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ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1995 PROGRAM PLAN

Supporting Technology for U.S. Competitiveness in Electronics

Electronics and Electrical Engineering Laboratory

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

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NIST

NIST SEEKS YOUR COMMENTS

EEEL reviews its plans regularly to keep them focused on the most important 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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U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

TECHNOLOGY ADMINISTRATION
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Bibliographic Information

Abstract

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST laboratories, is providing measurement and other generic technology critical to the competitiveness of the U.S. electronics industry and the U.S. electrical-equipment industry. This *1995 Program Plan* describes the projected metrological support that EEEL intends to provide to U.S. industry.

Keywords

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

Ordering

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OVERVIEW

INTRODUCTION

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST laboratories, is providing supporting technology and services that are critical to the competitiveness of the U.S. electronics industry and the U.S. electrical-equipment industry.

Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.7 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 $196 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 a multiplicity of factors bearing on competitive products. 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 the five-year period from FY 1995 through FY 1999, with a special focus on FY 1995. The plan implements the general strategic directions described in EEEL's *1994 Strategic Plan.*

In carrying out its plans, EEEL responds to the critical measurements needs of U.S. industry. Selected needs have been documented in a recent wide-ranging assessment called *Measurements for Competitiveness in Electronics*, prepared by EEEL in consultation with U.S. industry and other NIST laboratories and published in April 1993.[6]

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.[7]

EEEL customers also include other government agencies (Federal, state, and local), educational institutions, the research community wherever it is located -- in industry, government agencies, or educational institutions, and indirectly supports the general public through its services to the organizations already named. EEEL provides measurement capability and other services that help those Federal, state, and local agencies fulfill their many responsibilities in areas such as defense, energy, transportation, communications, health, safety, and law enforcement.

DELIVERABLES

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

Table 1: DELIVERABLES

Measurement Capability
absolute accuracy
reproducibility
materials reference data
Technology Development
Fundamental Research

Measurement Capability

EEEL focuses the largest part of its resources on the development 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:

> NIST's special technical capability for measurement development is needed.
>
> NIST's acknowledged impartiality is needed 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.

These reasons, and others, 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 its 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 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. These programs include NIST's own Advanced Technology Program ($430 million in FY 1995), the interagency Technology Reinvestment Project (about $400 million in FY 1995), and many programs of other Federal agencies.

An example of a major technology-development project to which EEEL and other parts of NIST are contributing is electronic data exchange. 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 here 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:[8]

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 current 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 a suitable project 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 1994 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

	FY94
Communications	
publications	214
software requests	120
talks	274
consultations	974
visits	467
visitors	733
meetings	
attendees	920
contributors	51
Joint Activities	
standards organizations	
staff participating	80
memberships	90
professional societies	
memberships	260
cooperative research	176
consortia (incl. forming)	4
guest scientists	79
Paid Services	
custom measurement development	140
standard reference materials	102
calibration service customers	450
training courses	13

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 these directly served industries provide support to nearly every other industrial and service sector, the indirect benefits of EEEL's work are substantial.

Electronics Industry

The electronics industry and the chemical industry are the two largest manufacturing industries in the United States, as shown in Table 4.[9] The most recent value available for the chemical industry is for 1991, so the comparison of shipment sizes with the electronics industry in 1993 is not obvious. The electronics industry is the largest employer with 1.7 million workers, more than the next two largest manufacturing industries combined.

Table 4: LARGEST U.S. MANUFACTURING INDUSTRIES (1993)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[9(a)]	303	1,695
Chemical[9(b)]	269 (1991)	841
Automotive[9(c)]	257	787
Petroleum Refining[9(d)]	140	74 (1991)
Aerospace[9(e)]	112	587

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.[10] 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 and Materials
Communications Equipment
- commercial, industrial, military
- telephone, telegraph
- intercommunications, alarm, traffic control
- broadcast, studio, and related products
- search and detection, navigation and guidance

Computers and Peripherals
- computers
- magnetic and optical storage
- printers, plotters

Industrial Electronics
- control, processing, display
- testing and measuring equipment

Electromedical Equipment
Consumer Electronics
- television
- radio
- audio and video recording and playback

The shipments of the U.S. electronics industry have been essentially flat in constant dollars over the five-year period from 1988 to 1992 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 3.5 percent; but the price deflator for the Gross Domestic Product increased at a compound average rate of nearly 3.9 percent over the same period, neutralizing those gains in terms of constant dollars. Over the six year period from 1988 to 1993, employment in the industry has fallen in every year, at a compound average rate of -4.2 percent per year, based on actual data.[11]

Electrical-Equipment Industry

The products of this 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 are also heavy users of electrical equipment, consuming more than 14 percent, by dollar value, of all electrical equipment shipped in the United States.

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.

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

Finally, three cross-cutting fields are shown. Electromagnetic compatibility focuses on measurement support for nearly every other category located higher in the table. Similarly, 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. An example is automated product descriptions to support the manufacturing of electronic and electrical products. 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

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	
electromagnetic compatibility	current
electronic data exchange	current
national electrical standards	current

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.

EEEL provides some measurement support for all of the technologies marked "current" in Table 7, even if those efforts are small ones. 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.

Table 8: FY 1994 RESOURCES

Funds (in EEEL)	$millions	percent
base	26.8	59
non-base		
from NIST[1]	5.6	12
from outside NIST		
development[2]	10.2	23
services[3]	2.7	6
total	45.2[4]	100
Funds (outside EEEL)	2.2	
Staff	number	percent
paid		
full-time permanent	283	70
other	39	10
total paid	322	80
unpaid		
guest scientists	79	20
total unpaid	79	20
total	401	100

Notes on Funding
[1]53 percent from Advanced Technology Program
[2]83 percent from other Federal agencies
[3]80 percent from calibrations services
[4]Total does not add due to rounding.

RESOURCES

EEEL's funding and staff resources for FY 1994, 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 base funds are provided by the Congress directly to NIST for the programs conducted in the NIST laboratories. The non-base funds come from multiple sources, but predominantly from three sources: funds transferred from NIST's Advanced Technology Program for support of its programs, funds transferred to NIST by other Federal agencies for the development of measurement capability supporting their programs, and funds provided by U.S. industry and other agencies for calibration services. The funds expended outside of EEEL are a combination of funds provided by the Congress and funds provided by other Federal agencies.

Table 9: ESTIMATED FY 1995 RESOURCES

Funds (in EEEL)	$millions	percent
base	27	60
non-base		
from NIST	6	13
from outside NIST		
development	10	22
services	3	6
total	46	100[1]
Funds (outside EEEL)	6	

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

For FY 1995, EEEL anticipates a small increase in the funds expended in EEEL to the level shown in Table 9. EEEL anticipates a major increase in the funds expended outside EEEL to $6 million.

PLANNING

EEEL reflects its plans and accomplishments in five types of published documents, as shown in Table 10. Also shown are typical publication intervals and time horizons. The most recent assessments of measurement needs are contained in *Measurements for Competitiveness in Electronics*. The measurement needs assessments are published on an irregular schedule, either individually or in groups as they are completed. EEEL has published groups of measurement needs assessments in three of the last six years. The assessments provide EEEL's 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 second document in Table 10, 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 but extending five years into the future also. 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 10: PUBLISHED PLANNING DOCUMENTS

Document	Publication Interval (years)	Time Horizon (years)
needs assessments	irregular	10
strategic plan	2	5
program plan	1	5
technical accomplishments	1	1 backward
impact studies	irregular	10 backward

Table 11 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 the measurement needs assessments are also shown: surveys of industry's measurement needs conducted by EEEL to support the assessments, and reviews of the assessments by industry.

Table 11 shows both documents completed in FY 1990-1994 and documents planned for FY 1995-1996. As indicated in the key at the bottom of the table, the assessments are marked "a" in Table 11. 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 publication of the assessment for the named technical field. The surveys are marked "s" in the table. They employ either written questionnaires or sets of telephone calls to, or visits with, 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 11 is contained in the endnotes.[12]

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, additional customer surveys, and workshops. For example, EEEL, in cooperation with the Advanced Research Projects Agency, is planning a major workshop on the measurement needs of the semiconductor industry for January, 1995.[13] It will have broad representation from the 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 roadmaps of both the Semiconductor Industry Association and 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 according to EEEL's organizational structure. This structure contains two offices and five divisions.

Table 11: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

Fields	'90	'91	'92	'93	'94	'95	'96
semiconductors	a	r,a	i	a,s	.	a,s	a
magnetics	a	.	r	a	.	.	a
superconductors	a	.	.	a,i	.	.	.
low frequency	.	.	.	.	.	.	
microwaves	a,r	.	.	a	.	.	.
lightwaves							
lasers	a	r	.	a,r	.	.	.
optical-fiber communications	a		i	a,r	.	.	a
optical-fiber sensors	a	.	.	a,r	.	.	a
optical information storage	.	.	.	.	.	.	a
optical signal processing	.	.	.	.	.	.	.
optical computing	.	.	.	.	.	.	.
computers	.	.	.	.	.	.	.
video	a	.	.	r,a	.	.	.
power	.	.	.	.	.	i	.
Cross-Cutting Fields							
electromagnetic compatibility	a	r,i	.	r,a	.	.	.
electronic data exchange	.	.	.	.	.	.	.
national electrical standards	.	.	.	.	.	.	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

The five divisions in EEEL manage and conduct programs. The two offices manage programs, but do not conduct them. One is the Office of Microelectronics Programs (OMP). It manages a NIST-wide program, funded by base (NIST) funds, in support of the semiconductor industry. Part of its program is conducted within the various divisions of EEEL, and part is conducted within the divisions of several other NIST laboratories. The second office is the Office of Law Enforcement Standards. It manages a NIST-wide program in support of the law-enforcement community. At present, the program of this office is conducted in two NIST laboratories: EEEL and the Chemical Science and Technology Laboratory. This program is supported entirely by funding from other Federal agencies.[14]

Both the offices and the divisions describe their work in terms of projects. The projects are the fundamental building blocks of this program plan. The descriptions of these projects follow, arranged by office and division. Each project contains two pages of text that state the needs addressed, the technical approach taken by NIST, the major plans for FY 1995, and the major accomplishments for the past fiscal year, FY 1994. Thereafter, a chart called the five-year plan summarizes the major accomplishments that will be pursued by that project during FY 1995 to FY 1999. The header for each project conducted in a division shows the name of the group or groups within the division conducting the project. The offices are not further subdivided into groups.

The projects implemented by the offices and divisions are responsive to EEEL's *1994 Strategic Plan*. The strategic plan, which is published separately, is organized in terms of the fields of technology supported. The relationship between the projects in the program plan and the fields of technology in the strategic plan is shown in Table 12.

Table 12: CROSSWALK BETWEEN STRATEGIC PLAN AND PROGRAM PLAN

STRATEGIC PLAN: FIELDS OF TECHNOLOGY	PROGRAM PLAN: PROJECTS	Page
SEMICONDUCTORS	Linewidth Metrology	19
	Plasma Processing and Chemical Vapor Deposition	21
	Low Concentration Measurements and Standards for Moisture in Process Gases	23
	Surface Metrology for Semiconductor Manufacturing	25
	Materials Measurements and Properties for Semiconductor Packaging	27
	Nanoelectronics	83
	Semiconductor Characterization	87
	Thin-Film Characterization	93
	Electrical and Thermal Characterization	90
	Test Structure Metrology for Advanced Semiconductor Manufacturing	96
	Plasma Chemistry - Plasma Processing	47
MAGNETICS	Microstructural Analysis for Electromagnetic Technology	169
	Magnetic Instruments and Materials Characterization	172
	Magnetic Recording Metrology	175
	Nanoprobe Imaging for Magnetic Metrology	178
SUPERCONDUCTORS	High-Performance Sensors, Infrared Detectors, and Mixers	157
	High-T_c Electronics	160
	Superconductor Interfaces and Electrical Transport	182
	Superconductor Standards and Technology	185
LOW FREQUENCY	Generation and Measurement of Precise Signals	56
	Waveform Acquisition Devices and Standards	59
	Measurements for Complex Electronic Systems	63
	AC-DC Difference Standards and Measurement Techniques	66
	Improved Impedance Calibration Service	72
MICROWAVES	Power Standards and Measurements	103
	Impedance, Attenuation, Voltage Standards and Measurements	107
	Network Analysis and Measurement	111
	Noise Standards and Measurements	119
	Antenna Measurement Theory and Application	135
	Metrology for Antenna, Radar Cross Section and Space Systems	141
	Microelectronics Metrology	115
	Electromagnetic Properties of Materials	150
	Special Test Measurements and Calibrations	146
LIGHTWAVES	Source and Detector Measurements	191
	Fiber and Integrated Optics	194
	Fiber and Discrete Components	201
	Optical Fiber Sensors	198
	Semiconductor Materials and Devices	204
	Dielectric Materials and Devices	207
VIDEO	Video Technology	50
POWER	Measurements to Support Electric Utilities	41
	Dielectrics Research	44
ELECTROMAGNETIC COMPATIBILITY	Standard Electromagnetic Fields and Transfer Probe Standards	124
	Emission and Immunity Metrology	130
ELECTRONIC DATA EXCHANGE	Automated Electronics Manufacturing	53
NATIONAL ELECTRICAL STANDARDS	Quantum Voltage and Current	75
	Quantum Resistance and Capacitance	78
	Resistance Standards and Measurement Methods	69
	Josephson Array Development	163
	Nanoscale Cryoelectronics	166

ENDNOTES

1. *1994 Electronic Market Data Book*, Electronic Industries Association, p. 2 (1994).

2. See Table 4 and endnote 9.

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. Preliminary figure for 1993 from the Edison Electric Institute, Washington, DC (December, 1994).

5. *1994 Electronic Market Data Book*, Electronic Industries Association, p. 5 (1994).

6. *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).

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

8. Some definitions of fundamental research exclude from consideration 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.

9. All shipments figures in the table are *product data* in current dollars. They are also estimates since no firm shipment data for 1993 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) *1994 Electronic Market Data Book*, Electronic Industries Association, pp. 2 (1994). (b) The shipments figure is from 1991, the year of most recent data, and is used as an estimator for 1993. *1994 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 11-1 (January 1994). (c) The figures shown reflect both the motor-vehicle bodies and supporting parts industries. *1994 U.S. Industrial Outlook*, pp. 35-1 and 35-23. (d) The employment figure is from 1991, the year of most recent data, and is used as an estimator for 1993. *1994 U.S. Industrial Outlook*, p. 4-1. (e) *1994 U.S. Industrial Outlook*, p. 20-1.

10. For a detailed analysis of that structure, see *Measurements for Competitiveness in Electronics*, Electronics and Electrical Engineering Laboratory, pp. 40-42 (April 1993).

11. Employment was 2.0999 million in 1989 and was 1.6947 million in 1993. *1993 Electronic Market Data Book, Electronic Industries Association*, p. 5 (1993) and *1994 Electronic Market Data Book, Electronic Industries Association*, p. 2 (1994).

12. All documents noted in Table 11 are shown below. They cover the period 1990 to 1996.

Semiconductors

1990	a	Chapter 2, "Semiconductors", *Emerging Technologies in Electronics*, Second Edition, Electronics and Electrical Engineering Laboratory, National Institute of Standards and Technology, Report No. NISTIR 90-4260 (February 1990).
1991	r	Industry review of draft: Robert I. Scace, *Metrology for the Semiconductor Industry*, Report No. NISTIR 4653 (September 1991).
1991	a	*Metrology for the Semiconductor Industry* (See preceding note.)
1992	i	Albert N. Link, *Economic Impact on the U.S. Semiconductor Industry of NIST Research in Electromigration* (January 1992).
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	"$Hg_{1-x}CD_xTe$ Characterization Measurements: Current Practice and Future Needs", *Semiconductor Science and Technology*, Vol. 8, pp. 753-776 (1993).
1995	a	Silicon semiconductor measurement needs assessment, to be completed in 1995.
1995	s	*Optical Characterization Methods Survey* for materials, processing, and manufacturing in the semiconductor industry, to be completed in 1995.
1996	a	Compound semiconductor measurement needs assessment, to be completed in 1996.

Magnetics

1990	a	Chapter 4, "Magnetics", *Emerging Technologies in Electronics*, Second Edition.
1992	r	Industry review of draft: Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.
1993	a	Chapter 5, "Magnetics", *Measurements for Competitiveness in Electronics*, First Edition.
1996	a	Magnetics measurement needs assessment, to be completed in 1996.

Superconductors

1990	a	Chapter 3, "Superconductors", *Emerging Technologies in Electronics*, Second Edition.
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

None.

Microwaves

1990	a	Chapter 8, "Microwaves", *Emerging Technologies in Electronics*, Second Edition.
1990	r	Industry review: Chapter 8, "Microwaves", *Emerging Technologies in Electronics*, Second Edition.
1993	a	Chapter 7, "Microwaves", *Measurements for Competitiveness in Electronics*, First Edition.

Lasers

1990	a	Chapter 7, "Lasers", *Emerging Technologies in Electronics*, Second Edition.
1991	r	Industry review: Chapter 7, "Lasers", *Emerging Technologies in Electronics*, Second Edition.
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

1990 a Chapter 5, "Lightwaves: Optical-Fiber Communications", *Emerging Technologies in Electronics*, Second Edition.

1992 i Albert N. Link, *Economic Impact of NIST-Supported Standards for the U.S. Optical Fiber Industry: 1981 - Present* (February 1992).

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.

1996 a Optical-fiber communications measurement needs assessment, to be completed in 1996.

Optical-Fiber Sensors

1990 a Chapter 6, "Optical-Fiber Sensors", *Emerging Technologies in Electronics*, Second Edition.

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.

1996 a Optical-fiber sensors measurement needs assessment, to be completed in 1996.

Optical Information Storage

1996 a Optical information storage measurement needs assessment, to be completed in 1996.

Optical Signal Processing

None.

Optical Computing

None.

Computers

None.

Video

1990 a Chapter 9, "Video Technology", *Emerging Technologies in Electronics*, Second Edition.

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

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

Power

1995 i Economic impact assessment of the value of NIST calibration services for electrical power and energy, to be completed in 1995.

Electromagnetic Compatibility

1990 a Chapter 10, "Challenges to Emerging Technologies: Electromagnetic Compatibility", *Emerging Technologies in Electronics*, Second Edition.

1991 r Industry review: Chapter 10, "Challenges to Emerging Technologies: Electromagnetic Compatibility", *Emerging Technologies in Electronics*, Second Edition.

1991 i Albert N. Link, *Estimates of Economic Impact of NIST Research in Electromagnetic Compatibility/Interference (EMC/EMI) Metrology* (December 1991).

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.

Electronic Data Exchange

None.

National Electrical Standards

1996 a National electrical standards measurement needs assessment, to be completed in 1996.

13. *International Workshop on Semiconductor Materials Characterization: Present Status and Future Needs*, a workshop on measurement needs to be 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.

14. National Institute of Justice, Federal Bureau of Investigation, and the National Highway Traffic Safety Administration.

OFFICE OF MICROELECTRONICS PROGRAMS

Project: LINEWIDTH METROLOGY

FY 95 Fund Sources: STRS, OMP, ATP, OSRM, SEMATECH

Staff (7.5 staff-years; Manufacturing Engineering Laboratory)

Professional	M. POSTEK (SEM)	J. POTZICK (OM)	R. Silver
	J. Lowney*	R. Larrabee* (GR)	A. Vldar (GR)
Technician	S. Jones	L. Carroll*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Critical dimension (CD) measurements must be made with high precision during the manufacture of integrated circuits. Accuracy is also important, but more for development and pilot line operations. This project supports all aspects of this need. CDs affect device operation. For example, the 66-MHz version of the Intel Pentium™ microprocessor would operate at 100 MHz or more if its CD were reduced to 0.6 μm.

Technical Approach: Two programs exist in semiconductor linewidth metrology (optical microscopy (OM) and scanning electron microscopy (SEM)) with a third (scanning probe microscopy) beginning in 1995. Substantial NIST efforts have gone into optical microscopy, which has physical limitations based on the properties of light. The industry once thought that scanning electron microscopy would become the metrology tool of choice for submicrometer metrology, but it also has limitations based upon the interaction of the electron beam with the specimen. Scanning probe microscopy has limitations including tip bending during the measurement scan, hysteresis, and the need for tip characterization. Programs to develop understanding of these measurement techniques and their limitations and the development of models to improve the measurement processes are currently in hand.

FY 95 Plans

Optical microscopy:

- Reduce uncertainties for SRM 473 by using a vendor capable of providing better edges. Reduce uncertainties by using the new ISO approach to computation of uncertainty. Develop photomask chrome edge waviness and run-out measurement technique.

- Develop the design and partially complete the overlay measurement system. Design the first iteration of an overlay standard.

- Compare the current green-light metrology system to the new ultraviolet-light measurement system. Install and optimize the aerial image simulation program into the current computer system and add the aerial image enhancements to the ultraviolet microscope. Then, prove the concept of improved photomask metrology by means of stepper emulation.

Scanning electron microscopy:

- Procure a second batch of SRM 2090 and issue the standard. This will be the first production batch.

- Conduct a follow-on to the NIST Workshop on "Electron Beam Interaction Modeling for Metrology and Microanalysis in the Scanning Electron Microscope" in conjunction with the 1995 Microbeam Analysis Society Meeting.

- Continue the development sequence of the Monte Carlo Modeling - MONSEL - series and compare model data with actual SEM data. This is being facilitated through interaction with both Motorola and Digital Equipment Corporation production facilities under the SEMATECH contract.

Related Developments

CRADAs exist with the following partners:

- Metrologix and IVS - establish and implement a user-friendly algorithm for the measurement of SEM sharpness.
- ANATECH - techniques for cleaning electron-beam-induced contamination from SEM samples.
- Topometrix - develop SEM-based metrology instrument having scanned probe capability.
- E. Fjeld Company - develop high performance SEM stage for the Hitachi SEM. Digital Equipment Corporation and AT&T want production versions of the stage once the development is completed.
- MOXTEK - develop standards for SEM and scanned probe instruments using technology the company has developed in soft X-ray diffraction grating technology.

FY 94 Accomplishments and Impacts

- Obtained a SEMATECH consulting contract lasting the calendar year. Phase I covered a study of the lithometrology needs and capabilities of the microelectronics industry. Phase II covers projects in SEM metrology, optical metrology and scanned probe metrology.

- Developed UV microscope to replace green light instrument to improve certification capability to 0.25 μm. It is operating with all of the hardware to be used in the final configuration. Initial computer control systems are complete. The system is capable of two-dimensional raster scans. A patent disclosure was filed on the strut joint in the Stewart platform for the ultraviolet microscope.

- Procured the second batch of the optical microscope standard SRM 473.

- Procured the new SEM magnification standard SRM 2090 and modified the metrology SEM to measure it, including redesign of the specimen motor stage to accommodate larger sample motion and optimization of the computer-based measurement program. First and second iterations of the production version were received from Texas Instruments (TI) and were inspected. Feedback on their acceptability was sent back to TI; the production process is being refined.

- Held first International NIST Workshop entitled "Electron Beam Interaction Modeling for Metrology and Microanalysis in the Scanning Electron Microscope" at the SCANNING/SEEMS 94 Meeting May 17-20, 1994 in Charleston, South Carolina.

- Developed project with a U.S. company on measurement of proximity X-ray masks and projection e-beam (SCALPEL) masks. The X-ray lithography portion is in conjunction with a Defense Advanced Lithography Program. Metrology of structure width on both types of masks is possible using NIST transmission electron microscopy techniques.

Project: PLASMA PROCESSING AND CHEMICAL VAPOR DEPOSITION

FY 95 Fund Sources: STRS, OMP

Staff (3.5 staff-years; Electronics and Electrical Engineering Laboratory (EEEL), Chemical Science and Technology Laboratory (CSTL), and Physics Laboratory(PL))

Professional	J. WHETSTONE (CSTL)	R. J. van Brunt (EEEL)	J. K. Olthoff (EEEL)	J. R. Roberts (PL)
	M. A. Sobolewski (CSTL)	R. W. Davis (CSTL)	M. R. Zachariah (CSTL)	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Advanced measurement methods, fundamental reference data, reference plasma discharge cells, and predictive models are needed to develop and operate new plasma etching and chemical vapor deposition (CVD) reactors. These tools include mass and optical spectroscopy and electrical measurements useful for control and diagnostics of low-temperature plasma reactors; computational models describing flow fields, temperature fields and particle trajectories; and fundamental thermochemical and kinetics data on chemical systems for CVD reactor geometries.

Technical Approach: Improved process models and sensors are critical to the design of 0.12-μm manufacturing equipment. The predictive models required will be based on semi-empirical to fully fundamental methods by the beginning of the next century. These rely heavily upon a knowledge base describing the basic physical and chemical mechanisms occurring in etching and deposition reactors. The measurements and data necessary include accurate rf voltage and current measurements, kinetic-energy distributions of mass identified ions correlated with optical properties, laser-induced fluorescence measurements in plasmas, and validated computational models of gas flow, temperature profiles, particle formation mechanisms, and particle trajectories in CVD reactors. Advanced plasma processing techniques using a reference discharge, such as the Gaseous Electronics Conference (GEC) rf Reference Cell now being tested in numerous laboratories, are used to calibrate diagnostic measurements, test chemical kinetics models processes, and learn about the inherent physical characteristics of the discharge that control limitations on reproducibility.

FY 95 Plans

- Construct a new GEC Reference Cell with an inductively-coupled plasma (ICP) source. Use mass spectrometry to measure the degree of dissociation of O_2, N_2, CF_4, H_2, and SF_6 in the ICP source over a wide range of plasma conditions for validation of model assumption. Use spatially resolved optical diagnostic methods to determine concentration profiles.

- Investigate ion kinetic energy distributions for high E/N Townsend discharges in neon and hydrogen to test modeling assumptions concerning the equilibrium of ion energies of rf plasmas.

- Prepare ion kinetic energy data from rf plasmas in He, H_2, O_2, and H_2 for archival publication.

- Organize and edit a special issue of the *NIST Journal of Research* dedicated to research performed on GEC rf Reference Cells.

- Implement and test Langmuir probe system on GEC Reference Cell having an ICP source to complement optical diagnostic and mass spectroscopic techniques. Measure electron concentrations and dc plasma

potential. Compare results with electrical data to further refine models of the electrical behavior of rf discharges.

Related Developments

- Etching and film deposition using plasma processes have grown substantially over the past five years. The dollar volume of equipment sold has more than doubled. Plasma technology is a way of adding energy to a chemical process so it works at or near room temperature rather than at elevated temperatures. This sharply reduces diffusion effects that tend to smear out the fine features of structures on the wafer, a most unwanted side effect.

FY 94 Accomplishments and Impacts

- Measured the kinetic-energy distributions for ions sampled from rf discharges in H_2, He, N_2, and O_2, and in mixtures of Ar-H_2, He-N_2, and Ar-O_2. Results were used for validation of model calculations, and were presented at several conferences. Correlations between ion energies and electrical and optical measurements were investigated.

- Plasmas in hydrogen and argon-hydrogen mixtures are of interest because of their use in the cleaning of silicon surfaces. Detected the presence of fast neutrals for the first time in discharges containing H_2 using time- and spatially-resolved optical emission spectroscopy. Determined the probable sources of these fast neutrals by investigating ion kinetic energies and fluxes. The results of these experiments were documented in two archival papers that were submitted to *Applied Physics Letters* and *Journal of Applied Physics*.

- Measured the kinetic-energy distributions for ions in high electric field-to-gas density (E/N), dc "Townsend" discharges in argon and nitrogen, and compared them with distributions calculated from known collisional cross sections. The comparison allowed an evaluation of the performance of the ion energy diagnostic device, and validated the cross section data that are commonly used by plasma modelers. Results were submitted to *Physical Review E*.

- Hosted the 47th Annual Gaseous Electronics Conference on October 18-21, 1994 at NIST.

Project: LOW CONCENTRATION MEASUREMENTS AND STANDARDS FOR MOISTURE IN PROCESS GASES

FY 95 Fund Sources: STRS, OMP

Staff (2.5 staff-years; Chemical Science and Technology Laboratory)

Professional	J. R. WHETSTONE*	J. T. Hodges	G. E. Scace
	J. P. Looney*	W. G. Cleveland*	A. Vidar (GR)
Technician	B. L. Shomaker*	J. D. Melvin*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Moisture is one of the most important and prevalent contaminants in process gases that contribute to device rejection and reduced productivity. Current water vapor measurement standards are limited to concentration levels above 2 parts per million by volume (ppm_v). New processes used for fabrication of submicrometer scale devices require measurements of moisture levels down to 15 parts per billion by volume (ppb_v). Improved measurement standards are needed to provide a sound basis for evaluation of existing measurement technology and development of improved measurement methods.

Technical Approach: Reliable measurements at these low levels of water vapor concentrations require development of improved absolute and working standards. Working standards take the form of precision humidity generators and are used for routine generation of gas streams of known moisture concentration. Generators saturate input gas streams with moisture over the desired concentration range. Absolute moisture concentration measurements are made using a gravimetric hygrometer that separates and quantifies both the moisture and carrier gas. A recently fabricated gravimetric hygrometer has an anticipated lower operating point that lies between 10 and 100 ppm_v. Characterization of precision generator operation is performed gravimetrically to demonstrate correct operation of a generator's saturation stage over the range of overlapping operation of the two methods. Once a generator's operation is demonstrated over the range afforded by the gravimetric hygrometer, it is used over its full operating range. A new precision generator, the low-frost-point moisture generation (LFPG) facility, is being constructed and will operate between approximately 10 ppb_v and 500 ppm_v (500,000 ppb_v). It will be the working standard NIST uses to generate known moisture concentration gases at these levels, is directly related to fundamental measurement standards, and is fabricated to conform with high purity gas handling technology common to IC manufacturing.

Measurement methods capable of detecting moisture at levels in the 1 to 10,000 ppb_v range were surveyed. Optical spectroscopic techniques will be pursued because they have robust measurement capabilities and good sensitivities at these low concentrations. An absorption technique was identified that utilizes a "ring-down cavity" method having effective absorption pathlengths of several kilometers, thereby providing the necessary sensitivity for low concentration measurements. Diode laser sources operating in the near IR provide reliable, narrow band cavity excitation. This technique also has the potential for on-line measurement capability for process monitoring. Spectral water absorption features near a wavelength of 1.39 μm will be used. Using gravimetric methods and the LFPG, we can determine the fundamental line strengths in this spectral region over several orders of magnitude. Once determined, these fundamental line strengths can serve as primary measurement standards and may provide the means to extend optical techniques over many orders of magnitude with the potential to make reliable measurements into the parts per trillion by volume (ppt_v) (parts per10^{12} region).

FY 95 Plans

- Commission moisture generation facility (LFPG) to operate between 10 ppb_v and 500 ppb_v, assessing its performance with gravimetric methods over the upper part of the generator's operating range.

- Complete prototype ring-down cavity apparatus and demonstrate the technique for water vapor using pulsed laser sources.

- Obtain and integrate a frequency-stabilized diode laser system as a source at 1.39 μm wavelength in the ring-down apparatus and initiate testing with the LFPG and gravimetric hygrometer.

Related Developments

- Industry standard specification limits for moisture content of many process gases have been limited to 0.5 ppm_v for several years because measurements of lower moisture levels are not supportable by NIST calibrations. Buyers of these gases have specified lower moisture levels in company specifications and suppliers have tried to meet those requirements, but with considerable misgivings on both sides.

FY 94 Accomplishments and Impacts

- Identified optical ring-down cavity techniques to pursue as a high sensitivity method for moisture concentration measurements.

- Began construction of moisture generation facilities capable of creating moisture concentrations as low as 10 ppb_v.

- Demonstrated operation of two primary components of the gravimetric hygrometer.

Project: SURFACE METROLOGY FOR SEMICONDUCTOR MANUFACTURING

FY 95 Fund Sources: STRS, OMP

Staff (1.8 staff-years; Chemical Science and Technology Laboratory)

Professional	J. FINE	T. Jach*	C. J. Powell*
Technician	R. L. King*	J. D. Melvin*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: The National Technology Roadmap for Semiconductors emphasizes the crucial role of defects and microroughness on the performance of future semiconductor devices. Improved characterization methods are needed to check that thin dielectric films have the desired properties. These include the microroughness and defect structure of the film-substrate interface.

Technical Approach: NIST has developed a non-contact optical instrument for measuring surface roughness that is being further developed for improved characterization of microroughness and surface defects of device surfaces, and the changes in microroughness and defects following processing steps. This instrument, a scanning scattering microscope (SSM), has a roughness sensitivity of about 2 nm. The goal is to develop the SSM as an improved metrological tool by increasing its spatial resolution, scan speed, and data acquisition rate so that it can be used to identify processing parameters that cause minimum surface damage. Another NIST-developed technique, grazing angle X-ray photoemission, will be applied to the characterization of oxidation, film deposition, and etching processes on silicon surfaces. This technique can give information about the chemical state of the silicon surface following various processing steps such as film deposition and etching. Other techniques of potential utility are being investigated.

FY 95 Plans

- Design optical system for auto-focus of laser beam in SSM and visual imaging of sample surface.
- Develop kinetic electron emission technique for investigating the electronic and defect properties of ultra-thin insulating layers on semiconductors.
- Determine performance capabilities of new atomic force microscope (AFM) and compare surface topography measurements on very smooth semiconductor surfaces using SSM and AFM techniques.
- Investigate the surface chemistry of silicon oxidation using grazing angle X-ray photoemission spectroscopy.

Related Developments

- A Standard Reference Material™ 2135c for sputter depth-profiling, consisting of alternating layers of chromium and nickel on a silicon substrate is being developed. Materials have been fabricated and certification measurements are in process.

FY 94 Accomplishments and Impacts

- Identified a new class of defect generation processes in ion-bombarded ionic insulators.

- Constructed an improved Scanning Scattering Microscope using high-resolution scanning techniques and rapid data acquisition to allow a 240 x 240 pixel image to be acquired in about 15 minutes, a 50-fold improvement in speed over the original prototype instrument.

- Evaluated commercially available Atomic Force Microscopes and selected an instrument for purchase with Surface and Microanalysis Science Division funds that will be used for comparative measurements with the SSM.

Project: MATERIALS MEASUREMENTS AND PROPERTIES FOR SEMICONDUCTOR PACKAGING

FY 95 Fund Sources: STRS, OMP, NASA, Air Force, Army, Navy

Staff (5.4 staff-years; Materials Science and Technology Laboratory)

Professional	D. T. READ	E. S. Drexler	J. M. Phelps*	R. R. Keller*
	A. J. Slifka *			
	G. T. DAVIS*	B. Dickens*	A. S. DeReggi*	
	J. R. MANNING*	W. J. Boettinger*	F. W. Gayle*	C. A. Handwerker*
	D. Josell*	K. W. Moon*	J. A. Warren*	M. E. Williams*

name in capital letters = project leader; * = person works on project part time

Need Addressed: Materials found in advanced packaging structures are produced differently from bulk materials (for example, metal thin films are vapor-deposited). Their mechanical properties are usually different from bulk materials of the same composition and test procedures for bulk materials cannot be applied to many important component materials of electronic packaging and interconnect structures. Industry needs data for modelling and simulation of mechanical, electrical, and thermal behavior of packages to support proper engineering design and evaluation.

Technical Approach: Develop techniques for studying mechanical behavior (e.g., tensile, fatigue) of metals, cure and moisture content of polymers, and solderability applicable to materials in the forms in which they are used in electronic devices. The techniques and data are chosen to be useful for advanced engineering methods (e.g., finite element analysis) in improving the designs and reliability of packaging and interconnect materials and structures.

FY 95 Plans

- Continue to develop and apply methods for studying the dependence of thin film mechanical properties on important variables such as production process (e-beam evaporation, sputtering, etc.), temperature, fatigue cycles, size, material species and type, and microstructure. Explore possibilities for experimental correlations between electromigration, stress-induced voiding, and applied stress.

- Apply electron beam moiré to high resolution experimental mechanics studies of advanced electronic interconnect structures produced by industrial partners (such as a high density interconnect structure, and ball grid arrays) and to mechanical reliability of interfaces as found in electronic packaging structures.

- Develop techniques of sample preparation and spectroscopic and gravimetric examination to deduce state and amount of absorbed moisture in filled and unfilled polyimides and epoxies used in electronic packaging.

- Devise a test structure and test method which will exhibit "pop-corning" (abrupt formation of voids in polymers) reproducibly under simulated solder reflow conditions. Relate results on concentration and form of water in packaging materials to the phenomenon of "pop-corning".

- Continue development of solderability tests and measurements of solder wettability using the wetting balance. Determine the additional physical parameters necessary to obtain consistency between the

measured wetting force, contact angle and meniscus rise during wetting balance tests. Measure and develop models for the rate and extent of solder spreading due to reaction with the substrate. The reaction will be modeled as a diffusion process.

- Organize two workshops for the Solder Engineering Working Group, the first to provide an introduction of the group capabilities to industrial representatives and the second to include modellers and technologists from industry who joined the group as a result of the first workshop.

Related Developments

- D.T. Read is new associate technical editor of the Journal of Electronic Packaging.

- The NCMS-led consortium on Development of Alternatives to Lead-Containing Solders asked for NIST work on solderability of lead-free solders and assigned NIST responsibility for phase diagram evaluations used in selecting candidate lead-free solders and for preparation of test samples of the candidate solders. Consortium members include representatives from major U.S. companies and national laboratories.

- Tom Davis was asked to participate in reviews of SRC-sponsored projects in electronic packaging and meetings of the SRC Technical Advisory Board.

FY 94 Accomplishments and Impacts

- Developed piezoelectric-driven tensile test machine that allows practical cyclic operation and reduces thermal drift of the load signal significantly. Compared tensile behavior of e-beam evaporated thin films of copper and aluminum. Found that they behave similarly, with copper slightly stronger.

- Established collaborations with Sandia National Laboratory and a U.S. company on thin-film mechanical properties. Experiments with Sandia showed a) metal thin films produced at other laboratories can be exchanged and tested and b) sputtered copper thin films are much stronger than e-beam evaporated films.

- Developed method to assess differences in cured polyimide films using photoacoustic spectroscopy, enabling measurement of polymeric materials to check reproducibility of cure. Measurements differentiate between different polyimides, between anisotropic polyimides cured at different heating rates (gives different degrees of anisotropy), and between the same polyimide cured in air and in nitrogen. It can find a layer of a second, similar polyimide under a top layer several μm thick.

- Measured spectra of solvents ranging from toluene to methyl alcohol to understand addition of water to dry and water-containing materials. Started assessing water take-up by polyimide/silica bilayers.

