The intense competition for a magnetic data storage market exceeding $50 billion/year has led manufacturers to push the limits of drive technologies. Heads and media are affected by nm-scale morphological and electronic properties which directly or indirectly influence the performance of current drive designs with regard to speed and storage capacity. Nm-scale measurements of roughness, critical dimensions, field patterns, and local electronic processes provide information about the fundamental operation and ultimate performance limitations, which is useful in the development process. In addition, nondestructive, quality-assurance measurements can be performed during the manufacturing process on components prior to assembly of a complete drive. Scanned probe microscopies such as atomic force microscopy (AFM), magnetic force microscopy (MFM), and scanning potentiometry are examples of imaging techniques that are uniquely qualified for these applications because of the nm-scale dimensions of the various probes. NIST has recognized that there is a need to develop and test SPM techniques, demonstrate their usefulness, and generally facilitate the transfer of the latest innovations in SPM technology to the storage industry. [See also Magnetic Recording Metrology project.]

Current Tasks:

1. SPM imaging of magnetic materials and devices

FY 1997 Developed high-resolution scanning potentiometry based on SPM; Provided images of devices being developed by U.S. company for MR heads; Installed and tested e-beam system for depositing ultra-pure magnetic films for MFM tip coatings.

FY 1998 Develop data acquisition and analyses for "dip stick" adhesion force microscopy.

FY 1999 Develop high-bandwidth (>500 MHz) scanning potentiometry for imaging magnetic thin film devices; Develop theoretical understanding of phase imaging for applications to friction/adhesion studies; Improve voltage sensitivity and spatial resolution of scanning potentiometry instruments; Develop controlled chemistry of tip coatings for quantitative measurement of adhesion and stiction between disk drive components.

FY 2000	Build and test puck level scanning potentiometry instrument; Perform measurements of electromagnetic fields as a function of frequency a few nm above the air bearing surface of thin film recording heads.
FY 2001	Develop SPM instrumentation for molecular scale tribology; Develop surface potential imaging of disk drive components; Transfer resulting technology to industry.

2. SPM Metrology

FY 1995	Demonstrated superparamagnetic cantilever coatings for MFM in collaboration with the University of Nebraska; hailed by SPM manufacturers as the first step towards quantitative MFM; NIST employee sent to U.S. company, as part of NIST Industry Fellows Program, to develop SPM for industrial applications.
FY 1996	Developed standards and standard measurement practices for MFM; Designed Magnetic Imaging Reference Sample (MIRS) as a qualitative reference for MFM; Started three-way collaboration among ourselves, a U.S. company, and the Electron Physics Group of the Physics Laboratory at NIST; Improved MFM resolution and image interpretation by investigating new cantilever coatings.
FY 1997	Began significant distribution of MIRS.
FY 1998	Task transferred to Magnetic Recording Metrology Project.

3. Magnetic resonance force microscopy (MRFM)

FY 1996	Began development of MRFM for three-dimensional imaging of magnetic phenomena.
FY 1997	Constructed optical fiber interferometer for cantilever motion detection, constructed rf circuit for sample excitation, observed resonance for first time, and developed imaging algorithm to generate real space magnetic resonance image output. (*1998 MSL Strategic Plan*)
FY 1998	Demonstrated MRFM imaging with better than 1-μm resolution in three dimensions; Constructed 3-axis magnet cryostat for MRFM at 1 K. (*1998 MSL Strategic Plan*)
FY 1999	Install and test diffusion furnaces for fabrication of ultra sensitive cantilevers; Develop high-bandwidth MRFM techniques for imaging electromagnetic fields at frequencies as high as 1 GHz; Develop capabilities for micromachining high-performance, specialized SPM cantilevers; Fabricate ultra high sensitivity cantilevers for single-spin atomic-scale MRFM; Fabricate cantilever chips with integrated detectors for single-spin atomic-scale MRFM. (*1998 MSL Strategic Plan*)
FY 2000	Demonstrate atomic resolution MRFM; Integrate fiber optic motion detector, cantilever, rf resonator, and magnetic films, onto a microchip for ultra-sensitive magnetic resonance spectroscopy; Optimize MEMS (micro-electro-mechanical) processing for totally integrated microchip MRFM instruments and magnetic resonance spectrometers. (*1998 MSL Strategic Plan*)
FY 2001	Study atomic scale magnetic phenomena relevant to the development of heads and media; Study organic structures and processes with the MRFM; Establish world class facility for atomic resolution magnetic resonance imaging. (*1998 MSL Strategic Plan*)

4. Develop low-temperature SPM

FY 1989	Bathysphere cryostat (developed at NIST for superconductor transport studies) adapted for scanning tunneling microscopy (STM).
FY 1996	Began construction on cryogenic multimode AFM to extend SPM capabilities to low temperatures for fundamental studies of magnetic phenomena.
FY 1997	Completed construction of low temperature AFM cryostat and tested at room temperature.
FY 1998	Task transferred to Magnetic Recording Metrology Project.

SUPERCONDUCTORS

Superconductor Interfaces and Electrical Transport

Project Leader: Jack W. Ekin

Staff-Years: 2.0 Professionals, 1.0 Contract, 1.0 Technician, 1.0 Graduate Student

Funding Sources: NIST (STRS, 37%), Other Agency (63%)

Objective: Develop measurement methods and obtain data for industry and for other projects within the Division in support of low-temperature and high-temperature superconductor applications in magnetics, power transmission, electronics, and microwaves. Characterize superconductor interfaces to aid in the commercial application of superconducting high current density wire and integrated circuits. Use unique measurement capabilities to develop transport and electromechanical measurement methods of the highest sensitivity and accuracy to assist industry in improving the performance of commercial thin films and wires.

Background: The high-temperature-superconductor (HTS) industry has asked for NIST's help to measure and develop high quality contacts and interfaces for both thin-film and bulk superconductor devices. The basic interface conduction and noise mechanisms are not yet understood. In magnet technology, both HTS and low-temperature superconductor (LTS) magnets are being developed in the direction of higher fields (for nuclear magnetic resonance and high-energy physics) and larger magnets (especially with the increased interest by U.S. industry in superconductor power conditioning magnets since the announced deregulation of power utilities). Both directions lead to higher magnetic loading of the superconductor, which necessitates the need for measurements of the effect of stress on their electrical performance. The new HTS materials also have significant magnetic field anisotropy which has created a new set of measurement problems and modeling equations for conductor performance.

Current Tasks:

1. Develop metrology for characterization of electromechanical performance of superconductors and perform measurements needed by industry to create a database for commercial design of large superconductor magnet systems and transmission lines

FY 1996 Developed technique for accurately measuring the Young's modulus of niobium-tin superconductors at cryogenic temperatures to resolve a long standing 300% discrepancy in values reported in the literature; Designed state-of-the-art apparatus for measurement of the anisotropy of J_c with respect to magnetic field angle, for characterization of HTS at high currents in magnetic fields approaching 30 T.

FY 1997 Measured the effect of fatigue degradation of high-purity aluminum in large aluminum-stabilized conductors and showed potential for 40% reduction in materials design requirements; Modified transverse-stress apparatus for stress-free and axial-strain measurements of a Nb_3Sn tape for testing a three-dimensional strain-effect model; Installed and tested new 18 T magnet system for electromechanical testing of high-field superconductors.

FY 1998 Modified the high-field axial-strain apparatus to allow accurate testing of high-strength wire and tape conductors; Developed test method for measuring the transverse-stress effect in multifilamentary BSCCO (bismuth-strontium calcium copper oxide) conductors; Developed metrology for tensile measurements of short (1 cm gage length) rolling-assisted biaxially aligned textured substrate (RABiT) substrates at cryogenic temperatures; Collaborated with Colorado University on finite element modeling of yttrium-barium-copper oxide (YBCO) coated conductors; Completed draft of first part of text book on cryogenic metrology.

FY 1999 Measure transverse-stress effects on ion beam assisted deposition (IBAD) coated superconductors; Measure residual resistance ratio on Ni substrates; Complete draft of book on cryogenic metrology, edit, conduct data searches.

FY 2000 Write paper on residual resistance ratio of Ni substrates; Measure fatigue properties of Bi-2223 under transverse compressive stress; Measure transverse compressive stress effects in Bi-2212 superconductors; Develop improved axial-strain measurement technique.

2. Develop metrology for evaluating superconductor interfaces and obtain database needed by industry for the development of high-quality electronic contacts

FY 1996 Measured the 4 K, high-field (up to 12 T) tunneling characteristics of thallium interfaces fabricated at NIST using films from two manufacturers; Obtained the first high-magnetic-field tunneling conductance measurements of neodymium-cerium-copper-oxide films in collaboration with the University of Maryland; Discovered possible correlation between magnetic-field-dependent zero-bias conductance peak and evidence for d-wave pairing symmetry; Developed a method for improving the measurement sensitivity of our tunneling conductance measurements and obtained the first high-sensitivity transport properties of vertical a,b-axis superconductor/normal-metal junctions; Order-of-magnitude improvement over c-axis normal-metal interfaces achieved; Record specific resistivity of 2 x 10^{-9} ohm-cm^2 obtained for planar YBCO interfaces.

FY 1997 Measured conductance characteristics of YBCO/gold contact system as a function of oxygen annealing temperature; Determined an optimal annealing temperature range of 550 °C to 600 °C for that contact system; Established that Au diffusion along grain-boundary is the cause for reduction in contact resistance; Extended the zero-bias conductance measurement of YBCO/Au junctions to fields of 18 T and temperatures below the lambda-point in order to discriminate between the Anderson-Appelbaum model and mid-gap states model for zero-bias conductance anomalies; Acquired necessary equipment for setting up low-frequency noise measurement.

FY 1998 Developed electromechanical test capability for wire-bond pull strength and interfacial shear strength experiments; Tested for a correlation between interface mechanical properties and the specific interface resistivity; Developed low-frequency noise measurement for HTS/Au junctions and characterize noise behavior in terms of junction area, temperature, and bias voltage; Began fabrication of Au contacts to YBCO in the ab-plane direction using ramp-edge junction geometry; Explored new approaches to low-resistance contact without oxygen annealing.

FY 1999	Develop and test a model for treating the transport properties and noise characteristics of high-temperature-superconductor surfaces; Write a paper on noise data and modeling transport properties and noise at YBCO interfaces.
FY 2000	Develop contacts with high conductivity for high-current coated film conductors; Develop wire bond techniques for high-temperature superconductors with low specific resistivities and optimized mechanical strength, for use in high-Q pickup coils, as well as passive filter and antenna applications.

High Performance Sensors, Converters, and Mixers

Project Leader: Erich N. Grossman

Staff-Years: 2.5 Professionals, 1 Postdoc Researcher

Funding Sources: NIST (STRS-23%), Other Agency (77%)

Objective: Develop millimeter-wave and infrared sensors and frequency converters for measurements and standards in support of other NIST divisions. Apply advanced superconducting integrated circuit fabrication, cryoelectronic, infrared, mm-wave, and other techniques to solve measurement problems at the limits of technology. Projects cover applications of Superconducting Quantum Interference Devices (SQUIDS), and in the infrared (IR), precise radiometry, frequency synthesis, spectroscopy, and imaging.

Background: The project represents the consolidation of previously separate efforts in mid- and far-infrared measurements and standards development on the one hand, and low-noise SQUID development on the other. The project now focusses more closely on infrared measurement technology. Mid- and far-infrared technology (wavelength >10 μm) is now a large industry. Originally aerospace and defense-related, it is now moving to many purely commercial applications in security, night vision, materials testing, quality assurance, and more. As such applications proliferate, supporting needs for measurements and standards technology are also increasing. Accurate measurement of total power and power spectral density (i.e., radiometry and low- resolution spectroscopy) is a recognized calibration problem for manufacturers of focal plane arrays and blackbody sources. This project, in collaboration with other NIST organizations (Divisions 844, 838, 815, 811) and private industry, develops precision electrical substitution radiometers based on superconducting thermometers. They can be used for radiometric measurement of absolute temperature (refining ITS-90 in the 50-200 K range), calibration of blackbodies and focal plane arrays at low power levels (⟨100 nw), absolute laser power measurements, and audio-frequency electrical power measurements. This project also investigates the properties of IR microantennas, and microantenna-coupled diodes. Metrology of these devices is a key issue for developers of millimeter-wave and IR imagers, engineered emissivity surfaces, and IR rectifiers. They are also key components in IR and optical frequency synthesis systems being developed for time and frequency metrology. The incorporation of IR microantennas with uncooled IR sensor materials, such as VO_2 is a key to developing new wireless telecommunications applications at far-IR frequencies. Finally, SQUID preamps enable the integration of high sensitivity far-IR sensors into large format staring arrays, using the SQUIDS as elements of a high speed multiplexer. The development of large format arrays is expected to enable new applications of far-IR imaging, particularly for satellite-borne remote sensing.

Current Tasks:

1. Develop absolute radiometer for the low background infrared (IR) facility (NIST Radiometric Physics Division), for the measurement of light with a wavelength in the range of 10 μm

FY 1986	Concept of Kinetic Inductance Thermometer (KIT) developed.
FY 1990	Demonstrated closed-loop resolution of 1 picowatt using KIT without absorber.
FY 1993	KIT integrated with absorber which degraded resolution by more than a factor of 1000.
FY 1995	Dropped KIT in favor of transition-edge thermometer to improve manufacturing; Stabilized absorber to improve resolution; Demonstrated ability to fabricate transition-edge thermometers.
FY 1996	Delivered radiometer to NIST/Physics Laboratory's Radiometric Physics Division (now Optical Technology Division).
FY 1997	Designed and built second-generation radiometer (RAD II) with integrated blackbody source, demonstrating absolute accuracy of 0.1%.
FY 1998	Continue design and construction of RAD II.
FY 1999	Continue design and construction of RAD II; Present design of source assembly and performance in application to NASA bolometer characterization at NEWRAD '99.

2. Develop infrared antennas and diodes for solar power generation

FY 1995	Project begun with funding from Air Force; Collaboration with NIST/Physics Laboratory's Time and Frequency Division to develop accurate measurements of efficiency of infrared antennas and lithographic diodes.
FY 1996	Fabricated near-IR antenna using electron-beam lithography; Fabricated lithographic metal-insulator-metal diodes.
FY 1997	Continued development and IR testing of antennas and metal-insulator-metal diodes; Measured efficiency of each.
FY 1998	Compile and publish results.
FY 1999	Continue work under CRADA with ITN Energy Systems; Analyze tunneling in asymmetric MIM diodes; Fabricate submicron asymmetric MIM's and test at wavelengths of 10 μm, 5 μm, and below.

3. Develop infrared antennas and bolometers for focal plane arrays (room-temperature antenna-couples bolometers for imaging)

FY 1996	Cooperative Research and Development Agreement (CRADA) established with U.S. company; Proposal for multimode antenna-coupled array developed.
FY 1997	Designed, fabricated, and optically tested room-temperature dipole antenna/bolometers for 10-μm detection and imaging.
FY 1998	Compiled and published results; Established second CRADA with company on measurement of "engineered emissivity" surfaces; Measured and analyzed angle-dependent reflectance and transmittance at room temperature and 77 K of samples supplied by company. Preliminary data on first sample delivered to industrial partner.
FY 1999	Collect further reflectance data on initial samples; Develop anodic etching facility for inhouse fabrication of photonic crystals in silicon.

4. Develop AC/DC thermal converter

FY 1994	Initiated project to apply kinetic inductance thermometers to improve the accuracy at which alternating and direct voltage signals could be compared; Discussions held with collaborators in Electricity Division. (*1998 EEEL Strategic Plan*)
FY 1995	Performance analysis made of alternating and direct voltage converter using transition-edge thermometers. (*1998 EEEL Strategic Plan*)
FY 1996	Delivered chips and cryogenic mounts to Electricity Division; Performed preliminary alternating and direct voltage conversion measurements (with Electricity Division). (*1998 EEEL Strategic Plan*)
FY 1997	Provided improved chips and mounting assemblies to Electricity Division; Sensor noise level corresponding to 2 ppm precision demonstrated in AC/DC measurement using transition edge thermometers. (*1998 EEEL Strategic Plan*)
FY 1998	Developed proposals for funding further work on AC/DC substitution; Developed Nb-Ta transition edge sensors for operation at lower critical temperatures for performance advantages; Integrated assembly into Electricity Division's "NIST Automated Comparator System 2" (Gaithersburg); Comapred cryogenic converter to secondary transfer standard (Semiconductor Junction Thermal Converter) for the first time, obtaining agreement to within 12 ppm at 4 μm and 100 Hz in current comparator mode.
FY 1999	Consult with Electricity Division on means to improve availabilty and useability of devices for wider user community.

5. Wireless telecommunications at terahertz frequencies

FY 1996	Initiated program to develop antenna-coupled vanadium-oxide room-temperature bolometer.
FY 1997	Developed phase pattern metrology of lithographic antennas at frequencies of atmospheric absorption lines.
FY 1998	Final report to NSA written; Applied for patent on new technique for bias and readout of VO_2 bolometers that enables operation on metal-semiconductor transition.
FY 1999	Write paper on experimental VO_2 transition edge bolometer results, including performance with new readout technique.

6. Develop multiplexed arrays of 100 mK superconducting bolometers (with Nanoscale Cryoelectronics Project)

FY 1996	Wrote proposal to NASA, in collaboration with Goddard Space Flight Center.
FY 1997	Demonstrated SQUID multiplexing capability and measure noise equivalent power (NEP) of bolometers with optical absorbers; Demonstrated operation at 20 kHz using individual SQUID chips; Designed 1 x 8 array.
FY 1998	Fabricated and tested 1 x 8 multiplexer; Integrated multiplexer with superconducting transition-edge sensors and 100 mK cryostat; Measured upper limit on back-radiated switching transients; Multiplexer speed of 1 MHz (pixel rate) measured.
FY 1999	Integrate SQUID Multiplexing chips and transition-edge bolometers with GSFC mechanical "pop-up" design; Incorporate far-IR absorption structures optimized for 250 μm wavelength and measure absorptance.

Josephson Array Development

Project Leader: Clark A. Hamilton

Staff-Years: 3.9 Professionals

Funding Sources: NIST (STRS-41%, ATP-16%), Other Agency (43%)

Objective: Advance the sensitivity, accuracy, convenience, and speed of electronic measurement by developing Josephson array circuits, components, measurement algorithms, software and systems for such uses as improved dc voltage standards, fast programmable dc standards, intrinsic ac voltage standards, and waveform synthesizers. Support industrial, military, and international standards laboratories in the realization and use of Josephson standards. Support EEEL requirements for maintaining the national volt.

Background: Manufacturers of modern precision electronic components and instrumentation need intrinsic electrical standards at a level of accuracy above that achievable by traditional electrical metrology and artifact standards. The characterization and calibration of modern digital voltmeters, reference standards, and converters between analog and digital signals require the development of new and improved intrinsic standards for the generation and measurement of dc and ac voltage. Josephson array devices are intrinsic voltage standards that meet these requirements and they have become the accepted legal method to represent the SI Volt. This project and its predecessors have revolutionized precision voltage measurement through the development of the world's first practical Josephson-junction array standards. Continuing research is aimed at the development of new Josephson integrated circuits that are many orders of magnitude faster and meet the need for intrinsic voltage standards that cover a broad range of frequency and amplitude. Target customers are electronic instrument makers, DoD contractors, and national and military standards labs (Sandia, Army, Navy, Air Force). Superior electrical metrology has and will continue to enhance the competitive position of the U.S. electronics industry.

Current Tasks:

1. Develop second-generation dc Josephson standards operating at one volt and at ten volts

FY 1996	Developed and delivered prototype of compact Josephson voltage standard (JVS) to NASA. This standard is now circulating among 8 NASA standards centers and provides an order of magnitude improvement in their voltage measurement capability.
FY 1997	Developed an improved compact JVS for the Department of Energy; Organized and ran the 1997 National Conference of Standards Laboratories (NCSL) JVS interlaboratory comparison.
FY 1998	Developed and taught a three day course on the compact JVS for 20 NASA metrologists; Tested and delivered the improved compact JVS to Department of Energy; Designed a third generation compact JVS with smaller size, integral reversing switching, and improved software. The new instrument is

	compatible with all previous JVS implementations and can be used to upgrade more than 50 such systems around the world.
FY 1999	Complete and test first prototype of third generation compact JVS; Supply one unit to the Electricity Division for further testing; Develop and commercialize a manual low thermal reversing switching that mounts directly on the front of commercial dc Zener voltage references; Participate in the 1999 NCSL JVS interloaboratory comparison.
FY 2000	Commercialize third generation compact JVS; Add a small low power 4 K cryocooler to compact JVS to eliminate the need for liquid helium.

2. Develop programmable Josephson voltage standards

FY 1996	Demonstrated high accuracy sine wave synthesis with programmable JVS. Patent on programmable JVS issued.
FY 1997	Demonstrated programmable JVS at output voltage greater than 1 V.
FY 1998	Performed first high accuracy (5 parts in 10^7) comparison of the programmable JVS source and a state-of-the -art thermal voltage converter; Demonstrated the programmable JVS as a reference for the EEEL Watt balance experiment in both velocity and force modes; Set up collaborations with LCIE (France) and OFMET (Switzerland) for applications of the programmable JVS. (*1999 Budget Narrative*)
FY 1999	Develop, test, and deliver the final version of the programmable JVS to the Watt experiment in Gaithersburg. (*1999 Budget Narrative*)
FY 2000	Develop improved programmable JVS chips and systems with improved yield, output voltage, and ease of use. (*1999 Budget Narrative*)
FY 2001	Commercialize programmable JVS. (*1999 Budget Narrative*)

3. Develop pulse-programmable Josephson voltage standards (JVS)

FY 1996	Applied for patent on pulse programmable JVS invention; Demonstrated pulse programmable JVS experimentally.
FY 1997	Used pulse-programmable JVS to synthesize sine waves at frequencies from 1 kHz to 1 MHz.
FY 1998	Integrated 16 Gb/s digital pattern generator into the pulse programmable ac JVS.
FY 1999	Develop new ultra small junction technology to allow the pulse programmable JVS to operate at higher voltages. (*1999 Budget Narrative*)
FY 2000	Design, fabricate, and test a pulse programmable JVS for operation over the range +1 V to -1 V.

4. Develop a Josephson voltage synthesis system based on single flux quantum (SFQ) voltage multipliers (New task)

FY 1999	Act as NIST technical representative on the development of SFQ voltage multiplier under a Phase II SBIR grant with U.S. company; Develop test hardware for SFQ voltage multiplier chips.
FY 2000	Test SFQ voltage multiplier at NIST.

Nanoscale Cryoelectronics

Project Leader: David A. Rudman

Staff-Years: 7.0 Professionals, 1.0 Technician, 2.7 NRC Postdoc, 1.0 PREP Postdoc, 2.0 Guest Researchers

Funding Sources: NIST (STRS-26%), Other Agency (74%)

Objective: Develop unique electronic devices and systems operated at milliKelvin temperatures for applications in fundamental metrology and industrial instrumentation.

Background: Electronic devices operated at the reduced noise levels afforded by cryogenic temperatures offer the ultimate in measurement accuracy and sensitivity. The goal of Nanoscale Cryoelectronics is to exploit this benefit of low temperatures and use microcircuit technology to develop new devices for fundamental metrology and industrial instrumentation. This project presently focuses on two such devices: an electron pump capable of counting electrons one-by-one and an x-ray detector that senses the temperature rise of electrons in a metallic absorber. The electron pump, based on ultra-small tunnel junctions, can accurately transfer a specified number of electrons to a capacitor. The pump will provide the basis for a new fundamental standard of capacitance and may lead to an improved measurement of the fine structure constant. The x-ray detector achieves far better energy resolution than conventional detectors, and has demonstrated significant improvements in materials analysis for semicomductor fabrication and other industrial applications. The same technology is now being applied to visible and infrated radiation and even to mass spectrometry for large molecules like DNA.

Current Tasks:

1. Develop single-electron pump for metrological applications

FY 1991	NIST Competence funding received for the first of five years to support the development of an accurate electron pump.
FY 1992	Error rate of electron pump analyzed and shown to require at least five tunnel junctions for metrological accuracy.
FY 1993	Five-junction electron pump fabricated and tested.
FY 1994	Experimental results on the five-junction pump demonstrated an accuracy of 0.5 part per million.
FY 1995	Seven-junction pump designed, fabricated, and underwent preliminary testing.
FY 1996	Demonstrated a seven-junction pump with an accuracy of 15 parts per billion and an average time of 10 minutes between leakage events in the hold mode.
FY 1997	Determined by direct measurement that the electron temperature in an operating pump is too low to explain the observed error rate, indicating that errors are proably due to photon-induced cotunneling.
FY 1998	Assembled first prototype of capacitor standard based on counting electrons, consisting of seven junction electron pump, single-electron tunneling spectrometer, and cryogenic vacuum-gap capacitor (fabricated by Electricity

	Division); Successfully operated standard with an imprecision better than 1 ppm.
FY 1999	Improve present standard to an imprecision of 0.1 ppm; Construct apparatus necessary to transport system to Gaithersburg for comparison to the calculable capacitor; Determine frequency dependence of vacuum gap capacitor. (*1998 MSL Strategic Plan*)
FY 2000	Compare electron counting standard to calculable capacitor to confirm accuracy of capacitance measurement (in collaboration with Electricity Division). (*1998 MSL Strategic Plan*)
FY 2001	Develop secondary standard for capacitor calibration based on new system. (*1998 MSL Strategic Plan*)

2. Develop microcalorimeters as x-ray detectors

FY 1996	Demonstrated an x-ray microcalorimeter with an energy resolution of 8 eV at 6 eV and a count rate of 100 counts per second; Obtained NASA funding to work toward an energy resolution of 2 eV for x-ray astronomy over three years.
FY 1997	Demonstrated transition-edge x-ray microcalorimeters with energy resolutions as low as 7.2 eV at 6 keV and (in a separate experiment) count rates as high as 800 cps.
FY 1998	Demonstrated a microcalorimeter with an energy resolution near 3 eV at 2 keV; Began development of microcalorimeter arrays.
FY 1999	Develop photolithographic techniques for fabricating arrays of microcalorimeters for x-ray imaging arrays; integrate arrays with SQUID-based multiplexers; Improve single pixel energy resolution at 6 keV.
FY 2000	Fabricate and test arrays of microcalorimeters for x-ray imaging applications.

3. Develop practical X-ray system for microanalysis applications

FY 1996	Fabricated and tested a complete x-ray system, including adiabatic demagnetization refrigerator, Superconducting Quantum Interference Device (SQUID) preamplifier, and superconducting transition-edge microcalorimeter; Interfaced system to an electron microscope and demonstrated resolution of 8 eV resolution in x-ray fluorescence spectra.
FY 1997	Fabricated and tested an improved adiabatic demagnetization refrigerator and cryostat with reduced liquid helium consumption; Increased the effective detection area of the microcalorimeter from 0.06 mm^2 to 6 mm^2 using a capillary x-ray lens; Demonstrated artifact-free fluorescence spectra at an energy resolution of 10 eV or less for a wide range of samples.
FY 1998	Demonstrated 0.1 μm diameter contaminant particle analysis on Si substrates, in line with National Technology Roadmap for Semiconductors goals; Demonstrated the first energy dispersive spectrometry of chemical shift in Al and Fe compounds.
FY 1999	Utilize improved energy resolution microcalorimeters in develop practical chemical shift measurement techniques; Apply system to new materials characterization problems.
FY 2000	Test use of microcalorimeter array to increase collection area and effective count rate of detector system; Develop capability for use in other, non-SEM-based, x-ray materials analysis systems, such as total relection x-ray fluorescence.

4. Develop transition-edge microcalorimeters for optical and ultraviolet applications

FY 1997	Obtained NASA funding to develop optical detectors based on transition-edge sensor microcalorimeters.
FY 1998	In collaboration with Stanford, fabricated optical microcalorimeter sensors, and installed on optical telescope at Stanford for testing.
FY 1999	Fabricate detectors on membranes to improve performance; Verify performance with non-optical tests in adiabatic demagnetization refrigerator.

5. Develop transition-edge bolometers for infrared applications

FY 1997	Demonstrated an infrared transition-edge bolometer with a noise equivalent power of 3×10^{-18} W/Hz^{½}; Successfully tested a discrete-component version of the SQUID multiplexing circuit to be used with bolometer arrays.
FY 1998	Began development of imaging arrays of bolometers based on transition edge sensors; Constructed an adiabatic demagnetization refrigerator for testing infrared detectors; Fabricated transition edge sensors on micromachined "pop-up" Si substrates (made at NASA) suitable for high density arrays; Demonstrated the first SQUID-based multiplexer with performance appropriate to read out large arrays.
FY 1999	Fabricate and test arrays of "pop-up" transition edge sensor bolometers; Test with SQUID multiplexer.

6. Develop cryogenic microcalorimeters for high-mass spectrometry

FY 1997	Demonstrated the application of cryogenic microcalorimeters to high resolution time-of-flight mass spectrometry of large molecules.
FY 1998	Acquired a high resolution magnetic sector mass spectrometer for the development of cryogenic detectors; Constructed an adiabatic demagnetization refrigerator for mass spectrometer project.
FY 1999	Integrate cryogenic detector system onto mass spectrometer; Compare performance to conventional detectors; Determine resolution at masses greater than 100 kDa.
FY 2000	Perform mass spectrometry on large molecules of interest, including DNA.

High-T_c Electronics

Project Leader: Ronald H. Ono

Staff-Years: 3.5 Professionals, 1.0 Guest Researcher, 1.0 NRC Postdoc, 0.5 Technician

Funding Sources: NIST (STRS-52%, ATP-5%), Other Agency (43%)

Objective: Use the unique properties of high-temperature superconductors to develop new devices and electronics for measurements and standards for the electronics industry. Develop new measurement techniques, devices, and circuits in support of the emerging superconducting electronics industry.

