NISTIR 5832

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1996 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

April 1996

NIST

NIST SEEKS YOUR COMMENTS

EEEL reviews its plans regularly to keep them focused on the most important measurement needs of the U.S. electronics and electrical-equipment industries. Comments on this plan are invited and should be sent to the following address:

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Abstract

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST laboratories, is providing measurement capability and other generic technology critical to the competitiveness of the U.S. electronics industry and the U.S. electrical-equipment industry. This *1996 Program Plan* describes the technical projects that EEEL plans to conduct in fiscal year 1996 to provide metrological support to U.S. industry.

Keywords

commercialization of technology; electrical-equipment industry; electronics industry; international competitiveness; measurement capability; metrology

Ordering

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INTRODUCTION

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST laboratories, is providing metrology, supporting technology, and services that are critical to the competitiveness of the U.S. electronics industry and the U.S. electrical-equipment industry. NIST's support of metrology is important for the buying and selling of goods in domestic and international markets and for enabling quality manufacturing at competitive costs.

Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.67 million employees.[1] The electronics industry and the chemical industry have the largest values of shipments, about $300 billion per year each.[2] The electronics industry exerts extraordinary influence on the performance of every other U.S. industry.

The U.S. electrical-equipment industry is smaller than the U.S. electronics industry but is still quite large, with shipments of about $50 billion per year.[3] Among the products included in those shipments are the various types of equipment used by the electric utilities and their customers. The electric utilities use their equipment to provide $202 billion of electricity annually.[4]

These industries are battling for market share in increasingly competitive international markets. The United States is experiencing an unfavorable and rapidly worsening balance of trade for electronic products overall.[5] The consumer electronics market has been lost; and the computer market, traditionally a strong area for the United States, has eroded significantly. The electrical-equipment industry is also struggling against strong competitors in many market segments.

There are many factors contributing to this situation: social, economic, and technical. Among the technical factors is a critical one that NIST can address: the need for improved measurement capability. Both the electronics industry and the electrical-equipment industry are outstripping the measurement capability required for competitiveness. The lack of adequate measurement capability adversely affects many factors bearing on competitiveness. For example, all of the following are affected: product performance, price, quality, compatibility, time to market, and implementation of new management strategies, such as concurrent engineering.

NIST is helping by providing measurement capability that supports the efforts of U.S. industry to improve its competitiveness. This program plan describes the support that EEEL provides. The plan addresses work in the current fiscal year, FY 1996, and several years before and after. The plan implements the general strategic directions described in EEEL's *1994 Strategic Plan*.[6]

In carrying out its plans, EEEL responds to the critical measurements needs of U.S. industry. Selected needs have been assessed and documented by EEEL in a variety of ways that are described in the section called "Planning" below. The most wide-ranging of these assessments is *Measurements for Competitiveness in Electronics*, prepared by EEEL in consultation with U.S. industry and other NIST laboratories and published in 1993.[7]

MISSION

EEEL's mission is to promote economic growth, and especially international competitiveness, by providing measurement capability of high economic impact focused primarily on the critical needs of the U.S. electronics and electrical-equipment industries. In fulfilling this mission, EEEL strives to provide leading-edge capability supportive of each of the major steps required to realize competitive products in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. Good measurement support is essential for accelerating the commercialization of technology, a primary requirement for improved U.S. competitiveness.

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 analyzed 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.[8]

EEEL's customers also include: other government agencies (Federal, state, and local); educational institutions; the research community, whether located in industry, government agencies, or educational institutions; 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, and law enforcement.

DELIVERABLES

Table 1: DELIVERABLES
Measurement Capability
absolute accuracy
reproducibility
materials reference data
Technology Development
Fundamental Research

EEEL provides three major classes of deliverables. They are listed in Table 1 and are discussed below.

Measurement Capability

EEEL focuses the largest part of its resources on the development 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.*
>
> 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.

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

They themselves 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 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 measured materials reference data on the 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, it must give rise to special reasons for EEEL to be the performer. For example, the project may have originated with a NIST staff person and may show unique prospects of high value, or it may require facilities or capabilities available only at NIST. An example is the development of selected process technology for semiconductor manufacturing, such as silicon-on-insulator process technology.

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 the principal measurement needs of the U.S. electronics 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 role arises primarily from the need for objectivity in developing infrastructural improvements for the marketplace in electronics. 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:[9]

> 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* directed toward potential outcomes benefitting measurement development. 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.

MEANS OF DELIVERY

EEEL provides its deliverables by three principal means, as shown in Table 2: communications, joint activities, and paid services. FY 1995 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 not with distinct trends. All continue to be important to effective delivery. An examination of the workload on staff members indicates that they are operating at capacity in terms of the number of technology-transfer activities that they can handle.

Table 2: MEANS OF DELIVERY

Communications	**FY95**
publications	238
software requests	116
talks	288
consultations	620
visits	438
visitors	440
meetings	
attendees	2800
contributors	63
Joint Activities	
standards organizations	
staff participating	50
memberships	66
professional societies	
memberships	244
cooperative research	130
consortia (incl. forming)	2
guest scientists	84
Paid Services	
custom measurement development	125
standard reference materials	115
calibration service customers	380
training courses	29

INDUSTRIES SERVED

Table 3: SERVICES

Information
- generation
- manipulation
- transfer
- storage
- display

Energy
- generation
- control
- transfer
- storage
- conversion

The Electronics and Electrical Engineering Laboratory directly serves the electronics industry and the electrical-equipment industry. The products of these industries provide two principal classes of services -- information and energy -- as shown in Table 3. The products of the electronics industry provide principally information services but also a significant number of energy services. For example, lasers generate light for carrying information in optical fibers; lasers also generate light as energy for cutting and welding. Similarly, semiconductor devices store and manipulate information in computers; they also control energy in power systems. In contrast, the products of the electrical-equipment industry provide energy services virtually exclusively. Because the electronics and electrical-equipment industries provide support to nearly every other industrial and service sector of the U.S. economy, the indirect benefits of EEEL's work are substantial.

Electronics Industry

Based on annual shipments of products, the electronics industry and the chemical industry are the two largest manufacturing industries in the United

Table 4: LARGEST U.S. MANUFACTURING INDUSTRIES (1994)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[10(a)]	329	1,670
Chemical[10(b)]	316	842
Automotive[10(c)]	297	934
Petroleum Refining[10(d)]	123	75 (1992)
Aerospace[10(e)]	95	552

States, as shown in Table 4.[10] The electronics industry is the largest employer with 1.67 million workers, which is almost as many as the next two largest manufacturing industries combined.

The electronics industry produces a broad spectrum of products. This spectrum is outlined in Table 5 using a condensed version of the structure employed by the industry itself, through the Electronic Industries Association.[11] 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. The electronics industry exerts extraordinary influence on the performance of every other U.S. industry and affects the lifestyle of every U.S. citizen.

Table 5: ELECTRONIC PRODUCTS

- **Electronic Components**
- **Consumer Electronics**
  - television and other video
  - audio
  - mobile
  - home information
  - media
- **Telecommunications Equipment**
  - commercial, industrial, military
  - broadcast, studio, and related
  - telephone and telegraph
- **Defense Communications**
  - search and detection
  - navigation and guidance
- **Computers and Peripheral Equipment**
  - computers
  - storage
  - input/output
  - terminals
- **Industrial Electronics**
  - controls
  - processing
  - industrial process display and control instrumentation
  - test and measuring equipment
- **Electromedical Electronics**
- **Other Related Products and Services**

The shipments of the U.S. electronics industry have been virtually unchanged in constant dollars (that is, in real terms) over the five years from 1989 to 1993 for which actual data, as opposed to estimated data, are available. Specifically, over this period U.S. shipments in current dollars grew at a compound average rate of 3.1 percent per year;[12] but the price deflator for the Gross Domestic Product increased at a compound average rate of 3.3 percent per year over the same period, neutralizing those gains in terms of constant dollars. Employment in the U.S. electronics industry has been falling for some years now, most recently at a compound average rate of 3.4 percent per year for the period 1992 through 1994.[13]

Electrical-Equipment Industry

The products of the electrical-equipment industry are outlined in Table 6, 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 electrical utilities. Automobiles, too, rely heavily on electrical equipment, accounting for about 14 percent, by dollar value, of all electrical equipment shipped in the United States.[14]

Table 6: 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

PROGRAM STRUCTURE

The fields of technology of the electronics and electrical-equipment industries that EEEL addresses currently, or plans to address in future years, are shown in Table 7. 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 an entirely separable set of categories to describe these technologies and the products made from them. The arrangement in Table 7, however, has been found workable. In this scheme, products are generally associated with the first applicable category on the list, as described in the following several paragraphs.

The three materials categories that lead the list (semiconductors, magnetics, and superconductors) represent measurement support provided for materials, discrete components, and integrated components for which the key material from which they are made seems the most convenient way of classifying the technology employed.

The three frequency-based categories (low frequency, microwaves, and lightwaves) that follow represent measurement support for materials, discrete components, integrated components, and equipment for which frequency seems the best way of classifying the technology employed.

The computer category 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 semiconductors and magnetics.

The video category 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.

Table 7: FIELDS SERVED (CURRENT AND FUTURE)

Fields	
semiconductors	
silicon	current
compound semiconductors	current
magnetics	
magnetic information storage	current
magnetic sensing	current
power materials	future
superconductors	
low temperature	current
high temperature	current
low frequency	
radio frequency	current
audio frequency	current
direct current	current
microwaves	
microwave signal processing	current
microwave computing	current
microwave transmission	current
lightwaves	
lasers	current
optical-fiber communications	current
optical-fiber sensors	current
optical information storage	future
optical signal processing	future
optical computing	future
computers	future
video	
vision	future
signal processing	current
transmission	current
information storage	current
displays	current
power	
generation	future
transmission	current
control	current
storage	future
conversion	current
Cross-Cutting Fields	
national electrical standards	current
electromagnetic compatibility	current
electronic data exchange	current

The power category focuses on measurement support for materials, equipment, and systems of principal interest to the electrical-equipment industry and the electric utilities.

Finally, three cross-cutting fields are shown. The first of these, national electrical standards, focuses on developing and maintaining 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, electromagnetic compatibility, focuses on measurement support for nearly every other category located higher in the table.

The third and final cross-cutting field, electronic data exchange, focuses on test methods for 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 technologies marked "current" in Table 7. EEEL sees a need to provide support for the several technologies marked "future" in the table but lacks the resources to launch even small 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 and electrical-equipment industries. As for any industry, the electronics and electrical-equipment 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.

RESOURCES

EEEL's funding and staff resources for FY 1995, the most recently completed year, are shown in Table 8. 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 measurement capability supporting their programs. The "Other Funding" comes from multiple sources, the largest single part of which is derived from reimbursements for the cost of calibrations services provided to EEEL's customers. The funds expended outside EEEL but inside NIST

Table 8: FY 1995 RESOURCES

Funds (in EEEL)	$millions	percent
NIST Funding	31.3	70
Other Agency Funding	8.2	18
Other Funding	5.2	12
total	44.8[1]	100
Funds (outside EEEL)	5.4	
Staff	number	percent
paid		
full-time permanent	274	70
other	35	9
total paid	309	79
unpaid		
guest scientists	84	21
total unpaid	84	21
total	393	100

Notes on Funding
[1]Total does not add due to rounding.

are a combination of funds provided by the Congress directly to NIST and funds provided by other Federal agencies.

At the time this document was written, NIST's funding levels for FY 1996 had not yet been determined; so no funding information for that year could be provided here.

PLANNING

EEEL reflects its plans and accomplishments in five types of published documents, as shown in Table 9. Also shown are typical publication intervals and time horizons. The measurement needs assessments are published on an irregular schedule, either individually or in groups as they are completed. The assessments provide analyses of the measurement problems for which the electronics and electrical-equipment industries most need NIST's assistance. The measurement needs assessments are prepared 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. The program plan focuses on implementation of the strategic directions in specific programmatic goals, with an emphasis on the current year and following year, and extending as far forward as five years. The technical-accomplishments document describes accomplishments for the most recently completed year. The impact studies are published on an irregular schedule and translate accomplishments into economic terms.

Table 9: PUBLISHED PLANNING DOCUMENTS

Document	Publication Interval (years)	Time Horizon (years)
needs assessments	irregular	10
strategic plan	3	5
program plan	1	5
technical accomplishments	1	1 backward
impact studies	irregular	10 backward

Table 10 provides more information about the two irregularly published planning documents: 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 10 shows the documents completed in FY 1993-1995 and, also, the documents planned for FY 1996-

Table 10: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

Fields	'93	'94	'95	'96	'97
semiconductors	a,s	.	a	s	a
magnetics	a	.	.	.	.
superconductors	a,i	.	.	.	.
low frequency	.	.	.	.	a
microwaves	a	.	.	a	.
lightwaves					
lasers	a,r	.	.	.	.
optical-fiber communications	a,r	.	.	.	.
optical-fiber sensors	a,r	.	.	.	.
optical information storage	.	.	a	.	.
optical signal processing	.	.	.	.	.
optical computing	.	.	.	.	.
computers	.	.	.	.	.
video	r,a	.	.	a	.
power	.	.	i	a	.
Cross-Cutting Fields					
national electrical standards	.	.	.	.	a
electromagnetic compatibility	r,a	.	a,r	.	.
electronic data exchange	.	.	.	.	a

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

1997. As indicated in the key at the bottom of the table, the assessments are marked "a" in Table 10. The reviews are marked "r." The 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 industrial technical and managerial personnel. The impact studies are marked "i" in the table. They are sponsored by EEEL or the NIST Program Office and are conducted with the assistance of economists and industry experts to determine how completed work has affected industry. A full list of all of the documents referenced in Table 10 is contained in the endnotes.[15]

EEEL employs other mechanisms to gather information important for planning. These mechanisms may or may not result in formal documents. Among them are individual contacts with industry representatives by all staff members, round-robin measurement intercomparisons, informal customer surveys, and workshops. For example, in consultation with the Telecommunications Industry Association, EEEL periodically updates its understanding of the most important measurement needs affecting the optical-fiber communications industry. EEEL also participates in the development of industry "roadmaps" that lay out long-range plans for technical progress in specific industries and that have significant implications for needed measurement support from NIST. Examples are the roadmap of the semiconductor industry, under the auspices of the Semiconductor Industry Association, and the roadmap of the optoelectronics industry, under the auspices of the Optoelectronics Industry Development Association.

ORGANIZATION OF THIS PROGRAM PLAN

The pages that follow describe EEEL's program plan in detail. The program plan is arranged by the fields of technology shown in Table 7 on page 7. The fields of technology define EEEL's programmatic structure as shown in EEEL's *1994 Strategic Plan.* EEEL conducts a number of projects in support of each field of technology; these projects are responsive to the strategic plan. The projects are the fundamental building blocks of this program plan. Descriptions of these projects follow. Each description states the objective of the project, the background of the project, the several tasks that constitute the project, and the milestones required to

Table 11: CROSSWALK BETWEEN EEEL'S PROGRAMMATIC AND ORGANIZATIONAL STRUCTURES

PROGRAMMATIC: FIELDS OF TECHNOLOGY	ORGANIZATIONAL: OFFICES AND DIVISIONS
Semiconductors	Semiconductor Electronics Division Office of Microelectronics Programs
Magnetics	Electromagnetic Technology Division
Superconductors	Electromagnetic Technology Division
Low Frequency	Electricity Division
Microwaves	Electromagnetic Fields Division
Lightwaves	Optoelectronics Division
Video	Electricity Division
Power	Electricity Division
National Electrical Standards	Electricity Division
Electromagnetic Compatibility	Electromagnetic Fields Division
Electronic Data Exchange	Electricity Division
Law Enforcement	Office of Law Enforcement Standards

complete the tasks. The table of contents, which begins on page iii, provides a complete listing of all projects, arranged by field of technology.

EEEL's program is implemented through the two offices and five divisions that comprise EEEL's organizational structure. The programmatic areas, or fields of technology, in which these organizational units conduct projects are shown in Table 11. The table indicates that a given organizational unit may support more than one programmatic area. For example, the Electricity Division supports five programmatic areas.

The five divisions in EEEL manage and conduct programs. The two offices matrix manage programs across the NIST Laboratories. One is the Office of Microelectronics Programs (OMP). It manages a NIST-wide National Semiconductor Metrology Program (NSMP), a focused, matrix-managed effort addressing the semiconductor industry's metrology needs which are identified in the 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 Materials Science and Engineering Laboratory, the Manufacturing Engineering Laboratory, the Chemical Science and Technology Laboratory, and the Physics Laboratory. The second office is the Office of Law Enforcement Standards. It manages a NIST-wide program in support of the law-enforcement community. This program is funded entirely by two other Federal agencies: the National Institute of Justice of the U.S. Department of Justice, and the National Highway Traffic Safety Administration of the U.S. Department of Transportation. The program is conducted within EEEL and three other NIST laboratories: the Building and Fire Research Laboratory, the Computing and Applied Mathematics Laboratory, and the Chemical Science and Technology Laboratory. The Office of Law Enforcement Standards is somewhat different from that of the other EEEL organizational units, all of which are focused on support of the U.S. electronics and electrical-equipment industries. However, the projects of this office are included in this plan.

Table 12 associates every project in this program plan with the EEEL organization conducting it, accounting for all five divisions and two offices.

Table 12: EEEL ORGANIZATIONS AND THE PROJECTS THEY CONDUCT

ORGANIZATIONS: OFFICES AND DIVISIONS	PROJECTS
SEMICONDUCTOR ELECTRONICS DIVISION	Dielectric Reliability Metrology MicroElectroMechanical Systems (MEMS) Metrology for Nanoelectronics Interconnect Reliability Metrology Metrology for Process and Tool Control Metrology for Devices and Packages Thin-Film Process Metrology Silicon-on-Insulator Metrology Optical Characterization Metrology Electrical Characterization Metrology
OFFICE OF MICROELECTRONICS PROGRAMS	NIST-wide Semiconductor Programs
ELECTRICITY DIVISION	Generation and Measurement of Precise Signals Waveform Acquisition Devices and Standards Measurements for Complex Electronic Systems AC-DC Difference Standards and Measurement Techniques Impedance Standards and Measurement Techniques Video Technology Metrology for Electric Power Systems Dielectrics Research Automated Electronics Manufacturing Quantum Voltage and Current Quantum Resistance and Capacitance Resistance Standards and Measurement Methods Plasma Chemistry - Plasma Processing
ELECTROMAGNETIC FIELDS DIVISION	Power Standards and Measurements Impedance, Attenuation, Voltage 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 High Speed Microelectronics Metrology Electromagnetic Properties of Materials Standard Electromagnetic Fields and Transfer Probe Standards Emission and Immunity Metrology
ELECTROMAGNETIC TECHNOLOGY DIVISION	Microstructural Analysis for Electromagnetic Technology Magnetic Instruments and Materials Characterization Magnetic Recording Metrology Nanoprobe Imaging for Magnetic Metrology High-Performance Sensors, Converters, and Mixers High-T_c Electronics Superconductor Interfaces and Electrical Transport Superconductor Standards and Technology Josephson Array Development Nanoscale Cryoelectronics
OPTOELECTRONICS DIVISION	High Speed Source and Detector Measurements Optical Fiber Metrology Integrated Optics Metrology Fiber and Discrete Components Optical Fiber Sensors Semiconductor Materials and Devices Dielectric Materials and Devices Laser Radiometry
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

ENDNOTES

1. *1995 Electronic Market Data Book*, Electronic Industries Association, p. 1 (1995).

2. See Table 4 and endnote 10.

3. This is a rounded value based on the value of $48 million calculated for 1990. 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.

4. Final figure for 1994 from the Edison Electric Institute, Washington, DC (November 14, 1995).

5. *1995 Electronic Market Data Book*, Electronic Industries Association, p. 4 (1995).

6. *Electronics and Electrical Engineering Laboratory: 1994 Strategic Plan*, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, NIST Report No. NISTIR 5409 (April 1994).

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

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

9. 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.

10. All shipments figures in the table are *product data* in current dollars. They are also estimates since no firm shipment data for 1994 were available at the time of publication of the referenced documents. 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. Product data reflect all products classified in the named industry and sold by all industries. 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) *1995 Electronic Market Data Book*, Electronic Industries Association, p. 1 (1995). The data associated with (b), (c), (d), (e) come from the International Trade Administration of the U.S. Department of Commerce and will be published by the Bureau of the Census in the *Statistical Abstract of the United States 1995* in late 1995. In the past, these data have been published in the *U.S. Industrial Outlook*, but that publication was discontinued with the edition of January, 1994. For (c) the figures shown reflect both the motor-vehicle bodies and supporting parts industries. For (d), the employment data for 1992 are the most recent available and are thus used as an estimator for 1994.

11. *1995 Electronic Market Data Book*, Electronic Industries Association, p. 3 (1995) and product-specific areas throughout the publication.

12. Shipments were $260.094 billion in 1989 and $294.235 billion in 1993. *1995 Electronic Market Data Book*, Electronic Industries Association, p. 3 (1995).

13. Employment was 1.786 million in 1992 and 1.670 million 1994. *1995 Electronic Market Data Book*, Electronic Industries Association, p. 1 (1995).

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

15. All documents referenced in Table 10 are shown below. They cover the period 1993 to 1997.

Semiconductors

1993	a	Chapter 4, "Semiconductors", *Measurements for Competitiveness in Electronics*, First Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, 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).
1995	a	*International Workshop on Semiconductor Materials 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.
1996	s	*Optical Characterization Methods Survey* for materials, processing, and manufacturing in the semiconductor industry, to be completed in 1996.
1997	a	Compound semiconductor measurement needs assessment, to be completed in 1997.

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.
1993	i	Robert L. Peterson, "An Analysis of the Impact on U.S. Industry of the NIST/Boulder Superconductivity Programs: An Interim Study", Report No. NISTIR 5012 (November 1993).

Low Frequency

1997	a	Low frequency needs assessment, to be completed in 1997.

Microwaves

1993	a	Chapter 7, "Microwaves", *Measurements for Competitiveness in Electronics*, First Edition.
1996	a	Measurement needs assessment, in the form of a workshop, will be conducted in the area of wireless communications and will address both antennas and materials. Publication of findings may not occur until FY 1997.

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.

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.

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.

Optical Information Storage

1995	a	*Optical Data Storage: A NIST Multi-Laboratory Strategic Planning Workshop*, Gaithersburg, MD (July 25, 1995).

Optical Signal Processing

None.

Optical Computing

None.

Computers

None.

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.
1996	a	Video needs assessment, to be completed in 1996.

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).
1996	a	Power needs assessment, to be completed in 1996.

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

Electronic Data Exchange

1997	a	Electronic data exchange needs assessment, to be completed in 1997.

National Electrical Standards

1997	a	National electrical standards measurement needs assessment, to be completed in 1997.

SEMICONDUCTORS

Office of Microelectronics Programs

Office Director: Robert I. Scace

Staff: 3 professionals (1 physicist, 1 electrical engineer, 1 secretary)

FY96 funding: $10.4 million (as of end FY95)

Funding sources: NIST

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

Background: NIST has developed metrology for the semiconductor industry for over 40 years in EEEL and its predecessors. Ten 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 defined in the 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

FY95: Developed calibrated atomic force microscope (CAFM).
Procured high resolution field emission scanning electron microscope (FESEM) and compatible scanning probe microscope (SPM) for combined metrology system.

FY96: Perform first pitch/step height calibrations with the CAFM.
Optimize operation of combined FESEM+SPM metrology system.

2. Plasma and CVD Process Measurements

FY95: Demonstrated utility of radio frequency (RF) measurements to monitor polymer build-up in plasma reactors.
Modified Gaseous Electronics Conference Radio Frequency (GEC RF) Reference Cell to accept inductively coupled plasma source.
Measured/published spatial distribution of carbon-fluorine (CF) radicals in $CF_4/O_2/Ar$ plasmas.

FY96: Complete selected electron-impact mechanism and ion-molecule reaction kinetics database.
Design and construct 300mm RF plasma discharge cell as reference reactor (GEC II).

3. Optical CD and Overlay Metrology

FY95: Published quantitative analysis of new ultraviolet (UV) linewidth microscope.
Optical and mechanical system components designed and partially fabricated.

FY96: Overlay system assembled and tested.
UV linewidth microscope qualified for standard reference material (SRM) calibrations.

4. Fundamental Process Control Metrology for Gases

FY95: Developed prototype calibration system for partial pressure residual gas analyzers (RGAs).
Developed primary and transfer flow standards for inert gases (10-1000 sccm).
Published comparative evaluation of thermal mass flow controllers.

FY96: Complete primary and transfer standards for low flow (0.1-10 sccm).
Develop and validate models for RGA performance.

5. Moisture Concentration Measurements in Process Gases

FY95: Demonstrated quantitative capability of optical ring-down cavity method.
Completed construction of prototype moisture generation system.

FY96: Apply frequency stabilized diode laser to quantitative ring-down cavity method.
Offer moisture calibration services (20 ppb and above).

6. Metrology for Contamination-Free Manufacturing

FY95: Fabricated particulate samples used to establish detection limits for commercial tools.
Completed design of rotating-disk chemical vapor deposition (CVD) reactor.

FY96: Provide appropriate particulate standards in the 25 to 200 nm size range.
Fabricate rotating-disk CVD reactor to validate particle nucleation and growth models.

7. Thin Film Profile Measurement Methods and Reference Materials

FY95: Introduced SRM2137 as first boron implant in silicon standard.
Organized profilometry round-robin for Secondary Ion Mass Spectrometry (SIMS) crater depth measurements.

FY96: Develop neutron activation analysis protocol for arsenic in silicon.
Develop methods for ultra-shallow profiling using SIMS.

8. Radiometric Metrology for Deep Ultraviolet Lithography

FY95: Developed method for calibrating discharge lamps used for UV photoresist stabilization.
Continued work with commercial partner to improve accuracy of UV probes.

FY96: Begin development of dielectric barrier discharge source as potential ultraviolet/deep ultraviolet (UV/DUV) standard.
Develop an improved transfer UV meter for photolithography applications.

9. Wafer and Chuck Flatness

FY95: Interferometric flatness metrology system for 300mm wafers demonstrated.
Thickness variation interferometer conceived and demonstrated as lab breadboard.

FY96: Complete 300mm flatness interferometer and apply to chuck distortion measurements.
Commercialize thickness variation interferometer with industrial partner.

10. Optical Scattering for Wafer Surface Metrology

FY95: Developed a new standard reference material for low-level bidirectional reflectoin distribution function (BRDF) measurements.
Verified accuracy of new low-level BRDF instrumentation to better than 1%.

FY96: Develop reference wafers (with commercial partner) to calibrate fab line haze meters.
Investigate scattering from particles on Si surfaces to determine size and composition.

11. Improved Characterization of Microroughness and Near-Surface Defects

FY95: Developed advanced scanning scattering microscope (SSM) using latest optical techniques.
Initiated comparative measurements of particles using the SSM and the atomic force microscope (AFM).

FY96: Establish detectable limits of surface roughness using the advanced SSM.
Measure interface topography of buried SiO_2/Si interfaces.

12. High Accuracy Two Dimensional Measurements

FY95: Brought Moore Model M48 coordinate measuring machine system on-line for large two dimensional artifacts and began offering calibration service.
Developed positioning system for the NIST small artifact instrument.

FY96: Continue development of the NIST small artifact instrument.
Establish accuracy of the system through interlaboratory testing.

13. Improved High Temperature Thermometry

FY95: Completed selection and stability testing of platinum/palladium (Pt/Pd) thermocouples through 1450 °C.

FY96: Complete reference function data collection for Pt/Pd thermocouple at NIST and the Italian national standards laboratory, Instituto di metrologia "G. Colonnetti" (IMGC). Develop calibration methods for thin film thermocouples up to 1000 °C.

14. Micromechanical Measurements

FY95: Measured local strains around a via in a multichip module-laminate (MCM-L) high density interconnect structure.
Improved microtensile machine with installation of piezoelectric drive and controller.

FY96: Apply electron beam moire technique to measure strains in ball grid array structure.
Explore the use of microelectromechanical system (MEMS) techniques to measure tensile properties of very small samples.

15. Solderability Measurements and Optimization

FY95: Results of NIST solderability research included in the Institute for Interconnecting and Packaging Electronic Circuits (IPC) Joint Industry Standard.

FY96: Develop theory for non-isothermal, reactive wetting.
Apply this theory to the design of a new wetting test.

16. Thermoset Cure and Performance

FY95: Showed that moisture accumulates as liquid-like water at polymer/silica interfaces.
Demonstrated new method for determining thermal diffusivity of thin polymer films on Si.

FY96: Measure hygroscopic expansion of polymeric materials used in electronic packaging.
Determine influence of a confining, impermeable substrate on thickness expansion.

Dielectric Reliability Metrology

Project Leader: John S. Suehle

Staff: 1.8 Professionals, 1.0 Post Doc, 0.2 Technicians

Full funding level: $0.5 M

Funding sources: NIST-STRS (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 and new oxide processes require fast and effective reliability characterization techniques. Physically correct models and tests to predict reliability of thin oxides 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 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

FY91 Organized, designed, and conducted an international Joint Electron Device Engineering Council (JEDEC) interlaboratory experiment (with nine labs) to evaluate two JEDEC-proposed dielectric breakdown test methods involving current- and voltage-ramp stresses. Analyzed the measurement results and found good agreement.
Modified a commercial hot chuck and controller to enhance capabilities for making measurements of test-line temperatures repeatable at the wafer level.

FY92 Developed a document for Wafer-Level Testing of Thin Dielectrics which was accepted as Electronic Industries Association (EIA)/JEDEC Standard JESD35.

FY93 Presented first Time Dependent Dielectric Breakdown (TDDB) data at temperatures up to 400 °C. Before this time it was not known if silicon dioxide could be used for high temperature electronics.

FY94 Improved understanding of TDDB in thin silicon dioxide films by verifying the electrical field dependence of the mechanism at low stress electrical fields (4×10^6 V/cm) by using novel high-temperature wafer-level probe station.

FY95 Revised and had approved by committee ballot two new 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 TDDB for bimodal failure distributions.
Performed TDDB characterization of 9 to 22 nanometer thick oxides with unipolar and bipolar pulsed bias stress over wide range of temperature and electric field.

FY96 Coordinate joint JEDEC-ASTM (American Society for Testing and Materials) working group to develop standard for gate oxide integrity tests.

FY97 Develop improved lifetime model for gate oxides less than 20 nanometers thick and operating under either time invariant or varying voltages operating under dc and ac conditions.

2. Develop micro-hotplate gas sensor

FY92 Filed three patents on the micro-hotplate and tin oxide gas sensor. (Collaboration with the Chemical Science and Technology Laboratory [CSTL]).