- Developed new solderability test using wetting balance measurements and a range of steam-aging test conditions to produce surfaces of different solderability. Developed a method for extracting time-temperature solder contact angle data from the wetting balance test measurements and area-of-spread tests. Such data acquired for any substrate/flux/solder combination can be used for design of soldering processes and for evaluation of the sensitivity of solder alloys to changes in flux activity.

- A workshop entitled "Materials Metrology and Data for Commercial Electrical and Optical Packaging and Interconnection Technologies" and sponsored by NIST, Semiconductor Research Corporation, Institute for Interconnection and Packaging of Electronic Circuits, and Optoelectronics Industry Development Association was held in Gaithersburg on May 5-6, 1994.

OFFICE OF LAW ENFORCEMENT STANDARDS

Project: LAW ENFORCEMENT TECHNOLOGY

FY 95 Fund Sources: NIJ, NHTSA, FBI

Staff (5.5 staff-years)

Professional	K. M. HIGGINS*	D. E. Frank	A. G. Lieberman	J. A. Worthey
Technician	N. E. Waters			

name in capital letters = project leader; * = person works on project part time

Need Addressed: In the current political climate, gun control and crime on the streets are receiving increased attention, as is the issue of overcrowded correctional facilities. In its two major program areas, communication systems and weapons/protective equipment, OLES is establishing standards to clearly delineate to law enforcement agencies how best to enhance the efficiency and effectiveness of their operations through the application of emerging technologies in electronics, materials, analytical analysis, and weapons. The private sector has recognized that law enforcement personnel are increasing their capabilities to apply sophisticated equipment and systems, and many companies are expanding their product lines to include equipment specifically for law enforcement use. In many instances, such manufacturers utilize the NIJ/NHTSA standards, developed by OLES, as the basis of product design.

The adoption by the law enforcement community of the products of emerging technologies often involves critical issues which may have both safety and legal ramifications. In this respect, law adoption differs from private sector application. Inadequate equipment performance can adversely affect the general population when such performance increases the cost of public safety, precludes arrests, or results in evidence found to be inadmissible in court. The standards developed by OLES for other-agency promulgation enable the cost-effective procurement of equipment that meets the unique needs of law enforcement.

Technical Approach: Apply the resources of EEEL and other NIST laboratories to the technological needs of law enforcement, conducting research to enable manufacturers to develop equipment and systems suitable for such use. Specifically: develop performance standards for promulgation by the National Institute of Justice (NIJ) and the National Highway Traffic Safety Administration (NHTSA) and prepare tutorial guidelines on specific law enforcement equipment and systems. Assist NIJ/NHTSA in the implementation of testing programs, and the establishment of consumer product lists, which identify equipment that complies with their performance standards. Review ongoing NIST research to benefit new correctional facilities which could potentially lead to the expansion of two additional programs in the areas of construction standards and security systems for corrections.

FY 95 Plans

- Complete the draft standard for photoradar devices for submission to NHTSA.
- Complete the draft standard for laser speed-measuring devices for submission to NHTSA.
- Update and complete the draft standard for dialed-number recorders for submission to NIJ.
- Initiate research on the potential of body-armor trauma plates to ricochet, hitting unprotected areas of the wearer.
- Validate the test method to define commercially available ammunition as armor-piercing.

- Provide technical support for the development of a universally applicable quality assurance program for body armor manufacturers, which includes the certification of ballistic performance of all lots of material.

- Continue to provide technical support to the Federal Bureau of Investigation (FBI) in the development of integrated systems digital network (ISDN) digital intercept system (DIS).

- Prepare a law enforcement industry national standard for the ISDN/DIS for NIJ publication.

- Establish a ballistics research laboratory.

- Support the traffic radar devices quality assurance testing program of the International Association of Chiefs of Police (IACP) as requested.

- Develop and support laser speed measuring device (LIDAR) quality assurance testing program of the IACP.

- Provide NIJ with the technical support required to address the expansion of two potential program areas, i.e., construction standards and security systems for corrections.

- Provide technical assistance and administrative support to the Less-than-Lethal weapons technology program at NIJ.

- Serve as Department of Commerce (DoC) core representative for law enforcement to the Technology Reinvestment Program.

Related Developments

- The Memorandum of Understanding, signed by the Director of EEEL and the Acting Director of the National Institute of Justice in 1993 continues to provide the basis for the major source of funding for the OLES program.

- The National Armor Advisory Board, which was established by NIJ with OLES assistance, is continuing in its role as an adjunct to the Law Enforcement Technology Advisory Council (LETAC), formerly TAPAC.

FY 94 Accomplishments and Impacts

- Developed test methods for determining conformance of photoradar speed measuring devices to proposed NHTSA specifications. Completed preliminary laboratory and field tests of these systems.

- Demonstrated the feasibility of evaluating the operating characteristics of laser-speed measuring devices through the use of an OLES-developed target simulator.

- Continued to provide technical support to the FBI in the development of a standard for the ISDN intercept system.

- Revised the NHTSA Model Minimum Performance Specifications for Police Traffic Radar Devices.

- Supported the NIJ Compliance Testing Program for body armor.

- Supported the IACP test program for traffic radar devices.

Project: LAW ENFORCEMENT TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Provide technical support to FBI in development of ISDN. [NIJ, FBI]					
Prepare draft NIJ standard for ISDN/DIS. [NIJ, FBI]					
Complete the draft standard for photoradar devices. [NHTSA]					
Complete the draft standard for laser speed measuring devices. [NHTSA]					
Develop quality assurance testing program with IACP for LIDAR devices. [NHTSA]					
Initiate research on body-armor trauma plates. [NIJ]					
Validate the test method for armor-piercing ammunition. [NIJ]					
Support the development of a quality assurance program for body armor manufacturers, which includes the certification of the ballistic performance of material lots. [NIJ]					
Establish a ballistics research laboratory. [NIJ]					
Support the quality assurance testing programs of the IACP for speed measuring devices (traffic radar, LIDAR, photoradar devices). [NHTSA]					⇒
Update and complete the NIJ standard for dialed number recorders. [NIJ]					

Project: LAW ENFORCEMENT TECHNOLOGY (concluded)

FISCAL YEARS	95	96	97	98	99
Provide support to NIJ for development of new program areas. [NIJ]					⇒
Provide technical assistance to the Less-than-Lethal weapons technology program at NIJ. [NIJ]					⇒
Serve as DoC core representative for law enforcement to the Technology Reinvestment Program. [NIJ]					

Project: FORENSIC SCIENCE TECHNOLOGY

FY 95 Fund Sources: NIJ

Staff (0.5 staff-years)

Professional	K. M. HIGGINS*

name in capital letters = project leader; * = person works on project part time

Need Addressed: One of the most powerful investigative tools available to the criminal justice system today is deoxyribose nucleic acid (DNA) profiling. Tremendous strides have been made with this technology, but DNA testing continues to advance. New techniques will be developed and existing systems will be improved. The NIJ's Science and Technology Division will be at the forefront of this research by providing funding for technological advances, acting as a bridge between science and criminal justice, and helping to put the state-of-the-art technology on the front lines of law enforcement.

Additionally, the settlement of controversial scientific issues being argued in federal courts has not been simplified by the recent Supreme Court ruling on the rules of evidence in the case of Daubert v. Merrell Dow Pharmaceuticals. Rather than having a fairly rigid rule for gauging whether scientific testimony is admissible, judges will now have to be more flexible in letting experts testify. Trial judges will have greater discretion in allowing scientific testimony and will have to look more closely at the underlying scientific methods of the testimony instead of just the overall acceptability of the conclusions. In other words, any scientific evidence can be introduced at a trial, and it will then be accepted or challenged on the same basis as any other kind of evidence. One of the cornerstones of effective, non-refutable, admissible scientific testimony will be found in the use of standardized, industry-accepted methods and approaches to evaluate evidentiary materials. OLES will serve at the center of this development process, assisting federal, state, and local forensic science practitioners to apply new technologies efficiently, effectively and safely.

Technical Approach: Along with the advent of televised courtroom dramas has come the recognition that law enforcement personnel are increasing their ability to apply sophisticated equipment and systems to forensic applications. The consequences of inadequate equipment performance or techniques can affect the general public as, for example, when the technology is not properly applied and the evidence obtained is inadmissible in court. OLES will develop analytical techniques and standard reference materials (SRM's) and collections for forensic science applications.

OLES will initiate work with the forensic science community at the federal (FBI, ATF, and Secret Service), state and local (IACP and ASCLD) levels to identify the areas of greatest concern and to set priorities for the work to be done. Much of this interchange of information will find its roots in OLES's participation in the major forensic meetings and seminars. With priorities identified, OLES will begin its mission to provide the forensic science community with SRM's, standards, guidelines, and reports. The three forms of documentation can be further characterized as follows:

a) Standard — A formal document, in standard format, which details the performance which the equipment or instrument is required to give, and the test methods by which its actual performance is to be measured. A standard, in general, is a detailed, highly technical document, which is addressed to the technician who will do the testing.

b) Guideline — Written in non-technical language which addresses both the potential purchaser and user of the equipment or instrument. A guideline includes a general discussion of the equipment or instrument, its important performance attributes, the various models currently on the market, objective test data where

available, and any other information which might help the reader make a selection among the various options or alternatives available.

c) Report — Any document, other than a standard or a guideline, which results from the research performed by OLES. A report may discuss new test methods which have been developed, explain the rationale for the selection of particular test methods, document detailed test results, report on research findings, or report the results of state-of-the-art surveys. It is evident that reports are extremely varied in content, format, and function. The only requirement is that they be useful to the law enforcement and criminal justice system.

FY 95 Plans

- Issue the standard reference material for DNA typing, employing the polymerase chain-reaction (PCR) technique.

- Investigate methods for the typing of mitochondrial DNA.

- Work with NIJ to update the report entitled, "Standard Reference Collections of Forensic Science Materials: Status and Needs."

- Provide NIJ with the level of support required to address the development of two other program areas, i.e., terrorism and drugs.

FY 94 Accomplishments and Impacts

- The NIST Biotechnology Group, sponsored in part by OLES, pursued two major quality assurance related efforts during FY 94: 1) Validation of SRM 2391 Materials; and 2) Re-testing and certification of SRM 2390, DNA Profiling Standard.

- SRM 2391 is a polymerase chain reaction (PCR)-based DNA profiling standard developed for the forensic and paternity testing communities. The FY 94 efforts focused on validating the proposed components through two extensive interlaboratory studies, i.e., round robin tests.

- Additionally, new electrophoretic methods for separating Short Tandem Repeat (STR) polymorphisms, important to the PCR-based technologies, were developed. STR's have rapidly gained interest among forensic scientists as a means of human identification as they are amenable with degraded DNA which is often found in forensic samples.

Project: FORENSIC SCIENCE TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Issue the standard reference material for DNA-typing employing the polymerase chain-reaction technique. [NIJ]					
Investigate methods for the typing of mitochondrial DNA. [NIJ]					
Develop update to 1977 report entitled, "Standard Reference Collections of Forensic Science Materials: Status and Needs." [NIJ]					
Provide support to two other program areas, i.e., terrorism and drugs. [NIJ]					

ELECTRICITY DIVISION

Project: MEASUREMENTS TO SUPPORT ELECTRIC UTILITIES

FY 95 Fund Sources: STRS; DoE, EPRI, NTP, PEAC, Fees

Staff (6.4 staff-years)

Professional	G. FITZPATRICK	F. Martzloff	M. Misakian	T. Nelson
	R. Turgel*	O. Petersons* (GR)	J. K. Olthoff*	E. Simmon
Technician	J. Chandler	J. Pitt*	A. Secula	

name in capital letters = project leader; * = person works on project part time

Need Addressed: This project aims to meet the following needs of electric utilities and power equipment manufacturers: 1) the need for measurement infrastructure to support new and evolving technologies, such as optical devices used for revenue metering, to maintain the high reliability and efficient transmission and distribution of electrical power systems; 2) the need for traceable calibrations of electrical energy meters on which annual revenue for utilities, estimated at greater than $181B, depends; 3) the need for accurate measurements of power system disturbances to assess their effects on sensitive equipment, such as personal computers, and the reverse problem of how end-use devices corrupt the quality of electric power; and 4) the need for accurate measurements of electrical parameters used in bioeffects research, which are required to protect public health, and support the safe and efficient use of electric power. The estimated economic impact due to conservative designs of power systems and potential devaluation of property values due to uncertainty of bioeffects is near $1B per year.

Technical Approach: NIST provides guidance in the accurate measurement of high voltages and currents, electric and magnetic fields, and electric power and energy through the quantification of measurement uncertainties and errors. NIST has been instrumental in showing how improper protection can result in potential damage to sensitive electronics. This project provides the support necessary for making accurate electrical and magnetic measurements, and guidance in the use of protective devices for sensitive and expensive electronics equipment. Among the specific goals for this project are: 1) develop techniques for the calibration of optical current transducers using analog techniques for 0.1% uncertainties or less, and for the characterization of high-voltage impulse reference measurement systems with 1% uncertainties; 2) provide measurement and consultative support to the Department of Energy (DoE), the Electric Power Research Institute (EPRI), and the National Toxicology Program (NTP) bioeffects programs; and 3) develop a new approach for coordinating cascaded, surge-protective devices.

FY 95 Plans

- Develop a special watthour calibration at 120 V, 5 A, power factors of 0.5 and 1.0, with uncertainties of 0.02% at reduced cost and shorter turnaround time.

- Develop calibration methods for optical current transducers (OCTs) over the range from 100 to 10 000 A with uncertainties of 0.1% or less using analog techniques.

- Develop reference measurement systems meeting the requirements of IEEE Standard 4 on High Voltage Test Techniques and of the International Electrotechnical Commission (IEC).

- Participate in the development of international standards on electromagnetic compatibility through IEEE Working Group on Power Quality, the IEC Subcommittee on high frequency phenomena, and the IEEE Committee on Power Quality.

- Provide surge protection technology transfer to the Electric Power Research Institute (EPRI) Power Electronics Application Center (PEAC).

- Determine statistical distribution of errors for three-axis probes used for measuring magnetic fields from appliances.

- Complete editing of IEEE P1308 on extremely low frequency (ELF) electric and magnetic field (EMF) measuring instrumentation required for final approval by the IEEE Standards Board.

- Provide measurement support, such as site visits and consultation for bioeffects studies, as required for DoE, NTP, EPRI, and EPRI-PEAC.

Related Developments

- The IEEE Power Engineering Society Emerging Technologies Subcommittee is developing a Trial Use Standard (P1304) on OCTs.

- A California administrative law judge ruled that fields from new powerlines must be reduced by at least 4%, provided that the cost differential does not exceed 4%.

- The U.S. Energy Policy Act of 1992 provides for $65M in electric and magnetic field research over five years. NIST participates in an interagency committee established to provide planning and recommendations.

FY 94 Accomplishments and Impacts

- Developed curve-fitting techniques for the determination of the magnitude of the transimpedance of OCTs with uncertainties of 0.1%. OCTs for metering are required to have ratio errors of 0.3% or less.

- Developed convolution technique for evaluation of measurement errors of high voltage impulse dividers and reference measurement systems which was subsequently incorporated into revised IEEE Standard 4 on High Voltage Test Techniques. This standard is widely used in the acceptance testing of high voltage equipment by utilities before the equipment is placed in service.

- Wrote a draft of a new IEC document entitled "Mitigation of External Influences" providing guidance on shielding, filtering and protection against external disturbances. This standard is used by the designers of new facilities and by their contractors.

- Wrote a paper co-authored by staff from EPRI-PEAC on potentially-damaging surge effects occurring in house wiring circuits.

- Wrote a report describing magnetic field measurements performed at the Veterans Administration Medical Center in West Los Angeles, California for the Electric Power Research Institute, and measurements of ac electric fields as well as ac and dc magnetic fields performed in animal exposure facilities at the Illinois Institute of Technology Research Institute for NIH/NTP; reported the results to the research sponsors.

- Performed comprehensive calculations related to uncertainties of three-axis probes used for measurements of magnetic fields from electrical appliances and reported the results in the NIST Journal of Research.

- Prepared versions of IEEE Draft Standard P1308 on extremely low frequency (ELF) measuring instrumentation. The document is the first to address the problems associated with these measurements and NIST will coordinate with the IEC to develop a parallel document.

- Calibrated approximately 89 devices for revenues of $238K. The devices calibrated included 21 current and voltage transformers, 43 watthour standards, 14 energy Measurement Assurance Programs (MAP), and 11 dividers.

Project: MEASUREMENTS TO SUPPORT ELECTRIC UTILITIES

FISCAL YEARS	95	96	97	98	99
Upgrade equipment and methods for calibration services. [STRS, OA, Fees]	———	———	———	———	———
Develop measurement support for optical voltage and current measurements. [STRS, OA]	———	———	———		
Improve range and accuracy of dc high-voltage measurements. [STRS]	———				
Develop metering methods for non-sinusoidal quantities. [STRS]	———	———	———		
Develop techniques for impulse waveform analysis with improved accuracy. [STRS]	———				
Develop calibration methods for electro-optic and magneto-optic sensors. [STRS, OA]	———	———	———		
Develop and characterize systems used to measure high-voltage pulses required in international commerce in electrical power equipment. [STRS]	———	———	———	———	———
Provide improved measurement methods for surveying power quality parameters. [STRS, OA]	———	———			
Develop standards for power quality monitoring instruments. [STRS; OA]	———	———	———		
Provide electrical and magnetic field measurement support and consultation for DoE/NTP/EPRI. [OA]	———	———	———	———	———
Prepare revisions of IEEE draft standard (P1308) and existing standard (P644). [OA]	———				

Project: DIELECTRICS RESEARCH

FY 95 Fund Sources: STRS, DoE, EPRI, NRC, Air Force, NFPRF

Staff (2.1 staff-years)

Professional	R. VAN BRUNT	P. von Glahn*	J. K. Olthoff*	K. L. Stricklett*
	F. D. Martzloff*	S. L. Firebaugh*		

name in capital letters = project leader; * = person works on project part time

Need Addressed: This project responds to the following industrial and other agency needs: 1) concern of the electrical manufacturers and utilities about the formation and detection of highly toxic compounds such as S_2F_{10} and $S_2O_2F_{10}$ in SF_6 gas-insulated power systems; 2) issues being addressed by the Nuclear Regulatory Commission on evaluation of electrical insulation integrity as it relates to commissioning and life extension of nuclear power plants; 3) problems encountered by the Air Force about occurrence of corona discharges and related aging in high-voltage cables used in the space environment; and 4) a need by the National Fire Protection Research Foundation (NFPRF) to evaluate proposed standards for lightning protection systems based on early streamer emission technology.

Technical Approach: In the area of gaseous dielectrics, NIST is developing advanced mass spectrometric and chromatographic methods for sensitive detection of toxic discharge by-products in SF_6 insulated systems. It is also providing fundamental data on ionization, dissociation, and production rates needed to understand the mechanisms by which gaseous discharge by-products are formed in power systems. Advanced, computer-based partial-discharge data recording systems are being developed at NIST together with associated stochastic analysis software. These systems allow a more complete analysis of partial-discharge signals from insulation tests than is possible with the existing state-of-the-art measurement systems that are commercially available. The introduction of these systems into laboratory investigations and factory tests are expected to significantly enhance the information content of partial-discharge measurements that should prove particularly useful for the monitoring of insulation aging. A literature survey is presently underway as part of an effort to assess the scientific basis for advanced lightning protection systems.

FY 95 Plans

- Complete analysis of data production rates for S_2F_{10}, S_2OF_{10} and $S_2O_2F_{10}$ from corona discharges in SF_6/O_2 mixtures and prepare results for archival publication.
- Complete measurements of positive-ion appearance potentials for S_2F_{10}, S_2OF_{10}, and $S_2O_2F_{10}$ and prepare results for archival publication.
- Prepare bibliography on partial-discharge measurements applied to cables.
- Demonstrate use of partial-discharge data recording system for investigation of insulation aging and report results in an archival publication.
- Construct and test a partial-discharge (PD) data recorder that can be applied to PD measurements under dc voltage conditions.
- Prepare an annotated bibliography on early streamer emission lightning protection systems.

Related Developments

- A Cooperative Research and Development Agreement (CRADA) is being formed to apply the NIST partial-discharge data recording system to acoustic monitoring of discharge activity in large, commercial oil-filled power transformers.

- The NFPRF has requested that NIST examine the scientific basis for early streamer emission lightning protection devices being considered as a standard.

- The IEEE Dielectrics and Electrical Insulation Society invited R.J. Van Brunt to present the keynote Whitehead Memorial Lecture at the 1994 IEEE Conference on Electrical Insulation and Dielectric Phenomena in recognition of his contributions to the field.

- R.J. Van Brunt serves as principal investigator for a joint U.S.-Polish project with the Electrotechnical Institute of Poland to investigate partial-discharge induced aging of epoxy insulation.

FY 94 Accomplishments and Impacts

- Completed the definitive work on a plasma chemical model for decomposition and oxidation of SF_6 in corona discharge and published an invited archival paper on the model in a special issue of *Physica Scripta*.

- Designed, constructed and tested a new "reference" corona discharge cell, and used the cell to investigate the production of S_2F_{10}, S_2OF_{10}, and $S_2O_2F_{10}$ from corona discharges in SF_6/O_2 gas mixtures. Preliminary results were reported to the S_2F_{10} CRADA and at the 47th Annual Gaseous Electronics Conference.

- Developed and tested a partial-discharge signal digitizer and data recording system. The system was described in conference papers presented at the 1994 IEEE International Symposium on Electrical Insulation and the Third Volta Colloquium on Partial Discharge Measurements.

- Measured appearance potentials of ions produced by electron-impact induced dissociative ionization of SF_6, SF_4, SF_5Cl, S_2F_{10}, SO_2, SO_2F_2, SOF_2, and SOF_4, and presented results at the 7th International Symposium on Gaseous Dielectrics.

- Measured the modifications to surfaces of cast epoxy resin due to exposure to partial discharges, and presented the results at the 7th International Symposium on Gaseous Dielectrics.

- Documented a procedure for measuring trace quantities of S_2F_{10}, S_2OF_{10}, and $S_2O_2F_{10}$ in SF_6 using a gas chromatograph-mass spectrometer at the 7th International Symposium on Gaseous Dielectrics.

- Completed an invited archival paper entitled "Nonstationary Behavior of Partial Discharge During Discharge-Induced Aging of Dielectrics," that was accepted for publication in a special issue of Proceedings of the I.E.E.-A.

- Presented a paper entitled "Decomposition of Sulfur Hexafluoride by X-rays" at the 7th International Symposium on Gaseous Dielectrics.

- Presented a paper entitled "Decomposition of SF_6 and Production of S_2F_{10} in Power Arcs" at the 7th International Symposium on Gaseous Dielectrics.

- Completed experimental tests to examine electrical discharge initiation in fluids using a pulsed YAG laser to produce a pressure transient at the interface between the electrode and the insulator. The tests showed that the discharge rate was influenced by the laser and that breakdown can be triggered by the laser pulse.

Project: DIELECTRICS RESEARCH

FISCAL YEARS	95	96	97	98	99
Document results from measurement of S_2F_{10}, S_2OF_{10} and $S_2O_2F_{10}$ production in SF_6/O_2 corona. [EPRI, DoE]					
Document results of appearance potential measurements of S_2F_{10}, $S_2O_2F_{10}$ and S_2OF_{10}. [EPRI, DoE]					
Document GC/MS method for measuring trace S_2F_{10}, $S_2O_2F_{10}$ and S_2OF_{10}. [EPRI, DoE]					
Prepare bibliography on partial-discharge measurement. [NRC]					
Prepare bibliography on early streamer emission lightning protection systems. [NFPRP]					
Use partial-discharge data recording system to investigate dielectric aging. [STRS]					
Construct partial-discharge recorder for use with dc measurements. [Air Force]					
Test nuclear power plant cables for presence of partial-discharge. [NRC]					

Project: PLASMA CHEMISTRY - PLASMA PROCESSING

FY 95 Fund Sources: STRS

Staff (2.0 staff-years)

Professional	J. K. OLTHOFF	R. J. Van Brunt*	M. Rao (GR)	S. B. Radovanov* (GR)
	K. L. Stricklett*	E. D. Simmon*	G. FitzPatrick*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: The semiconductor industry requires information about the chemical and physical processes occurring in processing discharges in order to implement new surface modification methods currently being used to replace wet chemistry processes. As greater demands are placed upon these plasma etching processes, improved control and characterization of the etching plasma become essential. This requires a clear understanding of how different conditions in an etching reactor affect both the plasma and the diagnostics that probe and control the discharges. The development of well characterized discharges allows the testing and calibration of diagnostic measurements, provides benchmark data for the validation of plasma models, and enables learning about inherent physical characteristics of the discharge that determine the limitations on reproducibility. The plasma processing program at NIST is dedicated to the development, characterization, and understanding of reference discharges required to support the semiconductor manufacturing industry.

Technical Approach: Several reference discharge cells are in operation at NIST for the characterization of diagnostics, validation of models, and investigation of the physical processes of discharges. These discharges include Gaseous Electronics Conference (GEC) rf reference cells with capacitively- and inductively-coupled sources and a dc Townsend discharge cell. A wide array of plasma diagnostics, such as mass spectrometers with ion energy analyzers, optical emission detection, electrical probes, Langmuir probes, and laser-induced fluorescence, are used to probe these discharges in such a way as to allow comparison of results. Specific areas of investigation utilizing the cells include: 1) the effects of electrode-surface charging on plasma and diagnostic performance; 2) chemical composition of inductively-coupled etching plasmas; 3) development and characterization of ion energy analyzers for use in industrial reactors; and 4) investigation of the effects of ion-molecule collisions on the energy of plasma ions striking the electrodes of rf reactors. Supporting these experiments is a concerted program to measure fundamental reference data required for the analysis of plasma processing data. These measurements are performed at NIST, or in collaboration with other institutions, and include collisional cross sections, dissociation rates, drift velocities, and mobilities that are required to relate the data measured by diagnostics to predictions by theoretical models.

FY 95 Plans

- Complete measurements and analysis of ion kinetic energy distributions (IEDs), electrical measurements, and optical emission from various gases and gas mixtures, such as helium, oxygen, nitrogen, hydrogen, and Ar-O_2 in order to determine the correlation between different diagnostic measurements. Prepare results for archival publication for plasmas with pressures ranging from 1.3 to 66.6 Pa, and powers ranging from 1 to 20 W.

- Install a second GEC rf reference cell with an inductively-coupled plasma (ICP) source similar to those in use on commercial reactors. Apply mass spectrometric techniques to determine the gas composition of high-density plasmas generated in the ICP source using O_2, N_2, and CF_4 source gases, over a range of powers from 10 to 100 W.

- Redesign the high electric field-to-gas density ratio (Townsend) dc discharge for improved alignment and for use with different mass spectrometers. Use the new apparatus to confirm energy analyzer performances, measure IEDs in dc discharges in hydrogen and neon, and use the data to evaluate ion-molecule collisional cross sections.

- Investigate feasibility of fabricating micro-machined energy analyzers for use in commercial plasma etchers in collaboration with University of New Mexico and Sandia National Laboratory.

- Design and construct a prototype electro-optic charge measuring device for use in monitoring surface charging of various metals, insulators, and semiconductors. Use the device to measure charge retention on surfaces of interest to the plasma processing and dielectrics communities.

Related Developments

- A special issue of the NIST Journal of Research is being prepared which will be devoted to work on the GEC rf Reference Cell. Contributions from ten or more laboratories where this cell is used are expected. J. K. Olthoff is serving as guest editor.

FY 94 Accomplishments and Impacts

- Hosted the 47th Annual Gaseous Electronics Conference at NIST, which has become a major forum for presentation and discussion of work on plasma chemistry and plasma processing. R. J. Van Brunt from NIST served as the Secretary for this conference.

- Investigated surface charging present on electrodes exposed to rf plasmas by monitoring the changes on measured IEDs when replacing an aluminum electrode with a stainless steel electrode. These data showed that more accurate IEDs could be obtained using a sampling aperture in a stainless steel electrode.

- Completed the study of optical emission and IEDs from Ar-H_2 plasmas in the GEC rf reference Cell, and submitted an archival paper for publication in the *Journal of Applied Physics*. This work integrated the data from three distinct plasma diagnostics in order to fully understand the source and identity of particles striking surfaces exposed to the plasma. The study provided insight into the mechanisms that may affect the use of these plasmas for the cleaning of silicon surfaces.

- Performed a detailed investigation of the optical emission, electrical parameters, and IEDs for pure hydrogen plasmas in the GEC rf Reference Cell. The first published evidence of energetic (kinetic energies exceeding 100 eV) neutral hydrogen atoms in an rf hydrogen plasma was observed, and an archival paper was submitted to *Applied Physics Letters*. The presence of energetic neutrals in rf plasmas has been proposed by theoretical models, but has rarely been observed experimentally.

- Prepared an archival paper for *Physical Review E* presenting kinetic energy distributions for ions sampled from diffuse, low-current dc (Townsend) discharges. These data suggest that the charge-exchange cross sections for N_2 and Ar, may be lower than the presently accepted values.

- Began construction of a simplified test system for Pockels Cell surface-charge sensors to investigate charge deposition and migration on surfaces of materials of interest to the plasma processing community.

Project: PLASMA CHEMISTRY - PLASMA PROCESSING

FISCAL YEARS	96	96	97	96	99
Measure optical emission profiles, ion energy distributions and electrical waveforms from rf discharges in the GEC rf Reference Cell for Ar+O_2 and He+N_2 gas mixtures. [STRS]					
Modify drift tube-mass spectrometer and measure ion energy distributions in gases of interest to the semiconductor industry. [STRS]					
Measure ion energy distributions from reactive etching plasmas using SF_6+O_2 and CF_4+O_2 gas mixtures. [STRS]					
Develop and test system to perform phase-resolved ion energy distribution measurements at discharge electrodes. [STRS]					
Extend measurements of energy distributions for ions sampled from dc Townsend discharges to high E/N (>10 x 10^{-18} Vm^2) and to other gases of interest, such as hydrogen and neon. [STRS]					
Investigate the influence of electrode surface charging on current and voltage waveforms, ion energy distributions, and optical emission measured from plasmas. [STRS]					
Fabricate and characterize micro-machined ion energy analyzers for use in reactive ion etchers. [STRS]					
Construct reference inductivity-coupled plasma source, and investigate chemical gas composition and ion energy distributions. [STRS]					

Project: VIDEO TECHNOLOGY

FY 95 Fund Sources: STRS, ATP

Staff (5.5 staff-years)

Professional	B. F. FIELD*	P. A. Boynton	C. Fenimore	G. R. Jones
	E. F. Kelley	C. T. Van Degrift		

name in capital letters = project leader; * = person works on project part time

Need Addressed: This project addresses three related needs: 1) 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). 2) Advanced digital video is expected to be one of the largest drivers for the National Information Infrastructure (NII). Maximum benefit will accrue to the industry and consumers only if advanced digital video is implemented in an interoperable manner to allow seamless connection between information providers, common "bit-way" distributors, and information appliances. The current U.S. share of the world market for video image generation, processing, transmission, and display is $38B per year. This is expected to grow by an additional $15B per year with continued U.S. leadership.
3) 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. The lack of standards restricts the U.S. electronics industry by reducing competition between suppliers of display products. The current world market for displays is $11B per year.

Technical Approach: Video quality is affected by the optical properties of cameras, by mathematical algorithms and electrical circuitry used to process and transmit the information, by the electro-optic properties of the display devices, and by the task viewing requirements. NIST will first develop a collection of measurement tools, for the evaluation of digital video signals subjected to compression processing. Each tool will be dedicated to a specific impairment and will provide meaningful quantitative values for video quality for that impairment. This will allow a user to apply an appropriate subset of evaluation tools to obtain an overall quality figure consistent with the task requirements. NIST is working with and coordinating industry groups to ensure that advanced digital video will be implemented in an interoperable manner on the NII. This includes holding workshops to discuss industry problems and developing technical laboratory demonstrations to illustrate solutions to the identified problems. The goal is to enable a hierarchy of digital video standards to be seamlessly supported by the NII. NIST will simultaneously develop methods for the characterization of video quality of displays. Initial efforts will focus on objective measures such as gray scale, uniformity, viewing angle, and brightness. Future work will include correlating objective measures with the characteristics of the human vision system to correlate display quality with measurable quantities.

FY 95 Plans

- Collaborate with the National Information Display Laboratory, at the request of the Electronics Industry Association, on a round-robin evaluation of a color cathode-ray-tube display.

- Document metrics and verification procedures previously developed on the Princeton Engine for video quality. Extend these metrics to other computing platforms to provide standard program code for use by industry.

- Conduct joint research under the auspices of the International Standards Organization (ISO), TC159, SC4, to develop measurements of the effects of ambient light on display surfaces.

- Continue collaboration and technical research with industry groups investigating the problem of interoperability of advanced video systems and the Information Infrastructure.

- Implement the measurements contained in the proposed ISO standard 9241 for the characterization of displays and report on the evaluation to the technical committee (TC159).

Related Developments

- NIST Advanced Technology Program announced a focused area program in "Digital Video in Information Networks."

FY 94 Accomplishments and Impacts

- Designed, assembled, and tested a laboratory for the characterization of flat panel displays. This includes a large light integrating sphere, a five-axis display positioner, various light sources, display signal sources, multiple spectraradiometers, two charge-coupled display imaging systems, lens systems, and appropriate computer based controllers and data acquisition systems. This will permit a variety of measurements including large-area and individual pixel photometry and colorimetry.

- Developed several simulation and modeling programs for the Princeton Engine to enhance its ability to be used as a display simulator. An internally computed image of the Macbeth Color Checker Chart was developed for the colorimetric calibration of laboratory monitors.

- Developed an interactive method to use the Princeton Engine to measure perceptible noise threshold in video images. This work was done in collaboration with an industrial laboratory under a Cooperative Research and Development Agreement (CRADA). The work was later extended to determine how scintillation (speckle) noise masks the perception of clamp (line structure) noise. Both studies were reported (separately) at Society for Information Display conferences.

- Held a workshop on May 10-11, 1994, in Washington DC, to highlight technical issues for industry and government decision makers with respect to Advanced Digital Video in the National Information Infrastructure. The workshop was organized by NIST with co-sponsorship by six other industry organizations. Over 180 individuals attended. A NIST Information Report (NISTIR 5457) has been prepared and over 650 copies have been distributed by request. The Digital HDTV Grand Alliance was particularly appreciative of NIST's efforts to focus attention on the problem of interoperability.

- Purchased and installed a UNIX-based workstation and video frame buffer for the development of video quality metrics. Tools for the testing of video sequences have been developed and the National Telecommunication Information Administration (NTIA) video quality metrics were implemented. Tests revealed a discrepancy between the Princeton Engine implementation and the workstation implementation; this problem was traced to the differing video sampling rates of the two systems. This sensitivity to sampling rate was previously unreported.

Project: VIDEO TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Automate, maintain, and develop measurement procedures for a photometric flat panel testing laboratory capable of complete display and individual pixel characterization. [ATP]					
Develop improved video quality metrics for high-bit-rate video information and for flat panel display artifacts. [STRS]					
Develop robust technology-independent tests for flat panel displays on which to build voluntary standards. [ATP]					
Evaluate proposed techniques to encode and display video material to ensure interoperability between entertainment-and computer-systems. [STRS]					
Develop rapid display-testing procedures, and develop robotic systems for complete panel characterization at "production line" speeds. [ATP]					
Extend display tests (including advanced panel models) to evaluate display performance related to human vision models. [ATP]					
Replace the Princeton Engine with a state-of-the-art video processing system. [STRS]					

Project: AUTOMATED ELECTRONICS MANUFACTURING

FY 95 Fund Sources: STRS, ATP, U.S. Navy, SEMATECH

Staff (4.1 staff-years)

Professional	B. GOLDSTEIN*	M. R. McCaleb	M. J. McLay	C. H. Parks
	J. A. St. Pierre			

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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. The information must be correct, complete, unambiguous, and efficient. Among the technical challenges is the development of adequate information models and standards that describe the essential characteristics of electrical and electronic products.

Technical Approach: NIST will support harmonization of standards by developing methods for testing for compatibility among the different potential standards developed through the various standardization efforts. NIST will also demonstrate technology for data exchange for general product information over a national network and this work will be extended to data on component specification. NIST is also assisting SEMATECH—the semiconductor manufacturing technology consortium—to implement this new manufacturing approach. Later, a similar type of support will be extended to the manufacture of other electronic products.

FY 95 Plans

- Support development of product data standards in the development, fabrication, testing, and support of millimeter and microwave tubes. Aid in the formation of government and industry user groups for Microwave and Millimeter-Wave Advanced Computational Environment (MMACE) application framework.

- Evaluate the Python programming language for use as a core element in the MMACE Research and Engineering Framework. Identify required language capabilities for MMACE and suggest language extensions.

- Continue defining a conformance and certification methodology and standardization for SEMATECH's Computer Integrated Manufacturing (CIM) Framework. This includes helping to define ways of applying the CIM Framework to domains other than semiconductor manufacturing.

- Extend an Initial Graphics Exchange Specification (IGES) protocol for hybrid microcircuits as reported in NIST Technical Note 1295 into a broader, layered electrical product application protocol for adoption by ANSI. Develop example implementations at NIST and assist developers of application protocol translators. Begin integration with related STEP application protocols in the electrical product domain.

- Continue to assist in the development of Application Protocol (AP) 210, provide feedback to the application protocol development team, and extend the prototype CAD-to-AP210 translator to include component terminal connection information and layered printed circuit conductor routing.

- Continue development of the NIST testbed in support of the Automated Electronics Manufacturing program, and pursue cooperative research arrangements with industry, universities, consortia, standards organizations, and government laboratories.

Related Developments

- NIST Advanced Technology Program announced a focused area program in "Computer Integrated Manufacture for Electronics."

FY 94 Accomplishments and Impacts

- Developed the first portions of a CAD-to-AP210 translator, for use with the Racal-Redac CAD system. As a consequence of this work, identified 149 issues of ambiguity or error in the Committee Draft version of Application Protocol 210.

- Continued to lead the Electronic Business Reply Card (EBRC) demonstration team of the National Initiative for Product Data Exchange (NIPDE) Electronic Commerce of Component Information (ECCI) project. Helped develop and show demonstration software at CALS Expo, November 1993. Hosted ECCI workshop at NIST, March 1994.

- Participated as U.S. Delegate at International Electrotechnical Commission TC93 Design Automation committee meetings and proposed new work item to convene a Working Group 5, Test, Validation, Conformance and Qualification Support. The goal of Working Group 5, which is chaired by NIST personnel, is to investigate and test validation, conformance and qualification methodologies for international standards related to electrical and electronic product data exchange. The working group is currently seeking expert members from the international community. Helped establish an information repository for use by all the working groups within TC93.