Background: High-temperature superconductivity (HTS) has opened the possibility for operating superconducting electronic instrumentation at temperatures accessible with present-day cryocoolers. Low-temperature superconductors have already been used to produce unique standards, such as the Josephson volt, and measurement apparatus, such as Superconducting Quantum Interference Devices. Equivalent HTS devices would expand the applicability of these devices far beyond standards and research laboratories. Thus the primary "customer" for the devices being developed by this project are the other NIST divisions responsible for standards and measurement techniques in areas such as the volt, and infrared, terahertz, and microwave radiation. The project will also provide support for the emerging HTS superconducting electronics industry, both through measurements and through the development of HTS devices and circuits.

Current Tasks:

1. Develop microwave testing for unpatterned HTS films (Collaboration with EEEL R-F Technology Division)

FY 1996 Improved sheet resistance (R_s) and power handling measurements; With industrial collaborators, compared cavity resonator measurements to other techniques; Transferred cavity technique to interested parties.

FY 1997 Developed variable temperature measurement capability with dielectric-loaded cavity resonator, including *in-situ* variable coupling; Improvements increased Q of resonator by factor of 10 (equivalent to increasing measurement sensitivity by factor of 10).

FY 1998 Implemented variable temperature high power R_s measurements using dielectric-loaded cavity resonator; Constructed cavities to handle full 75 mm wafers.

FY 1999 - 2000 Evaluate dielectric resonator for R_s measurement standards; Compare with international efforts in standardized HTS microwave measurements.

2. Characterize microwave performance of HTS films

FY 1996	Began study of R_s as a function of film processing parameters, using films made at NIST and from industrial collaborators.
FY 1997	Compared microwave properties of films deposited under different conditions; Provided measurements on films produced by different manufacturers.
FY 1998	Evaluated microwave performance of samples diced from wafers from a variety of manufacturers; Performed measurement intercomparisons with different laboratories.
FY 1999- 2000	Carry out intercomparisons with laboratories outside of the U.S. as well as U.S. industrial labs.

3. Develop cryogenic microwave device measurement capabilities (with EEEL Electromagnetic Fields Division)

FY 1996	Developed techniques for calibrated cryogenic microwave probing of superconducting devices; Used probe station to improve measurements of HTS devices patterned by different techniques.
FY 1997	Successfully modeled coplanar waveguide device performance based on measurements of unpatterned films; Implemented measurements of third-harmonic generation (TOI) as a function of microwave power; Found only weak dependence of TOI on patterned techniques; Measured harmonic generation as a function of line width and length
FY 1998	Implemented automatically calibrated high power measurement capability; Investigated effect of film properties on device performance.
FY 1999	Investigate nonlinear properties of thin film superconductors and dielectrics.

4. Develop HTS Josephson junction technology for measurements and standards applications

FY 1996	Tested alternative junction technology (bicrystals) for application to voltage standards and other measurements; Fabricated first bicrystal junctions on sapphire substrates; Developed novel multilayer process for HTS circuits.
FY 1997	Completed study of junctions on sapphire bicrystals; Completed demonstration of multilayer circuit fabrication.
FY 1998	Completed evaluation of stacked-junction circuit performance; Transferred technology to industry; End sub task.
FY 1999	Evaluate electron-beam irradiated junctions, bicrystal junctions, and ramp-edge junctions for use in ac voltage standards.

5. Develop HTS bolometers as improved radiometers

FY 1996	Measured electrical noise in HTS films at transition temperature on different substrates, including silicon; Noise approached the Johnson limit, verifying that films are appropriate for thermometer applications (with U.S. companies).
FY 1997	Fabricated HTS films on large-area silicon membranes; Devices currently under test for use in electrical substitution radiometers (same collaborations).
FY 1998	Fabricated prototype electrical-substitution radiometer using HTS transition-edge thermometer (same collaborations).
FY 1999	Develop fabrication technology for single pixel, high speed HTS bolometers; Evaluate feasibility of fabrication YBCO hot-electron bolometers for heterodyne detection in the THz regime.

6. Develop micromachined ion traps (with NIST/Physics Laboratory's Time and Frequency Division)

FY 1996	Developed initial design to test micromachining concepts for ion trap fabrication; Selected laser cutting as most appropriate initial approach for substrate machining.
FY 1997	Fabricated and assembled first micromachined ion traps; Traps currently under test by Time and Frequency Division.
FY 1998	First generation of micromachined traps tested successfully by Time and Frequency Division; Improved rf trap fabricated.
FY 1999	Based on results from tests of first devices, fabricate improved traps.

Superconductor Standards and Technology

Project Leader: Loren F. Goodrich

Staff-Years: 1.0 Professional, 1.0 Technician

Funding Sources: NIST (79%), ATP (19%), Other (2%)

Objective: Provide standards, measurement techniques, quality assurance, reference data, and issue clarification for both high- and low-temperature superconducting wire technology in support of applications involving U.S. industry such as magnetic resonance imaging, and development of laboratory magnets, fault current limiters, magnetic energy storage devices, motors, generators, and transmission lines.

Background: The project is internationally recognized as the leader in the development of standards for critical-current measurements and is leading the international effort for all superconductor standards. This effort is vital to U.S. industry, which now concentrates on conventional low-temperature superconductor (LTS) materials. This effort is becoming more vital to U.S. industry as additional new applications that use high-temperature superconductors (HTS) are commercialized. One of the most important performance parameters for large-scale applications is the critical current, I_c, of a superconductor, which is the current level that under given conditions, marks the transition between the superconducting state and the normal state. The critical current is difficult to measure correctly and accurately, and these measurements are often subject to scrutiny and debate. This is especially true for measurements on HTS. This project's primary activities are I_c measurement metrology, interlaboratory comparisons, and development of international standards. International standards for superconductivity are created through International Electrotechnical Commission (IEC) Technical Committee 90 (TC 90). Goodrich is the Chairman of TC 90, the U.S. Technical Advisor to TC 90, the Convener of Working Group 2 (WG2), and U. S. Expert to six of the eight WGs.

Current Tasks:

1. Develop international standards for superconductivity through IEC

FY 1996	Worked on draft documents from Working Groups (WGs) 1, 2, 4, 6, and 7; Approved Committee draft for voting from WG 2.
FY 1997	Held fourth TC 90 meeting in China; Worked on documents from WGs 1, 2, 3, 4, 5, 6, and 7.
FY 1998	Voted on Committee drafts from WGs 2 and 7; Document from WG2 (created by Goodrich and Stauffer) was published as the first international standard for superconductivity; Stauffer became the Administrator to the U.S. Technical Advisory Group; Participated in fifth TC 90 meeting held in Germany; Worked on documents from WGs 1, 3, 4, 5, 6, and 7, and 8; Japanese National Committee (JNC) proposed work on four new documents.
FY 1999	Final voting of documents from WGs 1 and 7; Initial voting on documents from WGs 5 and 6.

FY 2000	Sixth TC 90 meeting to be held, may be held in Boulder.

2. Develop metrology for I_c measurements on HTS

FY 1996	Completed final report on U.S. comparison in project under Versailles Project on Advanced Materials and Standards (VAMAS); Completed comparison in Europe; Planned comparison in Japan; Planned second stage international comparison.
FY 1997	China reported results of their comparison which confirmed the results from the U.S. comparison; Japan completed their domestic comparison.
FY 1998	Second stage interlaboratory comparison cancelled because of problems with time and samples; Helped draft standard for measurement of I_c in HTS materials; Submitted three sections to final VAMAS report on HTS I_c comparisons; Completed construction and initial testing of high-current, variable-temperature I_c measurement system for HTS samples with temperatures from 4 K to 90 K, fields from 0 T to 8 T, and angles from -90° to 90°; Made measurements up to 100 A on HTS samples.
FY 1999	Develop and test custom 400-A power supply that can deliver current pulses and waveforms with durations from 33 ms to 90 ms; Extend variable-temperature system to 250 A; Provide data to U.S. conductor manufacturers.
FY 2000	Conduct a U.S. interlaboratory comparison of variable-temperature I_c measurements using HTS samples.

3. Develop metrology for I_c measurements on LTS

FY 1996	Created an accurate database of magnetic field and temperature dependence of I_c up to temperatures of 5.0 K in liquid helium; Confirmed capability to measure I_c at 12 T with current pulses
FY 1997	Developed I_c measurement capability up to 200 A in helium gas over the temperature range of 4.2 K to 18 K to determine the temperature stability margin for ITER and magnets that operate near 10 K; Created database for the temperature stability margin of niobium tin compound (Nb_3Sn) wires; Studied effect of sample coil diameter on the measured I_c.
FY 1998	Measured I_c as a function of magnetic field and temperature of a niobium titanium alloy (Nb-Ti) wire with currents up to 180 A., to be used as control sample for variable-temperature I_c measurements of HTS samples.
FY 1999	Measure I_c as a function of field and temperature of a Nb-Ti wire up to 400 A.

4. Develop metrology for sensitive low-temperature measurements

FY 1996	Finished fabrication and testing of custom simulator; Loaned I_c simulators to two U.S. laboratories; Developed and verified capability to acquire voltage-current characteristics using variable-duration current pulses.
FY 1997	Developed capability of delivering 5000 current pulses to sample in a 12 T magnetic field to study fatigue due to Lorentz force cycling.
FY 1998	Implemented and verified differential thermometry to control temperature gradients in samples during variable-temperature I_c measurements. Terminated task 4 in 1998; will consolidate future milestones into other tasks.

LOW FREQUENCY

AC-DC Difference Standards and Measurement Techniques

Project Leader: Joseph R. Kinard

Staff-Years: 2.0 Professionals, 1.0 Technician

Funding Sources: NIST (50%), Other Government Agencies (17%), Other (33%)

Objective: Provide U.S. industry with the link between the direct voltage and current standards and alternating quantities by maintaining and improving the U.S. national standards of ac-dc difference, and the working standards, measurement systems, and techniques needed to provide viable calibrations and measurement services for thermal converters and shunts.

Background: Nearly all measurements of electric power, energy, alternating voltage and alternating current are traceable to the volt and ohm (dc quantities) through thermal transfer standards. Modern electronics makes possible digital instruments which can produce and measure alternating voltage and current parameters with precision and stability rivalling those of the best direct voltage and current standards. Improved NIST thermal transfer standards are needed to support the development, testing, production, and maintenance of such instruments. Thermal transfer standards are used to measure a quantity called "ac-dc difference," where ac, literally "alternating current," refers to the time varying signals and dc literally "direct current," refers to time invariant signals. NIST has developed new standards, nearly as good as existing national standards, based on semiconductor and thin-film processing technologies that are about to be commercialized and hence widely available. Present NIST standards are inadequate to calibrate these devices over their full range of capability. Moreover, manufacturers are introducing high-output current amplifiers and improved high-voltage resistors. An extension of the parameter space and improved accuracies of NIST calibration services are required to support these developments.

Work is underway to develop new primary, thermal transfer standards operating at cryogenic temperatures and with sensitivity approaching the quantum limit. This effort builds on the experience gained in the development of film multijunction thermal converters and on the design and application of extremely sensitive cryogenic thermometers. The new standards are expected to reduce uncertainties from the present lowest value of 0.8 μV/V to 5 μV/V to $<$0.1 μV/V to 1 μV/V. A new investigation of bootstrapping techniques to support high-voltage and current measurements is also being performed. This will be based on earlier, pioneering NIST work in this field and is expected to result, not only in improved NIST services, but in better, more efficient techniques for industrial standards maintenance as well. The U.S. has the largest manufacturing industry for thermal transfer instrumentation. NIST continues to provide support for this U.S. industry through an expanded ac-dc difference calibration service, Cooperative Research and Development Agreements (CRADAs), and international comparisons and cooperations.

Current Tasks:

1. Maintain the primary, reference, and working sets of thermal transfer standards for ac-dc difference; provide and improve the ac-dc difference calibration service for voltage from 0.1 V to 1000 V at 2 Hz to 1 MHz; and for current from 1 mA to 100 A at 2 Hz to 100 kHz

FY 1994	Studied the voltage dependence of thermal converters in the 200 V to 1000 V range and re-characterized the NIST high-voltage standards.
FY 1995	Studied and re-characterized thermal converter standards at 10 Hz to permit reduction in calibration uncertainties; Provided new ac-dc difference reference values from 10 kHz up to 30 MHz to maintain consistency between this activity and NIST's higher frequency ac-dc difference calibration service.
FY 1996	Fabricated and tested new high-current, multi-converter module to replace damaged traditional converters; Published results; Fabricated and tested high-voltage, binary divider to confirm scaling of 200 V to 1000 V ranges (recent international comparisons revealed significant variations between national laboratories at these voltages); Prepared documentation for extending transfer shunt calibrations up to 100 kHz.
FY 1997	Completed total reassessment of ac-dc difference calibration service uncertainties with significant reductions; Prepared documentation for extension of transfer shunt calibration down to 10 Hz.
FY 1998	Performed first NIST transfer shunt calibrations at 100 A and 100 μA; Compared transfer shunt and thermoelement build-up methods at 10 Hz; Completed international comparison at 500 V - 1000 V; Upgraded automated system with new signal sources, computers and software; Presented results at Conference on Precision Electromagnetic Measurements (CPEM'98) of inductive voltage divider comparison to high-voltage converter build-up; Designed new laboratory module.
FY 1999	Renovate primary standards group mountings; Replace aging connectors on reference and working standards; Compare inductive voltage divider to high-voltage standards; Obtain formal approval for new uncertainties; Participate in high-frequency international comparison.
FY 2000	Establish new thin-film current transfer standards; Reduce calibration uncertainties at high voltage.

2. Develop new thin-film converter technology and assist with the transfer of this technology to industry

FY 1990	Perfected stress-balanced, multilayer membrane required for thin-film converter fabrication.
FY 1991	Mounted and tested completed chips.
FY 1992	Developed improved bonding pads for thin-film converters to greatly reduce errors as current converters; Received patent in February 1995; Directed cooperative program with industrial partner for the development and production of thin-film multijunction thermal converters.
FY 1993	Designed and produced integrated micropotentiometers which combined high performance multijunction converter and thin-film output resistors on the same chip; Received patent in February 1994.
FY 1995	Solved a remaining problem with wafer cleaning and metal to metal contacts, and continued successful production of converter chips; Fabricated additional

	converter chips, mounted, and characterized as working standards; Provided chips to DoD and Sandia laboratories as per agreements.
FY 1996	Characterized thin-film converters at various voltages, currents, and frequencies at room and cryogenic temperatures and began study to incorporate these devices as reference and working standards; Constructed and tested new thin-film thermal converter chips for currents above 0.5 A; Presented invited summary paper at CPEM 96 on thin-film converters.
FY 1997	Began development of broadband mounting substrate to permit extension of integrated micropotentiometer and thin-film converter frequency range.
FY 1998	Designed basic geometry for new high-current multijunction thermal converters; Built vacuum chamber for testing new converters; Collaborated with Semiconductor Electronics Division on construction of front surface etching chamber; Began chip modeling in collaboration with graduate student working at Sandia National Laboratories.
FY 1999	Produce high-current multijunction thermal converters using front surface etching; Test alternative designs for new converter to obtain optimum performance.
FY 2000	Develop new packaging for thin-film multijunction thermal converters. (*1998 EEEL Strategic Plan*)

3. Develop new low-temperature thermal converter standards and study fundamental limitations on the thermal transfer process

FY 1995	Began study of low-temperature converter design using alternative superconducting transition edge device as sensor; Determined that transition edge device appears more conducive to fabrication and incorporation into converter than kinetic inductor as originally planned.
FY 1996	Assembled cryogenic system; Made prototype converter chips using transition edge thermometers; Began initial testing of new low-temperature devices.
FY 1997	Developed suitable designs and geometries for low temperature standards and investigated fundamental limitations on the thermal transfer process; Achieved first ac-dc difference measurements at cryogenic temperatures; Presented results in paper at the IMTC/97 in Ottawa.
FY 1998	Fabricated second generation of low-temperature converter chip and mounting; Compared low-temperature converter to conventional standards; Performed first ever thermal transfer measurements at microwatt signal power levels; Presented results on low-temperature converter at CPEM'98.
FY 1999	Design shorter transmission line for cryostat; Compare low-temperature converter to fast reversed dc source; Improve supporting electronics for low-temperature converter.
FY 2000	Confirm accuracy of low-temperature converters and establish them as primary standards, if appropriate.

4. Support the measurement of ac quantities through interaction with industry and other national laboratories

FY 1995	Trained professional staff member and provided equipment and extensive calibrations to the Mexican national measurement laboratory, CENAM; Participated in an international comparison of a multijunction thermal converter travelling standard at the highest uncertainty level.

FY 1996-97	Participated in international comparisons of high-frequency thermal converters with the laboratory responsible for their maintenance in Spain (INTA); Assisted various companies to develop improved thermal converter instrumentation; Presented tutorial on thermal transfer standards at II Semetro, Brazil.
FY 1998	Provided training for guest scientist Moses Temba, a metrologist in ac-dc difference measurements from the South African National Laboratory; Performed comparison of fast reversed dc source with ETL, Japan; Sponsored ac-dc transfer topical session at CPEM'98; Established collaboration with Sandia National Laboratories for vacuum package development; Compared results of 1 kV bilateral comparison with NRC, Canada.
FY 1999	Train guest scientists from the national metrology laboratory of Egypt.
FY 2000	Train guest scientists from the national metrology laboratory of Brazil; Cooperate with CENAM, Mexico, to improve their thermal transfer standard calibrations.

Waveform Acquisition Devices and Standards

Project Leaders: T. Michael Souders, Nicholas G. Paulter, Jr.

Staff-Years: 4.0 Professionals, 0.5 Technician

Funding Sources: NIST (44%), Other Government Agencies (50%), Other (6%)

Objective: Develop standards, test methods, and analysis techniques for waveform acquisition devices. Expand and improve the present time domain waveform measurement services to support high performance samplers and digitizers, as well as fast pulse and impulse sources, operating over frequencies to 50 GHz.

Background: Manufacturers and users of time domain instrumentation need state-of-the-art methods and standards for characterizing the performance of increasingly sophisticated products. Waveform sampling has become a critical, pervasive technology in instrumentation and continual advances are being made. The digital oscilloscope market alone was estimated to be $80 M in 1999. This industry needs advances in standards, test methods and error analyses to facilitate continued growth. In turn, the computer, telecommunications and integrated circuit industries (each critically dependent on sampling technology) will all benefit. Improved optoelectronic technology will be needed for advancement and development of state-of-the-art electronic devices, semiconductor structures, and printed circuit board materials. NIST has pioneered many of the techniques and standards used today for testing and calibrating precision time domain instruments and systems. In response to new advances in devices and products, NIST will expand and improve the present time domain waveform measurement services to support high performance samplers and digitizers, as well as fast pulse and impulse sources, operating over frequencies up to 50 GHz. Specific goals include: (1) developing and applying accurate sampling comparator systems to measure the settling parameters of fast pulse generators, amplifiers, and digital-to-analog converters (as well as making accurate voltage measurements); (2) providing error analyses on the effects of non-idealities in sampling systems; (3) researching and developing optoelectronic devices and techniques for ultra-fast sampling and pulse generation applications and electric-field probing; and (4) supporting and contributing to consensus standards for specifying and testing waveform acquisition devices, and standards for pulse terminology and characterization.

Current Tasks:

1. Data converter/waveform recorder testing

FY 1996	Began development of a wideband oscilloscope calibration system in response to needs articulated by the Air Force.
FY 1997	Completed version 1 of oscilloscope calibration system and delivered to sponsor; Concluded pulse measurement round-robin.
FY 1998	Published paper on pulse measurement round-robin and found need for more definitive measurement capability in first two nanoseconds following a step transition; Developed procedure for calibrating reference step generators and

	incorporated version 2 of oscilloscope calibration system delivered to Air Force.
FY 1999	Develop test procedures for oscilloscope aberrations.
FY 2000	Incorporate aberrations tests into oscilloscope calibration system and deliver to AF sponsor.
FY 2001	Update oscilloscope calibration system with new deconvolution routines.

2. Sampling comparator systems (SCS)

FY 1994	Began development of wideband (10 Hz - 200 MHz) sampling voltmeter.
FY 1995	Developed quasiequivalent-time time-base, probe control, and memory management circuits; Produced a working prototype voltmeter.
FY 1996	Presented paper on voltmeter design, architecture and error sources.
FY 1997	Began development of a triggerable-oscillator time-base; Carried out feasibility study for a 5 GHz bandwidth comparator for use in SCS.
FY 1998	Delivered wideband sampling voltmeter to sponsor; Completed 75% of new comparator design (5.3 GHz bandwidth and ± 2 V operation in simulations); Completed design and fabrication of new time-base for SCS.
FY 1999	Complete design and fabricate new comparator; Incorporate new time-base into SCS; Begin development of new SCS based on sampling voltmeter mainframe.
FY 2000	Complete new voltmeter-based SCS; Test performance of new comparator; Begin development of high accuracy, low frequency comparator.
FY 2001	Offer 5 GHz bandwidth fast settling parameter calibration services; Complete high accuracy comparator.

3. Pulse measurement services

FY 1996	Evaluated deconvolution algorithms, selected and coded new algorithm for use in pulse parameter estimation software; Developed control and automation software to upgrade pulse parameter measurements.
FY 1997	Developed new algorithm to measure linearity of oscilloscope time-bases; Provided special calibrations of two commercial pulse calibrators, including uncertainty envelope for entire measured waveform.
FY 1998	Wrote, presented paper on time-base measurement method; Began development of new deconvolution algorithm; Developed polynomial interpolation algorithm to correct for time-base errors.
FY 1999	Obtain 50 GHz oscilloscope impulse response estimate using nose-to-nose method; Complete paper on new deconvolution algorithm; Begin LabVIEW™ based system for new pulse measurement services.
FY 2000	Complete LabVIEW™ based pulse measurement system; Develop and incorporate measurement techniques for pulse aberrations; Obtain magnitude estimate of 50 GHz oscilloscope response using swept frequency method.
FY 2001	Offer 50 GHz bandwidth fast pulse calibration services.

4. Optoelectronic technology

FY 1996	Introduced optical delay/splitter to reduce laser jitter effects from 7 to 0.5 ps.
FY 1997	Tested diode-laser based system operation; Made improvements in operating frequency and optical pulse duration.
FY 1998	Achieved 0.6 ps optical pulse width from diode laser system.

FY 1999-2000	Begin determination of impulse response estimate of 50 GHz oscilloscope using optoelectronic method.
FY 2001	Complete optoelectronic determination of impulse response.

5. Pulse Measurement Applications

FY 1996	Developed time-domain method to measure the dielectric constant of printed wiring board materials; Used inexpensive equipment to implement method and provide accuracy comparable to frequency domain techniques.
FY 1997	Investigated repeatability of the dielectric measurement technique; Reported results in paper; Studied various transmission line structures for extracting permittivity of dielectrics with low d_K values.
FY 1998	Developed new printed wiring board (PWB) sample holder that reduced measurement variability by factor of 4; Developed PWB transmission line probe that reduced measurement uncertainty in commercial lab by 50%.
FY 1999	Conclude PWB transmission line probe by improving bandwidth and implementing an overvoltage protection design.

Waveform Synthesis and Impedance Metrology

Project Leader: Nile M. Oldham

Staff-Years: 4.0 Professionals, 2.0 Technicians

Funding Sources: NIST (50%), Other Government Agencies (30%), Other (20%)

Objective: Provide calibrations and special tests and develop new measurement capability to support the basic quantities of voltage, current, phase angle, power/energy, ratio, and impedance using waveform synthesis and sampling techniques as well as classical electrical measurement methods spanning a frequency range of dc to 100 MHz.

Background: Industrial, university, and government laboratories have calibration requirements for basic instrumentation standards to support calibrators, digital multimeters (DMMs), impedance (LCR) meters, and phase meters. With multifunction/multirange capability, wide frequency ranges, and sophisticated self-calibration features, the ability to provide a comprehensive coverage of the calibration quantities for these instruments, at desired accuracies and ratios, is increasingly challenging. The market for these instruments is over $550 million annually. Similarly, the power industry legally requires NIST traceability to equitably distribute over $215 billion of electric energy generated annually. High-accuracy power measurements are required to determine the efficiency of electric equipment during development and manufacture, and for quality control. Power and energy measurements have been complicated by an increasing proportion of nonlinear loads and alternate energy generators, which produce nonsinusoidal waveforms with frequency components in excess of 100 kHz. In response to the above needs, new waveform generation and measurement capability at NIST will be developed to support the basic quantities of voltage, current, phase angle, ratio, and impedance, using techniques for generating and measuring voltage and current waveforms over the frequency range up to 100 MHz. Specific goals include: (1) developing techniques to measure generalized impedances at signal frequencies up to 1 MHz; (2) developing automated measurement systems capable of providing near state-of-the-art traceability for voltage, current, resistance, and phase angle in the frequency range from dc to 30 MHz; and (3) developing new 60 Hz power/energy standards and extending the frequency range of power measurements up to 400 kHz.

Current Tasks:

1. Voltage and current

FY 1996 — Extended the range and characterized the multifunction calibration system (MCS) for the calibration of currents up to 10 A; Developed a model to describe the low frequency performance of thermal voltage converters; Developed a scheme to reduce low voltage measurement uncertainties due to complex loading errors; Began organizing an international comparison of electrical units (with North, South, and Central America) using DMMs as transportable standards.

FY 1997	Trained participants and began the Interamerican Metrology System (SIM) International Comparison of Electrical Standards using DMMs; Completed software to use the digitally synthesized source (DSS) to make precise low frequency (0.1 Hz to 100 Hz) ac measurements.
FY 1998	Documented the MCS in a NIST Technical Note; Reported on the intermediate results of the SIM comparison; Began a study on the use of the Internet to enhance special tests of DMMs.
FY 1999	Complete the SIM International Comparison; Offer a new Internet-based special test service for multifunction calibrators (using transportable DMMs).
FY 2000	Develop new standards to support ac voltage measurements from 1 mV to 500 mV between 1 MHz and 30 MHz; Develop instrument models to enhance the Internet-based test service.
FY 2001	Apply Internet-based test techniques to other areas of electrical metrology.

2. Impedance

FY 1995	Completed an analysis of uncertainties of capacitance calibrations; Developed a VXIbus-based impedance synthesizer and used it to test bioelectrical impedance analyzers for sponsor (National Institutes of Health); Began using a commercial capacitance meter for the calibration of capacitors; Evaluated a new commercial fused silica capacitor.
FY 1996	Completed the impedance calibrator; Demonstrated a multirange 3-voltmeter probe to measure inductors; Demonstrated a modeling-based system for characterizing 4-terminal pair capacitors.
FY 1997	Completed a prototype system for characterizing 4-terminal pair capacitors at frequencies up to 1 MHz; Completed the 3-voltmeter probe and began using it to calibrate inductors; Documented the capacitance calibration services.
FY 1998	Evaluated the 3-voltmeter probe-based digital impedance bridge as a means for calibrating standard inductors; Completed the system to measure 4-terminal-pair capacitors (capacitance and dissipation factor) up to 10 MHz.
FY 1999	Complete an error analysis of the measurement system and offer a special test for 4-terminal-pair capacitors; Complete new control software to automate the binary inductive divider bridge and evaluate it as a means of calibrating inductive dividers and 3-terminal capacitors.
FY 2000	Develop a general-purpose impedance bridge that employs a waveform generator locked to a waveform sampler; Investigate the use of LCR meters as transportable standards in an Internet-based special test for impedance.
FY 2001	Begin automation of the impedance calibration test sets and document the new measurement services.

3. Phase

FY 1993	Developed a VXIbus-based system for calibrating phase meters and generators ("VXIbus" refers to Institute of Electrical and Electronics Engineers Standard 1155-1992, a specification for the backplane interconnection and communications protocol of standard-sized modules).
FY 1994	Simulated a phase measuring system for measuring very-high-frequency omni-directional ranging (VOR) phase meters for aircraft navigation system now expected to be in use beyond 2000.
FY 1995	Developed a VXIbus-based test set for VOR phase meters.

FY 1996	Tested and delivered a VXIbus-based system for testing the phase meters in VOR receivers to the sponsor.
FY 1997	Developed an improved VXIbus-based test set for VOR phase meters.
FY 1998	Offered a special test service for VOR phase meters.
FY 1999	Upgrade the NIST sampling phase meter to measure phase angle generators at any phase angle at frequencies up to 200 kHz; Extend phase measurements from amplitude ratios of 10:1 to ratios of 100:1.
FY 2000	Develop a new phase meter based on a digital waveform generator and sampler that operates up to 500 kHz; Upgrade and document the VOR phase standard.

4. Power and energy

FY 1994	Demonstrated a power measurement at a signal frequency of 200 kHz to support wideband commercial wattmeters and power system analyzers.
FY 1995	Began the planning stage of a NIST-sponsored international comparison of 50/60 Hz power.
FY 1996	Completed the first stage of the international comparison (with the national measurement laboratories of Canada and Germany); Demonstrated a 3-voltmeter technique for measuring wideband power at frequencies up to 500 kHz; Assumed chair of ANSI Committee on Electricity Metering (C-12).
FY 1997	Began development of a new 50 Hz - 400 Hz power measurement system; Completed half of the 50/60 Hz international comparison.
FY 1998	Constructed and tested the main components of a new 50 Hz to 400 Hz bridge; Investigated a new sampling technique to achieve limited-range power uncertainties of less than 10 ppm; Reported on the Consultative Committee on Electricity and Magnetism (CCEM) International Comparison of 50/60 Hz Power.
FY 1999	Assemble a prototype version of the new power bridge, develop control software, and begin evaluating the system as a replacement for the existing bridge; Complete the CCEM International Comparison. (*1998 MSL Strategic Plan*)
FY 2000	Complete and document the new power bridge; Develop a limited range sampling wattmeter capable of measuring complex power with frequency components up to 500 kHz. (*1998 EEEL Strategic Plan*)
FY 2001	Expand the range of the sampling wattmeter and offer special tests for single-phase power to 500 kHz.

