NISTIR 5337

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1994 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

December 1993

NIST

NISTIR 5337

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1994 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

December 1993

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 1994 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

Copies of this document are available as Order No. PB94-126901 from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161, at (800) 553-6847 or (703) 487-4650.

TABLE OF CONTENTS

OVERVIEW

INTRODUCTION

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST Laboratories, is providing supporting technology that is 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 (1.8 million in 1992) and is in a virtual tie with the chemical industry for largest shipments (nearly $300 billion for 1992).[1] The electronics industry exerts extraordinary influence on the performance of every other U.S. industry.

For the electrical-equipment industry, U.S. shipments are $48 billion (1990).[2] Among the products included in those shipments are the various types of equipment used by the electric utilities. They provide $187 billion of electricity annually (1992).[3]

These industries are battling for market share in increasingly competitive international markets. The United States is experiencing an unfavorable and worsening balance of trade for electronic products overall.[4] The consumer electronics market has been lost; and the computer market, traditionally a strong area for the United States, is showing signs of erosion. 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 -- but one critical factor that NIST can address is measurement capability. Both the electronics industry and the electrical-equipment industry are outstripping the available measurement capability required for competitiveness. The lack of adequate measurement capability adversely affects virtually every step required to realize competitive products. Adversely affected are product performance, price, quality, compatibility, time to market, and implementation of new management strategies, to name a few factors.

NIST can help by providing measurement capability that supports the efforts of U.S. industry to improve its competitiveness. This program plan describes the part of that support that EEEL will provide. This plan addresses the five-year period from FY 1994 through FY 1999, with a special focus on FY 1994. This 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. These 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.[5]

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, about 72 percent of EEEL's customers are from U.S. industry. When last surveyed, 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.

EEEL customers also include other government agencies (Federal, state, and local). EEEL provides measurement capability and other services that help those agencies fulfill their many responsibilities in areas such as defense, energy, transportation, communications, health, safety, and law enforcement. EEEL's measurement services also support educational institutions.

EEEL indirectly supports the general public through its services to the organizations already named. EEEL serves the research community wherever it is located -- in industry, government agencies, or educational institutions.

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 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:

They may feel that NIST's special technical capability for measurement development is needed.

They may feel that 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 may feel that 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*, beginning on page 21.

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.

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 the 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. The technology realized in that instrument or circuit is transferred 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 organizations exist to fund technology development, and some have considerable resources. Thus, the additional resources that EEEL could provide would not be significant. These organizations include NIST's own Advanced Technology Program ($200 million per year beginning in FY 1994), the interagency Technology Reinvestment Project ($500 million per year beginning in FY 1993),[6] and many of the 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. 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:[7]

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

Table 2: MEANS OF DELIVERY

Communications	**FY93**
publications	214
software requests	279
talks	290
consultations	1710
visits	420
visitors	1000
meetings	
attendees	900
contributors	65
Joint Activities	
standards organizations	
staff participating	47
memberships	90
professional societies	
memberships	280
cooperative research	94
consortia (incl. forming)	3
guest scientists	42
Paid Services	
custom measurement development	159
standard reference materials	103
calibration service customers	450
training courses	11

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.[8] FY 1993 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 the number of technology-transfer activities that they can handle.

INDUSTRIES SERVED

Table 3: SERVICES

Information
- generation
- manipulation
- transfer
- storage
- display

Energy
- generation
- control
- transfer
- storage
- conversion

The Electronics and Electrical Engineering Laboratory 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.

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] Each has estimated annual shipments approaching $300 billion per year for 1992; the difference between them is not significant, given the different ways the values were determined. The electronics industry is the largest employer with 1.8 million workers, more than the next three largest manufacturing industries combined.

The electronics industry produces a broad spectrum of products. This spectrum is outlined in Table 5 using a condensed version of the structure employed by the industry itself, through the Electronic Industries Association.[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 4: LARGEST U.S. MANUFACTURING INDUSTRIES (1992)

Industry	Shipments ($billions)	Employment (thousands)
Electronics[9(a)]	288	1,808
Chemical[9(b)]	279	853
Automotive[9(c)]	227	873
Petroleum Refining[9(d)]	130	72
Aerospace[9(e)]	113	652

The shipments of the U.S. electronics industry have been essentially flat over the five-year period from 1988 to 1992. Employment in the industry has been falling, with a compound average growth rate of -3.7 percent per year over the same period.

Table 5: ELECTRONIC PRODUCTS
Electronic Components and Materials
Communications Equipment
commercial, industrial, military
telephone, telegraph
intercommunications, alarm, traffic control
broadcast, studio, and related
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

Electrical-Equipment Industry

The electrical-equipment industry is considerably smaller than the electronics industry but is still quite large. This industry shipped $48 billion of products in 1990.[11] The products of this industry are outlined in Table 6, where they are arranged by the basic services that they provide. Included in this sum, among other products, are all of the electrical products used by the electrical utilities to provide $187 billion of electricity annually (1992).[12] 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.

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.

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

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 peculiar to video and beyond the more 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 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.

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

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 technologies marked "future" in the table but lacks the resources to launch even a small program.

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. It is not unusual for EEEL to have 50 collaborative activities underway with other NIST Laboratories at any given time.[13]

Table 8: FY 1993 RESOURCES

Funding	$millions	percent
base	23.7	56
non-base		
from NIST[1]	2.8	6[4]
from outside NIST		
development[2]	13.2	31
services[3]	2.8	7[4]
total	42.5	100
Staff	number	percent
paid		
full-time permanent	298	77
other	45	12
total paid	343	89
unpaid		
guest scientists	42	11
total unpaid	42	11
total	385	100

Notes on Funding
[1]71 percent from Advanced Technology Program
[2]87 percent from other Federal agencies
[3]78 percent from calibrations services
[4]difference due to rounding more exact dollar values

RESOURCES

EEEL's funding and staff resources for FY 1993, the most recently completed year, are shown in Table 8. Base funding is provided by the Congress directly to NIST for the programs conducted in the NIST Laboratories. Non-base funding comes from multiple sources, but predominantly from three sources: funding transferred from NIST's Advanced Technology Program for support of its programs, funding transferred to NIST by other Federal agencies for the development of measurement capability supporting their programs, and funding provided by U.S. industry and other agencies for calibration services.

For FY 1994, EEEL anticipates an increase in its overall funding to the level shown in Table 9.

Table 9: FY 1994 RESOURCES (estimated)

	$millions
base	28
non-base	17
total	45

PLANNING

EEEL reflects its plans and accomplishments in five types of published documents, as shown in Table 10. Also shown are typical publication frequencies 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 five 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

Table 10: PUBLISHED PLANNING DOCUMENTS

Document	**Frequency of Publication** (years)	**Time Horizon** (years)
needs assessments	irregular	10
strategic plan	2	5
program plan	1	5
annual report	1	1 backward
impact studies	irregular	10 backward

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, focusing principally on the current year but extending five years into the future also. The annual report, which will be published for the first time at the end of 1993, provides a statement of accomplishments for the most recently completed year. The impact studies are published on an irregular schedule, as they are completed.

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: MEASUREMENT NEEDS AND IMPACT DOCUMENTS

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

Table 11 shows both documents completed in FY 1990-1993 and documents planned for FY 1994-1995. As shown 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.[14] For two fields -- optical signal processing and optical computing -- no special analyses are yet planned because these fields are still in early stages of development.

EEEL employs other mechanisms, as well, to gather information important for planning. These other 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, and workshops. For example, EEEL, in cooperation other NIST Laboratories and Government agencies, held a workshop in October, 1993 to determine the requirements, technical barriers, and innovations associated with emerging components for electric and hybrid-electric vehicles. This workshop is providing the basis for subsequent efforts to identify associated critical measurement needs. Further, EEEL, in cooperation with the Advanced Research Projects Agency, is planning a major workshop on the measurement needs of the semiconductor industry for October, 1994. It will have broad representation from the industry.[15]

RESPONSE TO STRATEGIC PLAN

The pages that follow describe in detail EEEL's plan for response to its *1994 Strategic Plan*. The material is organized into a series of projects. The description of each project contains two pages of text that state the objective and significance of the project in general terms, the major accomplishments for the past fiscal year, FY 1993, and the major plans for the current fiscal year, FY 1994. Thereafter, a chart called the five-year plan summarizes the major accomplishments that will be pursued by that project during the period FY 1994 to FY 1999.

The projects are arranged according to the offices and divisions that comprise EEEL's organizational structure. EEEL is organized into four divisions, each of which is subdivided into groups. In addition, EEEL contains two offices that fund and manage, but do not conduct, programs. One is the Office of Microelectronics Programs (OMP). It manages a NIST-wide program in support for the semiconductor industry. Part of its program is conducted within the various divisions of EEEL and part within the divisions of other NIST Laboratories. In the attached descriptions of the projects of the divisions, the annotation "OMP" appears next to work funded by the OMP Office. 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, virtually all of its program is conducted within the various divisions of EEEL. This second office is supported entirely by funding from other Federal agencies.

Table 12 shows how the fields of technology of the *1994 Strategic Plan* relate to the various projects conducted by EEEL.

Table 12: CROSSWALK BETWEEN STRATEGIC PLAN AND PROGRAM PLAN

STRATEGIC PLAN: FIELDS OF TECHNOLOGY	PROGRAM PLAN: PROJECTS	Page
SEMICONDUCTORS	Nanoelectronics	69
	Semiconductor Characterization Technology	73
	Thin-Film Characterization	80
	Electrical and Thermal Characterization	77
	Test Structure Metrology for Advanced Semiconductor Manufacturing	83
	Plasma Chemistry - Plasma Processing	33
MAGNETICS	Magnetics	172
SUPERCONDUCTORS	Superconducting Metrology	154
	Detectors and Thermal Converters	160
	High-Temperature Superconducting Films and Electronic Devices	163
	Superconductor Standards	166
	Conductor Systems	169
	Superconductor Structure and Properties	175
LOW FREQUENCY	Generation and Measurement of Precise Signals	42
	Waveform Acquisition Devices and Standards	45
	Measurements for Complex Electronic Systems	48
	AC-DC Difference Standards and Measurement Techniques	51
	Improved Impedance Calibration Service	57
MICROWAVES	Power Standards and Measurements	89
	Impedance, Attenuation, Voltage Standards and Measurements	93
	Network Analysis and Measurement	97
	Noise Standards and Measurements	105
	Antenna Measurements, Theory and Applications	119
	Metrology for Antenna, Radar Cross Section and Space Systems	124
	MMIC Standards and Measurements	101
	Electromagnetic Properties of Materials	132
	Special Tests, Measurements and Calibrations	128
LIGHTWAVES	Optical-Fiber Measurement Systems and Standards	139
	Optical-Fiber Sensors	142
	Integrated Optoelectronics	145
	Measurements for Sources and Detectors	148
	Laser Power and Energy Measurements	151
VIDEO	Video Technology	36
POWER	Measurements to Support Electric Utilities	27
	Dielectrics Research	30
ELECTROMAGNETIC COMPATIBILITY	Standard Electromagnetic Fields and Transfer Probe Standards	114
	Emission and Immunity Metrology	110
ELECTRONIC DATA EXCHANGE	Automated Electronics Manufacturing	39
NATIONAL ELECTRICAL STANDARDS	Quantum Voltage and Current	60
	Quantum Resistance and Capacitance	63
	Resistance Standards and Measurement Methods	54
	Cryoelectronic Metrology	157

ENDNOTES

1. All shipments figures were compared in current dollars. They are also estimates since no firm shipment data for 1992 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 of these industries compared. 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 data for the largest five manufacturing industries came from the following sources: (a) Electronics Industry: *1993 Electronic Market Data Book*, Electronic Industries Association, pp. 2, 5 (1993). (b) Chemical Industry: *1993 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 11-1 (January 1993). (c) Automotive Industry: The figures shown include both the motor-vehicle and supporting parts industries. *1993 U.S. Industrial Outlook*, pp. 35-1 and 35-18. (d) Petroleum Refining Industry: The employment figure is from 1990, the year of most recent data, and is used as an estimator for 1992. *1993 U.S. Industrial Outlook*, p. 4-1. (e) Aerospace Industry: *1993 U.S. Industrial Outlook*, p. 20-1.

2. The definition used for the electrical-equipment industry 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.

3. Preliminary figures for 1992 from the Edison Electric Institute, Washington, DC (November 1993).

4. *1993 Electronic Market Data Book*, Electronic Industries Association, p. 5 (1993).

5. *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).

6. The Technology Reinvestment Program will fund new work in FY 1994 as well. Its future thereafter will apparently be determined on a year-by-year basis.

7. 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.

8. EEEL in previous strategic plans has reported also the number of industrial research associates working in EEEL. However, the cooperative research and development agreements that NIST has developed with industry have made this category irrelevant. The agreements define a general relationship that enables researchers from participating companies to work at NIST for varying lengths of time without additional special agreements for each researcher. Unrelated to these agreements, guest scientists come to NIST from U.S. universities and foreign countries.

9. All shipments figures in the table are *product data* in current dollars. They are also estimates since no firm shipment data for 1992 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) *1993 Electronic Market Data Book*, Electronic Industries Association, pp. 2, 5 (1993). (b) *1993 U.S. Industrial Outlook*, International Trade Administration, U.S. Department of Commerce, p. 11-1 (January 1993). (c) The figures shown include both the motor-vehicle and supporting parts industries. *1993 U.S. Industrial Outlook*, pp. 35-1 and 35-18. (d) The employment figure is from 1990, the year of most recent data, and is used as an estimator for 1992. *1993 U.S. Industrial Outlook*, p. 4-1. (e) *1993 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. See endnote 2 for information about the definition used for the electrical-equipment industry.

12. Preliminary figures for 1992 from the Edison Electric Institute, Washington, DC (November 1993).

13. For example, at the end of FY 1990, when a count was last made, EEEL had 51 collaborative efforts in place as follows: Manufacturing Engineering Laboratory (7), Chemical Science and Technology Laboratory (12), Physics Laboratory (6), Materials Science and Engineering Laboratory (13), Building and Fire Research Laboratory (3), Computer Systems Laboratory (2), and Computing and Applied Mathematics Laboratory (8). Some of these collaborative efforts involved the transfer of funds.

14. All documents noted in Table 11 are shown below.

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*
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).
1994	a	Compound semiconductor measurement needs assessment, to be completed in 1994.
1994	s	Optical characterization methods for materials, processing, and manufacturing in the semiconductor industry, to be completed in 1994.
1995	a	Measurement needs assessment for semiconductors broadly, to be completed in 1995.

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.

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

1995	a	Low-frequency measurement needs, to be completed in 1995.

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.

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.

Optical Information Storage

1995	a	Optical information storage measurement needs assessment, to be completed in 1995.

Computers

1994	a	Computers measurement needs assessment, to be completed in 1994.

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

1994	i	John D. Ramboz, *Economic and Technical Impacts and Value of the NIST Calibration Services for Electrical Power and Energy*, to be completed in 1994.
1995	a	Power measurement needs assessment, 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

1995	a	Electronic data exchange needs assessment, to be completed in 1995.

National Electrical Standards

1995	a	To be addressed as part of the low-frequency measurement needs assessment in 1995.

15. *Semiconductor Materials Characterization: Present Status and Future Needs*, a workshop on measurement needs to be conducted on October 24-28, 1994 in Gaithersburg, MD, sponsored by the National Institute of Standards and Technology, the Advanced Research Projects Agency, and other organizations.

OFFICE OF MICROELECTRONICS PROGRAMS

Project: NIST-WIDE SEMICONDUCTOR MEASUREMENTS PROGRAM

FY 94 Fund Sources: STRS, SEMATECH

Staff (34.7 staff-years total, 16.2 staff-years outside EEEL)

Professional	ROBERT I. SCACE
Secretary	Alice T. Ensign

Objective: Apply technical skills from across the Institute to develop and deliver metrology needed by the semiconductor device, materials, and equipment industries.