- Presented conformance and certification status at NIST/SEMATECH third quarter status review. Attended CIM SEMATECH framework training class and discussed SEMATECH effort with regard to conformance testing of the CAD Framework Initiative (CFI). (CFI is a non-profit consortium to develop CAE domain frameworks.)

- Developed Python language module to simplify creation of World Wide Web Common Gateway Interface (CGI) scripts. The software was distributed to Python users on the Internet. Feedback from users indicated the desire for a workshop to discuss the evolution of the language. Workshop planned for FY95.

- Investigated use of World Wide Web server and Mosaic client for electronic distribution of the NIST Storeroom catalog. Initial work uncovered a number of limitations of the Mosaic technology. These will be presented at the Federal Mosaic Consortium to provide feedback to the National Center for Supercomputing Applications (NCSA), developers of Mosaic.

- Completed and delivered draft of "Layered Electrical Products" application protocols to Initial Graphics Exchange Specification (IGES) Electrical Applications Committee.

Project: AUTOMATED ELECTRONICS MANUFACTURING

FISCAL YEARS	95	96	97	98	99
Help U.S. Navy form MMACE Users Group, define research and engineering framework, and develop tools. [Navy]					
Extend and demonstrate software translator between commercial tool and STEP AP210. [STRS]					
Coordinate international testing support; test/validate electronic product data exchange standards. [STRS, ATP]					
Expand hybrid microcircuit protocol into a layered electrical product applications protocol for IGES. [STRS]					
Promote standardization and test of SEMATECH's CIM Application Framework. [SEMATECH]					
Develop electronic commerce applications and distribute through Manufacturing Technology Centers. [STRS]					

Project: GENERATION AND MEASUREMENT OF PRECISE SIGNALS

FY 95 Fund Sources: STRS, AF, NASA, NIH, Fees

Staff (7.0 staff-years)

Professional	N. M. OLDHAM*	B. C. Waltrip*	A. D. Koffman*	O. B. Laug*
	B. A. Bell*			
Technician	P. S. Hetrick*	R. H. Palm*	M. E. Parker*	

name in capital letters = project leader; * = person works on project part time

Needs Addressed: 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 accuracy ratios, is increasingly challenging. The market for these instruments is over $500M annually. Similarly, the power industry legally requires NIST traceability to equitably distribute the $181B of electric energy generated annually. High-accuracy power measurements are required to determine the efficiency of electric equipment during development and manufacture, and for quality control. Power and energy measurements have been complicated by an increasing proportion of nonlinear loads and alternate energy generators, which produce nonsinusoidal waveforms with frequency components in excess of 100 kHz.

Technical Approach: In response to the above needs, new waveform generation and measurement capability at NIST will be developed to support the basic quantities of ac voltage, current, phase angle, ratio, and impedance, using techniques for generating and measuring voltage and current waveforms over the frequency range: dc to 100 MHz. Specific goals include: 1) extending automatic inductive divider measurement capability up to 1 MHz; 2) developing techniques to measure generalized impedances in the dc to 1 MHz range; 3) developing phase standards capable of static and dynamic measurements from 2 Hz to 20 MHz and power/energy standards that operate from dc to 400 kHz; and 4) developing calibration services, where necessary, with measurement uncertainties in the range of $\pm 10^{-6}$ at dc to $\pm 10^{-2}$ at the highest frequencies.

FY 95 Plans

- Complete the development of a high current transconductance amplifier with 100 A rms output at 100 kHz, with 5 V rms compliance voltage.
- Complete a NIST Technical Note describing the Multifunction Calibration System (MCS) and the routine calibration of typical functions available on precision DMMs.
- Design and develop a new waveform generator capable of synthesizing sine waves at frequencies up to 1 MHz for a wideband sampling digital impedance bridge (DIB).
- Design and develop the analog section of a new dual-channel digitally synthesized source, and demonstrate a working generator capable of synthesizing sine waves to 1 MHz, with amplitude and phase resolution of 4 ppm and 1 microradian, respectively.
- Complete system and demonstrate a wideband power measurement to 200 kHz at any power factor using a wattmeter based on the three voltmeter method, with uncertainties less than 1% (1 σ) over the full range.

Related Developments

- High accuracy, 8 1/2 digit, DMMs are presently used to provide NIST traceability for five electrical quantities; LCR meters could do the same for impedance parameters.

- DMMs and LCR meters will prove useful in a Laboratory Accreditation Program for auditing industrial laboratories for many electrical quantities.

- NIST licenses were granted to an electronic instrument manufacturer for the NIST 20-A wideband transconductance amplifier and the NIST DSS-4. Both are now commercially available products.

- NIST has been asked to calibrate a new wideband wattmeter that operates up to 600 kHz.

FY 94 Accomplishments and Impacts

AC Voltage/Current Measurements

- Constructed and tested the digital circuitry, using a direct digital synthesis chip and a programmable logic device, for implementing a programmable delay generator, which will serve as a precision phase shifter in a new dual-channel, digitally synthesized source.

- Announced a 25-point Special Test for DMMs at a cost of $750 with a one week turn-around time. Completed low voltage step-down calibrations (200 mV to 2 mV) of the set of micropot standards, improving the high frequency uncertainties by up to 50 % (supported by an informal comparison with Physikalisch-Technische Bundesanstalt).

- Evaluated a new "three voltmeter" technique for the measurement of inductance. The DIB is used to establish a virtual ground at the connection between the reference impedance ZR and a test impedance ZT. RMS measurements are made of three voltages, VR, VT, and V, the total voltage across both impedances. This is the same information obtained from the sampling approach and provides an independent check not involving fits of complex functions to sampled data.

Impedance Measurements

- Presented a paper at Conference on Precision Electromagnetic Measurements (CPEM)'94 describing the design and performance of the NIST digital impedance bridge. Improved the present DIB to achieve a midrange accuracy of 50 to 200 parts in 10^6.

- Modified the Binary Inductive Voltage Divider (BIVD) bridge to demonstrate the ability of intercomparing two gas capacitors with a resolution of 1 part in 10^8. This bridge is autobalancing and provides ability to intercompare nominally equal capacitances, including dissipation factor, out to 20 kHz.

- Presented papers at Instrumentation and Measurement Technology Conference '94 and CPEM '94 on an error decomposition method, based on structural models of decade and binary IVDs. Under contract, a duplicate BIVD bridge, control software, and operating instructions were delivered to Sandia National Laboratories.

Phase Measurements

- Simulated a phase measuring system, based on a time interval analyzer, to calibrate VOR phase meters at an uncertainty of ±0.001°.

Power/Energy Measurements

- Demonstrated the ability to measure 200 kHz power at unity power factor, good to an estimated uncertainty of ±1%, using NIST standards and commercial equipment.

Project: GENERATION AND MEASUREMENT OF PRECISE SIGNALS

FISCAL YEARS	95	96	97	98	99
Complete CALCOM Tech Note for the MCS and routine DMM calibrations. [STRS]					
Develop new dual-channel digital source to replace the sources used in the Power/Energy and Impedance projects. [STRS, AF]					
Develop a high-current transconductance amplifier with 100 A rms output at 100 kHz. [STRS, Sandia]					
Complete new inductance probe to extend DIB measurements from 10 μH to 10 H in the 10 Hz to 100 kHz frequency range. [STRS, AF]					
Extend BIVD bridge into a bridge to measure capacitance and dissipation factor to 100 kHz. [STRS,AF]					
Develop impedance with computable frequency response to 1 MHz. [STRS]					
Employ Sampling Voltage Tracker in a modified DIB to measure impedances out to 1 MHz. [STRS]					
Establish calibration service for LCR meters. [STRS, AF]					

Project: WAVEFORM ACQUISITION DEVICES AND STANDARDS

FY 95 Fund Sources: STRS, Fees, Air Force AGMC (CCG),; ATP

Staff (5.0 staff-years)

Professional	T. M. SOUDERS*	N. G. Paulter	O. B. Laug*	J. P. Deyst
	W. L. Gans	A. D. Koffman*	B. A. Bell*	
Technician	P. S. Hetrick*	R. H. Palm*		

name in capital letters = project leaders; * = person works on project part time

Need Addressed: Makers 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 $1.1B in 1990, and sales of waveform recorders and analyzers reached $718M 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 (IC) industries (each critically dependent on sampling technology) will all benefit. Improved optoelectronic (OE) and electro-optic (EO) technology will be needed for advancement and development of state-of-the-art electronic devices, semiconductor structures, and printed circuit board materials.

Technical Approach: 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 from dc to 50 GHz. Specific goals include: 1) developing and applying accurate sampling comparator systems to measure the settling parameters of fast pulse generators, amplifiers, and digital-to-analog converters (as well as making accurate rms voltage measurements); 2) providing error analyses on the effects of non-idealities in sampling systems; 3) researching and developing OE and EO 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.

FY 95 Plans

Data Converter/Waveform Recorder Testing

- Develop initial testbed for testing analog-to-digital converters (ADCs) with resolution to 16-bits and sample rates to 1 GHz.

- Complete first round of pulse round robin; develop software tools to analyze results.

Sampling Comparator Systems (SCS)

- Design and develop new probe control, time base and data management, and auto-calibration circuits for the wideband sampling voltmeter needed to meet design goals of 0.01% uncertainty to 1MHz, and 0.2% to 50 GHz.

- Develop test algorithms and signal processing tools for waveform measurement and analysis using the SCS.

Pulse Measurement Services

- Generate software for implementing the algorithms and procedures for performing the set of fast pulse Special Tests on the PC-based 20 GHz sampling system.

Optoelectronic/Electro-optic Technology

- Design and assemble a prototype EO-based pulse measurement system, capable of handling up to 200 V peak, temporal uncertainty of ±50 ns, and voltage uncertainty of ±1%.

Related Developments

- Oscilloscopes with 50 GHz bandwidth are produced by two U.S. manufacturers; NIST calibration of their time-domain parameters is often requested. However, since NIST presently does not have the required capability, customers must turn to the National Physical Laboratory (UK) to provide these measurements.

- Recent advances are producing Si/Si-Ge alloy heterostructure devices capable of operating at frequencies in excess of 40 GHz. This will bring low cost silicon integrated circuit technology to the microwave and high-speed digital electronics communities. GaAs heterostructure devices are being developed that have bandwidths exceeding 200 GHz.

FY 94 Accomplishments and Impacts

Data Converter/Waveform Recorder Testing

- Completed final testing on the NIST reference pulse generator for the industry round-robin intercomparison on pulse waveform measurement capability. The first two participating laboratories have now completed their measurements.

- Completed analysis on "Bounds on Least-Squares Sine-Fit Errors Due to Harmonic Distortion and Noise" and reported results at the IEEE Instrumentation and Measurement Technology Conference in May, 1994. Sine fit routines are used extensively in testing digital oscilloscopes, ADCs, and other signal processing applications.

Sampling Comparator Systems

- Completed an initial time base design for the wideband sampling voltmeter using a modified voltage ramp approach that will permit rms measurements to be made within 0.5 s, even for low frequency (down to 100 Hz) input signals. Conventional time-bases take over 4 minutes for the same measurements.

- Investigated a phase plane compensation technique for reducing the nonlinearities of the NIST Sampling Comparator System (SCS). This method and the results of implementing it on the SCS were presented in a paper given at the Instrumentation and Measurement Technology Conference '94 in Hamamatsu, Japan, in May 1994.

Pulse Measurement Services

- Completed a comparative analysis of the temperature performance, in terms of their relative voltage temperature coefficients, for each of two commercial 20 GHz sampling systems used in the fast pulse measurements laboratory. A factor of 8 difference was found between the temperature coefficients of the two systems.

Optoelectronic/Electro-optic Technology

- Demonstrated that the YAG laser system, and associated pulse compression, selection, and time delay optics can produce 2.5 ps wide optical pulses (λ = 532 nm) with sufficient power (0.5 W peak) for activating photoconductive switching devices. Observed electrical pulses had approximately 16 ps risetimes, as measured with two 20 GHz bandwidth oscilloscopes.

- Improved the performance of a photoconductor pulse generator package to reduce the reflections from >7% to <2% due to impedance discontinuities in the connectors and sampler.

Project: WAVEFORM ACQUISITION DEVICES AND STANDARDS

FISCAL YEARS	95	96	97	98	99
DATA CONVERTER/WAVEFORM RECORDER TESTING					
Conduct round-robin pulse measurement intercomparisons (for ns and ps regimes). [STRS]	———	———	———		
Develop testbed for testing high resolution sigma-delta ADCs as well as very high-speed (0.1 to 10 GS/s) ADCs. [STRS]	———	———	———	———	———
SAMPLING COMPARATOR SYSTEMS					
Apply phase plane compensation to reduce distortion in sampling comparator systems. [STRS, Sandia]	———				
Develop new time base and control instrumentation for use with sampling probes. [STRS, AF]	———				
Develop personal-computer based sampling comparator system for measurements of rms voltage, power, and wideband impedance. [AF]	———	———	———	———	———
PULSE MEASUREMENT SERVICES					
Upgrade pulse measurement system and develop CALCOM documentation for SP250 measurement services (BW=20 GHz). [STRS, AF]	———	———			
Develop special test system for measuring pulse parameters down to t_r = 5 ps (BW = 50 GHz). [STRS, AF]		———	———	———	———

Project: WAVEFORM ACQUISITION DEVICES AND STANDARDS (concluded)

FISCAL YEARS	95	96	97	98	99
OPTOELECTRONIC/ELECTRO-OPTIC TECHNOLOGY					
Develop a high-voltage (100 to 1000 V) EO-based pulse measurement system to complement present NIST pulse measurement systems. [STRS, ATP]					
Develop a high temporal resolution (<1 ps) sampling system with 1% amplitude uncertainty. [STRS]					

Project: MEASUREMENTS FOR COMPLEX ELECTRONIC SYSTEMS

FY 95 Fund Sources: STRS, Air Force AGMC (CCG)

Staff (3.0 staff-years)

Professional	T. M. SOUDERS*	H. Engler*	A. D. Koffman*	G. Stenbakken*
Technician	P. S. Hetrick*	R. L. Palm*		

name in capital letters = project leader; * = person works on project part time

Needs Addressed: 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. Consequently, industry needs cost-effective testing and calibration methods throughout the spectrum of electronic products. For example, typical test costs for mixed-signal Integrated Circuits (ICs) range from 20% to 50% of 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.

Technical Approach: It has been shown that the testing strategies developed at NIST have had a positive impact on production costs where these strategies have been applied. These cases have included both analog and mixed-signal products, such as data converters and multirange measurement instruments. However, the problem of how to model increasingly complex systems, to estimate bounds on prediction errors, and to account for effects of nonmodel errors remains. Furthermore, the mathematical sophistication presently required of the user is often an impediment to rapid implementation of the approach. In response, NIST will continue to develop improved methods and techniques for optimum testing scenarios, and will develop implementation software that relieves the user of much of the mathematical burden. Specific goals include: 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.

FY 95 Plans

- Develop MATLAB™ subroutines to optimize the models of devices under test, and to compute quality assurance tools, including on-line tests of residuals, results from validation tests, and computation of individual and simultaneous confidence levels.

- Develop a software user interface (to operate under MATLAB™-Windows) for providing data entry, model construction, assessment of model accuracy, test point selection, and response prediction.

- Expand the model for the ac section of a commercial multifunction calibrator to include its self-calibration features; extract accuracy and completeness information.

Related Developments

- Self-calibrating systems are proliferating at all levels of complexity: IC, board, instrument and automatic test equipment system levels. While they can enhance confidence and reduce test costs, they introduce additional error sources, are poorly understood, and are not optimized. In addition, they can obscure and complicate traditional testing practices. Better theoretical understanding and new modeling tools are needed to address these problems.

- IC manufacturers have expressed a need for better estimates of confidence intervals when using the NIST testing strategies approach. Better estimates will allow them to achieve the greatest cost reductions, while still meeting the quality requirements of their customers.

FY 94 Accomplishments and Impacts

- Developed and tested most of the 26 subroutines that are needed to implement the Testing Strategies Toolbox software package. These subroutines are used to perform test point selection, compute prediction variance, predict errors from reduced test data, compute various statistics, plot matrix pictorials, and setup "pseudomodels" for demonstration purposes.

- Conducted the third three-day NIST workshop on "Testing Strategies for Analog and Mixed-Signal Products" in June 1994, with eleven attendees from nine organizations.

- Generated an archival paper entitled "Empirical Linear Prediction with Application to Quality Assurance in Industrial Manufacturing," in collaboration with G. Hwang of Cornell University and L. Hung-Kung of the NIST Computing and Applied Mathematics Laboratory's Statistical Engineering Division. This paper provides a rigorous mathematical basis for the NIST Testing Strategies method, and derives expressions for computing confidence intervals associated with the predicted test results.

- Developed an initial time-domain simulation model of the ac voltage section of a precision commercial multifunction calibrator. This model can serve to provide a reduced testing requirement, as well as the basis for examining the self-calibration features of the instrument.

Project: MEASUREMENTS FOR COMPLEX ELECTRONIC SYSTEMS

FISCAL YEARS	98	98	98	98	99
TESTING STRATEGIES					
Document mathematical framework for assessing risks (e.g., undetected model error) using NIST approach. [STRS]					
Apply empirical modeling techniques to efficient testing strategies for multi-range/multifunction instruments. [AF]					
Develop a software toolbox (suitable for commercialization) for implementing the NIST testing strategies methods. [STRS, AF]					
Develop a theory for self-calibrating systems: develop a high level representation scheme and analysis engine for describing and analyzing S-C systems. [STRS]					
DEVICE/SYSTEM ANALYSIS					
Develop hardware-efficient approaches to on-line fault detection in analog and mixed-signal systems. [STRS]					

Project: AC-DC DIFFERENCE STANDARDS AND MEASUREMENT TECHNIQUES

FY 95 Fund Sources: STRS

Staff (3.5 staff-years)

Professional	J. R. KINARD*	T. E. Lipe	D. Hernandez-Villaseñor (GR)
Technician	C. B. Childers		

name in capital letters = project leader; * = person works on project part time

Needs Addressed: Nearly all measurements of electric power, energy, ac voltage and ac current are traceable to the volt and ohm (dc quantities) through thermal transfer standards. Modern electronics makes possible instruments which can produce and measure ac parameters with precision and stability rivalling those of the best dc standards. Improved NIST thermal transfer standards are needed to support the development, testing, production, and maintenance of such instruments. NIST has developed new standards, nearly as good as existing national standards, based on semiconductor and film processing technology that will be commercialized and hence widely available. Present NIST standards are inadequate to calibrate them over their full range of capability.

Technical Approach: NIST will build on experience gained in the development of film multijunction thermal converters (MJTCs) and in the design and application of extremely sensitive cryogenic thermometers to develop a new type of thermal converter with sensitivity approaching the quantum limits. Film MJTCs will be used as interfaces between such converters and more conventional designs operating at room temperature. The new standards are expected to reduce uncertainties from the present lowest (0.8 to 5 ppm) to less than 0.1 ppm to 1 ppm.

FY 95 Plans

- Design and begin fabrication of an experimental thermal converter using a cryogenic temperature sensor (kinetic inductance or edge detector) in collaboration with the Semiconductor Electronics and Electromagnetic Technology Divisions.

- Complete the Dewar/vacuum system to be used to provide the environment for the cryogenic thermal converter.

- Mount and study the performance of film MJTCs at liquid helium temperatures to determine their efficiency and relate their performance to that at room temperature.

- Complete documentation of the extension of transfer shunt and current converter calibrations up to 100 kHz and down to 10 Hz.

- Develop new techniques to evaluate the high-voltage performance of a new automated thermal transfer standard under a Cooperative Research and Development (CRADA) with Julie Research Laboratories.

- Assist Ballantine Laboratories under a CRADA to bring jointly developed film MJTCs and micropotentiometers to commercial production.

Related Developments

- The commercial availability of the new thin-film MJTCs and other high-performance thermal converters will result in continuing demands on NIST for lower ac-dc difference uncertainties at voltages below 100 V. The availability of better quality, high-voltage range resistors and the investigations underway at

NIST and at thermal converter manufacturers will place demands on NIST for reduced uncertainties at levels from 100 V to 1000 V.

FY 94 Accomplishments and Impacts

- Made 775 measurements in the calibration of 21 thermal transfer standards for a calibration income of $162k in FY 94. Supported research work and new or improved measurement capabilities in the national laboratories of Australia, Canada, Germany, and Portugal.

- Won an *R&D 100* Award jointly with the Semiconductor Electronics Division and Ballantine Laboratories for the development of thermal converters based on film and semiconductor fabrication technology. Received a patent for film multijunction micropotentiometers.

- Completed a CRADA with Guildline Instruments for the evaluation of a new automatic thermal transfer standard.

- Established contact with Professor M. Wuttig and Dr. C. M. Su, University of Maryland, as part of the study of making low-stress metal films and low-stress dielectric layers required for the film MJTCs. After preliminary measurements of stress, they measured the temperature of sputtered material during the sputtering process using NIST converters. Wuttig and Su believe that NIST devices and their technique will permit better, real time characterization of the sputter process which is needed by the semiconductor processing industry.

- Continued measurements on the thin-film MJTCs over a wide range of frequencies and conditions. As voltage converters, the bifilar MJTCs have ac-dc differences of less than 1 ppm at 1 kHz, less than 10 ppm from 0.3 to 100 kHz, and less than 50 ppm at 1 MHz. Overall efficiency and temperature coefficient improve at temperatures down to 100 K and below. The results were presented at the 1994 Conference on Precision Electromagnetic Measurements (CPEM).

- Carried out an informal comparison of thermal converter calibrations with the German national laboratory, Physikalisch-Technische Bundesanstalt (PTB). M. Klonz brought a thermal voltage converter to the CPEM in June, and returned to NIST the first week in August to conclude a series of measurements comparing the measurement capabilities of NIST and PTB at 500- and 1000 V. Analyses of the data are under way here and in Germany.

- Began measurements of special 5-mA and 2.5-mA thermoelements as part of a CRADA with Best Technology, Incorporated Results show ac-dc differences of less than 1 ppm as current converters at 1 kHz. A paper, *Improved Vacuum Thermocouples*, was accepted and presented at CPEM '94.

- Established a CRADA with Julie Research Laboratories (JRL) for the study of high-voltage, 200- to 1000-V, thermal converters and build-up techniques. Characterized NIST high-voltage transfer standards have been sent there for study and some newly constructed JRL resistor modules have been measured at NIST. This work resulted in a paper at CPEM '94.

- Carried out an informal international comparison of ac-dc current measurements covering 10 mA to 10 A. Dr. Freitas from INETI, the Portuguese national laboratory, brought current converters and shunts calibrated by INETI and PTB for measurement at NIST. NIST and PTB data disagreed; the discrepancies, while not large enough to affect calibration, revealed the need for joint work in this area.

Project: AC-DC DIFFERENCE STANDARDS AND MEASUREMENT TECHNIQUES

FISCAL YEARS	95	96	97	98	99
Develop documentation for extended current calibrations. [STRS]					
Complete study of converters at lower frequencies to reduce uncertainties. [STRS]					
Investigate high-voltage range resistors and comparison techniques. [STRS]					
Deliver thin-film MJTCs to DoD and Sandia primary laboratories. [STRS]					
Study characteristics, including ac-dc difference, of thin-film MJTCs at cryogenic temperatures. [STRS]					
Fabricate and evaluate new CMOS-foundry MJTC designs. [STRS]					
Study performance of thin-film MJTCs as voltage and current converters from audio frequency to megahertz range. [STRS]					
Characterize and fabricate additional integrated micropotentiometers. [STRS]					
Assemble cryogenic system for the evaluation of new primary standards. [STRS]					
Complete preliminary design and begin fabrication of new prototype primary standards using superconducting temperature sensors. [STRS]					
Begin evaluation of prototype low-temperature primary standard converters. [STRS]					
Confirm accuracy of new low-temperature converters and establish them as NIST primary standards, if appropriate. [STRS]					

Project: RESISTANCE STANDARDS AND MEASUREMENT METHODS

FY 95 Fund Sources: STRS, Fees

Staff (5.0 staff-years)

Professional	R. F. DZIUBA	R. E. Elmquist	D. G. Jarrett
Technician	T. P. Moore	J. D. Neal	

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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 pressure, force, temperature, 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 — 372 standards and 7 MAPs in FY 94. 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 the calibration of impedance meters, and research to support commercialization of the cryogenic current comparator (CCC) for improved scaling in bench instrumentation.

Technical Approach: The new quantized Hall resistance (QHR) standard provides a powerful tool for the development and evaluation of new resistance materials and standards. NIST will develop new automated scaling systems based on cryogenic current comparators, automated systems for improved calibration of 10 kΩ and multi-megohm standards, and the bridges and standards needed for ac calibrations. The new scaling systems will reduce errors to the few parts in 10^9 level while reducing the amount of effort needed to maintain working standards by a factor of five. The measurement system for ac resistors is planned to be used for standards in the range from 10 Ω to a megohm at frequencies up to a few kHz. Uncertainties will range from a few tenths of a ppm to five ppm, the former occurring in the 10 - 100 Ω range and the latter at the extrema. Work will continue on development of a CCC using high-temperature superconductors; the prototype will have sub-ppm ratio accuracy and will be able to operate at 77 K using a refrigerator.

FY 95 Plans

- Complete two step-downs from the national standard (QHR) to the one-ohm working standards, and one transfer between the QHR and the SI ohm via the calculable capacitor.
- Complete switching and other components of an automated CCC for scaling between the QHR and working standards, and among working standards at the part in 10^8 uncertainty level.
- Complete automation of the 10 kΩ bridge.
- Automate the detector, and complete and test software for determining the linearity of the active ratio arms of an automated bridge for use in the resistance range from 10^7 to 10^{14} Ω.
- Construct 100 and 1 kΩ coaxial ac-dc resistors with computable frequency response to be used as standards in the ac resistance calibration system under development, having a target uncertainty of better than ±1 ppm.
- Evaluate the magnetic shielding effectiveness of the new YBCO (yttrium-barium-copper-oxide) structure upon which the performance of the prototype high-performance CCC is based.

Related Developments

- Discussions have been held on the development of improved resistance standards with a U.S. company which has recently bought the precision instrumentation interests of a long-time manufacturer of resistance standards, bridges, and ratio standards.

FY 94 Accomplishments and Impacts

- The total FY94 calibration income for resistance was $366k which included 408 tests on 372 standard resistors along with 7 MAPs; assisted a U.S. company by verifying a ratio standard, thus enabling their accreditation by NAMAS.

- Development was begun of a CCC for operation at 77 K, using high-temperature superconductor (HTS) ceramic shields and a HTS-based SQUID detector. The first prototype was successfully tested at 77 K at the 1-ppm level. A design for a second HTS CCC has been completed and is being commercially fabricated. Also, external magnetic shielding using HTS thick-film coatings on large-diameter thin-wall tubes is being developed for NIST commercially. A landmark paper describing this work was presented at the 1994 Conference on Precision Electromagnetic Measurements (CPEM).

- Three comparisons between the QHR national standard and the 1 Ω bank of working standards were completed. The results of these measurements indicate that the mean value of the 1 Ω bank differs from its predicted mean value by about 0.015 ppm. No adjustment was made since this difference is within our allotted standard uncertainty of 0.02 ppm for this component of our calibration uncertainties, but a study of all of the data is underway to ensure the quality of the calibration services.

- Design, construction, and testing of special 100 Ω resistors were completed. Because of their rugged cylindrical construction these resistors do not exhibit any significant changes as a function of barometric pressure. A thermistor probe is permanently mounted with each resistor to monitor its temperature changes. They will serve as an intermediate reference bank when scaling from the QHR to the 1 Ω, 1 kΩ, or 10 kΩ resistance levels. Measurements indicate a mean drift of <0.1 ppm/year, and a mean temperature coefficient at 25 °C of -0.04 ppm/K.

- The design and construction of a programmable guarded British Post Office (BPO) connector panel for the 10 kΩ measurement system has been completed. A computer-controlled gantry is used to move a 4-BPO fixture over a horizontal array of 72 connectors and lower it to make a four terminal guarded connection. Measurements indicate that the contact resistance repeatability of the BPO connectors including resistance variations of 12 m of AWG 12 cable is 10 μΩ ± 4 μΩ. The design and construction of the main ratio arms with programmable offsets of 1 ppm, 5 ppm, and 10 ppm have also been completed.

- Construction of a temperature/humidity air bath to support calibrations of multi-megohm standards was completed. This air bath features a working volume of approximately 0.25 m^3, dual isolated connector panels, and convenient portals for inserting saturated salt solutions to control the humidity. It is of double-walled construction and has a microprocessor-based controller. Measurements indicate that long-term temperature stability of the bath is on the order of 0.01 °C. This will improve the quality of calibrations while reducing their turnaround time. A second air bath, similar in design and construction, is near completion and will be used with the measurement system for calibrating special 10 kΩ standard resistors.

Project: RESISTANCE STANDARDS AND MEASUREMENT METHODS

FISCAL YEARS	95	96	97	98	99
Complete automation of 10-kΩ bridge. [STRS]					
Develop ac resistance measurement capability. [STRS]					
Automate resistance measurements from 10MΩ to 1TΩ. [STRS]					
Support laboratory accreditation; evaluate commercial instrumentation and construct audit packages. [STRS; Fees]					
Institute a calibration service for resistances > 1 TΩ. [STRS]					
Develop ac cryogenic current comparator bridge. [STRS]					
Develop system for calibrating ac shunts. [STRS; Fees]					
Develop "intelligent" resistance standards. [STRS]					
Develop cryogenic current comparator bridge using high-T_c superconductors. [STRS; Fees]					

Project: IMPROVED IMPEDANCE CALIBRATION SERVICE

FY 95 Fund Sources: STRS, DoD

Staff (3.5 staff-years)

Professional	N. B. BELECKI*	Y. M. Chang	N. M. Oldham*	J. Q. Shields*
	B. C. Waltrip*			
Technician	S. B. Tillett			

name in capital letters = project leader; * = person works on project part time; ‡ = guest scientist

Need Addressed: 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 kHz to 100 kHz 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

Technical Approach: The needed expansion of the calibration services has two parts: the establishment of impedance standards with known frequency response up to 100 kHz, and the development of comparators. Work at the highest accuracy will take advantage of NIST calculable capacitors and the bridge technology developed for their use. Instrumentation used in calibrations will be based on techniques developed at NIST for waveform generation and analysis.

FY 95 Plans

- Develop an improved probe for the existing Digital Impedance Bridge (DIB) for measurements of inductances from 10 μH to 10 H over frequencies from 50 Hz to 100 kHz using the three-voltmeter method with target uncertainties at midrange of ± 30 ppm (1 σ).

- Deliver a documented 100 V Binary Inductive Voltage Divider Bridge that operates up to 20 kHz to the calibration laboratory to automate the process of calibrating inductive voltage dividers.

- Complete a Technical Note documenting the procedures used in the Capacitance MAP service.

- Establish a primary calibration reference of fused silica capacitance standards in oil and evaluate its uncertainty, in order to reduce day-to-day fluctuations of capacitance to below ± 0.1 ppm.

- Complete a procedure to permit automated 1 kHz calibrations of mica-dielectric capacitors using commercial impedance meters in the 50 to 200 ppm uncertainty range.

Related Developments

- Fused silica reference capacitors with performance capabilities said to be two orders of magnitude better than those of currently available standards are now commercially available. NIST must improve uncertainties by two orders of magnitude in the audio frequency range in order for full advantage to be taken of these standards and to support development of the next generation of LCR meters.

FY 94 Accomplishments and Impacts

- Performed 401 calibrations on 250 standard capacitors, inductors, and inductive voltage dividers this FY for a total of $213k income.

- Completed the analysis of errors and the assignment of total uncertainties for capacitance calibrations (according to NIST Technical Note 1297) for the Type-2 and Type-12 capacitance bridges. Updated the section on impedance measurements of the SP250, including tables of calibration uncertainties for various types of capacitance standards. The new calibration uncertainties comply with the guidelines of NIST Technical Note 1297, using the coverage factor of k=2.

- Added a high voltage amplifier to the BIVD bridge to permit operation at over 300 V from 10 Hz to 100 kHz and incorporated a new injection/detection circuit (Conference on Precision Electromagnetic Measurements [CPEM '94] paper) to permit measurements with test IVD input or output grounded. Drafted a NIST Internal Report describing the operation of the bridge and its controlling software.

- Delivered and evaluated a prototype DIB for inductance calibrations to find differences ranging from 20 ppm to 200 ppm, with data from the Maxwell-Wien bridge and standard deviations between 20 ppm and 450 ppm. A paper describing the work was given at CPEM '94. These findings led to modifications of the DIB to improve its performance.

- Completed measurements for an international comparison of 10 mH inductance standards being conducted by the national standardizing laboratory of Germany, Physikalisch-Technische Bundesanstalt. The Maxwell-Wien Bridge and a modification of the DIB using the three voltmeter method were both used. The agreement between the Maxwell Wien Bridge and the DIB - three voltmeter method measurements was better than 10 ppm, considerably smaller than the combined 1 σ - uncertainties.

- Completed the evaluation of the use of a commercial meter as an inductance comparator with the result that all standards inductors at all frequencies covered are calibrated using the substitution method described in NISTIR 4466. This further reduces the dependence of the calibration service on the Maxwell-Wien bridge.

- Monitored the five (10 pF) fused–silica capacitance standards in the oil bath to show that they are fairly stable, with the transient variations (of each capacitor) being less than 0.06 ppm and to lay the basis for improved precision in capacitance calibrations.

Project: IMPROVED IMPEDANCE CALIBRATION SERVICE

FISCAL YEARS	95	96	97	98	99
Deliver a BIVD system to calibrate programmable and manual dividers at voltages up to 100V. [STRS]					
Establish a reference of fused silica capacitance standards in the calibration laboratory. [STRS]					
Replace the existing inductance calibration system with the DIB at appropriate inductance/frequency points. [STRS]					
Evaluate the errors in determining the frequency response of C standards in terms of toroidal cross capacitors from 400 Hz to 10 kHz. [STRS]					
Replace the existing mica capacitor calibration system with LCR meters at a frequency of 1 kHz. [STRS]					
Augment the present capacitance calibration system with a second BIVD bridge to extend the frequency range. [STRS]					
Design, construct, and analyze a new transformer bridge for comparing capacitors from 10 to 100 kHz. [STRS]					
Extend the frequency response characterization of capacitors in terms of the toroidal cross capacitor to 100 kHz. [STRS]					
Establish a calibration service for LCR meters. [STRS, DoD]					

Project: QUANTUM VOLTAGE AND CURRENT

FY 95 Fund Sources: STRS, DoD, Fees

Staff (5.5 staff-years)

Professional	A. F. CLARK	N. B. Belecki*	P. T. Olsen*	J. E. Sims
	R. L. Steiner	G. Stenbakken*	E. R. Williams*	N. Zimmerman

name in capital letters = project leader; * = person works on project part time

Need Addressed: This project and the companion project on quantum resistance and capacitance provide the required legal basis for virtually all electrical measurements in the United States. This project generates 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 internationally accepted SI system 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 is being used to evaluate new measurement techniques and standards for automated and highly accurate dissemination of these units. The research also may result in an electronic replacement for the kilogram, the last remaining SI artifact standard. The application of the new single electron tunneling phenomena to the determination of the electronic charge or the fine structure constant is also being investigated.

Technical Approach: 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 SI ampere; monitor the kilogram in terms of electrical units via the SI 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 constant current standards.

FY 95 Plans

- Determine the NIST value for the watt to 0.1 parts per million (ppm) and report it to the Consultive Committee for Electricity for the next adjustment of the units on July 1, 1995.

- Initiate redesign of the NIST watt experiment with the objective of 0.01 ppm uncertainty for monitoring the kilogram.

- Complete the transfer of the magnetic field calibration service to the Navy Primary Standards Laboratory and complete the training of Navy personnel.

- Replace the Josephson array system computers and software to provide a consolidated system compatible with the automated voltage calibration laboratory and the watt/electronic kilogram experiment.

- Initiate studies to determine the source and impact of charge noise on single electron tunneling devices for metrological applications, especially the capacitance charging experiment, in collaboration with the Electromagnetic Technology and Semiconductor Electronics Divisions, and the Manufacturing Engineering Laboratory's Precision Engineering Division.

Related Developments

- At the Conference on Precision Electromagnetic Measurements, major instrument manufacturers reported on an extensive comparison of 10 V Josephson array systems throughout the United States, using 10 V Zener references as the transfer standards. Several of the national standards laboratories from around the world reported on similar but much less extensive comparisons. The general consensus was that array systems are not foolproof and must be checked often, and that Zener references have significant (0.1 ppm) and not well understood instabilities.

- The Bureau of International Weights and Measures has initiated a study of both NIST's and the National Physical Laboratory's kilogram experiments with the objective of developing an electronic means of monitoring the mass of The Kilogram, the last artifact standard in the SI system of units.

- At recent American Physical Society meetings, extensive interest has been shown in single electron effects in both metal and semiconductor systems, with several invited sessions and many contributed papers. Metrology still remains the most often cited application.

- The Army Primary Standards Laboratory has developed the capability to manufacture Josephson array voltage standard systems for application in mobile standards laboratory vehicles and is planning the construction of about 30 such units.

FY 94 Accomplishments and Impacts

- Improved the voltage calibration service to more than double the capacity, replaced all of the existing obsolete computer systems, and trained the personnel on the 1 V Josephson array system in preparation for the planned acquisition of a new array system for direct calibrations.

- Generated new data for weighing and voltage for the NIST watt, demonstrating a precision of 0.1 ppm, and reported it to the 1994 Conference on Precision Electromagnetic Measurements.

- Initiated the transfer of the magnetic field calibration service to the Navy Primary Standards Laboratory by constructing a low field calibration system, shipping it to San Diego, California, and training Navy personnel in its use.

- Demonstrated the application of a single electron tunneling electrometer as the detector in a bridge at millikelvin temperatures to measure the capacitance ratio, to a precision of 3 ppm, of two newly-developed, cryogenic vacuum capacitors whose leakage resistance was greater than 10^{18} ohms.

- Documented the noise characteristics of Zener voltage references with over 1000 Josephson array measurements and provided manufacturers with methods for improved product performance. Completed a 10 V MAP with all 10 other Josephson array users in the U.S. demonstrating equivalence to 0.02 ppm, the noise level of the transfer standards.