Measurements for Complex Electronic Systems

Project Leader: Gerard N. Stenbakken

Staff-Years: 2.0 Professionals, 0.2 Guest Scientist, 0.1 Technician

Funding Sources: NIST (51%), Other Government Agencies (49%)

Objective: Develop improved methods and techniques for optimum testing scenarios by: (1) developing better mathematical models and test procedures; (2) estimating the confidence and test coverage in a given calibration or test procedure; (3) developing a Testing Strategies Software Toolbox; and (4) researching modeling approaches and techniques that accommodate the effects of embedded software.

Background: For both manufacturers and users, the testing and calibration costs of complex electronic devices and instrumentation have become a dominant factor in total life-cycle costs. For example, typical test costs for mixed-signal integrated circuits range from 20% to 50% of the sale price. Similarly, in the acceptance and field maintenance of electronic equipment, the costs of testing can equal or exceed the initial purchase price. Confidence levels, test coverage, and test and calibration procedures are often inadequate to assure the extremely low defect levels and tight performance tolerances that are now required. This is a generic problem throughout the spectrum of electronic products. It has been shown that the testing strategies developed at NIST can have a substantial impact on the production costs. These cases have been made for both analog and mixed-signal products, such as data converters and multirange measurement instruments. However, the existing strategies are often inadequate for systems that rely on embedded software. New approaches are needed to accommodate software-driven systems that are adaptive, reconfigurable, or highly nonlinear. The prominence of quantization in these systems in part determines the approaches that can be used; new approaches are needed for both coarsely quantized systems, such as digital communications devices, and high resolution quantized systems, such as instrumentation systems.

Current Tasks:

1. Testing strategies

FY 1989 — Evaluated limitations of linear models, and developed a capability for modeling second order time-domain sensitivities; Published papers on "Time-Domain Testing Strategies and Fault Diagnosis for Analog Systems" and "Ambiguity Groups and Testability".

FY 1990 — Successfully applied NIST-developed testing strategies to a population of 128 commercial 13-bit analog to digital converters; Achieved 0.03 least-significant-bit (rms) uncertainty in linearity estimates at all 8192 codes using 64 measurements; Presented paper on method and results.

FY 1991 — Conducted the first NIST testing strategies workshop; Initiated use of NIST method by two integrated circuits manufacturers in production testing; Announced commercial software product based on NIST work; Published

	tutorial paper in IEEE's *Spectrum* and paper on analog to digital converter application in a conference proceedings.
FY 1992	Developed an accurate error model for multifunction instrument and demonstrated effective test results with 80% reduction in test cost; Began analysis of theoretical performance limits of empirical models.
FY 1993	Prepared two papers on modeling and test point selection for a commercial thermal transfer standard; Conducted second testing strategies workshop.
FY 1994	Established theoretical basis for, and proof of, maximum likelihood properties of empirically derived error models; Developed expressions for statistical confidence intervals for results obtained from linear models; Began development of Testing Strategies Toolbox; Conducted third testing strategies workshop.
FY 1995	Completed work on procedures to estimate the effects of nonmodel errors and to compute prediction intervals that account for them; Demonstrated application of nonmodel error analysis to two instruments and began applying the approach to a NIST calibration service (with estimated savings to customers of $26k per test); Completed subroutines and user interface for NIST Testing Strategies Toolbox; Demonstrated prototype; Developed and demonstrated an empirical model and efficient test plan for a multifunction calibrator.
FY 1996	Completed 2/3 of NIST Testing Strategies Toolbox tutorial guide (mathematical background) and 1/2 of user's manual (in browsable hypertext), and released version 1.0; Completed analysis and issued first test report based on NIST High-dimensional Empirical Linear Prediction (HELP) approach and presented paper on results.
FY 1997	Prepared and conducted fourth workshop and training program (for DoD sponsors); Completed Toolbox tutorial guide and user's manual, and completed and released version 2.0 of toolbox; Demonstrated NIST approach on commercial multirange ac voltage standard; Developed a plan for an adaptive modeling approach in which calibration history is used to iteratively reduce subsequent calibration costs.
FY 1998	Documented NIST testing strategies methods for analog and mixed-signal devices; Made available NIST Toolbox software for public distribution; Presented workshop and training of the NIST HELP Toolbox to Swedish national calibration laboratory representative; Compared and evaluated six adaptive modeling approaches.
FY 1999	Evaluate theoretical limits in applying Expectation Maximization to adaptive modeling; Apply HELP methodology to a commercial, wideband, thermal ac voltage standard.
FY 2000	Assess methods for incorporating severe nonlinear behavior into the HELP methodology; Respond to feedback from industry on the use of HELP; Provide a workshop and assist industry on the use of HELP.

2. Device/system analysis

FY 1992	Began feasibility study of new, hardware-efficient, on-line error detection approach for analog systems.
FY 1993	Completed study of on-line error detection scheme and documented results.
FY 1994	Assisted Office of Law Enforcement Standards in development of integrated services digital network (ISDN) telecommunications equipment draft standard.

FY 1995	Developed approach for analyzing self-calibrating systems and applied to a self-calibrating instrument; Began development of ISDN standard for state and local law enforcement agencies.
FY 1996	Continued development of the ISDN standard.
FY 1997	Continued development of the ISDN standard.
FY 1998	Completed ISDN standard distributed to industry for comments.
FY 1999	Incorporate industry comments and submit final draft ISDN standard to Department of Justice (DOJ). Task completed.

3. Testing embedded systems

FY 1997	Submitted proposal and received Director's approval for a NIST 5-year Competence Project on Strategies for Testing Software embedded Systems.
FY 1998	Began task on strategies for testing software-embedded systems; Identified example of industry areas where the testing of systems having embedded software is problematic; Selected NIST-developed wideband sampling voltmeter as a test case; Developed approach for modeling and a plan for testing this system; Chose analytic tools to model system.
FY 1999	Become familiar with analytic tools useful in analyzing testability of embedded software systems; Apply analytic tools to selected test cases; Hold a workshop to solicit inputs from industry on testing embedded software systems; Gather test data on selected test cases; Develop model of at least one selected test case; Develop improved test plan for selected test cases; Compare improved test plans with traditional test methods.
FY 2000	Publish paper on new analytic techniques; Determine generic approach to analyzing systems with embedded software; Develop software for generic analysis of the testability of embedded software systems; Participate in workshop on testing embedded software.
FY 2001	Select additional test cases; Apply software to new cases; Publish paper on new generic approach.
FY 2002	Develop additional analytic tools to analyze systems with embedded software; Refine software to make use of additional analytic tools.

RADIO FREQUENCY

* New project
** This project combined the previous two projects, "Impedance, Voltage, and Dimensional Standards and Measurements" and "Power Standards and Measurements."

High-Speed Microelectronics Metrology

Project Leaders: Dylan F. Williams

Staff-Years: 3.0 Professionals, 1.0 Technician, 1.0 Student

Funding Sources: NIST (88%), Other (12%)

Objective: Support the electromagnetic characterization of microelectronic structures and devices.

Background: This project was formed in 1989 to address industry demands for metrology appropriate to monolithic microwave integrated circuits (MMICs), which have become increasingly prevalent in low-cost, low-power wireless communications systems. This demand led to the creation, with industry funding, of the NIST Industrial MMIC Consortium, which was recently extended beyond its initial five-year lifetime. The project has been expanded to include high-speed microelectronics packaging and nonlinear device characterization. Nonlinear characterization has now become a separate project.

Current Tasks:

1. Develop metrology and software for on-wafer characterization

FY 1989	Formed NIST/Industrial MMIC Consortium.
FY 1990	Developed multiline Thru-Reflect-Line (TRL) calibration method and software, now accepted as the most accurate on-wafer calibration method available.
FY 1991	Developed first procedures to accurately measure characteristic impedance and capacitance of planar transmission lines on lossless dielectric; Developed calibration comparison method; Fabricated CPW standards and distributed them to consortium.
FY 1992	Published General Waveguide Circuit Theory, accounting for conductor loss; Applied calibration comparison method to assess error in industry measurements; Found errors as large as seventy percent; Developed improved photoresist process.
FY 1993	Developed calibration method based on lumped elements; Designed calibration verification procedures and completed on-site tests.
FY 1994	Reduced size of calibration set using compact on- and off-wafer standards; Demonstrated effectiveness of accuracy assessment methods in tests at Consortium sites; Designed and fabricated on-wafer noise test structures.
FY 1995	Released MultiCal® software for improved calibration; Developed equivalent circuit theory for coupled lines; Tested method to verify probe station according to ANSI Standard Z540; Fabricated and tested microstrip artifacts.
FY 1996	Introduced multiline TRL for low-cost network analyzers; Developed off-wafer coplanar-waveguide calibration accounting for changes in contact geometry; Demonstrated algorithm for calibration in multiconductor lines; Determined requirements for certifying on-wafer artifacts as SRMs; Initiated IEEE Working Group to develop Standard on Microwave Network Parameters; Fabricated prototype Reference Materials (RMs).

FY 1997 Explored membrane probe calibration; Studied an improved Open-Short-Load-Thru (OSLT) calibration; Began converting MultiCal® software to standalone code with C++ links; Developed software for comparing internal vector network analyzer calibrations; Finalized Reference Material qualification procedures for on-wafer standards; Fabricated and began qualification of a limited number of RMs.

FY 1998 Released an improved Open-Short-Load-Thru (OSLT) calibration; Compared standard industry developed calibrations for membrane probes to TRL; Completed the development of a 4-port measurement capability; Introduced on-wafer standards as Reference Materials; Completed worst-case error analysis of on-wafer standards; Stand-alone software for comparing internal vector network analyzer calibrations; Released on-wafer standards as Reference Materials.

FY 1999 Develop calibration for membrane probes and compare it to standard industry calibrations; Develop improved calibration methods that account for inherent differences in microstrip calibrations, compensation for via-hole differences, and other microstrip calibration errors; Complete error analysis required to release on-wafer standards as Standard Reference Materials; Assemble automated probe station and automate TRL measurements; Support the development and application of an on-wafer noise source; Work with company to commercialize NIST's line-reflect-match (LRM) calibration for non-ideal standards.

2. Develop procedures for characterization of electronic packaging

FY 1992 Developed new method to measure characteristic impedance of transmission lines built on lossy dielectrics such as silicon; Identified industrial need for time-domain network analyzer (TDNA), particularly for packaging.

FY 1993 Developed method to measure impedance parameters of devices built on lossy dielectrics; Established CRADA with industrial partner; With industry cooperation, demonstrated feasibility of applying multiline Through-Reflect-Line calibration for time domain network analysis.

FY 1994 Began industrial cooperation to characterize flip-chip MMICs; Established cooperative research program with instrument manufacturer.

FY 1995 Introduced MultiCal® calibration for time domain network analyzer; Characterized flip-chip MMIC components.

FY 1996 Designed test structures for flip-chip MMIC packages and three-ports; Developed TDNA software in BASIC; Optimized TDNA parameters.

FY 1997 Collaborated with industry on characterization of interconnects on silicon; Released TDNA software for standalone use or as front tend to MultiCal®.

FY 1998 Developed improved characterization of single-mode transmission lines on silicon; Collaborated with industry on characterization of active digital devices.

FY 1999 Integrate TRL calibration software and 4-port measurement software; Develop interface between 4-port measurement software and multiconductor transmission line analysis method; Apply methods to characterizing: miniature cables, coupled lines on silicon, conductor backed coplanar waveguide; Compare NIST multiport measurements to measurements performed using the JEDEC guideline; Write multiport calibration software compatible with scattering-parameters measured with NIST's time-domain network analysis calibration software (TDNACal); Collaborate with company on the development of methods for measuring low impedance levels found in power/ground plane problems.

3. Develop methods for the at-speed test of digital integrated circuits

FY 1998	Designed and fabricated power sensors useful for creating a chip with known voltages and currents; Participated in industrial interconnect evaluation projects with U.S. company, the Mayo Clinic, and the University of Colorado; Initiated collaboration with university on on-chip sampling methods.
FY 1999	Test power sensors and develop a chip with known voltages and currents for use in calibrating instruments for at-speed digital test; Collaborate on the construction of an on-chip sampling system and test measurement accuracy; Collaborate with Electromagnetic Technology Division on the development of probes and probing systems.

4. Develop procedures for characterizing thin-films

FY 1994	Developed on-wafer measurement concepts for extracting material parameters.
FY 1995	Cooperated with Division 814 to study superconducting thin films.
FY 1996	Cooperated with Electromagnetic Properties of Materials Project to apply frequency domain network analysis to material characterization; Improved transmission/reflection software to account for nonideal lines; Investigated thin-film characterization methods with industry.
FY 1997	Introduced methods to characterize dielectric thin films deposited on planar transmission lines; Applied methods to commercial samples.
FY 1998	Investigated methods to characterize magnetic thin films. Fabricated test structures to investigate using membrane probes to characterize thin films.
FY 1999	Complete analysis of coplanar waveguide (CPW) thin-film characterization method and publish results; Apply thin-film characterization methods to microstrip lines in collaboration with SEMATECH; Fabricate and test standard structures for testing thin films with a U.S. company; Develop methods to characterize magnetic thin films; Collaborate with Georgia Institute of Technology on the development of membrane probes to characterize thin films; Collaborate with Electromagnetic Technology Division on time-domain characterization of thin magnetic films. (*1998 EEEL Strategic Plan; 1999 Budget Narrative*)

5. Exchange technology through workshops

FY 1991	Organized on-wafer measurement workshop at International Microwave Symposium (IMS).
FY 1994	Organized on-wafer measurement workshops at IMS and Automatic Radio Frequency Techniques Group (ARFTG).
FY 1995	Organized measurement workshops at Electrical Performance of Electronic Packaging and Wireless Communications meetings.
FY 1996	Founded and chaired Wireless Communications Conference; Organized on-wafer measurement workshop and short course on package measurements; Organized technical agenda for short course on wireless measurements.
FY 1997	Participated in organizing 1997 International Microwave Symposium: organized workshop program, on-wafer measurement workshop, special session on multiconductor transmission lines, and Plenary Session; Organized

	and chaired 49th ARFTG Conference and 1997 Wireless Communications Conference.
FY 1998	Organized packaging workshop, special session on digital interconnects, and special session on broadband telecommunications for the 1998 International Microwave Symposium; Organized and chaired the 1998 IEEE Radio and Wireless Conference.
FY 1999	Organize ARFTG and Microwave Theory and Techniques Symposium (MTT-S) measurement workshops and MTT/ARFTG joint session on electronic packaging.

Nonlinear Device Characterization

Project Leaders: Donald C. DeGroot

Staff-Years: 3.0 Professionals, 1.0 Student

Funding Sources: NIST (89%), Other (11%)

Objective: To develop new and general methods of characterizing nonlinear devices and components used in digital wireless communications, and to transfer the methods to industrial research and development laboratories.

Background: This project is newly formed in FY 1999 to specifically tackle radio frequency metrology for nonlinear electronics and components used in digital wireless communications. The activities were initially cultivated in High-Speed Microelectronics Project and are supported with Competence Project funding. Nonlinearities in active devices and passive components have deleterious effects on digitally-modulated communications, and are of primary concern to the wireless communications industry. The Nonlinear Device Characterization Project is directly supporting national and international trade through metrology development for electronic device characterization and a passive intermodulation measurement intercomparison. Additional activities include partnership with the National Wireless Electronics System Testbed (N-West) to correlate nonlinearity measurements with communication system performance, and broadband measurements of extremely nonlinear digital transistors.

Current Tasks:

1. Develop new and general measurements for active nonlinear devices

FY 1999	Form new Project; Acquire key components and assemble Phase I measurement system; Develop Phase I calibration software; Verify commercial NNMS calibrations; Study nonlinear device model verification.
FY 2000	Verify Phase I measurement system. Characterize RF amplifiers with Phase I system; Correlate nonlinear device measurements with computer-aided design (CAD) model predictions; Correlate nonlinear device measurements with system performance.
FY 2001	Develop improved methods of calibrating commercial NNMS; Assemble expert measurement system and calibration methods; Verify nonlinear device models with Phase I measurements; Evaluate existing nonlinear device characterization methods.
FY 2002	Verify expert measurement system; Identify general methods for nonlinear CAD model verification; Determine optimal nonlinear device characterization scheme.
FY 2003	Develop general approach to nonlinear device characterization.

2. Establish measurement assurance for passive nonlinear component characterization

FY 1999	Develop PIM measurement error model; Direct PIM measurement intercomparison.
FY 2000	Correlate PIM with system performance; Complete intercomparison study.

3. Develop calibrated time domain network analysis (TDNA)

FY 1999	Release new version of TDNACal with full OSLT calibration; Develop new software modules for compatibility with second commercial oscilloscope.
FY 2000	Add multiline and multiport calibrations to TDNACal; Complete two-port error model.

4. Characterize high-speed digital transistors with linear and nonlinear device measurements

FY 1999	Analyze accuracy and repeatability of three-port Si calibrations. Design calibration standards for two-port Si diode characterization.
FY 2000	Apply Phase I nonlinear device measurements to Si diode characterization.

5. Exchange technology through participation in standards and professional society committees

FY 1999-2000	Participate in two IEC TC46 WG6 meetings and present reports on U.S. PIM measurement intercomparison; Serve as Technical Program Chairman for the 53rd ARFTG Conference on Nonlinearity Characterization; Serve on Technical Program Committee for IEEE 7th Topical Meeting on Electrical Performance of Electronic Packaging.

Power, Voltage, and Impedance Standards and Measurements

[This project combined the previous two projects, "Impedance, Voltage, and Dimensional Standards and Measurements" and "Power Standards and Measurements."]

Project Leader: George Free

Staff-Years: 3.75 Professionals, 4.0 Technicians

Funding Sources: NIST (40%), Other Government Agencies (25%), Other (35%)

Objective: Develop coaxial and waveguide power standards, micro calorimeters, measurement techniques, and automated instrumentation which supports and provides the calibration services for power transfer standards; Provide measurement services in voltage, impedance, and dimensional metrology. The frequency range is from 10 kHz to 110 GHz depending on the specific measurement service. Enhance voltage and impedance services through system development, and develop improved transfer standards and new measurement techniques.

Background: The development and maintenance of standards and calibration systems for radio frequency power, impedance, voltage and dimensional measurements impact most manufacturers and users of electrical/electronic instrumentation which operate in this frequency range. The greatest area of impact is in supplying standards, calibrations and/or measurement methods with which both the manufacturer and the user of the instrumentation can insure that the device operates within the manufacturer's specifications. While for the user this is important with respect to specific applications, for the manufacturer it is important for their domestic and international marketing success. In the design and development of new electronic devices several of these services guarantee the performance of the variety of components which make up the completed device.

The measurement of microwave power is one of the most fundamental test requirements, necessary for the determination of output levels of signal generators, radio and television transmitters, all types of radars, and wireless communication sources. Systems and products that are overdesigned because of poor power standards are expensive and non-competitive. All commercial applications of microwave energy, including communications, navigation, surveillance, manufacturing, aerospace, medicine, defense, entertainment, and advanced computing require accurate measurement of microwave power. International marketing of U.S. microwave instrumentation and devices requires power standards that are recognized and accepted by our trading partners. The ability to accurately measure microwave power over the frequency ranges from 10 MHz to 100 GHz in coaxial transmission line, and from 8 GHz to 110 GHz in waveguide is needed to support a wide range of applications. Faulty measurement or overdesign of products result in expensive and non-competitive products.

Current Tasks:

Note: priorities determine the scheduling of technical work and are reflected in the milestones that follow. Changes in priorities result in some tasks having periods of limited activity.

Power

1. Provide consultation and calibration services for bolometer and thermistor mount power calibrations in the frequency range 100 kHz to 10 MHz

FY 1998	Designed, constructed and tested 4-port to 1-port (grounded) adaptor to improve the reflection coefficient calibration of bolometer and thermistor mounts.
FY 1999	Finish testing and calibrate 4 port to 1 port adaptor; Complete analysis of uncertainties using this adaptor.
FY 2000	Provide consultation and calibration services for bolometer and thermistor mount power standards in the frequency range 100 kHz to 10 MHz.

2. Develop coaxial power standards using a specific commercial connector (Type N) for use over the frequency range from 1 MHz to 18 GHz

FY 1994	Published calorimeter evaluation method in a technical journal.
FY 1995	Calibration service for standard received final NIST approval; Resolved calibration uncertainty issue.
FY 1996	Established quality control charts for service based on three NIST standards.
FY 1997	Assembled, tested and calibrated one standard; Calibrated customer and NIST standards; Updated NIST quality control charts.
FY 1998	Assembled and tested two standards; Calibrated customer and NIST standards; Updated NIST quality control charts.
FY 1999	Develop new low frequency standard for 1 to 100 MHz; Design and construct type N calorimeter and measurement system.
FY 2000	Test and calibrate Type N calorimeter and associated standards and measurement system.
Ongoing	Provide assembly, test and calibration service for standards.

3. Develop power standards for systems having 2.4 mm conductors and coaxial connectors for use over a frequency range from 1 MHz to 50 GHz

FY 1994	A private company agreed to develop a prototype transfer standard.
FY 1995	Received and tested the transfer standard; Designed and began fabrication of a microcalorimeter.
FY 1996	Tested and approved prototype transfer standard with improved design; Finished microcalorimeter assembly and began uncertainty evaluation.
FY 1997	Completed uncertainty evaluation; Developed transfer technique and specified instrumentation for a calibration service.
FY 1998	Assembled and tested transfer instrument.
FY 1999	Initiate calibration service; Document uncertainty evaluation; Provide standards and transfer instrumentation to Other Agency customer.
Ongoing	Provide calibration service for standards and commercial sensors.

4. Develop new waveguide power standards for use over the frequency range from 18 to 110 GHz

FY 1994	Assembled the WR-15 (50 to 75 GHz) calorimeter and transfer standards.
FY 1995	Completed operational tests of the isothermal mode on the WR-22 (30 to 50 GHz) calorimeter; Developed thermal model using finite element analysis to improve the calorimeter evaluation.
FY 1996	Completed uncertainty evaluation of WR-15 calorimeter; Began WR-10 (75 to 110 GHz) evaluation.
FY 1997	Continued uncertainty evaluation measurements of WR-10 calorimeter; Started WR-22 evaluation.
FY 1998	Completed uncertainty evaluation of WR-22 calorimeter; Re-evaluated WR-15 calorimeter.
FY 1999	Complete uncertainty evaluation of WR-10 calorimeter; Take repeatability measurements to determine Type A uncertainty for the WR-42 (18 to 26 GHz) calorimeter.
FY 2000	Complete uncertainty evaluation of WR-42 calorimeter.

5. Provide calibration and measurement services for microwave power

FY 1994	Developed a direct comparison system for power calibration services in Type N connectors, revised all uncertainty statements for power to conform to NIST policy and international guidelines.
FY 1995	Developed techniques for the Army for providing power calibration in systems using Type N connectors at frequencies above 18 GHz.
FY 1996	Added power calibration services for GPC-7 connectors to the direct comparison system; Reduced measurement time of low frequency power measurements done in six-port laboratory and low frequency impedance laboratory.
FY 1997	Conducted experiments with thermo-electric and diode, and the 2.4 mm thin-film power sensors in the process of developing calibration transfer systems.
FY 1998	Improved power calibration services in the WR-22 and WR-15 waveguide bands; Completed construction of 0.05-50 GHz direct comparison power calibration system for the Navy.
FY 1999	Evaluate and deliver 0.05-50 GHz direct comparison power calibration system to the Navy; Complete development of the NIST 2.4 mm coaxial direct comparison power calibration system (to 50 GHz); Complete development of a calibration service for thermo-electric and diode power sensors; Improve power calibration services in the WR-10 waveguide bands.
Ongoing	Provide coaxial and waveguide calibration, measurement and consultation services to 110 GHz.
Ongoing	Provide calibration, measurement services and consultation in high power from 1 to 1000 MHz at 1 to 1000 watts.

6. Develop high power microwave system, (10W to 1000W, 10 MHz to 1000 MHz) for the Air Force

FY 1995	Determined optimum technique for transfer standards calibration; Investigated availability of high power components and instrumentation.

FY 1996	Developed system architecture; Purchased most system components and instrumentation; Assembled prototype system; Began writing operational software; Began uncertainty analysis.
FY 1997	Assembled final hardware configuration; Integrated high power amplifier in system; Completed uncertainty analysis of calibration technique.
FY 1998	Completed assembly and tests of system.
FY 1999	Complete documentation of system; Calibrate transfer standards at specified frequencies and power levels; Deliver transfer standards to sponsor; Initiate NIST high power calibration service; Add reflection coefficient measurement capability to system using internal 6-port.

7. International comparisons

FY 1998	As pilot laboratory, submitted proposal to International Bureau of Weights and Measures for WR-22 comparison and solicited participation from foreign national standards labs; Prepared and measured new WR-22 transfer standards for use in comparison; Sent three standards to first participating laboratory; Participated in WR-15 comparison at 62 GHz.
FY 1999	Measure and circulate WR-22 transfer standards; Participate in WR-10 comparison.
FY 2000	Continue to measure and circulate WR-22 transfer standards.
FY 2001	Compile and publish results of WR-22 of comparison.

<u>Voltage</u>

1. Provide calibration, measurement services and consultation for the high accuracy thermal voltage converters (TVCs) at frequencies from 10 kHz to 100 MHz

FY 1996	Completed rf voltage comparison measurements with Spanish standards laboratory; Revised calibration reports according to new NIST policy for thermal voltage converters, micro-potentiometers, peak-to-peak detectors, thermistor mounts, milliwatt power meters; Completed recalibration of NIST voltage working standards against NIST-Gaithersburg calibrated standards from 0.5 V to 3 V from 30 kHz to 100 MHz to improve uncertainties; Completed round-robin calibration of 4 TVC transfer standards (0.5 V-3.0 V) at (1, 10, 30, 50, 70, 100) MHz.
FY 1997	Completed evaluation of working standards above 3 V from 30 kHz to 100 MHz; Re-evaluated uncertainties and disseminated to customers; Completed report on round-robin measurements in voltage.
FY 1998	Started testing of NIST standards using new automated calibration routine; Started intercomparison of NIST standards in order to implement a rational error analysis; Continued to document the measurement system.
FY 1999	Complete measurements of NIST standards and error analysis for the measurement system.
Ongoing	Provide calibration services in rf voltage from 0.4 V to 600 V from 10 kHz 1000 MHz.

2. Provide calibrations, measurement services and consultation for high frequency thermal voltage converters in the frequency range 1 MHz - 1000 MHz

FY 1998	Designed, assembled and tested new high frequency TVC system; Calibrated one volt NIST standards in terms of power standards; Using step up techniques started calibrating 2.4 V and 7 V NIST thermal voltage converter standards.
FY 1999	Complete calibration of 2.4 V and 7 V NIST standards; Complete error analysis and issue new uncertainties; Finish documentation of high frequency TVC system.
Ongoing	Provide consultation and calibration services for high frequency TVCs.

3. Provide calibrations, measurement services and consultation for micro-potentiometers in the voltage range 1 μV to 0.2 V in the frequency range of 10 kHz to 1000 MHz.

FY 1998	Designed, assembled and tested new micro-potentiometer measurement system; Started calibration of NIST micro-potentiometer standards using thermistor mounts and step down techniques.
FY 1999	Finish calibration of NIST micro-potentiometers; Complete error analysis and issue new uncertainties; Complete documentation for the system.
Ongoing	Provide consultation and calibration services for micro-potentiometers.

Impedance

1. Provide calibration and measurement services and consultation in impedance measurements from 10 kHz to 300 MHz

FY 1995	Calibrated and documented high frequency Twin-Tee bridge for the coaxial termination calibration service.
FY 1996	Completed international comparison in Quality Factor of inductance standards; Enhanced capacitance measurement service with state-of-the-art instrumentation; Did initial test on equipment from 100 kHz to 30 MHz.
FY 1997	Completed documentation on enhancement of capacitance measurement service; Performed uncertainty analysis; Announced expanded frequency range in the calibration of two terminal capacitance standards.
FY 2001	Test three-terminal capacitance standards using enhanced measurement system from 100 kHz to 30 MHz. Document three-terminal capacitance measurements and announce expanded frequency range from 100 kHz to 30 MHz.
Ongoing	Provide impedance calibrations from 10 kHz to 200 MHz.

Dimensional Characterization of Microwave Components

1. Provide consultation and dimensional measurement of coaxial airlines, waveguide sections and materials

FY 1996	Upgraded coordinate measuring machine and expanded versatility; Compiled user's manual on operation; Measured: 2.4 mm, 2.92 mm, 3.5 mm, 7 mm, 14 mm airlines, WR-10 & WR-15 devices, ferrite samples; Assisted other EEEL personnel in construction of calorimeter, radiometer, waveguide standards, and

	thickness measurements; Assisted personnel in Time and Frequency Division with atomic clock setups.
FY 1997	Provided dimensional measurements of airlines and verification of characteristic impedance from dimensional measurements.
FY 1999	Do experiments to determine repeatability of measurements for transmission line length and relationship between airgauging and laser micrometer measurements of transmission line components;. Complete error analysis of 14 mm and 7 mm transmission line calibrations. Complete documentation for the dimensional measurement of airlines.
Ongoing	Provide consultation and calibration service for transmission lines; provide in-house calibrations for materials group and other division projects as needed.

Network Analysis and Measurement

Project Leader: John Juroshek

Staff-Years: 1.0 Professionals, 1.5 Technicians

Funding Sources: NIST (60%), Other Government Agencies (20%), Other (20%)

Objective: To provide traceability for microwave measurements in scattering parameters, impedance, and attenuation. Support the microwave industry by developing standards and new measurement techniques. To develop methods for assessing and verifying the accuracy of automatic network analyzers.