Significance: Semiconductor manufacturing is a measurement-intensive activity. Measurements have until now consumed about 30 percent of the manufacturing cost of integrated circuits, but the SIA Workshop allocated only five percent as the goal from now until the next century. Conversely, metrology was identified as one of seven pervasive technologies needed by the industry for the foreseeable future. The clear implication is that reliable, cost-effective metrology is essential, and that if this can be correctly applied a major cost saving for the industry will result. A wide range of measurements is needed to meet the needs of the semiconductor industry, as described in the reports of the 1992 SIA Technology Workshop. Current projects managed through this Office, while only the beginning of a full-scale NIST-wide response to those needs, address issues raised in the Workshop reports and the technical roadmaps defined by them. Six NIST-funded projects and one SEMATECH project are covered here. All are driven by trends toward smaller feature sizes on chips, requirements for *ab initio* process models, and more stringent electrical and thermal demands on IC packaging.

FY 94 Plans

- Benchmark litho-metrology needs of the microelectronics industry and compare with available metrology tools. For SEMATECH, define where NIST can develop means to match tool capabilities to these needs.

- Measure kinetic-energy distributions of ions from rf plasmas in pure gases and gas mixtures and of free radical and intermediate chemical species in plasma and CVD reactors to improve process modeling.

- Measure the thermal expansion of thin films of polymeric materials to determine strain effects and their relationships to composition of the polymer, cure, and thermal expansion.

- Determine the microstructures created by solder wetting and solidification to help improve reliability of soldering of semiconductor devices to printed circuit boards.

- Measure mechanical properties of aluminum, copper, and multilayer (Al and Cu with titanium) thin films to help improve interconnect reliability.

- Complete Mobile Calibration Unit and deliver to SEMATECH by 1/1/94.

Related Developments

- Impending legislation on removal of Pb from solder alloys makes it imperative that new solder alloy systems be developed that meet high manufacturing and performance standards, as well as environmental standards.

- Two NRC postdoctoral fellows are working in Boulder on interconnect materials.

FY 93 Accomplishments

- Published review of measurement of critical dimensions on X-ray masks using transmissive SEM techniques.

- Measured influence of trace amounts of gas-phase oxygen, water, and nitrogen on argon discharges, to model plasma processes in GEC cell.

- Designed new methods of measuring interfacial strain between polymers and silicon.

- Designed new accelerated aging test to amplify minor defects in surfaces which lead to solderability defects and to simulate component solderability after storage.

- Developed initial test procedures for measuring thermomechanical strains in plated-through-holes and other specimens.

- Two spectroradiometers designed, constructed, calibrated and delivered to SEMATECH.

OFFICE OF LAW ENFORCEMENT STANDARDS

Project: LAW ENFORCEMENT TECHNOLOGY

FY 94 Fund Sources: OA: NIJ, NHTSA, FBI

Staff (6.0 staff-years)

Professional	L.K. ELIASON	N.J. Calvano	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

Objective: Apply the resources of EEEL and NIST overall 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. Prepare reports on topics of interest to law enforcement personnel based upon NIST research and develop analytical techniques and standard reference materials for forensic science application. 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.

Significance: Law enforcement agencies continue 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 ability to apply sophisticated equipment and systems to forensic applications. Many companies are expanding their product lines to include equipment specifically for law enforcement use. Often these manufacturers use the standards developed by the Office of Law Enforcement Standards (OLES) for NIJ/NHTSA as the basis of product design. The adoption by law enforcement 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.

FY 94 Plans

- Issue the standard reference material for DNA-typing, employing the polymerase chain-reaction technique.
- Complete the standard for photoradar devices.
- Complete the standard for laser speed-measuring devices.
- Complete the standard for sharp-instrument-penetration-resistant armor.
- Initiate research on body-armor trauma plates.
- Develop a method to test armor-piercing ammunition.

Related Developments

- The Director of EEEL and the Acting Director of the National Institute of Justice (NIJ) signed a new Memorandum of Understanding, which is intended to continue the OLES program for another five years. Following the appointment of the new NIJ Director, the development of a multi-year program plan with an increase in OLES funding in the out-years is anticipated.

- Body armor manufacturers continued to participate in the NIJ Compliance Testing Program, submitting over 150 models for testing during FY 93. Likewise, radar speed-measuring device manufacturers continued to participate in the International Association of Chiefs of Police test program. Two new models were tested for compliance with the NHTSA specifications, and another 750 were subjected to critical performance testing for quality assurance purposes. While both of these programs are voluntary, law enforcement agencies require demonstrated compliance with the OLES-developed standards as a condition of purchase.

- The National Armor Advisory Board (NAAB) industry representatives have agreed to work toward the development of a quality assurance program for universal application by all body armor manufacturers, and to develop a program to certify the ballistic performance of all lots of material sold to body armor manufacturers. This represents the first time that all segments of the body armor industry have agreed to pursue uniform quality assurance practices to ensure that the final product consistently meets the protection needs of the law enforcement community.

FY 93 Accomplishments

- Completed the development of test methods for sharp-instrument-penetration-resistant armor.

- Drafted a standard for the flammability of mattresses for detention and correction facilities.

- Developed test methods for photoradar speed-measuring devices and completed preliminary laboratory tests of these systems.

- Demonstrated the feasibility of evaluating the operating characteristics of laser-speed-measuring devices and initiated tests of these devices.

- Continued to provide technical support to the FBI in the development of integrated-systems, digital-network, intercept systems.

- Completed initial round robin tests of prototype standard reference materials for DNA-profiling, employing the polymerase chain-reaction technique.

- Issued AutoBid for 1993 vehicle year; published reports on locks for corrections facilities, mattress flammability, trunked radio systems, a test procedure for handgun accuracy, and a guide to voice privacy for police communication systems.

- OLES assisted the National Institute of Justice in establishing a NAAB as an adjunct to the NIJ Technology Assessment Program Advisory Council (TAPAC). The Board is composed of body armor manufacturers and their materials suppliers, and representatives of both law enforcement rank and file membership and management.

ELECTRICITY DIVISION

Project: MEASUREMENTS TO SUPPORT ELECTRIC UTILITIES

FY 94 Fund Sources: STRS; OA:TVA, DOE, EPRI, NTP; PEAC, DOE, Calibration Fees

Staff (6.4 staff-years)

Professional	G. FITZPATRICK	F. Martzloff	M. Misakian	T. Nelson
	W. E. Anderson*	M. Fulcomer*	J. K. Olthoff*	E. Simmon
Technician	J. Chandler	J. Pitt*	A. Secula	

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

Objective: To develop technologies in support of the electric utilities and manufacturers of electric power equipment. Specifically, to develop (a) improved techniques for the measurement of both steady-state and transient voltages above 1000 volts and currents above 100 amperes, electric power and energy, (b) technologies to characterize the quality of electric power delivered to end users and also the compatibility of end-user equipment with power systems, and (c) calibration and measurement techniques required to characterize electric and magnetic fields, and ion densities.

Significance: Electrical energy metering throughout the U.S., which is directly traceable to NIST calibrations, results in annual revenue for utilities exceeding $187 billion (1992). The industry needs developments in technology and support for evolving international standards, particularly for new devices, such as optical current transducers (OCTs). Accurate measurements are needed to assess the effects of power system disturbances on sensitive equipment and of electronics systems on power quality. Measurements related to electrical parameters used in bioeffects research are needed to support development of safe and efficient electric power and end-use systems. The estimated economic loss due to uncertainty over bioeffects is near $1 billion/year.

FY 94 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 OCTs over the range from 100-10,000 A with uncertainties of 0.1% or less using curve-fitting of high-resolution digitized waveforms.

- Evaluate the concept of reference measurement systems and verify tests defined by International Electrotechnical Commission IEC 60-2, High Voltage Measurement Techniques.

- Participate in the development of international standards on electromagnetic compatibility.

- Provide technology transfer to the EPRI Power Electronics Application Center (PEAC).

- Provide measurement support and consultation for bioeffects studies as required for Department of Energy (DOE), National Toxicology Program (NTP), Electric Power Research Institute (EPRI) and EPRI-PEAC; e.g. site visits for DOE, NTP, and EPRI.

- Solve measurement uncertainty problem specific to the coil probe used for measuring magnetic fields from appliances. Perform a comprehensive study of the measurement uncertainty of the three-axis probe and submit a manuscript describing the results to an archival journal.

- Prepare the third draft of the new IEEE Power Engineering Society (PES) Standard (P1308) on extremely low frequency (ELF) measuring instrumentation, and prepare revisions to PES Standard (P644).

Related Developments

- IEEE Power Engineering Society Emerging Technologies Subcommittee plans to finish a draft of Trial Use Standard (P1304) on OCTs and circulate for vote by the end of 1994.

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

- The U.S. Energy Bill of 1992 provides for $65 million in electromagnetic fields research over five years. NIST is represented on an Interagency Committee established to provide planning and recommendations.

FY 93 Accomplishments

- Executed a CRADA to develop calibration techniques for OCTs. Demonstrated linearity of the NIST OCT from 200 A to 10 kA of better than 0.1% and reported the results at a conference.

- Calibrated approximately 105 devices for revenues of $250,000. The devices calibrated included 26 current and voltage transformers, 44 watthour standards, 15 instruments as part of energy Measurement Assurance Programs (MAPS), and 19 dividers.

- Developed model-based deconvolution technique for high-voltage impulse waveforms. Demonstrated insensitivity to noise at levels up to 5% and improved fit of oscillatory waveforms.

- Evaluated the suitability of Kerr cells as reference measurement systems defined by IEC 60-2. The results were published in two companion conference papers.

- Provided EPRI with three Technical Bulletins on Power Quality Issues.

- Completed calculations of measurement uncertainty when ac magnetic fields from electrical appliances are characterized using single-axis and three-axis coil probes and published the results in the *NIST Journal of Research*. Measurements were shown to differ from the field at the center of the probe by as much as 20%, depending upon probe orientation and proximity to the source.

- Conducted site visits to the University of Kentucky, State University of New York at Stony Brook, and the University of Utah on behalf of EPRI to characterize ac and dc magnetic fields in exposure systems. Results of measurements were reported to the sponsor and researchers. Similar site visits were made to the Illinois Institute of Technology Research Institute on behalf of the National Toxicology Program (NTP) and to the University of Quebec on behalf of Hydro-Quebec.

- Published a primer on in vitro studies with ELF magnetic and electric fields as a special edition of the journal *Bioelectromagnetics*. Nearly 100 requests for reprints of the primer, the first of its kind, were received within three months of its publication.

Project: MEASUREMENTS TO SUPPORT ELECTRIC UTILITIES

FISCAL YEARS	94	95	96	97	98
Upgrade equipment and methods for calibration services. [STRS, OA-Calibrations]	—	—	—	—	—
Develop measurement support for optical voltage and current measurements. [STRS, OA]	—	—	—		
Improve range and accuracy of DC High Voltage measurements. [STRS]	—				
Develop methods for non-sinusoidal quantities for metering. [STRS]	—	—	—	—	
Develop techniques for impulse waveform analysis with improved accuracy. [STRS]	—				
Investigate electro-optic and magneto-optic sensors. [STRS, OA]	—	—	—		
Develop and characterize systems used to measure pulses required in international commerce in electrical power equipment. [STRS]	—	—	—	—	—
Provide improved measurement methods for surveying power quality parameters. [STRS, OA]	—	—	—		
Determine response of varistors to fast pulses. [STRS, OA]	—				
Develop standards for power quality monitoring instruments. [STRS, OA]	—	—	—	—	
Provide measurement support and consultation for DOE/NTP/EPRI. [OA]	—	—	—	—	—
Prepare revisions of draft standard (P1308) and existing standard (P644). [OA]	—	—			

Project: DIELECTRICS RESEARCH

FY 94 Fund Sources: DOE, EPRI, NRC, STRS

Staff (2.0 staff-years)

Professional	R. J. VAN BRUNT	E. W. Cernyar*	F. Martzloff*	J. K. Olthoff*
	K. L. Stricklett*	P. vonGlahn*		

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

Objective: To develop advanced measurement methods and data needed to detect and to understand the physics and chemistry of partial-discharge phenomena in gaseous, liquid, and solid dielectric materials in electrical equipment. These pheomena are responsible for material degradation and the formation of highly toxic and corrosive by-products.

Significance: Partial discharges occur at localized sites in electrical insulation where there is enhancement of the electric field. Their occurrence is generally associated with insulation deterioration and eventual breakdown. Of particular concern to industry is the formation during partial discharge of toxic compounds, such as S_2F_{10}, in SF_6-insulated power systems, that represent a possible health hazard. The information provided by this project permits the development of improved techniques for detecting partial discharge and related discharge by-products in electrical equipment required for better assessment of insulation integrity and determination of safer operating procedures.

FY 94 Plans

- Measure and calculate the S_2F_{10} production rate from partial discharge in SF_6/O_2 mixtures with and without the presence of epoxy insulation.

- Measure the appearance potentials of positive ions produced by electron-impact ionization of $S_2O_2F_{10}$, S_2OF_{10}, SF_5Cl, and $S_2O_5F_2$.

- Complete construction of a "compact" Gas Chromatograph - Mass Spectrometer system for detection of S_2F_{10} and related discharge byproducts in SF_6.

- Perform measurements of partial discharge in phenylxylyl ethane (capacitor fluid) and triggered breakdown in transformer oil.

- Complete an assessment of the applicability of existing time domain spectroscopy and partial discharge analysis methods for nuclear power plant cable-condition monitoring.

- Construct and test partial-discharge data recorder, develop related stochastic analysis software, and document the results of partial-discharge measurements and simulations for point-dielectric gaps.

Related Developments

- A cooperative research and development agreement (CRADA) was formed to address the problems of detecting S_2F_{10} in SF_6 and understanding the conditions under which this compound is formed or destroyed in gas-insulated power systems. The research at NIST is conducted in collaboration with the Oak Ridge National Laboratory and Ontario Hydro with funds administered through DOE and EPRI.

- The Nuclear Regulatory Commission is implementing a program to assess the condition of instrument and control cables used in nuclear power plants as part of its license renewal and life extension procedures. NIST has been asked to play a role in this program in providing technical assistance in evaluating and developing measurement methods.

- R.J. Van Brunt has been invited to present the keynote Whitehead Memorial Lecture at the 1994 IEEE Conference on Electrical Insulation and Dielectric Phenomena. The lecture, entitled "Physics and Chemistry of Partial Discharges - Recent Advances and Future Challenges," will also be published in a special issue of the *IEEE Transactions on Electrical Insulation.*

- R.J. Van Brunt presently serves as Secretary for the 47th Annual Gaseous Electronics Conference to be hosted by NIST in 1994, Chairman of the IEEE Technical Committee S-32-11 on Gaseous Dielectrics, member of the Advisory Committee for the 11th International Conference on Gas Discharges and Their Applications, member of the Technical Committee for the Third Volta Colloquium on Partial Discharge, member of the Organizing Committee for the International Symposium on Gaseous Dielectrics, Associate Editor of the IEEE Transactions on Dielectrics and Electrical Insulation, and member of the Administrative Committee of the IEEE Dielectrics and Electrical Insulation Society.

FY 93 Accomplishments

- Work was done on development of a procedure to detect S_2F_{10} and related discharge by-products in SF_6 and the use of this procedure to measure S_2F_{10} production rates in corona discharges; applied in an archival paper published in the *IEEE Electrical Insulation Magazine.*

- Electron scattering and negative ion formation by SF_6 discharge by-products, including S_2F_{10}, S_2OF_{10}, $S_2O_2F_{10}$, SOF_2, SOF_4, SO_2F_2, SF_4, and SO_2, were measured, and the results were covered in two archival papers published in the *Journal of Chemical Physics* and in *Plasma Chemistry - Plasma Processing.*

- Computer simulations and laboratory experiments were used to demonstrate the importance of including effects of memory propagation in the interpretation of data on stochastic properties of partial discharge and the results were published in an invited archival paper.