FY93 Developed the first monolithic tin oxide gas sensor realized with commercial processing by silicon micromachining. (Collaboration with CSTL)

FY94 Conducted a study on the reliability of micromachined polysilicon heaters when subjected to constant current stress. High-gain Optical Beam Induced Current (OBIC) imaging was used for the first time to examine the structural effects of stress on the devices. The results indicate that the resistance drift exhibited by the resistors during stress is due to electromigration of the dopant atoms.

FY95 Designed a new micro-hotplate chip, NIST21, and had fabricated by the Microelectronics Research Laboratory (NSA). The devices have tungsten metallization for improved heater stability and reliability.

FY96 Demonstrate four-element gas sensor array for compositional gas analysis with CSTL.

FY97 Complete prototype of multi-element chemical sensor array and demonstrate in industrial application.

MicroElectroMechanical Systems (MEMS)

Project Leader: Michael Gaitan

Staff: 1.6 Professionals, 1.7 Guest Scientists, 0.5 Graduate Research Fellows, 0.2 Technicians

Full funding level: $0.5 M

Funding sources: NIST (44%), Other Government Agencies (56%)

Objective: Provide domestic industry with infrastructure for improved accessibility of MEMS manufacturing, develop techniques for MEMS device design and characterization, performance testing, and parameter extraction, and provide novel MEMS-based devices for metrology applications.

Background: The emerging technology of MicroElectroMechanical Systems (MEMS) utilizes mechanical structures, fabricated in an integrated-circuit-based process, to miniaturize mechanical elements and perform new functions. 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 $14 billion by the year 2000, enabling almost $100 billion in new or improved systems. Domestic industrial needs for MEMS manufacturing include the integration of electromechanical structures with microelectronic circuits and the development of characterization techniques of electromechanical properties that relate to device geometry and the manufacturing processes. Meeting this objective will enable industry to manufacture competitive, cost-effective products, improved manufacturing processes, device performance, and device reliability. In addition, MEMS devices have applications for in-situ semiconductor fabrication process monitoring and control, a critical element recognized by the National Technology Roadmap for Semiconductors, as a key step required for the next generation of semiconductor devices.

Current Tasks:

1. Develop thermal flat-panel display

FY91 Initiated a program to develop a complementary metal oxide-semiconductor-(CMOS-)based thermal flat-panel display. Demonstrated the concept of fabricating micro-heating elements through a commercial CMOS process. Designed, fabricated through the University of Southern California/Information Sciences Metal Oxide Semiconductor Informational Services (MOSIS), performed silicon micromachining on CMOS chips, and tested the elements for applications as infrared emitters or pixels in a thermal flat-panel display.

FY92 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.

FY93 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.

FY94 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.

FY95 Initiated a 3-year program to build prototype thermal flat-panel displays. (Collaboration with industrial partner)

FY96 Work with industrial partner to design, fabricate, and test 64 x 64 pixel array prototype thermal display integrated circuits to be inserted in optical projection system for the first phase field demonstration. Initiate work to design and fabricate 128 x 128 pixel array prototype thermal display integrated circuits for the second phase of the task.

FY97 Complete designs, fabricate, and test 128 x 128 pixel array prototype thermal display ICs to be inserted in optical projection system. Begin work to design and fabricate 256 x 256 pixel array prototype thermal display integrated circuits for the third phase of the task.

FY98 Complete designs, fabricate, and test 256 x 256 pixel array prototype thermal display integrated circuits to be inserted in optical projection system.

2. Develop microwave power sensor

FY91 Began development of a CMOS equivalent to the multijunction thermal converter fabricated in the Semiconductor Process Laboratory. (Collaboration with the Electricity Division) Initial designs sent to the MOSIS service for fabrication.

FY92 Fabricated improved designs of thermal converter elements and tested ac/dc conversion accuracy to 1 megahertz with conversion error under 200 parts per million.

FY93 Initiated a program to develop a high-precision low-cost RF and microwave power sensor to 10 gigahertz. Fabricate transmission lines and power sensors. Began the CRADA with industrial partner.

FY94 Demonstrated the concept of fabricating silicon micromachined microwave transmission lines in CMOS technology. Tested the transmission line elements to 20 gigahertz and demonstrated the benefits of silicon micromachining to reduce the attenuation of the lines.

FY95 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 gigahertz.

FY96 Develop a working prototype microwave power meter in collaboration with industrial partner. Incorporate the transmission line elements and the microwave power sensors with circuits on an IC chip and test and characterize the elements and circuit performance.

FY97 Integrate analog-to-digital converter and input/output electronics with power sensor IC in collaboration with industrial partner. Begin work to package the IC and interface to a microwave connector.

FY98 Build a working prototype hand-held microwave power meter in collaboration with industrial partner.

3. Develop electromechanical test structures/promote MEMS infrastructure

FY92	Designed test structures to determine design rules needed for design and fabrication of CMOS-compatible MEMS devices.
FY93	Submitted a design library to MOSIS of CMOS-compatible MEMS devices and test structures. MOSIS announced its official support of CMOS compatible MEMS as a result of this effort.
FY94	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 electromechanical test structures. A test chip was also designed in collaboration with others at NIST.
FY95	Installed interferometric microscope system for measurement of deflections of the electromechanical test structures. Began measurements of the test structures.
FY96	Work 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. Complete characterizations of cantilever and fixed beam MEMS test structures.
FY97	Make plans for future activities, based on the results of the workshop.

Metrology for Nanoelectronics

Project Leader: Joseph G. Pellegrino

Staff: 2.5 Professionals, 1.5 Technicians

Full funding level: $0.8 M

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

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 nanometers). 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 (having feature sizes between 10 and 100 nanometers) devices 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

FY94 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.

FY95 Designed equipment and software for in-situ optical reflectometry. Designed multiple-wavelength reflectometer to improve thickness resolution to 5 nanometer level.

FY96 Use in-situ X-ray fluorescence capability in MBE growth chamber to measure and control composition and possibly thickness of MBE layers. Equip MBE with in-situ ellipsometer for measuring thickness, composition, and roughness of MBE layers. Initiate plans to implement pyrometric interferometry as an in-situ optical probe to measure temperature.

FY97 Correlate various in-situ measurements of the alloy composition and thickness, compare with the results of ex-situ techniques, and address differences.

FY98 Develop an in-situ X-ray-based capability to determine epilayer thickness and measure strain in real time during growth. Develop research materials and methods to improve standards.

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

FY93 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 nanometers 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.

FY94 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)

FY95 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.

FY96 Study 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)

FY97 Develop measurement capability to assess the effects of interfaces on the device performance of dual-pulsed pseudomorphic high electron mobility structures (PHEMTs).

FY98 Measure the influence of the interface quality on the performance of non-(100) oriented advanced heterostructures used in both electronic and optoelectronic applications.

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

FY91 Generated nanometer-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)

FY92	Grew high-quality GaAs samples for the quantum-Hall resistance standard. (Collaboration with Electricity Division)
FY93	Studied nanometer-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)
FY94	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)
FY95	Continued scanning tunneling microscopy effort (Collaboration with MEL); and helped on 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)
FY96	Install focused-ion-beam (FIB) lithography system in MBE chamber for patterning III-V and possibly silicon wafers. Assist optimization of STM system for measuring nanostructures. Grow specialized heterostructures for electronic and optoelectronic devices. (Collaboration with University of Iowa and others).
FY97	Fabricate quantum wires and dots on wafers with FIB. Perform MBE regrowth on pre-FIB processed substrates to investigate feasibility of three-dimensional device stacking. Utilize FIB lithography to develop research artifacts for improved standards.

Interconnect Reliability Metrology

Project Leader: Harry A. Schafft

Staff: 1.6 Professionals, 0.2 Technicians

Full funding level: $0.4 M

Funding sources: NIST (89%), Other Government Agencies (11%)

Objective: Provide domestic manufacturers with test structures, test methods, and diagnostic procedures for improving the reliability of metal interconnects used in integrated circuits and promote the use of a building-in reliability approach within the semiconductor industry.

Background: Interconnect reliability in integrated circuits continues to be a topic of intense interest, as evidenced by an increasing number of publications on the subject each year. This intense interest is the result of the planned aggressive scaling of integrated circuits and the need for ever greater product reliability, as expressed in the National Technology Roadmap for Semiconductors. The key underpinning of efforts in this area is the development of the measurement tools and standards to facilitate the goals of the industry.

Current Tasks:

1. Develop electromigration standards and metrology methods

FY88 Submitted drafts of three electromigration-related documents for balloting as standards to the American Society for Testing and Materials (ASTM), a U.S. voluntary standards organization, through its Subcommittee F1.11 on Quality and Hardness Assurance. Developed a wafer-level test station for making steady state and pulsed electromigration stress tests at temperatures as high as 300 °C. Initiated pulsed stress electromigration testing. Completed collaborative effort with a large semiconductor company and the NIST Statistical Engineering Division on the statistics of electromigration testing.

FY89 Discovered a new measurement interference for highly accelerated electromigration stress tests. Developed a new, state-of-the-art wafer test station to perform dc and pulsed electromigration stress tests at room temperature to over 300 °C. Designed a test chip (NIST-2) for use in optimizing the procedure for measuring the thermal conductivity of thin, dielectric films and for conducting pulsed and dc electromigration stress tests.

FY90 Demonstrated that the pulsed enhancement of electromigration is dependent on current density. Guided the adoption of three ASTM standards for electromigration that represent first standards for the characterization of interconnect metallizations.

FY91 Completed study of power lognormal distribution for modeling electromigration failure times which predicted much lower early reliability values for metallizations. Designed a test chip (NIST 13) to evaluate validity of power lognormal distribution for describing electromigration-related failures.

FY92 Showed that the classical electromigration stress test can be used at ultra-high stress levels. Discovered an unusually large enhancement of conductor lifetime under pulsed dc stress that depends on current density and oxide thickness.

FY93 Characterized the power lognormal distribution for modeling electromigration failure-time data which include a quantification of the length dependence and of a worst-case estimate of the early reliability of conductor lines.

FY94 Initiated work on a new package-level electromigration test station. Began interlaboratory electromigration comparison.

FY95 Completed initial draft of a Joint Electron Device Engineering Council (JEDEC) standard for calculating the acceleration factors for electromigration for JEDEC Committee 14.2. Completed extensive revisions to ASTM F 1261, Standard Method for Determining the Average Electrical Width of a Straight,Thin-Film Line, including a bias and precision statement (from the results of an interlaboratory experiment) for subcommittee F1.11.

FY96 Complete revision of ASTM standard guide for designing electromigration test structures and of ASTM standard for characterizing electromigration. Explore new room temperature method for package-level electromigration stress tests.

FY97 Complete second electromigration interlaboratory experiment to determine the precision of the ASTM standard method for characterizing electromigration.

FY98 Complete revision of ASTM standard method for characterizing electromigration.

2. Develop thin-film characterization methods

FY88 Initiated work on developing techniques for measuring the thermal conductivity of thin-film dielectrics used in very large scale integrated circuits.

FY89 Reported results of thermal conductivity measurements of thin-film silicon dioxide.

FY90 Began a study to evaluate the use of Matthiessen's Rule for electrically determining the thickness of aluminum-based metallizations.

FY91 Explored use of sophisticated mechanical probe to evaluate electrical method for measuring metal film thickness.

FY92 Began exploration of a scanning electron microscope as means to evaluate electrical method for measuring metal film thickness.

FY93 Developed method for making cross sections of metal-film specimens for SEM examinations using a scanning electron microscope.

FY94 Refined use of Matthiessen's rule to measure thickness of metal films by an electrical method. Demonstrated agreement with calibrated measurements. (Collaboration with Rensselaer Polytechnic Institute) Measured thermal conductivity of different types of oxide films.

FY95 Documented the use of Matthiessen's rule for determining aluminum film thickness and line cross-sectional area from electrical resistance measurements.

FY96 Complete selective thermal conductivity measurements of silicon dioxide thin films and modeling experiments to improve characterization. Continue an

	interlaboratory experiment to verify the reproducibility of thickness measurements of thin metal film using Matthiessen's rule.
FY97	Complete draft of a JEDEC standard for determining the electrical thickness of thin metal films using resistance measurements.

3. Develop improved temperature coefficient of resistance (TCR) metrology

FY90	Prepared a draft standard on the measurement of the TCR of interconnect metallizations in response to a JEDEC request.
FY91	Developed JEDEC standard based on previously NIST-developed standard for measuring and using metallization TCR at request of JEDEC.
FY92	Revised the Electronic Industries Association Joint Electron Device Engineering Council Standard on measuring and using TCR of a metallization.
FY93	Developed a surface-temperature probe for improved temperature measurement capability, used as a calibration source in second interlaboratory experiment.
FY94	Completed first draft of Bias and Precision Statement for JEDEC TCR standard (JESD33).
FY95	Documented the results of the JEDEC interlaboratory 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.
FY96	Project completed.

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

FY89	Developed plans for highlighting the critical changes needed for industry to meet future reliability and market-entry demands.
FY90	Developed technical program for the International Reliability Physics Symposium (IRPS) 1990 that introduced new focus for the Symposium: Building-In Reliability.
FY91	Promoted building-in reliability approach for industry by delivering invited keynote talks at IRPS, European Symposium, Reliability of Electron Devices, Failure Physics, and Analysis (ESREF) Workshop sponsored by the Semiconductor Research Council.
FY92	Took lead role at industry request, in developing technical advisory group from the industry for continuing an important workshop for wafer level reliability.
FY93	Developed a management structure for the Wafer Level Reliability Workshop to enable it to be a self-sustaining entity.
FY94	Began plans for the preparation of an invited presentation on BIR at a reliability conference in Budapest and of an invited paper on the same subject for a special issue of the Microelectronics and Reliability Journal.
FY95	Prepared three papers to promote a more rapid transition from a testing-in-reliability to a building-in-reliability approach in the semiconductor industry.
FY96	Work with members in the semiconductor industry to develop plans and organize a seminar on building-in reliability (BIR) for customers of semiconductor vendors.
FY97	Make plans for other seminars and papers with industrial colleagues.

Metrology for Process and Tool Control

Project Leader: Michael W. Cresswell

Staff: 3.0 Professionals, 0.2 Guest Scientist, 1.4 Technician

Full funding level: $0.9 M

Funding sources: NIST (84%), Other Government Agencies (16%)

Objective: Develop advanced test-structure-based electrical measurement methods and related reference materials for industry with a primary emphasis on overlay and linewidth metrology and calibration; interact with standards groups to provide a metrology base for the semiconductor tool industry.

Background: Succeeding 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 during wafer fabrication is a key factor affecting device performance and overlay control is essential for economically viable manufacturing. Reliable metrology for monitoring these parameters has been identified in the National Technology Roadmap for Semiconductors as a central requirement for maintaining the necessary fabrication-process control. The demands on gate-length and overlay metrology are increasing as the complexity of integrated circuits increases from one generation to the next. Of the several techniques of linewidth-control and overlay metrology, only electrical test structures currently have a measurement reproducibility that conforms with future projected error budgets.

Current Tasks:

1. Develop metrology for electrical linewidth

FY88	Documented and extended statistical model and error analysis for characterizing the performance of a submicrometer lithography based on electrical test structure measurements.
FY89	Demonstrated lithography-process diagnosis using rule-based analysis of spatial linewidth variations extracted from multiple design-rule structures replicated in polysilicon on 100 millimeter wafers.
FY90	Developed and demonstrated guidelines for characterizing electron-beam pattern-generator linewidth control by extracting electrical linewidth measurements from electrical test structures.
FY91	Compared measurements extracted from scanning electron microscope measurements and measurements using electrical cross-bridge structures having design linewidths to 0.3 micrometers.
FY92	Applied principles of empirical tap-width correction to linewidth extraction from cross-bridge test structures having bridge lengths shorter than 10 micrometers.

FY93	Demonstrated static measurement precision of 1 nanometer for lines with 350 nanometer design linewidths.
FY94	Compared measurements of lines having drawn widths from 0.35 micrometers to 1.5 micrometers by a range of metrological techniques including optical, electrical, and scanning electron microscopy.
FY95	Showed agreement to within 10 nanometers for several materials for electrical linewidth and the Molecular Measurement Machine (M^3) when operating in scanning-tunneling-microscope mode. Optical and electrical linewidth measurement differences are on the order of 100 nanometers.
FY96	Develop first electrical linewidth test structures with atomically-planar sidewall features having known sidewall slopes in monocrystalline material. Test to identify origins of critical dimension (CD) metrology methods divergence.
FY97	Develop electrical test structures having features with atomically-planar vertical sidewalls, which will enable co-calibration by transmission optical and scanning electron microscope metrology. Design, fabricate, and test potential future reference materials for lithography using light with a wavelength of 193 nanometers.

2. Develop metrology for electrical overlay

FY91	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 nanometers electrical metrology with commercially-available test equipment.
FY92	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.
FY93	Demonstrated the dynamic precision of electrical overlay test structures to be 1.5 nanometers, and their uncertainty less than 10 nanometers, by comparing electrical measurements with those made by the NIST Line-Scale Interferometer.
FY94	Developed and obtained patents for improved optical overlay-instrument calibration substrates and for electrical certification of graduated scales.
FY95	Designed, fabricated, and electrically tested substrates at multiple sites co-inspected by the NIST Line-Scale Interferometer.
FY96	Present paper at SEMATECH to invited industry audience on new hybrid optical-electrical test structure to facilitate pixel-calibration of optical overlay systems. Initiate a consortia with industry to evaluate new overlay-metrology methods. Develop plan to implement mix-and-match overlay metrology for 193 nanometer lithography system.
FY97	Incorporate electrical null-detectors into hybrid optical-electrical test structures to enable fabrication-process corrections of tool- and wafer-induced shift.

3. Promote development of X-ray metrology infrastructure

FY92	Led development of consensus among eight DoD industry contractors for mask-support ring dimensional standards for ARPA X-ray lithography based on finite-element analysis of residual distortion for beam-line applications.

FY93	Extended capability of mask-support ring dimensional standard for point-source systems.
FY94	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.
FY95	Prepared revisions to draft of U.S. standard and obtained concurrence with the Japanese on almost all major points previously under contention.
FY96	Achieve agreement between U.S. industry and Japan on final draft of new international voluntary standard.
FY97	Develop standard test structures to facilitate rapid low-cost inspection of feature placement on X-ray masks by beam writers.

4. Initiate Back End of Process Characterization

FY94	Identified potential process control issues. Obtained design rules.
FY95	Designed contact resistor test strip and a back end of process test chip (NIST 23). Delivered designs to contractor.
FY96	Test and evaluate test strip and chip. Deliver test code to industrial collaborator.

Metrology for Devices and Packages

Project Leader: Allen R. Hefner

Staff: 4.0 Professionals, 1.0 Graduate Research Fellow, 1.0 Visiting Scientist, 0.1 Faculty Hire

Full funding level: \$1 M

Funding sources: NIST (75%), Other Government Agencies (25%)

Objective: Promote the efficient and reliable application of semiconductor devices by: developing advanced device and package characterization methods; metrology, data, and techniques for advanced device and system simulation; and support of and participation in national and international standards and industry organizations.

Background: The project addresses needs at the boundary between the device and the device in its application. The National Technology Roadmap for Semiconductor identifies integration of component-level electrical, thermal, and mechanical models for semiconductor devices and packages, 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. Structures and operation of devices are advancing rapidly where high performance and high efficiency are required. 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. In addition, the high-speed, high-current density, and high-power dissipation levels of advanced circuits and devices have increased the importance of microelectronic package electrical and thermal characteristics to overall system performance.

Current Tasks:

1. Develop package thermal characterization and analysis techniques

FY89	Completed a five-year program for providing the semiconductor industry with methods for thermal characterization of microelectronic packages; three test methods finished this year, six overall.
FY90	Developed transient thermal model for ultra-small structures to aid in defining practical limits for the electrical measurement of temperature for these structures. Structures less than about 50 micrometers on a side represent a lower practical limit.
FY91	Demonstrated that for gallium arsenide devices on a silicon substrate, the thermal spreading resistance in the thin gallium arsenide layer beneath the device significantly increases the total thermal resistance of the device.
FY92	Completed development of a compact thermal component modeling procedure (including chip, package, and heatsink) designed for use in advanced electro-thermal system simulators.

FY93 Assisted Sandia Laboratories in the evaluation of a packaging thermal test chip designed at Sandia.

FY94 Extended NIST TXYZ thermal analysis program to include multilayer, microelectronic structures.

FY95 Developed in-house capability for computational fluid dynamics (CFD) simulations using FLOTRAN (packaged with ANSYS) and proprietary code from the University of Maryland.

FY96 Complete CFD simulations and measurements of package array in a 'lap-top-like' enclosure to assess package modeling and characterization issues important for this type system. Determine applicability of micromachined, thermally isolated heaters for use as *local* heat flux sensors for packages.

FY97 Begin development of a robust package thermal characterization procedure applicable for packages to be used in free convection, portable electronics environment. Begin development of compact package modeling procedure for use in CFD simulations.

2. Develop metrology for microelectronic packaging and assembly

FY88 Evaluated status of superconductors for packaging applications. Concluded that materials are evolving too rapidly to allow a reasonable effort.

FY89 Completed research on two-dimensional modeling of gold-aluminum intermetallic diffusion under various bonding conditions.

FY90 Published a comprehensive reference book on wire bond yield and reliability resulting from a long-term program at NIST.

FY92 Developed procedure to improve high yield and fine pitch wire bonding.

FY93 Recommended practice for bonding and metallization for use on infrared detectors for Geostationary Operational Environmental Satellite.

FY94 Participated in a Department of Commerce 232 trade investigation into imported electronic packages.

FY95 Completed setting up the experimental apparatus to measure the 60 hertz vibration modes of capillary bonding tools. Preliminary measurements have been made. Completed study of wire bonding to multichip modules and other soft substrates. Performed finite element study of wire bonding to soft substrates. (Collaboration with Computing and Applied Mathematics Laboratory)

FY96 Finish second edition of comprehensive reference book "Reliability and Yield Problems of Wire Bonding and Microelectronics." Consult with industry on wire bonding production problems.

3. Develop and establish metrology for power semiconductor devices

FY89 Constructed nondestructive device failure test system capable of determining power device failure limits with current up to 100 amperes and voltages to 2000 volts.

FY90 Organized and hosted 6th NIST/IEEE Power Semiconductor Devices Workshop. The IEEE is an engineering professional society called the Institute of Electrical and Electronic Engineers.

FY92 Established failure limits and identified failure mechanisms for bipolar-mode field-effect transistor. Discovered unexpected tendency for this device to be thermally unstable.

FY94	Provided technical support and guidance to a flat-panel display manufacturer; characterized power failures in their system that led to a redesign.
FY96	Provide technical support and guidance on integration of design aspects and concurrent engineering to U. S. Navy's Power Electronic Building Block (PEBB) Program.
FY97	Develop required electrical measurement techniques for PEBB modules and chips.

4. Develop device modeling and metrology for system level simulation

FY88	Developed first analytic model for the Insulated Gate Bipolar Transistor (IGBT) and demonstrated its usefulness in describing device/circuit interactions.
FY89	Extended IGBT model to include transients and demonstrated the need to use nonquasi-static theory to describe transient behavior.
FY90	Incorporated IGBT model into a commercial circuit simulator in collaboration with a U.S. company.
FY91	Developed, verified, and documented parameter extraction measurement procedures for IGBT circuit simulator implementation.
FY92	Completed development of dynamic electro-thermal model for the IGBT.
FY93	Completed implementation of the 'buffer layer' IGBT model into the commercial circuit simulator.
FY94	Formed the NIST Model Validation Working Group.
FY95	Completed computer framework for technology computer-aided design within the Group.
FY96	Continue leadership role in Model Validation Group. Develop IGBT model validation procedures, organize IGBT model validation task group meeting. Investigate features required for a comprehensive model development platform.
FY97	Complete recommended IGBT model validation practices for model validation standards committees.

5. Develop physics for device-level modeling and simulation

FY89	Established the limitations of conventional device physics, based on uniform materials, for devices that have increasing doping gradients for dimensions to 0.1 micrometer.
FY90	Performed first principle calculations for changes in conduction and valence bands that occur as a result of either high doping or carrier densities or both in gallium arsenide and silicon. Calculated majority- and minority-carrier mobilities in heavily doped gallium arsenide and compared with experiments; calculations included in device simulators.
FY91	Verified device physics for gallium arsenide heterostructure bipolar transistors and results in a more accurate HBT simulator.
FY92	Calculated majority- and minority-carrier mobilities in heavily doped silicon and compared with experiments; calculations included in device simulators.
FY95	Calculated majority- and minority-carrier mobilities in heavily doped aluminum gallium arsenide as functions of aluminum concentration and doping densities and compared with experiments.

FY96	Implement aluminum gallium arsenide minority and majority carrier mobility model into commercial device simulator and investigate the influence of the model on device behavior.
FY97	Investigate with industry partners methods for measuring mobilities in aluminum gallium arsenide and other compound semiconductor materials.

Thin-Film Process Metrology

Project Leader: James R. Ehrstein

Staff: 3.0 Professionals, 2.0 Technicians

Full funding level: $1 M

Funding sources: NIST (100%)

Objective: Develop new and improved measurements, models, data and reference materials 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 places 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. Among the thin-film process metrology challenges, two are targeted initially: dielectric layers, particularly gate dielectrics, and ion-implant dosimetry. The National Technology Roadmap for Semiconductors identifies robust gate dielectrics with 5 nanometer thickness as a specific on-chip materials 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. The need for implanted reference materials for process transfer and industry reference is cited in "Metrology Roadmap: A Supplement to the National Technology Roadmap for Semiconductors."

Current Tasks:

I. Establish and transfer basis for accuracy of measurement of silicon-related dielectric layers, in both at-line and in-situ modes.

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

FY88	Certified and released the first Standard Reference Materials (SRMs) for thickness of silicon dioxide, at thicknesses from 50 to 200 nanometers.
FY89	Developed computer code and released documentation for ellipsometric analysis of thickness of dielectric layers and interface region.
FY92	Developed and certified 14 nanometer and 25 nanometer silicon dioxide thickness SRMs.

FY94	Developed and certified 10 nanometer silicon dioxide thickness SRMs. Completed intercomparison with nine select laboratories for measurements of 10 nanometer oxides; demonstrated interlaboratory repeatability consistent with industrial requirements. National Technology Roadmap for Semiconductors reaffirms critical nature of ultrathin gate oxide fabrication control.
FY95	Developed cooperative program with commercial source of reference materials to establish traceability to NIST for thin oxide materials.
FY96	Initiate CRADA experiments to establish traceability of ellipsometer-based Reference Materials.
FY97	Conduct interlaboratory, intermetrology study to develop a basis for standardization of thin film measurement tools other than ellipsometers.

2. Develop understanding of relation between silicon/dielectric layer interface roughness and optical characterization techniques for dielectric layer thickness and index

FY94	Used spectral ellipsometry measurements to validate interface model used for single-wavelength oxide Reference Material certification. The National Technology Roadmap for Semiconductors affirms need to understand and control surface on which gate oxide is grown.
FY95	Established capability for "Weak Localization" measurement technique to extract quantitative measure of electronic roughness at a layer-interface.
FY96	Extend this technique to the quantitative measurement of interface roughness in typical silicon metal oxide-semiconductor field-effect transistor (MOSFET) test structures.
FY97	Experimentally compare electrical measurements of interface roughness with optical, or other "beam-probe" determinations of roughness.

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

FY95	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 need for in-situ metrology of film thickness and gate dielectric composition.
FY96	Install and test chamber at NIST; measure optical constants for silicon substrates at temperatures to 1000 °C.
FY97	Begin program of determining optical constants of critical thin films of silicon at elevated temperatures.

II. Develop reference materials for ion implant dosimetry

FY92	Established need and potential guidelines at SEMATECH-sponsored workshop for transfer standards between implant dose and sheet resistance.
FY95	Initiated program to develop reference materials for ion implant dosimetry. Provided leadership and planning input to Third International Workshop on the Measurement and Characterization of Ultra-Shallow Doping Profiles in Semiconductors; edited Workshop Proceedings.
FY96	Model and initiate empirical tests of the sensitivity of the implant dose/sheet resistance relation (for boron) to starting material and implant condition parameters.

FY97 Complete implant cycle sensitivity determinations; determine optimum process cycle; determine whether dose standard can be done directly with a specific boron isotope; begin certification process for implant dose transfer standard.

Silicon on Insulator Metrology

Project Leader:	Peter Roitman
Staff:	1.0 Professional, 1.0 Technician, 1.0 Grantee/student
Full funding level:	$0.4 M
Funding sources:	NIST (57%), Other Government Agencies (43%)
Objective:	Develop advanced measurement methods for defect detection in silicon-on-insulator material; develop silicon-on-insulator material for insertion in silicon integrated circuit manufacturing; provide expertise to other government agencies regarding silicon-on-insulator programs.

Background: Silicon-on-Insulator (SOI) wafers have advantages over bulk silicon for isolation and process simplicity, for short channel device performance, and for applications involving low power, high temperature, high speed, integrated power, and radiation hardness (including soft errors). However, several different types of defects have been identified which are unique to these materials and the conditions of their fabrication. Identification of defect types and development of characterization techniques suitable to SOI are prerequisites to both the minimization of the number of defects, through process control, and to the commercial acceptance of the material. The primary focus of this project has been on the development of characterization techniques and methods, to facilitate material improvement to the point of commercial viability. Also, several government agencies have been involved in programs to develop SOI materials, due to particular requirements of their mission, and the project has interacted with them.

Current Tasks:

1. Develop characterization techniques for SOI material

FY88	Evaluated the many existing SOI technologies. SIMOX (formation of a buried oxide by high dose ion implantation) was chosen as the most promising and, hence, the focus of the project. Completed construction of high-temperature furnace essential for SOI (SIMOX) fabrication. Completed secondary ion mass spectrometry and Rutherford backscattering round robin to calibrate impurities of importance in SOI material. Developed the use of electron channeling patterns to nondestructively measure oxide precipitates and silicon dislocations.
FY89	Began work on transmission electron microscopy (TEM) and materials analysis. (Collaboration with Arizona State University) TEM cross-sections used to show effect of annealing temperature and ambient on oxide precipitates and dislocations in the silicon film.