Background: Vector network analyzers (VNAs) are the single most important instrument in the microwave industry. These instruments are commonly found on production lines, in calibration laboratories, and in research laboratories. Vector network analyzers are typically calibrated daily and the accuracy of their measurements can vary significantly after a calibration depending on the operator skills, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost effective techniques to monitor and control the accuracy of their microwave measurements. It also needs help in developing the techniques, procedures, and documents to ensure conformity with international standards. NIST directly supports the microwave industry by providing measurement traceability through calibration and related measurement services in scattering parameters. NIST also provides consultation to industry on measurement techniques and accuracy issues.

Current Tasks:
Note: priorities determine the scheduling of technical work and are reflected in the milestones that follow. Changes in priorities result in some tasks having periods of limited activity.

1. Provide and upgrade traditional calibration services for scattering parameters

FY 1993 — Initiated a calibration service for scattering parameters when using 2.92 mm diameter conductors (0.1-40 GHz) with coaxial connectors; Initiated WR-90 (8-12 GHz) and WR-62 (12-18 GHz) waveguide calibration services on the dual six-ports.

FY 1994 — Initiated a calibration service for scattering parameters in systems using 2.4 mm diameter conductors (0.1-50 GHz) and coaxial connectors.

FY 1995 — Began offering a reduced cost calibration service for systems using 2.92 mm and 2.4 mm diameter conductors on the commercial network analyzer.

FY 1996 — Purchased components for traveling verification kits; Assembled kits; Conducted initial measurements on kits; Added calibration services for time delay to existing scattering parameter services.

FY 1997 — Completed analysis software and report generating software for NIST S-parameter MAP, kits are now available for 3.5 mm, 2.92 mm, and 2.4 mm coaxial connectors; Conducted experiments on thermo-electric and diode power meters necessary to establish a calibration service; Investigated systems for transferring 2.4 mm power calibrations to industry; Began construction of

	a direct comparison system for 2.4 mm power calibrations; Developed a new method for measuring effective source mismatch of 3-port couplers and power dividers; Published results in Microwave Journal.
FY 1998	Initiated a new measurement service for VNAs using NIST traveling verification kits in 3.5 mm, 2.92 mm, and 2.4 mm coaxial line sizes. (*1998 MSL Strategic Plan*)
FY 2000	Offer a calibration service for effective source mismatch for 3-port couplers and power dividers.
FY 2001	Add calibration services for systems in currently unsupported connector types (i.e., 75 Ω, SMA, SMP, 1.85 mm).
Ongoing	Provide coaxial and waveguide calibration, measurement and consultation services to 110 GHz in scattering parameters.

2. Develop quality assurance procedures for network analyzers

FY 1993	Evaluated stability of a solid state impedance generator for use as a transfer standard in conjunction with a cooperative research and development agreement with the manufacturer.
FY 1994	Revised all uncertainty statements for scattering parameters to conform to NIST policy and international guidelines; Completed a cooperative agreement with a manufacturer of network analyzers to develop verification techniques.
FY 1995	Prepared a report on verification techniques for commercial network analyzers; Completed an Army sponsored project to investigate and recommend verification procedures for vector network analyzers.
FY 1996	Developed a software package that verifies and analyzes the performance of a commercial network analyzer by analyzing the difference in calibration constants; Began circulating software to industry.
FY 1997	Submitted a journal article on the statistical analysis of network analyzer data for publication in CAL LAB; Developed robust statistical procedures for analyzing measurement data from the Automatic Radio Frequency Techniques Group (ARFTG) measurement comparison program.
FY 2000	Develop network analyzer verification techniques for Industry.
Ongoing	Serve as pilot laboratory for the ARFTG measurement comparison program which is sponsored by an engineering professional society, the Institute of Electrical and Electronic Engineers (IEEE); Analyze data and issue formal reports to participants.

3. Develop dual six-port network analyzers

FY 1990	Developed waveguide six-ports for WR-42 (16-26 GHz), WR-28 (24-35 GHz), WR-15 (50-75 GHz), and WR-10 (75-110 GHz).
FY 1991	Developed line-reflect-line (LRL) software for calibrating the dual six-ports.
FY 1992	Developed 18-40 GHz coaxial six-ports using diode detector technology; Developed software and techniques for correcting the diodes for deviation from square law; Developed WR-42 (18-26 GHz) and WR-28 (24-35 GHz) dual six-ports for the Navy Primary Standards Laboratory.
FY 1994	Designed and built new test ports and standards for WR-22 (30-50 GHz) waveguide calibration services; Completed construction of 100 kHz to 1.0 GHz for the Air Force and procured and/or manufactured system components and devices to supplement calibration kits; Initiated documentation.

FY 1995	Developed line-reflect-match (LRM) calibration technique for the dual six-port which uses one port terminations instead of air lines; Completed equipment up-grade, testing and documentation of a dual six-port which operates over the frequency range from 0.25 GHz to 18 GHz; Delivered dual six-port system operating over the frequency range between 0.1 MHz and 1000 MHz to the Air Force and provided on-site training to Air Force personnel.
FY 1996	Modified current six-port software so that it runs on PC-compatible computers; Increased speed of six-ports with new software; Delivered dual six-port system operating over the frequency range between 0.25 GHz and 18 GHz to Army and provided on-site training to Army personnel; Ordered calibration and verification kits for devices with 3.5 mm, 2.92 mm, WR-42 and WR-28 connectors.
FY 1997	Completed construction of the 18-40 GHz dual six-port for the Air Force.
FY 1998	Documented system and delivered 18-40 GHz dual six-port to the Air Force; Completed construction of the 2-18 GHz dual six-port for the Navy.
FY 1999	Evaluate, document, and deliver the 2-18 GHz dual six-port to the Navy.

4. Develop, analyze, and improve NIST impedance standards

FY 1991	Developed techniques for modeling the dimensional variability in coaxial and waveguide airline standards.
FY 1991	Developed WR-90 waveguide standards; Developed new Type N, GPC-7 impedance standards.
FY 1996	Ordered and received improved air line impedance standards for 2.4 mm coaxial transmission lines; Developed computer program for analyzing surface roughness in airline standards; Began documentation of NIST coaxial impedance standards.
FY 1997	Upgraded 2.92 mm coaxial impedance standards; Began documentation of the uncertainty of NIST coaxial impedance standards.
FY 2000	Refurbish or rebuild NIST Type N impedance standards.

5. Develop automated data analysis techniques

FY 1990	Installed hardware for a local area network for calibration related activities.
FY 1992	Completed software development for on-line data management with the local area network.
FY 1993	Checked standard data base ready for online access by calibration staff.
FY 1996	Upgraded and automated quality control procedures; Transferred and converted all calibration, measurement, and quality control software to run under Windows™ on PC-compatible platforms.
FY 1997	Upgraded local area network capabilities; began running SAS statistical analysis software over the local area network; Upgraded PC computers and software on all dual six-ports; Began testing NIST developed ORACLE™ data base for microwave calibration activities.
FY 1999	Develop a single software package for NIST uncertainty values that can be used by all NIST programs; Develop techniques and software for analyzing Type A uncertainties of scattering parameter measurements; Reevaluate Type A uncertainties for scattering parameter measurements; Document Type A uncertainties for scattering parameter measurements.

FY 2000 Convert and upgrade 6-port measurement and data analysis from BASIC to LabVIEW™ or similar instrument control language.

Noise Standards and Measurements

Project Leader: James Randa

Staff-Years: 2.5 Professionals, 2.5 Technicians

Funding Sources: NIST (60%), Other Government Agencies (18%), Other (22%)

Objective: Develop methods for very accurate measurements of thermal noise; provide support for such measurements in the communications and electronics industries, as well as for other government agencies.

Background: Noise is a crucial consideration in designing or assessing the performance of virtually any electronic device or system that involves detection or processing of a signal. This includes not just communications systems, such as cellular phones or home entertainment systems, but also systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and mm-wave devices in these areas is already huge and is undergoing explosive growth. Important current trends which must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers, the demand for and lack of repeatable and traceable on-wafer noise measurement techniques, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters for industry are the noise temperature of a one-port source and the noise figure of an amplifier.

This project focuses on three areas. In traditional (connectorized) noise temperature measurements and calibrations, the aim is to cover the frequency range 1 GHz to 75 GHz, including 1 GHz to 40 GHz in systems using coaxial connectors. Concurrently, staff is also attempting to reduce the time required for such calibrations, thereby reducing the costs. The second general thrust of the project is in amplifier noise figure measurements, where the goal is to develop cost-effective measurement services for amplifiers with coaxial connectors over the frequency range 1 GHz to 18 GHz. The third major effort is in developing on-wafer noise measurement methods, first for noise temperature and subsequently for amplifier noise figure. Central to all three of these efforts is the new noise-figure radiometer system which is currently under development. It has been designed to measure either one-port noise temperature or amplifier noise figure, and it has the potential to be significantly faster than our existing radiometers.

Current Tasks:

Note: priorities determine the scheduling of technical work and are reflected in the milestones that follow. Changes in priorities result in some tasks having periods of limited activity.

1. Provide, upgrade and expand waveguide and coaxial noise-temperature calibration services and capabilities

   FY 1992 — Extended upper frequency limit of WR-42 (18-26.5 GHz) to 26 GHz (previously was 22 GHz).

FY 1993	Began new noise temperature special test services in WR-15 (50-75 GHz), WR-62 (12.4-18 GHz), and systems using 3.5-mm coaxial conductor (12-26 GHz).
FY 1994	Organized and presented a one day noise measurements seminar at the IEEE International Microwave Symposium in San Diego; revised measurement uncertainties per NIST guidelines.
FY 1995	Completed construction of WR-28 (26.5-40 GHz) noise-temperature calibration system; Began testing; Developed and documented improved technique for assessing adapter effects in noise temperature measurements.
FY 1996	Completed testing of WR-28 system; Revised and documented uncertainty analysis for waveguide noise-temperature calibrations; Developed plans for documentation of each Noise Project measurement service.
FY 1997	Documented and offered WR-28 measurement service; Fabricated improved coaxial primary standard; Revised, automated, and documented uncertainty analysis for noise temperature calibrations in coaxial systems; Compiled histories for check standards.
FY 1998	Began development of 2.4-mm coaxial measurement service .
FY 1999	Institute WR-15 measurement service; Institute noise-temperature measurement service for 2.4 mm coaxial sources; Perform stability tests on various noise sources; Compare different methods for adapter evaluation.
FY 2000	Provide noise temperature calibration, measurement and consultation services.

2. Serve as pilot laboratory for international noise temperature measurement comparison

FY 1992	Noise comparison proposed by NIST and approved (GTRF 92-2) with NIST as pilot lab.
FY 1993	International noise community canvassed for possible participants; preliminary plans made.
FY 1995	Noise sources were purchased for circulation among participants.
FY 1996	Developed protocol and schedule; Performed first round of NIST measurements; Measurements also completed at LCIE and NPL.
FY 1997	Completed measurements at other laboratories (PTB); Performed second round of measurements at NIST; Collected and analyzed results.
FY 1998	Wrote report and presented results. Task completed.

3. Develop noise-figure measurement capability

FY 1992	Completed development of noise-figure measurement theory and established possible experimental measurement procedure; Performed measurements to test the viability of this procedure.
FY 1993	Completed basic design of amplifier noise radiometer.
FY 1994	Completed and tested prototype of amplifier noise radiometer. Found to be stable to within 0.002 dB/day, 150 times better than present NIST systems. This promises to significantly reduce the need for repetition of measurements, thereby reducing the time for calibrations.
FY 1995	Refined noise-figure measurement techniques for low-noise amplifiers with adapters; Performed preliminary measurements on two low-noise amplifiers with adapters.
FY 1996	Completed measurements of two low-noise amplifiers with adapters.

FY 1997	Completed hardware and noise-temperature software for total-power radiometer for 8-12 GHz, to replace the existing system for noise temperature measurements and for use in the noise-figure measurement system.
FY 1999	Characterize and test new radiometer for 8-12 GHz; Analyze uncertainties for noise-temperature measurements with new system; Finalize software and interfaces for system.
FY 2000	Formalize noise-figure measurement techniques and write associated software; Construct and test new radiometer for 1-2 GHz; Offer a measurement or comparison service for amplifier noise figure for 8-12 GHz and 1-2 GHz.

4. Develop methods for on-wafer measurement of noise

FY 1992	Conducted preliminary experiment to measure the noise figure of a MMIC amplifier on wafer (in collaboration with MMIC project).
FY 1994	Measured one-port noise of a diode on-wafer at a frequency of 8 GHz using the prototype Noise-Figure Radiometer.
FY 1995	Designed, performed, and analyzed experiments to measure known and unknown noise temperatures on wafer at frequencies between 7.8 GHz to 8.2 GHz.
FY 1996	Refined, extended, and repeated experiment demonstrating capability of measuring noise temperature on wafer.
FY 1997	Documented on-wafer noise-temperature measurement methods and theory; Designed on-wafer noise-temperature transfer standard.
FY 1998	Fabricated and tested prototype on-wafer noise-temperature transfer standard(s).
FY 1999	Fabricate improved on-wafer noise-temperature transfer standards.
FY 2000	Fabricate and test improved on-wafer noise-temperature transfer standards; Initiate on-wafer noise-temperature round-robin comparison with industrial industry.

Antenna Measurement Theory and Application

Project Leader: Michael H. Francis

Staff-Years: 4.0 Professionals, 1.0 Technicians

Funding Sources: NIST (69%), Other Government Agencies (2%), Other (29%)

Objective: The near-field antenna characterization methods invented and developed by NIST, offer improved accuracy and reduced costs that are unmatched by other methods. However, new extensions of this technique are needed for advanced antenna designs. In response, NIST will develop near-field theory, standards, and methodology to support characterization of gain, pattern, and polarization of advanced multi-element antennas at frequencies up to 500 GHz. Specifically, NIST will extend cylindrical and spherical scanning capabilities to cover the frequency range 26.6 to 100 GHz and planar methods to cover the frequency range 40 to 500 GHz. Goals include (1) achieving uncertainties less than ±0.2 decibels in the gain, (2) implementing probe-position error correction for mm wave measurements, (3) determining field uniformity using spherical near-field techniques for antenna measurement range characterization, and (4) developing and testing adaptive phased array diagnostic methods.

Background: Manufacturers of new microwave products such as roadside communications, vehicle anti-collision radar and automatic traffic-light control, need practical, rapid and efficient methods for characterizing antenna performance. Operation at higher frequencies, the use of advanced phased arrays for steering beams, the use of conformal structures in aircraft, and the use of active arrays challenge existing methods. These systems also support national goals for information highways and personal communications, and new radars for air traffic control to make more efficient use of airspace without jeopardizing safety. Advanced civilian systems include new generations of communications systems at higher frequencies and with greater spatial discrimination to alleviate overcrowding of current and synchronous-orbit satellites. The personal communications market is estimated to be billions of dollars by the year 2000.

Current Tasks:

1. Develop planar near-field metrology for measuring microwave antennas operating at frequencies up to 500 GHz

   FY 1995 Completed first phase of the certification process for the new NIST 2.5 M by 2.5 M planar scanner; Documented certification plan for this range and distributed it to industry for use for their ranges; Incorporated fifth-order Taylor-series method for z probe-position error-correction into the planar near-field library.

FY 1996	Implemented two fully 3-dimensional iterative methods, the steepest descent method and the conjugate gradient method, to improve computational efficiency and convergence for probe-position error-correction.
FY 1997	Completed the certification process for the new 2.5 M by 2.5 M planar scanner and receiver; Conducted simulations on the effects of probe-position errors; Completed probe position error correction task for planar scanning; NIST awarded Bronze medal to Wittmann, Alpert, and Francis for this work.
FY 1998	Evaluated on-site planar near-field methods for determining phased-array aperture distributions; Many antennas require on-site periodic performance verification. Near-field techniques may be the only viable techniques to test next generation high performance antennas; Developed planar near-field review process; Published probe position error correction paper in IEEE Transactions on Antennas and Propagation.
FY 1999	Develop the facilities and methodology needed for near-field scanning antenna measurements in the region from 75 to 110 GHz (*1998 EEEL Strategic Plan*); Complete evaluation of on-site planar near-field methods.
FY 2000	Implement facility improvements and methodology for 75 to 110 GHz measurement system; Develop metrology and system for 110 to 170 GHz. (*1998 EEEL Strategic Plan*)
FY 2001	Begin measurement service for 75 to 110 GHz band; Complete 110 to 170 GHz measurement system. (*1998 EEEL Strategic Plan*)
FY 2002	Begin measurement service for 110 to 170 GHz; Develop metrology and system for 170 to 260 GHz. (*1998 EEEL Strategic Plan*)

2. Develop new metrology methods for rapid microwave antenna measurements and diagnostics

FY 1995	Evaluated the mirror/self-calibration method for determining antenna gain using three probes. Developed thermal imaging theory for rapid measurements used for determining antenna performance; Simulated measurements for thermal imaging method.
FY 1996	Completed analysis of mirror/self-calibration data and documented results; Conducted measurements on thermal imaging method in cooperation with the University of Colorado, Colorado Springs. Completed measurements on holographic (phaseless) antenna measurements for applications at mm and sub-mm frequencies.
FY 1997	Analyzed data obtained at Rome Laboratory to determine limitations and improvements to experimental techniques for near-field determination using thermal imaging; Published results.
FY 1998	Evaluated and reported on thermal imaging technique for rapid measurement or other applications; Compared to planar near-field results.
FY 1999	Evaluate holography method for use at frequencies from 50 to 75 GHz.
FY 2000	Develop array of low scattering probes.
FY 2002	Use low scattering probe array to evaluate a phased array.

3. Develop non-planar near-field measurements for antenna and probe measurements

FY 1995	Completed evaluation of the new spherical/extrapolation range. This range is capable of fast and accurate measurements of antennas up to 3.5 M in diameter in the frequency range from 1 to 75 GHz.
FY 1996	Published the calibration results on the standard gain horns for the International Gain Comparison measurements; Aligned vertical probe

transport on multipurpose range for cylindrical near-field measurements; Provided technical support and near-field probe measurements to JPL for cylindrical near-field measurements on satellite antenna.

FY 1997 Completed development of cylindrical capability and calibrated probes for intercomparison measurements to be made on suitable antennas using all available NIST ranges (two planar, cylindrical, and spherical); Documented rail alignment results for cylindrical scanning.

FY 1998 Constructed and measured a special Ku-band probe for quiet-zone evaluation task; Completed spherical scanning hardware and conducted initial quiet-zone measurements on multipurpose range; Completed measurements for certification of 2.5 by 2.5 m planar near-field scanner; Continued measurements on intercomparison begun last year.

FY 1999 Evaluate quiet-zone measurement data and perform additional tests as needed; Complete a report covering theory and application; Present results in journal papers and conference presentations; Document results for certification of 2.5 m by 2.5 m planar scanner; Develop method to improve extrapolation range analysis based on condition number; Complete intercomparison measurements for spherical, cylindrical and planar near-field ranges.

FY 2000 Develop 3-D probe-position correction method for spherical scanning.

FY 2001 Develop 3-D position correction for cylindrical scanning.

FY 2002 Refine spherical scanning for outdoor in-situ antenna testing.

4. Develop metrology for complex antennas for emerging technologies

FY 1994 Completed spectral merge analysis to determine antenna-array excitation using planar near-field measurements from several beam positions.

FY 1995 Completed software and analysis for spectral merge project; Completed analysis of a 60 GHz phased-array antenna using measurements taken on the new 2.5 M by 2.5 M planar scanner.

FY 1996 Documented the results of the spectral merge method for the alignment of phased arrays; Designed and constructed a 32 by 32 X-band (8.2 to 12.4 GHz) computer-controlled phased array to validate new antenna metrology and diagnostic methods.

FY 1997 Completed report documenting array evaluation using merged spectrum; Evaluated mutual coupling methods for rapid testing of phased arrays.

FY 1998 Designed an X-band antenna array for experimental work on array characterization and alignment; Developed program to implement and evaluate iterative array alignment techniques.

FY 1999 Investigate methods for multiple-reflection error compensation.

FY 2000 Develop merged spectrum method for non-rectangular phased array lattices; Reduce truncation errors through use of state-of-the-art representations (spheroidal wave functions, maximum entropy methods) for bandlimited functions. This work could potentially improve conditioning in probe position error correction algorithms.

5. Provide technology transfer through courses

FY 1995 Participated as major lecturers in short course, "Microwave Antenna Measurements" at California State University, Northridge.

FY 1996 Updated and presented NIST biannual short course, "Antenna Parameter Measurement by Near-Field Techniques," in Boulder; Presented NIST short

	course at Antenna Measurement Techniques Association Symposium; Updated short course with the Georgia Institute of Technology on "Near-Field Antenna Measurements and Microwave Holography."
FY 1997	Updated lectures for short course in collaboration with California State University, Northridge and Georgia Institute of Technology.
FY 1998	Presented NIST short course in Boulder; Presented short course with Georgia Institute of Technology.
FY 1999	Present short course with Georgia Institute of Technology; Participate in major lectures at California State University Northridge short course.
FY 2000	Present short course in Boulder; Present short course with Georgia Tech.
FY 2001	Present short course with Georgia Tech.
FY 2002	Host Antenna Measurement Techniques Association Symposium in Oct. 2001.

Metrology for Antenna, Radar Cross Section and Space Systems

Project Leader: Katherine MacReynolds

Staff-Years: 2.0 Professionals, 1.0 Technician

Funding Sources: NIST (20%), Other Government Agencies (79%), Other (1%)

Objective: NIST will develop the standards, measurement techniques, and instrumentation required for measuring critical performance parameters of earth terminals and satellites, and for the absolute calibration of the Air Force Satellite Control Network (AFSCN) metrology earth terminals. Critical parameters include noise temperature (T), antenna gain (G), earth terminal figure of merit (G/T), and satellite effective isotropic radiated power (EIRP). In addition, NIST will provide technical support to the Government Range Radar Cross Section (RCS) Measurement Working Group to improve the quality and reliability of range measurements. This will be accomplished by evaluating the measurement processes determining uncertainties, evaluating the design and analysis of required artifact standards, and providing the consultation and support necessary to establish a range certification process.

Background: Satellite communication is a finely tuned technology requiring accurate measurements of antenna gain, noise temperature, G/T (system gain divided by system temperature), and EIRP (effective isotropic radiated power) to assure optimum performance. Ground metrology stations needed to monitor performance of commercial and government satellites require traceability to the NIST standards. Some stations measure performance to determine incentive-clause payments to satellite contractors or charges billed to users or lessees. Industry and government own and operate a number of antenna- and radar cross section-test ranges of various types such as outdoor static, indoor (compact ranges), and other specialized ranges. Results obtained on one range do not always correlate with measurements taken on another range, even if this range is of the same type. In addition, some of these ranges are used for contractual verification of vendor performance. It is necessary that the results produced at these test ranges be of the highest accuracy possible and be repeatable from one facility to another to support communications system measurements such as multiple low-earth-orbit satellite systems for worldwide coverage and radar cross section measurements for new automobile radar systems.

Current Tasks:

1. Develop metrology for wireless communications systems

   FY 1994 Organized the Range Accreditation Workshop during the 1994 Antenna Measurement Techniques Association Symposium. The European Space Agency, the National Association of Testing Authorities in Australia and the National Voluntary Laboratory Accreditation Program (NIST) participated.

FY 1995	Analyzed performance of a Phased Array Sub-system (PASS) for the Air Force. This array serves as a transfer standard for their near-field range used to measure communications antennas; Completed special tests on four dual-port circular-polarized probes that will be used as standards for the Globalstar and Tempo domestic satellite programs.
FY 1996	Provided technical support and probe measurements for wireless base station antennas.
FY 1997	Began to develop data acquisition software using up-to-date personal computers for the planar and cylindrical ranges in the antenna laboratory; Completed facilities upgrade by managing installation of fire-proof absorbers and sprinkler systems for four near-field antenna ranges.
FY 1998	Initiated data acquisition software development using LabVIEW™ and Visual Basic; Collaborated with industry on obtaining a broadbeam antenna to be tested and measured on our new cylindrical near-field range.
FY 1999	Complete data acquisition software development; Evaluate commercial fan-beam, communication antenna; Evaluate FBI broadband log-periodic antennas.
FY 2000	Define anticollision radar system requirements; Evaluate existing metrology for system parameter measurements.
FY 2001	Develop new metrology and artifact standards for anticollision radar systems.

2. Develop microwave metrology applicable to Earth Stations

FY 1995	Collaborated with a U. S. company on developing near-field techniques to measure G/T, EIRP and saturating flux density for satellite and radar antennas in a controlled indoor-testing environment.
FY 1996	Analyzed G/T measurement techniques to determine if subarrays of a phased array are working properly.
FY 1997	Determined the G/T of an outdoor antenna under different operating conditions to predict system performance during a typical year; Collaborated with industry in development of software for predicting system performance.
FY 1998	Collaborated with Jet Propulsion Laboratory (JPL) in flux density measurements of extraterrestrial radio noise sources and gain calibrations of the 70 M diameter Goldstone antenna and other antennas at Owens Valley Radio Observatory; Began evaluation of software on system performance being developed under Phase II of a Small Business Innovation Research (SBIR).
FY 1999	Complete evaluation of SBIR phase II software; Calibrate 6 ft. dish for Air Force Satellite Control Network.
FY 2000	Determine G/T of an antenna both indoors and outdoors and evaluate ability to predict outdoor performance from indoor measurements.
FY 2001	Develop holographic methods for large antenna system diagnostics.

3. Develop metrology for radar cross section measurements

FY 1995	Completed the development and documentation of the uncertainty analysis for radar cross section measurements. The documentation has been published as a NIST report, NISTIR 5019; Completed the development and documentation for the polarimetric calibration of reciprocal-antenna radars (NISTIR 5033); Completed a report to sponsor entitled "A review of government radar cross

section ranges." The report is a result of three years of research activities by NIST scientists, who reviewed eight government RCS ranges during that time.

FY 1996 Initiated work on the polarimetric calibration of non-reciprocal radar systems; Started work on RCS Range Characterization and completed the major part of two range-specific uncertainty analysis reports for other agencies; Conducted research on technical questions in the area of imaging, specifically image quality and interpretation.

FY 1997 Organized and held an RCS Range Certification meeting at NIST in March 1997 for government and industrial RCS professionals; Developed criteria for range characterization and certification using ISO documents; Collaborated with Wright Patterson Air Force Base to launch a Certification Demonstration Project; Continued work on polarimetric calibrations and image quality and interpretation; Studied and recommended RCS standard artifacts and began measurement intercomparisons at different RCS facilities; Developed a standard for RCS measurements in collaboration with a voluntary RCS standards committee.

FY 1998 Organized and held the second NIST RCS Certification meeting in March, 1998; Submitted the Handbook for the Assurance for RCS Measurements to NCSL for review and to be considered as a national industry standard jointly created by NIST, DoD and NCSL; Implemented Range Book concept at the ranges of DoD demonstration project participants; Continued basic research in polarimetric RCS calibration; Developed codes to implement the nonlinear model constraints to improve estimates of the system parameters; Continued intercomparisons on cylinder measurements; Held workshop on RCS Uncertainty Analysis, cosponsored by NIST, AFRL and OSU; Initiated establishing RCS standard artifacts and Standard Reference Datasets.

FY 1999 Implement an RCS Certification Program to establish standards; Establish the basic AFRL cylinder set as NIST Standard Reference Materials, and establish supporting computations as NIST Standard Reference Datasets; Publish the RCS Standards Handbook as a guide to certification of RCS ranges; Establish a National RCS Certification Board, define certification procedures, and with DoD proceed with certification reviews; Hold third annual NIST RCS Certification meeting; Organize jointly with AFRL and Boeing, the second annual RCS Uncertainty Workshop; Continue tasks defined by the RCSMWG to aid RCS standardization. Tasks include evaluation of the results of intercomparison using the standard cylinder sets, evaluation of repeatability studies performed at AFRL, polarimetric calibration theory and data analysis, bistatic calibrations, and RCS range uncertainty analysis; Develop alternative standard artifacts to address specific calibration issues.

FY 2000 Complete tasks initiated in FY 1999 and pursue new tasks, as jointly defined by the RCS working group and NIST, leading to range certifications; Continue certification process for RCS ranges and increase involvement of RCS industry; Continue basic research to improve RCS standards.

Electromagnetic Properties of Materials

Project Leader: Claude Weil

Staff-Years: 5.0 Professionals, 0.15 Guest Researchers, 1.0 Technician

Funding Sources: NIST (54%), Other Government Agencies (36%), Other (10%)

Objective: Improve existing measurement methods for characterizing the complex permittivity and permeability of dielectric and magnetic materials, as well as conductor surface resistance, over the radio-frequency/microwave spectral range 300 kHz to 60 GHz. Develop new measurement techniques to support newly-emerging technologies. Provide measurement services and standard reference materials (SRMs) to industry and others. Organize and implement measurement intercomparisons.

Background: Bulk electronic materials are widely used in industry for applications such as printed wiring boards (PWBs), substrates, electronic and microwave components, antenna radomes and lenses, microwave absorbers, etc.. Thin films are widely used in microelectronic circuitry and substrate-based components. Computer-based design methods, which lead to significant cost savings, require very accurate data on the dielectric and magnetic properties of these materials over a wide spectral and temperature range. Much improved and new measurement methods of known uncertainties, are needed to meet this critical need. Dielectric SRMs provide measurement traceability to NIST and intercomparisons provide assessments of the national quality of material characterization.

Current Tasks:

1. Develop low-frequency fluid characterization techniques

FY 1996 Collaborated with MIT-Lincoln Lab (LL) and Genosensor Consortium in developing new automated techniques for DNA hybridization pattern detection using microelectrode array; Completed initial permittivity measurements on single-stranded DNA plus buffer solution, using 14 mm coaxial shielded-open technique, over range 0.3 -100 MHz.

FY 1997 Completed similar DNA measurements at low frequencies, 0.1-10 kHz using commercial liquid test fixture and NIST designed-fixture intended to overcome electrode polarization effects; Completed theoretical study of low-frequency relaxation in single and double stranded DNA; Performed preliminary capacitance measurements using DNA probes attached to microelectrode array developed by LL.