Project: QUANTUM VOLTAGE AND CURRENT

FISCAL YEARS	96	96	97	98	99
Determine NIST value for the watt. [STRS]					
Initiate redesign of watt experiment. [STRS]					
Replace Josephson array computers. [STRS]					
Initiate charge noise studies in SET devices. [STRS]					
Transfer the magnetic field calibration. service [DoD]					
Study array physics, microwave effects, and array applications. [STRS, DoD]					
Develop and apply procedures for monitoring the kilogram electronically. [STRS]					
Study the application of a single electron tunneling to metrology. [STRS]					
Determine applicability of high-speed digital circuits to variable voltage standards. [STRS]					

Project: QUANTUM RESISTANCE AND CAPACITANCE

FY 95 Fund Sources: STRS, DoD

Staff (5.0 staff-years)

Professional	M. E. CAGE	K. C. Lee	J. Q. Shields	A. Jeffrey
Technician	L. H. Lee			

name in capital letters = project leader; * = person works on project part time

Need Addressed: This project and the companion project on quantum voltage and current provide the required legal basis for virtually all electrical measurements in the U.S. The research being done on this project ties the U.S. legal system of electrical units to the SI system of units. To provide the nation with the world's best basis for electrical measurements, this project conducts measurements of the SI ohm and farad that have smaller uncertainties than that 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 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 techniques. 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 in industry and other government laboratories. Investigating the underlying physics will allow NIST to develop a quantized Hall resistance Standard Reference Material for industry.

Technical Approach: Develop measurement techniques to maintain world leadership in resistance and capacitance metrology. Maintain the U.S. legal farad. Realize the SI farad and ohm and support the Division's impedance and resistance calibration services. Support the maintenance of the U.S. legal ohm via the quantum Hall effect by investigating the underlying physics of two-dimensional electron gases. Fabricate quantum Hall samples for industrial support and for NIST programs, including a future quantum Hall Standard Reference Material. Investigate the effects of heterostructure growth parameters and alloy contacts on quantized Hall resistance values. Investigate the frequency dependence of standard capacitance measurement systems and of the quantized Hall resistance.

FY 95 Plans

- Procure the new 16 tesla magnet system for quantum Hall effect research and prepare for installation.
- Improve the digital-voltmeter-based quantum Hall resistance measurement system and assess whether it is capable of 5 parts in 10^8 uncertainty.
- Prepare and characterize new quantum Hall devices, measuring their contact resistances, critical currents, and temperature dependencies.
- Determine the maximum electric fields across the widths of quantum Hall specimens at high currents and explain the quantized voltages observed along the specimens.
- Design a 1:1, four terminal pair ac bridge for investigating the ac quantum Hall effect.
- Realize the SI farad from the calculable capacitor on a continuing basis.

- Determine the SI ohm from the calculable capacitor, the impedance chain, and the quantized Hall resistance.

Related Developments

- The Army and the Navy have expressed interest in obtaining quantized Hall resistance systems for their primary standards laboratories.

- The Army is interested in the possibility of a transportable quantized Hall resistance system with closed cycle refrigerator.

FY 94 Accomplishments and Impacts

- Analyzed the sources of measurement uncertainty contributed by all aspects of the automated digital voltmeter measurement system to determine uncertainty limits. A paper describing this work was published in the NIST Journal of Research.

- Studied various methods to measure the ac quantum Hall effect. Determined that a low-frequency ac bridge measurement of resistance ratios with a room temperature alternating current comparator is too labor-intensive to build and there is a serious frequency dependence of the standard resistors above 1 Hz. Also, an ac Kelvin bridge would introduce large errors in the quantized Hall resistance.

- Designed a set of low-cost photolithographic masks for testing geometrical effects on the resistance values of quantized Hall devices.

- Calculated the potential and current distributions across the width of a quantum Hall sample for applied currents between 0 μA and 225 μA. The calculations are in excellent agreement with the experiment. This work should benefit NIST in understanding the quantum Hall effect and in designing quantum Hall specimens that can operate at higher currents.

- Designed, prepared, and tested two new heterostructures whose electron densities were the most uniform of any samples tested. Furthermore, there were no significant deviations of the quantized Hall resistance from its ideal value for temperatures as high as 2 K. This is a significant step forward in producing samples that can operate at higher temperatures without sacrificing accuracy.

- Realized the SI farad twice by going from the calculable capacitor to the bank of 10 pF capacitors which maintains this unit between SI determinations.

- Determined the SI ohm from the calculable capacitor and the impedance chain. The SI ohm was also compared with the Ω-90 definition via the quantized Hall resistance. There is an apparent discrepancy between the 1988 values and the present realizations of Ω-90. Most of the effort has been devoted to resolving this discrepancy.

- Determined the voltage and temperature dependencies of five newly made 10 pF fused silica capacitors. The temperature cycling and the stability monitoring are continuing.

Project: QUANTUM RESISTANCE AND CAPACITANCE

FISCAL YEARS	95	96	97	98	99
Procure the new magnet system for quantum Hall effect research and prepare for installation. [STRS]	▬				
Improve the digital voltmeter quantum Hall resistance measurement system and determine if it is capable of an accuracy of 5 parts in 10^8. [STRS, DoD]	▬	▬	▬		
Determine the maximum electric fields in quantum Hall samples at high currents and explain why high currents can induce electronic transitions across quantum Hall samples. [STRS, DoD]	▬	▬			
Prepare a manuscript for the analysis of the current and potential distributions within quantum Hall samples. [STRS, DoD]	▬				
Investigate the ac quantum Hall effect. [STRS, DoD]	▬	▬	▬	▬	▬
Prepare and characterize quantum Hall samples. [STRS, DoD]	▬	▬	▬	▬	▬
Realize the SI farad from the calculable capacitor. [STRS]	▬	▬	▬	▬	▬
Determine the SI ohm from the calculable capacitor, the impedance chain, and the quantized Hall resistance. [STRS]	▬				

SEMICONDUCTOR ELECTRONICS DIVISION

Project: NANOELECTRONICS

FY 95 Fund Sources: STRS, OMP, ATP, Competence, ARPA

Staff (9.0 staff-years)

Professional	J. LOWNEY	A. Goldberg (GR)	J. Kopanski	J. Marchiando
	J. Pellegrino	J. Sharp* (PD)	W. Thurber	W. Tseng
	W. Miller (GR)	C. Richter (PD)	B. Sanborn	A. Smirl (GR)
Technician	D. Monk*	Fab Support		

name in capital letters = project leader; * = person works on project part time

Need Addressed: The reduction in feature sizes to near 0.1 μm predicted by the goals of the semiconductor industry for the early 21st century requires new and improved measurement methods to characterize the materials and processes to the 10-nm resolution scale. The yield and reliability of nanostructure (having feature sizes between 10 and 100 nm) devices depend critically 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 and evaluation techniques are needed by the compound-semiconductor industry to manufacture useful and reliable devices based on advanced quantum phenomena. 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 resolution of 10 nm.

Technical Approach: NIST addresses these needs by providing technological leadership to semiconductor manufacturers, specifically, by developing and evaluating the methods, tools, and artifacts needed to improve the state of the art in nanometrology (measurements on a scale of 10 to 100 nm) for semiconductor devices. NIST will provide silicon and compound-semiconductor device manufacturers with advanced metrological techniques and models, such as 10-nm-resolution scanning-probe, dopant-profiling methods as required by the Roadmap, to improve device performance and reliability. The program will include growing and analyzing III-V semiconductor epitaxial films and structures to study their growth kinetics and fabrication properties as needed for the reliable manufacture of nanostructure devices. Specific plans include developing and evaluating such methods as in-situ, molecular-beam-epitaxy (MBE) layer compositional control by X-ray fluorescence; X-ray diffraction and magneto-transport techniques for determining interface properties of superlattices and heterostructures; in-situ reflectometry of MBE layers for determining thickness, composition, and roughness; and focused-ion-beam (FIB) lithography and scanning-tunneling-microscope (STM) measurements of small (<0.1-μm) device structures such as quantum lines and dots.

FY 95 Plans

- Improve the performance of the scanning capacitance microscope and related probe techniques. Measure capacitance-voltage curves at points across processed wafers (mainly Si) down to 10-nm spatial resolution.

- Develop computer codes to model the SEM signals (backscattered, transmitted, and secondary) from nanostructures down to 10-nm level of accuracy. (Collaboration with Manufacturing Engineering Laboratory)

- Install in-situ X-ray fluorescence capability in MBE growth chamber to measure and control composition and possibly thickness of MBE layers. Simulate growth kinetics and compare to reflection-high-energy electron-diffraction (RHEED) signals.

- Equip MBE with in-situ specular and nonspecular optical reflectance apparatus for measuring thickness, composition, and roughness of MBE layers.

- Install focused-ion-beam lithography system in MBE chamber for patterning III-V and possibly Si wafers. Assist optimization of scanning tunneling microscope system for measuring nanostructures. (Part of Competence Project on Nanoelectronics with the Electricity Division and Manufacturing Engineering Laboratory)

- Grow heterostructures for optoelectronic devices. (Collaboration with University of Iowa) Study interface properties with X-ray diffraction and X-ray standing-wave techniques to optimize layer quality. (Collaboration with Materials Science and Engineering Laboratory)

- Characterize the properties of III-V interfaces by using crossed-magnetic-field techniques. Calculate the effect of electron-electron scattering on the mobility of GaAs.

- Use newly developed 3D collocation code to solve Poisson's equation and deduce dopant profiles by comparing calculated differential capacitance with SCM measurements.

Related Developments

- A possible collaboration with Los Alamos National Laboratories (LANL) in semiconductor modeling is being explored. LANL is signing a CRADA with the Semiconductor Research Corporation to establish a DoE Center for Semiconductor Modeling and Simulation. Other DoE laboratories are participating.

FY 94 Accomplishments and Impacts

- Wrote and documented a Monte Carlo code, MONSEL-I, to simulate the transmitted and backscattered signals from a multilayer specimen in a scanning electron microscope. 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. (Collaboration with Manufacturing Engineering Laboratory)

- Obtained capacitance-voltage curves with the SCM as a function of probe position. Tapping-mode capability on SCM reduces damage to probe and specimen and gives improved reproducibility and signal-to-noise ratio. Developed 3D collocation code to solve Poisson's equation for SCM. The SCM is a promising tool to obtain doping profiles in two dimensions and possibly also in depth.

- Completed successfully the characterization of the HgCdTe infrared detectors for the Television and Infrared Operational Satellite (TIROS) and Geothermal Operational Environmental Satellites (GOES) systems. Extensive report published. Methods developed by staff to improve detector performance and yield were transmitted to the detector suppliers.

- Measured anisotropic strain and tilt along orthogonal directions in InAlAs/InP heterostructures used in optoelectronic devices. Used the X-ray standing-wave technique to learn that the buried InAs strained layer in Pseudomorphic High Electron Mobility Transistors (PHEMTs) is only 76% coherent. (Collaboration with Materials Science and Engineering Laboratory)

- Established high-field magnet facility. Staff studied two-dimensional magnetophonon effect and universal conductance fluctuations in GaAs/AlGaAs heterostructures grown in Division's MBE system as well as in Si/Ge heterostructures grown at the Naval Research Laboratory.

Project: NANOELECTRONICS

FISCAL YEARS	95	96	97	98	99
III-V MBE-RELATED RESEARCH					
Conduct research on MBE growth kinetics, dopant incorporation, and lattice mismatch strain effects. Develop such techniques as migration-enhanced-epitaxy and atomic-layer-epitaxy for interface layer sharpness (<1 nm) and quantum-confinement applications. [STRS, ARPA]					⇒
Develop X-ray diffraction and X-ray standing-wave techniques to study interface and buried-layer properties at the atomic level. [STRS, ATP]					
Continue collaborative program with University of Iowa on photonic, electronic, and physical properties of III-V heterostructure-based devices. [ARPA]					
Develop in-situ X-ray fluorescence as a sensitive technique to control alloy composition of MBE layers to ~1%. [STRS]					
Develop STM and FIB lithography with Divisions 821 and 811 to pattern and study ultra-small structures (10 to 100 nm). [STRS]					⇒
SCANNING PROBE MICROSCOPY					
Develop and apply scanning capacitance microscopy to wafer mapping of electrical properties of silicon and compound semiconductors to resolution of 10 nm. [STRS, OMP]					⇒
Develop computer codes to deduce dopant profiles and interface properties from scanning capacitance measurements and codes to interpret SEM signals. [STRS, OMP; SEMATECH]					⇒

Project: NANOELECTRONICS (concluded)

FISCAL YEARS	95	96	97	98	99
MAGNETO-TRANSPORT MEASUREMENTS OF THIN LAYERS					
Characterize III-V heterostructure interfaces at atomic level (<1 nm) by magneto-transport effects. [STRS]					
Develop magnetoresistance as a two-terminal method to determine carrier density and mobility in layered materials to 1% level of accuracy. [STRS]					
FUTURE PROJECT PLANS					
Develop standard methods and artifacts based on prior research in project for improving metrology of growth and process parameters in compounds and Si.					⇒

Project: SEMICONDUCTOR CHARACTERIZATION

FY 95 Fund Sources: STRS, SRMPO, OMP, ATP; SEMATECH, Title III

Staff (9.5 staff-years)

Professional	P. AMIRTHARAJ	J Burnett (PD)	D. Chandler-Horowitz	N. Dhar (GR)
	J. Ehrstein	J. Kim	N. Nguyen	B. Rennex*
	B. Roughani (GR)	D. Seiler*	J. Sharp*	
Technician	D. Monk*	D. Ricks	J. Thomas	Fab Support

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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 for increased packing density and response time for high-speed performance places stringent demands on the current analytical probes. Further advances can be economically realized only with the enhanced yield possible with real-time in-situ control of materials growth and processing. The rapid advances in information-related technologies demand a robust electronic manufacturing base, currently estimated to exceed $700B and growing.

Technical Approach: Optical and electrical activity form the foundation of all the major electronic devices today. The Materials Technology Group has invested substantially in the past three years in upgrading its optical and electrical characterization facilities. Optical probes are attractive and powerful for a variety of reasons. They are: contactless and nondestructive, compatible with any transparent ambient, capable of remote sensing and compatible with hostile environments and hence useful for in-situ probing during growth and processing, and "table-top" procedures easily implemented by manufacturers. Electrical measurements and analyses, particularly from device structures, are a fundamental requirement before reliable operation can be established. More specifically, NIST will develop robust optical probes for in-situ analysis of Si and compound semiconductors and for the study of strain and impurities in technologically important materials and heterostructures. Novel electrical methods capable of elucidating the role of multiple carriers in complex systems will be studied and resistivity Standard Reference Materials (SRMs) required by the electronics manufacturers will be developed.

FY 95 Plans

- Design and build an in-situ metrology system, equipped with a real-time spectroscopic ellipsometer, and UHV processing chamber to measure the optical constants of Si at processing temperatures.

- Verify and apply state-of-the-art contactless spectroscopic methods for impurity metrology in Si for materials qualification and industry detection of contaminants.

- Complete certification and documentation for 100-mm Si resistivity SRMs; transfer SRMs to Standard Reference Materials Program Office and publish documentation.

- Determine the effect of various starting material and implantation parameters (species, energy, and dose) on the viability and performance of an implant dose-sheet resistance SRM in Si.

- Establish and verify detection limit and robust working range of analytical procedures for purity and crystal quality of high-purity Si for Defense Production Act Title-III materials qualification.

- Plan, design, fabricate, assemble and test optical reflectance monitor for alloy composition and film thickness to be instrumented on the Division III-V MBE growth chamber.

- Establish perturbation techniques and laser systems for resonant excitation spectroscopy, and apply them to investigate defects and strain effects.

- Develop microscopic measurement and 2-D scanning and alloy-composition/defect-distribution mapping capability for wafer qualification, and apply to epitaxial AlGaAs.

- Advance electrical transport studies of compound semiconductors using novel techniques including the reduced conductivity tensor scheme for the study of magnetoresistance in multicarrier systems.

- Complete optical characterization survey and analysis to determine the usefulness of optical probes in industry. Publish as NIST Special Publication.

- Coordinate, organize, and conduct the International Workshop on Semiconductor Materials Characterization: Present Status and Future Needs.

Related Developments

- The National Technology Roadmap for Semiconductors (NTRS) was developed by key U.S. technologists under the auspices of the Semiconductor Industry Association. It identifies NIST as the only place in the United States where the measurements needed for semiconductor processing are systematically developed and states that this work must be supported and expanded.

- A SEMI standards committee identified the need for a Compound Semiconductor Materials Roadmap similar to the NTRS. Other planning efforts including those of the Optoelectronics Industry Development Association Roadmap, the Electronics Industries Association Microwave Solid-State Electronics Division, and the National Electronics Manufacturing Initiative will have a significant bearing on this activity.

FY 94 Accomplishments and Impacts

- Demonstrated the use of Fourier transform infrared absorption for measurement of B and P in high-purity Si at densities $<10^{14}$ cm^{-3}. Both N_a - N_D and N_a + N_D can be observed using a double illumination procedure. This capability is required for Title III high-purity Si materials qualifications.

- Demonstrated the sensitivity of optical probes to interface roughness effects in AlAs/GaAs superlattices. Alloying effects are more prominent for the AlAs than the GaAs sublattice. (Collaboration with the Nanoelectronics Project)

- 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.

- Completed a review on utilization and limitations of six different optical characterization techniques. This review introduces technologists to the capabilities of the optical probes and provides the necessary background to understand their potentials and limitations.

- Completed analysis of electrical behavior of materials for high-performance IR detectors, by electrical characterization of liquid-phase epitaxially grown single-crystal films of mercury cadmium telluride.

Project: SEMICONDUCTOR CHARACTERIZATION

FISCAL YEARS	95	96	97	98	99
Develop in-situ spectroscopic analytical procedures for monitoring and controlling semiconductor growth and processing for Si IC manufacture and MBE compound semiconductor growth. [STRS, OMP, OA]					⇒
Develop wafer-level spectroscopic mapping techniques for compound semiconductors, with lateral resolution of 2 μm. [STRS, OMP, OA]					
Develop and perform electrical, impurity, and crystal quality analyses for high-purity silicon and compound semiconductors. [STRS, Title III]					⇒
Apply and enhance multicarrier magneto-transport capability (Hall effect) to compound semiconductor materials. [STRS]					
Establish perturbation techniques and laser systems for resonant excitation spectroscopy for study of heterostructures. [STRS]					
Develop high-resolution FTIR methods for photoluminescence and transmission of semiconductors. [STRS, OMP]					⇒
Develop prototypes and produce new SRMs, including implant dosimetry SRMs having 1% accuracy. [STRS, OMP, SRMPO]					⇒
Certify silicon resistivity SRMs to meet industrial requirements. [STRS, SRMPO]					
Survey and analyze industrial measurement requirements to identify techniques and related reference materials and data to be developed, improved, or standardized. [STRS, OMP, SEMATECH]					⇒

Project: ELECTRICAL AND THERMAL CHARACTERIZATION

FY 95 Fund Sources: STRS, OMP, ATP

Staff (3.6 staff-years)

Professional	A. HEFNER	V. Adams (GRF)	J. Albers	D. Berning
	D. Blackburn*	Y. Joshi (GR)		

name in capital letters = project leader; * = person works on project part time

Need Addressed: The National Technology Roadmap for Semiconductors 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 (TCAD) 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 to the point where high performance and high efficiency are required. Advanced device electrical and thermal characterization procedures and validation of models used in CAD 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 integrated circuits and devices have increased the importance of electronic package electrical and thermal characteristics to overall system performance.

Technical Approach: NIST addresses these needs by developing the theoretical foundations, standards, model validation procedures, and associated experimental techniques for the measurement of chip temperature, device electrical and thermal characteristics, and package electrical and thermal characteristics. NIST is developing with industry, accepted procedures for validating device models for circuit simulation. NIST is also developing procedures for characterizing the thermal and electrical performance of microelectronic packages that are compatible and useful for CAD of boards and systems. The methodology required to accomplish these goals will require measurement systems capable of switching 1200 A, 1200 V in 100 ns, temperature measurement with 1-μm spatial and 100-ns time resolution, and ultralow inductance (<10-nH) systems.

FY 95 Plans

- Facilitate the continued operation of the NIST Working Group on Model Validation: organize task groups, moderate meetings, coordinate activities with professional societies and standards organizations, and support with development of specific device test procedures.

- Continue collaborations under ongoing Cooperative Research and Development Agreements (CRADAs) to develop compact models for circuit simulation: develop high-voltage insulated gate bipolar transistor (IGBT) chip models and develop methods to extract parameters (General Electric), and transfer NIST IGBT extraction capability and buffer layer IGBT model template to Analogy, Incorporated.

- Complete investigation of temperature-sensitive parameters (TSP) such as threshold voltage and anode-to-cathode voltage for IGBT transient thermal impedance measurements: compare results of temperature measurements made last year using different TSPs with simulations and transient infrared temperature measurements.

- Continue to support NIST ATP programs related to semiconductor device electrical and thermal characterization: characterization and failure analysis of power devices in flat-panel display drivers and thermal analysis of multifilm modules.

- Complete development of computer framework for TCAD software including a semiconductor device simulation program, a semiconductor process simulator, interconnect analysis software, characterization and parameter optimization software, and other TCAD simulator and virtual wafer fabrication framework software.

- Develop expertise in package-electrical-parasitic metrology and modeling by investigating the use of time-domain reflectometry (TDR) and spectral analysis. Install the TDR system and identify critical package parasitic problems.

- Assist in the design, modeling, and testing of large-area IGBT power devices in support of the NIST ATP program. This will make use of the NIST high-power static and dynamic IGBT characterization systems for testing samples and the NIST TCAD framework and software tools for analysis of device, process, and package technologies.

- Conduct integrated thermal management system investigation including chip, package, circuit board, and convection environment. Included are construction of electrical and thermal test equipment for TSP and IR thermal measurements of 88-lead plastic quad flat pack (QFP) package, design of circuit board for wind-tunnel experiment on an array of the 88-lead package, and finite element analysis of system by means of existing programs, such as ANSYS and PC3D.

Related Developments

- As a result of collaborations between NIST, Analogy, Incorporated, and Motorola, Incorporated, Motorola introduced an ignition module simultaneously with the introduction of a software model for that module (by Analogy), heralded within the industry as the wave of the future. In a related development, Analogy has also announced the startup of a new modeling division which may become one of the few commercial sources of off-the-shelf analog-component models and characterization services.

- The Power Electronic Devices and Components Committee of the IEEE Industry Application Society has asked to cosponsor the NIST Working Group on Model Validation. NIST formed the Group to facilitate the development of comprehensive procedures for evaluation of circuit simulator models.

FY 94 Accomplishments and Impacts

- Formed NIST Model Validation Working Group. Five meetings have been held, and ten technical areas have been identified and Task Groups established. Active members number 120.

- Provided technical support as a mentor to the Semiconductor Research Corporation-sponsored integrated circuit (IC) power modeling project at the University of Florida. Participated in a joint University-sponsored televideo course on "Physical Circuit Models for Power ASIC Design."

- Continued sponsorship and organizational responsibility for Ion Implant Users Group. Meetings are held quarterly; ~230 members come from 26 states, Canada, England, and Scotland.

- Provided ATP project on Flat-Panel Displays with failure and characterization data on power ICs for row drivers that have led to a redesign of the power IC. The power MOSFET outputs and associated diodes were redesigned to better handle the turn-on transients.

- Extended the NIST TXYZ thermal analysis program to include multilayer microelectronic structures. This work now allows thermal analysis now using TXYZ on structures with any number of identifiable layers. Its potential application will be in areas including dielectrically isolated ultra low power circuits, GaAs ICs, and multifilm, 3-D circuits.

Project: ELECTRICAL AND THERMAL CHARACTERIZATION

FISCAL YEARS	95	96	97	98	99
Develop framework and expertise for TCAD simulations. [ATP]					⇒
Determine TSPs for IGBT transient thermal impedance measurements. [STRS]					
Analyze failure mechanisms of flat-panel display driver power integrated circuit in support of ATP. [ATP]					
Develop characterization and parameter extraction capability for very high power devices and packages. [ATP]					
Develop methods for characterizing important electrical parameters of semiconductor packages based on time-domain reflectometry, scattering parameters, and network analysis. [OMP]					
Organize and facilitate NIST Working Group on Model Validation and support with development of test procedures. [STRS]					⇒
Develop characterization and modeling capability for high-speed advanced semiconductor devices. [STRS]					⇒
Develop methods for characterizing thermal performance of microelectronic packages. [OMP, ATP]					⇒

Project: THIN-FILM CHARACTERIZATION

FY 95 Fund Sources: STRS, SRMPO, DNA, ARPA

Staff (4.5 staff-years)

Professional	D. BLACKBURN	N. Nguyen*	P. Roitman	S. Mayo*
Technician	Fab Support	B. Belzer	M. Edelstein	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Thin films are the cornerstone of the semiconductor manufacturing industry. The National Technology Roadmap for Semiconductors identifies robust gate dielectrics at 5-nm thickness as a specific on-chip materials issue that will impact the ability to achieve the 15-year goals of the Roadmap. This NIST work will provide the metrology support required by industry for the controlled processing of these films in the semiconductor manufacturing environment. The Roadmap acknowledges that the development of low-cost silicon-on-insulator (SOI) substrates will advance integrated circuit (IC) performance a full generation. This material has great potential in ultra-low-power, high-speed, high-temperature, integrated-power, and radiation-hard circuits. The work of this project supports the development of improved SOI material by applying advanced metrology techniques to the evaluation of SOI materials.

Technical Approach: Maintain advanced, state-of-the-art thin-film metrology capability in-house. Continue to support Standard Reference Materials (SRMs) in the 10- to 200-nm thickness range and develop an alternative approach for industry measurements assurance for films of thickness below 10 nm. Specifically, develop procedures for transferring NIST measurement accuracy and precision to standard-artifact-producing organizations outside NIST and for organizations to have NIST thin-film SRMs recertified at NIST. Characterize defects of thin-film Si (to 0.1-μm thickness) and buried SiO_2 layers.

FY 95 Plans

- Develop, with VLSI Standards, Incorporated, a procedure for assuring traceability to NIST of the company's 7.5-nm thin-film artifact without relying upon NIST to certify an SRM of that thickness range.
- Develop a procedure for recertifying NIST thin-film SRMs in the 10- to 200-nm range at the request of SRM customers.
- Plan and initiate an interlaboratory, intermetrology study to develop a basis for traceable standards for thin-film measurement instruments other than ellipsometers.
- Help improve the electrical characteristics of thin buried oxides by correlating electrical measurements on capacitors with annealing and implant conditions.
- Determine the formation mechanism of the silicon island precipitates in studies with Arizona State University by correlating TEM and other physical measurements with implant and annealing conditions.
- Provide technical support and assist in oversight of SOI projects for Advanced Research Projects Agency's (ARPA) low-power electronics initiatives.

Related Developments

- ARPA is planning a very low power electronics initiative to begin this year. NIST expects to play a significant role in the conduct of the program.

- A U.S. company is marketing a 7.5-nm thin-film reference artifact and is requesting support from NIST for traceability to NIST for the artifact. There are immediate plans for the company to work on a 4-nm artifact in response to industry demands. NIST is developing a formalized working relationship (CRADA) to provide the needed assistance.

FY 94 Accomplishments and Impacts

- Completed interlaboratory study of thin-film measurements (9 laboratories participated) for SiO_2 on Si films to a thickness of 10 nm. Results demonstrate industry capability adequate for current Roadmap milestone projected requirements.

- Issued first 10-nm SiO_2 on Si thin-film SRMs in response to industry requests.

- Completed upgrade of high-accuracy ellipsometer laboratory, including improved alignment procedure and increased automation. The alignment is now done using quadrant photodetectors to establish reference for angle of incidence, and principal angle of incidence is now determined under full computer control, with no operator interference. (Collaboration with the Materials Technology Group)

- Initiated shift away from only providing to industry NIST-certified SRM artifacts to the development of a traceability path to NIST not solely dependent on SRMs. Established collaboration with industry partner to develop procedures. This new approach is being investigated as a way of assuring response to industry needs in a timely manner and efficient utilization of NIST resources.

- Demonstrated that high-temperature anneals, up to 1350 °C, do not affect the defect nature of the silicon film, but do reduce the interface roughness.

- Provided considerable assistance in planning for ARPA's very low power electronics initiative and in evaluating proposals concerning SOI materials.

- Transferred NIST etching technology for defect determination in thin-film silicon SOI to industry. With industrial partner, found high-defect density in bound and etch back silicon on insulator (BESOI) wafers which contradicts general belief held by BESOI community.

- Extended analysis of current transport in the buried oxide of SOI wafers to a pulse mode. This allows electron and hole injection to be independently studied.

Project: THIN-FILM CHARACTERIZATION

FISCAL YEARS	96	96	97	98	99
Develop and maintain thin-film SRM recertification procedure. [STRS, SRMPO]					⇒
Develop and maintain procedures for traceability to NIST for thin-film artifacts <10 nm. [STRS, SRMPO]					⇒
Conduct interlaboratory intermetrology (e.g., ellipsometry, reflectometry, X-ray diffraction) study and report. [STRS]					
Develop procedures for providing thin-film calibration artifacts for films other than SiO_2 important to silicon industry. [STRS, SRMPO]					⇒
Develop procedures for calibrating artifacts for thin-film instruments other than ellipsometers. [STRS]					
Determine effect of dose rate on buried oxide thickness and quality for SIMOX material. [STRS, DNA]					
Develop and evaluate measurement methods for qualifying material and processing for SOI material. [STRS, DNA, ARPA]					
Provide technical support and assist in oversight of SOI projects for ARPA's low-power electronics initiatives. [STRS, ARPA]					⇒

Project: TEST STRUCTURE METROLOGY FOR ADVANCED SEMICONDUCTOR MANUFACTURING

FY 95 Fund Sources: STRS, OMP, ATP, Navy

Staff (11.9 staff-years)

Professional	L. LINHOLM	J. Albers*	R. Allen	D. Berning*
	M. Cresswell	M. Gaitan	S. Mayo*	J. Marshall*
	H. Schafft	C. Schuster	J. Suehle	M. Zaghloul*
Technician	L. Buck	C. Ellenwood	J. Owen	Fab Support

name in capital letters = project leader; * = person works on project part time

Need Addressed: In order to manufacture competitive, cost-effective semiconductor products, improved manufacturing process and tool control, device performance, and reliability have been recognized by the National Technology Roadmap for Semiconductors (NTRS), the SRC 2001 Reliability Roadmap, and many in the integrated circuit industry as key steps required for the next generation of products. Improved microelectronic test structures, test methods, data analysis techniques, and sensors are needed by industry for low-cost methods of determining and measuring key control and performance parameters. Improvements are needed to increase test coverage and assure product performance. Competent, focused, and unbiased development is necessary to enable improved technology transfer between tool and device manufacturers.

Technical Approach: The Integrated Circuits Technology Group will provide domestic manufacturers with improved test structures, test methods, and diagnostic procedures for evaluating tool performance, improving device reliability, characterizing and controlling manufacturing processes, and providing novel sensor-based metrology. NIST will develop the theories, standards, and associated techniques required for accurate electrical measurements of electrical linewidth and feature placement; develop sensors for assuring reliability of interconnects and oxides by controlling processes during manufacture; develop mechanical-based test structures for measuring thin-film mechanical properties and fabrication methodology for micro-electro-mechanical systems (MEMS); and design, develop, and deliver an integrated gas sensor array for controlling tool performance. Challenges include accurate measurement of electrical linewidth to dimensions of 0.18 μm and feature placement to 10 nm; complementary metal-oxide-semiconductor-compatible devices and design libraries to support test and calibration applications for thermal flat-panel displays and thermal converters; measurement techniques to characterize oxide and interconnect failure mechanisms from dc to 40 GHz and temperatures from -196 to 400 °C; and rapid-heating sensors for micromaterial processing and monitoring at temperatures from ambient to 1200 °C with response times less than 0.5 ms.

FY 95 Plans

- Establish correlation between electrical linewidth measurements and NIST Molecular Measuring Machine for patterned interconnect films. (Collaboration with Manufacturing Engineering Laboratory)

- Evaluate feasibility of scanning capacitance and inductance techniques for contactless determination of overlay from chemically and mechanically polished interconnect levels.

- Characterize the time-dependent dielectric breakdown (TDDB) behavior of 9- and 15-nm oxides when subjected to bipolar and unipolar ac stress waveforms. (Collaboration with National Semiconductor Corporation)

- Fabricate barrier-metal-based microhotplate structures for chemical sensing arrays.

- Complete construction and testing of package-level electromigration station.

- Document results of interlaboratory experiments for EIA-JEDEC JESD33 (temperature coefficient of resistance and joule heating) and ASTM F 1261 (linewidth) standard measurement methods.

- Develop thermal flat-panel displays for Navy-sponsored field demonstration. NIST will work to fabricate the displays and Optical E.T.C., Incorporated will work on the system level design and optical components. (CRADA with Optical E.T.C.)

- Develop cost-effective precision power sensors and field strength sensors. NIST will characterize the performance of silicon micromachined transmission lines and thermal converter elements for precision power measurement applications in the 1- to 10-GHz range. (CRADA with RF Microsystems)

Related Developments

- The NTRS identifies NIST as the only place in the U.S. where the measurements needed for semiconductor processing are systematically developed and states that this work must be expanded.

- The industry (including the NTRS and SEMATECH) is embracing NIST's building-in reliability (BIR) approach to improve the long-range reliability of the products they are manufacturing. The BIR approach is now the focus of the IEEE Integrated Reliability Workshop.

- The domestic advanced lithography community has standardized on the NIST/ARPA X-Ray Lithography Mask Support Ring.

- The Navy has chosen to transition the thermal flat-panel display demonstration currently supported in FY 95. This new effort is expected to be a $3M award over three years and is to be a collaborative effort between NIST, Optical E.T.C., and NRAD (Navy sponsor).

FY 94 Accomplishments and Impacts

- Demonstrated dynamic precision (repeatability) of electrical overlay test structures to be 1.5 nm (6 sigma), and uncertainty less than 10 nm (comparisons with NIST line-scale interferometer).

- Developed and obtained patents for improved electrical overlay calibration substrates, for miniaturized electrical linewidth to provide higher spatial resolution, for electrical certification of graduated scales, and for micromachined chemical sensors and applications.

- Improved understanding of TDDB in thin SiO_2 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.

- Refined use of Matthiessen's rule to measure thickness of metal films by an electrical method. Demonstrated agreement with calibrated NIST Scanning Electron Microscope measurements.

- Fabricated, tested, and evaluated large-area 128 × 128 MEMS thermal display.

- Designed and fabricated new low-loss, high-frequency on-chip transmission lines using MEMS fabrication method for high-frequency thermal converters for the 1- to 10-GHz range.

Project: TEST STRUCTURE METROLOGY FOR ADVANCED SEMICONDUCTOR MANUFACTURING

FISCAL YEARS	95	96	97	98	99
TEST STRUCTURES FOR IC MANUFACTURING					
Establish correlation between optical and electron-beam-based linewidth metrologies and electrical techniques. [OMP]					
Develop contamination-free electrical probing metrology which introduces no particulates during testing. [STRS]					⇒
Develop, demonstrate, and apply electrical test structure-based metrology for pattern feature placement and overlay for multiple layer patterns to less than 5 nm measurement precision. [OMP]					
Develop on-wafer, multilevel conductor-compatible overlay metrology with a goal of better than 20-nm precision. [STRS, OMP]					
Develop test structure-based metrology for determining performance of reliability in order to characterize interconnect systems. [STRS, ATP]					
INTEGRATED SENSORS FOR RELIABILITY					
Develop, characterize, and evaluate integrated sensor elements for improving reliability by monitoring in-situ and controlling deposition of films and gas species. Gases/materials to include concentration of hydrogen, oxygen, water, and hydrocarbons and resistivity of thin metal films. [OMP]					⇒

Project: TEST STRUCTURE METROLOGY FOR ADVANCED SEMICONDUCTOR MANUFACTURING (concluded)

FISCAL YEARS	96	96	97	98	99
TEST STRUCTURES FOR RELIABILITY					
Characterize reliability of thin oxide films to improve lifetime for ultra large scale integrated circuit processes. [STRS, OMP]					
Promote implementation of building-in reliability approach in industry and government; demonstrate approach for deposition of thin metal films or integrity of oxides. [OMP]					⇒
Revise standards for electromigration test structures and measurement techniques based on industry input. [OMP]					
INTEGRATED MEASUREMENT SYSTEMS					
Develop methodology for fabricating micromachined structures in silicon foundries to point of practical utilization. [Navy]					⇒
Design, fabricate, and evaluate sensors important for metrology, calibration, and standardization for use in controlling semiconductor manufacturing tools. Collaboration with other NIST divisions. [STRS]					⇒
Develop CMOS-compatible micromachined waveguides and thermal converters for precision wide-band sensors. Collaboration with Division 813. [Navy]					
Develop test structures and methods for determining thermo-electro-mechanical properties of thin films. [STRS]					

ELECTROMAGNETIC FIELDS DIVISION

Project: POWER STANDARDS AND MEASUREMENTS

FY 95 Fund Sources: STRS, DoD, Fees, NVLAP Fees

Staff (8 staff-years)

Professional	F. CLAGUE	W. Allen	J. Jargon*	J. Juroshek*
	G. Rebuldela*	D. Walker*	M. Weidman*	D. Williams*
Technicians	D. LeGolvan*	A. Monke*	M. Packer*	P. Voris

name in capital letters = project leader; * = person works on project part time

Need Addressed: Microwave power is the high frequency equivalent to 60 Hz 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 from 10 MHz to 100 GHz in coaxial transmission line, and from 18 GHz to 96 GHz in waveguides is needed to assure proper performance.

Technical Approach: Develop coaxial and waveguide transfer standards, microcalorimeters, measurement techniques, and automated instrumentation which supports and provides the calibration services for customer transfer standards. Develop a new standard from 10 MHz to 50 GHz in 2.4 mm coaxial line, with an uncertainty goal of 0.1 to 0.5 percent. Complete the evaluation of partially completed standards in WR-42, WR-22, WR-15, and WR-10 waveguide with uncertainties of 0.2 to 0.5 percent. Provide high-power (50 to 1000 watt) measurements and standards from 1 MHz to 1 GHz, and to 40 watts near 60 GHz, with uncertainties of 1 to 3 percent. Develop and maintain existing measurement systems and reference standards used in calibration services for power. [Note on waveguide band designations: WR-42 = 18 to 26 GHz; WR-28 = 26.5 to 40 GHz; WR-22 = 33 to 50 GHz; WR-15 = 50 to 75 GHz; WR-10 = 75 to 110 GHz.]

FY 95 Plans

- Continue the development of 2.4/3.5 mm coaxial power standards for use from 50 MHz to 50 GHz and a low-frequency version down to 1 MHz. Promote transfer standard development by one or more private companies through CRADAs.