	Established limits of detectability for electron channeling pattern technique for defect detection. Developed etch pit with scanning-electron-microscope counting technique for low-density defects in the silicon film.
	Developed a complementary metal oxide-semiconductor (CMOS) on SIMOX process at NIST. Designed two CMOS on SIMOX test chips.
FY90	Established 1300 °C as minimum temperature for dissolution of oxide precipitate complex. Industry adopted 1310 °C or 1325 °C as standard for SOI (SIMOX) processing. Established 600 °C as the minimum implant temperature required for low-defect-density silicon films.
	Developed and experimentally verified a theoretical model for the analysis of the capacitance-voltage curve of a complete SOI stack.
	Demonstrated the improvement in spectral fit which occurs as the ellipsometric model is made increasingly physical.
	Completed NIST3A4 mask set for CMOS on SIMOX test chip. Processed initial lots at NIST.
FY91	Proved that high-leakage currents in buried oxides were due to “pipes” of silicon caused by particles on the surface of the wafer during the SIMOX oxygen implant. Transferred potassium hydroxide etch technique and results to industry. Particle problem largely eliminated by industry.
	Developed modified Secco/HF etch for reliable delineation of silicon defects. Transferred technique to industry (has become industry standard).
	Proved existence of large numbers of silicon dangling bond defects uniformly distributed through buried oxide by spin resonance capacitance voltage, etc.
FY92	Showed reduction in silicon defect density by annealing sequence.
	Identified high-field conduction mechanisms for buried oxides.
	CMOS on SIMOX processing at NIST ended.
FY93	Demonstrated the effect of nitridation of the buried oxide, using nitrogen, ammonia, and nitrous oxide ambients.
	Explained the full mechanism for formation of silicon defects in high-dose SIMOX. Demonstrated the defect types present in bonded silicon wafers (BESOI) using the techniques developed for SIMOX. Showed the experimental physics of the formation of silicon precipitates in the buried oxide at low and medium dose.
FY94	Demonstrated the effect of high-temperature annealing in the range of 1300 °C to 1350 °C on silicon defect structure and interface roughness.
	Explained the mechanism for formation of silicon defects in low- and medium-dose SIMOX.
FY95	Showed leakage current in low-dose SIMOX due to effects of silicon precipitates.
FY96	Determine dose and annealing profile effects on optimized medium dose SIMOX quality using NIST defect counting method. Begin annealing study 'outside' normal envelope to determine if more optimal conditions exist.

2. Provide technical support and assist in oversight of SOI projects for other agencies of the U.S. government

FY88-94	The primary driver for SOI development in the U.S. was the need for radiation-tolerant electronics for satellite applications. The Defense Nuclear Agency and the Strategic Defense Initiative Office were the agencies primarily concerned. The project participated in contract reviews and planning activities with these agencies.

FY95-97 The application driver for SOI development changed to low power, battery-operated, portable electronics. The Advanced Research Projects Agency initiated a program in Low Power Electronics. The project is heavily involved with the planning and management of this program.

Optical Characterization Metrology

Project Leader: Paul M. Amirtharaj

Staff: 3.0 Professionals, 1.0 Post Doc

Full funding level: $0.8 M

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

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. Advance and optimize modulation spectroscopy for the study of compound semiconductor materials and microstructures. Employ selective excitation spectroscopy to analyze gallium nitride and related nitride alloys, and apply spectroscopic ellipsometry for the optical analyses of ultrathin semiconductor and insulator layers. Develop standard research materials and methods and compile data to improve standards.

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 for increased packing density and the complex device structures that use 10 to 100 layers place stringent demands on the current analytical probes. Further device advances can be commercially realized only with the enhanced yield possible with sophisticated and dependable characterization, including real-time in-situ materials monitoring. Optical and electrical activity form the foundation of all the major electronic devices today. Optical probes are attractive and powerful for a variety of reasons. They are contactless and nondestructive, compatible with any transparent gas, capable of remote sensing and compatible with hostile environments and, hence, useful for in-situ probing during growth and processing.

Current Tasks:

1. Develop metrology to identify and quantify impurities in silicon

FY88 Assisted American Society for Testing and Materials (ASTM), a voluntary standards organization in the U.S., though 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.

FY89	Published archival summary and extended report of analysis of International Round-Robin-on-Oxygen conversion-factor for infrared measurements.
FY90	Developed fully automated analytical procedure to study oxygen in double-side-polished silicon wafers.
FY91	Completed installation and testing of high resolution and high-stability Fourier transform interferometers for impurity analysis in Si.
FY92	Completed oxygen-in-silicon Standard Reference Material (SRM) production methodology.
FY93	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.
FY94	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 centimeter.
FY95	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.
FY96	Apply spectroscopic and photoconductive probes to investigate the origin of persistent-photoconductivity and/or slow traps in integrated circuit grade silicon.
	Apply FTIR spectroscopy to determine the densities of technologically important impurities in silicon, especially integrated circuit grade wafers.
FY97	Develop improved optical probes for process induced impurities in integrated circuit-grade wafers.

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

FY90	Developed and published "A Software Program for Aiding the Analysis of Ellipsometric Measurements, Simple Spectroscopic Models" as NIST Special Publication 400-84.
FY91	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.
FY92	Provided optical characterization of silicon carbide for X-ray mask application and cadmium zinc telluride substrates for infrared materials growth.
FY93	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.
FY94	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.
FY95	Completed one-of-a-kind selective-excitation system operable in the 350 to 1100 nanometer range and initiated comprehensive defect and impurity analyses in gallium nitride.

FY96	Complete automation of the selective excitation system, with capability from the ultraviolet to the infrared region of the optical spectrum, for high-resolution optical spectroscopy. Use system to investigate gallium nitride and related materials. Apply spectroscopic ellipsometry for the optical analyses of ultrathin semiconductor and insulator layers.
FY97	Conduct selective-excitation spectroscopy and analysis of dopants in gallium nitride including magnesium and silicon.

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

FY89	Organized and hosted the International Conference on Narrow-Gap Semiconductors and Related Materials in Gaithersburg, MD, June 1989.
FY90	Edited and published Proceedings of the International Conference on Narrow Gap Semiconductors.
FY91	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.
FY92	Distributed to major semiconductor companies a questionnaire regarding the use of optical characterization techniques for materials and device analysis by the semiconductor industry.
FY93	Wrote chapter on "Optical Properties of Semiconductors" for the *Handbook of Optics*, second edition, for the Optical Society of America and McGraw Hill. Provided review of all important optical properties and techniques for measuring them. Second mailing of optical characterization survey sent out.
FY94	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.
FY95	Organized and conducted the International Workshop on Semiconductor Characterization with 280 attendees, 40 invited speakers and 80 poster papers. Workshop provided up-to-date reviews of major characterization issues. 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.
FY96	Present invited paper entitled "Double Modulation Photoreflectance" at the Symposium on Diagnostic Techniques for Semiconductor Materials Processing, Materials Research Society Fall Meeting, November 1995. Publish Proceedings of the International Workshop on Semiconductor Characterization by the American Institute of Physics Press. Publish and distribute to industry NIST Special Publication 400-98 containing results of the Optical Characterization Survey. Contribute chapter on optical properties to book on properties of narrow-gap II-VI semiconductors published by Chapman-Hall, United Kingdom.

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

FY96	Initiate the Standard Reference Data (SRD) Project entitled, "Near Band-Edge Fundamental Parameters for III-V Binary Semiconductors."
FY97	Compile changes in above parameters in doped materials as a function of carrier density.
FY98	Compile above parameters for selected ternary alloys.

Plasma Chemistry - Plasma Processing

Project Leader: James K. Olthoff

Staff: 1.5 professionals, 1.0 guest scientist

Full funding level: $0.4 M

Funding sources: STRS (100%)

Objective: To aid the semiconductor industry in the characterization of discharges used in plasma processing. Specifically by investigating 1) the effects of surface charging, 2) the chemical composition of capacitively- and inductively-coupled rf plasmas, 3) the performance of ion energy analyzers for use as plasma diagnostics, 4) the effect of ion-molecule collisions on the ions striking surfaces exposed to the plasma, and 5) 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 5 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. A "GEC rf Reference Cell" is a test chamber, "cell", in which the plasma is sustained by applying a high frequency electric field, "rf". The GEC refers to the Gaseous Electronics Conference where the need for such a standard test system was first discussed. 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.

Current Tasks:

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

FY89	Interacted with SEMATECH concerning need for characterization and calibration of a mass spectrometer/ion energy analyzer and a Langmuir probe.
FY90	Fabricated and brought to full operation GEC rf reference cell with optical, mass spectrometric, and electrical diagnostics.
FY91	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.

FY92	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.
FY93	Measured effects of trace impurities, such as oxygen or water, on electrical characteristics of argon discharges.
FY94	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.
FY95	Edited special journal issue dedicated to research performed on GEC rf Reference Cells; Constructed new inductively coupled GEC rf cell.
FY96	Complete investigation of rf discharges in sulfur hexafluoride; Complete investigation of ion energy diagnostic measurements (IEDs) in dc Townsend discharges.
FY97	Extend mass spectrometric diagnostics techniques to inductively coupled plasmas.
FY98	Extend mass spectrometric diagnostics to rf plasmas in the presence of silicon wafers and transfer to industry.

2. Investigations of surface-charging in plasma processing

FY94	Observed effects of surface charging on ion energies in rf plasmas; Initiated compilation of surface-charge related bibliography.
FY95	Demonstrated measurement of electric fields using optical techniques; Completed surface charging bibliography.
FY96	Develop method to measure surface charge using optical techniques.
FY97	Extend optical techniques to measure surface charge on bulk insulators and semiconductors.
FY98	Extend further technique to measure surface charge in rf systems and transfer to industry.

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

FY95	Initiate investigation of known electron impact cross sections for carbon tetrafluoride (CF_4) and trifluorourethane (CHF_3).
FY96	Complete electron-impact investigation for (CF_4) and (CHF_3); Publish comprehensive paper and make summary data publicly available on World-Wide Web; Measure electron attachment to Dichloro-difluoromethane (CCl_2F_2) molecules and CCl_2 radicals.
FY97	Extend investigation to include electron impact cross sections for sulfur hexafluoride (SF_6) and chlorine (Cl_2).
FY98	Evaluate ion-molecule collision cross sections in CF_4, CHF_3, SF_6, and Cl_2 and transfer to industry.

Electrical Characterization Metrology

Project Leader: Jeremiah R. Lowney

Staff: 4.0 Professionals

Full funding level: $0.8 M

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

Objective: Provide technological leadership to semiconductor and equipment manufacturers and other government agencies by developing and evaluating the methods, tools, and artifacts needed to improve the state of the art in electrical methods and nanometrology (measurements on a scale of 10 to 100 nanometers) for semiconductor materials and processes; provide silicon and compound-semiconductor device manufacturers with advanced electrical metrological techniques and models to improve device performance and reliability.

Background: The reduction in feature sizes to near 100 nanometers 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 10 nanometer resolution scale. Industry needs NIST to provide the methodology, both experimental and theoretical, to evaluate and improve materials and processes by using electrical techniques. Measurements of the dopant density 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 nanometers. Scanning capacitance microscopy is being developed as a new tool to achieve this goal.

Current Tasks:

1. Develop scanning probe microscopy for dopant and overlay profiling

FY89 Demonstrated two-dimensional mapping of silicon resistivity striations with resolution of 40 micrometers by high-density four-probe structures.

FY90 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 micrometers can be mapped, which has important application to gallium arsenide and mercury cadmium telluride materials.

FY91 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).

FY92 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 millimeters. Began development of the capacitance-sensitive circuit and theoretical modeling of the SCM measurement.

FY93 Designed, constructed, and tested an SCM for nanoscale (10 to 100 nanometers) profiling of semiconductor junctions; the design is the first to take advantage of incorporating a commercial atomic force microscope (AFM).

FY94 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.

FY95 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 nanometer 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.

FY96 Establish reliable techniques to obtain SCM data of carrier profiles.

Apply SCM method to overlay metrology. Obtain solutions in 2D and 3D for the charge density in doped silicon wafers and simulate SCM data. Develop useful, simple methodology to relate SCM data to dopant profiles.

FY97 Interact strongly with equipment and user community to transfer NIST technology; identify needed Standard Reference Materials (SRMs) for SCM measurement standards.

2. Perform bulk/thin film magnetotransport analyses of carrier densities and mobilities; develop silicon resistivity Standard Reference Materials (SRMs)

FY89 Completed extensive evaluation of a technique for impedance measurement using time varying signals for high-resistivity silicon (from 2 to 50 ohm centimeter). Developed silicon resistivity SRMs.

FY90 Demonstrated validity of the impedance technique for measuring high-resistivity silicon by comparison with traditional techniques.

Certified 155 sets of bulk silicon resistivity SRMs (51 mm diameter, 0.01 to 180 ohm centimeter); transferred, to SRM office, 101 sets of these and the final 40 sets of spreading resistance SRMs.

FY91 Certified over 400 50.8 millimeter (2 in.) diameter wafers having resistivities, from 0.01 ohm centimeter to 200 ohm centimeter, for use in multiwafer silicon resistivity SRM sets.

Established facility for variable magnetic field transport measurements over the temperature range from 10 to 400 kelvin and tested specimens of aluminum gallium arsenide/gallium arsenide, indium antimonide/indium arsenide, and mercury cadmium telluride. Developed a procedure for efficient identification of single- or multiple-carrier conduction.

FY92 Developed and applied a general technique for analyzing multicarrier conduction. Made extensive Hall and resistivity measurements on several structures. Continued work on silicon SRMs.

FY93 Developed a simple, accurate measurement method for determining the electron density and Hall mobility of semiconductor layers, based on the magnetic-field dependence of the two-terminal magnetoresistance of a rectangular layer. Applied this method to characterize accumulation layers of n-type mercury cadmium telluride infrared (IR) detectors.

Provided NOAA with characterization study of mercury cadmium telluride detectors used in Geostationary Operational Environmental Satellite weather satellites.

Completed certification and system control measurements for 135 units of SRM 2547 100 millimeter diameter silicon resistivity at the 200 ohm centimeter level.

FY94 Established high-field magnet facility. Studied two-dimensional magnetophonon effect and universal conductance fluctuations in gallium arsenide/aluminum gallium arsenide heterostructures grown in Division's MBE system as well as in silicon/germanium heterostructures grown at the Naval Research Laboratory. Continued certification of silicon SRMs.

FY95 Determined carrier densities and mobilities in mercury cadmium telluride, III-V, and high-resistivity silicon samples. Completed calculations of mobility of gallium arsenide, including electron-electron and electron-phonon scattering. Continued to measure 100 millimeter silicon resistivity SRMs. Discovered photosensitivity of resistivity to fluorescent room light, which requires that two of the seven SRMs (1 and 10 ohm centimeter) be removed from series. Showed need for further research of cause of effect before proceeding with these two SRMs.

FY96 Provide information from electrical methods as to the cause of photoresponse in several of the 100 millimeter diameter silicon resistivity SRMs. Characterize the electrical properties of samples grown in molecular beam epitaxy machine, fabricated in focused ion beam machine, or supplied by industry.

FY97 Provide electrical characterization to Group and others at NIST; assess needs for further SRMs and measurement standards.

3. Develop and apply models of scanning electron microscope signals for critical-dimension metrology (Collaboration with Manufacturing Engineering Laboratory)

FY93 Surveyed and used existing code for modeling scanning electron microscope (SEM) signals.

FY94 Wrote and documented a new Monte Carlo code, MONSEL-I, to simulate the transmitted and backscattered signals from a multilayer specimen in an SEM. The code has been used to provide a quantitative description of the signals from a gold line on a silicon substrate used in critical-dimension metrology.

FY95 Completed improved Monte Carlo code, MONSEL-II, for simulating transmitted, backscattered, and secondary electron signals in SEM. The model target is three parallel lines on multi-layer substrates. Completed work on MONSEL-III, a code for simulating short lines and vias as well as tilted substrates. Compared results of simulations with those from measured scans to obtain line edge locations to less than 10 nanometers.

FY96 Develop methodology to optimize Monte Carlo simulations of SEM signals and enhance codes as required.

FY97 Advise industrial users of MONSEL-II and MONSEL-III regarding their proper use, and extend codes based on feedback from user community. Provide modeling for development of SRMs for critical-dimension metrology.

MAGNETICS

Nanoprobe Imaging for Magnetic Technology

Project Leader: John Moreland

Staff: 3.0 Professionals, 1.0 IPA Guest Researcher, 1.0 Technician

Full funding level: $0.7 M

Funding sources: NIST (70%), Other Government Agencies (30%)

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 nanometer-scale morphological and electronic properties which directly or indirectly influence the performance of current drive designs with regard to speed-on and storage capacity. Nanometer-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 nanometer-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.

Current Tasks:

1. SPM imaging of magnetic materials and devices

FY89	Invented "tunneling stabilized magnetic force microscopy" (TSMFM) using scanning tunneling microscopy for magnetic force microscopy.
FY90	Observed superconducting vortices with TSMFM – the first observation of vortex cores using force microscopy.
FY91	Began investigating the utility of TSMFM for imaging disk drive components; imaged bit tracks on hard disk.
FY92	Imaged domain walls in garnet films provided by Jet Propulsion Laboratory for studies of vertical Bloch line random access memories (MRAMs).
FY 93	Performed AFM and MFM on Permalloy thin-film MRAMs.
FY 94	Began collaboration with U.S. disk manufacturer, and observed nanoparticles causing high error rates on hard disks, with AFM. Several labs world wide by

	that time had adopted TSMFM. Guest researcher from Switzerland arrived to learn more about TSMFM and general MFM methods.
FY95	Organized focus session on applications of SPM in the recording industry at 2nd annual workshop on "Industrial Applications of Scanned Probe Microscopy," at NIST, Gaithersburg. Awarded patent for reading and recording with TSMFM. Demonstrated utility of AFM for measuring pole tip recession on thin film heads. Obtained first scanning potentiometry images of magnetoresitive test structures fabricated at NIST. NIST employee sent to U.S. company, as part of NIST Industrial Fellows Program, to develop SPM for industrial applications.
FY96	Provide facility open to industry collaboration to optimize SPM techniques for the development and production of disk drives. Image roughness and morphology of heads and media being developed for current and future storage technologies; focus on wear studies of the head media interface. Image magnetic fields near heads and media with better than 50 nanometer resolution; correlate images to spin-stand data from U.S. company. Investigate "dip stick" force microscopy for studying lubrication layers.
FY97	Develop high-resolution scanning potentiometry based on SPM; focus on development of magnetoresistive thin-film sensors; develop apparatus for simultaneous morphologic, magnetic domain, and surface potential images of active sensors. Develop friction force microscopy for stiction and lubrication studies of the head-media interface.

2. Magnetic resonance force microscopy (MRFM)

FY96	Develop MRFM for three-dimensional imaging of magnetic phenomena with better than 1-micrometer resolution
FY97	Develop high-bandwidth SPM techniques for imaging electromagnetic fields at frequencies above 1 gigahertz.
FY98	Develop capabilities for micromachining high-performance, specialized SPM cantilevers.
FY99	Demonstrate atomic resolution MRFM.
FY2000	Establish world class facility for atomic resolution magnetic resonance imaging.

3. SPM Metrology

FY95	Demonstrated superparamagnetic cantilever coatings for MFM in collaboration with the University of Nebraska; hailed by SPM manufacturers as the first step towards quantitative MFM.
FY96	Guest researcher from University of Nebraska to help develop MFM techniques. Develop standards and standard measurement practices for MFM; start three-way collaboration among ourselves, a U.S. company, and the Electron Physics Group of the Physics Laboratory at NIST. Improve MFM resolution and image interpretation by investigating new cantilever coatings
FY97	Develop SPM for critical dimensioning of media roughness and head pole-tip recession. Improve scanning potentiometry resolutions to the 1 microvolt and 1 nanometer levels.

4. Develop low-temperature SPM

FY89	Bathysphere cryostat (developed at NIST for superconductor transport studies) adapted for scanning tunneling microscopy (STM).
FY96	Begin construction on cryogenic multimode AFM in order to extend SPM capabilities to low temperatures for fundamental studies of magnetic phenomena. Perform low-temperature SPM on magnetic films and devices provided by U.S. company as part of its development of molecular beam epitaxy for nanoengineering colossal-magnetoresistance materials.

Magnetic Instruments and Materials Characterization

Project Leader: Ron B. Goldfarb

Staff: 3.0 Professionals, 1.0 Guest Researcher, 1.0 Student

Full funding level: $0.5 M

Funding sources: NIST (75%), Other Government Agencies (20%), Other (5%)

Objective: Develop instruments, devices, techniques, and theoretical models needed to characterize the magnetic properties of films, particles, and bulk and amorphous 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 recording, practical superconductors, medicine, power conversion, and high frequency electromagnetics.

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

Current Tasks:

1. Develop new magnetic measurement instruments and techniques

FY87	Developed method to measure the radio frequency permeability of toroidal samples; useful for characterizing ferrites and amorphous alloys.
FY90	Developed method of measuring harmonic susceptibilities of superconductors; useful for characterizing high-temperature superconductors.
FY91	Determined demagnetizing factors for cylinders; needed for all magnetic measurements on cylindrical samples. Developed Hall-probe magnetometer for measurement of losses in superconductor cables carrying transport current; applicable to DOE accelerator magnets.
FY92	Published major review of alternating-field susceptometry, including design, construction and calibration of susceptometers; interpretation and analysis of data.
FY93	Developed extraction magnetometer method to measure critical current of high-temperature superconductor samples.
FY94	Devised way to self-bias magnetoresistive sensors for magnetic read heads using Néel domain walls; patent disclosure filed.
FY95	Developed vibrating-sample-magnetometer software for in-house use. Developed pulsed-field apparatus for magnetic particle acceleration for applications in medicine.

FY96	Collaborate on reciprocating-sample method of magnetization measurements for Superconducting Quantum Interference Device (SQUID) magnetometer.
FY97	Develop a radio frequency susceptometer with variable field, frequency and temperature for thin magnetic films, ferrites, superconductors.

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

FY94	Began development of magneto-optical Kerr-effect scanning near-field optical microscope for the observation of magnetic domains.
FY95	Near-field optical microscope operational at moderate resolution. Began investigation of giant second-harmonic far-field Kerr-effect in collaboration with University of Colorado.
FY96	Complete near-field optical microscope to achieve 20-nanometer resolution using symmetry-sensitive detection. Develop second-harmonic capability at NIST; use to characterize magnetic interfaces and film surfaces. Apply to magnetoresistive multilayer films used in magnetic recording.
FY97	Demonstrate sub-picosecond time-resolved magnetic characterization using second-harmonic magneto-optic phenomena in the far-field. Characterize dynamical response of thin-film magnetic recording media at frequencies above 100 megahertz.
FY98	Adapt near-field optical microscope for use with pulsed laser. Determine utility of second-harmonic magneto-optics for near-field magnetic imaging. Develop sub-nanosecond pulsed magnetic field source capable of up to one-tesla fields.
FY99	Demonstrate time-resolved near-field imaging using box-car averaging of repeatable magnetic phenomena. Characterize limits to speed of magnetic reversal in recording head structures.
FY2000	Extend time-resolved magneto-optic imaging to single-shot measurement capability. Study nonreversible dynamical magnetic phenomena on a submicrometer scale. Characterize chaotic phenomena in nanoscale giant-magnetoresistance read head structures.

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

FY90	Measured susceptibility of Inconel alloys for hydrogen fuel valves in Space Shuttle.
FY94	Characterized ferritin nanoparticles; important in medical imaging.
FY95	Measured magnetic properties of new barium-iron-titanate ferrite materials with potentially high dielectric constant and saturation magnetization; applications in microwave communications.
FY96	Characterize magnetic properties of new ferrites. Collaborate with medical researchers on magnetic nanoparticles and molecules for medical applications.

4. Develop instruments, standard procedures, and calibration standards for ac loss determination in superconductors

FY87	Measured weak-link critical temperatures and lower critical fields in high-temperature superconductors using ac susceptibility; became standard method to characterize superconductors.
FY88	Measured the susceptibility of granular and powdered superconductors under alternating current. Measured oxygen isotope effect in bismuth high temperature superconductor.
FY89	Developed model for magnetization of rectangular superconductors. Developed method to measure flux creep in granular superconductors.
FY91	Showed how increases in temperature could greatly increase rate of flux creep in superconductors; applicable to DOE accelerator magnets.
FY94	Solved DOE measurement discrepancy problem and established standard method for measuring hysteresis losses in superconductor strand (Nb_3Sn).
FY95	Began use of measurements under alternating current to probe nonhysteretic losses in superconductors.
FY96	Develop methods to measure eddy-current coupling losses in practical superconductors; applications in transmission lines, motors, fusion magnets, accelerator magnets.

Magnetic Recording Technology

Project Leader: Stephen E. Russek

Staff: 5.0 Professionals, 1.0 Student

Full funding level: $0.8 M

Funding sources: NIST (70%), ATP and Other Government Agencies (30%)

Objective: Develops measurement methods and standards required by the magnetic data storage industry to further the development of ultra-high density magnetic recording and solid state magnetic memories; includes methods to characterize submicrometer magnetoresistive sensors and memory cells, the performance of advanced heads, and nanoscale magnetic recording techniques.

Background: Magnetic data storage is one of the key industries driving the revolutions 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 high frequency response and domain structure of sub-micrometer 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.

Current Tasks:

1. Develop methods to characterize submicrometer magnetoresitive devices for use in recording heads and magnetoresitive random access memory

FY94 Developed Micromagnetic Probe station to look at local magnetoresistance and domain structure in magnetoresistive sensors.

FY95 Characterized magnetoresistive device performance as a function of device size in collaboration with industry and the National Storage Industry Consortium. Performed and developed Barkhausen and low frequency noise, high current density, and magnetostriction measurements. Developed techniques to measure wafer level response to magnetic fields at frequencies up to 100 megahertz.

FY96 Investigate size effects on magnetoresistive tunnel junctions and magnetoresistive random access memory cells. Assist industry in characterizing read head sensors.

2. Develop computer models of magnetic devices

FY94	Developed micromagnetic model of dual-layer magnetic media. Developed model of magnetic force microscopy (in collaboration with Nanoprobe Imaging Project).
FY95	Developed micromagnetic and analytical models of giant magnetoresistive devices.
FY96	Perform detailed comparison of modeling results of spin-valve devices and magnetoresistive memory cells with experimental data. Package code for distribution to US magnetics companies. Begin development of standards for micromagnetic codes and round robin comparisons of standard sample.
FY97	Transfer software to industry.

3. Develop magnetic imaging standards (in collaboration with Nanoprobe Imaging Project)

FY95	Fabricated magnetic imaging standards.
FY96	Begin round robin tests of magnetic imaging using imaging standards.
FY97	Begin magnetic media survivability studies using magnetic imaging standards. Prepare imaging standards for general distribution.

4. Develop nanoscale magnetic recording system

FY95	Built prototype nanoscale recording system. Recorded and imaged bits using advanced commercial heads.
FY96,97	Upgrade nanoscale recording system to include precision linear and rotary motion of the stage. Implement 5-axis interferometer for precise control of head orientation. Begin precision recording studies.
FY98-2000	Perform precision recording studies to determine effects of fly height and head orientation. Package system for transfer to industry. Develop protocols for standard measurement of recording parameters.

5. Develop magnetic thin-film standards

FY96-97	Develop quantitative high-frequency thin-film permeameter in collaboration with industry. Develop thin-film permeability standards.

Microstructural Analysis For Electromagnetic Technology

Project Leader: Alexana Roshko

Staff: 2.0 Professionals, 2.0 Guest Researchers

Full funding level: $0.4 M

Funding sources: NIST (50%), Other Government Agencies (42%), Other (8%)

Objective: Develop an understanding of the relationships between processing, structure, and properties of electromagnetic materials, to aid in the development of measurement methods, standards, and technology.

Background: Microstructural issues remain one of the primary limitations for applications of high-temperature superconductivity (HTS), magnetic recording, nonlinear optics, and resistive fibers. Understanding and controlling the relationships between microstructure and properties are key to developing measurements and implementing new technologies in these areas. Microwave power handling, flux pinning, phase uniformity and stability, surface roughness, process reproducibility, and degradation due to processing, are a few of the issues restricting applications of HTS. For magnetic recording, to achieve higher recording densities and faster data storage and retrieval, materials must be further advanced. Small-diameter (<20 micrometers) fibers are used as radar obscurants by the military. Information on the microstructure and resistivity of these fibers for correlation with microwave scattering coefficients is needed. Electromagnetic (eddy current) standards are used in nondestructive testing of aircraft and parts to determine serviceability. Standards are under development to improve communication between users and eddy current equipment/probe manufacturers and to make flaw detection more reliable. Nonlinear optical materials are emerging with broad applications for the communications and medical industries. Greater understanding of these complicated materials is necessary to optimize performance. The further development and understanding of the microstructures of all these materials is important for supporting national goals of improved communications and competitiveness.

Current Tasks:

1. Develop database and understanding of structure-property relationships in high-temperature superconductors

   FY92 — Initiated program to develop Scanned Probe Microscopy (SPM) imaging of HTS thin films. Obtained first images of bismuth-strontium-copper oxide and chemically derived yttrium-barium-copper oxide films.

   FY93 — Developed reliable methods for obtaining scanning tunneling microscope images of yttrium-barium-copper oxide thin films. Measured morphologies of films deposited under a variety of conditions. Assisted in development of high current pressure contacts for yttrium-barium-copper oxide thin films. Studied critical-current density in yttrium-barium-copper oxide films with varying growth morphologies. Films with higher densities of growth features found to have higher critical-current densities in field.

FY94 Used etching and an atomic force microscope to measure dislocation densities in magnesium oxide substrates; determined that they are too low to control the density of screw dislocation growth features in epitaxial yttrium-barium-copper oxide thin films. Correlated an atomic force microscope and reflection high-energy electron diffraction (RHEED) measurements of surface morphologies of etched yttrium-barium-copper oxide films; found good agreement between the two techniques.

FY95 Measured influence of film thickness on the morphology and surface resistance of yttrium-barium-copper oxide films. Found that the size of islands increased with film thickness but does not affect surface resistance.

FY96 Investigate influence of different microstructural features on power-dependent microwave losses in yttrium-barium-copper oxide films. Develop morphological standards for screening yttrium-barium-copper oxide films for microwave applications.

2. Develop database and understanding of structure-property relationships in magnetic materials

FY94 Measured the grain size and texture of chromium underlayers for magnetic storage media using transmission electron microscopy (TEM). Found that both depend on the gas pressure during deposition.

FY95 Measured grain size and surface roughness of carbon overcoats on magnetic storage media deposited under different conditions. Found that carbon layer does not always replicate the morphology of the underlying film. Initiated TEM investigation of submicrometer magnetic sensors.

FY96 Continue industrial collaboration to study the influence of different sputter gases and pressures on the microstructure and magnetic properties of underlayers and cobalt-platinum-chromium media, in order to identify what microstructure is most likely to be suitable for 10 gigabits per square inch recording densities. Measure morphologies of submicrometer sensors to assist in the development of electromagnetic measurements for these materials.

3. Develop measurement methods and database for small-fiber resistivities

FY91 Evaluated coating integrity of metal-coated glass fibers using a scanning electron microscope. Designed/prototyped apparatus to determine small changes in impedance for multiple fiber (tow), production line manufacturing.

FY92 Compared microstructure of fibers with different coatings, using scanning electron microscopy. Measured resistivity of individual fibers.

FY93 Compared microstructure of fibers with different surface treatments using scanning electron microscopy. Measured resistivity of both conventional and environmentally friendly fibers.

FY94 Designed, built, tested, and delivered a Resistive Fiber Measurement system for Army.