FY 1998 Developed chopper-stabilized instrumentation for extremely low frequency (ELF) fluid measurements; Resolved problems relating to attachment of DNA probes to microelectrode array.

FY 1999 Demonstrate operation of new ELF fluid measuring instrumentation; Perform fluid measurements.

FY 2000 In collaboration with MIT Lincoln Lab, demonstrate DNA hybridization pattern detection measurements; Fabricate improved microelectrode arrays.

2. Develop improved resonator techniques for medium- and low-loss bulk solids

FY 1996	Completed refurbishment and improvement of the NIST 60-mm diameter mode-filtered cylindrical cavity to be used in planned NIST dielectric SRM service (greater operating frequency range, 6-13.5 GHz, and more accurate loss factor measurements over a wider range of losses); Completed exact solution for coaxial re-entrant cavity and wrote new software; Procured several re-entrant cavity and split-post resonator fixtures that provide advanced capability for characterizing PWBs; Improved accuracy of full sheet resonance technique for PWB measurements.
FY 1997	Completed complex permeability tensor measurements of ferrites biased by variable DC magnetic field at 2 and 10 GHz using modified dielectric post resonator method; Developed improved reentrant cavity technique for characterizing magnetic properties of medium-loss ferrites in range 150-1000 MHz.
FY 1998	Procured 150 MHz re-entrant cavity and specialized split-post resonator for characterizing ferrite substrates; Completed exact solution and software for split-cylinder (Kent) technique that yields more accurate data than commercially-supplied software; Completed new measurement software and uncertainty analysis for NIST 60 mm cylindrical cavity.
FY 1999	Complete exact solution and software for split-post resonator; Complete documentation on remodeled NIST 60 mm cylindrical cavity; Complete documentation of proposed dielectric SRM service for NIST Calibration Committee; Initiate new SRM service.
FY 2000	Continue to characterize customer's materials as requested.

3. Develop cryogenic metrology for characterizing high-TC superconductor (HTS) films, substrates, and ultra low-loss dielectrics

FY 1996	Improved our 4 to 120 K cryostat system with integrated sapphire rod resonator capable of measuring the microwave surface resistance, R_S of HTS films at 25 GHz; In collaboration with NIST Division 814, investigated variation of R_S for yttrium barium copper oxide (YBCO) with film thickness.
FY 1997	Procured higher-quality sapphire rod for better performance of above resonator; Fabricated new cryogenic fixture for measuring losses of ultra low-loss dielectrics using whispering-gallery mode (WGM) technique; Measured losses of the high-quality sapphire rod and alumina; In collaboration with Polish and Australian researchers measured losses of sapphire/rutile composites with possible application to temperature-compensated frequency standards.
FY 1998	Completed uncertainty and error analysis for dielectric resonator system.
FY 1999	Complete documentation of above; Perform further WGM measurements on ultra low-loss materials in collaboration with Polish and Australian researchers.
FY 2000	Complete ferrite permeability tensor measurements at liquid nitrogen (77 K) temperature.

4. Develop new metrology for characterizing thin substrates and thin films

FY 1996	In collaboration with High Speed Microelectronics Metrology Project, developed new "in-situ" techniques for measuring dielectric properties of thin substrates on which coplanar waveguide (CPW) transmission line structures have been patterned. Developed quasi-scalar model for deriving dielectric properties of substrates. Obtained broadband data on lanthanum aluminate, gallium arsenide and fused silica substrate materials.
FY 1997	Initiated collaborative efforts to fabricate microelectronic test structures, containing overlaid dielectric thin films, with industry, etc.; Began development of in-situ techniques for characterizing thin ferrite substrates.
FY 1998	Using CPW test structures fabricated by industrial partner, measured properties of overlaid thin-film dielectrics, including low-permittivity ("low-k") materials used in microelectronics packaging; Fabricated CPW structures on yttrium indium garnet (YIG) substrates; Sought to extract magnetic properties of YIG substrate using the quasi-scalar model.
FY 1999	Measure additional low-permittivity thin films using both CPW and microstrip structures; Develop new thin-film test structures using microstrip transmission lines; Begin investigation of resonator techniques for characterizing unpatterned dielectric thin films. *(1998 EEEL Strategic Plan)*
FY 2000	Continue measurements of both patterned and unpatterned dielectric thin films using resonator methods.

5. Develop improved and new techniques for characterizing bulk and thin-film ferroelectrics

FY 1996	Measured some bulk BSTO-oxide composites for Army client using 50 mm mode- filtered cavity; Supplied identical fixture to client.
FY 1998	Developed reentrant cavity technique for characterizing tunable ferroelectric thick films, under condition of up to 1000 volts applied bias, at a frequency of about 350 MHz; Procured fixture and high-voltage power supply.
FY 1999	Modify above fixture for improved accuracy under biased conditions and develop lumped-element theory for measurements; Perform relative RF tunability measurements on selected samples under bias; Measure quantity of ferroelectric samples using sleeved dielectric rod technique over temperature range of -50 to 150 C, no bias; Procure mode-filtered cavity fixtures for characterizing bulk ferroelectrics at 28 and 35 GHz for military sponsor; Collaborate with Electromagnetic Technology Division on ferroelectric thin-film measurements using CPW technique.
FY 2000	Complete above measurements on bulk ferroelectrics; Complete collaboration with Electromagnetic Technology Division on ferroelectric thin films; In collaboration with Army Research Laboratory, begin measurements of unpatterned ferroelectric thin films using resonator techniques.

6. Organize and participate in measurement intercomparisons

FY 1997	Published results of dielectric and magnetic measurement intercomparison of ferrites using 7 mm and 14 mm broadband coaxial air line technique.
FY 1998	Published results of dielectric and magnetic measurement intercomparison using the stripline cavity resonator.
FY 1999	Organize possible future national intercomparison of dielectric measurements using the broadband coaxial open-ended probe technique; Participate in

	international intercomparisons of dielectric fluid measurements and of microwave surface resistivity of high-temperature superconductor (HTS) films.
FY 2000	Organize possible future national intercomparison of dielectric measurements using the broadband coaxial open-ended probe technique, as well as the IPC 2.5.5 stripline resonator card technique; Participate in international intercomparisons of dielectric fluid measurements and of microwave surface resistivity of HTS films.

OPTOELECTRONICS

Dielectric Materials and Devices

Project Leader: Norman A. Sanford

Staff-Years: 4.3 Professionals, 2.0 Postdoc, 1.0 Students, 1.0 Guest Researcher

Funding Sources: NIST (87%), Other Government Agencies (9%), Other (4%)

Objective: Develop advanced measurements and critical evaluation criteria for dielectric and semiconductor materials used in optoelectronics systems, instrumentation, and sensors; interact with industry for the test and evaluation of advanced laser glasses and nonlinear optical materials; fabricate prototype devices from these materials.

Background: NIST's work in the characterization of dielectric materials, with emphasis on supporting new industrial developments in the field of integrated and guided-wave optics, began in 1988. The work has focused on rare-earth-doped laser glasses and ferroelectric ceramics such as lithium niobate and lithium tantalate. These materials are important since they are the backbone of new commercial directions of integrated optical technology. For example, compact solid-state glass waveguide lasers are viewed as key components for remote sensing and ranging technologies, applications requiring stable mode-locked operation for use in analog-to-digital conversion, and ultrafast sources for high-speed optical telecommunications. NIST works with industrial collaborators, supporting both device development and materials development and assessment, to help further this technology. NIST also works on the characterization of single domain and domain engineered lithium niobate and related ferroelectric ceramics. These materials are used extensively in optical communication systems for modulators, switches, and filters, and applications for sensors and control systems. Nonlinear optical characterization methods developed in this work is now generalized to the study of compound semiconductors. Furthermore, domain-engineered lithium niobate devices are now key elements in widely-tunable ultrafast and continuous optical parametric oscillators. These are in demand for such applications as biomedical diagnostics, ultrafast dynamics, transient spectroscopy, and eye-safe range finding. Project members fabricate devices for such NIST metrology instrumentation needs as high speed detector measurements, time and frequency standards, multimode fiber characterization, and wavelength standards.

Current Tasks:

1. Rare-earth-doped solid state laser and amplifier metrology

FY 1990-1997 First reported Nd-doped waveguide laser showing continuous operation; First reported Y-branch waveguide laser; Demonstrated various mode-locked Q-switched and coupled cavity waveguide lasers in silicate glass; First reported neodymium-diffused lithium tantalate waveguide laser; Demonstrated high efficiency phosphate glass waveguide laser; Demonstrated distributed-Bragg reflector waveguide lasers; Developed fully time dependent modeling codes and numerical analysis package for complex multiply-doped cw and pulsed waveguide lasers; Demonstrated stabilized operation of neodymium and erbium diffused lithium niobate waveguide lasers.

FY 1998 Demonstrated 180 mW of continuous output near 1550 nm, and tunability over 70 nm, for an erbium/ytterbium waveguide laser. This is the highest power for such a device reported to date; Measured absorption and emission cross sections, up-conversion of coefficients, and energy transfer efficiency in Er/Yb co-doped phosphate and silicate laser glasses; First known demonstration of Q-switching erbium-doped glass waveguide lasers near 1550 nm using semiconductor saturable absorbers; Established processing parameters for the fabrication of etched gratings in phosphate glass waveguides; Demonstrated ytterbium doped waveguide lasers for widely tunable operation near 1000 nm; Initiated collaboration with ITL for rigorous numerical modeling of active and passive guided-wave components.

FY 1999 Establish utility of hybrid mode-locked and Q-switched waveguide lasers for applications involving high-speed optical telecommunications, wavelength comb generation, and eye-safe range-finding; Explore advanced processing methods such as direct grafting of semiconductor saturable absorbers to waveguide surfaces and waveguide formation by UV writing; Begin designs incorporating the combined systems of rare-earth doped waveguides and semiconductor saturable absorbers; Demonstrate arrays of distributed-Bragg reflector waveguide lasers operating at wavelengths commensurate with the International Telecommunication Grid; Continue to explore collaboration with NIST/Physics Laboratory including NIST PL/University of Colorado Joint Institute for Laboratory Astrophysics (JILA) regarding applications of waveguide lasers.

FY 2000 Continue iterative experimental and theoretical work to optimize passively mode-locked waveguide lasers operating at repetition rates between 10 - 20 GHz; Continue and extend collaborative work with NIST/Information Technology Laboratory with numerical modeling of optoelectronic components; Examine the spectral decomposition of ultrafast mode-locked waveguide lasers for uses in optical comb generation and wavelength-division multiplexing; Continue to study and develop arrays of distributed-Bragg reflector lasers for the same applications.

2. Metrology of nonlinear optical materials

FY 1989 Characterized nonlinear bi-directional photorefractive mode coupling in lithium niobate waveguides.

FY 1994-1997 Constructed apparatus for Maker fringe analysis; Established theoretical models describing Maker fringe analysis of lithium niobate for examining birefringence variations due to fluctuations in strain and composition; Studies of domain-engineered lithium niobate initiated; Mapped uniformity of batches of lithium niobate wafers, measuring 76 mm and 100 mm in diameter, and correlated results with x-ray topography and with device yield results of industrial collaborators; Developed novel intersecting beam nonlinear optical analysis method; Investigated asymmetric poling fields in domain-reversed lithium niobate; Performed Maker fringe analysis on domain-reversed lithium niobate; Obtained preliminary atomic-force microscopy images of lithium niobate domains.

FY 1998 Refined Maker fringe analysis of strain effects in lithium niobate wafers; Conducted Maker fringe analysis on wafers sequenced from specially grown boules by an industrial collaborator; Obtained preliminary data of interfacial second-harmonic generation from glass layers; Collaborated with NIST/Physics Laboratory and JILA and fabricated numerous periodically-poled lithium niobate components for frequency standards research; Collaborated with Stanford University on Maker fringe analysis of epitaxial lithium niobate films and measured nonlinear optical coefficients of the films; Also performed Maker fringe analysis on vapor-transport equilibrated material from same collaborators; Performed transmission-electron microscopy studies of domain-reversed lithium niobate; prepared OH-reduced samples of lithium niobate in order to assess effect on poling hysterisis; Initiated Maker fringe analysis studies of GaN films grown on sapphire by collaborators at University of California, Santa Barbara (UCSB); Initiated Maker fringe analysis studies of diffusion-bonded layers of InP and GaAs fabricated by collaborators at an industrial laboratory; Demonstrated first known use of Maker fringe analysis to measure d.c. electrooptic coefficients.

FY 1999 Continue work with crystal manufacturers of lithium niobate, users of lithium niobate, in correlating the crystal quality, as revealed in nonlinear optical analysis, with device performance. This includes lithium niobate used in optical telecommunication systems and nonlinear optics. Develop detailed modeling for nonlinear optical analysis of gallium arsenide/indium phosphide and gallium nitride/sapphire layers; Extend work with UCSB collaborators for gallium nitride characterization, industrial collaborator for diffusion bonding studies, and Stanford University for examination of lithium niobate of varying composition, and correlate these various nonlinear optical results with high-resolution x-ray diffraction imaging; Perform detailed transmission electron microscopy (TEM) analysis of domain-engineered lithium niobate; Construct prototype optical parametric oscillator in domain engineered lithium niobate and/or lithium tantalate and use this source to extend nonlinear optical analysis of semiconductors and oxides; Extend collaboration with NIST/Physics Laboratory's Time and Frequency Division and JILA to include specialty optical parametric oscillators.

FY 2000 Apply prototype tunable optical parametric oscillators to the nonlinear optical analysis of diffusion-bonded semiconductor layers, epitaxially grown semiconductor films, and other oxides. Extend work to time domain and explore transient effects; continue work with NIST/Materials Science and Engineering Laboratory (MSEL) regarding x-ray diffraction imaging; Extend collaborative work with Stanford University on varied compositions of domain-engineered lithium niobate and include both nonlinear optical characterization and TEM analysis of the material.

Semiconductor Materials and Devices

Project Leader: Robert K. Hickernell

Staff-Years: 3.7 Professionals, 1.0 Technician, 3.0 Students

Funding Sources: NIST (91%), Other Government Agencies (9%)

Objective: Develop measurement methods and provide measurements to support the efficient manufacture of semiconductor optoelectronic devices; provide custom devices to support research in NIST, other Government laboratories, and industry.

Background: This project was established in 1994 and has earlier foundations in efforts dating to 1990-91 when NIST researchers contributed to metrology for the precision manufacturing of semiconductor epitaxial multilayers. The particular impact was in assisting the development of the first commercially available vertical-cavity surface-emitting lasers (VCSEL), which are used in short-distance data communication links. The project has extended the *ex-situ* measurements to *in-situ* monitoring during epitaxial growth, with the goal of advancing controlled-precision optoelectronic device manufacturing and the development of standard reference materials and data. Its efforts in developing high-precision measurements of source gas impurities will assist industry in improving the quality and consistency of the raw materials used to make semiconductor devices. Project researchers collaborate with industry and other Division researchers to develop measurements which support the manufacture and specification requirements for lasers used in data interconnect systems. The project fabricates novel lasers and detectors for use in detector metrology, high-speed measurements and sensor applications. Ultrashort pulse measurements are applied to semiconductor materials characterization and next-generation, high-speed communications research. Expertise is being developed in group III-nitride materials, which are used in displays, optical data storage, and solar blind detection, in the blue/ultraviolet region.

Current Tasks:

1. *In-situ* optical metrology and process control of epilayer manufacturing

FY 1997 Developed triggered data acquisition technique which reduced effect of substrate wobble by a factor of 10 in *in-situ* reflectance measurement; Increased operational state of crystal growth system to include source materials of indium, beryllium, silicon, and arsenic (As_2).

FY 1998 Reduced uncertainty in real-time group-III flux measurement to less than 1%; Completed hardware, repairs, safety training and document for use of phosphine in MBE growth system.

FY 1999 Apply *in-situ* measurements to the development of composition artifacts with ± 1% uncertainty; Develop periodically poled lithium niobate device for laser-based atomic absorption measurement; Develop spectroscopic pyrometry system to measure substrate temperature; Establish parameters for growth of InGaAsP on InP.

FY 2000	Evaluate mass desorption spectroscopy as a tool for *in-situ* group V ratio determination in InGaAsP growth; Measure group III flux using laser-based atomic absorption system.

2. *Ex-situ* characterization of semiconductor growth and processing

FY 1991	Characterized vertical-cavity surface-emitting laser (VCSEL) structures by X-ray, electron-beam, and optical metrologies, and by measurement simulations; Showed high degree of correlation among measurement methods for layer thicknesses, uniformity, and composition; Assisted industry in development of first commercially available VCSELs.
FY 1992 - 1995	See 1998 Program Plan.
FY 1996	Measured and modeled influence of effusion-cell temperature drift during distributed Bragg reflector manufacturing; Correlated high-resolution x-ray diffractometry measurements to reflectance spectroscopy and electron microscopy measurements of systematic and random period deviations in multilayers.
FY 1997	Correlated *in-situ* and *ex-situ* measurements to advance controlled-precision manufacturing; Investigated influence of manufacturing variations on VCSELs; Applied atomic force and scanning near-field microscopic measurements to nanoscale optoelectronic structure characterization.
FY 1998	Developed manufacturing and metrology of quantum-dot materials and devices; Grew and characterized samples in initial NIST inter-comparison of AlGaAs composition measurement.
FY 1999	Correlate *ex-situ* and *in-situ* measurements of composition and thickness on test standard wafers; Conduct additional measurement intercomparisons of test wafers among NIST laboratories; Quantify effects of x-ray rocking curve parameters on composition determination; Build robust cavity ring-down spectroscopy system and measure water concentration in nitrogen purge gas.
FY 2000	Conduct measurement inter-comparisons of composition test wafers among government and industry laboratories; Confirm x-ray rocking curve and photoluminescence measurements of composition by the Project with electron microprobe analysis by the NIST/Chemical Science and Technology Laboratory; Measure water concentration in phosphine gas with goal of 10 ppb sensitivity. (*1998 EEEL Strategic Plan*)

3. Semiconductor material and device metrology for advanced applications

FY 1993	Completed study of optoelectronic technology and metrology required to enhance computing; Established program to address the measurement needs of the VCSEL industry and applications of optoelectronic interconnects.
FY 1994 - 1995	See 1998 Program Plan.
FY 1996	Studied VCSEL measurands as function of environmental and drive parameters; Performed data interpretation and modeling of VCSEL emission properties; Determined measurement problems and technological barriers of group III-nitride technology.
FY 1997	Established ultrafast mode-locked laser and optical homodyne detection system for device and material characterization; Investigated spectral mode content of VCSEL devices for optical interconnects; Explored high-spatial resolution metrology development to support the group III-nitride industry.

FY 1998	Developed pump-probe station and measured carrier relaxation in semiconductor saturable absorbers; Developed and demonstrated general method for attaching error bars to intensity and phase measurements of ultrashort pulses; Determined refractive index dispersion of native AlGaAs oxides from reflectance and spectral ellipsometry measurements.
FY 1999	Extend ultrashort pulse metrology to the 1.06 μm and 1.5 μm spectral regions; Characterize semiconductor saturable Bragg reflectors for mode-locking in these regions; Measure index dispersion of buried native oxides using x-ray diffraction and optical reflectance spectroscopy; Analyze and report measurements of VCSEL transverse mode profiles by near-field scanning optical microscopy; Image GaN films and wafer-fused interfaces using high-resolution x-ray topography (HRXRT).
FY 2000	Correlate HRXRT measurements of GaN layers with nonlinear optical measurements to evaluate strain, defects, and nucleation layers; Correlate HRXRT measurements of wafer-fused interfaces with nonlinear optical measurements and sample fabrication to map interfacial defects and strain. Measure pulse-to-pulse jitter of successive mode-locked pulses from waveguide lasers.

4. Devices for advanced metrology

FY 1994	Formulated concept of environment (e.g., temperature, electromagnetic field) sensor using microcavity devices; Secured NASA support.
FY 1995	See 1998 Program Plan.
FY 1996	Designed, fabricated, and tested custom device which stabilized optical-pump coupling but maintained laser sensitivity to environment; Established and characterized fiber-interfaced optical power and sensing.
FY 1997	Advanced methods of photonic/electronic band engineering into ultrafast device metrology; Developed saturable Bragg reflectors for pulsed laser in high-speed detector metrology systems in the Division; Established capabilities and competence in the growth and fabrication of electrically injected semiconductor emitters.
FY 1998	Designed and grew saturable Bragg reflector which demonstrated mode-locked and q-switched operation of rare-earth-doped waveguide lasers at 1.06 μm; Developed and demonstrated native oxide fabrication techniques for current and optical mode confinement in VCSELs; Designed and grew resonant-cavity-enhanced photodiodes which demonstrated record bandwidth (50 GHz)-efficiency (>90%) products.
FY 1999	Design and grow saturable Bragg absorbers for mode-locking and q-switching of 1.5 μm waveguide lasers; Grow quantum-dot saturable absorbers for q-switched and/or mode-locked waveguide laser at 1.06 μm; Demonstrate wavelength-tunable lasers with graded quantum well widths; Demonstrate tunable laser based on quantum dot active region; Demonstrate optically and electrically addressable VCSEL with low-ripple optical pumping window.
FY 2000	Demonstrate mode-locked operation of waveguide laser with quantum dot saturable absorbers; Develop quantum dot growth for application in 1.5 μm region.

Fiber and Discrete Components

Project Leader: Sarah L. Gilbert

Staff-Years: 2.75 Professionals, 0.25 Technician, 1.7 Postdoc, 1.0 Student

Funding Sources: NIST (85%), Other Government Agencies (15%)

Objective: Develop measurement methods for characterization of optical fiber components and discrete components and develop standards needed by industry for these components.

Background: This project is concerned with the characterization of optical components and development of standards needed to calibrate commercial instruments which measure component properties. Wavelength standards are needed to calibrate instruments which measure the wavelengths of sources and characterize the wavelength dependence of components in wavelength division multiplexing optical fiber communication systems. Future optical communication systems will likely incorporate recently developed components, including many promising devices such as fiber lasers, dispersion compensators, and band pass filters containing Bragg fiber gratings. There is a need for standards and characterization of these components in order to both evaluate their reliability and ensure that the system specifications can be met. Polarization dependence such as polarization-dependent loss and polarization-dependent gain in components can affect a system's performance, especially when there are many components in the system. Presently, there are commercial instruments for measuring polarization-dependent loss, but no calibration standards exist for these instruments.

Current Tasks:

1. Wavelength standards for optical communications

FY 1990	Designed and constructed a single-longitudinal mode erbium-doped fiber laser and characterized its frequency noise.
FY 1991	Conducted spectroscopy of acetylene using the fiber laser to assess potential use for a wavelength standard; Developed a light emitting diode and absorption cell based moderate-accuracy wavelength standard.
FY 1993	Stabilized the fiber laser to a narrow absorption line of laser-cooled rubidium, demonstrating the system's potential as a high-accuracy wavelength standard.
FY 1994	Developed plan for meeting NIST traceability need for wavelength calibration at optical communication wavelengths via absorption cells to be distributed as standard reference material (SRM).
FY 1995	Built and tested hydrogen cyanide ($H^{13}CN$) vapor cells for moderate-accuracy wavelength references.
FY 1996	Developed acetylene absorption cell standard reference material; Measured the pressure-induced shift of acetylene absorption lines; Supplied three companies with fiber-pigtailed absorption cells.

FY 1997	Provided acetylene absorption cell SRM; Developed hydrogen cyanide absorption cell SRM; Transferred absorption cell technology to a company.
FY 1998	Provided hydrogen cyanide absorption cell SRM; Developed high-accuracy 1560 nm internal calibration reference.
FY 1999	Provide SRM 2517 (acetylene) and 2519 (hydrogen cyanide) units as needed; Develop high-resolution SRM; Investigate references for 1300 and 1600 nm regions. (*1999 Budget Narrative; 1998 MSL Strategic Plan; 1998 EEEL Strategic Plan*)
FY 2000	Provide SRM 2517 and 2519 units as needed; Provide high-resolution SRM; Develop SRMs for 1300 and 1600 nm regions; Develop high-accuracy 1300 nm internal calibration reference.
FY 2001	Provide SRM absorption cell units as needed.

2. Metrology for photo-induced Bragg gratings in optical fiber

FY 1992	Developed the capability to write Bragg reflection gratings in optical fiber.
FY 1993	Characterized fiber grating growth dependence on time and the intensity of the ultraviolet (UV) light, compared results with theoretical models.
FY 1995	Evaluated the thermal stability of fiber Bragg gratings written in hydrogen-loaded and unloaded optical fiber.
FY 1997	Investigated measurement techniques to characterize bulk glass UV photosensitivity.
FY 1998	Constructed apparatus for bulk glass index change measurements; Developed plan for nuclear magnetic resonance (NMR) studies of UV-induced defects; Began NMR measurements.
FY 1999	Conduct NMR measurements on UV-induced defects in hydrogen-loaded glass; Measure UV-induced index change in glass samples.
FY 2000	Conduct NMR and index measurements to study the role of boron and other dopants in UV photosensitivity.

3. Polarization-dependent loss and gain metrology

FY 1994	Developed plan for constructing a polarization-dependent loss (PDL) measurement system.
FY 1995	Developed two PDL measurement systems.
FY 1996	Completed characterization of PDL measurement systems; Characterized short-term stability PDL artifact reference.
FY 1997	Documented PDL measurement system; Studied PDL of fiber connectors; Developed polarization-dependent gain measurement capability and began measurements on a fiber amplifier.
FY 1998	Evaluated industry need for PDL artifact references and polarization-dependent gain metrology; Developed plan to meet PDL need. (*1998 MSL Strategic Plan*)
FY 1999	Evaluate PDL artifact reference at one wavelength; Construct wavelength-dependent PDL measurement system. (*1999 Budget Narrative; 1998 EEEL Strategic Plan*)
FY 2000	Develop PDL SRM; Conduct interlaboratory comparison on PDL measurement.
FY 2001	Provide PDL SRM.

4. Mode-Isolation Metrology for Polarization Maintaining Fiber

FY 1991	Began work on mode-isolation (h-parameter) measurement in high birefringence optical fiber at request of the Telecommunication Industries Association (TIA).
FY 1992	Conducted NIST/TIA interlaboratory comparison of mode-isolation measurements.
FY 1994	Participated in drafting a mode-isolation TIA fiber optic test procedure.
FY 1996	Worked with TIA to evaluate a new mode-isolation measurement technique.
FY 1997	Conducted and participated in a mode-isolation measurement interlaboratory comparison involving new technique.
FY 1998	Compiled interlaboratory comparison results.
FY 1999	Conduct interlaboratory comparison on mode-isolation measurement using high performance fiber cables. Task completed.

Integrated Optics Metrology

Project Leader: Matt Young

Staff-Years: 1.75 Professionals, 1.0 Postdoc, 1.0 Student

Funding Sources: NIST (85%), Other Government Agencies (15%)

Objective: Develop advanced measurement methods for integrated optical waveguides. Interact with standards groups to provide a metrology base for the optoelectronic communications industry.

Background: As the optical fiber industry moves toward local area networks and toward fiber to the home, there is increasing need for inexpensive passive components such as splitters. Additionally, such components are needed because long-distance telephony is retrofitting to wavelength division multiplexing. Several companies are manufacturing $1 \times N$ splitters or are about to market them. There are, however, no standard measurement procedures similar to those for fiber index profile and mode-field diameter, nor are there artifact standards similar to those for fiber geometry. Further, it is not obvious how to perform analogous measurements, for example, because the mode field pattern of an integrated optical waveguide is not circularly symmetric or because the fiber measurement is performed using a cutback technique or a mandrel wrap. Thus, several critical measurements need examination.

Current Tasks:

1. Develop metrology for integrated optical components

FY 1996	Continued development of low coherence reflectometer; Characterized Y-branch waveguides and measured dispersion of an optical waveguide and performed preliminary measurements on waveguides in various substrates; Began work on confocal microscopy of waveguide end faces for mode-field diameter measurements.
FY 1997	Measured reflections in integrated optical waveguides using low coherence reflectometer; Measured mode-field diameter of waveguide with near-field methods.
FY 1998	Measured refractive index profiles of integrated-optical guides; Developed optical low-coherence reflectometry (OLCR) to characterize wavelength division multiplexers; Made preliminary OLCR measurements on arrayed waveguide grating; Developed 2-dimensional finite-difference time-domain simulation for waveguide modeling.
FY 1999	Perform index profile measurements on diffused and polymer waveguides; Modify refracted near-field system for polarization-sensitive measurements of index profile; Assemble low-coherence interferometer for measurements of planar waveguide gratings; Study multiplexers using simulation and OLCR.
FY 2000	Establish experimental and theoretical limit between near- and far-field measurements of planar waveguides; Compare grating measurements via low coherence interferometer with phase of frequency domain techniques.

Optical Fiber Sensors

Project Leader: Kent B. Rochford

Staff-Years: 2.25 Professionals, 0.5 Technician, 2.75 Post Doc, 2.0 Student, 1.0 Guest Scientist

Funding Sources: NIST (80%), Other Government Agencies (16%), Other (4%)

Objective: Provide metrology to support the optical fiber sensor industry and develop advanced sensing technology for other government and industry laboratories. Provide polarization measurements and develop polarization standards for industry. Provide optical disc substrate measurements.

Background: NIST is responding to the growing fiber-optic sensors industry by developing standards and calibrations where few exist, assisting in the characterization of components and sensing methods, and educating the measurement community to the advantages of optical fiber sensors. This project provides the industry and other government agencies with traceability, measurement expertise, neutral evaluation of technologies, and pre-commercial development of advanced prototypes and recently developed a Standard Reference Material for linear retardance. Through this project, NIST provides Special Tests for retardance and is beginning an effort to calibrate optical disc retardance measurements and to investigate more general measurements on optical discs.