- Continue the development and evaluations of the new isothermal WR-42, -22, -15, and -10 microcalorimeters. The evaluation of the WR-15 calorimeter will be completed first.

- Continue the development of a 4 K superconducting WR-22 power standard to realize a 0.05% uncertainty.

- Develop the capability to operate a coaxial microcalorimeter at 1 mW. Evaluate uncertainties associated with measuring NIST model CN coaxial transfer standards at 1 mw from 0.5 to 18 GHz.

- Interact with industry and National Voluntary Laboratory Accreditation Program (NVLAP) office regarding final NVLAP technical requirements for calibration laboratory accreditation.

- Develop a microwave high power system and establish a calibration service for wattmeters from 10 to 1000 MHz and power levels from 1 to 1000 watts with an uncertainty of 1.5%.

- Provide calibration and measurement services for microwave power.

Related Developments

- Providing technical guidance to staff of the Instituto Nacional de Tecnica Aeronautica (INTA) of Spain who are building a copy of the NIST coaxial microcalorimeter.

FY 94 Accomplishments and Impacts

- Completed the construction of the WR-15 microcalorimeter and transfer standard. Construction has now been completed for the WR-10, WR-15, WR-22, and WR-42 microwave power standards.

- Designed, fabricated, and delivered forty NIST PM2 power measurement systems to the Air Force to measure microwave power at the 1 mW level at 1 GHz.

- The Direct Comparison Power Calibration System was brought on line for calibrating customer Type N power transfer standards.

- Carried out an International Comparison of power standards in WR-22 with the National Physical Laboratory (NPL) in the UK. Agreement between NIST and NPL was between 0.2 to 0.4%; present NIST uncertainty is 1.6%

- Delivered 3 NIST-designed Model CN coaxial transfer standards to the Singapore Standards Institute.

- Installed a new heat pump on a coaxial microcalorimeter and conducted tests to evaluate feasibility of providing customer calibration service at the 1 mW level.

- Initiated calibration services for power transfer standards in 3.5 mm coaxial connectors (1 to 26.5 GHz) on the dual six-ports.

- Developed software for using a commercial vector network analyzer to measure the efficiency of diode and thermoelectric power meters. This system is an order of magnitude faster than the dual 6-ports, but not as accurate.

- Calibrated 107 power standards for customers for an income of $242K.

- Reduced the rf loss in the WR-22 niobium waveguide to 0.05 dB/m. Further reduction to 0.01 dB/m is necessary to achieve the desired uncertainty of 0.05 % with the cryogenic power standard.

Project: POWER STANDARDS AND MEASUREMENTS

FISCAL YEARS	95	96	97	98	99
MICROCALORIMETER DEVELOPMENT					
Construct microcalorimeter for 3.5 mm and smaller coaxial power standards. [STRS, DoD]					⇒
Evaluate WR-10, -15, -22, -42 microcalorimeter. [STRS, DoD]					
Extend capability to operate coaxial microcalorimeter at 1 mW. [DoD]					
TRANSFER STANDARDS/CALIBRATION SYSTEMS DEVELOPMENT					
Construct coaxial thermistor standards for DoD and industrial laboratories. [DoD]					⇒
Develop new 2.4- and 3.5-mm transfer standards with new type of detector from 5 MHz to 50 GHz. [DoD]					
WORKING STANDARDS EVALUATION					
Evaluate 7-mm coaxial standards to 18 GHz. [STRS, Fees]					
Evaluate WR-42, WR-28, WR-15, WR-10 thermistor mounts. [STRS, Fees]					

Project: POWER STANDARDS AND MEASUREMENTS (concluded)

FISCAL YEARS	95	96	97	98	99
SUPERCONDUCTING STANDARDS					
Continue development of WR-22 power standards with uncertainty goal of 0.05 %. [DoD]					
Construct/evaluate device, if feasible. [STRS, DoD]					
CALIBRATION/MEASUREMENT SERVICES					
Provide power calibration service. [Fees]					⇒
Provide high power measurement services 1 MHz to 400 MHz. [Fees]					⇒
Provide technical support to NVLAP. [NVLAP Fees]					⇒

Project: IMPEDANCE, ATTENUATION, VOLTAGE STANDARDS AND MEASUREMENTS

FY 95 Fund Sources: STRS, DoD, Fees, NVLAP Fees

Staff (4.0 staff-years)

Professional	G. REBULDELA*	G. Free	R. Ginley*	J. Jargon*
Technicians	E. Pittman*	D. Seibold	G. Sherwood	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Manufacturers of electrical/electronic equipment and components, research and development laboratories, DoD 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. As electronic products become more complex, the burden will fall on NIST to develop more accurate voltage and impedance standards to support RF and microwave test equipment.

Technical Approach: Capabilities of present commercial instruments and systems approach those at NIST or require better measurements. In response to the demand for reduced uncertainties, standards, techniques, and systems for measuring voltage and impedance will be improved. Low frequency power measurements (100 kHz - 10 MHz) will be enhanced through improvements on the Twin-T impedance bridge and the rf voltage systems. Our goal is to: 1) reduce the uncertainty in impedance measurements to 0.01%; 2) re-evaluate voltage standards against those maintained in the Electricity Division from 30 kHz to 10 MHz and reduce the uncertainties from 0.10% to 0.02%; 3) extend the voltage re-evaluation from 10 to 1000 MHz on high frequency Thermal Voltage Converters (TVCs) with power standards.

FY 95 Plans

- Document the Twin-Tee Bridge for the 10 to 200 MHz range.
- Evaluate and document Twin-Tee Bridge for 100 kHz to 5 MHz range.
- Investigate other methods of measuring impedance to support power measurements using TVCs from 100 kHz to 20 MHz.
- Support 4-port measurements using capacitance and resistance.
- Develop 30 MHz receivers for DoD to support high precision attenuation measurements.
- Complete documentation for TVC and Micropot measurement systems operating from 1100 Hz to 1000 MHz.
- Provide calibration and measurement services for attenuation, impedance, and voltage.

- Provide dimensional measurement of coaxial air lines and waveguide sections for industrial and other agency customers and also to support NIST dual 6-port systems.

- Complete the documentation for the dimensional measurement of air-lines.

- Document international comparison in Quality Factor of inductance standards.

Related Developments

- For the past several years EEEL's Electricity Division has undertaken the development of thermal voltage converters using thin-film technology as a means of providing new standards with broader frequency coverage. Application of this technology includes fabrication of micropots for measurements of low levels of voltage. These new standards could have numerous applications in power and high frequency voltage metrology and undoubtedly impact measurement systems, standards, and calibration services.

- Two major U.S. companies have approached NIST to participate in discussions on rf power measurements for semiconductor plasma etching. Of major interest is where the industry is heading and what capability exists for rf high power measurements.

- A major U.S. manufacturer has recently introduced an impedance meter which operates from 1 MHz to 1.8 GHz. NIST is not able to provide traceable measurement support for this instrument because its specifications are better than the NIST uncertainty at the lower frequencies.

FY 94 Accomplishments and Impacts

- Calibrated 164 standards for customers for income of $165K.

- Calibrated a series of prototype resistors for a U.S. manufacturer from 50 kHz-2 MHz. Uncertainty of 0.01% is an order of magnitude better than past calibrations at NIST.

- Completed preliminary draft documentation for dimensional measurement of air-lines.

Project: IMPEDANCE, ATTENUATION, VOLTAGE STANDARDS AND MEASUREMENTS

FISCAL YEARS	95	96	97	98	99
DIMENSIONAL MEASUREMENTS OF AIR- LINE STANDARDS					
Complete documentation for the dimensional measurement of air-lines. [STRS]					
IMPEDANCE STANDARDS DEVELOPMENT/EVALUATION					
Investigate use of Z standards (ie; capacitance) to support VNA calibration. [STRS]					
LOW FREQUENCY IMPEDANCE MEASUREMENTS					
Publish report of international comparison of Q-standards. [STRS]					
Develop impedance measurement system to 5 MHz (Twin-T Bridge) with 0.01% uncertainty. [STRS, DoD]					
VOLTAGE MEASUREMENTS					
Document thermal voltage converter (TVC) system. [STRS]					
Document micropot system. [STRS]					
ATTENUATION STANDARDS (30MHz)					
Develop 30-MHz receiver to support DoD attenuation measurements. [DoD]					

Project: IMPEDANCE, ATTENUATION, VOLTAGE STANDARDS AND MEASUREMENTS (Concluded)

FISCAL YEARS	95	96	97	98	99
CALIBRATION/MEASUREMENT SERVICES					
Provide TVC/micropot calibration service. [Fees]					⇒
Provide low frequency impedance, resistance calibration services. [Fees]					⇒
Provide high accuracy attenuation calibration service at 1.25 MHz and 30 MHz. [Fees]					
Provide technical support to NVLAP. [Fees]					

Project: NETWORK ANALYSIS AND MEASUREMENT

FY 95 Fund Sources: STRS, DoD, Fees, NVLAP Fees

Staff (8.5 staff-years)

Professional	J. JUROSHEK	R. Ginley*	R. Kaiser	J. Major*
	G. Rebuldela*	M. Weidman*		
Technicians	D. LeGolvan*	A. Monke*	C. Ondrejka	M. Packer*
	E. Pittman*	K. Talley		

name in capital letters = project leader; * = person works on project part time

Need Addressed: Vector Network Analyzers (VNAs) are the single most important tool in the microwave industry. VNA's are used on production lines, and for research and development. VNAs are typically calibrated daily and their accuracy can vary significantly. The accuracy of a VNA is dependent on the skills of the operators, the quality of the calibration standards, the condition of the test ports, the calibration technique used, and the calibration verification procedures that are used. The microwave industry needs new, cost effective techniques to monitor and insure the accuracy of VNAs. The microwave industry also needs help in developing the techniques, procedures, and documents to ensure conformity with ISO-9000 requirements.

Technical Approach: NIST calibration services directly support the microwave industry by providing traceability and intercomparison of microwave measurements. We will continue to maintain the existing calibration services, expanding where necessary to higher frequencies and alternate or new services. New methods for providing cost effective calibration services will be explored. NIST also has a role in developing a better understanding of network analyzer uncertainty mechanisms and evaluating methods to assess and control the accuracy of a network analyzer. Information on these techniques will be disseminated to the industry.

FY 95 Plans

- Continue to evaluate existing validation and verification procedures for vector network analyzers. Develop new procedures and document their effectiveness.

- Continue to evaluate the uses of a commercial solid state variable impedance generator for use in VNA calibration and verification. Determine the advantages and disadvantages of verification using solid state variable impedance generators.

- Explore alternate methods for disseminating calibration services. Investigate possibility for using alternate services such as the Automated Radio Frequency Techniques Group (ARFTG) measurement comparison program to provide traceability of microwave measurements.

- Continue evaluating the use of commercial vector network analyzers as a cost effective tool for providing NIST calibration services.

- Develop calibration procedures for the low frequency (< 1 GHz) dual six-ports that are independent of air-lines. Investigate alternate six-port calibration methods that would increase the reliability and reduce the time and cost of calibration.

- Develop documentation that satisfies international quality standards for all dual six-ports used in calibration services.

- Establish a computer data base for customer calibrations.

- Participate as instructors in the ARFTG Microwave Metrology course.

- Provide calibration services for microwave scattering parameters of passive 1- and 2-port devices.

- **Construct and deliver 6-port VNA (100 kHz to 1 GHz) for the Air Force.**

Related Developments

- VNA users are seeking NIST advice about measurement methodology, traceability, uncertainties, and measurement assurance, suggesting that NIST must develop alternative approaches to conventional calibrations and new ways to insure the quality of VNA measurements.

- Demand for the Automatic Radio Frequency Techniques Group (ARFTG) measurement comparison program has grown substantially over the past few years. NIST is currently maintaining a data base on 109 comparisons by 41 different laboratories.

- Two U.S. companies have entered into an agreement to market an electronic tuner as an electronic calibration device, replacing physical standards.

FY 94 Accomplishments and Impacts

- Revised uncertainties for all dual 6-ports and made changes to uncertainty statements to be consistent with NIST Policy and international practice.

- Calibrated 161 customer 1- and 2-port standards for an income of $161K.

- Analyzed data and prepared reports for 30 participants in the ARFTG measurement comparison program.

- Completed measurements on solid-state impedance generator as part of a CRADA. As a result of these measurements, the manufacturer was able to improve the stability of the impedance generator.

- Completed and delivered (0.25 to 18 GHz) dual six-port to the Air Force.

- Initiated a calibration service for S-parameters with 2.4-mm coaxial connectors, which allows NIST to offer coaxial calibration services to 50 GHz.

- Designed and built new standards and test ports for the WR-22 (30 to 50 GHz) dual six-port which enables NIST to offer a WR-22 waveguide calibration service.

- Brought on-line a new 0.25 to 18 GHz dual six-port system with improved reliability to measure customer standards.

- Helped the Antenna and Materials Metrology Group establish a field strength service in WR-19 waveguide.

Project: NETWORK ANALYSIS AND MEASUREMENTS

FISCAL YEARS	96	96	97	98	99
SIX-PORT DEVELOPMENT					
Upgrade coaxial six-port (10 to 1000 MHz) for NIST. [Fees]	▬				
Construct and deliver coaxial six-port (10 to 100 MHz) to the Air Force. [DoD]	▬				
Construct and deliver coaxial six-port (18 to 40 GHz) to the Air Force. [DoD]	▬	▬	▬	▬	
VECTOR NETWORK ANALYZER (VNA) CHARACTERIZATION/MEASUREMENT TECHNIQUES					
Develop procedures to evaluate commercial VNA performance and disseminate to industry. [STRS, DoD]	▬	▬	▬		
Implement calibration procedures for VNAs using capacitance standards. [STRS]	▬	▬			
Develop procedures to verify and validate VNA performance. [STRS, DoD]	▬	▬	▬	▬	
Develop calibration procedures using lossy two-ports. [DoD]	▬	▬			
Develop calibration/verification procedures using tuneable impedance generator. [STRS]	▬	▬			

Project: NETWORK ANALYSIS AND MEASUREMENTS (concluded)

FISCAL YEARS	95	96	97	98	99
CALIBRATION/MEASUREMENT SERVICES					
Provide S-parameter calibration service. [Fees]					⇒
Develop alternative methods to disseminate VNA traceability. [STRS, DoD]					
MEASUREMENT ASSURANCE					
Develop quality manual and document measurement procedures and uncertainties for all six-port systems. [STRS]					
Analyze participant data for ARFTG measurement comparison program. [STRS]					⇒
Provide technical support to NVLAP. [Fees]					⇒
Re-evaluate and document uncertainties for all six-ports. [STRS]					

Project: MICROELECTRONICS METROLOGY

FY 95 Fund Sources: STRS, HPCC, OA, DoD

Staff (4.5 staff-years)

Professional	D. WILLIAMS*	R. Marks	J. Jargon*	D. Walker
Technician	J. Morgan			

name in capital letters = project leader; * = person works on project part time

Need Addressed: The United States electronics industry is developing high-speed and high-frequency microelectronic devices and products for applications in telecommunications (including wireless), high-speed computing, intelligent transportation systems, and collision avoidance. These industries lack inexpensive and accurate electrical measurement methods for cost-effective product design and development. NIST metrology support is critical if the United States is to rapidly commercialize new microelectronic technology and maintain world leadership in this high technology area.

Technical Approach: Develop metrology using time-domain and frequency-domain instrumentation to electrically characterize (d.c. to 300 GHz) microelectronic packaging and interconnections in addition to monolithic microwave integrated circuits (MMICs). Build on existing strengths in MMIC metrology and continue to develop on-wafer standards and calibration techniques critical to cost-effective commercialization.

FY 95 Plans

- Complete development of standard microstrip fabrication process and determine extent to which vias and process variations affect calibration repeatability and standardization.
- Advance time-domain network analysis technology through a Small Business Innovation Research (SBIR) project. Develop time-domain network analysis to characterize advanced microelectronic packaging, including multichip modules, using inexpensive time-domain instrumentation.
- Continue ATP-funded project intended to commercialize MMICs. Assess the microwave performance of low-cost flip-chip packaging and help build a high quality library of computer-aided design data.
- Continue to explore avenues for increasing use of NIST calibration verification techniques, possibly through an SBIR grant.
- Develop accurate and compact S-parameter calibrations for on-wafer measurement of MMICs.
- Investigate theory of, and calibrations for, coupled lines in microelectronics packaging.
- Collaborate with NIST's Electromagnetic Property of Materials Project to develop *in situ* on-wafer methods for characterizing dielectric properties thin films.
- Assist in developing an on-wafer microwave noise source with known noise temperature.
- Develop cryogenic on-wafer measurement system with the Electromagnetic Technology Division and the University of Hawaii.

Related Developments

- Cascade Microtech advertises that "Only Cascade Microtech has commercially-available LRRM standards that have been verified with NIST's GaAs TRL calibration." Verification results based on NIST methods have also appeared in conference presentations, trade magazines, and technical publications and in a one page writeup in Cascade's *MicroProbe Update.*

- The Electronics Industry Association formed a Microwave Solid-State Electronics Division to promote United States leadership and excellence in the microwave and millimeter wave industry.

- An electronic packaging workshop sponsored by NIST and three industry groups emphasized industry shortfalls in electrical characterization.

- Over 140 copies of MMIC calibration software have been distributed to over 36 U.S. companies. 42 copies of MMIC software were distributed this year. Requests for papers continued at the rate of about 40 per year.

- Williams and Marks were awarded the Automated Measurements Technology Award (1994) and Best Paper Award (1993) from the Automatic RF Techniques Group (ARFTG).

FY 94 Accomplishments and Impacts

- Tested accuracy assessment methods at NIST/Industrial MMIC Consortium laboratories. Tests showed that the methods effectively identified measurement errors of industrial calibrations.

- Developed time-domain transmission line characterization methods.

- Began development of extremely accurate measurements for computer aided design library of coplanar waveguide circuit components.

- Developed the first accurate microwave calibration technique for circuits fabricated on silicon. Method promises to aide industry in developing low-cost high-performance silicon MMICs.

- Developed a compact on-wafer calibration set for the imperfect resistors and lines typical of MMICs. Method reduces calibration set size while maintaining high calibration accuracy.

- Explored a method for adjusting off-wafer coplanar waveguide calibrations to compensate for substrate properties. Method is accurate yet eliminates on-wafer calibration artifacts.

- Developed methods for extracting materials parameters from on-wafer measurement, an essential first step in the development of accurate material characterization techniques from simple in situ on-wafer measurements.

- Developed equivalent circuit theory for lossy coupled lines and completed layout of test artifacts.

- Completed initial cryogenic experiments with the Electromagnetic Technology Division and the University of Hawaii; cooperated with Electromagnetic Technology Division on characterization of tunable cryogenic resonators.

- Organized on-wafer measurements workshop at the IEEE 1994 International Microwave Theory and Techniques Symposium (67 attendees) and at 1993 Automatic RF Techniques Group meeting (approximately 60 attendees).

Project: MICROELECTRONICS METROLOGY

FISCAL YEARS	98	98	98	98	99
MMIC S-PARAMETER METROLOGY					
Develop de-embedding theory, calibration, and measurement techniques (dc-350 GHz). [STRS,DoD, OA]					
Determine through experiment and simulation the fundamental limitations of probing technology. [STRS, DoD, OA]					⇒
Extend applicability of on-wafer CPW standards to, and if possible, above 60 GHz. [STRS, DoD, OA]					
Develop on-wafer noise source with well characterized noise temperature. [STRS, DoD, OA]					⇒
Develop and encourage use of verification methods for on-wafer measurements. [STRS, OA]					⇒
WAFER LEVEL STANDARDS DEVELOPMENT					
Complete development of coplanar fabrication capability. [STRS, DoD, OA]					
Develop microstrip and similar multiplane fabrication capabilities. [STRS, DoD, OA]					⇒
PLANAR FABRICATION FACILITY					
Acquire and install equipment. [STRS]					⇒

Project: MICROELECTRONICS METROLOGY (concluded)

FISCAL YEARS	95	96	97	98	99
PACKAGING AND INTERCONNECTS					
Develop in situ measurement methods characterizing thin lossy dielectrics based on on-wafer measurements (50 MHz to 40 GHz). [STRS, HPCC]					
Apply microwave calibration techniques to on-wafer time domain measurement. [STRS, HPCC]					⇒
Develop methods for characterizing discontinuities and apply them to problems in the electrical characterization of electronic packaging. [STRS, HPCC]					
Develop circuit theory for multiple modes of propagation and develop associated calibration methods. Quantify coupling and crosstalk. [STRS, HPCC]					⇒
Develop interconnection standards for microelectronics packaging. [STRS, HPCC]					⇒
Develop calibrations and measurements for mixed (digital and analog) microwave systems. [STRS, HPCC]					⇒
Develop calibrations and measurements for mixed electrical and optical systems. [STRS, HPCC]					⇒
CRYOGENIC PROBING					
Evaluate low temperature on-wafer probe system (4 Kelvin). [DoD]					
Develop high Tc standards and participate in joint experiments with Electromagnetic Technology Division. [STRS, DoD, OA]					⇒

Project: NOISE STANDARDS AND MEASUREMENTS

FY 95 Fund Sources: STRS, DoD, OA, Fees, NVLAP Fees

Staff (6.0 staff-years)

Professional	D. F. WAIT	S. Perera	J. Randa	
Technicians	R. L. Billinger	J. L. Rice	L. A. Terrell	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Noise influences many critical parameters of a system's performance, such as the range of a mobile phone or the quality of a TV picture. Noise can be used to characterize both components and systems and can be applied to a variety of measurement applications. By using noise as a test signal, systems can be evaluated for dynamic range and sensitivity, and tuned for maximum performance. The microwave industry is expected to double in the next five years. Cellular telephones, continued increased use by the automobile industry, and the expanding communications industry are driving this expansion. The telecommunications revolution brings increasingly greater demand for channel-carrying capacity. Channel-carrying capacity is inversely proportional to the noise which is therefore a critical parameter. One of the more critical parameters of low-noise, broad-band amplifiers is their noise performance. These are very difficult measurements, in part because no on-wafer primary noise standards exist anywhere. The target customers are the metrology laboratories, Department of Defense, and communications industries. Currently measurement repeatability and between-laboratory variations are about 0.4 dB, and even greater for on-wafer amplifier measurements. This is a difficult situation for the microwave industry because improved performance is hard to verify. Increasing the accuracy of noise figure measurements can lead to better designs, higher yields, and more competitive product specifications.

Technical Approach: The project goal is to provide cost-effective calibrations for noise standards and amplifiers with sufficient frequency band coverage and uncertainties adequate to meet customers' needs. Efforts include developing a new noise figure radiometer (NFRAD) designed to measure either one-port or amplifier noise and having the potential to be an order of magnitude faster than our existing radiometers. Noise figure measurements require seven times the number of steps used to measure noise sources, so speed is important. A new noise figure calibration service for 8 to 12 GHz amplifiers with coaxial connectors will be established, and the WR-22 and WR-28 radiometers will be completed, providing continuous frequency coverage from 1 to 75 GHz. We will extend noise measurement capabilities to on-wafer devices. Presently NIST uses coaxial noise sources and adapts them using the measured efficiency of the on-wafer probes. In the long term, NIST must develop on-wafer noise standards. The standards with the most potential, but hardest to achieve, are pseudo random noise standards based on superconducting shift registers. NIST has better resources for this avenue than any other national laboratory; as funding permits, this is an area that could revolutionize on-wafer noise measurements.

FY 95 Plans

- Bring the prototype Noise Figure Radiometer into operation over the 8 to 12 GHz range, including WR-90 capability.
- Finish the WR-22 noise calibration system, evaluate and document performance.
- Complete development of initial on-wafer methods to make one-port noise measurements.
- Establish a Noise Figure measurement service for 8 to 12 GHz coaxial line.

- Complete fabrication of the WR-28 noise calibration system.

- Update coaxial noise standard to lower its uncertainty.

Related Developments

- The establishment of the Monolithic Microwave Integrated-Circuit (MMIC) Consortium and progress toward on-wafer standards and measurements has emphasized the need for accurate noise-figure measurements and active device metrology.

- A microwave manufacturer has indicated that cost is a significant consideration for NIST calibration services, and costs need to be reduced.

FY 94 Accomplishments and Impacts

- Calibrated 11 customer noise standards for an income of $65K.

- Completed front of new amplifier noise radiometer that is capable of 0.002 dB/day stability, 150 times more stable than existing NIST noise calibration systems. It allows for faster measurements because in existing systems one half the measurement time is spent in obtaining information to eliminate system gain drift.

- Organized and presented a one day noise measurements seminar at the International Microwave Conference in San Diego, California.

- Measured one-port noise of a diode on-wafer at 8 GHz using the prototype Noise Figure Radiometer. These measurements verified the mechanical design of the Noise Figure System.

Project: NOISE STANDARDS AND MEASUREMENTS

FISCAL YEARS	95	96	97	98	99
IMPROVEMENTS TO SPECIAL TEST/CALIBRATION SERVICES					
Automate the WR-28 waveguide radiometer. [STRS]	▬▬				
Automate the coaxial radiometer. [DoD]	▬▬	▬▬			
Develop network/server for data collection. [STRS]	▬▬	▬▬			
Implement real-time statistical control and on-line error analysis. [STRS]	▬▬	▬▬	▬▬	▬▬	▬▬⇒
IMPROVEMENTS TO STANDARDS					
Develop 2.4 mm coaxial primary standards for broadband calibrations to 50 GHz. [STRS]		▬▬	▬▬		
Develop on-wafer noise source/standard. Reduce MMIC noise errors and disseminate to industry. [STRS, DoD, OA]		▬▬	▬▬	▬▬	
Develop pseudo-random noise standard to support MMIC in reducing on-wafer noise errors. [STRS, DoD, OA]		▬▬	▬▬	▬▬	▬▬

Project: NOISE STANDARDS AND MEASUREMENTS (continued)

FISCAL YEARS	95	96	97	98	99
IMPROVEMENTS TO RADIOMETERS					
Improve temperature stability on coaxial radiometers to 0.001dB / 4 h. [STRS]					
Develop dual radiometer from 1 to 18 GHz. [DoD]					
NOISE FIGURE METROLOGY-DISCRETE DEVICES					
Characterize noise parameters of a two-port. [DoD]					
Develop noise figure measurement procedure. [DoD]					
Provide technical support to NVLAP. [NVLAP Fees]					
Provide special test services. [DoD]					⇒
NOISE FIGURE METROLOGY-INTEGRATED SERVICES					
Develop probe station/deembedding procedures. [STRS, DoD, OA]					

Project: NOISE STANDARDS AND MEASUREMENTS (concluded)

FISCAL YEARS	96	96	97	98	99
Develop noise figure measurement procedure from 1 to 18 GHz for 3.5 mm coaxial line. [DoD]					
Develop on-wafer transfer standards from 1 to 18 GHz. [OA, DoD]					
Provide special test services. [Fees]					⇒
INTERCOMPARISONS/ROUND ROBINS					
Participate in national and international measurement comparisons. [STRS]					⇒
NOISE DIODE STUDY					
Study effects of ambient temperature and diode current on output temperature. [STRS]					
NOISE METROLOGY SEMINAR/SHORT COURSE					
Give short course to U.S. industry. [STRS]					

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS

FY 95 Fund Sources: STRS, Measurement Services, Air Force

Staff (4.0 staff-years)

Professional	M. KANDA*	D. Camell*	R. Johnk*	K. Masterson
	D. Novotny			
Technician	H. Medley*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: U. S. industry needs to be able to evaluate and control electromagnetic interference (EMI) that can impact economics and competitiveness, national security, health and safety. Well-defined electromagnetic (EM) reference fields are necessary for special test measurements, antenna research and development (R&D), the evaluation of EM field probes, and EM interference (EMI) 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.

Technical Approach: Develop methods and techniques for establishing continuous wave (cw), pulsed, and nonsinusoidal electromagnetic reference fields to 100 GHz, for use by NIST for calibration services. Current emphasis is in the frequency range up to 40 GHz and at 60 GHz and 95 GHz. Perform research and development on probes and related systems to measure EM fields and power densities; current emphasis includes the development of millimeter- wave electric field sensors up to 110 GHz and photonic sensors up to 40 GHz.

FY 95 Plans

- Perform a broadband evaluation (200 MHz to 5 GHz) of the NIST anechoic chamber using time-domain measurement techniques.
- Develop test methods for EMI shielding effectiveness of commercially available optical fiber bulkhead connector systems for frequencies from 200 MHz to 40 GHz.
- Establish a standard-field calibration service in the NIST anechoic chamber for the 43.5-to 45.5-GHz band with an accuracy of ± 1 dB.
- Evaluate the performance of the NIST open-area test site using time-domain measurement techniques.
- Fabricate and calibrate a transfer standard rf dipole set with response up to 2 GHz. The dipoles will allow band-limited detection of amplitude and phase in order to reduce errors presently encountered due to out-of-band signals at the open-area test site.
- Extend analysis and testing of optically linked probes and antennas for frequencies up to 30 GHz by incorporation of newer modulator designs such as optically pumped, vertical-cavity, surface-emitting lasers (VCSELs).

Related Developments

- The Federal Communications Commission has announced a policy requiring antennas used in EMI emissions tests to be calibrated with traceability to NIST.

- DoD primary standards laboratories have decided to use the NIST 6-mm dipole probes as transfer standards.

- NIST has been assigned to be a Pilot Laboratory by the Bureau International des Poids et Mesures (BIPM) and has conducted the international intercomparisons of electric field strengths from 27 MHz to 40 GHz with Electrotechnical Laboratory, Communications Research Laboratory, Istituto Elettrotecnico Nazionale, Galileo Ferraris and Servizio di Fisica Sanitaria.

- Motohisa Kanda is serving as vice chairman of International Commission A (Electromagnetic Metrology) of International Union of Radio Science (URSI).

FY 94 Accomplishments and Impacts

- Completed an analysis of absorbers for anechoic chamber characterization for frequencies from 30 MHz to 500 MHz and wrote a paper, "A low-frequency model for radio-frequency absorber," for the IEEE Transactions on EMC. The analysis characterizes wall of absorbers as a flat plane of lossy dielectric whose effective properties are determined by a statistical fit to scattering data. The analysis is important in understanding the use of anechoic chambers as a substitute for open-area site testing.

- Obtained time-domain data to characterize the NIST anechoic chamber. Some interesting early-time and late-time effects have been analyzed to provide better understanding of chamber anomalies that affect standard field calibrations. Experimental results correlate well with previous NIST measurements of absorber reflectivity.

- Evaluated various EM shielding effectiveness measurement techniques for optical fiber components with members of a consortium working under an ATP grant. Experimental apparatus was designed and refurbishment of the nested reverberation chamber was begun.

- Designed, developed and evaluated reference standard dipoles for the International Special Committee on Radio Interference (CISPR). Three different configurations have been designed, constructed and evaluated. These standard dipoles utilize a ferrite balun, a hybrid coupler or a dual coaxial feed. The final results were presented to ANSI (American National Standard Institute) C63.

- Made open-area test site measurements on a NIST spherical dipole standard radiator and on a NIST monopole radiator. Collected data on the repeatability of both units, on the loading effects on the spherical dipole as a function of height above the ground screen, and the spectrum of the monopole. The loading of the spherical dipole due to the proximity of the ground screen was found to be small. A report detailing these results was delivered to the sponsor and submitted to the NIST Journal of Research.

- Performed drive-point capacitance calculations of the 2-cm resistively tapered dipole antenna. The dipoles are planar, consisting of resistive metal with triangular geometry deposited on a wafer $LiNbO_3$ approximately 1 mm thick. The calculated capacitance values are consistent with reported literature values and with NIST time-domain measurements.

- Completed the design of measurement techniques and instrumentation for the new 43.5 to 45.5 GHz standard field measurement service.

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS

FISCAL YEARS	95	96	97	98	99
STANDARD FIELD GENERATION					
MEASUREMENT SERVICES					
Open-air test site (dipole 25-100 MHz, monopole 30 kHz-300 MHz), TEM cell (≤ 100 MHz), standard magnetic field loop (≤ 40 MHz), anechoic chamber (200 MHz-18 GHz). [Fees]	———	———	———	———	——— ⇒
Conduct BIPM Intercomparisons of electric field strengths (27 MHz to 40 GHz). [STRS]	———	———	———	———	
ANECHOIC CHAMBER					
Improve measurement capability (± 1 dB uncertainty) in the range 18 to 26 GHz; 26 to 40 GHz. [STRS, DE]	———				
Develop measurement capability (± 1 dB uncertainty) at 40 to 75 GHz. [STRS, DE, CCG]	———	———			
REVERBERATING CHAMBER					
Develop automated system (± 1 dB uncertainty) for 18 to 40 GHz range. [STRS, DE]	———				
Extend range to 40 to 75 GHz (± 1 dB uncertainty). [DE, OA]		———	———		

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS (continued)

FISCAL YEARS	95	96	97	98	99
Study pulse characteristics of NIST chamber. [OA]					
Study the hybrid combination with TEM cell. [OA]					
Analyze electronic mode stirring. [STRS, OA]					
Analyze emission measurements. [STRS]					
NEAR-FIELD PHASED ARRAY					
Design, build and evaluate array for 250 MHz; 750 MHz; 1000 MHz. [OA]					
Develop a broadband array (at least one octave bandwidth). [OA]					
STANDARD TRANSMITTING AND RECEIVING ANTENNAS					
Develop CISPR standard dipoles. [STRS]					
Implement use of broadband, nonresonant, phase-linear antenna for field measurement. [OA]					
Refurbish open-air test site (ground screen cover and mesh). [STRS, DE]					

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS (continued)

FISCAL YEARS	95	96	97	98	99
Build new anechoic chamber (larger than the existing one) for frequencies from 30 MHz to 100 GHz. [STRS, DE]					
FIELD MEASUREMENT					
CW ELECTRIC FIELDS ANTENNA DEVELOPMENT					
Develop 100 kHz to 18 GHz; 18 to 26 GHz; 26 to 40 GHz antennas. [STRS]					
Develop 40 to 75 GHz and 75 to 110 GHz transmitting and receiving antennas for field generation and measurement. [STRS, OA]					
MAGNETIC FIELD ANTENNA DEVELOPMENT					
Develop loop antenna to measure B and $\dot{B}$ (100 MHz to 18 GHz). [OA]					
ANTENNA FOR SIMULTANEOUS E AND H MEASUREMENT					
Develop three-loop antenna system from 10 kHz to 100 MHz. [STRS]					
Develop one-loop system with electro-optic modulator from 100 MHz to 18 GHz. [STRS, OA]					

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS (concluded)

FISCAL YEARS	96	96	97	98	99
PULSED ANTENNA DEVELOPMENT					
Develop broadband resistively loaded TEM horns (time domain) to 10 GHz. [STRS, OA]	———	———	—		
Develop active antenna and optically linked antenna. [STRS, OA]	———	———	———	———	———
Develop special EM field monitors for frequencies from 10 MHz to 15 GHz with ± 1 dB uncertainty: environment, dosimeter, nonlinear and/or nonisotropic media. [STRS, OA]	———				
TIME-DOMAIN METHODS					
Evaluate NIST anechoic chamber from 200 MHz to 10 GHz. [STRS]	———	———			
Evaluate uncertainty of NIST open test site for emission measurements. [STRS]	———	———			

Project: EMISSION AND IMMUNITY METROLOGY

FY 95 Fund Sources: STRS, Air Force, Army, Navy, FAA

Staff (7.0 staff-years)

Professional	M. KANDA*	D. Camell*	K. Cavcey	D. Hill
	R. Johnk*	G. Koepke	J. Ladbury	A. Ondrejka
Technician	H. Medley*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: Electromagnetic interference (EMI) frequently impacts one or more of four important areas: economics and competitiveness, national security, health and safety. Industry and regulatory agencies have requirements for practical yet rigorous measurement techniques in order to characterize and correct EMI problems. Industry must meet electromagnetic compatibility (EMC) standards to sell products in the world market. Industrial clients are both manufacturers of electronic equipment and EMC/EMI test laboratories. NIST research, development, and measurement procedures satisfy the needs of the EMC/EMI community.

Technical Approach: Develop and evaluate reliable test methods for electromagnetic emission and immunity of electronic devices, components, and systems. Major challenges are to provide reliable and cost effective methods for a large frequency range (10 kHz to 40 GHz) and for large test volumes. Current emphasis also includes development of time-domain techniques for obtaining pulse and broadband test results.

FY 95 Plans

- Develop radiated emissions and immunity measurement techniques and compare measurements and theory for a microstrip transmission line, for frequencies from 200 MHz to 2 GHz and for arbitrary power densities.

- Survey and analyze current methods and fixtures for measuring the shielding effectiveness and transfer impedance of various EMI gaskets and bonding materials and, if necessary, design a new fixture or measurement technique which will minimize errors and repeatability.

- Evaluate alternative methods (Band-limited noise, time-domain, and stepped-continuous wave) of frequency stirring for immunity measurements in reverberation chambers for frequencies from 400 MHz to 40 GHz and for electromagnetic field strengths up to 200 V/m.

- Develop and evaluate emissions measurement techniques in reverberation chambers by using the spherical dipole radiator to correlate with emissions measurements taken in the anechoic chamber and at the open-area test site for frequencies from 30 MHz to 1 GHz.

- Conduct an EMI/EMC Metrology Workshop and use the industry input as a guide for setting priorities for the emission and immunity metrology project. The attendees will prioritize EMI research projects suggested by industry and NIST.

Related Developments

- The European Community (EC) 1992 EMC Directive requires the standardization of EMC measurements throughout EC nations.

- The Federal Aviation Administration (FAA) now requires all commercial aircraft to be tested at 200 V/m for EMI survivability.

- Reverberating chamber technique developed by NIST has been adopted in several military (MIL) and international (CISPR) standards as an improved means for EMI immunity testing.

- Group members have made contributions to the standards committees of several national and international, professional and industrial organizations, such as IEEE Antennas and Propagation Society and EMC Standards Committees, American National Standards Institute Standards Committees, and the American Society of Testing and Materials Committee.

- Motohisa Kanda is serving as Editor of the IEEE Transactions on Electromagnetic Compatibility.

FY 94 Accomplishments and Impacts

- Analyzed radiated emissions and radiated immunity of a microstrip transmission line and compared with reverberation chamber measurements.

- Analyzed shielding effectiveness, quality factor, and time constant data measured from 400 MHz to 1 GHz on three small airplanes and performed measurements on a commercial jet. The shielding effectiveness is typically about 15 dB, and the time constant is about 15 ns because of the low quality factor. The results are important for high intensity radiated field (HIRF) and carry-on electronics EMI problems. Published results in NISTIR 5023.