- Measurements and calculations of the partial-discharge aging of cast epoxies and related nonstationary behavior of the discharge statistics were performed, and the results were presented in two conference papers.

- Work was completed for a CRADA to measure SF_6 decomposition by x-ray photolysis. The results are covered in a report prepared for the industry partner and in an abstract submitted to the 1994 International Symposium on Gaseous Dielectrics.

- An experiment was completed to demonstrate the refraction of light due to the presence of a divergent electric field in a Kerr media. The results were covered in a conference paper.

Project: DIELECTRICS RESEARCH

FISCAL YEARS	94	95	96	97	98
Document results from measurement and calculation of S_2F_{10} and S_2OF_{10} production rates from negative corona in SF_6. [CRADA]	▬▬▬				
Measure appearance potentials of positive ions in the mass spectra of SF_4, S_2F_{10}, SF_6, SOF_2, SOF_4, SF_5Cl, S_2OF_{10}, $S_2O_2F_{10}$, and $S_2O_5F_2$. [CRADA]	▬▬▬				
Measure production rates of S_2F_{10} and $S_2O_2F_{10}$ from corona discharges in SF_6/O_2 mixtures in the presence of epoxy insulation. [CRADA]	▬▬▬				
Build compact Gas Chromatograph - Mass Spectrometer system for detecting trace S_2F_{10} in SF_6. [CRADA]		▬▬▬			
Construct and test prototype of partial-discharge data recorder and develop related stochastic analysis software. [STRS]		▬▬▬			
Develop and test partial discharge reference source. [STRS]			▬▬▬		
Develop "standard" method for quantifying pulsating partial discharge exposure levels for use in aging tests applied to gaseous, liquid, and solid insulation. [STRS]				▬▬▬	▬▬▬

Project: PLASMA CHEMISTRY - PLASMA PROCESSING

FY 94 Fund Sources: STRS

Staff (1.5 staff-years)

Professional	J. K. OLTHOFF	R. J. Van Brunt*	S. B. Radovanov*	M. Sobolewski*
	J. R. Whetstone*	J. R. Roberts*		

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

Objective: To develop fundamental reference data, reference discharge cells, and advanced measurement methods to support semiconductor applications. Measurement methods will include the use of mass spectrometry with ion energy analysis and optical spectroscopy, which can be used for the control and diagnostics of low-temperature, glow-discharge reactors that are employed for plasma processes, such as plasma etching and deposition of silicon.

Significance: To achieve the goal of reduced feature size in advanced integrated circuit design, the semiconductor electronics industry has replaced older, wet-chemistry surface-etching techniques with more advanced and complex etching techniques that utilize surface modification by exposure to controlled gas discharges. As greater demands are placed upon these plasma etching processes, improved control and characterization of the etching plasma become essential. The measurement of kinetic-energy distributions of mass identified ions correlated with optical emission, Langmuir probe, and laser-induced fluorescence measurements can provide the refined information needed for a more complete understanding and control of the etching process. In order to advance industrial plasma processing techniques, it has become necessary to consider development of reference discharges such as the Gaseous Electronics Conference (GEC) rf Reference Cell now being tested in numerous laboratories. Such cells can be used to calibrate diagnostic measurements, test chemical kinetics models of the etch process, and learn about the inherent physical characteristics of the discharge that determine the limitations on reproducibility.

FY 94 Plans

- Measure the kinetic-energy distributions of ions sampled from rf plasmas generated in various gas mixtures, such as Ar-H_2, He-N_2, and Ar-O_2, and in pure gases, such as helium, oxygen, nitrogen, and hydrogen. These data are of particular importance for the verification of plasma models.

- Quantify the effects of electrode surface conditions on the ion energy distributions, optical emission, and electrical waveforms measured for simple plasmas generated in the GEC rf Reference Cell.

- Complete the analysis of (E/N) energy distributions measured for ions sampled from diffuse, high electric-field-to-gas-density ratio, dc discharges in argon and nitrogen, and prepare the results for archival publication.

- Redesign and rebuild the drift tube-mass spectrometer to allow improved alignment, enable the use of different ion sources, and simplify the mounting of different mass spectrometer systems.

- Complete the analysis of the effects of trace quantities of gas-phase water, oxygen, and nitrogen on the electrical waveforms measured for argon plasma generated in the GEC rf Reference Cell.

Related Developments

- A CRADA is being negotiated to investigate $CH_4/Ar/H_2$ plasmas using the ion energy analysis and electrical measurement techniques developed at NIST. A second CRADA is being drafted which involves a performance comparison between micro-machined ion-energy analyzers and ion-energy mass spectrometers available at NIST.

- In 1994 NIST will host the 47th Annual Gaseous Electronics Conference, which has become a major forum for presentation and discussion of work on plasma chemistry and plasma processing. Jean Gallagher and R. J. Van Brunt from NIST serve on the Executive Committee for this conference.

- A special issue of the *NIST Journal of Research* is planned which will be devoted to work on the GEC rf Reference Cell, and is anticipated to have contributions from ten or more laboratories where this cell is used. J. K. Olthoff will serve as guest editor.

FY 93 Accomplishments

- Measured ion energy distributions using a new mass spectrometer system capable of detecting ions sampled through an orifice in the grounded electrode of the GEC rf Reference Cell. Kinetic energy distributions were determined for ions sampled from argon plasmas over a wide range of plasma conditions, and were shown to be in agreement with previous data obtained using a different mass spectrometer system that was mounted in a different configuration. The results were accepted for archival publication in the *Journal of Applied Physics*.

- Measured kinetic-energy distributions for ions sampled from rf discharges in gas mixtures of argon and helium. The ion energy distributions were analyzed in light of known ion-molecule interactions and the results were accepted for publication in the *Institute of Electrical and Electronics Engineers Proceedings A*.

- Measured and calculated the kinetic-energy distributions of ions sampled from diffuse, low-current, dc "Townsend" discharges in argon and nitrogen using an improved experimental procedure. The results were in good agreement with calculations based on measured cross sections, and allowed a determination of the limitations of the diagnostic equipment.

- Measured the influence of trace amounts of gas-phase oxygen, water, and nitrogen on the current and voltage waveforms measured for argon plasmas in the GEC rf Reference Cell. Observed the first experimental evidence of the influence of electrode surface conditions upon the plasma.

Project: PLASMA CHEMISTRY - PLASMA PROCESSING

FISCAL YEARS	94	95	96	97	98
Measure optical emission profiles and ion energy distributions from rf discharges in the GEC rf Reference Cell for $Ar\text{-}O_2$, $He\text{-}N_2$, and $Ar\text{-}H_2$ gas mixtures. [STRS]	—	—			
Modify drift tube-mass spectrometer and measure K+ ion energy distributions in rare gases. [STRS]	—	—			
Measure ion energy distributions from reactive etching plasmas using $SF_6\text{-}O_2$ and $CF_4\text{-}O_2$ 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 conditions on current and voltage waveforms, ion energy distributions, and optical emission measured for plasma generated in the GEC rf Reference Cell. [STRS]	—	—	—	—	—

Project: VIDEO TECHNOLOGY

FY 94 Fund Sources: STRS, ATP

Staff (6.0 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

Objective: Develop the measurement support needed by domestic industry to process and transmit video information. Develop and test measures for video-quality impairments produced by high-bit-rate compression systems and flat panel displays. Provide industry capability for real-time video simulation through access to the NIST Princeton Engine. Improve the ability of American manufacturers to become competitive in the flat panel market by contributing to the modeling and simulation of flat panel displays, and by developing technology-neutral photometric-based standards for flat panel displays.

Significance: Advancement in video transmission and display technologies has led to the development of multiple competing technologies for the transmission and display of video images. These technologies include analog versus digital transmission, interlaced versus progressive imagery, and cathode ray tubes (CRT) versus flat panel displays. At present, video quality is a poorly defined measure that prevents industry from properly evaluating or comparing these competing technologies for specific applications. Video quality is affected by the optical properties of cameras, by mathematical algorithms and electrical circuitry used to process the information, by the electro-optic properties of display devices, and by the task-viewing requirements. In 1990, video signal processing, transmission, and display technologies were estimated to affect a world equipment market of $116 billion. NIST intends to develop industry-recognized metrics for video quality, photometric tests for flat panel displays, and standard practices related to the limits of human perception of flat panel display performance.

FY 94 Plans

- Extend the video quality metrics that have already been implemented on the Princeton Engine to rate, subjectively, high-bit-rate video material and color fidelity.

- Create a laboratory for the photometric and colorimetric testing of flat panel displays, and implement manual measurement systems for the photometric measurement of the gray scale, colorimetry, and cross talk of flat panel displays.

- Develop advanced models for flat panel displays, on the Princeton Engine, to permit a subjective evaluation of human-vision perception limits of display artifacts.

- Develop working relationships with standards-setting organizations (domestic and international) that have jurisdiction relevant to flat panel display performance.

- Continue collaboration and technical research with industry groups investigating the question of the interoperability of advanced television systems and computer video systems. These groups include the Society of Motion Picture and Television Engineers, the Task Force on Digital Image Architecture, and the Advanced Television Systems Committee.

- Continue collaborations, and explore new collaborations with U.S. industry where the real-time capabilities of the Princeton Engine may be used effectively to solve their video-processing problems.

Related Developments

- The report on High Definition Information Systems prepared by the House of Representatives Subcommittee on Technology and Competitiveness, July 1992, cited NIST as an agency well-positioned to coordinate standards-setting activities related to the harmonization of high definition information systems. Specifically, NIST was directed to "continue its research into component technologies of a high definition information system such as flat panel displays, signal processors, and high-rate data transmission systems."

FY 93 Accomplishments

- Quality metrics suitable for telecommunications applications that correlate with subjective ratings have been implemented on the Princeton Engine. A family of video test patterns has been developed for qualifying and calibrating our implementation (and others).

- Equipment for photometric and colorimetric testing of flat panel displays has been designed, ordered, and, in most cases, received. This equipment includes a colorimeter, spectroradiometers, a charge-coupled-device (CCD) imaging system, signal generators, a display positioning system, and a spherical panel surround.

- A Digital Imaging Seminar was held November 4, 1992, and attended by about forty industry participants to discuss the capabilities of the Princeton Engine, and to encourage industry collaborations with NIST.

- A program running on the Princeton Engine, which models an electro-optic flat panel display, has been developed to simulate the effects of variable viewing angle, cross talk, and varying circuit impedances. A second program has also been developed to demonstrate color and gamma shifts observed in displays that have a phosphor chemistry different from CRTs, such as an electro-luminescent panel.

- An interactive controller has been designed and constructed for the Princeton Engine. The controller allows the operator to adjust program parameters while maintaining eye contact with the output monitor. This is a required component for evaluating human vision perception limits while running simulations on the Princeton Engine.

- Compression of video sequences typically involves computing motion vectors; it has been proposed that these vectors could be used as the basis of an algorithm to modify the frame rate of the video signal. For example, the vectors could be used to display broadcast television on a computer display or vice versa. A study was conducted on the Princeton Engine using various methods to compute motion vectors and evaluate the quality of the resulting video sequences.

- A CRADA has been executed to evaluate the efficacy of real-time video processing algorithms. As a result of this work, a measurement method has been developed to quantify the threshold of noise objectionability as a function of the video processing method and the background subject matter.

Project: VIDEO TECHNOLOGY

FISCAL YEARS	94	95	96	97	98
Establish 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. [OA; 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. [OA; 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 94 Fund Sources: STRS; ATP; OA: U.S. Navy; CSL

Staff (4.1 staff-years)

Professional	B. L. GOLDSTEIN	A. H. Cookson*	M. R. McCaleb	M. J. McLay
	C. H. Parks			

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

Objective: Contribute to the technology development of neutral product data exchange specifications and automation frameworks for the electronics industry. Provide an impartial forum to resolve conflicts among competing and conflicting standardization efforts on the exchange of product data by the electronics industry. Work with industry and other government laboratories to develop a program to promote the transfer of technical information between the manufacturers of electronic parts and those that need parts for the design, manufacture, and repair of electronic systems.

Significance: Integral to the electronics industry are product standards and specifications that 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.

Currently, there are at least four established standards which can be used to transfer data among automated tools for fabricating electronic products. The industry's complaint is that these standards are not fully capable of expressing designs unambiguously and that "harmonization" is needed to avoid costly waste in design and manufacturing.

The future health of the U.S. electronics industry will also depend on its ability to perform current business functions, electronically, over the emerging national information superhighway. The automation of business practices, such as the search for and brokering of component information, will enable the industry to compete globally in a timely manner.

FY 94 Plans

- Lead the National Initiative for Product Data Exchange, Electronic Commerce of Component Information (NIPDE ECCI) Electronic Business Reply Card scenario and work towards "continuously available" demonstrations. Collaborate with SEMATECH on electronic commerce application demonstrations. Demonstrate viability of emerging collaboration tools via in-house demonstration projects, such as the NIST Electronic Store Room Catalog, and on-line calibration documentation.

- Formalize CRADA for joint development and demonstration of software to prove the viability of the candidate standard (ISO 10303-210) for printed circuit assemblies.

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

- Author a white paper on the application of Integrated Computer-Aided Manufacturing Definition(IDEF) technology to electronic commerce scenarios. Assist in the development and standardization of IDEF methodology.

- Serve as testbed to the International Electrotechnical Commission (IEC) TC93 "Design Automation" efforts to harmonize and standardize electronic product data exchange methodology. Establish TC93 working group on test.

- 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

- The SEMATECH Consortium has become interested in collaborative projects related to prototyping a virtual lab environment. At SEMATECH's request, submitted four project proposals to assist in the standardization of their Computer-Integrated Manufacturing Application Framework.

- Due to their interest in data exchange standards, submitted a proposal to the Defense Information Systems Agency to extend and demonstrate the work published in NIST TN 1295.

FY 93 Accomplishments

- Established multi-platform automation testbed to support the development of solutions to interoperability problems among CAD tools and electrical/electronic product data exchange standards.

- Led demonstration project team on the National Initiative for Product Data Exchange (NIPDE) Electronic Commerce of Component Information (ECCI) project. The objective of ECCI is to produce proof-of-concept demonstrations and vision papers showing how the National Information Infrastructure can be used to automate the brokering of electronic component information. Helped develop and deliver a demonstration of an Electronic Business Reply Card at the thirtieth Design Automation Conference (DAC), June 14-18, 1993. Sponsored several related working meetings, and worked with NASA to author two related white papers. Produced posterboards and brochure for Automotive Supplier Excellence Conference, September 18-30, 1993. Spoke at Smart Valley Technology Partnering Workshop, May 27, 1993, and Manufacturing Extensions Partnership workshop, February 4, 1993.

- Assisted the Tri-Services Microwave and Millimeter-wave Advanced Computational Environment (MMACE) program team in the development of a prototype framework, which integrates tools into a common environment with a consistent look and feel. Organized and conducted a four day technical meeting MMACE program. Helped to convert several MMACE documents to World Wide Web format for interactive electronic distribution. Gave presentation on the "Role of Standards in Vacuum Electronics" at the MMACE Release Workshop and again at the Vacuum Electronics Annual Review in June, 1993.

- Began developing NIST "Electronic Storeroom" catalog. Gave presentations on use of World Wide Web (WWW) Internet connectivity to SEMATECH, Government Services Canada, Computer Systems Laboratory, and NIST Information Systems Committee. Began preparing electronic document for NIST WWW on Josephson Array activities. Spoke at National Conference of Standards Laboratories symposium. Prepared preliminary Electricity Division on-line document with personnel and group activity associations.