Current Tasks:

1. Advanced sensor systems, components, and materials research

FY 1985	First demonstration of fiber annealing to remove birefringence.
FY 1986	Demonstration of optical fiber current measurements to 70 MA.
FY 1987	Extended study of precision of electro-optic and magneto-optic sensors published.
FY 1989	High speed, high sensitivity (100pT/$\sqrt{Hz}$ noise equivalent field) sensors based on the Faraday effect in yttrium-iron-garnet (YIG) demonstrated.
FY 1993	Demonstrated very-high-sensitivity magnetic field sensor (1.4pT/$\sqrt{Hz}$ noise equivalent field) using flux concentrators.
FY 1995	Developed and demonstrated laser-as-detector technique in optical fiber sensor systems; Completed self-calibrating temperature sensor system.
FY 1996	Thermally expanded an optical fiber core; Characterized and improved high-sensitivity magnetic field sensor system.
FY 1997	Evaluated novel garnets for magnetic field sensor system; Characterized thermally expanded core fiber; Began work on low-coherence sensor systems.
FY 1998	Developed accurate low-coherence ranging system; Developed fiber Bragg grating sensor demultiplexing method.
FY 1999	Develop novel magnetic sensor head; Support investigation of fiber sensors for electrical current calibrations.

FY 2000	Deliver fiber optic magnetometer for evaluation; Demonstrate extended dynamic range low-coherence system.
FY 2001	Develop calibrations for fiber Bragg grating sensors.

2. Basic metrology and standards development

FY 1988	Definitive study of birefringent linear retarder (waveplate) stability.
FY 1994	Tested prototype retardance standards and demonstrated very good performance for wavelength, temperature, and incident-angle dependencies.
FY 1996	Measured the Verdet constant of optical fiber with improved accuracy for Los Alamos National Laboratory; Completed interlaboratory comparison of retardance measurements with eight U.S. participants; Established 3 accurate retardance measurement methods.
FY 1997	Established Standard Retarder as a Standard Reference Material (SRM) and provided measurement support.
FY 1998	Conducted dialogue with industry to identify priority needs for new component measurements and standards.
FY 1999	Begin effort in fiber Bragg grating metrology; Begin effort in Mueller matrix polarimetry.
FY 2000	Conduct accurate measurements of Bragg grating parameters; Demonstrate imaging Mueller matrix polarimeter.
FY 2001	Extend fiber Bragg grating measurement capability; Offer special tests using Mueller matrix polarimeter.

3. Optical data storage

FY 1995	Began investigation of optical data storage industry needs; Participated in NIST planning workshop.
FY 1996	Identified and prioritized measurement needs of the compact disc replication industry.
FY 1997	Developed techniques for measuring disc retardance at 780 nm.
FY 1998	Conducted interlaboratory comparison of optical disc retardance; Determined accuracy of industry-proposed disc retardance measurement methods. (*1998 MSL Strategic Plan*)
FY 1999	Develop vertical birefringence measurement methods; Develop disc retardance SRM.
FY 2000	Provide disc retardance SRM; Develop optical disc tilt measurement capability.
FY 2001	Begin development of disc tilt SRM.

4. Optical fiber sensor commercialization

FY 1991	Transferred optical fiber annealing technology to U.S. company.
FY 1994	Transferred improved annealing technology to U.S. company.
FY 1996	Transferred optical fiber annealing technology to a second U.S. company.
FY 1997	Provided electric field sensor to a U.S. company for evaluation.
FY 1998	Transferred electric field sensor technology to a U.S. company.
FY 1999	Transfer flight compatible E-field sensor to industry; Identify licensees for sensor demultiplexing technology.
FY 2000	Transfer current sensor technology to semiconductor industry for processing diagnostics.

Optical Fiber Metrology

Project Leader:	Paul A. Williams
Staff-Years:	3.0 Professionals, 0.4 Guest Researchers, 0.3 Contractors
Funding Sources:	NIST (90%), Other Government Agencies (10%)
Objective:	Develop advanced measurement methods and Standard Reference Materials for optical fibers; interact with standards groups to provide a metrology base for the optoelectronic communication industry.

Background: During the 1980s, optical fibers were introduced into the nation's telecommunication system to carry large quantities of long distance information. As the technology matured, more fiber moved into metropolitan areas and local area networks. Local loops utilize many more connection points; therefore, dimensional tolerances are important and improvements are necessary for lower loss connectors. In addition, long distance link technology continues to improve. Bit rates are increasing and the advent of optical amplifiers allows for direct optical paths thousands of kilometers in length; this and other trends toward wavelength division multiplexing require improved measurements of fiber dispersion. Over the years, NIST's efforts have evolved along with the industry, focusing on a wide range of measurement problems as they became important, and assisting in their resolution. This has led to a close involvement with the Telecommunications Industry Association (TIA) and with international standards organizations. NIST has participated in the development of more than twenty TIA standards, often serving as a neutral party in their evaluation through interlaboratory comparisons. In recent years, the industry's need for standard reference materials (SRMs) has grown; NIST presently provides four SRMs for optical fiber and related metrologies and has three more close to release.

Current Tasks:

1. Develop dimensional metrology for optical fiber

FY 1996	SRMs for connector ferrule outside and inside diameter (pin gages) available for sale; Investigated optical interferometric measurement methods for connector protrusion/undercut.
FY 1997	Investigated mechanical measurement methods based on a contact probe for connector protrusion/undercut; SRM for coating diameter developed and delivered to NIST Manufacturing Engineering Laboratory for final measurements; Developed reference far-field measurement system for mode field diameter.
FY 1998	Developed reference near-field measurement system for mode field diameter; Perturbation theory relating near- and far-field measurements developed and tested experimentally.
FY 1999	SRMS for mode-field diameter and coating diameter available for sale. (*1999 Budget Narrative; 1998 EEEL Strategic Plan*)
FY 2000	Assemble and certify additional geometry SRM's as needed.

2. Develop dispersion metrology for optical fiber

FY 1996	Documented performance of polarization mode dispersion (PMD) SRM; Completed TIA chromatic dispersion round robin and documented chromatic dispersion SRM.
FY 1997	Chromatic dispersion SRM available for sale; Prototype PMD SRM manufactured by outside vendors.
FY 1998	PMD SRM testing completed; Developed broadband system to measure multimode fiber chromatic dispersion.
FY 1999	PMD SRM available for sale; Characterize multi-mode fiber chromatic dispersion in test specimens; Investigate chromatic dispersion in fiber Bragg gratings.
FY 2000	Develop, assemble, and certify non-mode-coupled PMD SRM's; Compare dispersion measurements on gratings with similar low coherence measurements.

3. Develop metrology for nonlinear fiber properties

FY 1996	Determined relation between four-wave mixing efficiency and zero dispersion wavelength - published results; Presented four-wave mixing work to TIA;
FY 1997	Determined whether four-wave mixing can predict chromatic dispersion length uniformity.
FY 1998	Developed a system for measuring zero dispersion wavelength as a function of fiber length; Developed stable, Q-switched fiber laser which operates below Raman threshold for use in high-sensitivity optical time domain reflectometer (OTDR).
FY 1999	Assess industry need and make appropriate improvements to four-wave mixing system for zero-dispersion wavelength mapping.(*1998 MSL Strategic Plan*)
FY 2000	Assess industry need for OTDR standards.

4. Develop metrology for system/field measurements

FY 1996	Evaluated and modified, with TIA, existing test procedures for multimode fiber bandwidth.
FY 1997	Completed multimode fiber bandwidth round robin with TIA members; Developed high resolution measurement method for differential mode delay (DMD) in multimode fibers at 850 and 1300 nm; Developed reference measurement system for multimode fiber bandwidth; Measured DMD on TIA round robin fibers.
FY 1998	Developed ultra-high sensitivity wavelength-tunable OTDR for determining the uniformity of Rayleigh backscatter along the length of fibers; Improved the spatial resolution of DMD measurements for multimode fibers; Compared time and frequency domain DMD techniques; Determined zero dispersion wavelength of multimode fibers as a function of launching conditions.
FY 1999	Characterize multimode fiber impulse response as a function of launch and receive; Investigate applications of high sensitivity wavelength-tunable OTDR.
FY 2000	Continue support of multi-mode bandwidth characterization via DMD measurements.

5. Develop metrology for fiber amplifiers

FY 1996	Initiated international round robin and obtained preliminary NIST measurements of noise.
FY 1997	Obtained results from U.S., Europe, and Japan on international round robin for spectral gain and noise figure of erbium doped fiber amplifiers (EDFA).
FY 1998	Continued international round robin on EDFAs; Designed spectral gain measurement system for EDFAs.
FY 1999	Initiate a NIST Measurement Assurance Program (MAP) for erbium doped fiber amplifier spectral gain of EDFAs; Perform EDFA spectral gain measurements and finalize test system.
FY 2000	Evaluate gain measurements in the presence of multiple signal channels; Develop suitable test system.

High Speed Source and Detector Measurements

Project Leader: Paul D. Hale

Staff-Years: 4.25 Professionals, 0.5 Technician, 1.0 Contractor

Funding Sources: NIST (64%), Other Government Agencies (30%), Other (6%)

Objective: Provide advanced metrology, standards, and measurement services relating to temporal properties of optical sources and detectors used in association with optoelectronic systems.

Background: High bandwidth measurements are needed to support high-performance systems which take advantage of the potential bandwidth of optical fiber. Systems presently being installed operate at 5 to 10 gigabits per second using pure optical time division multiplexing (OTDM) and research is being done on the next generation of OTDM systems at 20 to 40 gigabits per second. Methods are needed to characterize the impulse and frequency response of high speed sources and detectors to at least the third harmonic of the system modulation rate. As new optoelectronic technologies have emerged, NIST has developed new laser and detector standards to support this growth. For example, the reemergence of short wavelength applications, such as optical interconnects, has shown the need for concurrent development of applicable measurement standards and techniques specific to this technology. Burst mode operation in asynchronous transfer mode (ATM) networks requires characterization at very low frequencies. Increasingly tight tolerances in both digital and analog systems require frequency response measurements with low uncertainty. Source and detector noise measurements are required to predict low bit error rates (BERs) in computer interconnects, high carrier to noise ratios (CNRs) in analog systems, and to support erbium-doped fiber amplifier (EDFA) noise figure (NF) measurements using electrical noise methods. Intensive use of laser target designators by the armed forces requires traceable low level pulse power and energy calibration standards at 1.06 and 1.55 μm.

Current Tasks:

1. Develop optical noise measurements and standards

FY 1996 Documented industry needs for optoelectronic noise measurements; Began development of techniques and apparatus for measuring relative intensity noise (RIN) which are suitable for supporting optical amplifier noise measurements and low level measurements on distributed feedback (DFB) lasers; Completed cryogenic measurements of RIN of various diode laser sources.

FY 1997 Developed and characterized RIN measurement techniques supporting optical amplifier noise measurements and measurement of low RIN (-160 dB/Hz) DFB lasers; Studied spatial mode partition noise in vertical cavity surface emitting lasers.

FY 1998 Began development of a RIN standard based on a filtered Erbium-doped fiber-amplifier noise source.

FY 1999 Quantify sources of uncertainty in RIN standard and document for MCOM; Develop an optical power spectral density standard for calibrating automated optical spectrum analyzers.

FY 2000 Continue development of RIN and optical power spectral density standards measurements; Apply noise stnadards to EDFA noise figure measurements; Assist industry in developing standard test procedures for EDFA noise figure.

2. Develop impulse response and vector frequency response measurements

FY 1996 - 1997 Investigated photoconductive methods for calibrating optoelectronic response in both magnitude and phase.

FY 1998 Investigated nose-to-nose technique for calibrating oscilloscopes used to measure optoelectronic response in magnitude and phase; Compared several algorithms for correcting errors associated with oscilloscope impulse measurements including timebase distortion measurement, timing jitter, and drift; Began investigation of Hilbert transform method for determining optoelectronic phase.

FY 1999 Continue investigation of nose-to-nose technique for calibrating oscilloscopes used to measure optoelectronic response in magnitude and phase; Develop method for pulse reconstruction after timebase distortion correction and method for mismatch correction; Quantify effects of noise on optical impulse response measurement and correct for them.

FY 2000 Compare optical vector response measurement with scalar heterodyne response measurement; Continue investigation of Hilbert transform method for determining optoelectronic phase.

3. Detector scalar frequency response measurements

FY 1992 Received inquiries from industry for photodiode frequency response in the frequency range between 0.050 and 20 GHz; Investigated various measurement methods by literature search and talking to industry representatives; Acquired parts for heterodyne measurement system.

FY 1993 Constructed heterodyne measurement system operable over the frequency range between 0.05 and 30 GHz; Investigated candidates for transfer standards.

FY 1996 Documented uncertainty analysis of frequency response measurements of a photoreceiver/power sensor transfer standard; Built and characterized synthesized modulation source for high-resolution measurements (between DC and 1 GHz).

FY 1997 Continued documentation of photoreceiver/power sensor transfer standard towards a calibration service; Began documentation of calibration service for "bare" photoreceivers; Investigated industry and military need for 850 nm or 1550 nm wavelength ranges and frequency coverage up to 110 GHz; Extended measurement capability to 850 nm.

FY 1998 Continued documentation of photoreceiver/power sensor transfer standard as a calibration service; Completed investigation of repeatability in 1300 nm heterodyne system in InGaAs check standard. Resolution of 850 nm heterodyne system improved to 1.3 MHz for calibration service.

FY 1999 Complete documentation of 1300 nm heterodyne system for MCOM; Extend range of 850 nm and 1300 nm heterodyne systems to 65 GHz; Document uncertainties in 850 heterodyne system for calibration service.

FY 2000	Document 850 nm heterodyne system for MCOM.

4. Develop new time-resolved laser radiometry capability

FY 1996	Continued time-resolved low-level system upgrade including assessment of Type B uncertainties; Transferred technology for construction of six time-resolved low-level radiometers to sponsor; Calibrated two of these radiometers.
FY 1997	Calibrated remaining four time-resolved low-level sponsor-constructed radiometers; Continued low-level system upgrade; Constructed time-resolved low-level measurement system for 1.55 μm light.
FY 1998	Continued time-resolved low-level system upgrade and development of time-resolved low-level system for 1.55 μm light.
FY 1999	Design and construct prototype 1550 nm time-resolved radiometer for Navy.
FY 2000	Build and calibrate 1550 nm time-resolved radiometer for Navy.

Laser Radiometry

Project Leader: Chris Cromer

Staff-Years: 7.0 Professionals, 3.0 Contractors, 1.5 Technicians

Funding level: $1.7 M

Funding Sources: NIST (69%), Other Government Agencies (25%), Other (6%)

Objective: Develop measurement methods and standards for characterizing laser sources and detectors used primarily with continuous-wave (CW) radiation. Develop and maintain measurement services for laser power & energy, optical fiber power, and related parameters (e.g., spectral responsivity, linearity, etc.)

Background: The development of lasers in the 1960s opened the door to new technologies and industries that could make use of the peculiar properties of laser radiation (i.e., spatial coherence, temporal coherence, narrow line width, high irradiance levels, etc.). The implementation of laser sources into industrial systems as well as research laboratories has been historically limited or enhanced by the ability to accurately characterize the emitted radiation. Consequently, NIST has been developing and providing measurement services to the laser community since the late 1960s. As new wavelengths and laser types have emerged, NIST has developed the appropriate new detector standards and measurement techniques to support this growth. Optical power detectors continue to be the most common piece of test equipment for supporting optical fiber telecommunication systems and as the technology evolves, higher accuracy power measurements have become crucial. In addition to higher accuracy, calibration customers have requested that we improve our capability to measure other detector properties such as linearity and spectral responsivity. Medical uses of lasers are continuing to evolve, with photorefractive eye surgery and photodynamic drug therapy being recent examples where total beam energy and spatial beam quality are critical measurement requirements. Quantitative knowledge about the irradiance profile and propagation characteristics of laser beams is essential to understanding the properties of emerging new technologies such as vertical cavity surface emitting lasers (VCSELs). Other important industrial applications of beam profile standards include optical data storage, high resolution printing, and semiconductor photolithography. Applications for high power lasers such as laser welding and cutting, and laser isotope separation also require quantitative characterization of beam profile and laser power.

Current Tasks:

1. Develop spectral responsivity measurement capability for optical power detectors

FY 1996	Began assessment and improved measurement uncertainty; Performed special test measurements for customers.
FY 1997	Completed uncertainty improvement and analysis; automated measurement system, trained technicians, and implemented fully documented measurement services.

FY 1998 Continued improvement of measurement uncertainties, and provided enhanced calibration services to customers; Provided specialized tests to industrial and research communities as required; Began development of specialized tunable laser systems for spectral response.

FY 1999 Complete documentation for spectral responsivity calibration service. Task completed.

2. Develop and provide measurement services for optical fiber power meters

FY 1996 Developed linearity measurement capability for 850 nm; Developed tunable laser system for optical fiber power meter measurements.

FY 1997 Improved linearity and tunable laser measurement system to provide enhanced measurement support; Performed study of connector effects on measurements; Obtained formal approval for optical fiber power measurement services.

FY 1998 Continued improvement of measurement uncertainties; Developed improved transfer standards traceable to the high accuracy cryogenic radiometer; Provided enhanced measurement services to industry.

FY 1999 Using in-house capabilities to build new tunable diode lasers, expand wavelength coverage of tunable laser measurement; Increase the power available for calibrations as requested by industry; Provide measurement service to industry; Build system to characterize the angular response of transfer standard detector; Complete documentation for optical fiber power meter calibrations. (*1998 EEEL Strategic Plan*)

FY 2000 Design and build improved transfer standards suitable for calibration with the high accuracy cryogenic calorimeter.

3. Develop and provide measurement services for laser power and energy detectors

FY 1996 Implemented high power 1.06 μm calibration measurements; Continued high power round robin.

FY 1997 Modified high energy laser calorimeter; Investigated discrepancy with PTB.

FY 1998 Developed improved transfer standards traceable to the cryogenic radiometer for high power laser measurements; Developed linearity test methods for high power laser meters.

FY 1999 Provide measurement services to industry; Improve the measurement systems and update control software.

FY 2000 Improve automation of measurement process; Improve the accuracy of calibration services for laser power and energy.

4. Improve accuracy of laser and optical fiber power measurements

FY 1996 Installed and tested cryogenic radiometer; Built and tested automated measurement system.

FY 1997 Developed prototype secondary standards (diode trap and pyroelectric trap designs); Using new primary and secondary standards, began to disseminate measurements traceable to the cryogenic radiometer for optical fiber and laser power calibrations.

FY 1998 Continued development of improved transfer standards; Refined dissemination of measurements for optical fiber and laser power calibration services traceable to the cryogenic radiometer.

FY 1999 Develop improved cryogenic radiometer designs, with faster response time and improved dynamic range; Improve data acquisition software and measurement automation. Task ends this year. (*1998 MSL Strategic Plan*)

5. Develop beam profile measurement capability

FY 1996 Improved beam profile measurement systems; Investigated sources for use in a round robin.

FY 1997 Continued development of standards for beam profile measurements; Developed beam profile measurement capabilities for excimer lasers used in photorefractive eye surgery; Investigated methods for profile measurements of tightly focused beams used in optical data storage.

FY 1998 Used new beam profile standards in round-robin with industry; Investigated standards appropriate for medical applications of excimer lasers; Developed beam profile measurement capability for pulsed lasers.

FY 1999 Develop beam profile measurement techniques for very high irradiance at the focus of industrial lasers; Acquire and/or build instrumentation to measure DUV excimer laser beam profiles; Complete report on beam profile round robin activities. Task completed.

6. Develop deep ultraviolet (DUV) calorimeters for excimer laser measurement capability.

FY 1996 Requested by industry to expand capabilities for excimer laser measurements to 193 nm; Began search for candidate calorimeter volume absorbing materials a 193 nm; Participated in collaboration between NIST, Massachusetts Institute of Technology/Lincoln Laboratories, and SEMATECH on DUV photolithography issues.

FY 1997 Continued investigations of volume absorbing materials for use in extending existing DUV calorimeter design for measurements at 193 nm; Installed new excimer laser on loan from SEMATECH.

FY 1998 Completed the construction of primary standard laser calorimeters and measurement system for calibrations at 193 nm; Explored gas-purging techniques to prevent degradation of calorimeter windows.

FY 1999 Begin providing calibrations to industry customers; Begin developing concepts for primary standard calorimeters at 157 nm; Design and build optical system to produce uniform intensity DUV laser beam. (*1998 EEEL Strategic Plan; 1999 Budget Narrative*)

FY 2000 Build primary standard for 157 nm excimer laser energy measurements; Begin providing dose meter calibration services (overfill detectors).

7. Develop tunable laser system for laser and optical fiber power detector calibrations from 400 nm to 200 nm.

FY 1999 Build a CW Ti:Sapphire laser system suitable for calibration services measurements; Acquire and install pump laser; Acquire and begin test grating tunable diode laser based on MQW laser technology.

FY 2000 Begin performing calibrations with Ti:Sapphire laser over the 700 nm to 1000 nm spectral range; Make choice between nonlinear techniques with Ti:Sapphire laser and multiple-quantum-well (MQW) diode lasers; Investigate down-conversion of Ti:Sapphire laser with periodically poled Li Niobate or begin developing multiple diode laser systems to increase wavelength coverage.

FY 2001 Complete development of tunable laser system with coverage form 600 nm to 1800 nm; Begin providing laser and optical fiber power calibrations with the laser system.

VIDEO

Video Technology

Project Leader: Edward Kelley

Staff-Years: 5 Professionals

Funding Sources: NIST (100%)

Objective: Develop the measurement support needed by U.S. industry to process, transmit, and display digital video information. Initially, develop objective measures for the characterization of the video quality of display devices, including needed measurements for quantities such as gray scale linearity, uniformity, contrast ratio, viewing angle, and brightness. Similarly, develop a collection of measurement tools for the evaluation of digital video signals, that are subjected to compression processing, which will allow the user to apply an appropriate subset of the tools to obtain an overall quality figure consistent with the task requirements.

Background: Manufacturers of flat-panel displays and manufacturers who use flat-panel displays in their products need consistent, industry-accepted measurement standards for characterizing the performance of their displays. Standards or testing procedures presently existing in industry are in their infancy or nonexistent. The lack of standards restricts the U.S. electronics industry by reducing competition between the suppliers of display products. The current world market for displays is over $11 billion per year. Also, service and manufacturing industries providing, or interested in providing, digital video services or products need test measures for evaluating the quality of their video "product." There are at present no metrologically sound measures for characterizing the quality of digital video sequences processed by lossy signal compression methods and/or transmitted over digital networks. Such characterization is fundamental to product development and marketing (price/performance targeting).

As a neutral third party, NIST is uniquely positioned to develop non-proprietary measurement tools that do not favor one technology. Further, NIST's long involvement with voluntary standards organizations, and our metrological reputation within those organizations, permit us to cooperate effectively with industrial partners and have NIST-developed technology widely accepted.

Current Tasks:

1. Develop performance measurements for the objective characterization of flat panel displays

FY 1993 Designed measurement laboratory and ordered equipment, including colorimeters, spectroradiometers, charge-coupled-device (CCD) imaging system, signal generators, display positioning system, and spherical panel surround.

FY 1994	Assembled and tested laboratory equipment; Developed test procedures for calibrating instruments; Developed simulation and modeling programs for the Princeton Engine, a massively parallel video supercomputer, to visually simulate display performance.
FY 1995	Conducted and reported on a survey of Display Measurement Standards; Developed additional creative laboratory calibration procedures; Completed round-robin measurement using a cathode-ray-tube (CRT) display from the National Information Display Laboratory; Started evaluation of an international voluntary reflectance measurement standard.
FY 1996	Analyzed and reported on an international voluntary reflectance measurement standard; Continued development of measurement techniques for display characterization; Designed a transportable display simulator; Investigated the use of interference filters to evaluate colorimetric performance of detection systems; Developed a flat panel display characterization draft standard for the Video Electronics Standards Association (VESA).
FY 1997	Continued development of measurement procedures for display characterization, adding additional tests for viewing angle and other parameters to meet industry needs; Completed the first released version of the flat panel display characterization standard for the Video Electronics Standards Association (VESA) for direct view displays.
FY 1998	Refined measurement procedures and expanded the existing procedures to include projection display systems; Developed the Stray Light Elimination Tube (SLET) in support of projection display system metrology; Verified a display reflection model, and established a measurement technique for it; VESA Flat Panel Display Measurement (FPDM) Standard version 1.0 became the best selling VESA standard. (*1998 MSL Strategic Plan; 1998 EEEL Strategic Plan*)
FY 1999	Refine measurement procedures and expand to include other technologies and methods such as head mounted, head up, and stereoscopic display systems, (with a voluntary standards organization, if possible); Develop display reflection SRMs; Investigate Simulated Eye Design (SED) camera capabilities; Develop Display Measurement Assessment Transfer Standard (DMATS) prototype and begin preliminary round robin. (*1999 Budget Narrative*)
FY 2000	Continue to refine measurement procedures and expand to include other display technologies and methods; Develop the Simulated Eye Design camera; Develop the Camera Assessment Transfer Standard (CATS) for validating digital camera performance.

2. Develop video quality metrics for quantifying video compression and viewing artifacts

FY 1993	Implemented and analyzed quality metrics for telecommunications applications; Developed a family of video test patterns for qualifying and verifying performance of metric implementations.
FY 1994	Developed an interactive method to use the Princeton Engine to measure perceptible noise threshold in video images; Held industry workshop to highlight technical issues with respect to sending video over information networks; Purchased, installed, and developed tools for additional computing capability to support video quality metric research.
FY 1995	Performed experiment to estimate flicker perception for small text fonts on interlaced displays; Collaborated with industry partner to analyze performance

	issues related to noise filtering and blurring of video images; Helped develop Advanced Technology Program focused program on "Digital Video in Information Networks;" Prepared assessment of industry needs for video quality metrics.
FY 1996	Reported results of font flicker metric for interlaced displays; Developed performance revealing test patterns for digital video compression systems, including test for motion estimation characterization; Developed analysis tools to quantify generated errors.
FY 1997	Refined performance revealing test patterns and disseminated preliminary version to industry; Extended image blocking detector to incorporate elements of human visual system and reported initial results; Measured perceptibility of compression impairments in noisy video test materials.
FY 1998	Participated in collaboration with industry in the design of an international comparison of video quality metrics and ran initial validation steps; Extended quality analysis tools using discrete cosines to improve local feature extraction; Evaluated and refined existing techniques for incorporating elements of human visual system in feature extraction; Refined technique for producing test patterns with graded compression impairments.
FY 1999	Continue development of test patterns supporting multiple digital television (DTV) formats; Develop transient effects detector for motion impairments and noise and integrate analysis tools into performance metrics with test patterns; Characterize test pattern performance and transfer technology to industry through publication and dissemination of test patterns and objective metrics.
FY 2000	Complete the integration of MPEG-2 video analysis tools into a full performance metric with test patterns; Develop a pre-processing performance analyzer to provide a measure of criticality (degree of compression difficulty). (*1998 EEEL Strategic Plan*)

3. Participate in voluntary standards committee working groups to identify non-tariff trade barriers in new television standards (in collaboration with Semiconductor Electronics Division).

FY 1998	Hosted an international meeting of the Video Quality Experts Group (VQEG); Contributed to development of Society of Motion Picture and Television Engineers (SMPTE) test tape.
FY 1999-2000	Provide support to SMPTE, ITU (VQEG), and IEEE (G-2.1.6) by participating in digital television standards activities.

POWER

Dielectrics Research

Project Leader: James K. Olthoff

Staff-Years: 1.5 professionals, 1 guest scientist

Funding Sources: STRS (100%)

Objective: To respond to industrial and other agency needs related to electrical insulation and its interaction with electrical breakdown.

Background: This project began in the mid 1970's with funding from Department of Energy to investigate liquid and gaseous dielectrics. Initial work in gaseous dielectrics emphasized the production of corrosive and toxic by-products in SF_6 formed by exposure to electrical discharge. Present work emphasizes the investigation of partial discharge (PD) detection as a diagnostic of insulation conditions, and the use of SF_6 by the electric power industry. Specific areas of investigation include: 1) concern by the electrical manufacturers and utilities about the formulation and detection of highly toxic compounds in gas-insulated power systems; 2) concerns over the global warming potentials of gaseous dielectrics; and 3) problems encountered by the Air Force about occurrence of corona discharges and related aging in high-voltage cables used in the space environment.

Current Tasks:

1. Perform laboratory evaluation of techniques for cable condition monitoring

FY 1993	Requested by the Nuclear Regulatory Commission (NRC) to reactivate program on cable defect detection in nuclear power plant cables.
FY 1994	Initiated evaluation of partial discharge techniques for application as cable diagnostic; Established liaison with Brookhaven National Laboratory for acquisition of aged cable specimens.
FY 1995	Completed assembly of digital recording instrument for partial discharge analysis of cables; Evaluated novel Russian-based technology; Collected literature for bibliography on application of partial discharge diagnostics to cable evaluation.
FY 1996	Completed final version of digital recording instrument, and developed required analysis software.
FY 1997	Investigated the testing of cables to determine affect of PD detection techniques on cable lifetime. Curtailed research because NRC eliminated funding due to cost of proving safety of PD detection techniques, and systematic task shut down was begun.
FY 1998	Write final report to NRC on the application of PD detection on signal cable testing. Task completed.

2. Develop digital techniques for recording and analysis of partial discharges in insulation systems

FY 1993	Built prototype of digitizer and recording system for partial discharge measurement; Developed first generation of discharge data analysis software.
FY 1994	Applied digitizer to study partial-discharge-induced aging effects of cast epoxy resin similar to that used in gas insulated substations; Presented results in invited archival paper; Digitized design presented in conference paper.
FY 1995	Updated digitizer design for application to the measurement of partial discharges under direct as well as alternating voltage; Revised analysis software for easier use as a windows application; Applied digitizer to oil and alumina insulators.
FY 1996	Completed partial discharge measurements on alumina; Adapted recorder for acoustic detection of partial discharges.
FY 1997	Completed a new digitizer design and fabrication along with documentation, and delivered unit to sponsor.
FY 1998	Measured PD inception in SF_6/N_2 mixtures; Used the new digitizer system to study PD on epoxy surfaces.
FY 1999	Build and test co-axial discharge chamber for PD testing.
FY 2000	Evaluate dielectric properties of SF_6/N_2 mixtures, using the co-axial discharge chamber.