- Began radiated emission measurements in the NIST reverberation chamber from 400 MHz to 1 GHz. The project is intended to develop procedures for performing these tests and to provide a measure of the correlation between emission testing in reverberation and anechoic chambers and open-area test sites.

- Surveyed current methods and fixtures for measuring the shielding properties of EMI gaskets and developed a theoretical model for gasket characterization. Compared theoretical results for shielding effectiveness and transfer impedance with measured data from 10 MHz to 18 GHz. The goal is to reduce current 20 dB uncertainty by a factor of 10.

- Performed a minimum-phase analysis of Navy frequency-domain amplitude test data from 100 MHz to 2 GHz and obtained good results for the corresponding time-domain waveforms. The method provides a useful alternative to time-domain testing because it will allow frequency-domain test data to provide equivalent information.

- Completed the draft standard on testing cross-road photoradars that are used for automatic speed measurements by law enforcement agencies. This work is intended to result in a specification performance standard published by the National Institute of Justice (work carried out under the auspices of the EEEL Office of Law Enforcement Standards).

- Developed digital processing techniques for extraction and waveform analysis of weak signals in noise. These techniques have yielded encouraging results for signal-to-noise ratios on the order of one and will complement NIST time-domain antenna capability.

Project: EMISSION AND IMMUNITY METROLOGY

FISCAL YEARS	95	96	97	98	99
EMISSION AND IMMUNITY TESTING METHODOLOGY					
Develop electronic mode stirring for reverberating chamber. [STRS, OA]					
Improve electromagnetic interference (EMI) test methods on ground screen, 30 MHz to 1 GHz, ± 1 dB. [STRS, OA]					
Apply near-field phased array to immunity testing. [OA]					
Improve shielded room measurement methods by referencing measurements to well-characterized spherical dipole source. [OA]					
ANALYSIS OF EM FIELDS EFFECTS					
Develop time-domain techniques for resonance determination, 50 MHz to 5 GHz. [OA]					
Analyze EM effects of multiple sources in characterizing EMI environment by measurement and theory. [OA]					
Analyze effects and characteristics of electrostatic discharge. [Future programs to be determined.]					

Project: EMISSION AND IMMUNITY METROLOGY (continued)

FISCAL YEARS	95	96	97	98	99
EM FIELDS COUPLING					
Analyze shielding & reflectivity of materials for thin sheets and periodic geometries for 30 MHz to 10 GHz. [OA]					
Characterize and measure shielding effectiveness of gaskets from 50 MHz to 18 GHz. [STRS]					
Study penetration into systems: connectors; cables. [OA]					
Study penetration into systems: enclosures; devices. [OA]					
Complete theory and compare with integrated circuit/printed circuit board (IC/PCB) emission and immunity measurements from 200 MHz to 2 GHz. [ATP]					
Determine shielding effectiveness of optical components by developing a shielding effectiveness measurement fixture. [ATP]					
Determine correlation between radiated and conducted EMI. [OA]					
Determine mechanisms for radiated and conducted EMI based on current injection and radiated measurements. [OA]					
Develop sensors for radiated/conducted EMI. [OA]					

Project: EMISSION AND IMMUNITY METROLOGY (concluded)

FISCAL YEARS	95	96	97	98	99
EM ENVIRONMENTAL CHARACTERIZATION					
Develop techniques to characterize EM environments. [STRS, OA]					
Develop methodology for EM environment measurements. [STRS, OA]					
Develop standards for complex EM environments. [Future programs to be planned.]					

Project: ANTENNA MEASUREMENT THEORY AND APPLICATION

FY 95 Fund Sources: STRS, NASA, Air Force, Army, Navy

Staff (5.6 staff-years)

Professional	C. STUBENRAUCH*	M. H. Francis*	J. R. Guerrieri*	R. L. Lewis*
	K. MacReynolds*	L. A. Muth*	A. G. Repjar*	R. C. Wittmann*
Technician	S. Canales*	D. N. Dean*	D. T. Tamura*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Manufacturers of antennas and microwave systems incorporating antennas need practical, rapid and efficient methods for characterizing and demonstrating antenna performance. Operation at higher frequencies, the use of advanced phased arrays for steering single and multiple beams, the use of conformal structures in aircraft, and the use of active elements challenge existing methods. Civilian systems requiring advanced antennas include new generations of communications systems operating at higher frequencies and with greater spatial discrimination to address overcrowding of presently-used frequencies and (for satellites) synchronous orbit space. These systems include supporting 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. The personal communications market alone is estimated to be billions of dollars by the year 2000.

Technical Approach: NIST has shown that the near-field methods it invented for antenna characterization offer capabilities with respect to accuracy and spatial resolution (and freedom from the effects of weather) that are unmatched by other methods. However, developments are needed to address advanced antenna designs. In response, NIST will develop near-field theory, standards, and methodology to support characterization of advanced multi-element antennas operating at frequencies to 100 GHz, especially with respect to gain, pattern, and polarization. More specifically, NIST will develop cylindrical and spherical scanning methods for the range 26.6 to 40 GHz and planar methods for the range 40 to 100 GHz. Goals include: 1) achieving uncertainties less than ±0.2 dB in the determination of gain; 2) implementing probe position error techniques for millimeter wave measurements; 3) determining field uniformity assessment using spherical near-field techniques; and 4) developing and testing adaptive phased array diagnostic methods.

FY 95 Plans

- Investigate thermal imaging techniques for the measurement of antenna near-field amplitude and phase in the microwave frequency range. This technique shows promise both for rapidly collecting data for the planar near-field technique and for on-line diagnostic testing in an assembly line environment.

- Complete and evaluate measurements for the mirror-image/self-calibration technique for determination of gain. Include measurements using a polarization-sensitive reflector. Publish results.

- Report and publish the calibration results on the standard gain horns for the International Gain Comparison measurements.

- Complete the remainder of the certification process for the new NIST 2.5 m by 2.5 m planar scanner and receiver. Measure selected antennas obtained from other agencies or industry, specifically in the millimeter frequency range. Transfer scanner alignment technology and certification process to industry.

- Document the analysis of the spectral merge method for the alignment of phased-array antennas, and implement the method using an antenna measured on the planar near-field range.

Related Developments

- Rapid and accurate testing of large mobile phased-array antennas is required for communications and radar antennas. Correction techniques for probe-position errors on near-field scanners for this testing have been theoretically developed by NIST but need to be completely implemented and evaluated.

- At the Antenna Measurements Techniques Association symposium, NIST updated the industrial needs of two U. S. companies and consulted with others regarding problems in direct broadcast, global positioning, anticollision systems, and probe-position correction methods for near-field scanning.

- Andrew Repjar and Dennis Friday visited the MIT Lincoln Laboratory on March 9-10 to discuss collaborations on antennas and materials metrologies used in communications and electronic devices.

- The next generation of weather radars (NEXRAD), involving 200 large antennas, will require accurate gain and pattern measurements and traceability to NIST. The spherical near-field method with appropriate modifications needs to be developed for this purpose.

- Carl Stubenrauch consulted with the Jet Propulsion Laboratory (JPL). JPL plans to measure seven antennas on their cylindrical near-field range during the coming year. NASA will use these antennas to measure wind velocity from scattering measurements of the sea surface. Stubenrauch and Ronald Wittmann were also recognized by NASA Lewis Research Center for their contribution to the Advanced Communications Technology Satellite (ACTS) Project.

- Andrew Repjar is a member of the IEEE Administrative Committee of the Antennas and Propagation Society and serves on the antenna and radar cross section standards committee.

FY 94 Accomplishments and Impacts

- Completed evaluation of the new spherical/extrapolation range. It is a multi-purpose antenna range capable of fast and accurate measurements of antennas up to 3.5 meters in diameter in the frequency range from 1 to 75 GHz. This range is now in use for antennas/probes provided by industry.

- Completed spectral merge analysis and software to determine array excitation of phased-arrays by using planar near-field measurements from several steered beam positions. The method is used for beam alignments and element diagnostics.

- Completed second phase of certification process for the new 2.5 m by 2.5 m planar scanner for millimeter-wave antenna measurements. The NIST certification plan for this range, which can be applied to other ranges also, has been documented and is available to industry.

- Evaluated gain and polarization measurements on the international comparison antennas. These antennas were calibrated at 8-, 10-, and 12 GHz. This was the third NIST calibration of these antennas. Our calibration results and those from the other laboratories were presented at the IEEE Antennas and Propagation Symposium and will be included in a comprehensive report.

- Presented the NIST course on Antenna Parameter Measurement by Near-field Techniques to 21 participants from industry/other agencies and a measurements course to McClellan AFB personnel.

- Characterized the Sacramento Army Depot Planar Near-field Scanner before and after its move to its new site at McClellan AFB. The scanner is used primarily for Firefinder radar measurements.

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS

FISCAL YEARS	95	96	97	98	99
PLANAR NEAR-FIELD (PNF) MEASUREMENTS					
MEASUREMENT SYSTEM IMPROVEMENTS					
Update, document and streamline NF computer libraries. [STRS, OA]					
Improve on-line data processing on NF range. [STRS, OA]					
IMPROVED INSTRUMENTATION					
Improve receiver speed, accuracy and dynamic range. [STRS, OA]					
Obtain improved position control and accuracy. [STRS]					
THERMAL IMAGING DEVELOPMENT FOR MICROWAVE ANTENNA MEASUREMENTS					
Develop technology for accurate amplitude and phase measurements. [STRS]					
Construct a prototype system for rapid scanning using infrared camera. [STRS, OA]					
Evaluate system and compare measurement results to PNF results. [STRS, OA]					

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS (continued)

FISCAL YEARS	95	95	97	95	99
Transfer thermal imaging technology for microwave antenna measurements to industry. [OA]					⇒
PHOTONIC PROBE SENSOR DEVELOPMENT FOR ANTENNA SYSTEMS					
Acquire a prototype photonic probe; evaluate probe on PNF range; determine dynamic range and multiple reflection effects. [STRS, OA]					⇒
Construct a 1-dimensional array for rapid scanning; evaluate array in PNF/CNF measurement situations. [STRS, OA]					⇒
Transfer technology to in-situ measurement application. [STRS, OA]					⇒
Form consortium to participate in overall effort. [STRS, OA]					⇒
NON-PLANAR NEAR-FIELD MEASUREMENTS					
Refine measurement techniques and develop applications for outdoor in-situ measurements. [STRS, OA]					
Develop a permanent facility for non-planar measurements. [STRS]					

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS (continued)

FISCAL YEARS	95	95	97	95	99
Develop and implement analytical probe position correction method. [STRS, OA]					
NON-PLANAR ERROR ANALYSIS					
Derive upper-bound error expressions. [STRS]					
Verify expressions through simulation and tests. [STRS]					
Develop measurement tests to quantify actual errors. [STRS, OA]					
Perform analytical error correction. [STRS]					
TECHNOLOGY TRANSFER					
Document theoretical and measurement developments. [STRS, OA]					
Present near-field short courses and workshops to industries and other agencies: compile planar notes. [STRS, OA]					
Propose NIST scientist to participate in the IEEE/APS National Distinguished Lecturer Program. [STRS]					

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS (concluded)

FISCAL YEARS	95	96	97	98	99
COMPLEX ANTENNAS FOR EMERGING TECHNOLOGIES					
Develop phased-array alignment techniques. [OA]	▬				
Develop characterization methods for advanced millimeter- and submillimeter-wave antennas up to 1 THz (quasi-optics, holography). [STRS, OA]	▬	▬	▬	▬	▬
Study emerging antenna technologies (ongoing). [STRS, OA]	▬	▬	▬	▬	▬
Evaluate field-test measurement techniques. [OA]	▬	▬	▬		
Develop testing methods for direct broadcast, global positioning, and anticollision applications. [STRS, OA]	▬	▬	▬	▬	▬ ⇒

Project: METROLOGY FOR ANTENNA, RADAR CROSS SECTION AND SPACE SYSTEMS

FY 95 Fund Sources: STRS, JPL, Air Force, Army, Navy

Staff (3.0 staff-years)

Professional	A. G. REPJAR*	M. H. Francis*	J. R. Guerrieri*	R. L. Lewis*
	K. MacReynolds*	L. A. Muth*	C. Stubenrauch*	R. C. Wittmann*
Technician	S. Canales*	D. T. Tamura*		

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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 the 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 and other measurements for new toll/tag automobile radar/microwave systems will flourish during the next decade.

Technical Approach: 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. NIST will monitor commercial and civilian applications of microwave and radar technology and meet associated metrology needs as they can be identified and agreed upon by representative groups. Possible NIST responses will include test methods, artifact standards and calibration services. 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 error 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.

FY 95 Plans

- Measure gain of AFSCN Camp Parks 18-m antenna for elevations from 5 to 60 degrees, using Cassiopeia A (CAS A) and a calibrated noise source, to characterize gain changes vs. elevation angle. Compare with gains obtained using a gain comparison method, a 2-m antenna and a satellite beacon signal.

- Collaborate with Jet Propulsion Laboratory (JPL) in flux density measurements of extraterrestrial radio noise sources and gain calibrations of the 70-m Goldstone antenna and other antennas at Owens Valley Radio Observatory.

- Provide technical support to the government RCS Range Working Group to improve the quality and reliability of range measurements and standards. Develop measurement procedures and uncertainty analyses for establishing measurement accuracies.

- Evaluate G/T measurement procedures and results, using the sun and moon, for other agencies and industry.

Related Developments

- As a result of the JPL calibration and field measurements, all users of satellite receiving systems operating in the 33 GHz telemetry band for deep space applications will have accurately calibrated flux densities for Venus and will be able to measure gain and G/T of their systems.

- Radar cross section measurements are required for new toll/tag automobile radar systems being developed by industry.

- Improved measurement accuracies will allow enhanced design methods for the antenna and radar cross section community, and reduce retesting of antennas and models, lowering overall costs. Range improvements have been suggested for eight RCS ranges. This program is vitally important to the industry.

- Carl Stubenrauch and Ronald Wittmann were commended by the National Aeronautics and Space Administration (NASA) for their outstanding contribution in support of the Advanced Communications Technology Satellite (ACTS).

- Andrew Repjar, Lorant Muth and Ronald Wittmann serve on the IEEE Standards Committee which is updating antenna and RCS definitions for new technology.

- JPL has recently upgraded the 70-m antenna at Goldstone for determining the flux density of certain extraterrestrial radio sources. NIST will provide traceability to standards.

- NASA has an interest in calibration of an earth terminal to be used in the Advanced Communications Technology Satellite proof-of-concept system. Some of the techniques and measurements developed in the JPL effort will be directly applicable.

FY 94 Accomplishments and Impacts

- Determined the gain of the USAF 18-m antenna at Camp Parks using the 2-m standard gain antenna previously calibrated on the NIST planar near-field range. Results agree with ETMS (Earth Terminal Measurement System) measurements on the 18-m antenna using CAS A. The gain of the 60-foot antenna has also been obtained using the moon as a source. Error budgets for these three techniques have been constructed.

- Completed the development and documentation of the uncertainty analysis for radar cross section measurements. The documentation has been published as NISTIR 5019.

- Collaborated with JPL on the Deep Space Network Measurements. The flux densities of the radio sources, Venus and Jupiter, have been characterized at 32 GHz.

- NIST 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.

Project: METROLOGY FOR ANTENNA, RCS AND SPACE SYSTEMS

FISCAL YEARS	95	96	97	98	99
WIRELESS COMMUNICATION MEASUREMENTS					
Define toll/tag and anticollision radar system requirements. [STRS, OA]	▬	▬			
Evaluate existing metrology for system parameter measurements. [STRS, OA]	▬	▬	▬		
Develop new metrology and artifact standards. [STRS, OA]	▬	▬	▬	▬	▬
Transfer technology to industry and provide traceability to NIST. [STRS, OA]	▬	▬	▬	▬	▬ ⇒
EARTH TERMINAL MEASUREMENTS					
Conduct gain measurements for large antennas using radio sources and noise standards. [OA]	▬	▬			
Conduct gain measurements for large antennas using satellite signals and transfer standards. [OA]	▬				
Evaluate system temperature measurements. [OA]	▬	▬			
Update error budgets for gain measurements. [OA]	▬				

Project: METROLOGY FOR ANTENNA, RCS AND SPACE SYSTEMS (continued)

FISCAL YEARS	95	95	97	95	99
SATELLITE MEASUREMENTS					
Provide calibrations for satellite effective isotropic radiated power; update hardware and software for higher frequencies; further evaluate bit error rate methods for determining antenna parameters. [OA]	———	———	———		
STANDARD SOURCE MEASUREMENTS					
Perform certification for standard emitters (radio stars, satellite signals). [STRS, OA]	———	———	———	———	
CALIBRATION SERVICES FOR LARGE ANTENNAS					
Develop antenna pattern measurement capability. [OA]	———	———	———	———	⇒
Improve holographic methods for antenna diagnostics; provide a comprehensive measurement service. [STRS, OA]		———	———	———	⇒

Project: METROLOGY FOR ANTENNA, RCS AND SPACE SYSTEMS (concluded)

FISCAL YEARS	95	96	97	98	99
RADAR CROSS SECTION MEASUREMENTS					
Visit RCS ranges and develop plan of error analysis for different ranges. [OA]	▬				
Analyze measurement processes. [OA]	▬▬	▬			
Evaluate artifact standards. [OA]	▬	▬▬	▬		
Establish range verification process and provide traceability to NIST. [OA]	▬	▬	▬	▬	▬⇒

Project: SPECIAL TEST MEASUREMENTS AND CALIBRATIONS

FY 95 Fund Sources: STRS, OA, Fees

Staff (4.0 staff-years)

Professional	K. MacREYNOLDS*	M. H. Francis*	J. R. Guerrieri*	R. L. Lewis*
	A. G. Repjar*	C. Stubenrauch*		
Technician	S. Canales*	D. N. Dean*	D. T. Tamura*	

name in capital letters = project leader; * = person works on project part time

Need Addressed: Calibrations and special test measurements provide critical measurement services to industry and government laboratories. When measurements are based on NIST standards, the quality of the entire national measurement network is upgraded. Accurate standards ultimately reduce the cost and improve the performance of communication, radar, and other microwave systems.

Technical Approach: NIST will calibrate antennas and near-field probes for use as transfer standards, enabling other organizations to do their own measurements. NIST will perform special test measurements and performance evaluations when the highest accuracy and NIST facilities and expertise are required. As required, new measurement theory and methodology will be evaluated. Program focus is on mm-wave calibrations, circularly polarized antennas, on-line data processing, and improved probe calibration facilities.

FY 95 Plans

- Calibrate four probes for a U.S. company for INTELSAT communications satellite antenna traceability.
- Perform special tests and custom measurements on antennas and probes for industry and government using the near-field, extrapolation, and spherical probe ranges.
- Calibrate two probes for a U.S. company. The probes will be used as standards on their near-field facilities.
- Calibrate two sets of probes for McClellan AFB, and calibrate the transfer standard antenna to be used in testing their radar system.

Related Developments

- All of the near-field facilities at 18 U.S. companies and government agencies have been established with NIST assistance. NIST offers the only probe calibration service available in support of these facilities. With new facilities being planned and constructed, this demand is likely to increase.
- Two U. S. companies have visited Boulder to discuss possible NIST participation and measurement support in the development of a 94 GHz automated radar landing system for commercial aircraft. This system will allow landing during zero visibility conditions and will save the four largest carriers nearly $1B per year. NIST measurement services need to be developed at 75-100 GHz.
- NIST is planning with industry to measure antenna standards for a commercial world-wide satellite communication system. Such measurements are evidence of the need and impact of NIST services. In the last three years, NIST has provided special high accuracy measurements for over 30 antennas and probes for industry and government using the near-field, the extrapolation and the spherical probe ranges.

- Andrew Repjar, Lorant Muth, and Ronald Wittmann are members of the IEEE Antenna Standards Committee and the Antenna Measurement Committee.

- Carl Stubenrauch is Associate Editor of the IEEE Antennas and Propagation Society.

- Michael Francis is editor of the Antenna Measurement Techniques Association (AMTA) Newsletter.

- The cutback in a military satellite program (MILSTAR) will affect the rate at which the demand for calibrations in the mm-wave bands increases, but the demand will continue.

- New near-field facilities are being constructed by a number of laboratories and others are being planned. NIST calibration services will be required for probes used on these ranges.

- Industry queries regarding NIST certification of antenna and radar cross section measurement facilities have continued to increase during FY 94.

FY 94 Accomplishments and Impacts

- Completed calibration of four wideband horns for industry. These horns will serve as standards for measurements on INTELSAT antennas.

- Completed measurements for two standard gain horns and one open-ended waveguide probe for private industry. The probe will be used on their near-field facility.

- Completed calibrations on two open-ended waveguide probes for McClellan AFB to be used as standards for a planar near-field range used to measure large phased array radars.

- Completed evaluation of methods for measuring electrically large antennas at 90 to 100 GHz. The methods include spherical near-field, planar near-field, quasi far-field and compact range.

- Presented results on gain and polarization measurements on the international comparison antennas. These antennas were calibrated at 8-, 10-, and 12 GHz. This was the third NIST calibration of these antennas. Our calibration results and those from the other laboratories involved in the international comparison will be included in a comprehensive report.

- Measured antenna patterns of the National Oceanic and Atmospheric Administration (NOAA) radiometer at two frequencies, 24- and 32 GHz. Antenna is used to measure atmospheric attenuation due to water vapor and water droplets. This antenna is also being used on an experimental basis to determine sea state parameters.

- Completed highly accurate gain, polarization and pattern measurements for the 60 to 75 GHz dual-port circularly-polarized probes. These will serve as NIST standards for commercial and military antenna systems.

Project: SPECIAL TESTS, MEASUREMENTS AND CALIBRATIONS

FISCAL YEARS	95	96	97	98	99
EXTRAPOLATION RANGE MEASUREMENTS					
Improve real-time data analysis. [STRS]					
Evaluate extrapolation data-fitting techniques. [STRS]					
Obtain and calibrate circularly polarized check standards. [STRS, OA]					
Develop self-calibration/reflection technique. [STRS]					
Evaluate swept-frequency polarization techniques. [STRS]					
Complete international intercomparison of gain standards. [STRS]					
NEAR-FIELD MEASUREMENTS					
Implement multi-frequency/multi-beam measurements. [STRS, OA]					
Develop systems and techniques for millimeter-wave measurements. [STRS, OA]					
Develop fault analysis techniques for arrays. [OA]					

Project: SPECIAL TESTS, MEASUREMENTS AND CALIBRATIONS (concluded)

FISCAL YEARS	95	96	97	98	99
Develop minimum scattering probes. [STRS, OA]	▬▬▬	▬▬▬	▬▬▬	▬▬▬	▬▬▬⇒
SPHERICAL RANGE					
Develop a permanent facility for probe calibrations. [STRS]	▬▬				
Develop methods for range evaluation, using spherical measurements. [STRS]	▬▬▬	▬▬▬	▬▬▬		

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS

FY 95 Fund Sources: STRS, Air Force, BMD, CCG, Fees

Staff (7.0 staff-years)

Professional	C. M. WEIL	J. R. Baker-Jarvis	R. G. Geyer	M. Janezic
	C. A. Jones	B. F. Riddle	H. E. Bussey‡	Y. Kantor‡
Technician	J. H. Grosvenor			

name in capital letters = project leader; ‡ = guest researcher

Need Addressed: 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. Industry needs accurate characterization data and improved measurement methods, covering a wide spectral range as well as temperature range, for both existing and new materials in order to improve automated design processes and to ensure optimized performance at greatly reduced cost. For example, material measurement uncertainties of 1% for antenna designs are often required.

Technical Approach: NIST will implement, evaluate, and disseminate measurement methods to determine the complex permittivity and permeability of dielectric and magnetic materials over the rf/microwave spectral range 100 kHz to 100 GHz. During this process, NIST will: 1) identify and characterize reference materials; 2) provide standards and measurement services to industry; and 3) implement round robin intercomparisons with industry.

FY 95 Plans

- Complete the development of new algorithms and software for broadband frequency, transmission/reflection (T/R) material measurements with emphasis on high-permittivity ($\varepsilon > 50$) materials. Provide such software to industry.

- Develop sapphire rod resonator metrology to measure microwave characteristics of high temperature superconducting (HTS) films.

- Continue to select and characterize candidate magnetic reference materials. Perform round robin measurements with industry and other agencies, and complete NIST Internal Reports on this work.

- Develop the stripline resonator technique for high-precision measurements of dielectric and magnetic reference materials in the frequency range 150 to 2000 MHz, and complete the round robin intercomparison on stripline resonator measurements.

- Develop metrology to study ferrite material properties under dc-biased conditions, at various temperatures and for different power levels.

- Complete publication of the round robin intercomparison results on 7-mm coaxial-line measurements of nonmagnetic materials. Prepare publication on the similar intercomparison of magnetic materials, which is in progress.

- Continue the development of improved theory, software and calibration methods for material measurements using the open-ended coaxial probe, with emphasis on the "inverse" problem.

Related Developments

- NIST has been asked by industry to develop a capability to characterize the microwave performance of high temperature superconductor (HTS) films. The use of such materials in microwave components and circuits, including cellular phones, is a most promising application for ceramic superconductors.
- The National Center for Manufacturing Services (NCMS) Consortium is obtaining technical assistance from NIST on measuring the permittivity characteristics of their printed wiring boards.
- NIST has completed a collaborative study with a U.S. company on characterizing new absorbing composite materials using measurements and mixing rule theory. As a result, the company will save tens of millions of dollars in costs for integrated filter harnesses.
- NIST has been asked by the Air Force and industry to develop methods to measure the microwave properties of magnetic materials. These materials, used in next generation phased array antennas, need to be accurately characterized to achieve antenna performance and reduce development costs.
- A major U.S. company recognized the NIST materials team for their collaborative effort in the company's key programs involving dielectric measurements of liquids.
- Two foreign guest workers are collaborating in the Electromagnetic Properties of Materials (EPM) project work: Dr. Jerzy Krupka from Poland and Yehuda Kantor from Israel. Dr. Krupka visited NIST as part of a joint U.S. - Polish Sklodowska-Curie Foundation award.

FY 94 Accomplishments and Impacts

- Revised EPS_MU_3, the NIST software for material characterization, using transmission line techniques. This version is used by nine industrial companies, three DoD agencies and three academic laboratories.
- Completed material measurements in the frequency range 0.8 to 10 GHz for a major supplier of ceramics and ferrites.
- Completed the cryogenic-vacuum system used to hold the microwave dielectric rod resonator for measuring surface resistance of HTS films. The system operates at temperatures from 20 to 150K.
- NIST organized a round-robin intercomparison involving stripline resonator measurements from 150 MHz to 2 GHz with seven laboratories. Two dielectric and two magnetic material samples have been distributed.
- The round robin conducted using the 7-mm coaxial T/R method for nonmagnetic materials yielded results that demonstrate the need for accurate measurement techniques traceable to NIST.
- Developed software for 2-port method using 77-mm air-filled adapters for measuring thin films.
- Completed full-field models and software for coaxial open-ended probe measurements, accounting for probe lift-off and finite layer thickness. The measurements can be used for the non-destructive testing of materials between 10 MHz and 18 GHz.
- Completed report on measurements for a CRADA project with two U.S. companies to characterize absorbing materials for use in feed-through filters and to confirm mixing rule predictions.
- Received and installed electromagnet for metrology project to determine ferrite material properties.

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS

FISCAL YEARS	95	96	97	98	99
METROLOGY FOR COMPLEX PERMITTIVITY AND/OR PERMEABILITY OF BULK SOLID MATERIALS, VERY LOW TO HIGH LOSS					
Develop transmission line methods, 100 kHz to 18GHz. [OA]	▬	▬			
Optimize algorithms. [OA]	▬				
Develop high precision cavity methods for low-loss dielectric materials, 8 to 11 GHz. [STRS]	▬				
Develop special test/calibration services. [Fees]	▬	▬	▬	▬	▬
Develop metrology methods for inhomogeneous/anisotropic materials. [OA]		▬	▬	▬	▬
IMPLEMENT AND EVALUATE MEASUREMENT METHODS:					
Stripline resonator, 150 to 3000 MHz; Loaded waveguide, 450 to 750 MHz. [OA]	▬	▬			
Open-ended coaxial line, 3.5 mm. [STRS, OA]	▬	▬	▬	▬	▬
Large diameter (80 mm) coaxial line. [STRS]	▬	▬	▬		

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS (continued)

FISCAL YEARS	95	96	97	98	99
Develop non-destructive measurement methods for printed circuit boards and substrates. [STRS, OA]					
MICROWAVE CHARACTERIZATION OF HIGH-TEMPERATURE SUPERCONDUCTOR (HTS) FILMS AND SUBSTRATES					
Implement and evaluate cavity measurement methods. [STRS, OA]					
Implement and evaluate high-precision measurement method for HTS films and very low-loss substrates. [STRS]					
MICROWAVE CHARACTERIZATION OF DC-BIASED MAGNETIC MATERIALS					
Design measurement system for ferrite materials. [STRS, OA]					
Procure electromagnet and related components and construct system. [STRS]					
Evaluate method and reference materials. [STRS, OA]					
RESEARCH AND REFERENCE MATERIALS					
Establish nonmagnetic, low loss reference standards. [OA]					

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS (concluded)

FISCAL YEARS	95	96	97	98	99
Establish nonmagnetic, medium to high loss reference standards. [STRS, OA]					
Establish magnetic, medium to high loss reference standards. [OA]					
Establish thin film magnetic reference standards. [OA]					
REMOTE SENSING OF MATERIAL PHYSICAL PROPERTIES					
Develop moisture and density sensing methods. [OA]					
Develop methods for detection of microcracks and defects in polymers and composites. [STRS, OA]					
ROUND ROBIN INTERCOMPARISON ORGANIZATION					
Implement national intercomparison on coaxial transmission line measurements of low-loss nonmagnetic materials. [OA]					
Implement similar intercomparison of magnetic materials. [OA]					
Implement national intercomparison of both dielectric and magnetic materials using the stripline resonator. [OA]					

ELECTROMAGNETIC TECHNOLOGY DIVISION

Project: HIGH-PERFORMANCE SENSORS, INFRARED DETECTORS, AND MIXERS

FY 95 Fund Sources: STRS, NASA, Stanford University

Staff (5.2 staff-years)

Professional	M. CROMAR	E. Grossman	T. Harvey	J. Koch
	M. MacDonald* (CU)	C. Reintsema		
Technician	M. Crews*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: Users and manufacturers of infrared detectors require characterization and calibration of detector performance. The Physics Laboratory's Radiometric Physics Division requires an improved Absolute Cryogenic Radiometer (ACR) for blackbody and band-limited infrared radiation that provides higher accuracy and sensitivity than is available with the present commercial detector. New high-performance thin-film multi-junction thermal converters are expected to provide commercially available ac measurement capability comparable to that at NIST. NIST standards with uncertainties at the 0.1 ppm level will be required to support U.S. industry's improved capability. The Stanford University Gravity Probe-B program is a NASA supported test of predicted General Relativistic effects on an orbiting gyroscope. The readout for the position of the gyroscope requires specialized SQUIDs (Superconducting QUantum Interference Devices) with very low noise at very low frequencies and with other characteristics specific to this mission. Such SQUIDs are not available commercially at present. The NIST SQUID development is closely tied to the needs of the radiometer and the AC/DC thermal converter which both use SQUIDs as current sensors. Detection and measurement in the terahertz frequency range have been emerging as an important technology for remote atmospheric sensing, radar, materials characterization, and biology. Metrology to support U.S. industry in this area must be developed.

Technical Approach: The physical foundation of this NIST work is the low noise and high sensitivity of superconducting devices. A superconducting inductor or transition-edge detector coupled to a SQUID provides the most sensitive thermometer for power measurements. The temperature dependence of inductance can provide a power measurement sensitivity of a few parts in 10^9 for the Infrared Primary Standard when thermal stability problems are solved. Using either a transition-edge detector or a kinetic- inductance detector is expected to improve the sensitivity of the AC/DC thermal conversion measurements by a factor of between 10 and 100 over room temperature detectors. SQUIDs tailored for the specific requirements of the AC/DC thermal converter and the Gravity Probe-B project are fabricated using high- quality Josephson junctions and flexible design provided by the NIST superconducting integrated circuit fabrication facility.

FY 95 Plans

- Fabricate kinetic-inductance differential-thermometer integrated circuits for the ACR radiometer. Design and fabricate new chip mounting and contacting apparatus.
- Install a new differential thermometer in the radiometer cryostat and verify proper operation of the differential thermometer circuit.
- Measure the noise of the differential thermometer coupled to the absorber cone and the thermal platform. Identify and address any sources of excessive noise or drift.
- Increase the thermal time constant of the thermometer platform and measure the noise performance. The goal is an NEP of 10^{-11} $W \cdot Hz^{-½}$.

- Fabricate and test SQUIDs for the Gravity Probe-B project with switched input coils and equivalent input noise less than 1 $\mu\Phi_0 \cdot Hz^{-1/2}$ at 1 Hz.

- Determine the best detector (transition-edge, kinetic-inductance) for the AC/DC thermal converter and complete the system design.

- Fabricate and test a suitable detector for AC/DC thermal converter.

Related Developments

- Professor Cabrera's group at Stanford University has demonstrated a very sensitive heat detector based on a superconducting transition edge detector with a SQUID array readout. A similar approach will be considered for the AC/DC thermal converter.

FY 94 Accomplishments and Impacts

- Theoretically analyzed effects of partial coherence on room temperature Fourier Transform IR (FTIR) transmittance measurements of Si wafers and high temperature superconductor (HTS) substrates. Performed error analysis on the procedure used to extract far-infrared optical constants from such measurements. Built and tested an apparatus for performing FTIR transmittance measurements at 77 K.

- Fabricated and tested several antenna-coupled THz mixers based on YBCO step-edge junctions. Established an experimental system for measurement of microwave noise in HTS junctions, and measured microwave noise as a function of bias and temperature. For the lowest-noise device, a maximum available noise temperature was measured to be 32 ± 2 K at a physical temperature of 4.3 K. The peak noise temperature is within 1 dB agreement with published simulations of the ideal resistively-shunted junction model. The results imply that such junctions are capable of noise performance in millimeter-wave and terahertz detection and mixing applications that approach fundamental quantum mechanical limits.

- Confirmed a new model for kinetic-inductance fixed-point thermometers with inductance calculations. Made the first devices with this design, using a combination of the superconductors Nb and Nb-Ta, and succeeded in making a bridge that would produce a null. However, the behavior of this thermometer is different from the all-Nb devices made previously in that the noise is now strongly current-dependent.

- Developed and analyzed an alternative design for a temperature control system for the ACR radiometers, to increase the thermal time constant of the platform so that its dynamics occur on a time scale substantially longer than the dynamics of the radiometer detector. Fabricated a new set of radiometer chips and analyzed the thermal budget.

- Recovered the process for fabricating 300-K Nb microbolometers with high responsivity and low noise, and delivered devices to the Idaho National Engineering Laboratory. Measured the optical coupling efficiency at 740 μm and 10 μm from a 404-GHz laser into a log-periodic antenna.

Project: HIGH-PERFORMANCE SENSORS, INFRARED DETECTORS, AND MIXERS

FISCAL YEARS	95	96	97	98	99
Measure performance of infrared standard radiometer with new chips and increased thermal time constant. [STRS]	▬				
Improve performance of infrared standard radiometer, if necessary. [STRS]	▬	▬			
Design and fabricate first version of cryogenic AC/DC thermal converter. [STRS]	▬	▬			
Provide prototype cryogenic AC/DC thermal converter. [STRS]	▬	▬	▬	▬	
Fabricate, test, and deliver SQUIDs for the Stanford Gravity Probe-B program. [Stanford]	▬	▬	▬		
Develop antenna-coupled ambient temperature detectors. [STRS]	▬	▬			
Design and characterize infrared heterodyne receiver. [NASA]	▬	▬	▬	▬	

Project: HIGH-T_c ELECTRONICS

FY 95 Fund Sources: STRS, ARPA

Staff (6.0 staff-years)

Professional	D. RUDMAN	J. Beall*	R. Ono	L. Vale
	T. Harvey	D. deGroot	G. Kunkel (GR)	T. Kaplan* (CU)
Technician	M. Crews*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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 SQUIDs (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.

Technical Approach: The project develops fabrication and testing capabilities, and theoretical competence, for HTS devices in the areas of microwave and terahertz metrology and technology, infrared bolometry, and Josephson junctions. Each of these areas has both internal (NIST) and industrial customers. The project will work with the HTS communication industry to measure and improve the power handling capabilities of HTS devices, and with the Electromagnetic Fields Division to improve microwave measurement and characterization techniques for HTS films and devices. Work will be done with industry and with the Physics Laboratory's Radiometric Physics Division to develop and test HTS bolometers for calibrated radiometers; and to evaluate and improve HTS Josephson junctions for use in voltage standards, terahertz detectors (partially with the Physics Laboratory's Time and Frequency Division), and other devices to meet the measurement and application needs of industry.

FY 95 Plans

- Develop microwave testing and measurement techniques for HTS films and devices, including power dependence, in collaboration with industry and the Electromagnetic Fields Division.
- Continue to improve superconductor-normal-superconductor (SNS) step-edge Josephson junctions, and evaluate (through collaborations) other HTS Josephson technologies.
- Evaluate the potential of HTS Josephson junctions for voltage standards.
- Characterize HTS Josephson junctions for terahertz applications (partially in collaboration with the Time and Frequency Division).
- Develop HTS bolometers on micromachined Si substrates for metrological applications at infrared wavelengths (in collaboration with industry and the Radiometric Physics Division).

Related Developments

- Several U.S. companies have entered the HTS arena, anticipating rapid commercialization of a variety of HTS products from SQUIDs to current limiters to filters in cellular telephony. HTS magnets operating at 2 T and cooled with cryocoolers have been produced.

FY 94 Accomplishments and Impacts

- Fabricated the first HTS antenna-coupled microbolometers that use thermally-isolated epitaxial yttria-stabilized zirconia (YSZ) membranes on Si substrates. Measured the optical performance of the complete detector and found an optical noise equivalent power nearly a factor of two lower than the previous record for a liquid-nitrogen-cooled thermal detector, and a response time several orders of magnitude faster.

- With co-workers from the Physics Laboratory's Time and Frequency Division, measured heterodyne mixing products from YBCO step-edge junctions at 30 THz, and observed substantial conversion efficiency up to difference frequencies of 7 GHz.

- Measured stacked trilayer HTS junctions, in collaboration with the Josephson Array Development project, and found excellent critical current uniformity. These junctions may be appropriate for HTS voltage standards.