- Assisted in Federal Information Processing Standard (FIPS) standardization of IDEF methodologies, and participated in IDEF Users Group. Authored and/or presented the following papers:
  "Improving the Quality of Model Reviews with Computer Hypertext Technology".
  "Applying Hypertext to Managing Versions of a Standard," NISTIR 5245.

- Assisted in producing STEP Application Protocol 210, Version 0.7, on printed circuit assemblies.

- Published NIST TN 1295, "Initial Graphics Exchange Specification Hybrid Microcircuit Application Protocol."

Project: AUTOMATED ELECTRONICS MANUFACTURING

FISCAL YEARS	94	95	96	97	98
Help Tri-Services form MMACE Users Group, define requirements and hold workshops. [OA-DoD]	—	—			
Develop and demonstrate software translator between commercial tool and STEP AP210. [STRS, ATP]	—	—			
Coordinate international testing support; test/validate electronic product data exchange standards. [STRS, ATP]	—	—	—	—	—
Develop electronic commerce applications for electronics; distribute through Manufacturing Technology Centers and regional networks. [STRS]	—	—	—	—	—
Develop distributed hypertext documents for NIST internal and industry projects. [STRS, OA-DoD]	—	—	—	—	—
Expand, demonstrate and support standardization of NIST TN 1295. [STRS]	—	—	—		
Aid in development of electrical product data standards. [STRS]	—	—	—	—	—
Promote standardization and test of SEMATECH's CIM Application Framework. [OA-SEMATECH]	—	—	—		
Build toolkits for concurrent engineering of information exchange standards and for development of interoperable electronics automation tools. [STRS]		—	—	—	—
Develop and promote electronic commerce educational package. [STRS]		—	—	—	—
Support standardization of IDEF methodologies; study application of IDEF to electronic commerce. [OA-DoD (via CSL)]		—	—		
Manage ARPA projects and review ATP proposals. [STRS]	—	—	—	—	—
Serve as IGES Change Control Secretary. [STRS]	—	—	—		

Project: GENERATION AND MEASUREMENT OF PRECISE SIGNALS

FY 94 Fund Sources: STRS; OA: AF, NASA; Calibration fees

Staff (5.0 staff-years)

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

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

Objective: Develop techniques for generating and measuring voltage and current waveforms over the frequency range: dc to 100 MHz. Extend automatic inductive divider measurement capability up to 1 MHz and develop techniques to measure generalized impedances in the dc to 1 MHz range. Develop 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. Develop calibration services, where necessary, with measurement uncertainties in the range of ±1 ppm at dc to ±1% at the highest frequencies.

Significance: Industrial, university, and government laboratories have calibration requirements for basic instrumentation standards that span wide frequency ranges to support calibrators, digital multimeters (DMMs), impedance (LCR) meters, and phase meters. The market for these instruments is over $500 million annually. New waveform generation and measurement capability at NIST will support the basic quantities of ac voltage, current, phase angle, and impedance. The power industry legally requires NIST traceability to equitably distribute the $187 billion (1992) 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.

FY 94 Plans

- Construct and test a new dual-channel digitally synthesized source, which may be easily duplicated or commercialized, to replace the generators in the Power/Energy Calibrator and the Digital Impedance Bridge (DIB).

- Construct a second probe and support circuitry for the DIB to extend the range of inductance measurements from 10 μH to 10 H over a frequency range of 100 Hz to 100 kHz.

- Modify the Binary Inductive Voltage Divider (BIVD) Bridge to automatically intercompare nominally equal capacitors (for capacitance and dissipation factor) over a frequency range of 100 Hz to 100 kHz with <1 ppm uncertainty in the mid-audio frequency range.

- Implement and announce a new 25-point DMM special test for <$1000 with a scheduled 1-week turn-around time.

- Develop a measurement system and demonstrate a wideband wattmeter test (50 Hz to 200 kHz) at an uncertainty of <0.2%.

Related Developments

- High accuracy 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 400 kHz.

FY 93 Accomplishments

AC Voltage/Current Measurements

- Constructed and tested the prototype of the new digitally synthesized source (DSS-5) that is programmable in amplitude, frequency, and waveform via the IEEE 488 bus. Copies were delivered to Sandia, along with software that supports source calibration and use for testing DMMs.

- Constructed and tested a calculable current source based on the DSS-5 and a 2-A transconductance amplifier to show the feasibility of a calculable current source useful for calibrating current meters and DMMs.

Impedance Measurements

- Designed and constructed a new probe for the DIB to automate 2- and 4-terminal inductance measurements, based on a set of characterized ac resistors. The bridge is being evaluated as a possible replacement for the aging Maxwell Wien Bridge.

- A copy of the NIST BIVD Bridge (developed to test the temperature bridge on the NASA Zeno Project) was constructed and is being evaluated as a system for testing programmable inductive voltage dividers (IVDs). A technique was developed to extract error coefficients associated with the BIVD and a decade IVD based only on a knowledge of their physical structures.

- Designed a programmable delay generator to improve the phase linearity of a new dual-channel DSS. Also demonstrated a programmable logic device that can replace much of the digital circuitry in this instrument.

Phase Measurements

- Published an extensive archival paper describing the limitations imposed by the phase measuring electronics used in heterodyne interferometry. Developed a high-frequency, high-speed phase measurement system using a VXIbus-based time interval analyzer, computer, and stand-alone function generators.

Power/Energy Measurements

- Demonstrated a prototype portable power bridge with ±5 ppm stability for use as a transport standard for intercomparing power bridges at NIST and for international power comparisons.

Project: GENERATION AND MEASUREMENT OF PRECISE SIGNALS

FISCAL YEARS	94	95	96	97	98
Draft CALCOM Tech Note for routine DMM calibrations. [STRS]	■				
Develop new dual-channel digital source to replace the sources used in the Power/Energy and Impedance projects. [STRS; OA:CCG]	■				
Complete new inductance probe to extend DIB measurements from 10 μH to 10 H in the 10-Hz to 100-kHz frequency range. [STRS; OA:CCG]	■				
Set up and perform 200-kHz, 1.0-pF power measurement for a wideband wattmeter manufacturer. [STRS]	■				
Extend BIVD bridge into a bridge to measure capacitance and dissipation factor to 100 kHz. [STRS; OA:CCG]	■	■			
Develop programmable impedance transfer standard. [STRS]	■	■			
Develop impedance with computable frequency response to 1 MHz. [STRS]		■	■	■	
Employ Sampling Voltage Tracker in a modified DIB to measure impedances to 1 MHz. [STRS]		■	■	■	
Establish calibration service for LCR meters. [STRS; OA:CCG]			■	■	■

Project: WAVEFORM ACQUISITION DEVICES AND STANDARDS

FY 94 Fund Sources: STRS; Calibration; OA: Air Force AGMC (CCG)

Staff (4.6 staff-years)

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

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

Objective: Develop and provide pulse waveform calibration services and pulse measurement intercomparison programs. Research and develop laser systems, optoelectronic (OE) and electrooptic (EO) devices and techniques for ultra-fast sampling and pulse generation applications and electric-field probing. Develop and apply sampling comparator systems to traditionally analog applications, such as rms voltage measurement. Provide error analyses on the effects of non-idealities in sampling systems. Support and contribute to consensus standards for specifying and testing waveform acquisition devices, and standards for pulse terminology and characterization.

Significance: Waveform sampling has become a critical, pervasive technology in instrumentation. Data converter sales were $1.1 billion in 1990, and sales of waveform recorders and analyzers reached $718 million in 1991. This industry needs NIST advances in standards, test methods and error analyses to facilitate continued growth. In turn, the computer, telecommunications and IC industries (each critically dependent on sampling technology) will all benefit. Short-pulse lasers and OE/EO technology will be needed for advancement and development of state-of-the-art electronic devices, semiconductor structures and materials.

FY 94 Plans

Data Converter/Waveform Recorder Testing

- Start first phase of industry-NIST round-robin intercomparisons of pulse waveform measurement capability.

Sampling Comparator Systems

- Begin development of an improved time base for use with the NIST sampling comparator probes to maximize throughput (acquisition time < 1 s) at low frequencies (< 10 kHz). This development will make sampling comparator systems practical for use at frequencies as low as 10 Hz, which is important for high-accuracy impedance measurements and voltmeter applications.

- Reduce dynamic nonlinearity errors of NIST Sampling Comparator System (SCS), using a phase plane compensation approach. Target error reduction is ≥10 dB over the 20 - 200 MHz frequency range. Automatic test equipment applications of sampling comparator systems will broaden if their harmonic distortion can be effectively reduced.

Pulse Measurement Services

- Perform a comparative analysis of two commercial 20 GHz sampling systems for use as working standards in each of the time-domain calibration services offered by NIST. Selected system(s) will be incorporated in the NIST Automatic Waveform Analysis and Measurement System (AWAMS).

- Complete experimental analysis of the voltage and time temperature coefficients present in both AWAMS samplers (temperature dependence is currently a major error source in the AWAMS).

Optoelectronic/Electrooptic Technology

- Complete the development of the Nd:YAG laser-based sampling system (< 5 ps aperture).

- Optimize the electrical performance of the photoconductor pulse generator package. Reduce signal artifacts to ≤ 0.01% of peak, over a 16 ns epoch.

Related Developments

- Oscilloscopes with 50-GHz bandwidth are produced by two U.S. manufacturers; NIST calibration of their time-domain parameters is often required. However, since NIST presently does not have the required capability, customers are turning to National Physical Laboratory in the U.K. 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 93 Accomplishments

Data Converter/Waveform Recorder Testing

- Developed analytical bounds for parameter estimation errors produced by least-squares sinewave curve fitting. Effects of harmonic distortion and noise are included. Sine fit routines are used extensively in testing digital oscilloscopes and analog-to-digital converters (ADCs), and other signal processing applications.

- Developed a fast (200 ps transition duration), stable (<0.01% top and base line) pulse generator for use as the transfer standard in the round robin pulse measurement intercomparison program.

Sampling Comparator Systems

- Developed a 2-kΩ attenuator with 0.01% gain flatness to 1 MHz to extend the voltage range of the NIST sampling comparator probes from ±2 V to ±20 V.

- Established special test service for settling performance of step generators, based on the NIST Sampling Comparator System. Measurement uncertainties range from 0.2% in 2 ns to 0.02% in 10 ns.

Pulse Measurement Services

- Implemented and evaluated "nose-to-nose" measurement technique for determining the impulse response of fast samplers. This will allow a reduction of the dynamic response uncertainty associated with the sampler used in NIST calibration services, from ±3 ps to about ±1 ps.

- Upgraded AWAMS with new hardware (voltage and time standards) and software to improve system accuracy and ease of operation. Improved time-base uncertainty from ±0.5% to ±0.05%, and improved amplitude uncertainty from ±0.2% to ±0.05%.

Optoelectronic/Electrooptic Technology

- In collaboration with Division 812, developed GaAs, Si, and silicon-on-sapphire photoconductive device fabrication capability at NIST, exhibiting symmetric transient photoresponse with voltage.

- Applied electrooptic light modulation as a technique for rms voltage measurement. Achieved 0.1% uncertainty over 1-800 kHz range, at 1 V.

Project: WAVEFORM ACQUISITION DEVICES AND STANDARDS

FISCAL YEARS	97	95	96	97	98
DATA CONVERTER/WAVEFORM RECORDER TESTING					
Perform error analyses of test methods in IEEE Std. 1057. [STRS, OA-Sandia]	—				
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, OA: Sandia]	—	—			
Develop new time base and control instrumentation for use with sampling probes. [STRS, OA-DOD]	—	—	—		
Develop personal-computer-based sampling comparator system for measurements of rms voltage, power, and wideband impedance. [STRS]		—	—	—	—
PULSE MEASUREMENT SERVICES					
Upgrade pulse measurement system and develop CALCOM documentation for SP250 measurement services (BW=20 GHz). [STRS]	—	—	—		
Develop special test system for measuring pulse parameters down to t_r = 5 ps (BW = 50 GHz). [STRS, OA-DOD]		—	—	—	—
OPTOELECTRONIC/ELECTROOPTIC TECHNOLOGY					
Perform oscilloscope transient response calibration, using laser-based sampling system. [STRS OA-AF]	—	—			
Develop a high temporal resolution (<1 ps) sampling system with 1% amplitude uncertainty. [STRS]		—	—	—	—

Project: MEASUREMENTS FOR COMPLEX ELECTRONIC SYSTEMS

FY 94 Fund Sources: STRS; OA: 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

Objective: To promote greater efficiency and confidence in the testing and calibration of complex electronic systems. This includes the development of mathematical models, algorithms, and test procedures for the selection of optimal test points, signals and sequences, and the estimation of confidence and test coverage in a given calibration or test procedure.

Significance: With the growing complexity of electronic instrumentation, testing and calibration costs have become a dominant factor in total instrument life-cycle costs. For example, typical test costs for mixed-signal ICs range from 20% to 50% of sale price. Confidence levels, test coverage, and test and calibration procedures are often inadequate to assure the extremely low defect levels that are now required.

FY 94 Plans

- Develop software subroutines for the mathematical core of testing strategies (to be incorporated into a "toolbox" suitable for commercialization) to perform the following functions: modeling, test point selection, response prediction, and error estimation.

- Conduct the third NIST workshop on "Testing Strategies for Analog and Mixed-Signal Products."

- Document in an archival paper the FY 93 research work establishing stopping criteria, statistical error bounds, and confidence levels associated with empirical modeling.

- Apply testing strategies to the problem of reducing the test requirements for a precision calibration standard in Air Force inventory of test instruments.

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 93 Accomplishments

- Prepared and presented two papers on the application of the NIST testing strategies method to a multirange instrument. This research demonstrates that the NIST method, previously applied only to ICs, is also applicable to complex instruments.

- Completed an assessment of the risk versus cost of detecting model errors. Developed formula for computing the likelihood of making an error in prediction that exceeds a given size. Calculation can be made on-line to flag model errors.

- Proposed and tested a criterion for finding the optimum empirical model based on the singular value decomposition. A semi-heuristic formula was developed to estimate the prediction errors. This makes it possible to estimate the *true* accuracy of subsequent predictions as soon as the model is developed. The work has attracted the attention of the applied statistics community: American Statistical Association Senior Research Fellowship awarded to Cornell mathematician Gene Hwang to formalize the method.

- Demonstrated the feasibility of a new approach for on-line fault detection for analog circuits (Ohio University). The approach has potential for use in critical defense, transportation and medical applications.

Project: MEASUREMENTS FOR COMPLEX ELECTRONIC SYSTEMS

FISCAL YEARS	94	95	96	97	98
TESTING STRATEGIES					
Develop 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. [OA:AF]					
Develop a software toolbox (suitable for commercialization) for implementing the NIST testing strategies methods. [STRS]					
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 94 Fund Sources: STRS; OA: DoD; Calibration Fees

Staff (2.6 staff-years)

Professional	J. R. KINARD*	T. E. Lipe		
Technician	C. B. Childers			

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

Objective: Establish and maintain NIST primary and working thermal converter standards of ac-dc difference for the measurement and calibration of ac voltage, current, power, and energy; develop new thermal converter principles and technologies; provide calibration services for thermal current and voltage converters ranging from 2 Hz to 1 MHz for voltage and 2 Hz to 100 kHz for current, with uncertainties in the range of 0.8 to 200 ppm depending on device, frequency, and magnitude.

Significance: The calibration services supported by this project and the new technologies under development, such as thin-film multijunction thermal converters (MJTCs), provide the most viable and accurate link between measurements of rms ac voltage, current, and energy, and the dc standards by which the electrical units are maintained. The new thin-film MJTCs will offer secondary calibration laboratories both technology and performance that are close to primary standard capability.