3. Investigate impact of SF_6 use on global warming

FY 1996	Reviewed potential impact of SF_6 on global warming, and reviewed current state of knowledge concerning use of SF_6/N_2 mixtures as a possible substitute.
FY 1997	Organized workshop and reviewed literature to determine modifications required for use of SF_6-substitute gases in power equipment, per the request of EPA; Provided EPA with report of conclusions.
FY 1998	Hosted Gaseous Dielectrics VIII symposium with a theme of using SF_6/N_2 mixtures as replacement gases in electrical equipment.
FY 1999	Investigate state-of-knowledge related to decomposition by-products in discharges in SF_6/N_2 mixtures.
FY 2000	Assess electron-interaction data for SF_6, and develop a standard reference data set for electron collision with SF_6.

Metrology for Electric Power Systems

Project Leader: Gerald J. FitzPatrick

Staff-Years: 7.0 Professionals, 1.0 Technicians

Funding Sources: STRS (33%), Other Government Agencies (38%), Other (29%)

Objective: Develop measurement technologies and provide electrical calibration services to support the operation of electrical power systems, including those used by industry, electric utilities, and related equipment manufacturers; interact with standards groups to provide a metrology base for electric power-related measurements.

Background: NIST has operated research programs in metrology areas related to the measurement of electric power for many decades. Over the years the programs have evolved to respond to the increased use of electric power in the United States, to new technical advances in the industry, and to the challenges of deregulation. Currently energy metering of the more than 215 billion dollars worth of electrical energy used in the United States annually is traceable to NIST calibration services. NIST supports additional power-related measurement capabilities, such as impulse voltage measurements, high voltage ac calibrations, and high current calibrations. Tasks have also been performed in areas of concern to the electric utilities and the public in general, such as power quality, bioeffects of electric and magnetic fields, and energy efficiency in electrical equipment. In response to the demands of deregulation, NIST supports areas of research related to improved reliability of electric power systems, including partial discharge diagnostic development, and high-reliability low-cost optical sensors.

Current tasks:

1. Calibration services in support of the electric power industry

FY 1993	Modernized power and energy calibration facility.
FY 1994	Performed impact analysis of power and energy calibration service on electric utilities.
FY 1995	Developed fast turn-around calibration service for selected watthour meter calibrations; Reinitiated offsite high voltage tests.
FY 1996	Initiated international power and energy intercomparison by organizing exchange of standards with Canada and Europe; Modernized high voltage facility.
FY 1997	Began design of new power and energy calibration system; Began detailed documentation of high-voltage calibration systems.
FY 1998	Built and tested active resistive voltage divider for power and energy calibration system; developed set of dissipation factor standards for calibration of commercial units.
FY 1999	Design new current transformer calibration system.
FY 2000	Fabricate and test new current transformer calibration system.

2. Investigate applications and calibration methods for optical sensors applied to electrical measurements

FY 1993	Built and documented portable Kerr Cell for optical voltage measurements.
FY 1994	Developed 0.1% calibration method for optical current transducers (OCTs) at power frequency in phase and ratio using digital techniques.
FY 1995	Initiated test of commercially produced OCTs.
FY 1996	Continued testing of commercially produced OCTs.
FY 1997	Began review of industrial OCT usage.
FY 1998	Began testing of new commercially produced OCT; Evaluated sensitivity of digital techniques to OCT calibrations.
FY 1999	Develop calibration techniques for OCTs; Initiate review of industrial optical voltage transducer (OVT) usage. (*1998 EEEL Strategic Plan*)
FY 2000	Initiate testing of commercial and prototype OVTs, and develop calibration techniques.

3. Fast-transient measurements

FY 1993	Participated in round-robin testing of reference impulse measurement systems using NIST4 divider.
FY 1994	Completed and incorporated into IEEE standard for high voltage testing the convolution technique for impulse qualification used to achieve <0.5% uncertainties.
FY 1995	Documented comparative high voltage impulse measurement techniques.
FY 1996	Investigated and documented influence of heating effects on reference divider performance.
FY 1997	Documented the rebuilt and tested NIST4 impulse reference divider.
FY 1998	Began investigation of new deconvolution technique for impulse measurement error correction.
FY 1999	Develop integrated measurement system and conduct measurements for international comparison of high voltage impulse systems; report results to pilot laboratory.
FY 2000	Automate high voltage impulse measurement data acquisition and analysis.

4. Develop test procedures for energy efficient motors and transformers

FY 1993	Investigated industrial procedures for measuring efficiencies of electric motors (> 1 horsepower).
FY 1994	Investigated industrial procedures for measuring efficiencies of electric transformers.
FY 1995	Wrote test procedure for electric transformers for U.S. Department of Energy.
FY 1996	Wrote test procedures for electric motors for U.S. Department of Energy.
FY 1997	Published test procedures for energy efficient motors and transformers in the Federal Register, and documented statistical analysis of testing procedures.
FY 1998	Submitted draft Standard P114 on efficiency testing of single-phase induction motors to IEEE for review.
FY 1999	Prepare test procedures for DOE Notice of Proposed Rulemaking (NOPR) for transformers. (*1999 Budget Narrative; 1998 EEEL Strategic Plan*)
FY 2000	Develop energy efficiency performance standards for transformers; revise IEEE standard 114 for single-phase induction motors.

5. Metrology support for electric and magnetic field measurements

FY 1993	Published primer on conducting in-vitro bioeffect studies with extremely low frequency magnetic and electric fields.
FY 1994	Determined worse-case measurement errors using 3-axis magnetic fields probe to measure dipole magnetic fields, from electrical appliances.
FY 1995	Issued two industrial voluntary standards, IEEE Standards 644-94 and 1308-94, written at NIST in collaboration with industry; Published error distribution for 3-axis magnetic field probe used to measure magnetic fields.
FY 1996	Completed primer on magnetic and electric field measurements; Revised primer into draft standard; Developed for adoption internationally, and nationally.
FY 1997	Prepared "Committee Draft for Voting" in collaboration with International Electrotechnical Commission (IEC) working group for proposed international standard.
FY 1998	Prepared Final Draft International Standard on measuring electric and magnetic fields; Approved by National Committees to IEC and issued as Standard by IEC.
FY 1999	Participate in evaluation of need for IEC standard on fields from domestic appliances.

6. Applying metrology to power quality issues

FY 1993	Wrote three technical Bulletins on power quality issues.
FY 1994	Performed measurements and published two papers on surge propagation and mitigation in the Power Electronics Application Center (PEAC) Upside-Down House.
FY 1995	Completed three fundamental international standards documents on installation and mitigation for electromagnetic compatibility; Enlisted direct support from two electric utilities.
FY 1996	Documented need to characterize surge currents rather than surge voltages as a measure of power quality.
FY 1997	Wrote report on electromagnetic immunity of Personal Protection Devices for electric vehicles, and drafted technical bulletin on surge protection requested by a major insurance company.
FY 1998	Completed documentation of PEAC Upside-Down House facility and experimental results.
FY 1999	Catalyze cooperation among electric utilities, electrical equipment manufacturers, end-users, and standard writing bodies to resolve issues on equipment malfunctions erroneously attributed to poor power quality.
FY 2000	Complete major revision of three IEEE documents on surge environment (C62.41.1); Recommended Practices on Standard Waveforms (C62.41.2), and Recommended Practices on Surge Testing (C62.45).

NATIONAL ELECTRICAL STANDARDS

Ohm and Farad Realization and Dissemination

Project Leader: Randolph E. Elmquist

Staff-Years: 7.0 Professionals, 2.6 Technicians, 2.0 Guest Scientists

Funding Sources: NIST (90%), Other Government Agencies (10%)

Objective: Maintain the U.S. legal ohm and farad; support the Division's resistance and capacitance calibration services; provide industry, academia, and government with calibration services unequaled in scope and accuracy; develop new resistance and capacitance standards and improved measurement techniques; and participate in international comparisons of the ohm and farad and supporting experiments to realize the international definitions of the ohm and farad.

Background: The research work being done on this project is the key to tying the U.S. legal system of electrical units to the international system (SI) of units. Strong support in this research area allows NIST to provide the nation with the world's best basis for electrical measurements and to conduct measurements of the SI ohm and farad that have smaller uncertainties than those of any other nation. NIST's maintenance of the ohm by the quantum Hall effect -- a resistance standard dependent only on the values of fundamental constants of nature -- and the farad by the calculable capacitor -- a standard dependent only upon an SI length measurement -- provide a needed basis for measurement quality in U.S. industry. The activities of this project underlie the future development of not only the electrical measurement services provided to industry by NIST, but also the development of commercial high-precision instrumentation needed by industry to support advances in electronics. Methods developed by NIST for scaling of impedance measurements at the highest levels of accuracy will provide needed capabilities for extending the measurement range, voltage, and frequency for industry and other government laboratories.

U. S. industry requires accurate resistance and capacitance measurements for both quality and process control purposes. Not only are resistors and capacitors the most commonly used electronic components, they are important control parameters in the manufacture of semiconductor electronics and common tools for the measurement of temperature, pressure, force, light intensity, and other quantities via transducers. NIST's most visible link to these applied measurements is through the instrumentation industry. Accurate, traceable impedance measurements are vital to the development, testing, manufacturing, and maintenance of instrumentation. This is reflected in the volume of calibration work which accounts for about 50% of the Electricity Division's and over 11% of all of NIST's calibration income. The most challenging present needs are for new standards that are environmentally insensitive for supporting *in situ* maintenance of precision meters, ac resistance calibrations to support temperature measurements and calibration of impedance meters, and research to support commercialization of the cryogenic current comparator and quantum Hall effect systems for improved scaling in bench instrumentation.

NIST is uniquely qualified to interact with other national laboratories in the comparison of resistance and capacitance standards and the verification of scaling from the basic standards in support of the worldwide electronic instrumentation industry. Such comparisons ease impediments to international trade.
For description of single-electron tunneling work, see Task 3 of Quantum Voltage and Current project.

Current Tasks:

Resistance:

1. Determine the SI ohm

FY 1997	Reported improved SI-unit values of the von Klitzing constant and the fine structure constant; Initiated construction of bridges for the determination of the SI ohm over an expanded frequency range.
FY 1998	Designed alternating current (ac) four-terminal-pair bridge for use at multiple frequencies and built reference resistors at 6.45 kΩ, 12.9 kΩ, and 129.06 kΩ.
FY 1999	Evaluate standard resistors and extended frequency bridge at two or more frequencies.
FY 2000	Compare the ac quantum Hall effect (QHE) to well-characterized resistance standards at one or more frequencies using the extended frequency bridge.
FY 2001	Determine the SI ohm using a frequency other than the metrologically selected 1592 Hz.

2. Establish and maintain the national standards of resistance

FY 1996	Built and characterized 10 MΩ and 1 GΩ resistance transfer standards and initiated high resistance international comparison commissioned by the Consultative Committee on Electricity and Magnetism (CCEM).
FY 1997	Developed a new automated 4.2 K cryogenic current comparator (CCC) system for scaling measurements from 1 Ω to 10 kΩ designed to reduce scaling uncertainty to less than 0.01 parts-per-million.
FY 1998	Completed third leg of international comparison of high resistance and completed two measurements of the quantum Hall resistance (QHR).
FY 1999	Compare QHR representation and scaling with the International Bureau of Weights and Measures (BIPM) using traveling QHR system and resistance standards.
FY 2000	Complete CCEM high resistance comparison; Prepare and disseminate results. (*1998 MSL Strategic Plan*)

3. Provide resistance measurement services for our customers

FY 1996	Calibrated 327 standards at a cost to industry of $329,000; Automated 10 kΩ measurement system installed for customer calibrations.
FY 1997	Calibrated 303 standards for division income of $311,000; Automated calibration service for resistors below 1 Ω; Initiated development of an ac resistance bridge.

FY 1998	Designed calculable ac/dc resistance standards at 100 Ω, 1 kΩ, 129.06 Ω, and 1.2906 kΩ; Completed dc characterization of new calculable 1 kΩ ac/dc/resistor.
FY 1999	Complete ac characterization of 1 kΩ ac/dc resistor; Develop special ac resistance calibration service for 100 Ω and 1 kΩ resistors.
FY 2000	Provide calibration service for ac resistance; Provide calibrations to support Division's digital impedance bridge calibration of standard inductors.

4. Develop an automated system for the measurement of high resistance standards

FY 1996	Completed development of high resistance active-arm bridge system and began comparisons with existing systems.
FY 1997	Evaluated performance of the automated active-arm bridge system; Began construction of new Hamon devices to reduce scaling uncertainty.
FY 1998	Initiate active-arm bridge calibration service and extend resistance calibration range to 100 TΩ; Complete comparison with Sandia Labs at 1 TΩ and 10 TΩ. (*1998 MSL Strategic Plan*)

5. Develop an advanced quantized Hall resistance research and measurement capability

FY 1996	Acquired and installed a new QHE cryogenic system for increased magnetic field, variable temperature, and efficient sample exchange capabilities.
FY 1997	Designed and built new dc insert probe with high leakage resistance.
FY 1998	Refurbished automatic dc potentiometric QHR measurements, compatible with SI ohm measurement systems; Construct new automated digital voltmeter (DVM)-based QHR system.
FY 1999	Design and build probe insert for ac QHR measurements, compatible with SI ohm measurement systems; Construct new automated DVM-based QHR system.
FY 2000	Compare the resistance value of a single QHR device at both dc and ac.

6. Improve the quality and performance of quantized Hall devices

FY 1996	Determined the equivalent circuit of a quantized Hall device and calculated the intrinsic inductance and capacitance for resistance studies using ac.
FY 1997	Published a summary of QHE device preparation and characterization techniques.
FY 1998	Published study of current dependence of QHR contact resistance; Evaluated equivalent circuits of QHR devices.
FY 1999	Prepare quantum Hall devices suitable for both dc and ac measurements.
FY 2000	Determine appropriate characterization process for ac QHR devices.

7. Investigate resistance scaling techniques using cryogenic current comparators (CCC)

FY 1996	Constructed a prototype high-temperature superconductor (HTS) CCC working at 77 K, using thick-film thallium-based shields and a YBCO SQUID detector.
FY 1997-1998	Completed evaluation of HTS CCC bridge system and presented results and design criteria to metrology community; Applied for a patent on HTS CCC design.

FY 1999-2000	Develop improved HTS CCC using HTS SQUID with integrated flux transformer.

Capacitance:

1. Realize the SI farad

FY 1996	Reported a new value for the calculable capacitor determination of the SI farad.
FY 1997	Designed and constructed calculable capacitor bridge for use with an extended frequency range.
FY 1998	Conducted tests on improved blocking electrode geometry to reduce the effect of geometrical imperfections in calculable capacitor.
FY 1999	Evaluate calculable capacitor system and determine the SI farad at alternate frequencies.
FY 2002	Design and construct new adjustable mount for upper blocking electrode.

2. Provide the national unit of capacitance

FY 1996	Initiated an international comparison of capacitance for the CCEM.
FY 1997	Determined the effect of the mounting method of the capacitance elements on the temperature dependence of the reference capacitors.
FY 1998	Completed the international comparison of capacitance. (*1998 MSL Strategic Plan*)
FY 1999	Provide the unit of capacitance at 1000 Hz.
FY 2000	Provide the unit of capacitance at 100 Hz and 400 Hz.

Quantum Voltage and Current

Project Leader: Richard L. Steiner

Staff-Years: 5.0 Professionals, 1.0 Guest Scientist

Funding Sources: NIST (96%), Other Government Agencies (4%)

Objective: Maintain the U.S. legal volt; support the Division's voltage calibration services; and develop new voltage and scaling standards, measurement techniques, and means of disseminating the volt. Measure the U.S. unit of current as established from national resistance and voltage standards in terms of the internationally defined ampere; monitor the kilogram in terms of electrical units via the watt experiment; and determine the gyromagnetic ratio of the proton in terms of the U.S. electrical units. Apply the physics of these measurements and other new phenomena, such as single electron tunneling, to the development of improved measurements and standards, especially for current standards.

Background: The services provided by this project generate the basis for accuracy and compatibility for all voltage and current measurements throughout U.S. industry, technology, and science. The standards being produced by this project tie the U.S. legal system of electrical units to the international system (SI) of units permitting competitive products by U.S. industry in world markets. The research being done is the source of superior drift-free, high precision national standards for the volt and the ampere (and assists in the ohm and farad). The work also involves evaluating new measurement techniques and standards for automated and highly accurate dissemination of these units. Another very significant effect of this research focuses on the creation of an electronic replacement for the kilogram, the last remaining SI artifact standard, and exploring the application of the new single electron tunneling phenomena to the determination of the electronic charge or the fine structure constant or for application as a capacitance standard.

Current Tasks:

Voltage:

1. Provide the national unit of voltage

FY 1996	Replaced the computers that operate the Josephson 1-volt system and developed improved software for the operations and data analysis.
FY 1997	Participated in NCSL round robin of 15 U.S., Canadian, and Mexican Josephson array 10-V systems, with an uncertainty of 3×10^{-8} V/V.
FY 1998	Compared accuracy and uncertainty of NISTVolt® software against new and existing array system software.
FY 1999	Develop methods to decrease the uncertainty of 10-V Zener reference transfers to 5×10^{-8} V/V.

FY 2000	Develop capabilities to provide direct array-to-array comparisons of the U.S. national voltage standard system to calibration laboratories within NORAMET.
FY 2001	Implement 10 V Measurement Assurance Program (MAP) for calibration laboratories within NORAMET.

2. Improve the reliability of the voltage calibration systems

FY 1997	Satisfied increased demand over last year for customers' voltage calibration.
FY 1998	Ordered new Zeners and began regular monitoring to prepare for maintaining a lab standard bank of Zeners at the 10-V level.
FY 1999	Design plan to integrate Josephson array system into daily calibration of working standards at 10-V level.
FY 2000	Improve 10-V calibration service to the 0.05 ppm level with Zener volt bank.

Current:

1. Determine the value of the NIST watt

FY 1995	Redesigned the process for the alignment of the magnetic field, the coil motion, and the earth's gravitational force for reduced uncertainties.
FY 1996	Decreased the short term uncertainty to $1x10^{-7}$ W/W; Installed the new refractometer for the determination of the index of refraction and the new gravimeter for a more precise determination of the gravitational constant.
FY 1997	Achieved long term uncertainty of $1x10^{-7}$ W/W; Evaluated all systematic uncertainties (about 35 variables) in the NIST Watt determination; Improved automated operation to about 95% reliability.
FY 1998	Achieved long term uncertainty goal of 0.1 parts per million; Evaluated systematic uncertainties (about 35 variables) in the NIST Watt determination; Reported new value for Plank's constant with uncertainty of 0.087 ppm; Began conversion to improved system for monitoring the kilogram. Task completed. (*1998 EEEL Strategic Plan*)

2. Initiate redesign of the NIST watt experiment for the next generation of improvements for monitoring the kilogram

FY 1995	Initiated the redesign of the NIST watt experiment with the objective of monitoring the kilogram, including a vacuum or gas environment.
FY 1997	Initiated construction of the vacuum enclosure for the watt balance and reconstruction of the watt balance room.
FY 1998	Completed construction modifications to the nonmag building; Installed vacuum/gas enclosure.
FY 1999	Rebuild system into vacuum chamber; Redesign optics and electronics for vacuum and RFI shield feedthrough; Integrate programmable Josephson-array system into data acquisition network. (*1999 Budget Narrative; 1998 MSL Strategic Plan*)
FY 2000	Begin system test runs to recover 0.1 parts per million level capabilities; Design and build new pickup coils, balance pivot, vibration control system.
FY 2001	Achieve long term uncertainty of 0.01 parts per million in monitoring kilogram standard.

3. Demonstrate a single electron tunneling electrometer

FY 1993	Initiated studies for the application of single electron tunneling devices to metrological experiments such as capacitance calibrations.
FY 1995	Demonstrated the application of a single electron tunneling electrometer as the detector in a cryogenic capacitance bridge to determine a capacitance ratio to a few parts per million.
FY 1997	Determined location and characterization of charge noise in two devices; Commissioned new SET dilution refrigerator and laboratory.
FY 1998	Combined the NIST Boulder electron pump and the capacitance bridge and cryogenic capacitors to explore a capacitance calibration using single electron tunneling technology; Continued charge noise and initiated charge offset studies with Boulder. (*1998 MSL Strategic Plan*)
FY 1999	Investigate operations of SET devices at higher operating temperatures; Continue charge noise studies; Design cryogenic capacitor at 1.0000 pF.
FY 2000	Attempt a capacitor calibration via SET pump experiment for direct comparison to the NIST calculable capacitor; Validate new commercial standard at 0.1 ppm uncertainty level.
FY 2001	Improve electrometer and system to achieve 0.01 ppm uncertainty; Apply results to fine-structure constant determination. (*1998 EEEL Strategic Plan*)

ELECTROMAGNETIC COMPATIBILITY

Standard EM Fields and Transfer Probe Standards

Project Leader: Galen Koepke

Staff-Years: 5.5 Professionals, 0.5 Technician

Funding Sources: NIST (73%), Other Government Agencies (22%), Other (5%)

Objective: Develop methods and techniques for establishing continuous wave and pulsed electromagnetic (EM) reference fields to 100 GHz; develop and improve NIST's electromagnetic compatibility (EMC) and electromagnetic interference (EMI) calibration services; perform research and development on probes to measure EM fields and power densities; work in cooperation with responsible organizations for world-wide acceptance of U.S. products and practices with respect to specifications relating to EMC.

Background: Well-defined EM reference fields are necessary for antenna calibrations, antenna research and development, evaluation of EM field probes, and EM interference measurements. Commercial antennas and probes are generally unsuitable for metrology purposes, necessitating the development by NIST of probes which can serve as transfer standards necessary for traceability. This program area was ranked among the top priority items by the participants of the EMI/EMC Metrology Challenges for Industry Workshop. Specifically, industry clearly identified a need for NIST-traceable EM field measurements which reduce barriers to world-wide acceptance of U.S. products and practices, based on the principles of "one product, one technically valid international standard, one conformity assessment" (*1998 MSL Strategic Plan*).

Current Tasks:

1. Develop methods for establishing standard EM fields

FY 1995	Performed a time-domain evaluation of the NIST anechoic chamber which revealed absorber and cavity characteristics.
FY 1996	Analyzed rectangular open-ended waveguides for improved standard field generation in the frequency range between 200 to 500 MHz.
FY 1997	Extended NIST's standard field generation capability into the frequency range between 40 to 50 GHz; Developed precision sensor calibrations methodologies on cone/ground plane system.
FY 1998	Developed 1m scale model of co-conical field generation system for probe calibrations from 10 MHz to 40 GHz; Fabricated and evaluated 2.4m x 2.4m cone/ground plane system and designed 7.2m x 7.2m system; Completed uncertainty analysis for sensor calibration techniques.
FY 1999	Develop finite-difference time-domain (FDTD) models to simulate 3m co-conical system; Design termination for system and begin mechanical design;

	Fabricate and evaluate 7.2m x 7.2m cone/ground plane system; Extend sensor and antenna calibration capabilities to frequencies above 50 GHz.
FY 2000	Fabricate prototype 3m co-conical system and perform precision field mapping; Develop next-generation open-area test site (OATS) measurements using scale model experiments on 7.2m x 7.2m cone ground plane system.
FY 2001	Fabricate final 3m co-conical system and conduct probe calibrations for USAF; Conduct RF absorber and RC standards measurements on 7.2m x 7.2m cone/ground plane time-domain system.

2. Develop methods for facility characterization, proved laboratory instrumentation and procedures to reduce measurement uncertainties in calibrations

FY 1995	Extended the vertical monopole calibration service to frequencies up to 300 MHz.
FY 1996	Prepared documentation for loop antenna calibration service; developed a calibration service for radiated fields of standard source such as the NIST-designed spherical dipole radiator which is now a commercial product.
FY 1997	Extended monopole antenna calibration service from the current upper frequency limit of 300 MHz to 3 GHz (i.e., 3000 MHz); Developed a non-destructive materials measurement using NIST-developed free-space reflectivity measurement system; Developed edge-effect reduction procedure for more accurate material property estimates in dielectric panel measurements; Developed FDTD codes to simulate measurement processes; Conducted absorber evaluation for industry.
FY 1998	Developed methodology and FDTD codes to extracting material properties from highly dispersive carbon doped urethanes; Developed test techniques for RF absorber-lined evaluation.
FY 1999	Complete near-zone gain documentation for pyramidal horns from 500 MHz to 2600 MHz; Automate new precision positioner in anechoic chamber and measurements on refurbished OATS and TEM cells; Characterize anechoic chambers and establish uncertainty bounds for standard fields; Complete characterization of rf dipole and map field uniformity on the OATS; Resolve discrepancies between standard site method and standard antenna method for determining antenna factors; Provide measurement services for monopole antennas, antenna patterns from 30 to 1000 MHz, and reference rf emitters; Develop FDTD codes for measurement on ferrite tiles; Perform measurements on rf absorber and on selected RCS artifacts to provide NIST traceability. (*1998 MSL Strategic Plan*)
FY 2000	Develop more robust methods for OATS calibrations in high ambient field environments; Investigate reverberation chamber techniques for simultaneous calibration of multiple isotropic probes; Perform thorough uncertainty analysis for NIST free-space scattering systems; Develop advanced RF absorber-lined chamber test methods. (*1998 MSL Strategic Plan; 1998 EEEL Strategic Plan*)

3. Develop EM field probes for transfer standards

FY 1994	Performed theoretical and experimental evaluation of dipole electric field probe (dipole size: 2 cm).
FY 1995	Evaluated optically pumped, vertical-cavity, surface-emitting lasers for field probe applications.

FY 1996	Disseminated NIST-developed probe calibration techniques and uncertainty methodologies to standards committees.
FY 1997	Developed probes which will provide spectral information that can be used to discriminate against electromagnetic interference.
FY 1998	Improved concentric loop antenna system for electric and magnetic field measurements; Performed testing and characterization of field probe which provided spectral information.
FY 1999	Develop improved broadband linear antennas for OATS evaluation and calibrations; Develop new near-field standard probe to simultaneously measure both electric and magnetic fields up to 100 MHz.
FY 2000	Evaluate probes for EM field measurements for frequencies between 40 GHz and 100 GHz.

Emission and Immunity Metrology

Project Leader: David Hill

Staff-Years: 5.5 Professionals, 0.5 Technician

Funding Sources: NIST (71%), Other Government Agencies (21%), Other (8%)

Objective: Develop and evaluate reliable standards, test methods, and services related to electromagnetic emission and immunity of electronic devices, components and systems; emphasize immunity, as called for in the NIST Electromagnetic Immunity Workshop, needed by U.S. industry to participate fully in European markets for electronic instrumentation and goods.

Background: U.S. industry needs to evaluate and control electromagnetic interference (EMI) that can impact economics and competitiveness, national security, health, and safety. The uncertainties of electromagnetic emissions and immunity measurements need to be rigorously quantified and, in some cases, reduced to make EMI measurement results reliable and useful. Major challenges are to provide reliable and cost effective test methods for a large frequency range (10 kHz to 40 GHz and, eventually, higher) and for large test volumes. Industrial clients are both manufacturers of electronic equipment, and electromagnetic compatibility and interference (EMC/EMI) test laboratories. NIST research, development, and measurement procedures provide guidelines and support for the entire U.S. EMC/EMI community.

Current Tasks:

1. Develop radiated immunity metrology

FY 1994	Analyzed and measured the crosstalk between transmission lines on printed circuit boards; Developed the time-domain method for measuring the shielding effectiveness of aircraft cavities; Evaluated frequency stirring for reverberation chamber measurements of radiated immunity.
FY 1995	Analyzed and improved the reverberation chamber method for measuring the radiated immunity of printed circuit boards; Surveyed and analyzed measurement techniques for the shielding effectiveness of gaskets; Developed a nested reverberation chamber measurement method for shielding effectiveness of optical fiber bulkhead connector systems.
FY 1996	Developed and evaluated alternative methods (time-domain and stepped frequency domain) for immunity measurements in reverberation chambers; Analyzed a circular aperture for use as a standard in shielding effectiveness measurements.
FY 1997	Developed and evaluated a broadband method for measuring shielding effectiveness of gaskets.
FY 1998	Evaluated effectiveness of reverberation chambers for vehicle EMC testing with American Automobile Manufacturers Association.

FY 1999	Document NIST improvements in reverberation chamber metrology; Retest shielding effectiveness of optical fiber feedthroughs with improved measurement techniques; Obtain further industry support for testing.
FY 2000	Evaluate tradeoffs for mechanical and frequency stirring in immunity testing; Extend radiated immunity measurements to higher frequencies (above 40 GHz).

2. Develop radiated emissions metrology

FY 1995	Conducted a successful workshop on EMI/EMC measurement needs for industry; Analyzed and measured printed circuit board radiated emissions in the NIST reverberation chamber.
FY 1996	Correlated reverberation chamber radiated emissions measurements to other facilities.
FY 1997	Developed a spherical scanning theory for characterizing weak sources in the presence of noise.
FY 1998	Determined how to combine radiated emissions from components to estimate total system radiation; Developed a new transverse electromagnetic (TEM)-cell method for measuring weak electric-dipole and magnetic-dipole radiations.
FY 1999	Develop a near-field dipole array for measuring weak electric-dipole radiation; Develop reverberation chamber methods for measuring emissions from complex devices.
FY 2000	Develop broadband methods for radiated emissions; Extend radiated emissions measurements to higher frequencies (above 40 GHz).

3. Develop methods for facility characterization, improved laboratory instrumentation and procedures to reduce measurement uncertainties in calibrations.