- Developed techniques and thin-film calibration standards, in collaboration with the Electromagnetic Fields Division, to perform calibrated on-chip measurements of HTS passive microwave devices.

- Demonstrated large (greater than 1 mA) Shapiro steps at 38 K and 62 GHz in HTS SNS junctions. These steps are sufficient for use in programmable voltage circuits, but require capability to fabricate large numbers of junctions with similar characteristics.

- Demonstrated that the critical-current (I_c) versus junction-length in SNS junctions fabricated at NIST matches conventional theory of the proximity effect. This allows tuning of the I_c to match the requirements of different applications.

Project: HIGH-Tc ELECTRONICS

FISCAL YEARS	95	96	97	98	99
Improve laser ablation growth of HTS and dielectric films, including multilayers. [STRS]					
Develop microwave measurement techniques for HTS films and devices. [STRS]					
Characterize THz response of HTS Josephson junctions. [STRS]					
Evaluate HTS Josephson junctions for voltage standards. [STRS]					
Develop HTS bolometers. [STRS]					
Develop practical HTS circuits and devices for use in electronics. [STRS]					⇒

Project: JOSEPHSON ARRAY DEVELOPMENT

FY 95 Fund Sources: STRS, CCG, Sandia National Laboratory

Staff (6.2 staff-years)

Professional	C. HAMILTON	S. Benz	C. Burroughs	P. Booi
	B. Larsen	T. Harvey*	R. Kautz*	
Technician	M. Crews*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: Manufacturers of 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 A/D- and D/A converters, require the development of new and improved intrinsic standards for the measurement of ac and dc voltage. Target customers are electronic instrument makers, DoD contractors, and national and military standards laboratories (Sandia National Laboratory, Army, Navy, Air Force). Superior electrical metrology has and will continue to enhance the competitive position of the U.S. electronics industry.

Technical Approach: NIST has pioneered the development of practical Josephson voltage standards and, by encouraging the commercialization of these standards, has allowed U.S. industry to dominate the world market for Josephson voltage systems and components. Further work is needed to make these systems faster, easier to use, and more reliable. NIST will continue to improve the hardware and methodology to support the characterization of advanced precision electronic components and instrumentation. More specifically NIST will develop a new generation of programmable voltage standards that can move rapidly to any specified output voltage. Ultimately the new standards should be fast enough to synthesize ac waveforms. Objectives include: 1) demonstration of a programmable voltage standard with an output range of ±1 V and a settling time of 1 microsecond; 2) development of hardware and software to use the programmable voltage standard for the evaluation of components such as A/D- and D/A converters; and 3) exploration of methods for implementing a Josephson voltage standard at an operating temperature above 40 K; and (4) reduction of the size and weight of existing Josephson voltage systems.

FY 95 Plans

- Identify and correct sources of defects in programmable volt chip.
- Confirm accuracy of programmable volt design.
- Develop improved fabrication processes for submicrometer Josephson circuits, superconductor-normal-superconductor (SNS) junctions and high-T_c junctions as required for voltage standard and other metrological applications.
- Design and fabricate prototype integrated Josephson voltage standard electronics system.
- Perform a theoretical study of the limits on step amplitudes in SNS junctions as a precursor to the design of a 10-V programmable voltage standard.

Related Developments

- Commercialization of Josephson voltage standard chips will eliminate the need to fabricate and test standard chips at NIST for commercial applications.

- Intensive efforts continue in Germany, Japan, and Korea to duplicate NIST's success with 10-V Josephson voltage standards.

FY 94 Accomplishments and Impacts

- Designed, fabricated and tested a programmable voltage standard with 20+ bit accuracy, 9-bit resolution, and a range of ±77 mV. Submitted an application for patent.

- Tested stacked trilayer high-temperature superconductor junctions acquired through a collaboration with industry and found excellent critical-current uniformity. Both the stacked trilayer junctions and the NIST step-edge junctions have potential application to future programmable voltage standards.

- Fabricated the first all-niobium 10-V Josephson voltage standard chips and achieved a 75% yield. The new chips appear to successfully address a long-term problem of flux trapping.

- Continued to supply assistance as needed to the approximately 40 users of NIST Josephson voltage standard chips. Several letters of appreciation have been received; acknowledgements of NIST contributions appeared in four papers presented at CPEM.

- Transferred the technology for manufacturing Josephson voltage chips from NIST to a U.S. company, which now advertises 1-V and 10-V chips as well as complete voltage standard systems; the company's sales of its chips to date are approximately $100K. Sales of NIST-developed Josephson voltage standard components at three other companies continues at the rate of about $500K per year.

Project: JOSEPHSON ARRAY DEVELOPMENT

FISCAL YEARS	95	96	97	98	99
Demonstrate a fully functional 1-V programmable voltage standard. [STRS, CCG]	———	———			
Complete a theoretical design for a programmable voltage standard based on self-shunted SNS junctions. [STRS]	———				
Develop a process for fabricating submicrometer self-shunted Josephson junctions. [STRS, CCG]	———	———	———		
Fabricate a 10-V programmable Josephson voltage standard using small area SNS junctions. [STRS]			———	———	———
Explore various high-T_c junction technologies with potential for voltage standard application. [STRS, CCG]	———	———	———	———	———
Develop a compact, portable version of the current voltage standard system. [Sandia]	———				
Support Josephson voltage standard users as required. [STRS]	———	———	———	———	⇒

Project: NANOSCALE CRYOELECTRONICS

FY 95 Fund Sources: STRS, NASA, ONR

Staff (2.6 staff-years)

Professional	R. KAUTZ*	J. Martinis	M. Keller	T. Harvey*
Technician	M. Crews*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: The U.S. has established and must maintain its position at the forefront of electronic metrology. Ultra-small electronic devices operated at cryogenic temperatures offer unique capabilities that impact both fundamental metrology and industrial instrumentation. For metrology, nanoscale cryoelectronics offers a device for counting electrons that will provide a fundamental standard for capacitance and allow an essentially new determination of the fine structure constant. Another cryogenic device meets the need for an X-ray detector with improved energy resolution required for precise X-ray microanalysis. While the manufacture of microanalysis equipment is a relatively small industry ($100M per year), it provides essential support to the semiconductor and other high-technology industries, which would benefit greatly from improved microanalysis.

Technical Approach: The development of a quantum capacitance standard and a new measurement of the fine structure constant depend on the development of a device, called an electron pump, that accurately counts electrons. The electron pump is based on the Coulomb blockade effect in ultra-small (~100 nm) tunnel junctions operated at ultra-low temperature (~0.05 K). Fabricated by electron-beam lithography and operated in a dilution refrigerator, such devices can be used to pump electrons onto a capacitor one by one, at a rate determined by an external clock. This device will become metrologically important when electrons are counted with an error rate less than about 1 part in 10^9. An X-ray detector suitable for X-ray microanalysis with an energy resolution of a few electron volts can be made by using a normal-insulator-superconductor (NIS) tunnel junction and SQUID (Superconducting QUantum Interference Device) preamplifier to sense the X-ray-induced temperature rise of electrons in a normal metal film held at about 0.1 K. The goal of this work is a detector with an energy resolution of 20 eV at 6 keV, a response time of 10 μs, and an active area of 1 mm^2.

FY 95 Plans

- Fabricate and test an improved electron pump with seven tunnel junctions to verify a predicted counting accuracy of 1 part in 10^9.
- Fabricate and test a variety of NIS X-ray detectors to verify theoretical models of X-ray thermalization and heat diffusion that determine the scaling behavior.
- Design and begin fabrication of a portable dewar with an X-ray window and an adiabatic demagnetization refrigerator suitable for initial tests of NIS X-ray detectors in practical materials analysis systems.
- Develop room-temperature electronics for the SQUID preamplifier to be used with NIS X-ray detector.

Related Developments

- The project collaborates with the Electricity Division in developing a capacitance standard which makes use of single-electron counting.

- A U.S. company plans to market SQUID magnetometers having high output voltage and high bandwidth, and requested NIST help in the design. The commercial potential of SQUID magnetometry has recently attracted the interest of several companies.

- The field of single-electronics has attracted worldwide interest for its scientific and potential technological interest.

FY 94 Accomplishments and Impacts

- Finalized design of a seven-junction electron pump, and designed and fabricated instrumentation for controlling this electron pump, as part of long-range program to establish a fundamental standard for capacitance and a new measurement of the fine-structure constant. Demonstrated an error rate of 1 part in 10^6.

- Performed an experiment in which electron cooling was observed with an NIS junction, demonstrating the sensitivity of this type of detector.

- Verified 8-eV resolution of an NIS detector in measurement of thermal pulses applied to a normal metal. Achieved 17-eV resolution in measurement of 6-keV X-rays from an Fe^{55} source with an NIS detector.

- Developed and transferred high-output, high-bandwidth SQUID technology to a U.S. company, responding to that company's interest in marketing such a device.

Project: NANOSCALE CRYOELECTRONICS

FISCAL YEARS	95	96	97	98	99
Develop electron pump with a counting accuracy of 0.001 ppm. [STRS]					
Collaborate with Electricity Division to develop capacitance standard based on electron pump. [STRS]					
Develop a SQUID preamplifier to be used with NIS X-ray detector. [STRS, ONR, NASA]					
Develop a compact dewar for refrigeration of NIS X-ray detector. [STRS, ONR, NASA]					
Develop a NIS detector for large-area X-ray microanalysis with an energy resolution of 20 eV at 6 keV. [STRS, ONR, NASA]					

Project: MICROSTRUCTURAL ANALYSIS FOR ELECTROMAGNETIC TECHNOLOGY

FY 95 Fund Sources: STRS, Army, ATP

Staff (2.0 staff-years)

Professional	A. ROSHKO	L. Dulcie

name in capital letters = project leader; * = person works on project part time

Need Addressed: Microstructural issues remain one of the primary limitations for applications of high-temperature superconductivity, magnetic recording, and nonlinear optics. Industry must understand and be able to control the relationships between microstructure and properties, which are key to improving and implementing many technologies in these areas. In high-temperature superconductors, flux pinning, phase uniformity and stability, surface roughness, process reproducibility, and degradation due to processing, are a few of the issues restricting applications. For magnetic recording, advanced materials have already been developed and are in use. However, to achieve higher recording densities and faster data storage and retrieval, these materials must be improved and possibly replaced. Nonlinear optical materials are emerging with broad applications for the communications and medical industries. While significant progress has been made, greater understanding of these complicated materials is necessary to optimize performance for commercial applications. The further development and understanding of the microstructures of all these materials is important for supporting national goals of improved communications and competitiveness.

Technical Approach: To address these issues, NIST will perform detailed evaluations of the microstructures of a variety of electromagnetic materials by using scanning probe microscopies, electron microscopies and X-ray analysis. By correlating these data with measured properties, an understanding will be developed of how the microstructures depend on processing, and how they in turn influence properties. This knowledge will be used to determine the materials and processing conditions necessary to obtain desired properties for specific applications, such as step edge junctions, microwave devices, magnetic recording media, read-write heads, and compact blue-green lasers.

FY 95 Plans

- Characterize and correlate the microstructure and properties of YBCO thin films.
- Characterize the morphology of Cr thin film underlayers for recording media. Correlate with magnetic properties of media.
- Determine the solubility limits of rare earths in $LiNbO_3$ single crystals for nonlinear optical applications.
- Measure morphology and determine conductivity of short conductive fibers.
- Participate in ASTM Standards Committee for Eddy Current Standards.

Related Developments

- International competition in the areas of high-temperature superconductivity, magnetic recording, and nonlinear optics is strong. Currently U.S. companies hold a major share of the magnetic disk drive market. However, with a decreasing profit margin, continued materials improvements are crucial. There are large existing or potential markets in all of these areas.

FY 94 Accomplishments and Impacts

- Measured the dislocation densities in MgO substrates and determined that they are too low to control the observed density of screw dislocation growth features in epitaxial YBCO thin films. Concluded that the size and density of the thin-film growth features, which may contribute to flux pinning, can be controlled independently of the substrate.

- Measured grain sizes and textures of various underlayers being investigated by U.S. industry for magnetic storage media. Found that both size and texture depended on the gas pressure during deposition. Controlling the morphology of these underlayers is important for determining the magnetic properties of the overlayers.

- Measured the surface morphology of optical thin films ($KNbO_3$ and $LiTaO_3$) by atomic force microscopy. Found that the surface roughness for both materials is dependent on the deposition conditions, but is typically large relative to that required for efficient optical transmission.

- Made the first observation of ring features in bleached polymer films that an industrial partner is developing for optical waveguides. Made the first measurements of the edge roughness, which the collaborator is correlating with measurements of coupling losses.

- Correlated atomic-force microscopy (AFM) and reflection high-energy electron diffusion (RHEED) measurements of surface morphology of etched YBCO films. Found good agreement between the two techniques, and determined that AFM is more quantitative than RHEED.

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

- Prepared and had accepted by ASTM standards committee vote the document "Standard Practice for Determining the Impedance of Absolute Eddy Current Probes."

Project: MICROSTRUCTURAL ANALYSIS FOR ELECTROMAGNETIC TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Determine influence of YBCO film morphology on superconducting properties and device performance. [STRS]	———	———	———	———	———
Measure microstructure of magnetic thin films and correlate with magnetic properties. [STRS]	———	———	———	———	——— ⇒
Investigate the solubility limits and diffusion coefficients or rare earths into $LiNbO_3$ and $LiTaO_3$. [STRS, ATP]	———	———	———		
Measure morphology and conductivity of short conductive fibers. [Army]	———				

Project: MAGNETIC INSTRUMENTS AND MATERIALS CHARACTERIZATION

FY 95 Fund Sources: STRS, ATP, DoE

Staff (4.0 staff-years)

Professional	R. GOLDFARB	J. Dykes	A. Kos	T. Silva

name in capital letters = project leader; * = person works on project part time

Need Addressed: 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-superconductor and high-temperature-superconductor (HTS) 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 (MR) sensors; and researchers in medicine. NIST provides measurement services, often through collaborations, to laboratories that do not have magnetic measurement capability.

Technical Approach: Develop instruments, devices, techniques, and theoretical models needed to characterize the magnetic properties of particles, bulk and amorphous solids, and films 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. Develop a near-field Kerr-effect magneto-optical microscope with a resolution of 20 nm for the observation of magnetic domains. Invent novel ways to bias MR sensors for magnetic read heads. Investigate novel, granular, multilayer films for their MR properties. Design a magnetometer for the measurement of ac losses in superconductors at power frequencies. Collaborate with medical researchers on the use of magnetic nanoparticles in medical applications.

FY 95 Plans

- Synthesize and measure multilayer films of iron, nickel, and cobalt using fullerine C_{60} spacer layers. Prepare granular nickel-manganese films with different compositions and heat treatments. The goal of this project is to study and optimize the magneto-transport properties of novel magnetic structures.

- Complete the development of the scanning near-field magneto-optical microscope, and image domain structures in materials of interest to the magnetic recording industry. Typical materials include cobalt-palladium perpendicular recording media.

- Evaluate the magnetic sensitivity of Néel-wall-biased magnetoresistive sensors. This is a self-biasing technique invented at NIST to allow magnetoresistive films to be used as magnetic read heads.

- Develop transverse-field susceptometer and rf susceptometer, based on previous NIST developments in ac susceptometry. Develop ac susceptometer software.

- Collaborate with medical and biochemical researchers on the characterization of magnetic particles and molecules for use in medicine. Materials include: iron particles for use in drug delivery and in hyperthermia for the treatment of tumors, iron-storage molecules that can cause artifacts in magnetic-resonance images of the brain, and vanadium molecules for the treatment of diabetes.

- Determine the magnetic spin state of vanadium in a new mixed-valence compound made at Colorado State University in its development of new insulin-mimetic compounds for the treatment of diabetes in humans.

- Design and construct ac flux-integration magnetometer for ac loss measurements. Use the instrument to measure flux creep, eddy-current coupling, and matrix losses, and to test wires for large-scale fusion projects and tapes for applications of HTS in motors and power transmission.

- Participate in ac-loss interlaboratory comparison for the International Thermonuclear Experimental Reactor (ITER). NIST has been the major U.S. contributor in standardization and calibration of measurement procedures.

- Study the magnetic properties of new Ba-Fe-Ti-O compounds made in the Materials Science and Engineering Laboratory's Ceramics Division. Goal is to develop materials with high dielectric constant and saturation magnetization to replace iron garnets for low cost, miniaturized, microwave communications applications.

Related Developments

- The next generation of magnetic recording disks will use MR heads, but only a few U.S. companies do research in this area; the rest follow their lead. In following generations, giant-MR heads are anticipated, but there is little industrial research as yet.

- NIST contributions were cited by ITER management as having "great scientific as well as commercial significance because our contracts with U.S. superconducting wire manufacturers require their product meet a maximum loss specification... It is easy to see the financial implications of basing a product acceptance criteria on a faulty test procedure, but the technological implications could have been catastrophic for the operation of such a costly device."

FY 94 Accomplishments and Impacts

- Developed an improved eddy-current-decay apparatus for electrical resistivity measurement of pure metals. Achieved factor of ten improvement in measurement repeatability compared to existing technology.

- Designed and began construction of a scanning near-field optical microscope for magnetic domain imaging. The instrument, which employs the plasmon resonance of tiny silver-sphere probes, has a target resolution of 20 nm and will be used to characterize films for magnetic recording applications.

- Measured hysteresis losses in experimental HTS tape developed by a U.S. company. Measurements were designed to simulate the field variations expected in superconducting motor applications.

- Tested a new NIST method to bias MR sensors using small lithographically patterned NiFe pedestals on their top surface. Pedestals acted as domain-wall pinning sites. Kerr microscope images of the devices confirmed pinning of the domain walls by the lithographed pedestals.

- Developed a method of applying transverse-ac susceptibility to superconductors. The method probes the tilting of vortices by applying ac excitations orthogonal to a dc field. Evidence was found for the melting of the fluxon lattice in an HTS crystal.

Project: MAGNETIC INSTRUMENTS AND MATERIALS CHARACTERIZATION

FISCAL YEARS	95	96	97	98	99
Develop magnetic measurement instruments, such as magnetometers and rf and transverse-field susceptometers, and transfer the technology to industry when appropriate. [STRS, ATP]					⇒
Conduct fundamental studies of practical magnetic materials and new materials of current interest. [STRS]					⇒
Develop and use scanning near-field optical microscope for magnetic domain imaging of commercial films. [STRS]					
Characterize multilayer films containing C_{60} spacer layers. [STRS]					
Characterize magnetic particles and molecules, such as iron particles in drug delivery, of importance in medicine. [STRS]					
Provide consultation and measurements on ac loss behavior of superconductors for fusion energy and high energy physics projects. Participate in interlaboratory comparisons. [STRS, DOE]					⇒

Project: MAGNETIC RECORDING METROLOGY

FY 95 Fund Sources: STRS, ATP

Staff (4.0 staff-years)

Professional	S. RUSSEK*	R. Cross	J. Oti	C. Thompson
	S. Sanders*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: The large magnetic recording industry (world-wide market of $24.5B in 1992 for rigid-disk drives) is continually and rapidly advancing the state-of-the-art in high-density information storage and read devices. To maintain their competitive advantage in rigid-disk manufacture, U.S. firms must constantly look to new properties, such as giant magnetoresistance (GMR), of magnetic materials. The accurate characterization of new materials is often beyond the capability of small companies that are often the most eager to exploit them. Thus, NIST develops metrology to assist the magnetic recording industry, and develops techniques to characterize the performance of ultra-high density magnetic recording systems and the performance of submicrometer magnetoresistive (MR) sensors.

Technical Approach: Develop *scanning micromagnetic recording system (SMRS)* to allow characterization of ultra-high-density recording using commercial or experimental media, heads, and sliders (recording heads on mechanical actuators); to combine the ability to read and write conventional bit tracks under a variety of controlled conditions with the ability to image the magnetic structure; and to allow the characterization of advanced sensors without the need for full head fabrication. Development will be coordinated with the needs of commercial disk drive, head, and media manufacturers, and with the National Storage Industry Consortium (NSIC) heads program. Develop *micromagnetic models* of MR sensors and media to assist industry in the engineering and development of high-density magnetic recording; the effort will be coordinated with the experimental characterization of GMR sensors and advanced media in the project, and will be coordinated with specific industrial needs. Develop *characterization techniques for magnetoresistive sensors* for the new generation of submicrometer MR sensors to be used in ultra-high-density magnetic recording. Specific areas include: size effects in submicrometer spin valves, lithographic domain engineering, biasing techniques for submicrometer GMR devices, fabrication of nanosensors for imaging, spin-dependent transport and noise measurements, development of oxide MR materials for magnetometry applications, and micro-magnetostriction measurements. Develop a *micromagnetometer* to simultaneously characterize the magnetic and MR response of submicrometer MR devices.

FY 95 Plans

- Design, construct and evaluate precision SMRS to be installed in climate-controlled ultra-clean environment; use SMRS to begin characterization of advanced sliders for ultra-high density magnetic recording; characterize head performance and begin study of fundamental limitations, both in collaboration with NSIC; characterize the NSIC spin-valve slider (a spin-valve is a multilayer magnetic thin film used as a read head).

- Use micromagnetic modeling methods to model GMR devices and biasing techniques, high-density multi-layer perpendicular media, and magnetic-force microscope tips.

- Develop selected characterization methods supporting MR sensor development: begin study of size effects in submicrometer spin valves and biasing techniques for submicrometer GMR devices; conduct spin-dependent transport and noise measurements. Develop fabrication capability to support MR sensor work, including fabrication of nanosensors for imaging and Ag-permalloy sensors for use with the SMRS.

- Design micromagnetometer system to simultaneously characterize the magnetic and MR response of submicrometer MR devices.

Related Developments

- NSIC has established a five-year completion schedule for its "10 Gbits/in^2 head" demonstration project.

- A major U.S. company and NSIC have announced development of commercial spin-valve heads.

- A main goal of the recording industry is to develop standards for magneto-optical recording.

FY 94 Accomplishments and Impacts

- Improved model of GMR in multilayer granular films by incorporating electron mean free path, electron diffusion length, and grain geometry as parameters for determining the contribution of a grain. Replicated trends in the GMR behavior of practical films and enabled the easy separation of intralayer and interlayer GMR effects. Simulated the GMR response of dual-layer granular films for different types of disorder and found reasonable agreement with experimental behavior.

- Fabricated GMR devices with active areas as small as 0.3 μm by 0.7 μm from Fe-Ni/Ag thin films made at NIST, and Fe-Ni-CO/Cu films made at the University of Alabama. Discovered that in structures smaller than 2 μm by 2 μm, magnetoresistance, Barkhausen noise, and 1/f noise follow discrete steps as a function of small applied fields due to the switching of individual magnetic particles, which has important implications for the use of GMR sensors as read heads.

- Fabricated FeNi/Ag films and measured the dependence of their GMR on annealing conditions. Film sensitivity was found to peak at 335°C for five-minute anneals. Determined effect of annealing on grain size using atomic force microscopy. Modeled GMR behavior by varying grain packing fraction.

- Separated the effect of device heating from that of self-field as a function of increasing current in GMR read head test devices, which has important implications for modeling of current distributions.

- Measured, in collaboration with a U.S. company, magnetostriction and magnetoresistance of NiFe/Ag multilayer films exhibiting GMR. These materials were found to exhibit zero saturation magnetostriction concurrent with high sensitivity at low magnetic fields, which makes them attractive candidates for future read-head sensors in ultra-high-density magnetic storage systems.

- Studied NiFe thin-film devices that exhibit single-domain behavior for thicknesses less than 10 nm and device sizes less than 2 μm. Modeled the magnetization and the magnetoresistance using a Stoner-Wohlfarth model and found excellent agreement with experiment. The lack of domains, and therefore the elimination of Barkhausen noise, may have important device applications.

- Completed measurements of the time-decay response of MR and GMR sensors exposed to rapidly switched 10-mT magnetic fields. Observed that the GMR sensors turn on quickly, but turn-off is 10 times longer due to relaxation effects, which could be a severe problem for magnetic read heads.

Project: MAGNETIC RECORDING METROLOGY

FISCAL YEARS	96	96	97	98	99
Develop micromagnetic recording system in climate-controlled ultra-clean environment. [STRS]					
Characterize advanced sliders and ultra-high density magnetic recording systems. [STRS, ATP]					
Characterize advanced nanosensors for magnetic imaging. [STRS]					⇒
Develop micromagnetic modeling of magnetic recording heads and media for industry applications. [STRS]					⇒
Study size effects and biasing techniques in submicrometer spin valves. [STRS, ATP]					
Develop nanosensors for magnetic imaging and oxide MR materials for magnetometry applications. [STRS, ATP]					⇒
Develop methods for characterizing spin-dependent transport and noise in MR devices. [STRS, ATP]					
Develop SQUID-based micromagnetometer for characterizing magnetic recording heads. [STRS]					
Develop characterization techniques for ultra-high-density magneto-optic recording. [STRS]					⇒

Project: NANOPROBE IMAGING FOR MAGNETIC TECHNOLOGY

FY 95 Fund Sources: STRS

Staff (4.2 staff-years)

Professional	J. MORELAND	R. Thomson	P. Rice	P. Hopkins
Technician	J. Field*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: Magnetic recording technology is a $52B worldwide industry which consists mainly of tape- and disk-drive manufacturers. Driven by fierce domestic and foreign competition, U.S. industry has advanced to where nanometer-scale morphological, magnetic, and electrical properties play important roles in drive performance. Images showing microroughness, device dimensions, magnetic field patterns, and local electronic processes provide important information about the fundamental operation and ultimate limitations of drive components. In addition, images of components shipped for assembly can be used to determine quality before manufacture of the complete drive. Scanned probe microscopies (SPM) such as scanned tunneling microscopies (STM), atomic-force microscopies (AFM), magnetic-force microscopies (MFM), and scanning potentiometry are uniquely qualified for many of these applications because of the nanometer-scale dimensions of the various types of probes. Industry needs the development and testing of SPM techniques, the demonstration of their usefulness, and a means to facilitate the transfer of the latest innovations in SPM technology to appropriate audiences.

Technical Approach: The NIST approach lies in three broad technical categories: 1) By working closely with industry, NIST will help to determine which kinds of SPM technology developed by the scientific community may have a commercial impact; 2) By optimizing a given technique for a given measurement, NIST will establish standard levels of instrument performance; and 3) NIST will maintain an active research program to develop new imaging and image measurement techniques tailored to specific problems designated as areas of need by the magnetic recording industry, where SPM will have commercial impact.

FY 95 Plans

- Image media morphology with 0.1-nm lateral resolution and 0.01-nm vertical resolution, using scanned tunneling microscopy.

- Image roughness and morphology of heads and media with 2-nm lateral resolution and 0.1-nm vertical resolution, using atomic force microscopy.

- Image magnetic fields near heads and media with better than 50-nm lateral resolution and a force resolution of 10^{-12} N, using magnetic force microscopy.

- Develop scanning potentiometry of magnetoresistive (MR) heads and test devices with 50-nm lateral resolution and 1-mV voltage resolution.

Related Developments

- The recent interest in developing MR read-head technology by the major recording companies to increase storage densities has sparked interest in new MR and giant magnetoresistance (GMR) materials that require smaller bias fields and operate at room temperature. Higher storage densities require closer bit spacings and additional media development will be necessary. SPM techniques, which measure electrical

and magnetic properties at nanometer scales, are capable of shedding light on the fundamental recording mechanisms that limit MR and GMR disk drive performance.

- It is believed that future-generation disk drives will go to full-contact recording, thus, it is important to understand the nanoscale roughness and frictional forces that form the disk-head interface. This can only be done with SPM probes such as Lateral Force Microscopy and AFM.

- Several SPM manufacturers are actively pursuing a growing market for industrial applications. SPM techniques and corresponding image interpretation are becoming increasingly sophisticated. NIST must play an active role in the development of SPM technology so that it can track new technical approaches in SPM that are reliable and can be calibrated.

FY 94 Accomplishments and Impacts

- Initiated development of scanning potentiometry of superconductor-normal-superconductor step-edge junctions. Made first measurements of local voltage drops near the step edge.

- Completed a set of experiments comparing and contrasting various ways of using STM for surface modification of YBCO thin films (nanolithography). Found several regimes of film etching, including high-voltage oblation, chemical etching, surface milling, and oxygen migration.

- Made MFM measurements on samples of SmCo-coated AFM tips, received from University of Nebraska, to determine the tip-sample interaction forces. These permanent-magnet tips gave a very high response in MFM images, and the results were published in *Nanotechnology*.

- Obtained scanning potentiometry images of small GMR test structures. Potential images show charging effects, Si-substrate depletion regions, and voltage profiles along the device.

- Began an investigation of the wear rates of the carbon overcoats on commercial disk drive sliders with a U.S. company. Used tapping-mode AFM to study surface roughness before and after the heads are subjected to tens of thousands of start/stop cycles on a spin stand.

- Performed ac and dc lift-mode MFM on GMR multilayer films and patterned circuits provided by a U.S. company. Although the company thought there should be domain formation in these films, NIST did not seen any with MFM or standard Bitter methods. The company has also supplied Permalloy films for studying domain structure as a function of film thickness.

- Collaborated with the read-head development group of Maxtor Corporation, Longmont, Colorado to study problems in the current technology of disk drive manufacturing. Used MFM and AFM to image the fringing fields and topographies of disk media and thin-film inductive heads. Arranged for a NIST staff member to work at Maxtor Corporation under a NIST Industrial Fellow Program.

- Completed a study comparing several types of MFM that have been optimized for analyzing a "standard" bit pattern on a hard disk.

- Measured the size of the particles in Fe colloidal samples developed for cancer treatment, supplied by the Denver Medical Center of the University of Colorado, with the AFM and found them to be on the order of 10 nm in diameter.

Project: NANOPROBE IMAGING FOR MAGNETIC TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Provide facility open to industry collaboration in order to determine where SPM techniques will have an impact in magnetic recording manufacturing and development. [STRS]					⇒
Develop AFM for morphology and roughness measurements of pole tip recession and wear. [STRS]					
Develop micromachined cantilevers and SPM probe tips. [STRS]					
Develop magnetic resonance force microscope. [STRS]					
Apply MFM to image new thin-film heads and media being developed for high density storage. [STRS]					
Develop new scanned probes for quantitative magnetic field imaging. [STRS]					
Perform simultaneous AFM, MFM, and scanning potentiometry imaging on MR test devices. [STRS]					
Investigate high-bandwidth detection methods for SPM of magnetic devices at frequencies as high as 10 GHz. [STRS]					
Perform simultaneous AFM and friction force imaging of head and media surfaces. [STRS]					

Project: NANOPROBE IMAGING FOR MAGNETIC TECHNOLOGY (concluded)

FISCAL YEARS	95	96	97	98	99
Develop low-temperature AFM for fundamental studies of magnetic materials. [STRS]	▬▬	▬▬			
Participate in Industrial Fellow Program with Maxtor Corporation. [STRS]	▬▬				
Help organize the section on magnetic recording at the NIST workshop on Industrial Applications of Scanned Probe Microscopy. [STRS]	▬▬				

Project: SUPERCONDUCTOR INTERFACES AND ELECTRICAL TRANSPORT

FY 95 Fund Sources: STRS, ATP, ARPA, DoE/BES, DoE/OFE, Navy/NSWC

Staff (5.0 staff-years)

Professional	J. EKIN	S. Bray	S. Russek*	S. Sanders*
Technician	C. Clickner	N. Bergren		

name in capital letters = project leader; * = person works on project part time

Need Addressed: The high-temperature-superconductor (HTS) industry needs high quality contacts and interfaces for both thin-film and bulk conductors. Not even the basic interface conduction mechanism is yet understood. Recent data from this project have shown new evidence for magnetic scattering, which may have consequences for theoretical understanding of the origin of HTS. NIST has the measurement equipment and expertise to develop and understand HTS interfaces, and industry has looked to the NIST program for engineering help and an understanding of how to control the surfaces of these new materials. In magnet technology, both HTS and low-temperature-superconductor (LTS) magnets are being developed in the direction of larger magnets (ITER, for example) and higher fields (nuclear magnetic resonance (NMR), for example); both 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 opened a new set of measurement problems and modeling equations for conductor performance. NIST thus promotes the development of the HTS industry; many of the companies that have expressed a need for the expertise and the equipment available at NIST are small start-up companies without extensive infrastructure. Financial analysts expect the development rate for the emerging superconductor industry to be great over the next half-decade: at present, total stock valuations are about $500M, with a large growth rate projected to the $8B to $9B range by the year 2000.

Technical Approach: Provide experience and equipment for the study of superconductor interfaces not available in industry. The NIST equipment is not well suited for *production* of HTS interfaces, but unequaled in the *study* of interfaces, and thus NIST coordinates nicely with industry. The NIST thin-film fabrication equipment offers both sputter and laser-ablation deposition of HTS materials, reflection high-energy electron diffraction (RHEED) analysis, *in situ* characterization of process gas and background contaminants, ion-milling, and etching, all in the same vacuum chamber. *In situ* transfer capability to an Auger spectrometer is also available. The equipment to perform i*n situ* scanning tunneling microscopy surface analysis of HTS films is developed to allow surface conductivity maps immediately after film fabrication. Specialized lithographic patterns that correct for spreading resistance in the electrodes and permit testing of interfaces down to the micrometer level, with submicrometer patterning, are developed. The NIST instrumentation in the electromechanical area is the only apparatus in the United States for electrical transport measurements of superconductors at high magnetic fields, and therefore provides a national service to superconductor companies for conductor characterization and development. An automated high-field angle test apparatus is being developed to provide critical-current versus temperature, field, and field-angle maps at magnetic field levels not available in industry.

FY 95 Plans

- Perform an annealing study on a series of in-house fabricated YBCO-Ag and YBCO-Ag contact interfaces to determine the effect of oxygen annealing on contact resistivity and use the information to optimize contact performance.

- Fabricate *a,b*-axis contact interfaces; determine the crystalline anisotropy of the contact resistivity and its consequences for contact fabrication technology.

- Determine optimal regrowth conditions for ion-milled and etched YBCO surfaces.

- Develop and test Pt/Au buffer layers for the integration of HTS and silicon-based contact systems.

- Develop capability of fabricating YBCO on GaAs for microwave applications.

- Measure the effect of axial strain on the critical current of experimental Nb_3Sn superconductor at very high magnetic fields (23.5 T) for use in the design of NMR superconductor applications.

- Measure the effect of hoop strain on the critical current of Bi-based and Nb_3Sn superconductor rings.

Related Developments

- Many U.S. companies have begun new programs in HTS: electronics (for contacts), NMR security scanners, microwave devices, and cellular communication filters. HTS power transmission, high-field laboratory magnets, and motors are all in various stages of development.

- Many requests for information on the NIST thin-film YBCO/Ag interface conductivity measurements have been received, including requests from leading theorists such as Professor Alan Ginsberg of the University of Minnesota. The work was also cited in the Nota Bene section of High-Tc Update.

FY 94 Accomplishments and Impacts

- Wrote a chapter on electromechanical testing and modeling for a book entitled *Composite Superconductors*, edited by Kozo Osamura of Kyoto University. The critical J_c-B-strain surface, first discovered and modeled in our project group, was featured as the cover photo.

- Measured thin-film YBCO/Ag interface conductivity 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 YBCO.

- Obtained the first electromechanical data on a small *coil* of HTS Bi conductors. These data and their interpretation were the basis for a U.S. company finding a superior epoxy system for their Bi-magnet fabrication.

- Measured and published the first data showing that the critical point in HTS Bi-tape superconductor magnets will be at the ends of the magnet rather than at the high-field position in the middle as for LTS superconductors.

- Performed a time exposure experiment for measuring the degradation rate of YBCO surfaces. The results showed little effect of air exposure up to 100 minutes, much longer than expected. The interface conductivity data showed little difference from *in situ* processed contacts, indicating that considerable improvement may be possible with *in situ* contacts. The results were published in *Applied Physics Letters* and cited in the Nota Bene section of *High-Tc Update*.

Project: SUPERCONDUCTOR INTERFACES AND ELECTRICAL TRANSPORT

FISCAL YEARS	95	96	97	98	99
Study magnetic scattering at HTS interfaces. [STRS, ARPA]					
Determine YBCO/noble-metal annealing characteristics. [STRS, ARPA]					
Grow *a,b*-axis YBCO films and measure normal-metal interface properties. [STRS]					
Develop system and analyze J_c versus angle in HTS bulk and films. [STRS, ATP]					
Determine optimal regrowth of etched YBCO surfaces. [STRS, ARPA]					
Develop *in situ* scanning tunneling microscopy of HTS. [STRS, ARPA]					
Develop submicrometer HTS interface test capability. [STRS]					
Study YBCO on GaAs for microwave development. [DOE/BES]					
Measure and model electromechanical properties of LTS. [DOE/OFE]					⇒
Determine electromechanical properties of LTS and HTS composite ring structures. [Navy/NSWC]					

Project: SUPERCONDUCTOR STANDARDS AND TECHNOLOGY

FY 95 Fund Sources: STRS, DoE

Staff (3.2 staff-years)

Professional	L. GOODRICH	L. Cooley	A. Srivastava*
Technician	T. Stauffer		

name in capital letters = project leader; * = person works on project part time

Need Addressed: Manufacturers of superconducting wire need practical and accurate methods for characterizing critical current (I_c) and ac loss. Large magnet systems require 5% uncertainty or less and I_c values as high as possible. This requires accurate measurements of magnetic field, voltage, current, and temperature, and fabrication and precise control of advanced flux-pinning systems. In Nb-Ti, new artificial-pinning-center (APC) technology has complex materials science and analysis problems. For Nb_3Sn wires, the properties and handling of the sample mandrel can significantly affect the measured critical current. For high temperature superconductors, sample damage, sample variability, and mounting variability can significantly affect the measured critical current. The accurate and unbiased feedback of conductor performance and measurement considerations to U.S. manufacturers is important to maintain their competitive position in support of magnetic resonance imaging (MRI), electric power, laboratory magnets, and other applications. NIST activity in national and international standards activities helps U.S. industry compete.

Technical Approach: Provide standards, measurement techniques, quality assurance, reference data, and clarification of issues for both high- and low-temperature superconducting wire technology. Develop standards for critical current measurements; conduct research, interlaboratory comparisons, and standards creation under Versailles Project on Advanced Materials and Standards (VAMAS) and International Electrotechnical Commission (IEC) Technical Committee 90 (TC-90) on superconductivity. Represent, update, and seek input from U.S. industry throughout the process of standards creation in order to protect U.S. interest in international trade. Contribute to the precise characterization of Nb_3Sn wires for the International Thermonuclear Experimental Reactor (ITER) in which a critical current accuracy of 2% and a precision of 0.5% is a goal. Conduct research on new superconductors that use artificial flux-pinning-center technology to improve their performance. APC wire is replacing conventional Nb-Ti wires in some applications.