FY 94 Plans

- Fabricate preliminary devices for new primary standards using superconducting kinetic inductance thermometers (KITs), assemble cryogenic system, and begin evaluation of prototypes.

- Participate in three international intercomparisons of ac-dc difference at the levels of a few volts at audio frequency, at 100 - 1000 V up to 100 kHz, and in the megahertz region.

- Fabricate additional thin-film MJTCs and deliver mounted converters to the DoD primary laboratories. Fabricate and evaluate new integrated micropotentiometers.

- Study high-voltage ranges and the related voltage buildup process.

- Complete the documentation for the extension of transfer shunt and current converter calibration up to 100 kHz and down to 10 Hz. Test new automated comparator system.

- Study CMOS-foundry fabricated MJTCs and manufacture improved devices.

Related Developments

- Three CRADAs have been active or established. The CRADA to develop thin-film MJTCs is now approaching its third year and includes a full-time engineer working as a research associate. A CRADA was completed for the evaluation of a new automatic thermal transfer standard. A CRADA was established for the study of a new, high-performance thermoelement design.

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

FY 93 Accomplishments

- Increased the yield-per-wafer for the NIST thin-film MJTCs from a few percent to over 60%. More chips have been mounted, and characterization is continuing. The prospects that these converters will serve as very high-performance standards appear good. The ac-dc difference, as a voltage converter, of the bifilar MJTC is 0.6 ppm at 1 kHz, and the coaxial MJTC has only a few ppm ac-dc difference as a current converter out to 100 kHz. Began fabrication of new integrated micropotentiometers with improved output resistors and of additional types of thin-film MJTCs including differential designs and trifilar heaters.

- Investigated performance of a thin-film MJTC down to 10 K. The output emf for a given input power, i.e. efficiency, increases as the operating temperature decreases to about 100 K. Between 10 K and 100 K, the efficiency is nearly flat, or independent of temperature, so that the converter only responds to the applied power not to ambient temperature change. This insensitivity to temperature change is very desirable and extremely difficult to achieve. The ac-dc difference also shows signs of decreasing at low temperatures, but the hardware available has not yet permitted conclusive measurements to be made.

- Began study of new primary standards based on superconducting kinetic inductance thermometers (KITs) in order to meet the steadily decreasing uncertainties required to support new instrumentation and the NIST developed thin-film MJTCs. A preliminary chip design has been made, a fabrication strategy formulated, and several pieces of essential equipment, such as SQUIDS and cryostats, have been ordered.

- Filed two patent applications for the thin-film MJTC structures and the integrated micropotentiometers (μpots). The one for the μpots was allowed immediately with essentially no changes. This unusual action reflects the truly novel nature of these devices. The NIST patent attorney believes the second patent will also be allowed. It was not possible to place a contract with an outside processing lab for the manufacture of thin-film MJTCs because the only bid was over budget. The commercial CRADA partner on the thin-film MJTC project, is proceeding to arrange for commercial fabrication of both thin-film MJTCs and integrated μpots.

- Fabricated and evaluated multijunction thermal converters based on commercial CMOS, silicon foundry processing with the addition of one post-processing, etching step to remove silicon from under the heater and hot junctions. This powerful technology is under intensive development in all high-technology countries. It offers the possibility of micromachined devices and CMOS circuits combined on a chip with very little custom processing. The results from two production runs indicate that these converters, while not suitable high-level calibration standards, should be quite suitable for general instrumentation. Papers were given on these devices at the Instrumentation and Measurement Technology Conference '93 and the Transducers ’93 conferences.

- During FY 93, 767 points were calibrated on 34 standards for an income of $171 K.

- Tested a prototype rms voltage measurement system using the electrooptic effect. The output of the $LiTaO_3$ electrooptic cell was found to be stable to about 15 ppm, which is not stable enough to be useful. Any further work will involve a Potassium Dideuterium Phosphate cell as a possible candidate.

- Wrote the preliminary documentation for the extension of the current converter calibrations up to 100 kHz and down to 10 Hz, and presented a paper on this work at the National Conference of Standards Laboratories Workshop. Suitable sources for 20 A at 100 kHz have been procured. Automated ac-dc difference determinations are now possible, but not yet in routine use, over the whole parameter space.

Project: AC-DC DIFFERENCE STANDARDS AND MEASUREMENT TECHNIQUES

FISCAL YEARS	94	95	96	97	98
Develop documentation for extended current calibrations and automate current converter calibrations. [STRS]					
Complete study of converters at lower frequencies to reduce uncertainties. [STRS]					
Deliver thin-film MJTCs to DoD primary labs. [OA:AF]					
Investigate high-voltage range resistors and comparison techniques. [STRS]					
Study characteristics, including ac-dc difference, of thin-film MJTCs at cryogenic temperatures.[STRS; OA:AF]					
Fabricate and evaluate new CMOS-foundry MJTC designs. [STRS]					
Study performance of thin-film MJTCs as voltage and current converters from audio frequency to the megahertz range. [STRS; OA:Sandia]					
Characterize and fabricate additional integrated µpots. [STRS; OA:Sandia]					
Complete preliminary design and begin fabrication of new prototype primary standards using superconducting KITs. [STRS]					
Assemble cryogenic system and begin evaluation of prototype KIT converters. [STRS]					
Confirm accuracy of new low-temperature, KIT-based converters and establish them as NIST primary standards if appropriate. [STRS]					

Project: RESISTANCE STANDARDS AND MEASUREMENT METHODS

FY 94 Fund Sources: STRS, Air Force, Calibration Fees, CSD Project

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

Objective: To periodically re-establish the U. S. representation of the ohm based on the quantum Hall effect (QHE), and maintain the ohm over 17 decades of resistances from 100 μΩ to 1 TΩ. Disseminate the ohm via calibration services to over 300 standards laboratories from government, industry, and academia. Participate in international comparisons of the ohm. Develop new resistance standards, cryogenic current comparator (CCC) bridges, ac resistance measurement techniques, and automated calibration systems. Support experiments to realize the SI ohm, the SI watt, and the proton gyromagnetic ratio in water (γ'_p).

Significance: The services supported by this project provide the basis for accuracy and compatibility for all resistance measurements made throughout the U.S. industry, science, and technology. The new quantized Hall resistance (QHR) standard provides a powerful tool for the development and evaluation of new resistance materials and standards. Support of new commercial equipment including digital multimeters, impedance bridges, and ac thermometer bridges requires new resistance standards and measurement techniques.

FY 94 Plans

- Complete two QHR step-downs from 6453.20 Ω to 1 Ω in order to calibrate NIST working standards of resistance.

- Compare i=2 and i=4 QHR steps using CCC to check the CCCs 2:1 ratio. This check has bearing on the evaluation of errors in the CCC, which will be instrumental in deciding how to employ CCCs directly in the calibration services.

- Complete one transfer from SI ohm to QHR to provide data for the next adjustment of the fundamental physical constants for the Committee on Data for Science and Technology (CODATA).

- Undertake a comparison of the NIST Quantum Hall Effect (QHE) resistance system with the portable system developed by the Bureau International des Poids et Mesures (BIPM) to ensure the international compatibility of the U.S. resistance standard.

- Construct and characterize a 100-Ω bank of four resistors to provide a more accurate and reliable basis for the calibration of customers' standards.

- Design a high-T_c CCC with a view to the possible development of a commercial ratio standard superior to those presently available to industrial measurement laboratories.

- Fabricate Pd-alloy film resistors as prototype standards for use at cryogenic temperatures, particularly with CCCs.

- Design and construct an improved detection circuit for an ac Kelvin bridge; construct 100 Ω and 1 kΩ coaxial ac/dc resistors; and construct and evaluate ac/dc cryoresistors as final steps in the development of a service for ac resistors in the frequency range of 1 kHz and lower.

- Complete the automation of the 10-kΩ resistor calibration system to improve the calibration quality and reduce the turnaround time for the second largest population of standard resistors that is calibrated.

- Design and construct a temperature/humidity air bath to improve the quality of multi-megohm resistance measurements.

Related Developments

The proliferation of new digital multimeters and calibrators with accuracy specifications of a few ppm for resistance will increase the demand for both better standards and improved calibration services. The development of high-T_c superconductors may make it possible to construct CCC bridges that operate at liquid nitrogen temperatures. These devices would be more accurate than conventional bridges and be competitive with them for ease-of-use. The needs of the accreditation program may lead to the development of improved audit packages covering wide resistance ranges and odd-value resistances.

FY 93 Accomplishments

- Completed two comparisons of the QHR to the 1-Ω working group, thus calibrating the primary working standards of the resistance calibration service.

- Measured transfer resistors to support measurements of the SI ohm and the proton gyromagnetic ratio in water (γ'_p) in terms of the quantized Hall effect.

- Completed construction of a third CCC, which provides additional ratio of 129.06/1 to be used in comparing the i=2 step of the QHR to a 100-Ω resistor, and affords a redundant measurement for error analysis and quality purposes.

- Measured the pressure dependencies of commercial 100 Ω-, 6453.20 Ω-, and 10 kΩ-standards and presented a paper on this subject at the 1993 National Conference of Standards Laboratories (NCSL) Workshop and Symposium to bring awareness of these potential error sources to industrial users.

- Completed design and construction of a cell for determining the pressure coefficients of commercial 10-kΩ resistors to improve the quality of measurements performed by NIST and industry.

- Completed construction of prototype ac Kelvin bridge for resistors from 1 Ω to 1 MΩ over frequency range 15 Hz to 10 kHz. Wrote special software for balancing the in-phase and quadrature components of the bridge. The precision of the bridge is on the order of a few parts in 10^8. This work underlies a future calibration service for ac resistance.

- Implemented a current comparator bridge system for 2-kA shunts, expanding that service from 1 kA in response to customer inquiries.

- Designed and constructed a variable-temperature cryostat for determining the temperature dependence of Pd-alloy film resistors at liquid helium temperatures as part of an effort to improve resistance standards.

- Published NIST TN 1298 to document the resistance calibration services, and distributed more than 400 copies to interested industrial customers.

Project: RESISTANCE STANDARDS AND MEASUREMENT METHODS

FISCAL YEARS	94	95	96	97	98
Complete automation of 10-kΩ bridge. [STRS]					
Develop ac resistance measurement capability. [STRS]					
Develop improved resistance standards. [STRS; OA:AF]					
Evaluate commercial resistance instrumentation to support laboratory accreditation. [STRS; E&I-NVLAP]					
Construct audit packages to support laboratory accreditation. [STRS; E&I-NVLAP]					
Institute a calibration service for resistances > 1 TΩ. [STRS]					
Develop system for calibrating ac shunts. [STRS; E&I]					
Develop ac cryogenic current comparator bridge. [STRS]					
Develop cryogenic current comparator bridge using high-T_c superconductors. [STRS; Industry]					

Project: IMPROVED IMPEDANCE CALIBRATION SERVICES

FY 94 Fund Sources: STRS; OA: DoD; Calibration Fees

Staff (6.8 staff-years)

Professional	N. B. BELECKI*	S. Avramov‡	Y. M. Chang	N. M. Oldham*
	A. Sepulvada‡	J. Q. Shields*	B. C. Waltrip*	
Technician	L. H. Lee*	C. R. Levy	S. B. Tillett	

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

Objective: Provide U.S. industry with the impedance standards, measurement techniques, instrumentation, and measurement traceability needed for quality in the manufacture, sale, and maintenance of electronics products. Promote 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, support the NIST impedance calibration service and expand it to cover calibrations of capacitance(C), inductance(L), and dissipation factor(D), in the frequency range from 10 kHz to 100 kHz in support of new impedance (LCR) meters as shown.

	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 - 100 kHz
D uncertainty:	Not offered	±1 ppm

This requires both the development of comparison techniques valid over the intended frequency range, and a new standard with which to determine the values of standards at each frequency of use.

Significance: Electronic products are becoming increasingly complex, requiring complex testing to be done at high speed and high accuracies using automated systems. To support these products, programmable impedance meters which use modern electronics to achieve very high accuracies have been developed. These meters are not supported adequately by NIST services. At present, users obtain calibrated standards from Japan to cover the parameter space of LCR meters. Industrial customers have asked for improvements in the accuracy and frequency coverage of NIST services in order to take advantage of the full capability of LCR meters. Dissipation factor measurements, vital to the electronics and chemical industries, are needed throughout the frequency range from 50 Hz to 100 kHz and higher; these are presently supported by NIST only at 60 Hz. The most accurate meters rival NIST calibration uncertainties and require reduced uncertainties in our present frequency range for their calibration.

FY 94 Plans

- Complete the documentation for the inductance and inductive voltage divider calibration services.

- Expand and refine the capabilities of the automated binary inductive divider (BIVD) system for calibrating programmable inductive voltage dividers (IVDs) to include calibration of manual IVDs at voltages to 100 V. This will improve the support given to customers who use these dividers as the basis for impedance bridges and for angular and low-voltage measurements.

- Complete and deliver the prototype Digital Impedance Bridge (DIB) for the calibration of standard inductors in the audio-frequency range to the calibration laboratory. This bridge is intended to replace the failing (*circa* 1955) Maxwell-Wien bridge by which the henry is presently realized and upon which all inductance calibrations are based.

- Evaluate the DIB by comparison with the existing inductance calibration systems, with the intent of replacing them by the end of the fiscal year, and improving uncertainties by a factor of three to four.

- Complete a prototype inductance probe to extend the frequency range of the DIB to 100 kHz.

Related Developments

A domestic manufacturer will soon market fused silica reference capacitors with performance capabilities two orders of magnitude better than currently available standards. 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 93 Accomplishments

- Developed a simplified technique to determine the frequency response of capacitors using toroidal cross capacitors and a special transformer bridge. The bridge, structured to facilitate analysis of its errors, was designed and its primary transformer built. This system, when complete, will enable determination of the frequency response of capacitance standards over the mid-audio frequencies to within 0.1 ppm or better.

- Re-established the Measurement Assurance Program for capacitance, curtailed over ten years ago for the lack of an adequate transport standard. The new program is based on the use of an automated impedance meter with a fused-silica reference as the transport standard. The meter is extremely rugged and uncertainties of the order of ±2 ppm have been demonstrated. This has the effect of upgrading the capability of user laboratories by a factor of three to ten since their standards (which are frail) can be measured *in situ*.

- Completed and began evaluation of a BIVD-based system for the calibration of programmable IVDs. This system allows for hands-off testing of automated dividers and, consequently, more thorough evaluation of their errors and performance.

- Designed a new probe for the DIB in order to automate inductance calibrations. The probe permits a four-terminal measurement of an inductance in terms of a resistor whose value at each frequency is known. This approach should enable an improvement in the accuracy of the inductance service by a factor of four or more.

- Calibrated 103 standard capacitors, 119 standard inductors, and 27 inductive voltage dividers for an income of $217.5K during FY 93.

Project: IMPROVED IMPEDANCE CALIBRATION SERVICES

FISCAL YEARS	94	95	96	97	98
Deliver a prototype DIB for calibration of standard inductors at audio frequencies. [STRS; OA:AF]					
Redefine the BIVD system to calibrate manual dividers at voltages up to 100 V. [STRS; OA:AF]					
Complete a prototype probe to extend the frequency range of the DIB to 100 kHz. [STRS; OA:AF]					
Replace the existing inductance calibration system with the DIB at appropriate inductance/frequency points. [STRS]					
Extend the BIVD bridge to measure C and D at frequencies up to 100 kHz. [STRS; OA:AF]					
Evaluate the errors in determining frequency response of C standards in terms of toroidal cross capacitors in the range from 400 Hz to 10 kHz. [STRS]					
Augment the present capacitance calibration systems with a second BIVD bridge thus extending the frequency range. [STRS; OA:AF]					
Design, construct, and analyze a new transformer bridge for comparing capacitors from 10 kHz to 100 kHz. [STRS; OA:AF]					
Develop an impedance standard with a computable frequency response to 1 MHz. [STRS; OA:AF]					
Extend the frequency response characterization of capacitors in terms of toroidal cross capacitors to 100 kHz. [STRS]					
Establish a calibration service for LCR meters. [STRS; OA:AF]					

Project: QUANTUM VOLTAGE AND CURRENT

FY 94 Fund Sources: STRS; OA-DoD; Calibration fees

Staff (5.5 staff-years)

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

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

Objective: Maintain the U.S. legal volt. Support the Division's voltage calibration services. 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. Determine the gyromagnetic ratio of the proton in terms of the U.S. electrical unit; and 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.