FY 1996	Developed a general framework for evaluating the uncertainties in radiated emissions measurements; Evaluated the uncertainty in field strength and uniformity for alternative mode-stirring methods in reverberation chambers.
FY 1997	Evaluated the uncertainties in field measurements made in anechoic chambers, transverse electromagnetic (TEM) cells, and hybrid TEM-reverberation chambers.
FY 1998	Reduced measurement uncertainty for reverberation chamber from several dB to 1 dB; Developed a reciprocity theory to relate measurement uncertainty for emissions and immunity measurements.
FY 1999	Extend uncertainty methodologies to the issue of repeatability from site to site and from facility to facility.
FY 2000	Evaluate effects of equipment under test on emissions and immunity uncertainty; Reduce measurement uncertainties in immunity and shielding effectiveness by improving calculations of aperture in conducting sheet for isotropic radiation; Evaluate the uncertainties of new facilities and methods of emissions and immunity measurements; Extend uncertainty evaluations to higher frequencies (above 40 GHz).

ELECTRONIC DATA EXCHANGE

Infrastructure for Integrated Electronics Design

Project Leader: James A. St. Pierre

Staff-Years: 4.0 Professionals

Funding Sources: NIST (100%)

Objective: Develop tools and infrastructure for the electronics industry to facilitate the exchange of product data with a focus on the design phase and the interface to manufacturing. This includes supporting the development of harmonized standards to enable accurate translation of electronic part and product data between standards, developing technology to permit data exchange of electronic component information, and developing certification and conformance testing methods for object oriented software for the electronics industry.

Background: To implement new management strategies such as total-quality-management, flexible manufacturing, cooperative development, and concurrent engineering, manufacturers need several types of data in computer-accessible digital formats that can be shared among them, and between them and their suppliers. These product standards and specifications are integral to the electronics industry to enable the design, manufacture, documentation, procurement, and support of modern electronics.

The traditional forums for capturing designs and manufacturing information (engineering drawings and paper specifications) are being replaced by digital formats. This information must be correct, complete, unambiguous, and efficient. According to the Institute for Interconnecting and Packaging Electronic Circuits (IPC), National Technology Roadmap for Electronic Interconnections, "The transfer from design to manufacturing is done by a machine language that was never intended to convey design information." This summarizes a large problem facing the electronics industry today, in that a large amount of time is wasted as manufacturers wrestle with ambiguities in design files. Also according to the roadmap, "Most jobs (upwards of 70%) coming into a printed wiring board fabricator or assembler lack complete information." Among the technical challenges is the development of adequate information models and standards that describe the essential characteristics of electrical and electronic products. In addition, there is a current trend towards the use of virtual components. In order to easily exchange and incorporate these virtual components into commercial products, standards, infrastructure and methodologies are required to support this new paradigm.

As a neutral third party, NIST is uniquely positioned to develop, demonstrate, and test non-proprietary solutions, information models, and emerging standards. Also, NIST's long involvement with voluntary standards organizations permits us to contribute effectively to the development of compatible standards. *See also companion project, Infrastructure for Integrated Electronics Manufacturing.*

Current Tasks:

1. Provide support for International Design Automation Standards to create a consistent method for representation of electronic part/product data

FY 1991	Completed determination of data requirements necessary to manufacture, test, and ship Hybrid Microelectronic Assemblies; Shifted the focus of the activity to developing an Initial Graphics Exchange application protocol as the deliverable.
FY 1994	Developed software to exercise the robustness of emerging Application Protocol (AP) 210, “Printed Circuit Assemblies;” Chaired Working Group 5, Test, Validation, Conformance and Qualification Support of Technical Committee 93 of the International Electrotechnical Commission; Completed and delivered draft of “Layered Electrical Products” application protocols to a committee developing the Initial Graphics Exchange specifications.
FY 1995	Contributed to the Electrical/Electronic design team effort of PDES, Inc., to complete Committee Draft version of Application Protocol 210, and submitred it for approval as an ANSI standard; Developed automated electronic change control procedure for the components of the Initial Graphics Exchange Specifications and documented procedures in a NIST report.
FY 1996	Convened meetings of International Electrotechnical Commission working group to review existing standards for certification and conformance methodologies and define methodology requirements for all new standards submitted; Developed prototype library of layered electrical product object definitions and relationships; Reviewed compatibility of application protocols in the standard for the Exchange of Product Model Data with other electronic design standards and suggested modifications to resolve interoperability concerns.
FY 1997	Concluded development of the Geometric Dimensioning and Tolerance (GD&T) portion of the application protocol for printed circuit assemblies as it becomes an International Standard (ISO 1303 AP 210); Made significant contributions to the IGES standard for layered electrical products which achieved ANSI standard status; (ANSI US PRO/IPO-111-1996); Led the development of a proposal to establish a new working group on libraries of reusable electrotechnical products for the International Electrotechnical Commission (IEC); Established an IEEE study group on Electronic Commerce of Component Information (ECCI); Convened meetings of the IEC working group on test, validation, conformance and certification of standards related to electronics industry.
FY 1998	Organized and hosted an international Electronic Commerce of Component Information (ECCI) workshop at NIST, July 1998; Chaired the IEC working group on test, validation and conformance testing of standards; Led the development of guidelines for conformance testing; Convened meetings of the IEEE study group on Electronic Commerce of Component Information (ECCI).
FY 1999	Work to have guidelines for conformance testing officially adopted by IEC TC93; Review and comment on the IEC/TC93/WG1 Core Model for the Electronics Domain (CMED) to support international standards interoperability efforts.
FY 2000	Support TC93 efforts to implement conformance and certification guidelines for new standards.

2. Develop tools to facilitate Electronic Commerce of Component Information and tools for conformance testing.

FY 1993	Led demonstration project team for the National Initiative for Product Data Exchange to produce proof-of-concept demonstrations showing how the National Information Infrastructure can be used to automate the brokering of electronic component information.
FY 1996	Completed prototype electronic component dictionary browser and search engine for on-line parts dictionaries; Developed an advanced object oriented dictionary prototype.
FY 1997	Developed an object oriented dictionary browser tool to support ECCI, in collaboration with Silicon Integration Initiative; Developed a specification for a Product Information Viewer and its interface to the World Wide Web, and a phase-one implementation; Co-sponsored a workshop on Design Reuse and Intellectual Property Cores (Virtual Components) with DARPA and the EDA Industry Council.
FY 1998	Developed a dictionary translator, at the request of industry, which can convert the IEC electronic component dictionary (or generic company dictionaries) into the Component Information Dictionary Standard (CIDS) format; Demonstrated a standards based prototype of an Electronic Commerce of Component Information (ECCI) methodology in conjunction with the IIEM/ICM project; Developed a Java-based software utility to assist virtual component developers, which generated industry interest in commercialization of a portion of the software. (*1998 MSL Strategic Plan*)
FY 1999	Extend the current dictionary translator to accept the JEDEC dictionary; Work with Silicon Integration Initiatives to begin development of conformance test tools for the Electronic Component Information Exchange Standard; Support international efforts to test interoperability between European (IREP), Asian (ECALS), and U.S. (ECIX) electronic component information exchange standards. (*1999 Budget Narrative*)
FY 2000	Deploy conformance test tools, for the ECIX standard, to industry including documentation and on-line access to the tools; Expand efforts to test international interoperability of electronic component information exchange standards.

3. Provide support for the SEMATECH Computer Integrated Manufacturing Framework

FY 1994	Completed first year report to SEMATECH analyzing and documenting cost of certification and conformance testing for computer integrated manufacturing framework to be 27 to 30 work-years.
FY 1995	Developed and documented technical and business model definitions for certification and conformance testing (these models included, for example, plans for how the test suite would be generated, distributed, and executed, and who would pay for certification, maintenance, and dispute resolution).
FY 1996	Developed prototype semi-automated test generator approach; Refined technical and business model definitions; Concluded phase I of task with report to SEMATECH.
FY 1997	Completed extensions to the Java/Common Object Request Broker Architecture (CORBA)-based test environment for the SEMATECH CIM Framework, that will allow using this environment for other applications, such

	as printed wiring board Standard Recipe File Format of the Surface Mount Equipment Manufacturers Association.
FY 1998	Designed a new architecture for the Java/CORBA based test environment, which employs two Object Request Brokers (ORBs) communicating via the Internet Inter-ORB Protocol (IIOP); Developed plans, with a commercial company, to collaborate on development of a commercial version of the test environment.
FY 1999-2000	Develop a prototype of the two ORB test environment in collaboration with industry; Support the semiconductor industry's use of the NIST testing environment, including any commercial implementations based on the NIST testing environment; Extend the testing environment to support other relevant industries, such as the electronics manufacturing services industry.

Infrastructure for Integrated Electronics Manufacturing

Project Leader: Barbara L. M. Goldstein

Staff-Years: 3.0 Professionals

Funding Sources: NIST (100%)

Objective: Work with industry to develop tools and standards to enable a "plug and play" manufacturing software environment for the electronics industry. This includes methodologies and standards for linking Manufacturing Execution Systems (MES) to Enterprise Resource Planning (ERP) applications, across to design, down to equipment control, and across to suppliers and dispersed sites. This project will also help the industry adapt to an electronic commerce business paradigm.

Background: As outlined in the 1996 National Electronics Manufacturing Initiative Roadmap, electronics manufacturers face tremendous pressures in today's global manufacturing environment, where being first to market is often the chief determinant of market share. Customers expect to pay increasingly lower prices for increasingly more sophisticated products; i.e., custom products at mass-volume prices. Business competition pressures manufacturers to cut costs throughout the manufacturing process, instead of raising end-unit prices. Increasing product complexity forces manufacturers to maintain flexible factories of high-capital equipment and best-of-breed software applications. Globalization of the customer base is driving the need for globally distributed manufacturing facilities and suppliers, and international manufacturing partnerships. The complexity of and speed with which information must cross corporate barriers makes it virtually impossible for prime subcontractors to impose their software choices on their subcontractors, much less on an equal partner in a joint undertaking.

Meeting these challenges requires not only the available of manufacturing automation software, but the ability to rapidly integrate and customize those tools within a facility, and among key partners and suppliers. Such ease of integration will only be possible through the development of industry standards and enabling technologies. NIST has the opportunity to assist the electronics industry to reach consensus on common information exchange practices and standards, and to encourage collaborative research on integration technologies. *See also companion project, Infrastructure for Integrated Electronics Design.*

Current Tasks:

1. Support industry roadmapping and needs analysis efforts

FY 1997 Co-chaired National Electronics Manufacturing Initiative (NEMI) Factory Information Systems (FIS) Technical Working Group (TWG), which published a roadmap in the 1996 National Electronics Manufacturing Technology Roadmaps; Co-chaired NEMI FIS Technical Implementation Group (TIG), which created a technology gap analysis, five-year plan, and initial project portfolio, Chaired manufacturing integration strategy session with key industry participants; Chaired SPIE Conference on "Plug and Play Software for Agile Manufacturing" and published proceedings.

FY 1998 Co-chaired NEMI FIS TWG which developed a 1998 FIS Roadmap, and participated in developing a NEMI Supply Chain roadmap; Held several site visits and sponsored two industry workshops to assess needs of the Electronic Manufacturing Services (EMS; aka: Contract Manufacturing) community.

FY 1999 Publish NEMI FIS and Supply Chain roadmaps (December 1998); Present results in public forums.

FY 2000 Work with industry through NEMI to publish 2000 FIS Roadmap.

2. Encourage and perform collaborative research with industry and academia in manufacturing software integration, electronic commerce and Internet-based manufacturing

FY 1997 Worked with industry to develop plan for NEMI "Plug & Play Factory" project and obtained NEMI executive council support; Developed plan for multi-lab "Internet Commerce for Manufacturing (ICM) project"; Planned the development of an Object Oriented Printed Circuit Repository specification (this would allow the transfer and querying of intelligent object-oriented electronic product descriptions).

FY 1998 Initiated NEMI FIS Plug & Play Factory project which established interoperability testbed at Georgia Institute of Technology to research state-of-the-art integration approaches; Demonstrated early results of Plug and Play Factory project for NEMI Council and at industry workshops; Gained approval of ICM project within the NIST National Advanced Manufacturing Testbed (NAMT) and held architecture and industry requirements workshops and peer reviews.

FY 1999 Demonstrate use of open standards to contract electronics design and analysis services, and prove feasibility of contracting assembly services, with a NIST-designed printed wiring board, in Internet Commerce for Manufacturing project; Conclude NEMI FIS Plug & Play Factory project and transition the resulting specification to a standards organization for standardization; Participate in the Plug & Play Factory project through technology development and industry demonstrations; Develop a process model to allow electronic commerce to be incorporated into an electronic product life-cycle development process; Establish NEMI tasks and projects which are responsive to needs of the EMS industry; Explore mechanisms for the government to address growing electronics R&D gap due to the restructuring of the industry.

FY 2000 Continue to build the Internet Commerce for Manufacturing infrastructure and services; Conclude development of process model for electronic commerce and publish report.

FY 2001 Continue to build the Internet Commerce for Manufacturing infrastructure and services; incorporate industry sites as manufacturing services.

3. Support standards development efforts and provide tools to facilitate standards conformance

FY 1997 Completed development of a prototype testing environment for the SEMATECH CIM Framework, and published a web-based report demonstrating the work.

FY 1998 Explored commercialization of the Java/Common Object Request Broker Architecture (CORBA) testing environment with small semiconductor firm;

	Supported the development of the Standard Recipe Format File specification; Worked with the Plug & Play Factory project to develop an alternate web-based equipment communication paradigm to eventually replace the Generic Equipment Model (GEM) standard; Contributed to the development of the GenCAM standard for electronics design information and released first version of a Conformance Test Module.
FY 1999	Continue to pursue commercialization of the Java/CORBA test environment and to promote its use in other research efforts; Develop and demonstrate standards emerging from the Plug & Play Factory project.
FY 2000	Develop and demonstrate standards emerging from NEMI FIS or Supply Chain projects.

LAW ENFORCEMENT

Enabling Technologies for Criminal Justice Practitioners

Project Leader: Kathleen M. Higgins

Staff-Years: 3.0 Professionals, 1.0 Technician, 2.0 Support staff

Funding Sources: Other Government Agencies (100%)

Objective: To apply science and technology to the needs of the criminal justice community (including law enforcement, corrections, forensic science, and the fire service) by utilizing the resources of EEEL, other NIST laboratories, and external contract support as necessary. While the primary focus is on the development of minimum performance standards, which are promulgated by the sponsoring agency as voluntary national standards, studies leading to technical reports and user guidelines are also undertaken. To accomplish its objective, the Office of Law Enforcement Standards (OLES): (1) develops methods for testing equipment performance and for examining evidentiary materials; (2) develops standards for equipment and operating procedures; (3) develops standard reference materials; and, (4) performs other scientific and engineering research as required.

Background: The Office of Law Enforcement Standards was established in 1971 through a Memorandum of Understanding between the Departments of Commerce and Justice, and was based upon the recommendations of the President's Commission on Crime. The areas of research investigated by the Office include clothing, communication systems, emergency equipment, investigative aids, protective equipment, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic science community. The composition of OLES projects, which are sponsored by the National Institute of Justice (NIJ), the National Highway Traffic Safety Administration (NHTSA), and the Office of Management and Budget (OMB), varies depending upon the priorities of the criminal justice community at any given time. Consequently, no milestones are provided for FY 2000.

The objectives of NIJ include improving Federal, state and local criminal justice systems and related aspects of the civil justice system; preventing and reducing crimes; and fostering programs that offer a high probability of improving the functioning of the criminal justice system. Science and technology are among the tools utilized by NIJ to further these objectives and OLES renders support to NIJ in that program area. The projects that comprise OLES's program for NIJ are based upon the recommendations of the Law Enforcement and Corrections Technology Advisory Council and the needs for specific research expressed by the criminal justice community.

The NHTSA program is concerned with three types of speed-measuring devices: (1) conventional radar units; (2) the automated speed enforcement system, or photoradar; and, (3) laser speed-measuring systems. The projects that comprise NHTSA's program are based on input from both NHTSA and the International Association of Chiefs of Police. The projects reflect the needs of state and local law enforcement agencies for not only equipment standards, but also for permanent, self-sustaining testing programs to assure the reliability and accuracy of all radar units following the initial approval of a device.

OLES has been funded by OMB to facilitate the development of interoperability standards for ballistic imaging systems. Through the efforts of a team composed of staff members from EEEL and ITL, the first part of a proposed three-part standard was issued in FY 1996. Support for this program is expected to continue through the laboratory and field evaluations.

Current Tasks:

1. Develop quality assurance program for soft body armor

FY 1986	Published revision to NIJ Std. 0108.01, Ballistic Resistant Protective Materials and NBSIR 86-34444, Ballistic Tests of Used Soft Body Armor.
FY 1987	Revised body armor standard.
FY 1990	First year of multi-year effort to establish realistic quality control procedures for ballistic fabric used in body armor.
FY 1992	Completed and published the results of a limited experiment to investigate whether the physical size of body armor samples influences ballistic tests; Developed test methods to evaluate the resistance of armor to sharp instrument slashing and thrust attack.
FY 1993	Assisted NIJ in establishing the National Armor Advisory Board (NAAB).
FY 1994	Supported the NIJ Compliance Testing Program.
FY 1995	Discovered a flaw in the proposed aluminum plate test method for defining ammunition as armor-piercing; Assisted DARPA in the development of concealable military body armor.
FY 1996	Assisted DARPA in the development of concealable military body armor (continuation of program initiated in FY 1995); Tested and reported results on DARPA body armor.
FY 1997	Established working group within the NAAB to develop requirements for a quality assurance program.
FY 1998	Performed critical review of statistical quality assurance (QA) protocols used with ballistic resistant materials; Proposed specific recommendations for performance assurance of ballistic resistant materials; Incorporated the QA program into the revision of the NIJ Standard 0101.03, Ballistic Resistance of Police Body Armor. (*1998 EEEL Strategic Plan*)
FY 1999	Incorporate any modifications to program based on external review and further testing into .04 revision of body armor standard; Monitor data collection once program is instituted at testing laboratories. (*1998 EEEL Strategic Plan*)

2. Characterize oleoresin capsicum (OC) further in support of the less-than-lethal technologies program

FY 1988	Initiated three-year project to monitor the U.S. Army development effort to design and implement appropriate chemical delivery systems.
FY 1991	Began to identify the performance characteristics and requirements appropriate for inclusion in NIJ standards for less-than-lethal weapons to be established in FY 1992/93.

FY 1992	Initiated development of standard for less-than-lethal weapons delivery systems.
FY 1994	Initiated study to characterize oleoresin capsicum (OC).
FY 1995	Published NIJ Report 100-95, Preliminary Investigation of Oleoresin Capsicum; Provided technical assistance and administrative support to program.
FY 1996	Analyzed the contents of several cans of OC in connections with an incident involving the Baltimore County Police Department, where an individual exposed to the OC spray exhibited no significant reaction; prepared official "report of analysis".
FY 1997	Conducted preliminary tests for evaluation of the contents of 100 canisters of OC spray used by the Los Angeles County Sheriff's Department.
FY 1998	Worked with NIJ to identify another law enforcement agency in the local area from which to obtain canisters in order to proceed with project.
FY 1999	Begin evaluation of OC canisters from local agency; Develop plan to statistically analyze the resulting data to determine whether any measured quantities correlate with the failure patterns observed; Let contract to study toxicity, potency, and interrelationships of constituents of OC spray.

3. Investigate DNA profiling technologies further and develop additional SRMs as applicable

FY 1988	Developed preliminary standard for DNA reporting formats.
FY 1989	Initiated two-year project to refine reporting standards, standard materials for molecular weight quality assurance, and even more sensitive detection and non-isotropic probes.
FY 1991	Synthesized and characterized several potential standard reference materials; Examined DNA coding systems and advanced and emerging DNA instrumental techniques; Completed the development of a standard reference material (SRM) for DNA genetic typing.
FY 1992	Issued SRM 2390 for DNA quality assurance testing.
FY 1993	Completed initial round robin tests of prototype SRMs for DNA profiling, employing the polymerase chain reaction (PCR) technique.
FY 1994	Re-certified SRM 2390, the restriction fragment length polymorphism profiling standard; Validated the proposed components of SRM 2391; Developed new electrophoretic methods for STRs.
FY 1995	Issued SRM 2391, the PCR profiling standard; Investigated method for typing mitochondrial DNA; First phase of a mitochondrial interlaboratory study was completed; Developed new approach to PCR amplification (i.e., "Long PCR"); Implemented laser-induced fluorescence detection for rapid detection of electrophoretically separated PCR products.
FY 1996	Implemented Long PCR technology to aid in the rapid determination of human identity; Conducted several interlaboratory studies; Revalidated SRM 2390 and 2391.
FY 1997	Started the production and certification of a set of well-defined DNA standards for mitochondrial and general DNA sequencing; Meetings held to consider the formation of a consortium of DNA chip manufacturers.
FY 1998	Finalized the production and certification of a set of well-defined DNA standards for mitochondrial DNA sequencing; Completed recertification of SRMs 2390 and 2391; Developed interlaboratory study to examine issues of DNA quantification; Initiated the evaluation of the impact of NIJ grants to state laboratories; Investigated the use of matrix-assisted-laser-desoprtion and

		ionization time-of-flight mass spectrometry in accurate and rapid DNA testing.
	FY 1999	Continue evaluation of impact of NIJ grants to state laboratories; Issue DNA standards for mitochondrial sequencing; Test crime laboratories on ability to quantify low levels of DNA; Pinpoint specific problem areas in identifying mixed stains with multiplexed STR kits; Sequence and publish information about at least seven rare alleles.

4. Prepare Digital Intercept Standard for digital telephone systems

FY 1992	Initiated a project to assist the FBI in the development of a digital intercept system for integrated services digital network (ISDN).
FY 1995	Prepared ten of the final sixteen parts of the draft standard; Continued to provide programmatic and technical support to the FBI; Witnessed first article testing and critically reviewed test data; Reviewed and commented in 14 other program documents.
FY 1996	Prepared final six parts of the requirements documentation and began to develop test methods document.
FY 1997	Completed draft of test methods.
FY 1998	Integrated test methods with requirements documents to produce a unified standard.
FY 1999	Submit standard to outside and WERB review; Incorporate reviewers' recommendations and deliver standard, in camera-ready or electronic file format, to NIJ for promulgation.

5. Review and revision of standards

FY 1982	Three communication standards were revised to improve test methods and to change the classification system to achieve common transmission band identification; Revised metallic handcuff standard.
FY 1983	Additional two communication standards revised as above; Revised body armor standard.
FY 1984	Revised crash helmets standard.
FY 1985	Revised standards for riot helmets and face shields, body armor and personal FM transceiver standards.
FY 1987	Revised fixed and base station FM transmitters and mobile digital equipment standards.
FY 1988	Revised fixed and base station receivers standard.
FY 1989	Revised 9mm/45 caliber autoloading pistols and mobile antennas standards.
FY 1990	Revised body-worn FM transmitters standard.
FY 1996	Initiated collaboration with Canadian General Standards Board, CEN and ISO on soft body armor; Established contract with ITS for review of two NIJ communication standards and a FIPS on land mobile radio.
FY 1997	Published revisions of communication standards (0204.01 and 0205.01); Prepared statements of work and funding proposals for emergency vehicle sirens (0501.01), walk-through and hand-held metal detectors (0601.00 and 0602.00), and kits for preliminary identification of drugs of abuse (0604.00 and 0605.00); Continued support of land mobile radio effort.
FY 1998	Prepared drafts of body armor standard (0101.03), and autoloading pistols (0112.02) standards; Monitored progress and provided support to revise standards for chemical spot test kits and color reagents for preliminary

identification of drugs of abuse (0604.00 and 0605.00), walk-through and hand-held metal detectors (0601.00 and 0602.00), and x-ray systems for bomb disarmament (0603.00); Prepared draft guideline document on batteries.

FY 1999 Prepare drafts of ballistic resistant protective materials (0108.01), metallic handcuffs (0307.01), chemical spot test kits for preliminary identification of drugs of abuse (0604.00 and 060500), walk-through and hand-held metal detectors (0601.00 and 0602.00); Monitor progress and provide support to revision of ballistic helmet standard (0106.01) and x-ray systems for bomb disarmament (0603.00); Prepare draft guideline document on emergency vehicle sirens (0501.00), antennas (0204.02 and 0205.02) and video surveillance equipment.

6. Furnish technical support and assistance in key areas

FY 1990 Published report on lithium batteries, hands-free communication systems, and technical assessment of portable explosives vapor detection devices.

FY 1991 Prepared reports on handgun accuracy, trunked radio systems, body armor test fixtures, field strength measurements of high power transceivers, performance of dialed number recorders, and a standard for rechargeable transceiver batteries; Developed procedure for the analysis of residues of explosives and gunshots; Developed a guide to video surveillance equipment; Developed a computer program supporting the economical disposal of police vehicles.

FY 1992 Drafted report on instrumentation to measure forces on a holster when gun is withdrawn; Issued AutoBid, a computer program used by police departments for automobile fleet management.

FY 1993 Drafted standard for flammability of mattresses for detention and corrections facilities; Updated AutoBid; Published reports on locks for corrections facilities, trunked radio systems, a test procedure of handgun accuracy, a guide to voice privacy for law enforcement radio communication systems, and a standard for dialed number recorders.

FY 1995 Updated AutoBid; Served as DOC representative for law enforcement to the Technology Reinvestment Program.

FY 1996 Updated AutoBid; Initiated protective glove project; Assisted in establishment of program to produce guidelines for forensic laboratory design; Authored interagency agreement with FBI to develop automobile paint database in conjunction with RCMP; Lend support to BFRL in conjunction with U.S. Fire Administration to re-evaluate traditional "arson indicators".

FY 1997 Updated AutoBid as interactive web site; Prepared preliminary test requirements for protective gloves; Published guidelines for forensic laboratory design; Continued support of paint database development project; Published findings from test burns; Prepared findings from 2 drugs-of-abuse studies; Continued support of concealed weapons detection project within EEEL; Supported two programs within the Office of Applied Economics, i.e., minimizing costs of the Life Safety Code for Corrections Facilities and cost-effective decisions for police patrol vehicle disposal (auto rank).

FY 1998 Continued update of AutoBid as interactive web site; Prepared test protocol for protective gloves; Published "Forensic Science: Status and Needs" document; Continued support of projects (i.e., automobile paint database development; terahertz-wave concealed weapons detector; detection of electronic bomb detonators; computer database of Raman spectra of energetic materials; scientific study of body armor trauma plates; development of standards for knife/puncture resistant armor, concealed weapons detectors, and explosives detectors; non-eradicable marking(s) of firearms; and, development of Standard Reference Material for ballistic imaging systems); Published findings from continued work on burn pattern analysis and one drugs-of-abuse study; Continued support of two programs within the Office of Applied Economics as described above; Provided technical input and support to the rechargeable batteries testing program.

FY 1999 Continue support of projects (i.e., automobile paint database development, including addition of Asian and European partners; terahertz-wave concealed weapons detectors; detection of electronic bomb detonators; computer database of Raman spectra of energetic materials; scientific study of body armor trauma plates; assessment of Washington, D.C. laboratory capabilities; detection of gunpowder and explosive residues; emergency warning light systems evaluation; development of 2D monolithic microbolometer imaging arrays; development of test protocol for evaluation of Smart gun; development of standards for knife/puncture resistant armor and ALERT system; development of guidelines for concealed weapons imaging and detection systems, explosive/drug detectors, facial recognition systems, collection and preservation of electronic evidence; chem/bio detectors, and walk-through and hand-held metal detectors; and, development of SRM for ballistic imaging systems); Publish findings from continued work on burn pattern analysis and three drugs of abuse studies; Continue update of AutoBid and support of other two programs within the Office of Applied Economics as described above. (*1998 EEEL Strategic Plan*)

7. Support the quality assurance program for police traffic radar/lidar

FY 1991 Completed revision of model minimum performance specifications for radar units; Assisted independent laboratory with tests to determine compliance with specifications.

FY 1992 Initiated project to develop standard for laser based units (lidar); Initiated project to develop standard for photoradar.

FY 1994 Revised the Model Minimum Performance Specifications for Police Traffic Radar Devices; Supported the test program; completed preliminary laboratory and field tests of photoradar systems.

FY 1995 Supported the quality assurance testing program of the International Association of Chiefs of Police; Draft standard for laser speed-measuring devices completed and submitted to NHTSA; Model specifications published by NHTSA; Participated in reference speed comparison study with the Transportation Research Center, East Liberty, OH; Selected and equipped UC/Davis as IACP lidar test site; Prepared draft standard and submitted it to outside reviewers.

FY 1996 Presented and obtained approval for proposed revisions to conventional radar performance specifications; Published lidar standard.

FY 1997 Supported conventional radar and lidar test programs; Prepared draft of photoradar standard, undergoing outside review; Revised radar performance specifications to include approved changes.

FY 1998 Supported conventional radar and lidar test programs; Assisted in initiating the establishment of a second lidar test site.

FY 1999 Submit draft of photoradar standard to NHTSA for promulgation; Support second lidar test site; Publish revision to lidar standard.

8. Development of Interoperability Standards for Ballistic Imaging Systems

FY 1996	Published NISTIR 5855, "Specification for Interoperability Between Ballistic Imaging Systems; Part 1 - Cartridge Cases".
FY 1997	Developed test procedure for Part 1 of the standard; Developed ballistic data file conformance tester; Acquired cartridges for interoperability test.
FY 1998	Conducted laboratory evaluations of part 1 of the standard; Continued to support interoperability effort as directed by sponsor; Appointed as chair of the National Integrated Ballistics Identification Network (NIBIN) Technical Working Group.
FY 1999	Continue participation and lead role in Technical Working Group of NIBIN; Revise NISTIR 5855 based on results of laboratory tests; Conduct additional laboratory and subsequent field evaluations as appropriate; Continue to support interoperability effort as directed by sponsor.