FY 95 Plans

- Act as primary testing laboratory for the U.S. Home Team in the second ITER I_c Benchmarking Test; conduct interlaboratory comparisons with members of the ITER U.S. Home Team to determine the accuracy of I_c measurements on Nb_3Sn wires, and assist members in reducing their uncertainties.

- Complete the on-going VAMAS USA interlaboratory comparison of I_c measurements on $Ag/Bi_2Sr_2Ca_2Cu_3O_{10}$ tapes.

- Determine the measurement parameters, such as pulsed or dc methods, necessary for accurate I_c in variable-temperature conditions.

- Arrange and chair the IEC/TC-90 working group meetings at the Applied Superconductivity Conference and the IEC/TC-90 meeting in April 1995. Compile comments on draft IEC documents from the U.S. Technical Advisor Group. Host 1995 Low Temperature Superconductor Workshop.

- Assist U.S. industry to optimize properties of 5000-A/mm^2 artificial-pinning-center (APC) wire at 5 T and 4.2 K; explore advanced materials in APC thin films, and fabricate Nb_3Sn APC thin films.

- Quantify the proximity length for flux pinning materials; image, by combined microscopy techniques, a vortex becoming pinned and unpinned.

Related Developments

- The Japanese National Committee is setting an aggressive pace for and is dominating IEC/TC-90 standards creation in superconductivity. Japan has completed at least four interlaboratory comparisons on future standards and most of these have started a follow-up comparison. The present VAMAS activity in superconductivity has also established an aggressive pace.

- APC wire is becoming the industrial standard for many applications. A Japanese company achieved 4250 A/mm^2 in APC wire in FY94, breaking through the 4000 A/mm^2 barrier of the past decade. General Electric Company has announced real-time, during-surgery MRI capability using a new magnet design and a focus on new APC conductor designs.

- Motors, generators, dc powerlines, and fault-current limiters are being made from BSCCO wires and tapes being manufactured by U.S. companies.

FY 94 Accomplishments and Impacts

- Designed and implemented an interlaboratory comparison of I_c measurements among six U.S. laboratories on two Ag/$Bi_2Sr_2Ca_2Cu_3O_{10}$ tapes from U.S. manufacturers. Early results indicate that good agreement (2.3% variation at 77 K; 3.0% at 4.2 K) was achieved; detailed information on the sources of variability was obtained.

- Designed and completed an interlaboratory comparison of I_c measurements among 12 U.S. laboratories, using three NIST I_c simulators and a variety of methods, including dc and pulse current. All I_c measurements at a criterion of 10 μV were within 2% of the NIST value.

- Participated in an ITER interlaboratory comparison (Benchmarking Test) of Nb_3Sn I_c measurements. The results from the U.S. laboratories were good, showing a coefficient of variation of only 2 to 4%. The results from the international comparison had higher coefficients of variation, 10 to 14%.

- Completed and shipped a custom-designed 5-A superconductor I_c simulator. The simulator has six voltage outputs with various mutual inductances.

- Made precision resistivity and magnetoresistivity measurements on prototype stabilizers for superconducting magnetic energy storage (SMES) magnet systems in collaboration with Texas A&M University and industry to compare an eddy-current measurement technique against a conventional four-probe measurement. The comparison was within 0.1% for the most uniform bars.

- Contributed to the development of a flux pinning model for planar defects and for ribbon-shaped pins that occur in conventional and APC Nb-Ti wires. Found the important parameters for guiding improvements in the high-field performance of APC wires. Developed a method for assessing the pinning force of planar pins by measuring the tilt response of fluxons. Found evidence for melting of the fluxon lattice in a YBCO crystal. Discovered that the critical state of superconductors breaks into terraces, an observation which may lead to improved superconductor wire performance.

Project: SUPERCONDUCTOR STANDARDS AND TECHNOLOGY

FISCAL YEARS	95	96	97	98	99
Provide quality assurance, reference data, and issue-clarification to ITER on Nb_3Sn critical-current measurements. [DoE]					⇒
Participate in international comparisons of critical-current measurements; coordinate other measurements. [STRS]					⇒
Support national standards activities by coordinating U.S. interlaboratory comparisons. [STRS]					⇒
Provide leadership of national (ASTM) and international (VAMAS, IEC) standards activities in superconductivity. [STRS]					⇒
Develop critical-current standards for HTS wires; promote availability to U.S. manufacturers. [STRS]					
Perform research on variable-temperature, high-critical-current measurement system; interact with U.S. manufacturers and national laboratories to develop device as primary precision measurement system in 20 to 76 K region. [STRS]					
Collaborate with U.S. industry to achieve high critical-current density in APC conductors. [STRS]					
Collaborate with U.S. industry to determine fundamental pinning properties and upper limits to critical current in APC conductors. [STRS]					

OPTOELECTRONICS DIVISION

Project: SOURCE AND DETECTOR MEASUREMENTS

FY 95 Fund Sources: STRS, ARPA, Air Force, Army, Navy

Staff (13.9 staff-years)

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name in capital letters = project leader; * = person works on project part time

Need Addressed: The increased competitive pressures, nationally and internationally, of today's marketplace require that optoelectronic system manufacturers/users continually improve the sources and detectors on which these systems are based. Measurement methods and standards are critical to this effort. Optoelectronic source characterization requires quantitative knowledge about intensity distribution and propagation properties as well as intensity-noise stability. Detector characterization must include spectral, spatial, and frequency response information if the detectors are to be used effectively for their intended purposes. In addition to measurement methods, new detectors must be developed to support the growing need for highly accurate power/energy measurements.

Technical Approach: Provide metrology, standards, and measurement services for optical sources and detectors used in association with optoelectronic systems to meet industry needs. Specifically: 1) develop high accuracy, electrically calibrated, spectrally flat, pyroelectric detector system; 2) develop measurement methods and standards for characterizing the radiation from vertical-cavity surface-emitting lasers (VCSELs); 3) implement detector linearity measurement capability for optical power detectors to extend the NIST optical fiber power calibration measurement services; 4) develop improved frequency-response calibration capability; 5) improve and extend low level pulse laser measurement capability; and 6) develop state-of-the-art laser beam profile measurement capability.

FY 95 Plans

- Develop pyroelectric detector system capable of high accuracy (i.e. uncertainty < 1%) measurements over the wavelength region 400 nm to 10.6 μm, and spatial non-uniformity less than 0.5% across its surface.

- Develop methods to quantitatively measure beam profile and pointing stability, jitter, modulation response, and intensity noise of VCSELs.

- Improve optical power measurement accuracy by decreasing measurement uncertainty by 50%; includes installing and characterizing a high accuracy, cryogenic radiometer as a primary reference standard, and developing improved optical power transfer standard(s).

- Develop detector linearity measurement system capable of performing detector linearity measurements over a 60 dB range of powers at nominal wavelengths of 850-, 1300-, and 1550-nm.

- Develop capability to perform high-resolution (~100 KHz), low-uncertainty (<0.3 dB), frequency- response calibrations of optical detectors over a frequency range of 0 to 2 GHz at 1319 nm; extend frequency range of measurement capability of NIST system to 50 GHz or greater.

- Modify current low-level pulse laser measurement system to improve measurement accuracy and reduce measurement time at 1.06 μm. Develop capability to perform measurements at 1.54 μm to support "eye-safe" laser rangefinder systems.

- Develop state-of-the-art laser beam profile and intensity noise measurement capabilities at NIST. Develop measurement methods and standards for meeting industry needs for accuracy and traceability.

Related Developments

- NIST has received several requests for measurement support of excimer laser power meters used at a wavelength of 193 nm. This need stems from the imminent use of ArF excimer lasers for corneal sculpting (currently being considered for official approval by the FDA) which is expected to be a large industry need. In addition, the semiconductor photolithography industry is considering the use of ArF lasers to replace the current KrF (248 nm) lasers in an effort to get 0.25 μm lithographic resolution. NIST has recently started providing measurement services at 248 nm.

- Requests to NIST indicate a growing need by optoelectronic digital communication companies and cable TV companies for high-accuracy, high-resolution, frequency response measurements for detector characterization over the frequency range 0 to 2 GHz. It appears that as NIST develops the appropriate measurement capability, there will likely be a large (more than 20 items per year) calibration need by these industries.

FY 94 Accomplishments and Impacts

- Developed a measurement system to perform frequency response measurements on optical detectors at high resolution (~300 KHz) and low uncertainty (< 0.3 dB). Used this system to calibrate several detectors for industry. Completed a frequency-response intercomparison with the National Physical Laboratory (UK) which demonstrated good agreement between the two national laboratories. Results were presented at a conference of the Society of Photo-Optical Instrumentation Engineers.

- Developed a tunable wavelength calibration system which has been used to perform calibrations on optical fiber power meters at customer specified wavelengths in the 850-, 1400-, and 1550-nm regions. Used the system to perform limited-range, high-resolution spectral responsivity measurements on optical power detectors and, as a special test, to make spectral reflectivity measurements on coated detector samples for industry.

- Established NIST capability to perform excimer laser measurements at 248 nm, in collaboration with SEMATECH, to allow NIST to provide measurement services for excimer-based semiconductor lithography customers and other excimer laser users/manufacturers. Measurement system is based on specially designed standard calorimeters designed and built at NIST.

- Developed a prototype optical power detector linearity measurement system at 1290 nm; used it to provide linearity measurements to customers over a 60 dB power range. System has demonstrated a measurement resolution of 0.04% and is capable of both range linearity and range discontinuity measurements.

- Performed relative intensity noise (RIN) measurements on edge-emitting laser diodes at room temperature and 77 K, from 1 to 10 GHz. The comparison showed a decrease of as much as 38 dB in RIN when the lasers were cryogenically cooled, and represents the first time (to our knowledge) that cryogenic RIN measurements have been performed at frequencies as high as 10 GHz.

Project: SOURCE AND DETECTOR MEASUREMENTS

FISCAL YEARS	95	96	97	98	99
Develop spectrally flat, uniform electrically calibrated pyroelectric detector systems as reference for absolute responsivity measurement. [STRS, Air Force, Army]					
Improve optical power measurement accuracy by decreasing measurement uncertainty by 50%. [STRS, Navy]					
Develop measurement methods and standards for characterizing the radiation from vertical cavity surface emitting lasers (VCSELs). [STRS, ARPA]					
Implement detector linearity measurement capability for optical power detectors to extend the NIST optical fiber power calibration measurement services. [STRS, Navy, Army]					
Develop capability to perform high resolution (≈ 100 KHz), low uncertainty (<0.3 dB), frequency response calibrations of optical detectors over a frequency range of 0 - 2 GHz at 1319 nm. [STRS]					
Improve and extend low level pulse laser measurement capability. Modify current system to improve measurement accuracy and reduce measurement time at 1.06 µm. [Navy]					
Develop state-of-the-art laser beam profile measurement capability at NIST and develop measurement methods and standards that meet industry needs for accuracy and traceability [STRS]					

Project: FIBER AND INTEGRATED OPTICS

FY 95 Fund Sources: STRS, Navy, ATP

Staff (7.0 staff-years)

Professional	D. FRANZEN	B. Danielson	T. Drapela	S. Mechels
	J. Schlager	P. Williams	M. Young	D. Allen* (CU)

name in capital letters = project leader; * = person works on project part time

Need Addressed: Manufacturers and users of optical fiber and integrated optics need measurement procedures and Standard Reference Materials (SRMs) to aid manufacturing, quality control, incoming inspection, installation, and restoration. The movement of fiber into the local loop requires fibers with improved dimensional tolerances to meet requirements of improved, low cost connectors; also in this environment, optical time domain reflectometers (OTDR) are needed with improved spatial resolution. Optically amplified undersea systems operating at high bit rates over long optical lengths require precise measurements of chromatic and polarization-mode dispersion (PMD) properties. Test procedures are needed to characterize fiber and integrated optical amplifiers which are emerging in both long haul and local area applications.

Technical Approach: NIST will continue to provide the industry with SRMs for fiber cladding diameter; the SRMs are finding extensive use in the calibration of fiber drawing towers and quality control instrumentation. NIST will expand the geometry effort to include an SRM for coating diameter. NIST will continue to work through the Telecommunications Industry Association (TIA) to seek guidance and prioritize needs. Reference measurement methods and an SRM will be developed for zero-dispersion wavelength and slope. Artifact standards and measurement methods for PMD will be evaluated through industry measurement round robins. NIST will interact with the TIA and international standards groups to evaluate measurement methods for noise figure and spectral gain of erbium-doped fiber amplifier modules. An effort will be initiated to develop low-coherence measurements for spatially resolving losses in integrated optic guides.

FY 95 Plans

- Develop an SRM for determining fiber coating diameter (0.1 μm uncertainty).
- Complete very accurate measurement systems for determining chromatic dispersion parameters of optical fiber in the 1300- and 1550-nm spectral ranges. Develop an SRM for chromatic dispersion (0.2 nm acceptable for zero-dispersion wavelength; 0.1 nm desired), and complete necessary internal NIST documentation.
- Evaluate artifact standards for polarization-mode dispersion and complete a round robin with TIA members.
- Complete an interferometric system for determining group index of optical fibers in support of OTDR calibration.
- Conduct an international round robin on spectral gain and noise figure of erbium-doped fiber amplifiers and develop a NIST system to determine spectral gain.
- Develop a low-coherence reflectometer for measuring spatial loss in integrated optic guides.

- Continue to supply fiber cladding diameter SRMs to industry.

Related Developments

- Undersea systems are projected to operate at high bit rates over long optically amplified distances.

- Increased use of optical amplifiers and wavelength division multiplexing is forcing new fiber designs and network topologies.

FY 94 Accomplishments and Impacts

- Delivered a second batch of fiber geometry SRMs to Gaithersburg after initial run sold out. Corning, Incorporated and AT&T Network Systems adjusted their fiber drawing towers to agree with SRM 2520.

- Completed several round robin evaluations including: a long-term international comparison of measurement methods for fiber geometry involving laboratories in North America, Europe, and the Pacific; a TIA comparison of test procedures for coating geometry in which over 1000 measurements were analyzed; and a TIA comparison on methods for determining connector ferrule geometry.

- Completed construction of a frequency-domain phase-shift system for measuring chromatic dispersion at 1300 nm and 1550 nm, and examined long term stability of packaged fiber samples.

- Started PMD round robin with TIA members to evaluate test methods and PMD calibration standards, and developed a potential PMD artifact standard based on a waveplate stack.

- Demonstrated a very efficient all-optical sampling method for acquiring fast optical waveforms, using four-wave mixing in a semiconductor optical amplifier; reported the results at the 1994 meeting of Optical Amplifiers and Their Applications; the method was used to construct an OTDR at 1550 nm having millimeter spatial resolution with good sensitivity.

Project: FIBER AND INTEGRATED OPTICS

FISCAL YEARS	95	96	97	98	99
Fabricate and certify fiber cladding diameter SRMs. [STRS]					
Develop SRM for determining fiber coating diameter (0.1 μm uncertainty). [STRS]					
Participate in standards committees. [STRS]					⇒
Publish results of several round robins on fiber, coating, and ferrule geometry. [STRS]					
Complete and document systems for measuring chromatic dispersion. [STRS]					
Certify a SRM for chromatic dispersion. [STRS]					
Complete work on PMD standards and round robins. [STRS]					
Develop test methods and systems for optical amplifier characterization. [STRS]					
Complete OTDR standards. [Navy]					
Develop spatially resolvable loss measurements for integrated optic guides. [STRS]					

Project: FIBER AND INTEGRATED OPTICS (concluded)

FISCAL YEARS	95	96	97	98	99
Characterize bandwidth of multimode fiber for computer bus applications. [ATP]	▬▬	▬▬			
Identify and address major metrology needs in integrated optics. [STRS]					⇒

Project: OPTICAL FIBER SENSORS

FY 95 Fund Sources: STRS, DoD/LPS, DNA, LANL

Staff (4.5 staff-years)

Professional	M. DEETER	A. Rose	K. Rochford	S. Milián Bon (GR)
Technician	S. Etzel*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: Optical fiber sensors permit remote measurements of many physical variables which are often unmeasurable by other means. For example, optical fiber sensors are useful in electrically-noisy environments that can easily corrupt signals delivered by conventional sensors. The ultimate performance of optical fiber sensors depends on properties of both the optical sensing element (which may be the fiber itself) and the components which together define the complete sensor. Development of these sensors by other government and industrial laboratories requires well-characterized components and the availability of basic materials data.

Technical Approach: The Project undertakes the development and characterization of materials, components, and systems for the measurement of physical variables which benefit from various technical advantages offered by fiber optics. High-sensitivity ferrimagnetic iron garnets form the basis of a novel class of bulk magneto-optic sensors suitable for magnetic field and electric current measurements. These complex materials will continue to be the subject of a characterization program specifically focused on parameters relevant to magneto-optic sensing (such as magneto-optic sensitivity and frequency response). The properties of optical sources and other components, including modulators and novel optical fibers, will be investigated so that ultimately they can be efficiently integrated into sensing systems. For example, the stability and spectral output of low-coherence optical sources will be characterized since these are the primary contributing factors to the performance of several fiber-optic sensor technologies. Optical fibers with thermally-expanded core regions will be studied since such fibers may permit the use of lensless designs in a wide variety of fiber-optic sensors. The development of a standard optical retarder will serve both the optical fiber sensor and optical communications communities. Development of this device will progress toward the ultimate goal of Standard Reference Material certification.

FY 95 Plans

- Conclude characterization of sensing properties of new iron garnet materials grown by a U.S. company.
- Develop model to understand and predict temperature dependence of sensitivity of bulk iron garnet crystals.
- Characterize sensing properties of iron garnet films fabricated by a U.S. company for diffraction-based sensing.
- Establish as a Standard Reference Material a standard optical retarder developed through industrial interactions.
- Measure Verdet constant of optical fiber supplied by Los Alamos National Laboratory, to ±5% uncertainty.

- Continue development of a high-sensitivity wideband fiber-optic magnetic field sensor based on iron garnet materials for the DoD Laboratory for Physical Sciences (LPS).

- Develop and demonstrate self-calibrating fiber-optic temperature sensor for the Naval Warfare Assessment Division.

- Develop and demonstrate a high-speed fiber-optic current sensor for the Defense Nuclear Agency.

- Develop technology for modifying mode field diameter and numerical aperture of optical fibers through annealing techniques.

- Characterize relevant sensing parameters (e.g. source spectrum and stability) of commercial low-coherence optical sources.

- Characterize performance (including amplitude modulation) of commercial phase modulators

Related Developments

- A partnership between the Department of Energy and the "Big Three" automobile manufacturers has formed to develop electric and hybrid automobile technology for the next century. The PNGV program (Partnership for a New Generation of Vehicles) may provide an excellent channel through which to introduce fiber optic sensors (for measurements of electric current, voltage, rotation, etc.) into American automobiles.

- A workshop was recently held at NASA-Lewis (Cleveland) to identify impediments preventing the introduction of fiber optic sensors onto aerospace platforms. Concerns of life-cycle cost and reliability seemed to be the main obstacles to the widespread use of fiber optics in these environments.

FY 94 Accomplishments and Impacts

- Tested prototype standard retarders (including two which were fully-packaged); results indicated that the rhomb design met all performance targets (including wavelength, temperature, and incident-angle dependences) except long-term drift.

- Demonstrated that a new annealing technique (based on pre-anneal twisting) effectively eliminates residual linear birefringence in annealed coils of any type of single-mode optical fiber.

- Demonstrated that new iron garnet materials produced by a U.S. company exhibited more than an order of magnitude greater sensitivity and better frequency response than previously available iron garnets. The availability of these materials to the sensor community will eventually result in faster and much more sensitive magnetic field and electric current sensors than are now available.

- Designed and constructed a compact high-speed current sensor which exhibited similar sensitivity but much greater bandwidth (dc to 500 MHz) than a previous current sensor built at NIST. Device exploited coated right-angle prisms to produce the required right-angle reflections without the phase shifts which would otherwise distort the polarization state. Design requires only half the number of prisms as the first-generation device and is much simpler to assemble.

Project: OPTICAL FIBER SENSORS

FISCAL YEARS	96	96	97	98	99
Investigate improved sensor designs and materials for magneto-optic sensing. [STRS, LPS]					
Extend integrated optics technology to optical fiber sensors. [STRS, OA]					
Determine characterization and standardization requirements of domestic optical data storage industry. [STRS]					
Transfer current sensor technology to industry. [STRS]					
Investigate alternative polarimetric detection systems for low-frequency measurands. [CRADAs, OA]					
Characterize properties of available optical sources for use in optical fiber sensor. [STRS]					
Develop standard optical retarder for use as Standard Reference Material, having 90 degree retardance and 0.1 degree accuracy. [STRS]					
Participate in standards committees. [STRS]					⇒

Project: FIBER AND DISCRETE COMPONENTS

FY 95 Fund Sources: STRS, Air Force

Staff (2.6 staff-years)

Professional	S. GILBERT	R. Craig	P. Hale*	H. Patrick* (CU)

name in capital letters = project leader; * = person works on project part time

Need Addressed: Fiber-coupled components such as optical isolators, wavelength division multiplexers, and fiber amplifiers have recently been installed in advanced optical communication systems. Future systems will likely incorporate recently developed components, such as devices containing fiber gratings. Standards and characterization of these components are needed by industry in order to evaluate device reliability and maintain the specifications required by new systems. Polarization -dependent loss (PDL) and polarization-dependent gain in components affect a system's performance, especially when there are many components in the system. Commercial instruments are available for measuring PDL, but no calibration standards exist for them. Photo-induced Bragg gratings in optical fiber are likely to be incorporated in fiber lasers, dispersion compensators, and band pass filters, but the long-term stability of fiber gratings has not been evaluated, particularly under the conditions of exposure to intense laser light. Wavelength dependence of components will be important when wavelength division multiplexing is implemented. Wavelength standards are needed to calibrate instruments which will be used to characterize the wavelength dependence of these components.

Technical Approach: Wavelength standards: A moderate-accuracy wavelength calibration technique for the 1300- and 1550-nm regions, developed at NIST and based on molecular absorption lines as fixed wavelength references, will be transferred to a U.S. firm which plans to make a product for calibrating optical spectrum analyzers. This product will address the present need of ±0.1 nm accuracy for wavelength calibration. The near-future need of ±0.001 nm accuracy will be met by developing NIST Standard Reference Material absorption cells which have been calibrated at NIST to higher accuracy. Narrow absorption lines in atomic rubidium are being investigated for the high-accuracy wavelength reference at NIST. Fiber-grating-component characterization: A fiber laser incorporating fiber gratings is being developed to probe the narrow atomic lines. Work on photo-induced Bragg gratings in optical fiber addresses the need for characterization of fiber-grating-component stability. The frequency stability of the fiber laser developed for the wavelength standard task will be evaluated by measuring its noise relative to the stable rubidium absorption line. The stability of fiber gratings under exposure to laser light will be tested by monitoring the grating reflectivity during lengthy exposures to various wavelengths and intensities of laser light. In particular, laser wavelengths, such as 980 nm and 1480 nm, commonly used to pump fiber lasers and amplifiers, will be tested. Polarization-dependent loss and gain characterization and standards: Components for an apparatus to measure polarization-dependent loss in fiber devices are being tested for stability and polarization dependence. When the testing is complete, the apparatus will be constructed and its performance evaluated. A polarization-dependent loss standard will be developed to calibrate commercial instruments. A round robin measurement of this standard will be proposed at a Telecommunications Industry Association (TIA) meeting and feedback from this and other industry sources will be used to determine the specifications of the standard.

FY 95 Plans

- Construct fiber laser incorporating fiber gratings and test its suitability for spectroscopy of rubidium.
- Develop moderate-accuracy (0.1 nm) multiwavelength standards at 1300 nm and 1500 nm.
- Develop absorption cell Standard Reference Materials and evaluate HCN absorption cells.

- Evaluate frequency stability of fiber lasers containing fiber gratings.
- Evaluate stability of fiber gratings when exposed to 980-nm laser light.
- Evaluate stability and polarization dependence of the polarization-dependent loss system components.
- Construct a polarization-dependent loss measurement system.
- Propose a polarization-dependent loss round robin at the TIA meeting.

Related Developments

- The success of the erbium-doped optical fiber amplifiers has changed optical communications. It impacts the need for wavelength standards and places constraints on components of optical communication systems. Polarization effects in optical components, including the fiber amplifier itself, have become more important due to the additive effect of many components in a continuous optical network.
- Many different components containing fiber grating have been demonstrated recently and it is likely that more will appear in the near future. There are a variety of potential applications, such as fiber lasers, bandpass filters, and dispersion compensators. These developments have increased the importance of work on photo-induced Bragg gratings and will continue to impact this project as the field develops.

FY 94 Accomplishments and Impacts

- Constructed a fiber laser with fiber gratings operating in single longitudinal mode. The laser was 2 cm long to achieve single longitudinal mode, had ~95% reflectance gratings, 30-mW threshold, and 100-μW output with 180-mW pump power. The laser is a prototype of the fiber laser needed for the high-accuracy wavelength standard work.
- Completed the construction and characterization of a system for measuring the dependence of fiber coupler coupling ratio on polarization. A round robin is contemplated for this polarization dependence.
- Developed and began implementing a plan for constructing a high-accuracy polarization-dependent loss (PDL) measurement system, the first step for establishing a PDL standard.
- Completed a second-generation optical trap for the high-accuracy wavelength standard with improvements which reduce effects of background gas, improve the laser beam uniformity, and improve the response time to changes in rubidium vapor pressure.
- Completed a study of the time dependence of fluorescence in optical fiber when exposed to UV light. This work explains conflicting results obtained by others and is a step toward understanding the mechanisms responsible for photo-induced index changes in optical fiber.
- Completed the characterization of temperature stability of fiber gratings in Ge-doped, Ge/boron-doped, and hydrogen-loaded fiber. Showed that gratings in hydrogen-loaded fiber are less stable than those in non-hydrogen-loaded fiber.

Project: FIBER AND DISCRETE COMPONENTS

FISCAL YEARS	95	96	97	98	99
Develop "high-accuracy" (uncertainty 0.00001 nm) standard for 1550-nm region. [STRS]					
Develop high-accuracy (uncertainty 0.00001 nm) standard for 1300-nm region. [STRS]					
Develop absorption cell Standard Reference Materials. [STRS, AF]					
Work on wavelength-standard at 1300-nm and 1550-nm. [STRS, CRADA]					
Evaluate frequency stability of fiber lasers containing fiber gratings. [STRS]					
Evaluate stability of fiber gratings when exposed to laser light. [STRS]					
Characterize fiber grating components. [STRS]					
Construct a polarization-dependent loss measurement system. [STRS]					
Develop a polarization-dependent loss standard. [STRS]					

Project: SEMICONDUCTOR MATERIALS AND DEVICES

FY 95 Fund Sources: STRS, NASA, ARPA

Staff (3.7 staff-years)

Professional	R. HICKERNELL*	D. Christensen	J. Hill	M. McCollum
	D. Schaafsma*			

name in capital letters = project leader; * = person works on project part time

Need Addressed: The fundamental need of the semiconductor optoelectronics industry is to lower manufacturing costs in order to enlarge commercial market share. Companies involved in semiconductor epitaxy are moving toward in-process control of epilayer deposition to achieve higher device yield per wafer, particularly as higher performance devices demand tighter tolerances on layer composition and thickness. Simple, nondestructive testing of as-grown wafers at later stages in the manufacturing process must be calibrated to reference standards. To meet the shorter wavelength requirements for displays, optical data storage, and printing, laser and light-emitting diodes manufacturers use semiconductor alloys for which data on optical constants are limited. The development of measurement methodology for parallel optical data interconnects, using arrays of light-emitting devices, is in its infancy.

Technical Approach: NIST will develop and critically evaluate key measurements which have the greatest impact on reducing manufacturing costs for semiconductor optoelectronics. NIST will develop in-process monitoring techniques for epitaxial growth, and work with industry to implement the techniques in manufacturing line equipment. The purpose is to provide real-time feedback to control the composition and thickness of III-V epitaxial layers; the techniques will also be applicable to II-VI compound semiconductors. One goal is to limit elemental flux variation to 2% over the course of an eight-hour period. NIST will evaluate and compare the sensitivity and accuracy of optical, X-ray and electron probes of epilayer composition, thickness, and complex index of refraction, combining measurement data with simulation tools. The effect of growth nonuniformities on detector, emitter, and modulator operation will be characterized to improve device design and manufacturing processes. To support the computer data interconnect industry, NIST will develop techniques and disseminate data characterizing the effects of crosstalk between adjacent surface emitting lasers on the operation of optical fiber interconnect systems.

FY 95 Plans

- Determine the sensitivity of spectral reflectance, photoluminescence, X-ray, and transmission electron microscopy for measuring deviations in the growth of periodic semiconductor epilayer structures.

- Develop a variable-aperture, far-field photoluminescence technique for the study of emission from semiconductor microcavities.

- Improve the sensitivity and determine the accuracy of atomic absorption measurements for monitoring III-V epilayer growth.

- Develop a modified ionization gauge for the in-process measurement of elemental beam flux.

- Establish hardware and methodologies for the measurement of vertical-cavity surface-emitting laser (VCSEL) arrays; measure the effects of multiple device operation on the output wavelengths of arrayed VCSELs.

- Develop a prototype of a remote electromagnetic field sensor based on the optical pumping of vertical-cavity surface-emitting lasers.

Related Developments

- The 1994 Roadmap of the Optoelectronics Industry Development Association (OIDA), in its recommendations for optical communications, emphasizes the development of low-cost manufacturing technologies; in particular, it lists in-process monitoring and control of epitaxial growth as a priority item. The Roadmap states that "Steps should also be taken to strengthen metrology and standards-related work at NIST..."

- Several major U.S. companies have announced their involvement in developing technology using vertical-cavity surface-emitting lasers for applications ranging from computer interconnects to laser printing to optical data storage; until recently, the development effort has rested with a few small start-up companies.

FY 94 Accomplishments and Impacts

- Measured and evaluated the effect of vacancy diffusion and Al-Ga interdiffusion on GaAs quantum well heterostructures using the cross-sectional, micro-photoluminescence technique; the data support a new model of interdiffusion developed by university collaborators.

- Applied the cross-sectional, micro-photoluminescence technique to investigate the masking of gain peaks by cavity resonances in surface-normal photoluminescence measurements of vertical-cavity quantum-well lasers; used computer simulations and spectral reflectance measurements in correlating the photoluminescence data.

- Demonstrated atomic absorption spectroscopy (AAS) for monitoring the incident element beams during deposition of III-V semiconductor epilayers, and separated the effects of reflection and absorption in the reflection configuration of AAS. AAS is a promising, nondestructive technique for the in-process monitoring and control of thin-film deposition.

- Deposited AlGaAs distributed Bragg mirrors having high reflectance at visible wavelengths (485 to 720 nm); characterized the epilayers using X-ray diffractometry, reflectance spectroscopy, and transmission electron microscopy.

- Surveyed the measurement needs of the computer data interconnect industry and designed a research project which addresses the needs in laser array metrology. The intergroup project within the Optoelectronics Division will characterize the transverse mode, noise, jitter, and fiber-coupling properties of surface-emitting lasers.

Project: SEMICONDUCTOR MATERIALS AND DEVICES

FISCAL YEARS	95	96	97	98	99
Develop and refine measurement methodology for the composition and thickness of compound semiconductor heteroepitaxial layers. [STRS]					
Develop and evaluate techniques for the in-process measurement and control of compound semiconductor epitaxy. [STRS]					
Develop and apply measurement techniques to semiconductor optoelectronic devices used in computer data interconnects. [STRS, ARPA]					
Investigate and implement methods for remotely sensing electromagnetic quantities using vertically oriented semiconductor devices. [STRS, NASA]					
Develop novel semiconductor devices for advanced optoelectronics metrology. [STRS]					⇒

Project: DIELECTRIC MATERIALS AND DEVICES

FY 95 Fund Sources: STRS, IMRA, ATP

Staff (4.2 staff-years)

Professional	N. SANFORD	A. Aust	K. Malone	D. Veasey
Technician	J. Lankutis* (CU)			

name in capital letters = project leader; * = person works on project part time

Need Addressed: 1) Rare-earth doped glasses for integrated optical components: Rare-earth doped glass integrated optical components are becoming increasingly important as candidates for amplifier systems near 1300 nm and 1550 nm. The need exists to characterize the materials from which these devices are fabricated. 2) Grating devices for communication systems: Grating-based integrated optical components are gaining importance for wavelength division multiplexing, dispersion compensation, and for the fabrication of single-frequency lasers. Optical and analytical techniques are needed to evaluate grating uniformity, crosstalk, and efficiency. 3) Advanced processing of $LiNbO_3$: Rare-earth doping and domain engineering of $LiNbO_3$ are now recognized as important new technologies. Many examples of lasers useful for telecommunications, optical data storage, and biomedical applications have been published. The need exists to more fully characterize both the domain engineering processes and the rare-earth diffusion processes in this material.

Technical Approach: 1) Rare-earth doped glasses for integrated optical components: The Judd-Ofelt procedure will be used to evaluate the emission cross-section of various oxide glasses separately doped with Nd and Er. Ion-exchange techniques will be evaluated for use in forming optical waveguides. Gain, noise figure, and crosstalk will be evaluated for Er-doped glass waveguide amplifiers operating near 1550 nm, and promising Nd- and Pr-doped waveguides operating near 1300 nm. 2) Grating devices for communications systems: Holographic exposure, reactive-ion etching, and ion-beam milling will be used to form gratings on waveguide structures. Grating uniformity will be measured using atomic-force microscopy and optical scanning. Single frequency lasers will be fabricated by the use of distributed Bragg-reflector gratings. The utility of waveguide grating structures for chirp compensation and wavelength division multiplexing applications will be assessed. 3) Advanced processing of $LiNbO_3$: Diffusion rates and solubilities of (separately) Nd, Er, and Yb into $LiNbO_3$ will be measured. Substrate and thin-film uniformity measurements of $LiNbO_3$ will be performed using the Maker fringe method. Uniformity mapping will also be applied to domain-reversed segments. Work to stabilize green emitting self-doubling waveguide lasers fabricated in domain-inverted Nd-diffused $LiNbO_3$ will continue.

FY 95 Plans

- Measure gain and evaluate techniques for measuring noise figure for Er- and Nd-doped integrated optical waveguide amplifiers. Publish results.

- Optimize diffusion process for fabrication of single-mode waveguides at 1050 nm, 1320 nm, or 1550 nm in laser glasses. Calculate emission cross sections in Er-, Yb-, Nd-, and Pr-doped waveguide laser glasses.

- Develop single-frequency distributed-Bragg reflector waveguide lasers operating near 1050 nm in Nd-doped phosphate glass and near 1550 nm in Er-doped phosphate glass. Test linewidth by beating together independent lasers on a common substrate. Deliver single-frequency lasers to CRADA customer.

- Measure $LiNbO_3$ wafer and thin film uniformity by use of Maker-fringe scanning. Communicate results to ATP customers and others involved in the manufacture of integrated optical devices.

- Measure the solubility and diffusion rates of Er, Nd, and Yb into $LiNbO_3$ and publish results.

Related Developments

- Next generation wavelength-division multiplexed systems require relatively low (approximately 5-7 dB per stage) amplification with narrowband filters and Faraday isolation between stages. These constraints point to the application of integrated optical devices as amplifier components.

- Members of the German RACE program have recently demonstrated Er-diffused $LiNbO_3$ waveguide lasers with 30 mW of cw output power near 1550 nm. Single-frequency, tunable, and mode-locked lasers have also been demonstrated. The devices are useful for communication systems.

- Quasi-phased matched second-harmonic generating waveguides fabricated in $LiNbO_3$ have demonstrated 9 mW of blue light generation by the direct doubling of 54 mW from a laser diode. Target markets are optical data storage and reproduction graphics.

- The Optoelectronics Industry Development Association has stated the need to "accelerate the development and commercialization of short-wavelength lasers and suitable high-density optical recording systems and media."

FY 94 Accomplishments and Impacts

- Calculated emission cross sections for the special Nd-doped phosphate and silicate laser glasses supplied by a U.S. company. The calculation used the absorption spectra of the samples as data and employed the Judd-Ofelt technique for extracting cross sections.

- Constructed a Maker-fringe system for analysis of $LiNbO_3$ and $LiTaO_3$ wafer and film uniformity. This opto-mechanical system utilizes a Q-switched Nd:YAG laser and multi-axis computer controlled translation and rotation stages. The measurement technique is of importance in the analysis of epitaxial $LiNbO_3$ films and bulk $LiNbO_3$ substrates.

- Used analytical and optical methods to examine epitaxial $LiNbO_3$ waveguide films. Used atomic-force microscopy to establish grain size and surface roughness. Used M-line analysis to determine the number of optical modes that the waveguide films would support.

- Demonstrated the first passively Q-switched solid-state waveguide laser. The output pulses were characterized by 25-nm full-width-half-maximum and peak powers of 3 W.

- Fabricated a series of distributed Bragg reflector gratings on laser waveguides. These devices operated as single-frequency lasers.

- Delivered an integrated optical polarization-diversity receiver, fully integrated with waveguide polarizers and detectors and having immediate use in sensor systems for the monitoring of machine tool tolerances.

- Developed Nd diffusion-doped waveguide lasers in $LiNbO_3$ emitting green light as well as infrared. Amount of green radiation is significant compared to that from other frequency doublers in $LiNbO_3$.

Project: DIELECTRIC MATERIALS AND DEVICES

FISCAL YEARS	95	96	97	98	99
Establish waveguide fabrication and spectroscopy in rare-earth-doped phosphate-, silicate-, and tellurium oxide-based glasses. Maintain collaboration with industrial glass scientists and academic spectroscopists. [STRS]					
Develop methods to measure gain and noise in rare-earth-doped integrated optical amplifier systems. Interact with industry for measurement conventions. [STRS]					
Develop waveguide grating devices for single-frequency lasers, wavelength-division multiplexing, wavelength reference standards, and dispersion compensation. Interact with industrial partners for application development. [STRS, IMRA]					
Develop modified Maker-fringe mapping system to examine uniformity of $LiNbO_3$ and $LiTaO_3$ wafers, thin films, and domains. Team with industrial partners to correlate uniformity data with manufacturing quality control. [STRS, ATP]					
Establish diffusion rates and solubilities of Nd, Er, and Yb in $LiNbO_3$. Measure performance and stability of waveguide lasers and self-doubling waveguide lasers. Interact with telecommunication, optical data storage, and biomedical industry for applications of lasers. [STRS, ATP]					