Significance: The services provided by this project generate the basis for accuracy and compatibility for all voltage and current measurements throughout U.S. industry, technology, and science. The standards being produced by this project and by the companion Quantum Resistance and Capacitance 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. The research evaluates new measurement techniques and standards for automated and highly accurate dissemination of these units. The research also is creating a possible electronic replacement for the kilogram, the last remaining SI artifact standard, and is exploring the application of the new single electron tunneling phenomena to the determination of the electronic charge or the fine structure constant.

FY 94 Plans

- Improve the voltage calibration service to include a 30% increased capacity and measurement accuracy enhanced by a factor of 3 or more by instituting replacement of all of the existing computer automation, and plan the inclusion of a Josephson array system for direct transfer of reference values.

- Perform a direct array-to-array comparison of the U.S. national voltage standard system with that of Canada's at the National Research Council, Ottawa, Canada.

- Acquire the first set of weighing and velocity/voltage data, using the newly rebuilt watt balance.

- Generate a new value for the NIST watt to 0.1 ppm, and report it to the Conference on Precision Electromagnetic Measurements in Boulder, Colorado in June, 1994.

- Analyze the completed measurements of the solenoid used in the proton gyromagnetic ratio experiment and evaluate the systematic errors.

- Initiate the transfer of the magnetic field calibration service to the Navy Primary Standards Laboratory by constructing a low field calibration system for shipment to San Diego, California.

- Demonstrate the application of a single electron tunneling electrometer as the detector in a bridge to measure the ratio of two capacitors to 10 ppm at millikelvin temperatures.

Related Developments

- The Army Primary Standards Laboratory is developing industry's capability to manufacture about 30 portable 10 V Josephson array voltage standard systems for application in mobile standards laboratory vehicles.

- The Bureau of International Weights and Mesures (BIPM), according to its director, Dr. T. J. Quinn, is initiating a study of both NIST's and The National Physical Laboratory's (NPL) kilogram experiments. The objective is to develop an electronic means of monitoring the mass of the kilogram, the last artifact standard, in the SI system of units.

FY 93 Accomplishments

- Acquired, installed, and tested a new computer to replace the aged computers now used to run the voltage calibration facility. Explored several commercial software packages for automating the data acquisition and processing of customer calibrations.

- Continued to study the occurrence of fractional steps in the ac Josephson effect discovered in FY 92. Developed a theoretical model to simulate this unusual effect in the high T_c grain-boundary junctions and, through comparison with experimental data, concluded that the junctions are microstructurally several Josephson junctions in parallel. Documented the surprisingly frequent occurrence (about weekly) of half-integer steps in the series array of Josephson junctions used as the national standard, showed them to be exactly 0.50 of the expected step size to 2 parts in 10^8, and began development of software to avoid these in the voltage calibrations.

- Performed more than 3500 measurements of developmental Zener reference standards with the automated Josephson array voltage system to establish the reliability and variability of these improved solid state voltage references. Fed back the information to the manufacturers for further product development.

- Reactivated the proton gyromagnetic ratio experiment. Measured magnetic gradients with a cesium magnetometer, set up the portable Josephson volt system for integrated daily volt measurements, and completed three series of dimensional measurements resulting in a calculated magnetic field to 0.03 ppm.

- Redesigned and rebuilt the watt balance, improving the rigidity and the overall balance performance. Made voltage measurements in zero magnetic field demonstrating that several potential errors in both the voltage and weighing are less than about 0.01 ppm.

- Fabricated several new single electron tunneling devices using the National Nanofabrication Facility at Cornell University and the NIST-Boulder aluminum evaporation system. Demonstrated one of the devices as a detector to a capacitance bridge for balance between two 0.5 pF capacitors to 10 ppm at 30 mK and 10 Hz.

Project: QUANTUM VOLTAGE AND CURRENT

FISCAL YEARS	94	95	96	97	98
Extend the voltage calibration service. [STRS, Calibration fees]	▬				
Perform a direct array-to-array comparison. [STRS]	▬				
Analyze the completed gamma p measurements. [STRS]	▬				
Generate a new value for the NIST watt. [STRS]	▬				
Demonstrate the application of a single electron tunneling electrometer as the detector in a bridge. [STRS]	▬				
Transfer the magnetic field calibration service [OA-DoD]	▬	▬			
Study array physics, microwave effects, and array applications. [STRS, OA-DoD]	▬	▬	▬		
Develop and apply procedures for monitoring the kilogram electronically. [STRS]	▬	▬	▬	▬	
Study the application of single electron tunneling to metrology. [STRS]	▬	▬	▬	▬	▬

Project: QUANTUM RESISTANCE AND CAPACITANCE

FY 94 Fund Sources: STRS; OA: DoD

Staff (4.0 staff-years)

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

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

Objective: 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 and developing sample fabrication for NIST programs and industrial support, including a future quantum Hall SRM (Standard Reference Material).

Significance: The research work being done on this project and by the companion Quantum Voltage and Current project are the key to tying 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, NIST depends on this project to conduct 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 schemes. Methods developed by NIST for the 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 an SRM for industry.

FY 94 Plans

- Determine the SI ohm from the calculable capacitor, the impedance chain, and the quantized Hall resistance. This is essential for the 1995 readjustment of the fundamental constants.

- Improve the yield of high-quality electrical contacts of quantum Hall samples by controlling the depth distributions of indium alloys.

- Begin investigating the ac quantum Hall effect by constructing a sample probe with triaxial feedthroughs, coaxial cables and special sample mounts, and making preliminary measurements with an ac Kelvin bridge.

- Analyze the current and potential distributions within quantum Hall samples.

- Realize the SI farad from the calculable capacitor to maintain the legal U. S. unit of capacitance.

- Assemble a capacitance bridge with a wider frequency range to maintain the U. S. capacitance standards at frequencies other than 1592 Hz.

Related Developments

- A domestic company would like to have a CRADA with NIST for manufacturing a complete quantized Hall resistance system that includes a superconducting magnet, a He_3 refrigerator, and a cryogenic current comparator.

- The Navy would like to have NIST provide them with a quantized Hall resistance system.

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

FY 93 Accomplishments

- Demonstrated that the digital voltmeter method can be used to compare quantum Hall resistors to reference resistors with an accuracy of better than 0.1 ppm. The technique solves the difficult problem of scaling between the quantized Hall resistance and standard reference resistors (whose values can be compared with those obtained at NIST by using Measurement Assurance Programs - MAPs). This method can provide a simple and relatively inexpensive method for calibrating 10 kΩ resistors in industrial/primary laboratories.

- Electrical contacts were successfully made to the two-dimensional electron gases of two coated GaAs samples made for the European Metrology Organization (EUROMET) in France. The quantized Hall resistances of the two samples were in agreement with domestically produced samples, GaAs(7) and GaAs(8), to within several parts in 10^9 when cooled to 0.3 K.

- Two GaAs samples manufactured at NIST, a EUROMET GaAs sample, and a silicon MOSFET made in England were compared to the sample GaAs(7) using the automated potentiometric measurement system. The quantized Hall resistances were sample independent to within 2 parts in 10^9.

- A new digitized system was developed to look at breakdown events in quantum Hall samples. Three software programs were written to collect the data, compact the data set size into manageable proportions, and to compose composite images of numerous data sets. Several hundred data runs were taken on the GaAs(8) sample using this measurement system. A new way of taking the data by pulsing the current provides a much better method of characterizing the quantization of the breakdown by obtaining voltage spectra as a function of magnetic field.

- Three SI determinations of the farad were made during the year.

- A new capacitance bridge was designed to establish the following: a standard of dissipation factor at frequencies other than 1592 Hz; a standard of frequency dependence for capacitors; and a measurement capability of four-terminal-pair admittances at frequencies other than 1592 Hz.

- Two 10-pF capacitance standards were completed. Three more capacitors are being adjusted. The last three fused-silica capacitance standards were completed and are being temperature cycled.

Project: QUANTUM RESISTANCE AND CAPACITANCE

FISCAL YEARS	94	95	96	97	98
Investigate the ac quantum Hall effect. [STRS, OA-DoD]	—	—	—	—	—
Improve the electrical contacts of quantum Hall samples by achieving more uniform depth distributions of indium alloys. [STRS, OA-DoD]	—	—			
Prepare and characterize quantum Hall specimens. [STRS, OA-DoD]	—	—	—	—	—
Analyze the current and potential distributions within quantum Hall specimens. [STRS, OA-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]	—				
Assemble a capacitance bridge with a wider frequency range and identify design parameters for the reference capacitor. [STRS]	—				
Provide calibrations at multiple frequencies of capacitance standards based on the calculable capacitor. [STRS]	—	—	—	—	—

SEMICONDUCTOR ELECTRONICS DIVISION

Project: NANOELECTRONICS

FY 94 Fund Sources: STRS, STRS-OMP; OA-ARPA, OA-NOAA, OA-DNA

Staff (9.5 staff-years)

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

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

Objective: Provide technological leadership to semiconductor manufacturers 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. Provide silicon and compound-semiconductor device manufacturers with advanced metrological techniques and models, such as 20-nm-resolution scanning-probe, dopant-profiling methods as required by the Semiconductor Industry Association (SIA) Roadmap, to improve device performance and reliability. Grow and analyze III-V semiconductor epitaxial films and structures to study their growth kinetics and fabrication properties as needed for the reliable manufacture of nanostructure devices. Specifically, address such topics as in-situ, molecular-beam-epitaxy (MBE) layer composition control by X-ray fluorescence; interface properties of superlattices and heterostructures; and scanning tunneling microscope (STM) lithography and measurement of small (<0.1-μm) device features such as quantum lines and dots.

Significance: 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. NIST must provide the semiconductor industry with the methodology, both experimental and theoretical, needed to evaluate and improve these materials and processes down to 20-nm-scale resolution. Improved materials growth and evaluation techniques are needed by the compound-semiconductor industry to manufacture useful and reliable devices based on advanced quantum phenomena.

FY 94 Plans

- Optimize the performance of the scanning capacitance microscope (SCM). Measure reliably capacitance-voltage curves across processed wafers down to 20-nm resolution.

- Develop computer codes, such as ANSYS, to solve Poisson's equation in three dimensions, and deduce dopant profiles from SCM measurements.

- Provide magnetoresistance and Shubnikov-de Haas measurements and analysis to help evaluate HgCdTe infrared detectors for weather satellites.

- Develop and evaluate X-ray fluorescence from a reflection high-energy electron diffraction (RHEED) gun as an in-situ method to measure and control composition (down to ~1%) and possibly thickness of MBE layers.

- Develop passivation techniques to prepare wafer surfaces for scanning tunneling microscope (STM) lithography. Optimize the ultrahigh vacuum STM system for patterning and measuring nanostructures.

- Collaborate with the University of Iowa on growing heterostructures for optoelectronics devices. Collaborate with the Army Night-Vision Laboratory on growing GaAs on Si substrates. Study interface properties with X-ray and optical techniques to optimize layer quality.

- Characterize the properties of III-V interfaces by using magnetophonon and other magnetotransport techniques. Calculate the effect of electron-electron scattering on mobility.

Related Developments

- A 15-year semiconductor plan for silicon-based integrated circuit (IC) technologies was developed by key U.S. technologists under the auspices of the SIA. The SIA has identified NIST as having the responsibility to provide 2D and 3D dopant-profiling capability to the semiconductor industry to better than 100-nm resolution.

- A CRADA was finalized for scanning capacitance microscopy.

FY 93 Accomplishments

- Designed, constructed, and tested a scanning capacitance microscope (SCM) for nanoscale (10- to 100-nm) profiling of semiconductor p-n junctions; the design is the first to take advantage of incorporating a commercial atomic force microscope (AFM). Confirmed operation of the SCM by the simultaneous acquisition of AFM and capacitance-versus-position images. Measured the capacitance-voltage responses of metal-oxide-semiconductor (MOS) capacitors with the SCM. Began collaboration with SEMATECH intended to help calibrate and determine the resolution of SCM. SEMATECH has provided p-n junction specimens, together with corresponding computer-aided design and secondary ion mass spectroscopy (SIMS) data. The ANSYS finite-element package has been chosen to model the SCM data from these samples. The SIA Technology Workshop identified junction profiling as a key need for the development of future generations of ICs. The SCM method is the most promising, nondestructive approach to 3D profiling.

- Developed a simple, accurate measurement method for determining the electron density and Hall mobility of semiconductor layers, based on the magnetic-field dependence of the two-terminal magnetoresistance of a rectangular layer. Applied this method to characterize accumulation layers of n-type HgCdTe infrared (IR) detectors. Determined the electron density and mobility of the top accumulation layers of several differently processed detectors from the fit to the magnetoresistance data at high magnetic field. Measured ~20% variations in accumulation-layer density on the different elements of a multi-element detector, demonstrating the capability of this method to determine the effects of process variations. The IR detector industry needs simple methods to characterize devices and to determine the effects of processing steps on device reliability.

- Conducted high-resolution (1-arcsec resolution) X-ray diffraction measurements of single monolayer AlAs/GaAs superlattices fabricated by the Division's MBE facility using several different growth techniques. Results indicate that the samples grown by migration-enhanced epitaxy (MEE) are more highly strained ($20.05 \pm 0.77 \times 10^{-4}$ rad) and have more tilt ($5.91 \pm 0.19 \times 10^{-4}$ rad) than the same superlattice structures grown using the interrupted-growth (IG) technique ($15.29 \pm 0.77 \times 10^{-4}$ rad and $1.12 \pm 0.19 \times 10^{-4}$ rad, respectively). They also show that the MEE technique produces a more abrupt superlattice interface. These results show the competing advantages of the IG technique for reduced strain and the MEE technique for enhanced abruptness. Industry needs this knowledge to be able to grow epitaxial layers of atomic-scale heterostructures that need well-defined layer thicknesses and sharp interfaces for carrier confinement and proper device operation.