FY95 Investigated novel resistivity measurement method using Scanned Probe Microscopy/Potentiometry technique for smaller diameter (<5 micrometers) fibers.

FY96 Develop quantitative resistivity method using Scanned Probe Microscopy/Potentiometry.

FY97	Evaluate methods for determining resistivity of submicrometer-diameter fibers with lengths less than 1 micrometer.

4. Develop eddy current standards

FY92	Incorporated comments and criticisms from military and industry to create consensual eddy current probe impedance document.
FY93,94	Prepared, and had accepted by ASTM vote, eddy-current probe impedance document "Standard Practice for Determining the Impedance of Absolute Eddy Current Probes."
FY95	Prepared draft document for characterizing physical and electrical properties of eddy current probes.
FY96	Continue work on eddy current characterization document.
FY97	Develop/prepare draft document for characterization of eddy current instrumentation.

5. Develop measurement methods and database on microstructure of optical materials

FY92	Supplied materials data necessary to enable formation of optical waveguide laser in lithium tantalate through co-diffusion of neodymium and titanium.
FY93	Began measurements of growth of epitaxial potassium niobate thin films for optical device applications. First observation of ring features in bleached polymer films of company for optical waveguides.
FY94	Made first measurements of edge roughness of polymer waveguide films. Data used in development of a model to predict coupling losses. Measured surface morphology of optical thin films (potassium niobate and lithium tantalate) prepared by U.S. companies.
FY95	Began studies of growth mechanism and surface roughness of epitaxial titanium dioxide thin films for photocatalytic applications, critical factors for use.
FY96	Map and characterize chemistry and defect structure of large-area lithium niobate wafers to aid Maker fringe measurement, and to aid company in processing of ring laser gyroscopes. Characterize growth morphology of titanium dioxide thin films to aid development for photocatalytic applications.

SUPERCONDUCTORS

Superconductor Interfaces and Electrical Transport

Project Leader: Jack W. Ekin

Staff: 2.0 Professionals, 3.0 Students, 2.0 Technicians

Full funding level: $0.8 M

Funding sources: NIST (50%), Other Government Agencies (50%)

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. Not even the basic interface conduction mechanism is yet understood. For example, recent data in our group has shown new evidence for magnetic scattering, which may have profound consequences for the theoretical understanding of the origin of HTS and formation of high-quality interfaces. In the magnet technology area, both HTS and low-temperature superconductor (LTS) magnets are being developed in the direction of larger magnets and higher fields (as for nuclear magnetic resonance); 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 whole 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 to create a database for commercial design of large superconductor magnet systems

   FY94 Published chapter on electromechanical testing and modeling for book entitled *Composite Superconductors*; the critical J_c-B-strain surface, first discovered and modeled in our project group, was featured as the cover photo. Obtained first electromechanical data on a small *coil* of HTS bismuth conductor; these data and our accompanying interpretation were the basis for a U.S. company finding a superior epoxy system for their magnet fabrication. Measured and published the first data showing that the critical point in HTS bismuth-tape superconductor magnets will be at the ends of the magnet rather than at the high-field position in the middle as for low temperature magnets. Patents were filed by a U.S. company on new schemes for compensating for this effect.

FY95 Performed first very-high-field (23.5T) measurements of the effect of axial strain on critical current of experimental niobium-tin superconductor for use in the design of nuclear magnetic resonance superconductor applications. Measured effect of using dispersion hardened silver-magnesium-nickel sheath material in place of a silver sheath material on the irreversible strain limit of bismuth superconductors. Measured effect of reaction mandrel holder on prestrain and critical current of a niobium-tin candidate conductor for the International Thermonuclear Experimental Reactor design.

FY96 Develop technique for accurately measuring Young's modulus of niobium-tin conductors at cryogenic temperatures. Develop metrology for field-angle measurements at variable temperatures at very high magnetic fields.

FY97 Measure the strain-scaling parameters for ternary Nb_3Sn superconductors. Develop metrology for determining the effect of uniaxial strain on the critical temperature of Bi superconductors.

FY98 Develop metrology for electromechanical testing of magnet coil structures at elevated temperatures.

FY99 Obtain data base needed to extend the Strain Scaling Law to three dimensions.

2. Develop metrology for evaluating superconductor interfaces and obtain database for development of high-quality electronic contacts and Josephson junction devices

FY91 First high-temperature superconductor contact patents issued to NIST: "Method for Making Low Resistivity Contacts To High-T_c Superconductors," and "High-T_c Superconductor Contact Unit Having Low Interface Resistivity, and Method of Making."

FY92 Third HTS contact patent awarded to NIST: "High-T_c Superconducting Unit Having Low Contact Surface Resistivity."

FY93 Performed a time exposure experiment for measuring the degradation rate of the surfaces of superconductors made from yttrium-barium-copper oxide (YBCO); results showed little effect of air exposure up to 100 minutes, much longer than expected; interface conductivity data showed little difference from *in situ* processed contacts, indicating that considerable improvement may be possible with *in situ* contacts. Fourth HTS contact patent awarded to NIST: "High-T_c Superconductor Contact Unit Having Low Interface Resistivity."

FY94 Measured the conductivity at the interface between an yttrium-barium-copper oxide thin film and a silver contact; measurements covering five orders of magnitude of contact resistivity. Surprisingly, the transport characteristics of the interface indicated evidence for magnetic scattering over the entire conductivity range, indicating there may be a common important surface barrier in the thin film.

FY95 Performed an annealing study on a series of in-house-fabricated contact interfaces to determine the effect of oxygen annealing on contact resistivity and transferred the information to industry for optimization of the annealing conditions for *ex situ* contacts. Developed a new lead-gold buffer layer for the integration of HTS and silicon-based contact systems.

FY96	Measure annealing characteristics of the yttrium-barium-copper oxide and gold system and use the higher melting temperature of gold to determine whether the dominant effect of oxygen annealing contacts between the thin film and the gold contact is oxygen diffusion or noble metal diffusion. Measure performance of Tl-based and Nd-based oxide superconductor interfaces for contact fabrication and pairing symmetry modeling. Measure transport properties of *a,b*-axis contact interfaces; determine the crystalline anisotropy of the contact resistivity and its consequences for contact fabrication technology.
FY97	Develop metrology for electromechanical testing of wire bond contacts. Develop contact methods for single-crystal HTS radiometer for electrical substitution of power standards. Develop metrology for high-power microwave interface resistivity measurements.
FY98	Fabricate a-b axis YBCO film interfaces and measure the anisotropy of interface conduction. Develop *in situ* STM measurement system for conductivity mapping of HTS interfaces immediately after fabrication.
FY99	Develop submicrometer HTS interface test capability.

High Performance Sensors, Converters, and Mixers

Project Leader: Erich N. Grossman

Staff: 3.25 Professionals, 1.0 Guest Researcher, 1.0 Student, 0.25 Technician

Full funding level: $0.6 M

Funding sources: NIST (54%), Other Government Agencies (38%), Other (8%)

Objective: Develop electromagnetic field sensors and frequency converters for measurements and standards in support of other NIST divisions. Apply advanced superconducting integrated circuit fabrication, cryoelectronic, infrared, millimeter-wave, and other techniques to solve measurement problems at the limits of technology. Projects cover applications of 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 Superconducting Quantum Interference Device 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, with the Radiometric Physics Division, develops precision radiometers for this type of measurement. Accurate measurement of coupling efficiency, both for conventional surface absorbers and for IR micro-antennas, is also a great concern to commercial and military developers of next-generation IR sensors. Finally, this project, together with the Time and Frequency Division, develops mixers for frequency synthesis and high resolution spectroscopy in the IR. A number of applications, notably in wavelength-division multiplexed optical communication, require accurate measurement of very large frequency differences between two sources. The very high bandwidth of superconducting junctions naturally suggests them as candidates for such frequency metrology applications.

Current Tasks:

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

FY86	Concept of Kinetic Inductance Thermometer (KIT) developed.
FY90	Demonstrated a best case resolution of 1 picowatt using KIT without absorber.
FY93	KIT integrated with absorber which degraded resolution by more than a factor of 1000.

FY95	Dropped KIT in favor of transition-edge thermometer to improve manufacturing. Stabilized absorber to improve resolution. Demonstrated ability to fabricate transition-edge thermometers.
FY96	Deliver radiometer to Radiometric Physics Division, NIST.

2. Develop infrared antennas and diodes for solar power generation

FY95	Project begun with funding from Air Force. Collaboration with Time and Frequency Division, NIST, to develop accurate measurements of efficiency of infrared antennas and lithographic diodes.
FY96	Fabricate near-IR antenna, using electron beam lithography, and measure efficiency; fabricate lithographic metal-insulator-metal diodes and measure efficiency.

3. Develop infrared antennas and bolometers for focal plane arrays

(a) Room-temperature devices

FY90	Measured 50% coupling efficiency of lithographic spiral antenna to radiation in the 10 - 30 micrometer wavelength range.
FY93	Funding obtained through Idaho National Engineering Lab for antenna-coupled, 10-μm wavelength imaging arrays.
FY94	Measured significantly lower noise on ultrathin Nb microbolometers than on conventional bismuth bolometers (15 dB lower 1/f noise, NEP = 70 $pW/Hz^{1/2}$).
FY95	Measured cross-polarization rejection ratio for lithographic spiral antenna.
FY96	Complete project.

(b) Liquid-nitrogen-temperature Devices

FY94	Measured (then) world-record low noise (NEP = 9 $pW/Hz^{1/2}$) on antenna-coupled, high temperature superconductor transition-edge microbolometer.
FY94	Began collaborative project on suspended, surface-absorbing transition-edge bolometers with a U.S. company.
FY95	Measured world record low noise level (NEP = 1.5 $pW/Hz^{1/2}$) on company bolometers.
FY96	Measure world record low noise level (NEP = 1.0 $pW/Hz^{1/2}$) on company bolometers. Demonstrate imaging capability in a small linear array.

4. Develop mixers for frequency synthesis

FY93	Measured world record large bandwidth (5 terahertz) on Josephson junction made from yttrium-barium-copper oxide via Shapiro steps.
FY94,95	Measured bandwidth of 27 gigahertz on Josephson junction made from yttrium-barium-copper oxide at a frequency of 30 terahertz via direct microwave intermediate frequency.
FY95	Developed optical fiber-coupled mixer block for Josephson junctions made from yttrium-barium-copper oxide and observed mixing between stabilized laser diodes operating at a wavelength of 780 nanometers.

FY96	Measure bandwidth of the mixing of the laser signals; measure high-harmonic mixing performance in the frequency range from 70 gigahertz to terahertz.

5. Develop SQUIDS for Gravity Probe B

FY95	Delivered complete DC SQUIDS to Stanford University for possible use in a satellite based experiment. Low-frequency noise (1.9 x 10^{-30} J/Hz at 0.1 Hz) was somewhat larger than expected.
FY96	Terminate project at end of 1995 calendar year unless noise figure significantly improved.

6. Develop AC/DC thermal converter

FY94	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.
FY95	Performance analysis made of alternating and direct voltage converter using transition-edge thermometers.
FY96,97	Design and evaluate a detailed chip layout and cryogenic-to-room temperature transition will be designed and evaluated.

Josephson Array Development

Project Leader: Clark A. Hamilton

Staff: 3.25 Professionals, 0.25 Technician

Full funding level: $0.9 M

Funding sources: NIST (50%), Other Government Agencies (50%)

Objective: Advance the sensitivity, accuracy, and speed of electronic measurement by developing Josephson array circuits and systems for such uses as programmable dc voltage standards, waveform synthesizers, and frequency sources. 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 measurement of voltage. Josephson array technology provides the means to meet these requirements. 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 dc Josephson standards operating at one volt and at ten volts

FY84	Theoretical and processing advances make one volt Josephson standards feasible.
FY85	One volt Josephson chip developed.
FY86	Josephson array adopted as basis for national volt.
FY87	Ten-volt Josephson chip developed.
FY89	First commercial one-volt Josephson voltage standard system (using NIST chips).
FY87-94	NIST supplies 176 chips to 36 national, military, and commercial standards laboratories in 20 different countries.
FY93	The program NISTVolt approved by NIST for distribution to other standards laboratories using NIST Josephson Voltage standard chips.
FY94	First production of Josephson array chips by U.S. company.
FY95	Development of compact Josephson voltage standard for Sandia/NASA begins.
FY96	Prototype of compact system to be delivered.

2. Develop programmable Josephson voltage standards

FY93	Concept of programmable Josephson standard developed.
FY94	Publication of concept and first experimental results.
FY95	First useful measurements made with programmable standard. High speed bias system developed. Superconductor-normal-superconductor junctions developed to improve programmable voltage standard. Pulse driven concept invented.
FY96	Demonstrate high accuracy sine wave synthesis with programmable Josephson voltage standard.
FY97	Provide Electricity Division with Programmable Voltage Standard for dc and ac measurements.

3. Develop Josephson Array Oscillators

FY90	Concept of phase-locked two-dimensional (2D) arrays developed.
FY91	Demonstrated first coherent emission from two-dimensional arrays.
FY92	Received U.S. patent for two-dimensional array oscillator invention. Characterized frequency response of oscillators.
FY94	Demonstrated off-chip oscillator emission from in the frequency range between 52 and 230 gigahertz. Measured record narrow (10 kilhertz) phase-locked oscillator linewidth. Completed stability analysis of 2D arrays.
FY95	Determined intrinsic resonance structure in 2D arrays. Calculated stable phase-locking parameters in two-cell ladder array. Developed fabrication technology for array oscillators operating at a frequency of 300 gigahertz and emitting signals having milliwatts of power.
FY96	Demonstrate signals with milliwatt power from high-power oscillator designs. Measure power and linewidth off-chip.
FY97	Develop high-T_c phase-locked array oscillators for higher (terahertz) frequencies.

Nanoscale Cryoelectronics

Project Leader: Richard L. Kautz

Staff: 6.25 Professionals, 1.0 Student, 0.25 Technician

Full funding level: $1.1 M

Funding sources: NIST (75%), Other Government Agencies (25%)

Objective: Develop ultra-small electronic devices operated at cryogenic 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 x-ray 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 a new fundamental standard of capacitance and may lead to an improved measurement of the fine structure constant. The hot-electron x-ray detector achieves better energy resolution than conventional detectors without sacrificing either detection area or response time, and promises rapid commercial introduction in x-ray materials-analysis systems.

Current Tasks:

1. Develop single-electron pump for metrological applications

FY91	NIST Competence funding received for the first of five years to support the development of an accurate electron pump.
FY92	Error rate of electron pump analyzed theoretically and shown to require at least five tunnel junctions for metrological accuracy. Single- electron transistors required for testing pump performance fabricated, tested, and shown to be of adequate noise performance.
FY93	Five-junction electron pump fabricated and tested. Effect of environmental noise on pump accuracy investigated theoretically.
FY94	Experimental results on the five-junction pump were published, demonstrating an accuracy of 0.5 part per million.
FY95	Seven-junction pump designed, fabricated, and underwent preliminary testing.
FY96	Complete functional testing of the seven-junction pump. Begin development of capacitance standard in collaboration with Electricity Division.
FY97	Continue development of capacitance standard. Begin detailed experimental investigation of error mechanisms in electron pump.

2. Develop hot-electron microcalorimeters as X-ray detectors

FY94 Microcalorimeter based on sensing temperature of electrons in a metallic absorber operated at a very low temperature (near 100 mK) was conceived, fabricated, and tested, to demonstrate an energy resolution (22 eV at 6 keV) which is an order of magnitude improvement over conventional detectors. Achieved a sensitivity (3 x 10-13 $W/Hz^{1/2}$) which was the best ever recorded for a bolometric device.

FY95 Detectors with large area (0.25 mm^2) and fast response time (10 μs) demonstrated, using a normal-insulator-superconductor tunnel junction thermometer and a superconducting transition-edge thermometer operated with electrothermal feedback. Achieved an energy resolution of 0.2 eV for a small-area detector responding to a heat pulse, the best resolution ever obtained in any calorimetric technology.

FY96 Optimize performance of transition-edge thermometers to achieve the highest possible energy resolution in x-ray microcalorimeters.

FY97 Optimize detector geometry, materials, and electronics for specific x-ray applications. Investigate use of hot-electron sensors for detection of radiation other than x-rays.

3. Develop practical hot-electron X-ray system for microanalysis applications

FY95 Design, fabricate, and test cryostat with an adiabatic demagnetization refrigerator (ADR) to achieve an operating temperature of 80 millikelvin directly from a helium bath which nominally operates at a temperature of 4 kelvin (or 4000 millikelvin).

FY96 Install and test the operation of SQUID preamplifier, x-ray window, and hot-electron x-ray detector in the cryostat. Demonstrate the detection system as microanalysis tool.

FY97 Optimize performance of the hot-electron detection system for the highest energy resolution, largest detection area, and fastest response time. Develop efficient codes for rapid pulse analysis.

High-T_c Electronics

Project Leader: David A. Rudman

Staff: 4.25 Professionals, 1.0 Guest Researcher, 2.0 Students, 0.25 Technician

Full funding level: $1 M

Funding sources: NIST (50%), Other Government Agencies (50%)

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 Electromagnetic Fields Division)

   FY92 Collaborated with University of Colorado on measurement of microwave surface resistance (R_s) of HTS films using parallel plate resonator.

   FY93 Implemented dielectric cavity resonator technique for R_s measurements. Obtained significant improvement in measurement reproducibility. Developed novel technique to measure microwave properties of tunable thin film capacitors at cryogenic temperatures (with University of Colorado).

   FY94 Refined dielectric resonator technique. Compared results at different frequencies. Measured microwave properties of tunable capacitors made from strontium titanate at cryogenic temperatures (76 kelvin and 4 kelvin).

   FY95 Extended dielectric resonator technique to measure power dependence of R_s using pulsed microwave approach to avoid sample heating. Began industrial collaboration to improve and use measurement technique.

   FY96 Improve power handling measurements, including modeling of fields in cavity. With industrial collaborators, compare cavity resonator measurements to other techniques. Transfer cavity technique to interested parties.

2. Characterize microwave performance of HTS films (with Microstructural Analysis Project)

FY95	Measured dependence of low-power R_s on film thickness. Correlated with film microstructure.
FY96	Begin study of power dependence of R_s as a function of film processing parameters, using films made at NIST and from industrial collaborators. Correlate with film microstructure and dc electrical properties.
FY97	Continue study of microwave performance of HTS films. Compare results to models for microwave losses in superconductors. Compare performance of unpatterned films with patterned devices. Provide industry with guidance to understanding and improving performance.

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

FY93	Fabricated and measured the first thin-film tunable resonator, operating at a frequency of 5 gigahertz, made from HTS films and an electrically adjustable thin film capacitor, in collaboration with University of Colorado.
FY94	Developed cryogenic microwave test fixture and probe for testing HTS devices. Modified NIST calibration software (DEEMBED) for use with superconducting calibration standards to perform calibrated on-chip measurements. Performed calibrated measurements on tunable thin-film superconductor-ferroelectric microwave transmission lines and resonators.
FY95	Compared performance of HTS microwave devices patterned by different techniques (in collaboration with other laboratories). Completed procurement for cryogenic microwave probe station.
FY96	Develop techniques for calibrated cryogenic microwave probing of superconducting and other devices. Use probe station to measure power-dependent performance of HTS devices.
FY97	Provide industry with measurement support for cryogenic microwave devices using probe station, and transfer techniques to industry.

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

FY91	Developed superconductor-normal metal-superconductor (SNS) Josephson junctions using HTS films.
FY92	Improved junction fabrication process. Confirmed that devices behave as predicted by standard models.
FY93	Developed technique to increase resistance of the fabricated junctions. Coupled junctions to far infrared laser using lithographed antenna and measured response of the junctions up to the highest frequency that such junctions had ever been operated (8 terahertz). Fabricated world's first HTS SNS junctions and Superconducting Quantum Interference Devices (SQUIDs) over HTS ground plane. Demonstrated phase locking between two HTS junctions at frequencies up to 1.06 terahertz and temperatures up to 35 kelvin.
FY94	Measured heterodyne mixing products from HTS junctions at frequencies as high as 30 terahertz, with difference frequencies up to 27 gigahertz (in collaboration with other Groups). Demonstrated that HTS junctions produce

sufficiently large steps at a temperature of 38 kelvin and a frequency of 62 gigahertz for use in programmable voltage circuits.

FY95 Determined that microwave-induced Shapiro steps in these junctions flat to approximately 5 parts per million at a temperature of 4 kelvin and 100 parts per million at a temperature of 76 kelvin (both numbers measurement limited), indicating junctions may be appropriate for voltage standard applications. Demonstrated resonant phase-locking scheme for HTS arrays for use as mm-wave sources. Developed first SNS junctions on Si substrates (in collaboration with a U.S. company).

FY96 Determine applicability of SNS process to the fabrication of high-performance SQUIDs. Test alternate junction technologies for application to voltage standards and other measurements (in collaboration with several institutions).

5. Develop HTS bolometers as improved radiometers

FY94 Fabricated first HTS antenna-coupled microbolometers using thermally-isolated yttria-stabilized zirconia membranes on silicon substrates. Devices were the lowest noise, fastest liquid-nitrogen-cooled detectors ever.

FY95 Developed process to fabricate large-area HTS films on silicon membranes. Device geometry suitable for electrical-substitution radiometer.

FY96 Measure electrical noise in HTS films at transition temperature on different substrates to determine applicability to radiometer. Design, fabricate and test prototype HTS bolometer (with a U.S. company and Radiometric Physics Division).

FY97 Design and test prototype electrical-substitution radiometer for use as transfer standard (same collaborations).

FY98 Transfer bolometer fabrication to industry.

Superconductor Standards and Technology

Project Leader: Loren F. Goodrich

Staff: 1.0 Professional, 2.0 Students, 1.0 Technician

Full funding level: $0.4 M

Funding sources: NIST (50%), Other Government Agencies (47%), Other (3%)

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 will become 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.

Current Tasks:

1. Develop international standards for superconductors

FY89	International Electrotechnical Commission (IEC) Council established Technical Committee, TC 90, to create international standards for superconductivity.
FY90	First technical committee meeting held; two Working Groups formed. First working group meeting held; Goodrich became U.S. Technical Advisor to TC 90.
FY91	Working group meeting in Boulder; Goodrich became the Convener of Working Group 2 and drafted the first IEC standard test method.
FY92	Working Groups 1 and 2 draft documents were reviewed; a third working group was formed.
FY93	Five New Working Item Proposals were considered; chief architects assigned to each of these.
FY94	Japanese National Committee (JNC) created the first draft of three of the five proposals; Goodrich became Chairman of TC 90.

FY95	Working group meeting held to advance draft documents; meetings were held to discuss the status and existing Committee Drafts.
FY96	Work on draft documents.
FY97	Meetings to be held in China in October 1996.

2. Develop metrology for I_c measurements on HTS

FY93	Technical Working Area (TWA) "Characterization and Evaluation of High-Temperature Oxide Superconductors" proposed at meeting of Versailles Project on Advanced Materials and Standards (VAMAS).
FY94	Started separate interlaboratory comparisons of I_c measurements on HTS samples in U.S., Europe, and Japan. Two samples from U.S. industry were used.
FY95	Reported preliminary results of U.S. comparison, the first successful comparison of I_c on HTS; measurements in U.S. comparison completed and final report started.
FY96	The final report on U.S. comparison will be completed; comparisons in Japan and Europe will be completed; second stage comparison planned.
FY97	Conduct second stage interlaboratory comparison.
FY98	Analyze results from second stage and draft set of guidelines for measurement of I_c in HTS materials.

3. Develop metrology for I_c measurements on LTS

FY86	VAMAS established technical working area on superconducting and cryogenic structural materials.
FY87-88	First international interlaboratory comparison of I_c measurements started; three samples were used, one each from Europe, Japan, and USA. NIST discovered significant source of variation in measurements.
FY89	NIST asked to draft a test procedure for second comparison.
FY90,91,92	Second comparison started and continued, using NIST procedure; a NIST Standard Reference Material and a wire sample were used.
FY93	Final report on VAMAS comparison started.
FY94	NIST helped establish standard I_c measurement technique for superconducting wire to be used in the International Thermonuclear Experimental Reactor (ITER). Participated in and reported on the first ITER interlaboratory comparison of I_c measurements.
FY95	U.S. procedure used in a second ITER interlaboratory comparison. Conducted comparisons with members of the ITER U.S. Home Team to determine the accuracy of I_c measurements on superconducting wires and assist them in reducing their uncertainties; produced a 1-hour training video.
FY96	Create an accurate database of magnetic field and temperature dependence of I_c up to temperatures of 5.0 kelvin in liquid helium; develop I_c measurement capability up to 100 amperes in helium gas over the temperature range of 5 to 10 kelvin to determine the temperature stability margin for ITER and magnets that operate near 10 kelvin.

4. Develop metrology for sensitive low-temperature measurements

FY89	Developed first passive I_c simulator based on earlier NIST active simulator; new design is sample-substitution box which can be used to compare dc and pulse techniques for measuring I_c in HTS.
FY90	Direct comparison made of steady state and pulse techniques on HTS samples and an I_c simulator.
FY91	Developed new active simulator with I_c selectable from one thousandth of an ampere to 10,000 amperes; first 50-ampere I_c simulator built and used in an interlaboratory comparison.
FY92	Developed hybrid simulator which is easier to calibrate; conducted a simulator comparison with two other U.S. labs; developed high-current 100-300 ampere pressure contacts to HTS tapes; began design and construction of a high-current variable temperature cryostat.
FY93	Participated in VAMAS interlaboratory comparison of critical magnetic fields, using SRM-1457 to check magnetic field calibrations among 11 laboratories. Designed custom simulator of high mutual inductance to simulate coils. Started preliminary testing of high-current variable temperature cryostat.
FY94	Made transport residual resistivity ratio measurements on high purity aluminum bars to compare with eddy current decay method. Conducted a simulator interlaboratory comparison with 12 U.S. labs
FY95	Developed a custom simulator for a U.S. company; made transport magnetoresistivity measurements on high purity aluminum and copper bars to compare with eddy current decay method.
FY96	Finish fabrication and testing of the custom simulator; loan I_c simulators to two U.S. laboratories.

5. Develop metrology for artificial pinning-center (APC) superconductors

FY94	Measured magnetization of APC thin films to confirm anomalous behavior of I_c caused by layer structure. Discovered that the critical state of a superconductor with periodic pins is terraced.
FY95	Developed model for magnetic flux-pinning mechanism in superconductors with planar proximity-coupled pins. Completed research on ferromagnetic APC in niobium-titanium wires.
FY96	Project completed.

LOW FREQUENCY

Impedance Standards and Measurement Techniques

Project Leader: Norman B. Belecki

Staff: 1.2 professionals, 1.6 Technicians

Full funding level: $0.5 M

Funding Sources: NIST (56%), Other (44%)

Objective: Provide calibration services for impedance and impedance ratio standards, implement new standards, instrumentation, and measurement techniques in support of the Division's capacitance, inductance, and decade ratio transformer calibration services, expand the parameter space of those services to include frequencies up to 100 kilohertz, and establish the capability for routine, high-accuracy measurements of dissipation factor for standard capacitors.

Background: U.S. industry requires impedance standards, measurement techniques, instrumentation, and measurement traceability for quality assurance in the manufacture, sale, and maintenance of electronics products, the development of world-class instrumentation for impedance and related measurements, and the industry-wide use of impedance-based sensors for process monitoring and control. More specifically, an improved and expanded NIST impedance calibration service covering calibrations of capacitance, inductance, and loss (D) in the frequency range from 10 kilohertz to 100 kilohertz is needed to develop, produce, and maintain new LCR meters used throughout the electronics industry. Technical requirements are shown below.

	Have:	Need:
C uncertainty:	± 2 - 200 ppm	± 0.1 - 20 ppm
L uncertainty:	± 0.02 - 1%	± 0.0015 - 0.05%
Bandwidth:	50 Hz - 10 kHz	12 Hz to 100 kHz
D uncertainty:	Not offered	± 1 ppm

Most of the development of new standards and instruments is done in two other, closely related projects in the Division. In the first, Generation and Measurement of Precise Signals, development of automated instrumentation based on digital techniques for waveform generation and analysis to measure impedances over an extended frequency range (50 hertz - 100 kilohertz) takes place. Standards with known values and frequency response based on NIST calculable capacitors and the bridge technology developed for their use will result from of the Quantum Resistance and Capacitance Project. This project then melds the outputs of the other two into improved calibration services and provides for improved procedures, quality assurance, and maintenance of local standards for the calibration services.

Current Tasks:

1. Provide calibration support and other measurement services for industry

Calibrations

FY	Capacitance Standards	Inductance Standards	Impedance Points	Inductive Voltage Dividers
1990	178	147	465	37
1991	155	128	435	32
1992	159	146	433	31
1993	132	119	331	27
1994	103	119	368	26
1995	105	94	343	19

FY91 Completed an inductance comparison with the Canadian national measurement laboratory; Carried out a pilot Measurement Assurance Program (MAP) with the Army Primary Standards Laboratory.

FY92 Completed a pilot round-robin/MAP with four Los Angeles area laboratories; Completed refurbishing an oil bath to improve working capacitance standards.

FY93 Re-established the MAP for capacitance as a Special Test service.

FY94 Established a group of fused-silica capacitors to serve as working standards; Wrote and implemented software to improve inductance measurements by using predicted values of standards instead of last calibration results; Performed Special Tests on a divider from the Canadian national measurement laboratory, and three special capacitors from an aerospace company.

FY95 Completed an analysis of uncertainties of the capacitance calibrations; Developed new criteria for capacitor stability during calibration; Carried out an evaluation of the first new commercial fused silica capacitance standard for an aerospace company.

FY96 Publish capacitance MAP documentation; Complete capacitance calibration documentation; Provide calibration and special services as required.

FY97 Publish inductance calibration documentation; Provide calibration and special services as required.

FY98 Provide calibration and special services as required; Improve services as technology permits.

2. Automate the calibration of impedance standards

FY92 Made measurements to evaluate the prototype Digital Impedance Bridge for the calibration of inductors.

FY93 Evaluated a prototype automated binary inductive voltage divider system for calibrating inductive voltage dividers; Established a procedure to use a commercial impedance meter as a comparator to replace the manual Type 12 capacitance bridge for some capacitance standards.

FY94 Began using a commercial inductance meter as a comparator for all inductance calibrations; Completed an international comparison of inductors

(10 mH) with less than 5 parts per million disagreement with other national laboratories and less than 10 parts per million disagreement among three NIST methods (NIST uncertainties 19 –> 60 parts per million).

FY95 Implemented use of a commercial capacitance meter for the calibration of capacitors (capacitance greater than 1 nF, test frequency 1 kilohertz).

FY96 Test the prototype three-voltmeter Digital Impedance Bridge for inductance calibrations.

FY97 Implement use of the Digital Impedance Bridge for routine inductance calibrations; Evaluate the binary inductive voltage divider system as an automated capacitance comparator to replace the manual Type 2 bridge.