Project: NANOELECTRONICS

FISCAL YEARS	94	95	96	97	98
III-V MBE-RELATED RESEARCH					
Conduct research on MBE growth kinetics, dopant incorporation, and lattice mismatch strain effects. [STRS, OA-ARPA, ARL]	━━━	━━━	━━━	━━━	━━━ ⇒
Develop migration-enhanced-epitaxy and atomic-layer-epitaxy growth techniques for interface layer sharpness, quantum-confinement applications, and improvement of quantum-Hall-effect devices for the standard ohm. [STRS]	━━━	━━━	━━━	━━━	━━━
Correlate MBE materials properties and interface information for GaAs/Si substrates with HgCdTe device performance. [OA-NVL]	━━━	━━━	━━━	━━━	
Design, grow, and characterize optical waveguides, laser structures, and multiple quantum-well structures for NIST/Boulder projects. [STRS]	━━━	━━━			
Continue collaborative program with University of Iowa on photonic, electronic, and physical properties of III-V heterostructure-based devices. [OA-ARPA]	━━━	━━━			
Develop X-ray fluorescence as a sensitive in-situ technique to control alloy composition of MBE layers to ~1%. [STRS]	━━━	━━━	━━━		
Develop STM lithography with the Electricity Division and the Precision Engineering Division MEL/PED to pattern and study ultra-small structures. [STRS]	━━━	━━━	━━━	━━━	━━━ ⇒
SCANNING CAPACITANCE MICROSCOPY					
Develop and apply scanning capacitance microscopy to wafer mapping of electrical properties of silicon and compound semiconductors to 20-nm resolution. [STRS, STRS-OMP]	━━━	━━━	━━━	━━━	━━━ ⇒

Project: NANOELECTRONICS (concluded)

FISCAL YEARS	94	95	96	97	98
Develop computer codes to deduce dopant profiles from scanning capacitance measurements. [STRS, STRS-OMP]	━━	━━	━━	━━	━━ ⇒
MAGNETO-TRANSPORT MEASUREMENTS OF THIN LAYERS					
Characterize III-V heterostructure interfaces by magneto-transport effects. [STRS]	━━	━━	━━	━━	━━ ⇒
Develop and implement Shubnikov-de Haas effect as a tool to evaluate and characterize two-dimensional electronic properties of accumulation layers produced by passivation processes for infrared detectors. [STRS, OA-NOAA]	━━				
Develop magnetoresistance as a two-terminal method to determine carrier density and mobility in layered materials. [STRS]	━━	━━	━━		
Provide needed consulting services related to detector characterization, packaging, bonding, and metallization. [OA-NOAA]	━━	━━			
FUTURE PROJECT PLANS					
Develop in-situ characterization techniques for monitoring and controlling growth and process parameters for Si and III-V semiconductor device fabrication.		━━	━━	━━	━━ ⇒
Develop standard methods and artifacts, based on prior research in project, for improving metrology of growth and process parameters.			━━	━━	━━ ⇒

Project: SEMICONDUCTOR CHARACTERIZATION TECHNOLOGY

FY 94 Fund Sources: STRS, STRS-OMP, STRS-SRMPO; OA-ARPA, OA-TITLE III

Staff (7.7 staff-years)

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

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

Objective: Provide U.S. manufacturers of semiconductor electronic devices with state-of-the-art measurements and materials analysis capabilities to obtain quantitative assessment of the device-relevant optical and electronic properties and to provide the foundation for in-situ, real-time control and monitoring. Develop the measurement methodology, the theoretical foundation and data analysis procedures, standards, and accurate measurements for impurity concentrations, carrier densities and mobilities, and thin-film and interface properties down to submonolayer thicknesses. Current challenges to be met include quantitative analysis of dopants to densities $<10^{12}$ cm^{-3} in high-purity Si; micro-spectroscopies for study of small structures (<2 μm); and thin-film (d < 10 nm) spectroscopic ellipsometry measurements and modeling improvements for SiO_2/Si needed by the Si integrated circuit (IC) industry as set forth in the Semiconductor Industry Association (SIA) Roadmap and for Standard Reference Material (SRM) development.

Significance: Optical and electrical activity in semiconductors form the foundation of all major electronic devices used today. Electronic device manufacturers are increasingly relying on contactless and nondestructive optical probes for on-line and in-situ processing and growth monitoring and analysis. Advancing the state of the art in understanding the optical and electrical properties and their associated metrology is critical to the continued growth of the industry.

FY 94 Plans

- Establish impurity metrology through the development of a calibrated optical detection capability for trace impurity analysis in Si at levels below 10^{13} cm^{-3}.

- Advance ellipsometry-based metrology of thin (<15 nm) SiO_2 on Si to improve the understanding of the optical properties of SiO_2 on Si thin oxides and interfaces, and to improve data analysis methods and experimental accuracy for production of thin SRMs.

- Develop a system to implement a new microscopic photoreflectance technique for the characterization of microstructures and compound semiconductors, with lateral resolution of 2 μm.

- Support the in-house materials growth and development and nanotechnology effort with optical and electrical characterization.

- Complete a review paper on the optical properties and characterization techniques for HgCdTe and related infrared detector materials.

- Develop a multicarrier transport technique to determine carrier concentrations and mobilities of liquid-phase-epitaxially grown HgCdTe.

- Certify and deliver sufficient quantities of 100-mm silicon resistivity SRMs to meet industry's needs. 900 units over seven different levels are projected. Publish documentation of the certification process.

- Develop an improved understanding of the industry's needs for silicon or compound semiconductor-based SRMs, and improve collaboration with the industry for more effective development of such SRMs. Review the compound semiconductor industry with a view towards defining critical issues and needs.

- Complete the optical characterization survey and analysis to determine the usefulness and effectiveness of optical characterization techniques in industrial situations.

- Plan and coordinate the organization and technical aspects of the International Workshop on Semiconductor Materials Characterization: Present Status and Future Needs.

Related Developments

- A 15-year semiconductor plan for silicon-based IC technologies was developed by key U.S. technologists under the auspices of the SIA. The SIA report indicated that NIST is the only place in the U.S. where the broad range of measurements needed for semiconductor processing is routinely and systematically developed, and that the NIST initiative in semiconductor metrology must be supported and further expanded to ensure that measurement capabilities keep pace with IC technology development. Group activities for improved ellipsometric characterization of thin dielectric layers and for the development of in-situ spectroscopic process-monitoring techniques address two of the expressed needs.

- Requests for a number of SRMs, such as layer sheet resistance, film stress, and thickness of multiple-layer dielectrics was one of the significant outputs of a multisponsor International Workshop on Process Control Measurements for Advanced IC Manufacturing, held in Austin, Texas, in November, 1992.

- Organized and held a workshop on optical characterization techniques for industrial participants of the ARPA Infrared Materials Program. The workshop provided a review of spectroscopic techniques and established standards for a range of measurement conditions and calibration procedures.

FY 93 Accomplishments

- Wrote chapter on "Optical Properties of Semiconductors" for the *Handbook of Optics*, second edition, for the Optical Society of America and McGraw Hill. Provided review of all important optical properties and techniques for measuring them.

- Advanced the state of the art of photoreflectance spectroscopy for semiconductor analyses through the use of double-modulation and multiple-pump beams. Detailed analysis of complex laser structures is now possible.

- Achieved an advance in the quantitative understanding of the optical properties of the SiO_2/Si interface region by conducting accurate spectroscopic-ellipsometry measurements and by developing an analysis that, for the first time, comprehensively accounts for strain and microroughness. This is a necessary step in the development of thin ($d < 10$ nm) SiO_2/Si SRMs.

- Completed certification and related measurements for 100 sets of SRM 2551 for Interstitial Oxygen in Silicon. Analysis of data indicates an uncertainty of certification, relative to the master calibration set, of better than 0.17% (2σ). SRMs are required by IC manufacturers to determine oxygen concentrations.

- Completed certification and system control measurements for 135 units of SRM 2547 100-mm Diameter Silicon Resistivity at the 200-Ω-cm level. SRMs are required by industry as standards for resistivity measurements.

Project: SEMICONDUCTOR CHARACTERIZATION TECHNOLOGY

FISCAL YEARS	94	95	96	97	98
Monitor industrial measurement requirements to identify techniques needing to be developed, improved, or standardized. [STRS]	———	———	———	———	——— ⇒
Perform electrical and other purity and crystal quality analyses and consult for high-purity silicon. [OA-Title III]	———				
Develop prototypes and produce new SRMs, such as ion implant dosimetry SRMs with 1% accuracy. [STRS, STRS-SRMPO]	———	———	———	———	——— ⇒
Certify silicon resistivity SRMs to meet industrial requirements. [STRS, STRS-SRMPO]	——				
Apply and enhance multicarrier magneto-transport capability (Hall effect, etc.) to compound semiconductor materials. [STRS]	———	———			
Develop high-resolution FTIR methods for photoluminescence and transmission of semiconductors. [STRS, STRS-OMP]			———	———	——— ⇒
Develop improved methods for analysis of trace elements in silicon and compound semiconductors to levels below 10^{12} cm^{-3}. [STRS, STRS-SRMPO]	———	———	———		
Develop spectroscopic ellipsometry and related methods for analysis of materials and thin (d < 10 nm) overlayers on semiconductors, including native oxides. [STRS, STRS-SRMPO, STRS-OMP]	———	———	———	———	———
Survey and analyze optical characterization methods used in the semiconductor industry. [STRS]	———				
Advance absolute concentration measurement for oxygen-in-silicon by two times to an accuracy of ≈3%. [STRS, STRS-SRMPO]		———			

Project: SEMICONDUCTOR CHARACTERIZATION TECHNOLOGY (concluded)

FISCAL YEARS	94	96	96	97	98
Develop wafer-level spectroscopic mapping techniques for compound semiconductors with lateral resolution of 2 µm. [STRS, STRS-OMP, OA]		—	—		
Develop in-situ spectroscopic analytical procedures for semiconductor growth and processing. [STRS, STRS-OMP, OA]		—	—	—	—
Plan and coordinate the organization and technical aspects of the International Workshop on Semiconductor Materials Characterization: Present Status and Future Needs. [STRS, OA-SEMATECH, OA-ARPA]	—	—			

Project: ELECTRICAL AND THERMAL CHARACTERIZATION

FY 94 Fund Sources: STRS; CRADA; OA-ATP

Staff (3.75 staff-years)

Professional	A. R. HEFNER	J. Albers	D. Berning	D. Blackburn*
Technician	TBD			

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

Objective: Provide U.S. manufacturers and users of semiconductor devices with cost-effective means to determine the electrical and thermal performance of advanced devices and packages and to determine the validity of component models used for system simulations. More specifically, develop the theoretical foundations, standards and associated experimental techniques required for the accurate measurements of chip temperature, device electrical and thermal model parameters, and package electrical parasitics. Develop temperature measurement methods for GaAs monolithic microwave integrated circuits (MMICs) and Si ultra-large-scale integrated (ULSI) circuit chips with powers up to 100 W/cm^2, model parameters for large (up to 5-cm chip diameter) power devices, and package electrical parasitics for power (1000 W) and multichip modules. Current challenges to be met include the measurement of chip temperatures with a spatial resolution of ±1 μm and a temporal resolution of ±1 μs, device model parameters for 2000-V, 400-A, 100-ns turn-off time devices and modules, and extraction of package electrical parasitics in situ.

Significance: The Semiconductor Industry Association (SIA) Roadmap identifies device and package model characterization, integration of thermal and electrical computer-aided design (CAD) tools for devices, thermal management, and integrated design/simulators for thermal, electrical, and power management for packages as important technical areas in need of development and support to achieve the 15-year goals of the Roadmap. The electrical and thermal characterization procedures and the device models used in circuit simulation CAD tools have not kept pace with the application of the new device types. In addition, the higher power dissipation levels of high-density integrated circuits and high current density power devices have resulted in thermal management becoming a much more important aspect in the overall design of the electronic system. Furthermore, higher speed and higher current density semiconductor devices have also increased the importance of package and circuit board interconnect electrical parasitics. The NIST work provides designers of advanced electronic systems with verified design and characterization tools similar to those available to designers of conventional logic and memory circuits, and also better integrates the design process for the electrical and thermal aspects of the system, as well as package interconnect parasitics.

FY 94 Plans

- Form the NIST Working Group on Circuit Simulator Model Validation: organize working group, moderate meetings, and provide technical support for development of device test procedures.

- Continue collaborations established under ongoing Cooperative Research and Development Agreements (CRADAs) to develop compact component models for circuit simulation: develop high-voltage insulated gate bipolar transistor (IGBT) models and transfer NIST IGBT extraction capability to CRADA members. Also, begin collaboration on electro-thermal simulation of hybrid electric vehicles as appropriate. This project may involve a CRADA with Oak Ridge National Laboratories and a U.S. manufacturing company.

- Complete the investigation of temperature-sensitive parameters (TSP) for IGBT transient thermal impedance measurements: complete test systems for threshold voltage and emitter-base voltage as TSP, compare methods using different TSPs, support findings with simulation and infrared measurements, and prepare to publish a description of the preferred method.

- Support NIST ATP programs related to the electric and thermal characterization of semiconductor devices.

- Complete the development of a computer framework for finite element thermal simulation, and the automation of transient infrared thermal measurements. Also, complete the development of a software program for multilayer thermal analysis using recursion relation.

- Begin to develop package-electrical-parasitic metrology and modeling capabilities by investigating the use of time-domain reflectometry and spectral analysis for characterizing and modeling semiconductor package parasitics.

- Continue to develop the capability to characterize and model high-power modules: complete the construction of high-current IGBT test systems, and begin finite element thermal simulations of IGBT modules. The long-term goal is to develop compact circuit simulator modeling capability for high-power modules, including semiconductor chips, module interconnect parasitics, and electro-thermal interactions.

Related Developments

- One of the NIST ATP grant awards focuses on the development of metal-oxide-semiconductor- (MOS-) gated, large-area power devices. Principals on this project will interact with company researchers on this new work. The full extent of interaction will be determined by possible NIST ATP funding for this effort.

- Staff of the Electrical and Thermal Characterization Project is collaborating with counterparts in Sandia National Laboratories in the development of new tools for evaluating the thermal performance of the packaging of semiconductor microelectronic chips. This is one of the first projects undertaken in the context of the technical agreement signed by NIST and Sandia earlier this year.

FY 93 Accomplishments

- Introduced the electro-thermal power system simulation methodology. This effort included the first known development of compact thermal models for thermal components to be implemented in a widely used, commercial software simulation package. The SIA sees the development of electro-thermal simulation capability as a critical need.

- Established the failure limits of a state-of-the-art power device, the bipolar-mode field-effect transistor (BMFET), by detailed examination of its failure characteristics using the NIST nondestructive test system. This work identified serious design and practical problems with the device. The results of the study are being used by the manufacturers in redesigning the structure. Efforts such as this are critical, if the new devices brought onto the market are to perform reliably and predictably.

- Implemented the buffer layer model for IGBT into the commercial software simulation package. This implementation was done for the model developed several years ago at NIST. At that time, buffer layer devices were not common, as they are now. Since the early NIST paper, it has been recognized that the buffer layer structure is superior to irradiated devices (to reduce lifetime), and buffer layer devices predominate in the field. (The early NIST paper detailed the advantages of these devices compared to conventional IGBTs.) It is critical to have valid models available in simulators for the latest device types.

Project: ELECTRICAL AND THERMAL CHARACTERIZATION

FISCAL YEARS	94	95	96	97	98
Develop frameworks for thermal simulation and automated transient infrared thermal measurements. [STRS, STRS-ATP]	—				
Investigate temperature-sensitive parameters for IGBT transient thermal impedance measurements. [STRS]	—	—			
Develop characterization and modeling capability for very high power devices and packages (IGBT modules). [STRS, STRS-ATP]	—	—	—		
Develop methods for measuring and modeling important electrical parameters of semiconductor packages based on Time-domain reflectometry, S-parameters, and network analysis. [STRS, STRS-OMP]	—	—	—	—	
Organize NIST Working Group on Model Validation and support with development of test procedures. [STRS]	—	—	—	—	— ⇒
Develop circuit simulator models for other advanced high-power semiconductor devices, including power devices. [STRS, STRS-ATP]		—	—	—	
Develop characterization and modeling capability for high-speed advanced semiconductor devices. [STRS, STRS-OMP]			—	—	— ⇒
Investigate the inclusion of reliability aspects into circuit simulator models. [STRS]				—	— ⇒
Develop methods for measuring thermal properties of small GaAs and Si devices using combination of simulation and measurements. [STRS, OA-MIMIC]		—	—		
Develop high spatial resolution temperature measurement based upon Raman spectroscopy. [STRS-MIMIC]	—	—	—		

Project: THIN-FILM CHARACTERIZATION

FY 94 Fund Sources: STRS, STRS-SRMPO-WCF, STRS-SRMPO-DEV; OA-DNA, OA-Army (SDC)

Staff (4.75 staff-years)

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

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

Objective: Provide U.S. manufacturers of semiconductor devices with cost-effective means to determine the conformance of thin-film properties with design and process specifications. More specifically, develop the theoretical foundations, standards, and associated experimental techniques required for the accurate measurements of thickness, optical constants, defect densities, and interface properties of SiO_2 and Si thin films. Characterize the thickness and optical properties of thin oxides to 5-nm thickness and characterize the defects of thin-film Si (to 0.1-μm thickness) and buried SiO_2 layers. Current challenges to be met include reducing the SiO_2 measurement uncertainty to less than ±1 nm, developing a theoretical and experimental understanding of the SiO_2-Si interfacial region, and developing diagnostics for the defect nature of thin-film Si and buried oxide.