FY98 Replace the Type 2 bridge and document the new system (Task end).

3. Rejuvenate and improve the calibration service for inductive voltage dividers

FY95 Trained new technician to calibrate inductive voltage dividers; Established check standards for the calibration system.

FY96 Train another new technician; Evaluate new binary divider system for calibrations of inductive voltage dividers at frequencies greater than 1000 hertz.

FY97 Re-evaluate the decade transformer standard now used as a reference; Implement use of binary divider system and modelling approach to improve inductive divider system calibrations.

FY98 Complete documentation of this calibration area (Task end).

AC-DC Difference Standards and Measurement Techniques

Project Leader: Joseph R. Kinard

Staff: 2.0 Professionals, 1.0 Technician, 1.0 Guest Scientist

Full funding level: $0.7 M

Funding sources: NIST (73%), Other (27%)

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 microvolts per volt to 5 microvolts per volt to <0.1 microvolts per volt to 1 microvolt per volt. 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, 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 volt to 1000 volts at 2 hertz to 1 megahertz; and for current from 1 milliampere to 20 amperes at 2 hertz to 100 kilohertz

FY86	Studied multijunction thermal converters and established them as the NIST primary standards of ac–dc difference for alternating voltage and current.
FY88	Recharacterized thermal voltage converters and reduced uncertainties in the frequency range 0.1 megahertz - 100 megahertz.
FY94	Studied the voltage dependence of thermal converters in the 200 volt - 1000 volt range and recharacterized the NIST high-voltage standards.
FY95	Studied and recharacterized thermal converter standards at 10 hertz to permit reduction in calibration uncertainties; Provided new ac-dc difference reference values from 10 kilohertz up to 30 megahertz to maintain consistency between this activity and NIST's higher frequency ac-dc difference calibration service.
FY96	Fabricate and test new high-current, thin-film thermal converter units to replace damaged traditional converters; Fabricate and test high-voltage, binary divider to confirm scaling of 200 volt - 1000 volt ranges; Recent international comparisons revealed significant variations between national laboratories at these voltages; Extend and document transfer shunt calibrations up to 100 kilohertz, down to 10 hertz, and up to currents of 20 ampere.
FY97	Complete and publish total reassessment of ac-dc difference calibration service uncertainties with a view to significant reductions.

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

FY89	Designed structure and photomasks for prototype thin-film multijunction thermal converters.
FY90	Perfected stress-balanced, multilayer membrane required for thin-film converter fabrication.
FY91	Mounted and tested completed chips.
FY92	Developed improved bonding pads for thin-film converters to greatly reduce errors as current converters; Patent granted February 1995; Cooperative program with industrial partner directed to the development and production of thin-film multijunction thermal converters.
FY93	Designed and produced integrated micropotentiometers which combined high performance multijunction converter and thin-film output resistors on the same chip; Patent granted February 1994.
FY95	Solved a remaining problem with wafer cleaning and metal to metal contacts, and continued successful production of converter chips; Fabricate additional converter chips, mount, and characterize as working standards; Provide chips to DoD and Sandia laboratories as per agreements.
FY96	Characterize thin-film converters at various voltages, currents, and frequencies at room and cryogenic temperatures and incorporate these devices as reference and working standards.
FY97	Develop and publish description of broadband mounting substrate to permit extension of integrated micropotentiometer frequency range; Employ these devices as reference and working standards.

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

FY93	Developed preliminary design for low-temperature primary standard converters based on superconducting kinetic inductance thermometer sensor.
FY94	Began equipment procurement; Performed preliminary, low-temperature ac-dc difference measurements on thin-film multijunction thermal converters.
FY95	Began study of low-temperature converter design using alternative superconducting transition edge device as sensor; Transition edge device appears more conducive to fabrication and incorporation into converter than kinetic inductor as originally planned.
FY96	Assemble cryogenic system, make prototype converter chips, and begin evaluation of new low-temperature devices.
FY97-98	Confirm accuracy of new low-temperature converters and establish them as NIST primary standards, if appropriate.

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

FY93	Cooperative program with industrial partner directed to the improvement of single junction thermoelements; second cooperative program directed to characterization of a new automated thermal transfer standard.
FY94	New cooperative program with industry directed to the improvement of voltage coefficients and frequency compensation for their high voltage range resistors; cooperative program with University of Maryland, Department of Materials and Nuclear Engineering, directed to utilization of thin-film multijunction thermal converters to measure properties of sputtered metals during deposition.
FY95	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
FY96-97	Participate in and publish results for international comparisons of multijunction thermal converters.

Waveform Acquisition Devices and Standards

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

Staff: 5.0 Professionals, 0.4 Technician

Full funding level: $0.7 M

Funding sources: NIST (67%), Other Government Agencies (28%), Other (5%)

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 up to 50 gigahertz.

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. Data converter sales were $1.1 billion in 1990, and sales of waveform recorders and analyzers reached $718 million in 1991. 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 gigahertz. 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

FY89 — Institute of Electrical and Electronic Engineers (IEEE) issued *Trial Use Standard for Digitizing Waveform Recorders*, developed under NIST leadership; Many NIST-developed test methods are included.

FY90 — Studied effects of timing jitter in sampling systems, award-winning paper published.

FY91	Characterized filters for analog-to-digital converter test bed; Subcommittee on A/D converters formed under IEEE.
FY93	Developed reference pulse generator for use in pulse measurement intercomparison program (round-robin); Analyzed performance of least-squares sine wave curve fitting algorithms used in digital oscilloscope and A/D converter testing.
FY94	Began pulse measurement round-robin; Studied phase-plane compensation method to reduce dynamic nonlinearity errors in sampling channels, presented paper on results.
FY95	Developed analysis of bounds on frequency response estimates derived from uncertain step response data and presented paper; Completed testbed hardware for characterizing high performance A/D converter (up to 14 bits, 1 gigahertz sample rate); Quantified the systematic and random uncertainties associated with the test method proposed in IEEE Standard 1057 for measuring time-base linearity errors.
FY96	Begin development of a wideband oscilloscope calibration system for Air Force sponsor; Revisit phase plane analysis as a general method for characterizing and specifying the nonlinear behavior of A/D converters
FY97	Complete development of oscilloscope calibration system; Conclude first pulse measurement round-robin and publish results.
FY98	Conclude phase plane analysis and publish results
FY99	Complete development of the high performance A/D converter testbed; Incorporate test methods into IEEE Standard 1241.

2. Sampling comparator systems

FY91	Completed design of custom integrated circuit comparator for sampling applications; Goals: 2.5 gigahertz bandwidth, elimination of "thermal tails" (settling to 0.1% in 2 ns).
FY92	Comparators fabricated at foundry and incorporated into sampling comparator system (SCS); Design goals met.
FY93	Developed ultra-flat response, ± 20 Volt attenuator for SCS.
FY94	Began development of wideband (10 hertz - 200 megahertz) sampling voltmeter with Air Force sponsorship.
FY95	Developed quasiequivalent-time time-base, probe control, and memory management circuits; Produced a working prototype voltmeter.
FY96	Complete, test, document, and deliver sampling voltmeter instrument; Extend phase-plane characterization of SCS nonlinearity models using 2-tone input signals.
FY97	Upgrade Sampling Comparator System using new time-base and control circuitry developed for sampling voltmeter; Begin development of a 5 gigahertz bandwidth comparator for use in SCS applications.
FY98	Complete development of new comparator and incorporate into SCS; Offer 5 hertz bandwidth fast settling parameter calibration services.

3. Pulse measurement services

FY92	Fast pulse metrology program transferred from Boulder; Broadband pulse measurement services reestablished in Gaithersburg.
FY93	Began special measurement services for settling performance using SCS; Implemented "nose-to-nose" method for measuring the impulse response of

	high speed scopes; Developed improved gallium arsenide photoconductors for high-speed pulse generation.
FY94	Provided assessment of pulse energy measurements for InkJet print head industry (using SCS); Brought new, computer-based pulse measurement system on-line.
FY95	Trained new operator to perform the 65000 series of NIST Special Tests; Completed error analyses for Impulse Spectrum Amplitude, Baseband Pulse Parameters, and Pulse Delay Time tests.
FY96	Develop control and automation software to implement oscilloscope time-base calibration procedures and to upgrade pulse parameter measurements; Evaluate deconvolution algorithms for use in pulse parameter estimation software.
FY97	Upgrade time delay and impulse spectrum amplitude measurement services; Begin characterization of 50 gigahertz sampler.
FY98	Complete characterization of 50 gigahertz sampler and incorporate into broadband pulse measurement system.
FY99	Document the capabilities of the NIST 50 gigahertz bandwidth sampling system; Offer 50 gigahertz bandwidth fast pulse calibration services.

4. Optoelectronic technology

FY92	Installed laser system and associated diagnostics; Designed photoconductors (for photoconductive pulse generator) and developed fabrication process.
FY93	Added pulse selector to laser system and started photoconductor performance tests; Designed and tested prototype photoconductor electrical package; Developed new broad-band electrooptic voltage measurement technique.
FY94	Improved performance of packaged photoconductor and reduced aberrations; Developed time-domain-reflectometry method for measuring the dielectric constant of printed wiring board materials; Completed evaluation of electro-optic voltage measurement system; Found stability of system to be inadequate for precision pulse metrology work.
FY95	Investigated potential replacement laser systems; Ordered diode-laser system; Extended time-domain printed wiring board measurement technique to provide dielectric loss information.
FY96	Test diode-laser based system operation; Make improvements where needed; Test photoconductor performance using diode-laser system.
FY97	Determine impulse response of NIST's pulse calibration system using diode-laser based system.
FY98-99	Develop an optoelectronic-based, high temporal resolution (<1 ps) sampling system with 1% amplitude uncertainty; Characterize the diode-laser system pulse output waveform.

Generation and Measurement of Precise Signals

Project Leader: Nile M. Oldham

Staff: 5.0 Professionals, 1.5 Technicians

Full funding level: $0.8 M

Funding sources: NIST (50%), Other Government Agencies (32%), Other (18%)

Objective: Develop new waveform generation and measurement capability at NIST to support the basic quantities of voltage, current, phase angle, power/energy, ratio, and impedance using techniques for generating and measuring voltage and current waveforms over the frequency range up to 100 megahertz.

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 ratios, is increasingly challenging. The market for these instruments is over $500 million annually. Similarly, the power industry legally requires NIST traceability to equitably distribute the $202 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 kilohertz. 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 megahertz. Specific goals include: (1) extending automatic inductive divider measurement capability up to 1 megahertz, (2) developing techniques to measure generalized impedances at signal frequencies up to 1 megahertz, (3) developing phase standards capable of static and dynamic measurements in the frequency range from 2 hertz to 20 megahertz, (4) developing power/energy standards that operate at frequencies up to 400 kilohertz, and (5) developing calibration services, where necessary, with measurement uncertainties in the range of $\pm 10^{-6}$ for time invariant signals to $\pm 10^{-2}$ at the highest frequencies.

Current Tasks:

1. Voltage and current

FY87 Began development on a new alternating voltage standard and a wideband transconductance amplifier.

FY88	Presented papers describing a digitally synthesized source (DSS) and a transconductance amplifier; Began trial calibration service for digital multimeters (DMMs).
FY89	Completed a DSS to generate signals at frequencies up to 50 kilohertz with calculable voltage output and a transconductance amplifier with an output current of 20 A and maximum operating frequency of 100 kilohertz.
FY90	Developed a technique to measure low voltages (2 mV - 200 mV) at frequencies up to 1 megahertz with a factor of 10 improvement in uncertainty; Patents issued on the DSS and the transconductance amplifier and licensed both to a commercial instrument manufacturer.
FY91	Completed initial development of the multifunction calibration system (MCS) and offered Special Tests for DMMs (all functions); Demonstrated the DSS as a calculable current source.
FY92	Completed two measurement assurance programs for ac voltage using the DSS.
FY93	Completed a new version of the DSS controlled using a standard computer interface with an output current of 100 amperes and delivered 15 copies to sponsor (Sandia National Laboratories - SNL).
FY94	Announced a 25-point multifunction Special Test for DMMs with one-week turn-around time.
FY95	Completed development of a new transconductance amplifier; Offered new 230-point test for DMMs used to provide state-of-the-art traceability for multifunction calibrators.
FY96	Construct and test a new dual-channel digital generator to produce signals at frequencies up to 1 megahertz; Extend the current range, characterize the MCS for the calibration of currents up to 10 amperes; Initiate international comparison of electrical units (with countries in North, South, and Central America and the Caribbean) using DMMs as transportable standards.
FY97	Construct copies of the new digital generator for use in other test facilities; Report on the international comparison; Complete documentation and quality manual for the MCS and offer extended calibration services.
FY98	Develop a Special Test service for DMMs used by NIST's voluntary laboratory accreditation program to audit basic electrical units (voltage, current, and resistance).

2. Impedance

FY90	Designed a new dual-channel, digitally synthesized source as a first step in modernizing low-frequency ratio and impedance bridges in the Division.
FY91	Demonstrated a digital impedance bridge (DIB) using a dual-channel, digitally synthesized source; Developed a programmable 30-bit binary inductive voltage divider (BIVD).
FY92	Incorporated the BIVD into an automatic bridge to measure the linearity of precision commercial inductive voltage dividers.
FY93	Constructed and tested a sampling probe for the DIB to measure standard inductors; Used the BIVD bridge to evaluate a temperature bridge for use in a NASA Space Shuttle experiment.
FY94	Completed and documented the sampling probe for the DIB; Described a new error decomposition method for characterizing inductive voltage dividers based on modeling techniques.

FY95	Developed an "instrument-on-a-card" (VXIbus-based) impedance synthesizer and used it to test bioelectrical impedance analyzers for sponsor (National Institutes of Health).
FY96	Complete the 3-voltmeter probe for inductance; Complete the impedance calibrator.
FY97	Develop a system for characterizing 4-terminal pair reference impedances at frequencies up to 1 megahertz by estimating model parameters.
FY99	Complete a general-purpose impedance bridge which employs sampling voltage tracker probes and the new digital generator; Offer special tests for LCR meters.

3. Phase

FY88	Initiated a calibration service for digital phase meters for signals with frequencies between 1 hertz and 50 kilohertz.
FY90	Developed a dynamic test method for high frequency phase meters to support laser interferometry.
FY91	Completed development of a phase standard for signals between 1 and 20 megahertz and identified the phase meters in commercial interferometers as major source of error; Developed a state-of-the-art sampling phase meter and offered a Special Test for phase generators which produce signals at frequencies up to 100 kilohertz.
FY92	Developed new signal processing algorithms for the NIST sampling phase meter; Developed a self-calibration technique to characterize phase meters and generators out to 20 megahertz.
FY93	Developed a VXIbus-based system for calibrating phase meters and generators.
FY94	Simulated a phase measuring system for measuring very-high-frequency omni-directional ranging (VOR) phase meters for aircraft navigation.
FY95	Developed a VXIbus-based test set for VOR phase meters.
FY96	Complete and deliver a VXIbus-based system for testing the phase meters in VOR receivers to the Army.
FY97	Offer a Special Test service for VOR phase meters.
FY98	Upgrade and document the NIST phase angle calibration facility and offer extended calibration services.

4. Power and energy

FY88	Completed two new calibrators for the power/energy calibration facility, based on digitally synthesized generators; Began development of an audio-frequency current-comparator-based power bridge.
FY89	Participated in an international comparison of audio-frequency power (NIST only participating national lab with capability to measure power at signal frequencies above 5 kilohertz); Began development of a prototype power-frequency sampling wattmeter.
FY90	Completed the NIST audio-frequency power bridge.
FY92	Completed the prototype power-frequency sampling wattmeter.
FY93	Investigated the possibility of using a miniature current-comparator-based power bridge as an ultra-stable transport standard for international comparisons.

FY94	Demonstrated a power measurement at a signal frequency of 200 kilohertz to support wideband commercial wattmeters and power system analyzers.
FY95	Began the planning stage of a NIST-sponsored international comparison of 50/60 hertz power.
FY96	Complete the first stage of the international comparison (with the national measurement laboratories of Canada and Mexico); Assume chair of Standards Committee of Electricity Metering (C-12).
FY97	Develop new wideband (50 hertz - 500 kilohertz) power measurement system
FY98	Report on the international comparison of 50/60 hertz power.
FY99	Document power measurement capabilities at frequencies up to 500 kilohertz and offer extended calibration services.

Measurements for Complex Electronic Systems

Project Leader: T. Michael Souders

Staff: 2.0 Professionals, 0.2 Guest Scientist, 0.1 Technician

Full funding level: $0.4 M

Funding sources: NIST (67%), Other Government Agencies (33%)

Objective: Develop improved methods and techniques for optimum testing scenarios by: (1) developing improved mathematical models and test procedures, especially for self-calibrating systems; (2) estimating the confidence and test coverage in a given calibration or test procedure; and (3) developing a Testing Strategies Software Toolbox.

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 problem of effectively disseminating this technology remains. Specific goals include: (1) developing a software toolbox for test engineers that relieves the burden of complex mathematical software development; (2) Providing tutorial background documentation of the NIST testing strategies approach; (3) Developing and conducting workshops on the use of the approach and software toolbox; and (4) applying the approach to new testing problems or device types.

Current Tasks:

1. Testing strategies

FY89	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".
FY90	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.
FY91	Conducted the first NIST testing strategies workshop; Two integrated circuits manufacturers began using NIST method in production testing; a testing

company announced 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.

FY92	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.
FY93	Prepared two papers on modeling and test point selection for a commercial thermal transfer standard; Conducted second testing strategies workshop.
FY94	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.
FY95	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
FY96	Develop tutorial guide and user's manual and issue first Toolbox release; Prepare and conduct workshop and training program for DoD sponsors
FY97	Develop a plan for an adaptive modeling approach in which calibration history is used to iteratively reduce subsequent calibration costs; Demonstrate NIST approach on new device type or architecture.
FY98	Document NIST testing strategies methods for analog and mixed-signal devices.

2. Device/system analysis

FY92	Began feasibility study of new, hardware-efficient, on-line error detection approach for analog systems.
FY93	Completed study of on-line error detection scheme and documented results.
FY94	Assisted Office of Law Enforcement Standards in development of integrated services digital network (ISDN) telecommunications equipment.
FY95	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.
FY96	Complete and disseminate ISDN standard.

MICROWAVES

High-Speed Microelectronics Metrology

Project Leaders: Roger B. Marks and Dylan F. Williams

Staff: 5.0 Professionals, 1.0 Technician

Full funding level: $1.0 M

Funding sources: NIST (80%), Other Government Agencies (15%), Other (5%)

Objective: Support the electromagnetic characterization of microelectronic structures

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 was embodied in the creation and industry funding of the NIST Industrial MMIC Consortium, which was recently extended beyond its initial five-year charter. In the meantime, the project has been expanded to include high-speed microelectronics packaging, to which the on-wafer measurement technology developed in the project is also applicable.

Current Tasks:

1. Develop metrology and software for on-wafer characterization

FY89	Installed on-wafer probe station and network analyzer.
FY90	Developed multiline Through-Reflect-Line calibration method and implemented it in software which has been widely distributed.
FY91	Developed first procedures to accurately measure characteristic impedance and capacitance per unit length of planar transmission lines on lossless dielectric.
FY92	Completed and published General Waveguide Circuit Theory, accounting for effects of metal loss in planar lines.
FY93	Developed calibration method based on lumped elements.
FY94	Reduced size of calibration set using compact on-wafer standards and improved off-wafer calibration to accommodate demands for low-cost calibrations.
FY95	Released MultiCal software for improved calibration. Developed equivalent circuit theory for coupled lines.
FY96	Investigate methods to reduce size of microstrip calibration sets.
FY97	Introduce improved microstrip calibration sets. Introduce calibration methods for symmetric coupled lines.

2. Standardize on-wafer measurements, develop verification tools, and introduce traceability paths

FY89	Formed NIST/Industrial MMIC Consortium.
FY90	Completed on-wafer round robin.
FY91	Developed calibration comparison method.

FY92	Applied calibration comparison method to assess error in industry measurements. Found errors as large as seventy percent.
FY93	Designed calibration verification procedures and completed on-site tests.
FY94	Demonstrated effectiveness of accuracy assessment methods in tests at Consortium sites.
FY95	Tested new method to verify probe station in accordance with a voluntary industry standard (ANSI Standard Z540).
FY96	Determine requirements for certifying on-wafer artifacts as Standard Reference Materials. Initiate a Working Group to develop a voluntary Standard on Microwave Network Parameters.
FY97	Qualify on-wafer artifacts as Standard Reference Materials. Submit voluntary Standard on Microwave Network Parameters for adoption by relevant standards body.

3. Design and fabricate calibration artifacts and test structures

FY90	Designed coplanar waveguide (CPW) standards and built prototypes.
FY91	Fabricated CPW standards and distributed them to consortium.
FY92	Developed improved photoresist process. Developed wafer thinning process for microstrip standards.
FY93	Designed and fabricated on-wafer noise test structures.
FY95	Fabricated and tested microstrip artifacts.
FY96	Fabricate coupled-line test structures.
FY97	If warranted, fabricate prototype Standard Reference Materials.

4. Develop procedures for time domain network analysis (TDNA)

FY92	Identified industrial need to apply network analyzer calibration methods to time domain instruments, particularly for electronic packaging characterization.
FY93	With industry cooperation, demonstrated feasibility of applying multiline Through-Reflect-Line calibration for time domain network analysis.
FY94	Established cooperative research program with instrument manufacturer to study time domain transmission line characterization.
FY95	Introduced process for calibrating time domain network analyzer using MultiCal software.
FY96	Optimize TDNA parameters. Release TDNA software. Write paper on TDNA for the magazine *IEEE Spectrum*.
FY97	Begin development of millimeter-wave TDNA.

5. Develop procedures for characterization electronic packaging

FY92	Developed new method to measure characteristic impedance of transmission lines built on lossy dielectrics such as silicon.
FY93	Developed method to measure on-wafer impedance parameters for devices built on lossy dielectrics. Established cooperative research agreement with industrial partner.
FY94	Began industrial cooperation to characterize flip-chip MMICs.

FY95	Characterized flip-chip MMIC components. Designed test structures for characterizing packaging elements, including flip-chip bumps and solder joints.
FY96	Characterize flip-chip MMIC packages and substrate effects.

6. Develop methods to characterize cryogenic on-wafer devices

FY93	Designed, fabricated, and tested cryogenic test structures.
FY94	Completed cryogenic experiments with Electromagnetic Technology Division (Div. 814) and University of Hawaii.
FY95	Cooperated with Division 814 on tunable cryogenic resonators.
FY96	Begin effort on cryogenic interconnection characterization with Division 814 and Georgia Institute of Technology.

7. Material characterization

FY94	Developed concepts for extracting material parameters from on-wafer transmission line measurements.
FY95	Cooperated with Division 814 to study superconducting thin films.
FY96	Cooperate with Electromagnetic Properties of Materials Project to apply time-domain network analysis (TDNA) to material characterization, improve transmission/reflection software to account for nonideal lines, and investigate thin-film characterization methods in collaboration with Sematech.
FY97	Introduce methods to characterize isotropic thin films deposited on planar transmission lines.

8. Exchange technology through workshops

FY91	Organized on-wafer measurement workshop at International Microwave Symposium (IMS).
FY94	Organized on-wafer measurement workshop at IMS and at Automatic RF Techniques Group Conference.
FY95	Organized measurement workshop at a topical meeting on Electrical Performance of Electronic Packaging. Organized session on measurements for Workshop on Wireless Communications.
FY96	Chair Second ISHM (International Society for Hybrid Microelectronics) Advanced Technology Workshop on Wireless Communications. Organize on-wafer measurement workshop at IMS.
FY97	Organize special session on multiconductor transmission lines at International Microwave Symposium.

Power Standards and Measurements

Project Leader: Fred Clague

Staff: 4.0 Professionals, 3.0 Technicians

Full funding level: $0.9 M

Funding sources: NIST (26%), Other Government Agencies (41%), Other (33%)

Objective: Develop coaxial and waveguide transfer standards, microcalorimeters, measurement techniques, and automated instrumentation which supports and provides the calibration services for customer transfer standards.

Background: Microwave power is the high frequency equivalent to 60 hertz power. Information can only be passed from one place to another by means of energy transfer, and is therefore a commodity as are gas and electricity. The measurement of microwave power is one of the most fundamental test requirements since it is needed to verify output levels from signal generators, radio and television transmitters, all types of radar, and communication sources. Systems that are overdesigned because of poor power standards are very expensive. Commercial providers and users of microwave energy, including communications, navigation, surveillance, manufacturing, aerospace, medicine, defense, entertainment, and advanced computing require accurate measurement of microwave power. International trade of microwave instrumentation and devices requires power standards recognized and accepted by the trading partners. The ability to accurately measure microwave power over the frequency ranges from 10 megahertz to 100 gigahertz in coaxial transmission line, and from 18 gigahertz to 96 gigahertz in waveguide is needed to assure proper performance.

Current Tasks:

1. Develop coaxial power standards using a specific commercial connector (Type N) for use over the frequency range from 50 megahertz to 18 gigahertz

FY87	Initiated program to rebuild the coaxial microcalorimeter and transfer standards.
FY88	Refurbished and tested the calorimeter; Designed new transfer standard.
FY89	Completed prototype transfer standard; Assembled instrumentation to automate calorimeters.
FY90	Completed uncertainty analysis of calorimeter; Negotiated arrangement with private company to provide the thermistor bead assembly for the connector mount; Finished automated calorimeter software.
FY91	Completed total uncertainty analysis of calorimeter.
FY92	Began special test service providing direct calorimeter calibration of the connector mounts.

FY93	Solved connector mount internal resonance problem; Published report describing connector mount; Published report describing calorimeter. Delivered 12 connector mounts to sponsor and company customers.
FY94	Published calorimeter evaluation method in a technical journal.
FY95	Calibration service received final NIST approval; Resolved calibration uncertainty issue.
FY96	Calibration service in full operation.

2. Develop power standards for systems having 2.4 millimeter conductors and coaxial connectors for use over a frequency range from 1 megahertz to 50 gigahertz

FY91	Initiated NIST program to develop calibration service; Found that a transfer standard is not commercially available.
FY92	Determined that a particular commercial power sensor is a suitable basis for new thin-film bolometric transfer standard.
FY94	A private company agreed to develop a prototype transfer standard.
FY95	Received and tested the transfer standard; Designed and began fabrication of a microcalorimeter.
FY96	Refine transfer standard design; Finish microcalorimeter construction and begin uncertainty evaluation.
FY97	Complete uncertainty evaluation; Develop transfer technique and instrumentation for a calibration service.
FY98	Initiate and document calibration service.

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

FY87	Initiated program to restore or build new microcalorimeters starting with WR-22 (33-50 gigahertz).
FY88	Began parallel effort to develop a WR-22 cryogenic power standard.
FY89	Completed design of the WR-22 calorimeter.
FY90	Finished drawings for the WR-22 calorimeter.
FY91	Assembled WR-22 calorimeter; Completed design of the WR-42 (18-26 gigahertz) and WR-15 (50-75 gigahertz) calorimeters; Assembled three WR-15 transfer standards.
FY92	Assembled the WR-42 calorimeter; Completed design of WR-15 calorimeter; Finished construction of the WR-42, WR-22 and WR-15 transfer standards.
FY93	Completed assembly of WR-42 and WR-10 (75-110 gigahertz) calorimeters; Finished WR-10 transfer standards.
FY94	Assembled the WR-15 calorimeter and transfer standards.
FY95	Completed operational tests of the isothermal mode on the WR-22 calorimeter; Developed thermal model using finite element analysis to improve the calorimeter evaluation.
FY96	Complete uncertainty evaluation of WR-15 and WR-10 calorimeters.
FY97	Complete uncertainty evaluation of WR-42 and WR-22 calorimeters.

4. Provide calibration and measurement services for microwave power.

FY90	Initiated a calibration service for power (0.01-33 gigahertz) in systems using conductors having a 3.5 mm diameter.
FY94	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.
FY95	Developed techniques for the Army for providing power calibration in systems using Type N connectors at frequencies above 18 gigahertz.
FY96	Add power calibration services for GPC-7 connectors to the direct comparison system; Reduce measurement time of low frequency power measurements done in six-port laboratory and low frequency impedance laboratory.
FY97	Add calibration service for thermoelectric and diode power meters.
Ongoing	Provide coaxial and waveguide calibration services to 110 gigahertz for microwave power.
Ongoing	Provide calibration and measurement services and consultation in: high power from 1 watt to 1000 watts (1-30 MHz), 1 watt to 500 watts (30-400 MHz).

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

FY95	Determined optimum technique for transfer standards calibration and investigated availability of high power components and instrumentation.
FY96	Develop system architecture; Purchase system components and other instrumentation; Complete operational software and calibration of transfer standards at reduced power levels.
FY97	Integrate high power amplifier in system; calibrate transfer standards at specified frequencies and power levels; complete analysis of calibration technique.
FY98	Complete documentation of system and transfer standards; Deliver transfer standards to sponsor; Establish NIST high power calibration service.

Impedance, Attenuation, Voltage Standards and Measurements

Project Leader: Greg Rebuldela

Staff: 2.0 Professionals, 2.0 Technicians

Full funding level: $0.6 M

Funding sources: NIST (35%), Other Government Agencies (35%), Other (30%)

Objective: Provide measurement services in voltage, impedance and attenuation for commercial and internal projects over a frequency range from 10 kilohertz to 1000 megahertz. Enhance services through system development, improved transfer standards and new measurement techniques.

Background: Manufacturers of electrical/electronic equipment and components, research and development laboratories, DoD Federal laboratories, and industrial standards laboratories continually demand better uncertainties, broader frequency coverage, and improved standards and measurement techniques. Voltage, attenuation, power and impedance are important electromagnetic quantities that support the production and performance verification of signal generators, receivers, voltmeters, spectrum analyzers, and field strength meters. Traceable measurements are required to support the quality and reliability of these instruments. These instruments are used in the production and testing of civilian and military aircraft, radar, space exploration, nuclear research, and other applications. Improvements in new electronic products require better support and NIST is responding through enhanced measurement technology.

Current Tasks:

1. Provide calibration and measurement services and consultation in impedance measurements from 30 kilohertz to 300 megahertz

FY91	Implemented low frequency calibration services (< 200 megahertz) using a commercial impedance bridge.
FY96	Document Twin-Tee Bridge for operation in the frequency range between 10 megahertz to 200 megahertz; Evaluate and document Twin-Tee Bridge for operation in the frequency range between 100 kilohertz and 5 megahertz. Document international comparison in Quality Factor of inductance standards.
Ongoing	Provide calibration service for impedance using signals in the frequency range from 30 kilohertz to 300 megahertz.

2. Extend frequency range and improve accuracy of capacitance calibrations

FY96	Replace outdated measuring instruments with state-of-the-art instrumentation. Do initial test on equipment in the frequency range from 10 kilohertz to 20 megahertz.
FY97	Determine uncertainty; Announce expanded frequency range in the calibration of two and three terminal capacitance standards.

3. Develop calibration service for coaxial terminations, thermistor mounts, and thermal voltage converters over the frequency range 10 kilohertz to 1 megahertz

FY95	Calibrated and documented high frequency Twin-Tee bridge for the coaxial termination calibration service.
FY96	Publish documentation of the coaxial termination calibration service.
FY97	Test new instrumentation for measuring input impedance of devices under test.

4. Develop and test new methods for the calibration of Inductance, Capacitance, Resistance (LCR) and Automatic Network Analyzer (ANA) instrumentation

FY96	Study new approaches for the calibration of LCR and ANA instrumentation; Evaluate approaches.

5. Determine resistivity of NIST airline standards

FY95	Designed and constructed measurement system to measure resistivity of airline components. Completed initial testing.
FY96	Test NIST airline standards that have diameters in the range 3.5 millimeters to 14 millimeters to determine resistivity.

6. Provide calibration and measurement services and consultation in attenuation measurements at frequencies of 1.25 megahertz (6 dB step) and 30 Megahertz (0 dB to 120 dB)

7. Provide calibration and measurement services and consultation in voltage at frequencies from 100 hertz to 1000 megahertz, and voltages from 1 microvolt to 600 volts

FY96	Complete documentation of Thermal Voltage Converters and radio frequency Micropotentiometer systems operating from 100 hertz to 1000 megahertz; Complete round-robin measurements in thermal voltage converters, analyze data and report to participants; Complete comparison measurements with Spanish laboratory.
FY97	Evaluate present voltage standards against transfer standards calibrated by the Electricity Division at reduced uncertainties. Re-evaluate uncertainties and disseminate to customers; Research availability or design voltage transfer standard with low frequency response from 30 kilohertz to 1000 megahertz.

FY98 Adopt voltage transfer standard to automate high frequency calibration system which operates at frequencies from 10 megahertz to 1000 megahertz; Design system, develop software and perform initial tests; Evaluate measurement uncertainties.

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

FY96 Complete documentation for the dimensional measurement of airlines.

Network Analysis and Measurement

Project Leader: John Juroshek

Staff: 3.0 Professionals, 4.0 Technicians

Full funding level: $1.0 M

Funding sources: NIST (23%), Other Government Agencies (52%), Other (25%)

Objective: Provide traceability for microwave measurements in scattering parameters and power. Support the microwave industry by developing standards and new measurement techniques. Develop methods for assessing the accuracy of automatic network analyzers.

Background: Vector network analyzers 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. They also need help in developing the techniques, procedures, and documents to ensure conformity with international standards. NIST directly supports the microwave industry by providing traceability with their calibration service in scattering parameters and power. NIST also has a role consulting and providing guidance on accuracy related issues.

Current Tasks:

1. Provide and upgrade traditional calibration services for scattering parameters

Ongoing	Provide coaxial and waveguide calibration services to 110 gigahertz in scattering parameters.
FY90	Initiated calibration service in scattering parameters and power for systems with conductor diameters of 3.5 millimeters (0.01-33 gigahertz).
FY93	Initiated a calibration service for scattering parameters when using 2.92 millimeter diameter conductors (0.1-40 gigahertz) with coaxial connectors; Initiated WR-90 (8-12 gigahertz) and WR-62 (12-18 gigahertz) waveguide calibration services on the dual six-ports.
FY94	Initiated a calibration service for scattering parameters in systems using 2.4 millimeter diameter conductors (0.1-50 gigahertz) and coaxial connectors.
FY95	Began offering a reduced cost calibration service for systems using 2.92 millimeter and 2.4 millimeter diameter conductors on the commercial network analyzer.
FY96	Initiate a new calibration service based on traveling verification kits; Add calibration services for time delay to existing scattering parameter services.
FY97	Develop low frequency impedance standards using thin film techniques.

FY98	Add calibration services for systems using currently unsupported connector types.

2. Develop quality assurance procedures for network analyzers

Ongoing	Serve as pilot laboratory for the Automatic RF Techniques Group's (ARFTG) Intercomparison 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.
FY91	Completed draft documentation for six-port calibration services; Initiated a measurement comparison program for the IEEE Automatic RF Techniques Group (ARFTG).
FY92	Evaluated and initiated calibration services on commercial vector network analyzer.
FY93	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.
FY94	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.
FY95	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.
FY96	Develop new verification software for commercial network analyzers.
FY97	Develop quality assurance documentation that conforms to international requirements; Help Department of Defense establish a verification program for network analyzers.

3. Develop dual six-port network analyzers

FY90	Developed waveguide six-ports for WR-42 (16-26 gigahertz), WR-28 (24-35 gigahertz), WR-15 (50-75 gigahertz), and WR-10 (75-110 gigahertz).
FY91	Developed line-reflect-line (LRL) software for calibrating the dual six-ports.
FY92	Developed 18-40 gigahertz 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 gigahertz) and WR-28 (24-35 gigahertz) dual six-ports for the Navy Primary Standards Laboratory.
FY94	Designed and built new test ports and standards for WR-22 (30-50 gigahertz) waveguide calibration services; Completed construction of 100 kilohertz to 1.0 gigahertz for the Air Force and procured and/or manufactured system components and devices to supplement calibration kits. Initiated documentation.
FY95	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 gigahertz to 18 gigahertz; Delivered dual six-port system operating over the frequency range between 0.1 megahertz and 1000 megahertz to the Air Force and provided on-site training to Air Force personnel.

FY96	Modify current six-port software so that it runs on newer computers; deliver dual six-port system operating over the frequency range between 0.25 gigahertz and 18 gigahertz to Army and provided on-site training to Army personnel; Complete hardware assembly of a dual six-port operating over the frequency range between 18 gigahertz and 40 gigahertz for the Air Force. Procure calibration and verification kits for devices with 3.5mm, 2.92mm, WR-42 and WR-28 connectors. Modify existing six-port software. Test system hardware and operational software.
FY97	Complete dual six-port which operates at frequencies between 18 gigahertz and 40 gigahertz, evaluate, document and deliver to the Air Force.
FY98	Develop faster wide-bandwidth six-ports.

4. Develop, analyze, and improve NIST impedance standards

FY91	Developed techniques for modeling the dimensional variability in coaxial and waveguide airline standards.
FY91	Developed WR-90 waveguide standards; developed new Type N, GPC-7 impedance standards.
FY96	Develop improved air line impedance standards for systems having coaxial connectors and 2.92 millimeter diameter conductors; develop computer program for analyzing surface roughness in airline standards.
FY97	Develop air line standards for dielectric supported transmission lines.

5. Develop automated data analysis techniques

FY90	Installed hardware for a local area network for calibration related activities.
FY92	Completed software development for on-line data management with the local area network.
FY93	Check standard data base ready for online access by calibration staff.
FY96	Upgrade and automate quality control procedures.
FY97	Upgrade local area network capabilities.
FY98	Upgrade data base capabilities for remote access of check standard and customer historical data.

Noise Standards and Measurements

Project Leader: James Randa

Staff: 3.0 Professionals, 3.0 Technicians

Full funding level: $0.9 M

Funding sources: NIST (56%), Other Government Agencies (33%), Other (11%)

Objective: Develop methods for highly accurate measurements of thermal noise; provide support for such measurements in the communications and other electronics industries as well as in 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 millimeter-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 gigahertz to 75 gigahertz, including 1 gigahertz to 25 gigahertz 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 gigahertz to 18 gigahertz. 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 an order of magnitude faster than our existing radiometers.

Current Tasks:

1. Improve and expand waveguide and coaxial noise temperature capabilities

   FY92 Extended upper frequency limit of WR-42 (18-26.5 gigahertz) to 26 gigahertz (previously was 22 gigahertz).

FY93	Began new noise temperature special test services in WR-15 (50-75 gigahertz), WR-62 (12.4-18 gigahertz), and systems using 3.5-millimeter coaxial conductor (12-26 gigahertz).
FY94	Organized and presented a one day noise measurements seminar at the IEEE International Microwave Symposium in San Diego; revised measurement uncertainties per NIST guidelines.
FY95	Completed construction of WR-28 (26.5-40 gigahertz) noise-temperature calibration system; began testing. Developed and documented improved technique for assessing adapter effects in noise temperature measurements.
FY96	Complete testing of WR-28 system; document and offer WR-28 measurement service. Complete and test WR-22 (33-50 gigahertz) system; document and offer WR-22 service. Automate and document uncertainty analysis for coaxial noise-temperature calibrations.
FY97	Introduce improved coaxial primary standard and new total power radiometer into noise temperature measurements. Update software. Develop, automate, and document uncertainty analysis for noise temperature calibrations in waveguide.

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

FY92	Noise comparison proposed by NIST and approved (GTRF 92-2) with NIST as pilot lab.
FY93	International noise community canvassed for possible participants; preliminary plans made.
FY95	Noise sources were purchased for circulation among participants.
FY96	Develop protocol, perform first round of NIST measurements, schedule and commence circulation of noise sources among other participating laboratories.
FY97	Completion of measurements at other laboratories; perform second round of measurements at NIST; collect and analyze results.
FY98	Write report and present results.

3. Develop noise-figure measurement capability

FY92	Completed development of noise-figure measurement theory and established possible experimental measurement procedure. Performed measurements to test the viability of this procedure.
FY93	Completed basic design of amplifier noise radiometer.
FY94	Completed and tested prototype of amplifier noise radiometer. Found to be 150 times more stable (changes less than 0.002 dB/day) than present NIST systems. This promises to significantly reduce the need for repetition of measurements, thereby reducing the time for calibrations.
FY95	Refined noise-figure measurement techniques for low-noise amplifiers with adapters; performed preliminary measurements on two low-noise amplifiers with adapters.
FY96	Complete total-power radiometer which operates at frequencies between 8-12.4 gigahertz, to replace the currently used system in noise temperature measurements and for use in the noise-figure measurement system.
FY97	Construct and test noise-figure radiometer over the frequency range 2-4 gigahertz.

4. Develop methods for on-wafer measurement of noise

FY92	Conducted preliminary experiment to measure the noise figure of an amplifier on wafer.
FY94	Measured one-port noise of a diode on wafer at a frequency of 8 gigahertz using the prototype Noise-Figure Radiometer.
FY95	Designed, performed, and analyzed experiments to measure known and unknown noise temperatures on wafer at frequencies between 7.8 gigahertz to 8.2 gigahertz.
FY96	Refine, extend, and repeat on-wafer noise-temperature measurements. Develop possible designs for on-wafer noise-temperature transfer standards; perform preliminary tests.
FY97	Complete design and testing of on-wafer noise-temperature transfer standard. Begin development of on-wafer noise figure measurement methods.
FY98	Perform preliminary on-wafer noise-figure measurements.

5. Provide noise temperature calibration services

FY93	Calibrated 15 customer noise standards.
FY94	Calibrated 11 customer noise standards.
FY95	Calibrated 13 customer noise standards.
FY96	Continue to calibrate customer noise standards.

Antenna Measurement Theory and Application

Project Leader: Carl F. Stubenrauch

Staff: 5.0 Professionals, 2.0 Technicians

Full funding level: $1.0 M

Funding sources: NIST (53%), Other Government Agencies (15%), Other (32%)

Objective: NIST has shown that the near-field methods it invented for antenna characterization offer capabilities with respect to accuracy (and freedom from the effects of weather) that are unmatched by other methods. However, developments 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 to 100 gigahertz. Specifically, NIST will develop cylindrical and spherical scanning capabilities with extension to the frequency range, 26.6 to 40 gigahertz and planar methods for the frequency range, 40 to 100 gigahertz. Goals include (1) achieving uncertainties less than ±0.2 decibels in the gain, (2) implementing probe position error correction for millimeter 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 antennas and microwave systems incorporating antennas 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 100 gigahertz

FY94 Aligned the x-, y- and z- axes of the 2.5 meter by 2.5 meter planar scanner to extend capability to millimeter(mm)-wave measurements.

FY95 Completed first phase of the certification process for the new NIST 2.5 meter by 2.5 meter 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.
FY96	Complete full three-dimensional Taylor-series method for probe-position error-correction; Investigate two promising 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. Update and present antenna measurements course at NIST; Update and present antenna measurements course at California State University, Northridge.
FY97	Complete the certification process for the new 2.5 meter by 2.5 meter planar scanner and receiver; Conduct simulations on the effects of probe-position errors and report on the effect of various probe-position correction methods. Cosponsor antenna measurement course with Georgia Institute of Technology.
FY98	Evaluate on-site planar near-field methods for determining phased-array aperture distributions. Many antennas require periodic performance verification. Near-field techniques may be the only viable techniques to test next generation high performance antennas.
FY99	Develop methods for mm-wave measurements at frequencies from 75 to 110 gigahertz.

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

FY93	Implemented the mirror/self-calibration method for determining antenna gain. This method allows testing of transmitting antennas in just a few minutes.
FY94	Conducted initial measurements for the mirror technique in the laboratory.
FY95	Evaluated mirror technique using three probes. Developed thermal imaging theory for rapid measurements used for determining antenna performance; Simulated measurements for thermal imaging method.
FY96	Complete analysis of mirror/self-calibration data and publish results; Conduct preliminary measurements on thermal imaging method in cooperation with the University of Colorado, Colorado Springs.
FY97	Design, build and conduct thorough test of thermal imaging method.
FY98	Report thermal imaging results; Compare to planar near-field results.
FY99	Construct a one-dimensional photonic probe array for rapid scanning; Evaluate array in planar near-field/cylindrical near-field measurement systems.

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

FY93	Upgraded cylindrical near-field software to include dual-polarized probes.
FY94	Evaluated cylindrical near-field measurements performed at the Jet Propulsion Laboratory (JPL); Measured JPL probes used to characterize the NASA Scatterometer satellite antenna.
FY95	Completed evaluation of the new spherical/extrapolation range. This range is capable of fast and accurate measurements of antennas up to 3.5 meters in diameter in the frequency range from 1 to 75 gigahertz.
FY96	Publish the calibration results on the standard gain horns for the International Gain Comparison measurements. Align vertical probe transport on multipurpose range for cylindrical near-field measurements. Provide technical

	support and near-field probe measurements to JPL for cylindrical near-field measurements on satellite antenna.
FY97	Intercompare measurements of gain, pattern and polarization on suitable test antenna for all NIST ranges (two planar, cylindrical, and spherical).
FY98	Develop three-dimensional probe-position correction for spherical and cylindrical near-field scanning. Develop upper bound error expressions. Develop technique to improve extrapolation range error analysis based on measurement condition number.
FY99	Refine the spherical near-field scanning technique for outdoor in-situ testing of antennas. Develop methods for range evaluations using spherical measurements.

4. Develop metrology for complex antennas for emerging technologies

FY92	Assisted NASA Lewis Research Center in evaluating the manufacturer's spherical near-field measurements to characterize the Advanced Communications Technology Satellite antenna. Discovered and corrected a problem in the contractor's software.
FY93	Completed report detailing the spectral merge theory as applied to steerable array antenna measurements (NISTIR 3981).
FY94	Completed first phase for spectral merge analysis to determine antenna-array excitation using planar near-field measurements from several beam positions.
FY95	Completed software and analysis for spectral merge project; Completed analysis of a 60 gigahertz phased-array antenna using measurements taken on the new 2.5 meter by 2.5 meter planar scanner.
FY96	Document the results of the spectral merge method for the alignment of phased arrays. Design and construct a 32 by 32 X-band (8.2 to 12.4 gigahertz) computer-controlled phased array to validate new antenna metrology and diagnostic methods.
FY97	Evaluate mutual coupling methods for rapid testing of phased arrays.
FY98	Test and evaluate new phased-array optimization algorithms.
FY99	Develop merged spectrum method for non-rectangular phased array lattices.

5. Provide technology transfer through courses

FY94	Presented short course, "Antenna Parameter Measurement by Near-Field Techniques."
FY95	Participated as major lecturers in short course, "Microwave Antenna Measurements" at California State University, Northridge.
FY96	Update and present short course, "Antenna Parameter Measurement by Near-Field Techniques."
FY97	Update lectures for short course, "Microwave Antenna Measurements" at California State University, Northridge.
FY98	Update short course with the Georgia Institute of Technology on "Near-Field Antenna Measurements and Microwave Holography."

Metrology for Antenna, Radar Cross Section and Space Systems

Project Leader: Michael H. Francis

Staff: 3.0 Professional, 1.0 Technician

Full funding level: $0.5 M

Funding sources: NIST (37%), Other Government Agencies (61%), Other (2%)

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 terminal. 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 including uncertainty budgets, by evaluating the design and analysis of required artifact standards, and by 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. Communications system measurements (IRIDIUM, GLOBALSTAR) and radar cross section measurements for new automobile radar systems will flourish during the next decade.

Current Tasks:

1. Develop metrology for wireless communications systems

FY94	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.
FY95	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.
FY96	Provide technical support and probe measurements for wireless base station antennas.
FY97	Conduct analysis of antenna performance on a broadbeam communication wireless antenna to be supplied by industry or other agency.
FY98	Define anticollision radar system requirements; Evaluate existing metrology for system parameter measurements.
FY99	Develop new metrology and artifact standards for anticollision radar systems.

2. Develop microwave metrology applicable to Earth Stations

FY93	Measured Air Force Satellite Control Network 18-meter diameter antenna for elevations from 5 to 60 degrees, using Cassiopeia A and a calibrated noise source, to characterize gain changes versus elevation angle; Compared with gains obtained using a gain comparison method, a 2-meter diameter antenna and a satellite beacon signal.
FY94	Evaluated G/T measurement procedures and results for other agencies and industry, using the sun and moon.
FY95	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.
FY96	Analyze G/T measurement techniques to determine if subarrays of a phased array are working properly.
FY97	Determine the G/T of an outdoor antenna and measure the system under different operating conditions to predict system performance during a typical year.
FY98	Collaborate with Jet Propulsion Laboratory (JPL) in flux density measurements of extraterrestrial radio noise sources and gain calibrations of the 70-meter diameter Goldstone antenna and other antennas at Owens Valley Radio Observatory.
FY99	Certify standard radio sources (radio stars, satellite signals); Develop holographic methods for large antenna system diagnostics.

3. Develop metrology for radar cross section measurements

FY94	Provided technical support to the government RCS Range Working Group to improve the quality and reliability of range measurements and standards.

Developed measurement procedures and uncertainty analyses for establishing measurement accuracies.

FY95 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 review of the Eglin Air Force Base Radar Cross Section ranges and submitted an uncertainty analysis report to Eglin personnel; 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 describes the activities, findings, and recommendations for future research by NIST. The report is a result of three years of research activities by NIST scientists, who reviewed eight government RCS ranges during that time.

FY96 Document range-specific uncertainty analyses for specific companies and other agencies. Conduct research on technical questions remaining in the area of imaging, specifically image quality and interpretation.

FY97 Study and recommend RCS standard artifacts and oversee measurement intercomparisons at different RCS facilities.

FY98 Develop a standard for RCS measurements in collaboration with a voluntary RCS standards committee. Investigate special research topics in the areas of polarimetric calibration, near-field effects, "wideband RCS" definition, imaging and coherent scattering matrix uncertainty.

LIGHTWAVES

Dielectric Materials and Devices

Project Leader: Norman A. Sanford

Staff: 3.0 Professionals, 1.0 Postdoc, 0.3 Student

Full funding level: $0.8 M

Funding sources: NIST (70%), Other Government Agencies (13%), Other (17%)

Objective: Develop advanced measurement methods for dielectric waveguide materials and processing procedures for these materials; 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 important components for remote sensing and ranging technologies. NIST has worked closely with industrial collaborators, involving both materials development and device development, to help further this technology. Additionally, NIST has worked on the characterization of lithium niobate and lithium tantalate. These materials are used extensively in optical communication systems for modulators and switches. Components fabricated from these materials also find widespread use in optical guidance and control systems. Furthermore, lithium niobate waveguide devices are key elements used in compact blue/green lasers, which are in demand for data storage and reproduction graphic technologies.

Current Tasks:

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

FY90	First reported neodymium-doped waveguide laser for continuous operation fabricated by ion-exchange in glass.
FY91	Mode-locking, Q-switching and tuning reported in waveguide lasers; first reported Y-branch waveguide laser and amplifier.
FY92	Dispersion of optical fiber amplifiers and rare-earth-doped waveguide amplifiers measured by low-coherence interferometry; first reported linewidth-narrowed, coupled-cavity waveguide laser; first reported neodymium-diffused lithium tantalate waveguide laser fabricated.
FY93	High efficiency, phosphate glass waveguide laser demonstrated and characterized.
FY94	Waveguide grating fabrication procedures established; waveguide lasers with distributed Bragg reflectors developed and characterized; passively Q-switched waveguide lasers demonstrated and analyzed.

FY95	Phosphate glass waveguide fabrication space investigated; numerical modeling study of continuous and pulsed erbium-doped waveguide lasers initiated.
FY96	Characterize near-field intensity profiles, effective indices and diffusion profiles of rare-earth-doped waveguides; model continuous and pulsed operation of waveguide lasers; fabricate erbium-doped waveguide laser for operation with a wavelength near 1.55 micrometers.
FY97	Study optimization of glass composition and laser design.

2. Metrology of nonlinear optical materials

FY89	Characterized photorefractive instabilities from two-wave coupling in lithium niobate waveguides formed by proton exchange.
FY94	Maker-fringe system constructed to map wafer uniformity for waveguide devices; theoretical model of reflected and transmitted Maker-fringe signatures established for various sample orientations and pump and signal polarizations; studies of domain-inverted segments in lithium niobate waveguides initiated.
FY95	Nonuniformities in index (and hence composition) mapped over 50 centimeter and 76 centimeter diameter lithium niobate wafers by Maker fringe analysis; thickness uniformity of lithium niobate wafers also mapped; initial correlations with x-ray topographs performed; Maker-fringe analysis used to help characterize thin lithium niobate films produced by industrial collaborators; cross-section and shape of domain-reversed segments in lithium niobate waveguides studied
FY96	Map 100 centimeter lithium niobate wafers by Maker fringe analysis, compare with x-ray topographs; characterize effects of wafer processing; fabricate and demonstrate sources for use in fiber metrology utilizing domain inversion in lithium niobate waveguides.
FY97	Establish measurement techniques for domain-reversed segments; extend studies of nonlinear materials to potassium titanyl phosphate and nonlinear polymers.

Semiconductor Materials and Devices

Project Leader: David H. Christensen

Staff: 3.5 Professionals, 1.0 Student, 1.0 Guest Researcher

Full funding level: $0.8 M

Funding sources: NIST (96%), Other Government Agencies (4%)

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. 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. In the field of optoelectronic interconnects, project researchers collaborate with industry and other Division researchers to develop measurements which support the manufacture and specification requirements for lasers used in interconnect systems. Metrology support is now under development for the group III-nitride manufacturers pursuing blue/ultraviolet sources for data storage and display applications.

Current Tasks:

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

FY94 — Atomic absorption spectroscopy (AAS) system installed on semiconductor growth chamber; aluminum gallium arsenide layer growth monitored; growth of Bragg reflectors measured by *in-situ* optical reflectance spectroscopy (ORS).

FY96 — Calibrate atomic absorption measurement to *ex-situ* measurements of epilayers; install and calibrate shallow-angle uv reflectance (UVR) monitoring; measure growth of quantum well and vertical-cavity surface-emitting lasers in real-time; model and compare AAS, ORS, and UVR measurements to published/other-agency measurements.

FY97 — Establish closed loop control of epilayer growth; investigate manufacture of test structures and/or reference standards for evaluation and optimization of growth stability; correlate *in-situ* monitored structures to *ex-situ* measurements to advance controlled-precision manufacturing; install *in-situ* reflectance difference monitor for surface/growth studies.

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

FY91 Vertical-cavity surface-emitting laser (VCSEL) structures characterized by x-ray, electron-beam, and optical metrologies, and by measurement simulations; high degree of correlation among measurement methods shown for layer thicknesses, uniformity, and composition; assisted industry in development of first commercially available VCSELs.

FY92 Distributed feedback VCSELs with distributed quantum wells fabricated and characterized; impact of correlated characterization verified by demonstrating the narrowest linewidth distributed feedback VCSEL and efficient optically-pumped VCSELs.

FY93 Dielectric function of individual quantum wells measured from distributed reflectance spectroscopy, and theoretical model of gallium arsenide quantum wells confirmed; cross-sectional micro-photoluminescence technique developed to distinguish features of buried semiconductor layers; correlation between cross-sectional and surface-normal emission measurements established.

FY94 Spatio-temporal evolution of vacancy-assisted aluminum-gallium interdiffusion in quantum well heterostructures quantified by cross-sectional micro-photoluminescence, new theoretical model confirmed, impact on semiconductor device manufacturing demonstrated; test structures for evaluation and optimization of epilayer uniformity developed.

FY95 Period deviations in distributed Bragg reflectors measured by reflectance spectroscopy and modeled; parameter space of interdiffusion-during-annealing studies extended to include matrix of arsenic overpressure and temperature

FY96 Measure and model influence of effusion-cell temperature drift during distributed Bragg reflector manufacturing; correlate high-resolution x-ray diffractometry measurements to reflectance spectroscopy and electron microscopy measurements of systematic and random period deviations in multilayers.

FY97 Advance precision *ex-situ* metrology of semiconductor test structures and/or measurement standards for evaluating and optimizing 3-D epitaxial uniformity; correlate *in-situ* monitored structures to *ex-situ* measurements to advance controlled-precision manufacturing.

3. Semiconductor material and device metrology for advanced applications

FY93 Completed study of optoelectronic technology and metrology required to enhance computing; program established to address the measurement needs of the VCSEL industry and applications of optoelectronic interconnects.

FY94 Metrology needs of the VCSEL industry assessed and complementary Division resources identified; program begun to assist industry with measurements and standards for VCSELs and their applications in fiber-based data interconnects.

FY95 VCSEL devices obtained from industry, and packaging for dc-biased and high-speed testing established; measurement stations and methods for measuring large-signal return-to-zero modulation bandwidth, turn-on jitter, near and far-field beam profile, and relative intensity noise established.

FY96 Study VCSEL measurands as function of environmental and drive parameters; perform data interpretation and modeling of VCSEL emission properties; determine measurement problems and technological barriers of group III-nitride technology; collaborate with NIST researchers on joint proposal for nitride measurements support to industry; develop initial measurement stations.

FY97 Characterize properties of group III-nitride epilayers by transmission electron microscopy, waveguide loss measurements, reflectance spectroscopy of vertical-cavity structures; correlate microstructure and interface quality with device structure measurands; technically support VCSEL metrology researchers and device manufacturers.

4. Devices for advanced metrology

FY94 Concept of environment (e.g., temperature, electromagnetic field) sensor using microcavity devices such as VCSELs, resonant-cavity light emitting diodes, and Fabry-Perot filters formulated; NASA support secured.

FY95 Simultaneous electrical and optical biased measurement station established; light-current-voltage, photocurrent spectra, and threshold conditions measured with mixed electro-optical addressing; power-by-light operation demonstrated on fully-packaged and non-contacted devices; industry, in-house, and university-supplied VCSELs tested.

FY96 Design custom device which stabilizes optical-pump coupling but maintains laser sensitivity to environment; fabricate and test prototype device; establish and characterize fiber-interfaced optical power and sensing.

Fiber and Discrete Components

Project Leader: Sarah L. Gilbert

Staff: 2.0 Professionals, 1.0 Postdoc, 0.7 Contractor, 0.1 Technician

Full funding level: $0.44 M

Funding sources: NIST (100%)

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

FY90 Designed and constructed a single-longitudinal mode erbium-doped fiber laser and characterized its frequency noise.

FY91 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.

FY92 Conducted high-resolution laser spectroscopy of rubidium to assess potential use for a high-accuracy wavelength standard in the 1500 nm region; Constructed moderate-accuracy wavelength standard for the Air Force.

FY93 Stabilized the fiber laser to a narrow absorption line of laser-cooled rubidium, demonstrating the system's potential as a high-accuracy wavelength standard; conducted a detailed study of the line shapes observed in this system.

FY94 Constructed a new rubidium vapor cell trap for the high accuracy wavelength standard in the 1500 nm region; Began investigating the use of hydrogen iodide and hydrogen cyanide as wavelength references in this region for

	moderate-accuracy wavelength standards; 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).
FY95	Built and tested hydrogen cyanide ($H^{13}CN$) vapor cells for moderate-accuracy wavelength references; Supplied two companies with absorption cells to evaluate whether absorption cell SRMs will meet their calibration needs.
FY96	Develop acetylene absorption cell standard reference material.
FY97	Provide acetylene absorption cell SRM; Develop hydrogen cyanide absorption cell SRM; Evaluate reproducibility of high-accuracy wavelength standard based on fiber laser spectroscopy of rubidium.

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

FY92	Developed the capability to write Bragg reflection gratings in optical fiber.
FY93	Characterized fiber grating growth dependence on time and the intensity of the ultraviolet light, compared results with theoretical models.
FY94	Investigated the correlation of fiber grating growth and blue fluorescence emitted during exposure to ultraviolet light; Constructed a single-longitudinal mode fiber laser incorporating fiber gratings.
FY95	Evaluated the thermal stability of fiber Bragg gratings written in hydrogen-loaded and unloaded optical fiber using either pulsed or continuous-wave light; Characterized the intensity and frequency noise of fiber lasers containing fiber gratings.
FY96	Characterize noise of fiber grating-stabilized diode lasers.
FY97	Investigate stability of fiber gratings under illumination of intense laser light.

3. Polarization-dependent loss and gain metrology

FY94	Developed plan for constructing a polarization-dependent loss (PDL) measurement system.
FY95	Assessed industry need for PDL standards; Developed two PDL measurement systems.
FY96	Complete characterization and documentation of PDL measurement systems; Develop PDL artifact standard; Assess industry need for fiber amplifier polarization-dependent gain metrology.
FY97	Provide PDL artifact standard for interlaboratory comparison; Develop polarization-dependent gain measurement system.

Integrated Optics Metrology

Project Leader: Matt Young

Staff: 1.5 Professionals, 0.7 Contractor

Full funding level: $0.4 Million

Funding sources: STRS (100%)

Objective: Develop advanced measurement methods for integrated optical waveguides. Interact with standards groups to provide a metrology base for lightwave 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 × 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

FY88	Developed a photo-thermal method for nondestructively measuring loss in channel waveguides.
FY94	Identified industry's need for measurements on passive waveguides.
FY95	Developed low coherence reflectometer for probing integrated optical waveguides. Started preliminary collaborations with university and industrial laboratory on integrated optical metrology.
FY96	Continuing development of low coherence reflectometer. Beginning work on far field scanning and confocal microscopy of waveguide end faces.

Optical Fiber Sensors

Project Leader: Sarah L. Gilbert

Staff: 2.0 Professionals, 0.3 Guest Researcher, 0.5 Technician

Full funding level: $0.5 M

Funding sources: NIST (72%), Other Government Agencies (25%), Other (3%)

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

Background: This project is responding to the growing fiber-optic sensors industry by developing standards and calibrations where few exist, characterizing sensor materials, assisting in the characterization of components and sensing methods, and in educating the measurement community to the advantages of using optical fiber sensors. We also provide the industry and other government agencies with traceability, measurement expertise, neutral evaluation of technologies, and pre-commercial development of advanced prototypes.

Current Tasks:

1. Advanced sensor systems, components, and materials research

FY85	First demonstration of fiber annealing to remove birefringence.
FY86	Demonstration of optical fiber current measurements to 70 megamperes
FY87	Extended study of precision of electro-optic and magneto-optic sensors published.
FY88	Research on Faraday effect in ferromagnetic iron garnets begun
FY89	High speed, high sensitivity ($100 pT/\sqrt{Hz}$ noise equivalent field) sensors based on Faraday effect in YIG demonstrated.
FY90	Annealing technology transferred to industry.
FY91	Documentation of fiber annealing technology published; work on high stability voltage sensors begun.
FY93	Demonstrated very-high-sensitivity magnetic field sensor ($1.4 pT/\sqrt{Hz}$ noise equivalent field) using flux concentrators; measured radiation effects in iron garnets; Explained polarization effects in Sagnac current sensors.
FY94	Completed study of impediments to commercialization of fiber sensors for Navy shipboard applications; Tested iron garnet materials produced by company under Small Business Innovative Research Program grant; Designed and constructed a high-speed, high-sensitivity current sensor; improved fiber annealing technique demonstrated.
FY95	Laser-as-detector technique developed and tested for use in optical fiber sensor systems; Self calibrating temperature sensor system completed; Field-tested high-speed fiber-optic current sensor; work on expanded core fiber for lensless coupling begun.

FY96	Define critical materials and design parameters for low-cost diffraction-based sensors; Thermally expand the core of optical fiber; Characterize and improve high-sensitivity magnetic field sensor system.
FY97	Deliver prototype magnetic field sensor system to sponsor; Develop diffraction-based sensors for multiple measurands; characterize thermally expanded core fiber.

2. Basic metrology and standards development

FY88	Definitive study of stability of birefringent linear retarders (waveplates).
FY91	Began work on h-parameter measurement in high birefringence optical fiber at request of the Telecommunication Industries Association (TIA).
FY92	NIST/TIA interlaboratory comparison of h-parameter measurements conducted.
FY94	Tested prototype retardance standards and demonstrated very good performance for wavelength, temperature, and incident-angle dependencies; Identified long-term drift problem due to humidity-induced effect; participated in drafting of TIA fiber optic test procedure on h-parameter measurements.
FY95	Developed and confirmed a model for the standard optical retarder package; Redesigned package to minimize water vapor transmission; Completed the lifetime testing of the standard retarder.
FY96	Establish Standard Retarder as a Standard Reference Material (SRM); Measure the Verdet Constant of Optical Fiber for Los Alamos National Laboratory; Perform special tests on retarders; Characterize surface effects on total internal reflectance retarders; work with TIA in verification of new h-parameter measurement method.
FY97	Support standard retarder SRM; Produce standard retarder for operation at wavelengths of 1550 nanometers and/or 780 nanometers.

3. Optical data storage

FY95	Began investigation of optical data storage industry (ODS) needs; Participated in NIST planning workshop.
FY96	Identify and prioritize measurement needs of the ODS Industry; Investigate applicable measurement techniques.
FY97	Develop techniques for optical disc characterization; Develop prototype optical disc standards for jitter and cross-talk; Determine applicability of replicated standards to recordable media.

4. Optical fiber sensor commercialization

FY91	Transferred optical fiber annealing technology to U.S. company.
FY94	Transferred the improved annealing technology to U.S. company.
FY95	Sent company yttrium iron garnet and annealed fiber current sensors for evaluation.
FY96	Transfer optical fiber annealing technology to second company.
FY97	Identify companies interested in diffraction based sensor technology or expanded fiber core technology.

Optical Fiber Metrology

Project Leader: Douglas L. Franzen

Staff: 4.5 Professionals, 0.3 Technician

Full funding level: $1.0 M

Funding sources: NIST (93%), Other Government Agencies (7%)

Objective: Develop advanced measurement methods and Standard Reference Materials for optical fibers; interact with standards groups to provide a metrology base for the lightwave 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 an SRM for fiber cladding diameter that is used to calibrate the draw towers for most of the fiber commercially manufactured in the United States, and is preparing several other SRMs.

Current Tasks:

1. Develop dimensional metrology for optical fiber

FY89	TIA asked NIST to develop cladding diameter SRM.
FY90	Contact micrometer developed with Manufacturing Engineering Laboratory, NIST.
FY91	Scanning confocal microscope developed; Limitations of video microscopy studied.
FY92	White light interference microscope developed; International round robin completed with the International Telegraph and Telephone Consultative Committee; SRM holder evaluated in TIA round robin.
FY93	Definitive publication on cladding diameter published in NIST Journal of Research; Cladding diameter SRM available for sale.

FY94	International round robin completed to evaluate SRM housings and calibrations; Completed TIA round robin on fiber coating geometry.
FY95	SRM for coating geometry developed; TIA round robin to evaluate ferrule and pin gages complete; NIST Tech Note written on geometry round robins.
FY96	SRMs for coating diameter and connector ferrule outside and inside diameter (pin gages) available for sale; Measurement methods developed for connector protrusion/undercut.
FY97	Connector protrusion/undercut SRM available for sale.

2. Develop dispersion metrology for optical fiber

FY93	Initiated development of frequency domain phase shift system for chromatic dispersion measurements.
FY94	Initiated development of measurement methods for polarization mode dispersion (PMD); Completed frequency domain phase shift system; Studied fiber configuration for chromatic dispersion SRM; Initiated PMD round robin with TIA members.
FY95	Completed evaluation of PMD methods; Completed PMD round robin; Initiated TIA round robin to evaluate chromatic dispersion reference fibers; Completed development of differential phase shift system to measure zero dispersion wavelength.
FY96	Document PMD SRM; Complete TIA chromatic dispersion round robin; Chromatic dispersion SRM documented and available for sale.
FY97	PMD SRM available for sale.

3. Develop metrology for nonlinear fiber properties

FY94	Identified key needs of industry and initiated NIST program.
FY95	Measured pulse response of Fabry-Perot filters and determined effect of non-linearities; Completed capability for measuring four-wave mixing effects.
FY96	Determine relation between four-wave mixing efficiency and zero dispersion wavelength - publish results; Present four-wave mixing work to TIA; contribute to test procedure development.
FY97	Complete TIA round robin on non-linear effects.

4. Develop metrology for system/field measurements

FY92	Developd time domain methods for calibrating optical time-domain reflectometer (OTDR) group delay; Constructed moderate accuracy wavelength standard to calibrate optical spectrum analyzers; Investigated mode-locked fiber lasers as strobes for optical waveform sampling.
FY93	Developed interferometric low-coherence techniques for fiber length and group delay measurements.
FY94	Developed artifact calibration standards for group index of single and multimode optical fibers; Demonstrated efficient optical waveform sampling based on four-wave mixing effects; Initiated program to determine optimum launching conditions for multimode fibers in support of fiber computer bus interconnects (ATP funded); Developed high resolution OTDR for local area network applications.
FY95	Delivered group index OTDR calibration artifacts to Navy; Designed beam optics system for multimode fiber bandwidth measurements.

FY96	Work with TIA to evaluate and modify existing test procedures for multimode fiber bandwidth.

5. Develop metrology for fiber amplifiers

FY94	Identified the key metrology issues for fiber amplifiers.
FY95	Collaborated with TIA and international standards groups to plan round robin for noise figure and spectral gain.
FY96	Initiate international round robin and obtain preliminary NIST measurements of spectral gain.

High Speed Source and Detector Measurements

Project Leader: Paul D. Hale

Staff: 4.0 Professionals, 2.0 Guest Researchers, 0.8 Technicians

Full funding level: $1.3 M

Funding sources: NIST (65%), Other Government Agencies (30%), Other (5%)

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 frequency and impulse response of high speed sources and detectors to at least the third harmonic of the system modulation rate. 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. The high resolution photolithography and corneal sculpting markets require pulsed excimer laser measurements. Intensive use of laser target designators by the armed forces requires traceable low level pulse power and energy calibration standards at 1.06 μm and 1.55 μm.

Current Tasks:

1. Develop vertical cavity surface emitting lasers measurement methods and standards

FY95	Developed methods to quantitatively measure large signal modulation response, turn-on jitter, and relative intensity noise (RIN) in vertical cavity surface emitting lasers.
FY96	Develop small signal sinusoid and impulse response measurement methods, investigate dependence of RIN on feedback for a well-defined system, investigate correlation between RIN and near-field beam profile.

2. Noise measurements and standards

FY94	Developed competence in RIN of diode lasers to determine limitations of existing measurement techniques.

FY95 Performed RIN measurements on edge-emitting lasers at room temperature and liquid nitrogen temperature (77 kelvin) over the frequency range between 1 to 10 gigahertz.

FY96 Document industry needs for optoelectronic noise measurements, develop techniques and apparatus for measuring RIN which are suitable for supporting optical amplifier noise measurements and cable television specifications, complete cryogenic measurements of RIN of various diode laser sources.

3. Develop impulse response measurement capability

FY93 A titanium-doped sapphire laser which produced very short pulses (100 fs) was completed, detectors and modulators with picosecond response evaluated.

FY94 Received calibration requests and, consequently, modified system to accommodate customers' detectors.

FY95 Performed two Special Test calibrations on optical power detectors

FY96 Develop tunable short (100 fs) optical pulse source operating at wavelengths of 1.55 micrometers or 1.3 micrometers, develop methods for calibrating optoelectronic frequency response in both magnitude and phase for frequencies above 40 gigahertz, investigate industry need for on-wafer and packaged device frequency response metrology.

FY97 Compare vector frequency response calculated using time domain method with heterodyne measurements.

4. Detector frequency response measurements

FY92 Received inquiries from industry for photodiode frequency response in the frequency range between 0.050 and 20 gigahertz, investigated various measurement methods by literature search and talking to industry representatives, acquired parts for heterodyne measurement system.

FY93 Constructed heterodyne measurement system operable over the frequency range between 0.05 and 30 gigahertz, investigated candidates for transfer standards, constructed 20 gigahertz transfer standard for Navy.

FY94 Extended heterodyne coverage up to 40 gigahertz and down to about 300 kilohertz, participated in frequency response intercomparison with the National Measurement Laboratory in Great Britain which demonstrated good agreement (differences of less than 0.12 dB at frequencies below 20 gigahertz and 0.21 dB below 33 gigahertz).

FY95 Developed method for transferring photoreceiver calibration, extended range of heterodyne system to 50 gigahertz and down to 100 kilohertz, calibrated over 20 detectors and transfer standards for industry.

FY96 Document frequency response measurements as a formal calibration service, develop synthesized modulation source for high-resolution measurements (between DC and 1 Gigahertz), continue comparison with the National Measurement Laboratory in Great Britain.

5. Develop new pulsed laser measurement capability

FY90-91 Delivered to SEMATECH, two prototype laser calorimeters to measure optical power for laser light at a wavelength of 248 nanometers to support photolithography industry.

FY92-93	Designed, constructed, and delivered two low-level radiometers for the Navy Metrology Center for measuring peak power of Q-switched pulses from laser target designator and range finder systems.
FY94	Established capability to perform excimer laser measurements at 248 nanometers.
FY95	Delivered seven low level radiometers, began upgrade of low-level pulse measurements system to improve accuracy by a factor of 2 and reduce measurement time.
FY96	Continue low-level system upgrade, design prototype radiometer to measure light with a wavelength of 1.55 micrometers.
FY97	Construct low level measurement system to measure light with a wavelength of 1.55 micrometers, deliver prototype radiometer to the Navy.

Laser Radiometry

Project Leader: Thomas R. Scott

Staff: 5.0 Professionals, 1.0 Contractor, 1.2 Technician

Full funding level: $1.5 M

Funding sources: NIST (68%), Other Government Agencies (27%), Other (5%)

Objective: Develop measurement methods and standards for characterizing laser sources and detectors used primarily with steady-state 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 linewidth, 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. For example, the relatively recent development of vertical cavity surface emitting lasers (VCSELs) has shown the need for concurrent development of applicable measurement standards and techniques specific to this technology. 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. Quantitative knowledge about the irradiance profile and propagation characteristics of laser beams is essential for analyzing the radiation propagating through optical systems containing lenses, fibers, etc. For example, high resolution printing or photolithography require the laser radiation to be precisely focused.

Current Tasks:

1. Develop VCSEL measurement standards and measurement methods

FY94	Recognized need for VCSEL measurements and successfully proposed program for funding.
FY95	Developed VCSEL measurement systems and techniques for beam profile, modulation response, jitter, and relative intensity noise.
FY96	Correlate VCSEL measurement results for beam profile, modulation response, jitter, and intensity noise as functions of ambient conditions (e.g., temperature).

2. Develop spectral responsivity measurement capability for optical power detectors

FY93	Project initiated to develop spectral responsivity capability for optical power meters.
FY94	Prototype system developed and used for special test measurements at uncertainties of ± 2%.
FY95	Improved system designed, equipment procured, and system established.
FY96	Assess and improve measurement uncertainty; perform special test measurements with uncertainties of ± 1%.
FY97	Automate measurement system, train technicians, and implement full measurement services.

3. Develop and provide measurement services of optical fiber power meters

FY87	Received numerous requests for optical fiber power measurements.
FY88	Developed parallel beam measurement capability for power measurements of laser beams operating at a wavelength of 850 nanometers and began offering measurement services at 100 microwatt power level.
FY89	Developed parallel beam measurement capability for wavelengths of 1300 and 1550 nanometers and offered associated measurement services at 100 microwatt power level.
FY90	Received requests for measurements using various types of connectors as requests for parallel beam measurement declined.
FY91	Developed automated measurement capability for connectorized fiber delivery to power meters at 100 microwatt power levels.
FY92	Added 670 nanometers and 780 nanometers to wavelength capability.
FY94	Compared various methods of measuring detector linearity and selected optimum method for optical fiber power meters.
FY95	Developed linearity measurement system for detectors of laser radiation at wavelengths of 1300 and 1550 nanometers and used for Special Test measurements over wide range (60 dB) of power.
FY96	Develop linearity measurement capability for 850 nanometers; obtain approval for optical fiber power measurement services.

4. Develop and provide measurement services for laser power & energy detectors

FY67-FY93	Developed and provided power measurement services at various wavelengths at powers up to 300 Watts.
FY94	Based on requests from material processing industry, procured high power lasers and began development of high power calibration capability for lasers operating at a wavelength of 10.6 micrometer.
FY95	Provided calibrations for laser output power up to power levels of 1 kilowatt and a wavelength of 10.6 micrometers; developed fiber delivery system for high power (500 W) 1.06 micrometer measurements; initiated high laser round robin.
FY96	Implement high power 1.06 micrometer calibration measurements; complete high power round robin.

5. Improve accuracy of laser and optical fiber power measurements

FY94	A survey of standards laboratories and customer input specified need for improved accuracy for laser and optical power measurements at NIST
FY95	Developed plan for obtaining improved primary standard and secondary standard; procurement of cryogenic radiometer initiated.
FY96	Install and test cryogenic radiometer; develop prototype secondary standards (diode trap and pyroelectric trap designs).
FY97	Using new primary and secondary standards, fully implement high accuracy measurement chain.

6. Develop beam profile measurement capability

FY93	Requested by industry to become involved in development of beam profile standards and measurements to support industry.
FY94	Participated with U.S. industry to help develop an international voluntary beam profile standard document; performed beam width round robin with industry.
FY95	Developed state-of-the-art beam profile measurement system; initiated second beam width and divergence round robin.
FY96	Complete round robin; finish NIST beam profile measurement system development; determine appropriate NIST traceability.
FY97	Develop beam positional stability measurement capability; develop beam profile measurement capability for pulsed lasers.

VIDEO

Video Technology

Project Leader: Bruce F. Field

Staff: 5.2 Professionals

Full funding level: $1.0 M

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

   FY93 Designed measurement laboratory and ordered equipment, including colorimeters, spectroradiometers, charge-coupled-device (CCD) imaging

	system, signal generators, display positioning system, and spherical panel surround.
FY94	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.
FY95	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.
FY96	Analyze and report on an international voluntary reflectance measurement standard; Continue development of measurement techniques for display characterization; Design a transportable display simulator and plan an interlaboratory colorimetric comparison using it; Investigate the use of interference filters to evaluate colorimetric performance of detection systems; Develop a flat panel display characterization standard for the Video Electronics Standards Association (VESA).
FY97	Continue development of measurement procedures for display characterization, adding additional tests for viewing angle and other parameters to meet industry needs; Begin correlation of objective measures with subjective human visual system perception.
FY98	Refine measurement procedures and continue correlation with subjective perception; Develop rapid display-testing procedures for "production line" speeds.
FY99	Conclude measurement development; Publish measurement procedures document (possibly in conjunction with a voluntary standards organization).

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

FY93	Implemented and analyzed quality metrics for telecommunications applications; Developed a family of video test patterns for qualifying and verifying performance of metric implementations.
FY94	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.
FY95	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.
FY96	Report results of font flicker metric for interlaced displays; Develop performance revealing test patterns for digital video compression systems, including tests for motion estimation characterization and bit-rate-control performance; Develop analysis tools to quantify generated errors.
FY97	Refine FY96 test patterns and extend by developing a transient effects detector and a pre-processing performance analyzer; Refine analysis tools to more closely correspond to human visual system perception.

FY98	Complete transfer of measurement technology to industry through publication and dissemination of test patterns and objective metrics.

POWER

Dielectrics Research

Project Leader: Richard J. Van Brunt

Staff: 2.5 professionals

Full funding level: $0.5 M

Funding Sources: STRS (30%), Other Government Agencies (70%)

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. Work in gaseous dielectrics emphasizes the production of corrosive and toxic by-products in sulfur hexafluoride formed by exposure to electrical discharge. Present work emphasizes the production of selected toxic by-products in SF_6 insulated equipment. Recently the program has evolved to address investigations of partial discharge detection as a diagnostic of insulation conditions. Specific areas of investigation for FY96 include: 1) concern by the electrical manufacturers and utilities about the formulation and detection of highly toxic compounds in gas-insulated power systems; 2) issues being addressed by the Nuclear Regulatory Commission on evaluation of electrical insulation integrity as related to commissioning and life extension of nuclear power plants; 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

FY93	Nuclear Regulatory Commission (NRC) requests NIST to reactivate program on cable defect detection in nuclear power plant cables.
FY94	Initiated evaluation of partial discharge techniques for application as cable diagnostic; Established liaison with Brookhaven National Laboratory for acquisition of aged cable specimens.
FY95	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.
FY96	Publish bibliography; Measure partial discharges in multi-conductor insulated, low voltage cable; Determine industrial consensus on acceptability criteria for cable test methods requiring overvoltage.
FY97	Assemble a parallel system for digital recording/stochastic analysis and time-domain reflectometry analysis; Compare results of time-domain spectroscopy with results of dielectric measurements.
FY98	Attempt field trials of transportable equipment and transfer results to industry.

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

FY93	Built prototype of digitizer and recording system for partial discharge measurement; Developed first generation of discharge data analysis software.
FY94	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.
FY95	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.
FY96	Deliver digitizer to acquire partial discharge data under direct voltage to Air Force; Complete partial discharge measurements on alumina; Adapt recorder for acoustic detection of partial discharges.
FY97	Complete modification and documentation of partial discharges recorder for acoustic detection of partial discharges.

3. Investigate production of decomposition by-products in sulfur hexafluoride exposed to electric discharge

FY90	Developed gas-chromatograph/mass-spectrometer technique to detect disulfur decafluoride down to concentration of 2 parts per billion.
FY91	Measured production rates of disulfur decafluoride production for corona discharge in sulfur hexafluoride; Measured dissociative electron capture cross sections for other sulfur hexafluoride decomposition by-products.
FY92	Observe production of other possibly toxic by-products; Measured dissociative electron cross sections for selected by-products.
FY93	Improved procedure to detect disulfur decafluoride by minimizing effects of contaminate interferences and hydrolysis of the samples; Measured decomposition of sulfur hexafluoride exposed to x-rays via a Cooperative Research and Development Agreement (CRADA) with industry.
FY94	Completed definitive work on plasma chemical model for decomposition of sulfur hexafluoride; Measured production rates of by-products from corona discharge in mixtures of sulfur hexafluoride and oxygen.
FY95	Wrote parts 1 and 2 of final report to disulfur decafluoride CRADA members; Measured appearance potentials of ions from sulfur hexafluoride by-products.
FY96	Complete final disulfur decafluoride report.

Metrology for Electric Power Systems

Project Leader: Gerald J. FitzPatrick

Staff: 6.0 Professionals, 2.0 Technicians

Full funding level: $1.3 M

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

Objective: Develop measurement technologies and maintain 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, and to new technical challenges and advances in the industry. Currently energy metering of the more than 202 billion dollars worth of electrical energy used in the United States annually is traceable to NIST calibration services. In the past, additional measurement capabilities, such as impulse voltage measurements, have been developed at NIST. 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. The knowledge gained in these areas of research is rapidly transferred to the public through publications and the establishment of measurement standards.

Current tasks:

1. Calibration services in support of the electric power industry

FY93	Modernized power and energy calibration facility.
FY94	Performed impact analysis of power and energy calibration service on electric utilities.
FY95	Developed fast turn-around calibration service for selected watthour meter calibrations; Reinitiated offsite high voltage tests.
FY96	Perform international power and energy intercomparison with Canada, Europe, and Mexico; Modernize high voltage facility.
FY97	Increase frequency range of power and energy calibrations.
FY98	Upgrade current transformer calibration system.

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

FY92	Build NIST optical current transformer (OCT) to measure at power frequency current.
FY93	Built and documented portable Kerr Cell for optical voltage measurements.

FY94	Developed 0.1% calibration method for OCTs at power frequency in phase and ratio using digital techniques.
FY95	Initiated test of commercially produced OCTs.
FY96	Complete test of commercially produced OCTs.
FY97	Initiate testing of optical voltage transformers.
FY98	Complete test of optical voltage transformers.

3. Fast-transient measurements

FY92	Constructed NIST4 reference impulse divider.
FY93	Participated in round-robin testing of reference impulse measurement systems using NIST4 divider.
FY94	Completed and incorporated into IEEE standard for high voltage testing convolution technique for impulse qualification used to achieve <0.5% uncertainties.
FY95	Documented comparative high voltage impulse measurement techniques.
FY96	Document NIST4 impulse reference divider.
FY97	Perform international comparison of high voltage impulse measurement systems.

4. Develop test procedures for energy efficient motors and transformers

FY93	Investigated industrial procedures for measuring efficiencies of electric motors (> 1 horsepower).
FY94	Investigated industrial procedures for measuring efficiencies of electric transformers.
FY95	Wrote test procedure for electric transformers for U.S. Department of Energy.
FY96	Write test procedures for electric motors for U.S. Department of Energy.
FY97	Publish test procedures for energy efficient motors and transformers in the Federal Register.

5. Metrology support for electric and magnetic field measurements

FY90	Publish archival paper on complexities of making magnetic field measurements away from power lines.
FY91	Investigated experimental parameters using linear and circularly polarized magnetic fields during in-vitro exposure studies.
FY92	Developed spot-measurement protocol for residential magnetic field measurements in collaboration with working group developing an international standard.
FY93	Published primer on conducting in-vitro bioeffect studies with extremely low frequency magnetic and electric fields.
FY94	Determined worse-case measurement errors using 3-axis magnetic fields probe to measure dipole magnetic fields.
FY95	Two industrial voluntary standards, IEEE Standards 644-94 and 1308-94, written at NIST in collaboration with industry were issued by the Institute for Electrical and Electronics Engineers; Published error distribution for 3 axis magnet field probe used to measure magnetic fields.
FY96	Complete primer on magnetic and electric field measurements; Revise draft standards, developed for adoption internationally.
FY97	Prepare final draft for proposed international standard.

6. Applying metrology to power quality issues

FY88	Published award-winning seminal paper entitled "Power Quality Site Surveys: Facts, Fiction and Fallacies."
FY89	Conducted investigation and published a NIST report, "Lightning and Surge Protection of Photovoltaic Installations."
FY90	Began now ongoing technology transfer with the Power Electronics Applications Center (PEAC).
FY91	Completed major revision of a voluntary recommended practice describing surge environments.
FY92	Began technical review of all technical publications by PEAC on power quality.
FY93	Wrote 3 technical Bulletins on power quality issues.
FY94	Performed measurements and published 2 papers on surge propagation and mitigation in the PEAC Upside-Down House.
FY95	Completed three fundamental international standards documents on installation and mitigation for electromagnetic compatibility; Enlisted direct support from 2 electric utilities.
FY96	Complete documentation of PEAC Upside-Down House facility and experimental results.
FY97	Catalyze cooperation among electric utilities, electrical equipment manufacturers, end-users, and standard writing bodies.

NATIONAL ELECTRICAL STANDARDS

Resistance Standards and Measurement Methods

Project Leader: Ronald F. Dziuba

Staff: 3.0 Professionals, 1.6 Technicians, 0.5 Student

Full funding level: $1.1 M

Funding sources: NIST (70%), Other (30%)

Objective: Establish and maintain the U. S. representation of the ohm based on the quantum Hall effect, and to provide industry, academia, and government with a calibration service unequaled in scope and accuracy. In order to achieve this, our plans include developing new resistance standards and resistance measurement techniques, participating in international comparisons of the ohm, and supporting experiments to realize the international definitions of the ohm and watt.

Background: Resistors are the most commonly used electronic component. U. S. industry requires accurate resistance measurements for both quality and process control purposes. Not only is resistance an important control parameter in the manufacture of semiconductor electronics, but it is a common tool for the measurement of temperature, pressure, force, light intensity, and other quantities via transducers. The NIST link to these applied measurements is through the instrumentation industry. Accurate, traceable resistance measurements are vital to the development, testing, manufacturing, and maintenance of instrumentation. This is reflected in the volume of calibration work. 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 for improved scaling in bench instrumentation.

The quantized Hall resistance standard provides a powerful tool for the development and evaluation of new resistance materials and standards. To maximize its effectiveness, NIST will develop new automated scaling systems based on cryogenic current comparators, automated systems for improved calibrations of resistance standards, and bridges and standards needed for ac resistance calibrations. Work will also continue on development of a cryogenic current comparator using high-temperature superconductors that will provide ratio uncertainty of less than one part per million with operation at 77 kelvin using a refrigerator.

NIST is uniquely qualified to interact with other national laboratories in the comparison of resistance standards and the verification of resistance scaling from the basic standards in support of the worldwide electronic instrumentation industry. Such comparisons could ease impediments to international trade.

Current Tasks:

1. Establish and maintain the national standards of resistance

FY90	Implemented the January 1, 1990 new representation of the U. S. ohm based on the quantum Hall effect (QHE) and the International Temperature Scale of 1990.
FY91	Installed and tested new QHE cryogenic system; Participated in international comparison of 1 ohm and 10 kilohm resistance standards.
FY92	Developed cryogenic current comparator (CCC) measurement system for comparing quantized Hall resistances (QHR) with 100 ohm resistance standards; Verified Hamon scaling process to 0.01 part per million using more accurate CCC ratios.
FY93	Completed construction of a third CCC with an additional ratio of 129.06/1 for use in measuring the i=2 step of the QHR; Completed two comparisons of the QHR to the 1 ohm working group.
FY94	Completed three comparisons of the QHR to the 1 ohm working group; Completed design, construction, and testing of a special 100 ohm bank of five resistors.
FY95	Completed three comparisons of the QHR to the 1 ohm working group; Participated in an international comparison of 1 ohm and 100 ohm standards with the national measurement laboratory of Australia.
FY96	NIST has been commissioned by the Consultative Committee on Electricity (CCE) to be the pilot laboratory for an international comparison of high resistance standards.

2. Provide resistance measurement services for our customers

FY93	349 standards calibrated at a cost to industry of $360,000; Reduced resistance calibration uncertainties and published NIST Technical Note 1298 on resistance measurements.
FY94	372 standards calibrated at a cost to industry of $366,000; Completed construction of a guarded coaxial connector panel for switching resistors.
FY95	360 standards calibrated at a cost to industry of $338,000; Completed development of an automated 10 kΩ measurement system.
FY96	Continuation of measurement services.

3. Develop an automated system for the measurement of high resistance standards

FY94	Completed design and construction of a temperature/humidity air bath for high resistance measurements.
FY95	Completed modifications of an electrometer for use as a programmable detector in an automated high resistance bridge with programmable voltage sources as ratio arms.
FY96	Complete hardware and software development of high resistance automated system.
FY97	Complete evaluation and documentation of system, and extend high resistance calibrations to 10^{14} ohm.

4. Improvement of resistance scaling using cryogenic current comparators (CCC)

FY91	Developed a more versatile technique using isolated current sources in a CCC bridge for measuring resistors.
FY92	Developed method for detecting leakage currents in CCC bridges.
FY93	Initiated a project to develop a high temperature superconductor (HTS) CCC for operation at 77 K; Confirmed feasibility by measuring the effectiveness of tubular HTS shields.
FY94	Constructed a prototype HTS CCC achieving a 1:1 ratio balance to within a part per million.
FY95	Consulted with three HTS research companies to push development of state-of-the-art HTS magnetic shields for constructing CCCs; Contracts sent out for the construction of magnetic shields using yttrium-barium-copper oxide and thallium-based HTS materials.
FY96	Construct a prototype HTS CCC using yttrium-barium-copper oxide and/or thick-film thallium-based shields.
FY97	Develop an automated HTS CCC system with a combined standard uncertainty of less than 0.1 part per million for measuring resistors from 1 ohm to 10 kilohm.
FY98	Complete evaluation of HTS CCC system and provide adequate documentation for commercialization.

Quantum Resistance and Capacitance

Project Leader: Marvin E. Cage

Staff: 4.0 Professionals, 1.0 Technician

Full funding level: $0.8 M

Funding sources: NIST (93%), Other Government Agencies (7%)

Objective: Maintain the U.S. legal farad; realize the internationally defined farad and ohm and support the Division's impedance and resistance calibration services; investigate the physics of two-dimensional electron gases, measure ratios of fundamental constants important in electrical measurements, and apply the resulting knowledge to the maintenance of the U.S. legal ohm via the quantum Hall effect; fabricate developmental quantum Hall devices and investigate the effects of heterostructures and alloy contacts on quantized Hall resistance values; and investigate the frequency dependence of standard capacitance measurement systems and of the quantized Hall resistance.

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. In order to provide the nation with the world's best basis for electrical measurements, NIST depends on this project to conduct measurements of the SI ohm and farad that have smaller uncertainties than those of any other nation. 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. NIST's maintenance of the ohm by the quantum Hall effect — a resistance standard dependent only on the values of fundamental constants of nature — provides a basis for NIST and industry to explore and implement new measurement schemes. Methods developed by NIST for scaling of resistance and impedance measurements at the highest levels of accuracy will provide needed capabilities for extending measurement ranges both in magnitude and frequency for industry and other government laboratories. Investigating the underlying physics will allow NIST to develop quantized Hall resistance Standard Reference Material for industry.

Current Tasks:

<u>Resistance</u>:

1. Determine the SI ohm

FY81	Initiated the development of the capability to determine the SI ohm from the newly discovered quantum Hall effect and the calculable capacitor.
FY90	Reported new values of the von Klitzing constant and the SI ohm.

FY94	Initiated performance tests of the calculable capacitor chain for an improved determination of the SI ohm.
FY95	Performed linearity checks on the 4 terminal pair bridge and continue transformer ratio measurements for the calculable capacitor chain.
FY96	Determined the SI ohm from the quantized Hall resistance and the calculable capacitor.
FY97	Design and construct bridges for an expanded frequency range for the determination of the SI over the expanded frequency range.
FY98	Determine the SI ohm using a frequency other than 1592 hertz.

2. Develop an advanced quantized Hall resistance research and measurement capability

FY93	Developed a method of using an electronic voltmeter for realizing the quantized Hall resistance values in the laboratory with sufficiently low uncertainty.
FY94	Evaluated the uncertainties in the voltmeter method, and initiate plans for the development of quantized Hall resistance measurements using alternating current (ac).
FY95	Determined the potential and current distributions in a quantized Hall device for assessing the maximum electric fields for resistance values for both direct current and alternating current.
FY96	Acquire, install and test a new quantized Hall measurement system for increased magnetic field and efficient sample exchange capabilities.
FY97	Design and build new insert probes with low losses and initiate quantized Hall resistance studies under alternating current.
FY98	Complete development of a computerized potentiometric measurement system for use with both ac and dc resistance studies under both alternating and direct current.

3. Improve the quality and performance of quantized Hall devices

FY93	Evaluated quantized Hall devices fabricated by NIST and others for suitability as standards.
FY94	Developed advanced alloy contact techniques for low resistance contacts and new patterning techniques for fabricating heterostructure devices.
FY95	Determined the equivalent circuit of a quantized Hall device and calculate the intrinsic inductance and capacitance for resistance studies using alternating current.
FY96	Prepare and test quantized Hall devices made from new low electron density heterostructures using the developed alloy contact techniques.
FY97	Publish a summary of quantized Hall device preparation and characterization techniques and test results.

<u>Capacitance</u>:

1. Provide the national unit of capacitance

FY93	Completed construction of the set of new standard reference capacitors (capacitance value: 10 picofarads) and determine their mechanical stability.

FY94	Designed and assemble a capacitance bridge with the potential for a wider frequency range bracketing the value presently used (1592 hertz).
FY95	Determined the temperature dependence and thermal cycling properties of the standard reference capacitors.
FY96	Provide the value of the national farad capacitor bank for calibration services with an uncertainty of 0.002 parts per million.
FY96	Initiate an international comparison of capacitance for the Consultive Committee on Electricity.
FY97	Determine the effect of the mounting method of the capacitance elements on the temperature dependence of the reference capacitors.
FY98	Complete the international comparison of capacitance and provide results and interpretation to the Consultive Committee on Electricity.

2. Realize the SI farad

FY60	Initiated construction of a calculable capacitor in order to connect the national units of impedance with the SI units.
FY74	Reported the determination of the SI farad from the calculable capacitor.
FY80	Initiated construction of a new, improved version of the calculable capacitor.
FY88	Determined the SI farad from the calculable capacitor.
FY93	Improved the conical nose piece that provides the end compensation for the calculable capacitor as part of continued improvements.
FY94	Evaluated the uncertainties in the calculable capacitor chain.
FY95	Determined the SI farad from the calculable capacitor.
FY96	Evaluate the error budget for the calculable capacitor determination of the SI farad.
FY97	Design and construct bridges for use with an extended frequency range for the calculable capacitor chain.
FY98	Determine the SI farad at one alternate frequency.

Quantum Voltage and Current

Project Leader: Edwin R. Williams

Staff: 6.0 Professionals, 3.0 Guest Scientists, 1.0 Postdoc, 0.5 Contractor

Full funding level: $1.3 M

Funding sources: NIST (89%), Other Government Agencies (4%), Other (7%).

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 affect 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:

<u>Voltage</u>:

1. Provide the national unit of voltage

FY93	Developed methods for calibration of the high accuracy digital voltmeters using the 10 volt Josephson array.
FY94	Monitored the values of solid state voltage references for stability and noise and characterize behavior during measurement intervals.
FY95	Tested the applicability of the new 10 volt Josephson arrays for research purposes in monitoring the value of solid state voltage references.

FY96	Provide the values of the set of three transfer, solid state voltage references in terms of the Josephson volt to the NIST voltage calibration laboratory with an uncertainty of 0.05 microvolts/volt.
FY96	Replace the computers that operate the Josephson 1-volt system and develop improved software for the operations and data analysis.
FY97	Incorporate new commercial 10-volt array into Josephson research system and perform array-to-array comparisons within NIST laboratories.
FY98	Perform a direct array-to-array comparison of the U.S. national voltage standard system with that of the National Research Council of Canada.

2. Improve the reliability of the voltage calibration systems

FY93	Rewired the voltage calibration benches for improved thermal noise characteristics and voltage stability.
FY94	Rewired the automatic switches that control the voltage calibration benches and the switching of customers voltage references for a three-fold increase in capacity.
FY95	Replaced the computers that operate the calibration benches for more efficient operation and greater capacity.
FY96	Provide voltage calibration services for customers' voltage references with an uncertainty of 0.2 parts per million.
FY96	Reevaluate the operational software for the voltage calibration system and modify with the necessary improvements for increased efficiency and capacity.
FY97	Plan the inclusion of a 10-volt Josephson array system as an integral part of the calibration services.
FY98	Purchase and install a 10-volt Josephson array system as an integral part of the voltage calibration system.

<u>Current</u>:

1. Determine the value of the NIST watt

FY92	Incorporated a superconducting magnet into the ampere balance for improved signal-to-noise performance and increased precision.
FY93	Evaluated voltage/velocity and force/weight data for limiting noise characteristics.
FY94	Generated a new value for the NIST watt with a precision of 0.1 parts per million.
FY95	Redesigned the process for the alignment of the magnetic field, the coil motion, and the earth's gravitational force for reduced uncertainties.
FY96	Determine a value for the NIST watt with an uncertainty of 0.1 parts per million and report it at the Conference on Precision Electromagnetic Measurements (CPEM).
FY97	Install the new refractometer for the determination of the index of refraction of the gas environment.
FY98	Install a new gravimeter for a more precise determination of the gravitational constant and provide an updated value of the NIST watt at the CPEM.

2. Initiate redesign of the NIST watt experiment for the next generation of improvements

FY95	Initiated the redesign of the NIST watt experiment with the objective of monitoring the kilogram.
FY96	Initiate redesign and construction of the NIST watt experiment to include vacuum or controlled gas environment.
FY97	Initiate redesign and construction of the watt balance with the objective of improving the moving coil balance procedure.
FY98	Monitor a kilogram mass with a precision of 0.1 parts per million.

3. Demonstrate a single electron tunneling electrometer

FY93	Initiated studies for the application of single electron tunneling devices to metrological experiments such as capacitance calibrations.
FY94	Developed the capability to fabricate single electron tunneling devices.
FY95	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.
FY96	Perform a bridge balance demonstrating the limit of the precision of the single electron tunneling electrometer and cryogenic capacitor system
FY97	Initiate studies of the charge offset or charge noise characteristics in single electron tunneling systems.
FY98	Combine the NIST Boulder electron pump and the capacitance bridge and cryogenic capacitors to demonstrate a capacitance calibration using single electron tunneling technology.

4. Provide magnetic field calibration services to the Navy Primary Standards Laboratory

FY93	Designed a low magnetic field calibration system for use at the Navy Primary Standards Laboratory.
FY94	Fabricated a low magnetic field calibration system.
FY95	Delivered the magnetic field calibration system to the Navy Primary Standards Laboratory, San Diego, California and initiate training of Navy personnel.
FY96	Complete training of Navy personnel and provide consultation on the implementation of the low magnetic field calibration system into the U.S metrological system.

ELECTROMAGNETIC COMPATIBILITY

Standard EM Fields and Transfer Probe Standards

Project Leader:	Motohisa Kanda
Staff:	5.5 Professionals, 0.5 Technician
Full funding level:	$1.1 M
Funding sources:	NIST (54%), Other Government Agencies (45%), Other (1%)
Objective:	Develop methods and techniques for establishing continuous wave and pulsed electromagnetic (EM) reference fields to 100 gigahertz; develop and improve NIST's antenna calibration services; perform research and development on probes to measure EM fields and power densities.

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 second among the top priority items by the participants of the recent EMI/EMC (electromagnetic interference/electromagnetic compatibility) Metrology Challenges for Industry Workshop, Boulder, January 1995. Thus, industry has clearly identified a need for measurement capabilities in the area of EM fields that are traceable to NIST.

Current Tasks:

1. Develop methods for establishing standard EM fields

FY90	Developed standard field capability using pyramidal horns in the frequency range between 18 to 40 gigahertz.
FY91	Developed a time-domain method for evaluation of absorbers in the frequency range between 30 to 1000 megahertz.
FY92	Completed development of the spherical dipole standard field radiator.
FY93	Completed automation of the standard field facilities.
FY94	Analyzed anechoic chamber absorber and compared with measurements; initiated development of small-sample radio frequency absorber quality measurement system.
FY95	Performed a time-domain evaluation of the NIST anechoic chamber which revealed absorber and cavity characteristics.
FY96	Analyze rectangular open-ended waveguides for improved standard field generation in the frequency range between 200 to 500 megahertz.
FY97	Extend NIST's standard field generation capability into the frequency range between 40 to 50 gigahertz.
FY98	Develop a radial, guided-wave cell for broadband field generation for frequencies up to 1 gigahertz.
FY99	Extend standard field generation capability to frequencies above 50 gigahertz.

2. Develop antenna and probe calibration service

FY92	Compared the standard-antenna and standard-field methods of antenna calibration and demonstrated close agreement.
FY93	Evaluated antenna-antenna interaction in vertical monopole calibrations and made instrumentation and mechanical improvements.
FY94	Developed and evaluated the standard dipoles and provided the results to voluntary standards committee.
FY95	Extended the vertical monopole calibration service to frequencies up to 300 megahertz.
FY96	Prepare documentation for loop antenna calibration service; develop a calibration service for radiated fields of standard source such as the NIST-designed spherical dipole radiator which is now a commercial product.
FY97	Extend monopole antenna calibration service from the current upper frequency limit of 300 megahertz to 3 gigahertz (i.e., 3000 megahertz).
FY98	Incorporate innovations in laboratory instrumentation to reduce measurement uncertainties in antenna calibrations.
FY99	Develop a new anechoic chamber with improved performance at lower frequencies.
FY2000	Upgrade the NIST open area test facility and develop a new facility at a remote site (because of high ambient field in Boulder) for antenna calibrations at frequencies below 200 megahertz.

3. Develop EM field probes for transfer standards

FY91	Improved response of double-gap loop sensor for electric and magnetic responses.
FY92	Developed an improved electric-field multiprobe system with increased bandwidth and reduced field line pickup.
FY93	Developed a special antenna array system and receiver to detect low-level signals.
FY94	Performed theoretical and experimental evaluation of dipole electric field probe (dipole size: 2 centimeters).
FY95	Evaluated optically pumped, vertical-cavity, surface-emitting lasers for field probe applications.
FY96	Disseminate NIST-developed probe calibration techniques and uncertainty methodologies to standards committees.
FY97	Develop probes which will provide spectral information that can be used to discriminate against electromagnetic interference.
FY98	Evaluate and improve concentric loop antenna system for electric and magnetic field measurements.
FY99	Develop and evaluate improved near-field probes for electric and magnetic fields and power density.

Emission and Immunity Metrology

Project Leader: Motohisa Kanda

Staff: 5.5 Professionals, 0.5 Technician

Full funding level: $1.1 M

Funding sources: NIST (52%), Other Government Agencies (47%), Other (1%)

Objective: Develop and evaluate reliable test and measurement methods for electromagnetic emission and immunity of electronic devices, components, and systems.

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 kilohertz to 40 gigahertz 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 for the entire EMC/EMI community.

Current Tasks:

1. Develop radiated immunity metrology

FY90	Developed and evaluated a hybrid chamber for broadband immunity measurement.
FY91	Developed time-domain method for broadband, radiated-field immunity measurement.
FY92	Evaluated the use of injection testing as a substitute for radiated immunity testing; developed and evaluated the use of the reverberation chamber for cable shield testing.
FY93	Analyzed and measured the shielding effectiveness of aircraft cavities; improved the time-domain method for shielding effectiveness measurements of thin sheets.
FY94	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.
FY95	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.

FY96	Develop and evaluate alternative methods (time-domain and stepped frequency domain) for immunity measurements in reverberation chambers; analyze a circular aperture for use as a standard in shielding effectiveness measurements.
FY97	Develop and evaluate a broadband method for measuring shielding effectiveness of gaskets; develop a shielding effectiveness measurement method for active electro-optical components.
FY98	Develop and evaluate new methods for radiated immunity measurements.
FY99	Extend radiated immunity measurements to higher frequencies (above 40 gigahertz).

2. Develop radiated emissions metrology

FY93	Developed and evaluated a three-loop system for low-frequency, radiated-emissions measurements.
FY94	Used the NIST spherical radiator to evaluate shielded-room measurements of radiated emissions.
FY95	Conducted a successful workshop on EMI/EMC measurement needs for industry; analyzed and measured printed circuit board radiated emissions in the NIST reverberation chamber.
FY96	Correlate reverberation chamber radiated emissions measurements to other facilities.
FY97	Incorporate time-frequency analysis in measurements for broadband, pulsed radiated emissions.
FY98	Determine how to combine radiated emissions from components to estimate total system radiation; develop and evaluate new methods for radiated emissions measurements.
FY99	Extend radiated emissions measurements to higher frequencies (above 40 gigahertz).

3. Improve measurement uncertainty estimates and methodology

FY96	Develop a general framework for evaluating the uncertainties in radiated emissions measurements; evaluate the uncertainty in field strength and uniformity for alternative mode-stirring methods in reverberation chambers.
FY97	Develop a general framework for evaluating the uncertainties in radiated immunity measurements; evaluate the uncertainties in field measurements made in anechoic chambers, transverse electromagnetic (TEM) cells, and hybrid TEM-reverberation chambers.
FY98	Evaluate uncertainties in emissions and immunity measurements due to the configuration of the test object; determine how to best combine separate uncertainties in field measurements to obtain total measurement uncertainty.
FY99	Extend uncertainty methodologies to the issue of repeatability from site to site and from facility to facility.
FY00	Evaluate the uncertainties of new facilities and methods of emissions and immunity measurements; extend uncertainty evaluations to higher frequencies (above 40 gigahertz).

Electromagnetic Properties of Materials

Project Leader: Claude Weil

Staff: 6.0 Professionals, 1.0 Technician

Full funding level: $1.2 M

Funding sources: NIST (57%), Other Government Agencies (39%), Other (4%)

Objective: Evaluate existing and new 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 kilohertz to 60 gigahertz. Provide measurement services, standard references materials (SRMs) and measurement fixtures to industry and others. Organize and implement measurement intercomparisons.

Background: Dielectric and magnetic materials have wide application throughout the electronics, microwave, communication and aerospace industries. Their applications include printed circuit boards, substrates, electronic and microwave components, sensor windows, antenna radomes and lenses, and microwave absorbers. Improved, low-cost and nondestructive measurement methods of known accuracies, covering a wide spectral and temperature range, plus SRMs, fixtures and services, are needed to support many specific industry needs. Intercomparisons provide assessments of the national quality of material characterization.

Current Tasks:

1. Develop metrology for medium-to-high loss bulk solids

FY93 Completed new software for the broadband transmission line method and provided software to industry; Developed large-diameter (77 millimeter) coaxial air line method; Completed study of air gap errors in 7 and 77 millimeter diameter coaxial geometries and published results; Measured ferrite-loaded composite material used for electromagnetic compatibility (EMC) feed-thru filters in automobile wiring harnesses and published results.

FY94 Selected and characterized candidate magnetic reference materials; Published results of intercomparison of dielectric measurements using the 7 millimeter diameter coaxial air line in journal article.

FY95 Evaluated the performance of two nontunable stripline resonators for dielectric and magnetic measurements in the frequency range 150 to 2000 megahertz; Completed an intercomparison with six laboratories using the stripline resonator; Completed intercomparison, involving 15 laboratories, of dielectric/magnetic measurements of ferrites using 7 and 14 millimeter diameter coaxial air line technique; Developed improved full-field solutions and software for the open-ended coaxial probe that includes probe lift-off and finite layer thickness; Fabricated fixture for lift-off error studies using 14 and 35 millimeter diameter probes and developed new calibration methods; Investigated methods of speeding-up software; Published theory, provided software to industry.

FY96 Complete development of 2-port open-ended coaxial aperture technique for characterizing dielectric and magnetic properties of thin (250 μm) polymer sheets. Measure polymer films using 77 millimeter diameter coaxial air line system and new fixture for 14 millimeter diameter air lines. With Fields and Interference Group, develop free-field time-domain techniques for measuring the properties of inhomogeneous honeycomb panels over the frequency range 50-1000 megahertz.

FY97 Complete SRM for magnetic materials.

FY98 Develop special test service for measuring complex permittivity and permeability.

FY99 Develop methods for measuring inhomogeneous and anisotropic materials.

2. Develop high-precision resonator techniques for low-loss bulk solids

FY94 Evaluated dielectric rod resonator technique with J. Krupka of Poland; Characterized isotropic and anisotropic low-loss ceramics using variable conductor spacing and multiple modes; Developed new technique using thin rod sample to characterize magnetic properties of demagnetized ferrites in the region, 2-20 gigahertz, work published in journal article.

FY95 Refurbished and improved the NIST 60-millimeter diameter transverse electric mode cylindrical cavity to provide coverage of the frequency range between 6 and 13.5 gigahertz and more accurate loss factor measurements. Fabricated SRM coupons from samples characterized in cavity for industry; Tested a semi-confocal Fabry-Perot resonator for characterizing thin substrates at a frequency of 60 gigahertz. Studied resonant modes and made material measurements. Evaluated a split-cylinder cavity for characterizing substrates and printed wiring boards (PWBs). Evaluated a dielectrically loaded version of this fixture that operates at a frequency from 2 to 6 gigahertz, and supplied same to industry.

FY96 Certify dielectric SRM; Refurbish the coaxial re-entrant cavity which has a fundamental resonance frequency of 300 megahertz; Characterize PWB samples; Evaluate a second re-entrant cavity fixture at a frequency of 2 gigahertz; Develop new full-field solutions for re-entrant cavity; Investigate air-gap errors; Characterize materials for optical bus project. Develop nondestructive full-sheet resonance method for PWBs.

FY97 Develop methods for measuring the permeability tensor of bulk ferrites biased by a constant magnetic field; Obtain tensor data at frequencies between 2 and 10 gigahertz, versus biasing field level.

FY98 Develop measurement methods for ferrites with applied low-bias magnetic fields (less than 80 kilo amp-turns per meter).

FY99 Determine feasibility of measurements at cryogenic and elevated temperatures; Develop Fabry-Perot resonator operating at frequencies of 77 and 94 gigahertz.

3. Develop metrology for the microwave characterization of high-temperature superconductor (HTS) films and substrates

FY95	Developed a cryostat system, which operates over the temperature range of 4 to 120 kelvin with integrated sapphire rod resonator to measure both the surface resistance, R_S, of high temperature superconducting films at a frequency of 25 gigahertz, and the dielectric properties of substrate materials for HTS films; Evaluated a similar resonator for operating at a frequency of 10 gigahertz using a liquid nitrogen bath.
FY96	Complete temperature measurements of yttrium barium copper oxide thin films supplied by NIST Electromagnetic Technology Division and thallium films provided by industry. Measure yttrium barium copper oxide thick films supplied by industry. Investigate the frequency dependency of the surface resistance for high temperature superconducting materials at a temperature of 77 kelvin.
FY97	Measure power-dependency of yttrium barium copper oxide thin and thick film samples over temperature range 4-120 kelvin to determine the nonlinear response.
FY98	Develop methods for characterizing substrate materials, semiconductors and demagnetized ferrites at cryogenic temperatures.

4. Develop low-frequency impedance measurement techniques

FY94	Supported PWB team by evaluating accuracy of a commercially-available instrument that characterizes substrate over the frequency range 1-1500 megahertz.
FY95	Collaborated with MIT-Lincoln Lab (LL) and Genosensor Consortium by developing new automated techniques for DNA hybridization pattern detection; Completed initial ε' measurements on DNA plus buffer solution and buffer alone, using 14 millimeter diameter coaxial shielded-open technique, over range 0.3 -100 megahertz and found consistent differences in ε' signatures.
FY96	Measure DNA at frequencies in the range between 1-1000 kilohertz using commercial liquid test fixture.
FY97	Complete theoretical study of low-frequency relaxation in DNA molecules.
FY98	Perform low-frequency DNA measurements using LL microelectrode array.

5. Develop metrology for characterizing thin-films

FY95	With Microwave Metrology Group, derived dielectric properties of thin substrates and applied dielectric thin-films using coplanar waveguide transmission line measurements.
FY96	With SEMATECH, fabricate test jigs for deriving thin-film dielectric properties of low-permittivity materials used in microelectronics packaging.
FY97	Develop techniques for characterizing thin-film ferroelectrics which are biased using a constant voltage.
FY98	Evaluate high precision method for high temperature superconducting films and very low loss substrates.

FY99	Investigate methods for measuring thin-film ferrites under both demagnetized and DC-biased conditions at both cryogenic and elevated temperatures.

6. Develop metrology for elevated temperature characterization of bulk solids

FY95	Completed survey of high-temperature (to 1500 °C) methods for characterizing bulk solids in the frequency range 10 to 1000 megahertz. Completed drawings of two fixtures capable of measurements over the temperature range -100 to 200 °C.
FY96	Procure environmental chambers and fabricate fixtures.
FY97	Design and begin construction of resonant fixture for dielectric measurements at temperatures to 1500 °C.
FY98	Complete fixture for dielectric measurements at temperatures to 1500 °C.
FY99	Measure dielectrics at elevated temperatures using resonant fixture.

ELECTRONIC DATA EXCHANGE

Automated Electronics Manufacturing

Project Leader: James A. St. Pierre

Staff: 4.0 Professionals

Full funding level: $0.8 M

Funding sources: NIST (91%), Other (9%)

Objective: Develop tools for the electronics industry to facilitate the exchange of product data. 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 semiconductor 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.

As a neutral third party, NIST is uniquely positioned to develop and demonstrate non-proprietary solutions and information models. Also, NIST's long involvement with voluntary standards organizations permits us to contribute effectively to the development of compatible standards.

Current Tasks:

1. Provide support for International Design Automation Standards to create a consistent method for representation of electronic part/product data

FY91	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.
FY92	Participated in a workshop on the harmonization of digital product data sponsored by the American National Standards Institute; Developed a first-draft harmonized model for net list connectivity and defined about 20 terms associated with the model.
FY93	Established multi-platform automation testbed to support the development of solutions to interoperability problems among computer aided design tools and electrical/electronic product data exchange standards.
FY94	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.
FY95	Contributed to the Electrical/Electronic design team effort of PDES, Inc., to complete Committee Draft version of Application Protocol 210, and submit 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.
FY96	Convene 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; Develop prototype library of layered electrical product object definitions and relationships; Review compatibility of application protocols in the standard for the Exchange of Product Model Data with other electronic design standards and suggest modifications to resolve interoperability concerns.
FY97	Conclude review and development of the application protocol for printed circuit assemblies as it becomes an International Standard; Complete review of conformance methodologies and publish report to transfer techniques to industry.

2. Develop tools to facilitate Electronic Commerce of Component Information.

FY93	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.
FY94	Continued to lead the Electronic Business Reply Card demonstration team, demonstrated software at CALS Expo, November 1993; Investigated use of World Wide Web server and Mosaic client for electronic distribution of the NIST storeroom catalog; Suggested improvements to Internet protocols at the Federal Mosaic Consortium.

FY95 Initiated and supported the creation of a Python Software Association to support all industries which use Python programming language.

FY96 Complete prototype electronic component dictionary browser and search engine for on-line parts dictionary; Develop an advanced dictionary prototype, an Object Oriented Printed Circuit Repository, based on object-oriented technology (this would allow the transfer of intelligent object-oriented electronic product descriptions and support querying of these objects).

FY97 Develop a working simulation of the printed circuit repository on the virtual factory floor; Develop a specification for a Product Information Viewer and its interface to the World Wide Web.

FY98 Conclude the development of a printed circuit repository with published specification of operation and demonstration model; Develop a process model to allow electronic commerce to be incorporated into an electronic product life-cycle development process.

FY99 Conclude development of process model for electronic commerce and publish report.

3. Provide support for the SEMATECH Computer Integrated Manufacturing Framework

FY94 Completed first year report to SEMATECH analyzing and documented cost of certification and conformance testing for computer integrated manufacturing framework to be 27 to 30 work-years.

FY95 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).

FY96 Develop prototype semi-automated test generator; Refine technical and business model definitions; Conclude task with report to SEMATECH.

4. Develop prototype framework to integrate design tools for Microwave and Millimeter-wave Advanced Computational Environment program

FY93 Organized and conducted four-day technical meeting to discuss MMACE requirements; Converted supporting documents to World Wide Web format for interactive electronic distribution.

FY94 Developed Python language module to simplify creation of Common Gateway Interface (CGI) scripts for implementation of a control panel for the advanced computations environment on the World Wide Web.

FY95 Acted as Contracting Officers' Technical Representative, guiding two software developers in creating the final control panel; Completed control panel demonstrated; Investigated Khoros and Fresco programming languages for use in this application.

FY96 Finalize creation of industry-supported Python Software Association to support use of Python in this computational environment and conclude task.

LAW ENFORCEMENT

Enabling Technologies for Criminal Justice Practitioners

Project Leader: Kathleen M. Higgins

Staff: 3.0 Professionals, 1.0 Technician, 2.0 Support staff

Full funding level: $1.2 M

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 and the other NIST laboratories. 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 this 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) and the National Highway Traffic Safety Administration (NHTSA), varies depending upon the priorities of the criminal justice community at any given time.

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 systems. 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.

Current Tasks:

1. Develop quality assurance program for soft body armor

FY86	Published revision to NIJ Std. 0108.01, Ballistic Resistant Protective Materials and NBSIR 86-34444, Ballistic Tests of Used Soft Body Armor.
FY87	Revised body armor standard.
FY90	First year of multi-year effort to establish realistic quality control procedures for ballistic fabric used in body armor.
FY92	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.
FY93	Assisted NIJ in establishing the National Armor Advisory Board (NAAB).
FY94	Supported the NIJ Compliance Testing Program.
FY95	Discovered a flaw in the proposed aluminum plate test method for defining ammunition as armor-piercing; assisted ARPA in the development of concealable military body armor.
FY96	Develop and define a soft material exemplar for police body armor (this exemplar will also be used to define ammunition as armor-piercing); test and report results on ARPA body armor.

2. Characterize oleoresin capsicum (OC) further in support of the less-than-lethal technologies program

FY88	Initiated three-year project to monitor the U.S. Army development effort to design and implement appropriate chemical delivery systems.
FY91	Began to identify the performance characteristics and requirements appropriate for inclusion in NIJ standards for less-than-lethal weapons to be established in FY92/93.
FY92	Initiated development of standard for less-than-lethal weapons delivery systems.
FY94	Initiated study to characterize oleoresin capsicum.
FY95	Published NIJ Report 100-95, Preliminary Investigation of Oleoresin Capsicum; provided technical assistance and administrative support to program.
FY96	Identify, quantify, and further characterize the pungent constituents of commercial off-the-shelf OC sprays.

3. Investigate DNA profiling technologies further and develop additional SRM's as applicable

FY88	Developed preliminary standard for DNA reporting formats.
FY89	Initiated two-year project to refine reporting standards, standard materials for molecular weight quality assurance, and even more sensitive detection and non-isotropic probes.

FY91	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.
FY92	Issued SRM 2390 for DNA quality assurance testing.
FY93	Completed initial round robin tests of prototype SRMs for DNA profiling, employing the polymerase chain reaction (PCR) technique.
FY94	Re-certified SRM 2390, the restriction fragment length polymorphism profiling standard; validated the proposed components of SRM 2391; developed new electrophoretic methods for STRs.
FY95	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.
FY96	Finalize the production and certification of a set of well-defined DNA standards for mitochondrial and general DNA sequencing; implement Long PCR technology to aid in the rapid determination of human identity; pursue the formation of a consortium of DNA chip manufacturers to address the needs of the forensic and paternity testing communities for a "human identity chip".

4. Prepare Digital Intercept Standard for digital telephone systems

FY92	Initiated a project to assist the FBI in the development of a digital intercept system for integrated services digital network (ISDN).
FY95	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.
FY96	Edit draft standard; submit standard to NIJ for publication.

5. Review and revision of standards

FY82	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.
FY83	Additional two communication standards revised as above; revised body armor standard.
FY84	Revised crash helmets standard.
FY85	Revised standards for riot helmets and face shields, body armor and personal FM transceiver standards.
FY87	Revised fixed and base station FM transmitters and mobile digital equipment standards.
FY88	Revised fixed and base station receivers standard.
FY89	Revised 9mm/45 caliber autoloading pistols and mobile antennas standards.
FY90	Revised body-worn FM transmitters standard.

6. Furnish technical support and assistance in key areas

FY90	Published report on lithium batteries, hands-free communication systems, and technical assessment of portable explosives vapor detection devices.
FY91	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.
FY92	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.
FY93	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.
FY95	Updated AutoBid; served as DOC representative for law enforcement to the Technology Reinvestment Program.
FY96	Revise handgun ammunition effectiveness report; update AutoBid.

7. Support the quality assurance program for police traffic radar/lidar

FY91	Completed revision of model minimum performance specifications for radar units; assisted independent laboratory with tests to determine compliance with specifications.
FY92	Initiated project to develop standard for laser based units (lidar); initiated project to develop standard photoradar.
FY94	Revised the Model Minimum Performance Specifications for Police Traffic Radar Devices; supported the test program; completed preliminary laboratory and field tests of photoradar systems.
FY95	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.
FY96	Revise radar performance specifications to include new definitions, requirements and test procedures for units with multiple antennas, fastest vehicle mode and same lane moving mode; submit performance standard to NHTSA for publication.