Significance: Thin films are the cornerstone of the semiconductor manufacturing industry. The Semiconductor Industry Association (SIA) Roadmap identifies robust gate dielectrics at 5-nm thickness, both high (for storage cells and capacitors) and low (for interconnect isolation) dielectric constant materials, and improved planarization methods as specific on-chip materials issues that will impact the ability to achieve the 15-year goals of the roadmap. The NIST work will supply needed materials understanding, measurement techniques and procedures, and calibration artifacts to support the reliable, controlled processing of these films in the semiconductor manufacturing environment. Silicon-on-insulator (SOI) promises to be an important technology for future circuits. It has great potential for low-power, high-speed, high-temperature integrated power, and radiation-hard circuits. Improved material quality and analysis tools will speed the application of SOI in these areas. The SIA Roadmap acknowledges that the development of low-cost SOI substrates would advance integrated circuit (IC) performance a full generation. Although the Roadmap does not explicitly address low-power electronics, independently or in relation to SOI, the needs are implied throughout the Roadmap in the calls for improved power management and control. The NIST work will support the development of improved SOI materials through the development of metrology tools and techniques, transferring them to industry and applying them to relevant SOI materials and processing problems.

FY 94 Plans

- Certify 40 10-nm-thick oxide layers, grown at NIST, as Standard Reference Materials (SRMs). These will be the first standards traceable to NIST at this thickness.

- Refurbish and modify the high-accuracy ellipsometer, including the detector and its electronics, improve alignment procedure, increase automation, and possibly add spectra capability.

- Develop long-term, sustainable metrology support for thin-film thickness in the semiconductor industry as a combination of SRM, measurement service, recertification, and industrial research collaboration.

- Begin development of wafer-surface preparation procedures, film growth procedures, and ellipsometric measurements and techniques for the development of 5- to 7-nm thin-film artifacts. This will include interactions with one or more U.S. companies through a CRADA.

- Employ the double-etch technique and transmission electron microscopy (TEM) to measure defect densities in silicon films. Develop processing sequences to reduce number of defects.

- Refine current-voltage (I-V) and capacitance-voltage (C-V) techniques for measuring buried-oxide leakage currents and traps. Combine etching, scanning electron microscopy, electron spin resonance (ESR), and secondary ion mass spectroscopy (SIMS) techniques to determine the nature of the residual leakage and hole trapping in the buried oxide. Develop process sequences to minimize the effects of trapping in the buried oxide.

- Begin investigation of thin oxide SIMOX (separation by implantation of oxygen) structures. Begin studies to determine the effects of dose and annealing on defect structures in thin buried oxides.

Related Developments

- ARPA is planning a very low power electronics initiative to begin in FY 95. NIST has provided assistance in the development of this program, as it includes SOI materials. SOI structures have potentially lower standby power than do bulk structures by a factor of about 100. SOI is a major contender for all portable, battery-powered electronics. NIST expects to play a significant role in the future in this program.

- A. U.S. company is marketing a 75-Å thin-film reference material. Because no NIST SRM exists at this thickness, it is not traceable to NIST and its usefulness is limited. NIST will work with the outside company to find the best ways to simultaneously meet the needs of the industry and their specific goals in this area.

FY 93 Accomplishments

- Prepared 75 thin-film SRM artifacts, including the first 16 14-nm artifacts grown and certified at NIST. Developed a 10-nm SRM and initiated an industrial interlaboratory study to verify its suitability as an industrial calibration artifact. These artifacts are needed by the semiconductor industry to assure the calibration of their critical thin-film metrology tools. It is important to provide artifacts of comparable thickness to those in actual use in the industry. It is also important that NIST actively participate with industry in metrology development, in addition to supplying needed artifacts.

- The initial round of the comprehensive experiment on the effect of nitrogen ambients during high-temperature annealing of SIMOX wafers was completed. Nitrogen, nitrous oxide, and ammonia ambients were used for portions of the annealing cycle. SIMS, etch pit measurements, TEM, ESR, and I-V measurements have been completed. The quality of the buried oxide and how the annealing environment affects that quality is critical to the success of SIMOX material. NIST is in an ideal position to study the effects of the ambient on the buried oxide quality due to measurement expertise and flexible high-temperature processing capability.

Project: THIN-FILM CHARACTERIZATION

FISCAL YEARS	94	95	96	94	98
Continue production of thin-film SRMs. [STRS, STRS-SRMPO]	━━━	━━━	━━━	━━━	━━━
Phase-in new thickness standards as needed. [STRS, STRS-SRMPO]	━━━	━━━	━━━	━━━	━━━
• Phase-in 10-nm SiO_2	━━━				
• Phase-in 5- to 7-nm SiO_2	━━━	━━━			
Develop measurement service, recertification procedure, and industrial collaborations for thin-film thickness. [STRS, STRS-SRMPO]	━━━	━━━	━━━	━━━	━━━ ⇛
• Develop measurement service	━━━				
• Develop recalibration procedure	━━━	━━━			
• Develop industrial collaborations	━━━	━━━	━━━	━━━	━━━ ⇛
Develop metrology for thin-film optical, electrical, and thermal characteristics. [STRS, STRS-OMP]		━━━	━━━	━━━	━━━ ⇛
Determine effect of dose rate on buried oxide thickness and quality for SIMOX material. [STRS, OA-DNA, OA-SDIO]	━━━	━━━			
Develop and evaluate measurement methods for qualifying material and processing for SOI material. [STRS, OA-DNA, OA-ARPA]	━━━	━━━	━━━	━━━	━━━

Project: TEST STRUCTURE METROLOGY FOR ADVANCED SEMICONDUCTOR MANUFACTURING

FY 94 Fund Sources: STRS, STRS-OMP; OA-DoD

Staff (12.5 staff-years)

Professional	L. LINHOLM	J. Albers*	R. Allen	D. Berning*
	M. Cresswell	M. Gaitan	D. Khera	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

Objective: Provide U.S. manufacturers and users of semiconductor devices and fabrication tools 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. More specifically, develop the theoretical foundations, standards, and associated experimental techniques required for accurate electrical measurements of electrical linewidth and feature placement, develop sensors for assuring reliability performance of interconnects and oxides by controlling processes during manufacture; develop fabrication methodology for Micro-Electro-Mechanical (MEMs) systems; and design, develop, and deliver an integrated gas sensor for monitoring and controlling process tool performance. Current challenges to be met include measurement of electrical linewidth to dimensions of 0.18 μm and feature placement of 10 nm; complementary metal-oxide-semiconductor (CMOS) compatible devices and design libraries; 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.

Significance: In order to manufacture competitive, cost-effective semiconductor products, improved manufacturing process and tool control, device performance, and reliability have been recognized by the Semiconductor Industry Association (SIA) Technology Roadmap, the Semiconductor Research Corporation (SRC) 2001 Reliability Roadmap, and many in the integrated circuit (IC) industry as key steps required for the next generation of domestic products. Improved microelectronic test structures, test methods, rapid data analysis techniques, and sensors provide a low-cost method of determining and measuring key control and performance parameters. Improved structures thoroughly validated as to capabilities, limitations, and interferences are needed to improve test coverage and assure product performance. Competent, focused, and unbiased development is necessary to assure equity between buyer and seller, and to enable improved technology transfer between tool and device manufacturers.

FY 94 Plans

- Prepare draft of X-Ray Lithography Mask Standard for balloting by the Semiconductor Equipment Manufacturers International (SEMI) International Standards Program.

- Demonstrate the utilization of Metrology of Alignment Test Structure (MOATS) technology for process-compatible registration in collaboration with Sandia National Laboratories.

- Develop post-processing techniques to improve the integrity of aluminum-tin oxide contacts on a CMOS-compatible micro-hotplate structure.

- Perform time-dependent-dielectric breakdown experiments on 10- to 25-nm gate oxides, and characterize electric field and temperature dependence of breakdown.

- Complete draft of a revised American Society for Testing and Materials (ASTM) Standard Guide F 1259-89 for the design of an electromigration test structure with narrow metal lines and metallizations having large grain sizes.

- Investigate uniformity and yield statistics of large-array integrated micromechanical elements. If successful, begin implementation of large-array (>16 by 16) microheating elements for thermal flat-panel display demonstration using computer and/or video signal control.

Related Developments

- The SIA 15-year plan lists 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 supported and expanded.

- NIST and Sandia have teamed to meet SIA goals by applying their resources to test structures for advanced lithography metrology, building-in reliability, sensor development, and packaging.

- Building-in reliability is the focus of NIST-initiated Institute of Electronic and Electrical Engineers (IEEE) Integrated Reliability Workshop.

FY 93 Accomplishments

- Developed a process and procedures for producing micromachined semiconductor devices through University of Southern California Metal-Oxide-Semiconductor Implementation Service (USC-MOSIS) in which two layers are added to the MOSIS complementary metal-oxide-semiconductor (CMOS) process to define regions to be micromachined later by the customer. Used the method for fabricating micromachined gas sensors to create an array of thermally isolated microbridges, which operate as individual sensor elements. Built the device and demonstrated the sensitivity of this sensor to hydrogen. The development of this capability by NIST permits the design and manufacture of micromachined parts in a shorter time and at a lower cost than previously possible, because a commercially available, standard, reliable process is used. Industry needs low-cost gas sensors for a variety of process control, safety, and environmental considerations.

- Developed a method of determining the relative positions of the images of an array of fiducial marks projected from a lithography mask onto a resist film on a substrate. This method provides an accuracy and precision almost an order-of-magnitude better than that available from any commercially available coordinate measuring system. Compared a selection of electrical measurements of the separations of parallel lines, up to 13.5 mm apart, with corresponding measurements made directly by the NIST Line Scale Interferometer and found that respective measurements agreed to within less than 10 nm. The new method provides the mask manufacturer with a very cost-competitive metrology, which is directly traceable to the metric of atomic spacings of single-crystal surfaces through the Molecular Measuring Machine being developed by NIST.

- Developed a high-temperature wafer-probing station which demonstrates that oxide breakdown tests can be conducted at temperatures as high as 400 °C, or more, without any deviation from the characteristics observed at the lower, more commonly used stress temperatures. Being able to conduct these accelerated stress tests at 400 °C offers the advantage of greatly reduced test time.

Project: TEST STRUCTURE METROLOGY FOR ADVANCED SEMICONDUCTOR MANUFACTURING

FISCAL YEARS	94	95	96	97	98
Establish correlation between optical and electron-beam-based linewidth metrologies and electrical techniques. [STRS-OMP, OA]	—	—			
Develop contamination-free electrical probing metrology. [STRS, OA]				—	— ⇒
Demonstrate robust 10-nm overlay metrology for thin conducting films on quartz substrates. [STRS, STRS-OMP, OA]	—				
Develop and demonstrate electrical test structure-based metrology for pattern feature placement and overlay that is traceable to NIST Molecular Measuring Machine. [STRS-OMP, OA]		—	—		
Develop on-wafer, multilevel conductor-compatible overlay metrology with a goal of better than 20-nm precision. [STRS, STRS-OMP, OA]		—	—	—	—
Develop and implement approaches to the commercialization and licensing of selected test structures/methods. [STRS, OA]	—	—	—	—	— ⇒
Characterize reliability of thin oxide films for ultra large scale integrated circuit processes. [STRS, 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. [STRS-OMP]	—	—	—	—	— ⇒
Develop, characterize, and evaluate integrated sensor elements for improving reliability by monitoring in-situ and controlling deposition of films. [STRS-OMP, OA]	—	—	—	—	

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

FISCAL YEARS	94	95	96	97	98
Design, develop, and evaluate micromachined structures and associated drive and control circuitry for dynamic thermal scene simulation. [OA-Army]					
Develop methodology for fabricating micromachined structures in silicon foundries to point of practical utilization. [OA-Army]					⇒
Design, fabricate, help evaluate sensors important for metrology, calibration, and standardization through collaboration with other NIST divisions. [STRS, OA]					⇒
Develop CMOS-compatible micromachined waveguides and thermal converters for precision wide-band sensors. [OA]					
Develop test structures and methods for determining thermo-electro-mechanical properties of thin films. [STRS]					

ELECTROMAGNETIC FIELDS DIVISION

Project: POWER STANDARDS AND MEASUREMENTS

FY 94 Fund Sources: STRS, OA, DOD, Calibration Fees

Staff (6.0 staff-years)

Professional	N. LARSEN	F. Clague	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

Objective: Establish NIST microwave power standards from 10 MHz to 100 GHz in coaxial line, from 18 GHz to 96 GHz in WR-42, -28, -22, -15 and -10 waveguides, with uncertainties of 0.1 to 0.5 percent. Develop new isothermal microcalorimeters for reference standards in WR-42, WR-22, WR-15, and WR-10 waveguides. 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 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.]

Significance: Microwave power is a fundamental quantity for every commercial and military application of microwave energy, including communications, navigation, surveillance, manufacturing, aerospace, medicine, defense, entertainment, and advanced computing. This program establishes a new generation of NIST microwave power standards to meet vital present and future needs of industry.

FY 94 Plans

- Continue the development of 2.4/3.5 mm coaxial power standards. Promote transfer standard development by one or more private companies, probably through CRADAs.
- Complete the construction and calibration of 40 automated 1 GHz/1 mW reference power measurement systems for the Air Force.
- Continue the evaluations of the WR-42, -22, -15, and -10 microcalorimeters. The evaluation of the WR-22 calorimeter will be completed as soon as power sources are available.
- Develop a new coaxial detector capable for use up to 50 GHz. Develop standards and calibration services using the new detector.
- Develop a low-frequency (down to 10 MHz) Type N coaxial mount, based on either a modified commercial device or the new detector being studied.
- Complete the development of a 4 K WR-22 power standard.
- Develop the capability to operate a coaxial microcalorimeter at 1 mW.
- Interact with industry and National Voluntary Laboratory Accreditation Program (NVLAP) office regarding final NVLAP technical requirements for calibration laboratory accreditation.
- Provide calibration and measurement services for power.

- Transfer calibration service for Type N thermistor mounts to Direct Comparison Measurement System.

Related Developments

- A major U.S. instrument company, by customer request, is considering establishing a calibration service for thermoelectric and diode-based power meters. These are not calibrated by NIST since they lack stability as a power transfer standard. NIST supports the calibrations by providing information and assistance on customer power transfer, using calibrated thermistor mounts or mount/adapter combinations.

- The Singapore Standards Institute and the Instituto Nacional de Tecnica Aeronautica (INTA) of Spain have inquired about purchasing the NIST designed Model CN thermistor mounts.

FY 93 Accomplishments

- Completed the construction of WR-42 microcalorimeter.

- Completed the construction of a new microwave microcalorimeter for WR-10.

- Assembled and calibrated the first 11 microwave power standards under the new premium calibration service.

- Received the first samples of a new dc-substitution microwave detector. Preliminary dc tests on a unit mounted in 2.4-mm transmission line indicated a low sensitivity, but also a promising beginning.

- Measured and delivered NIST CN thermistor mounts to two companies.

- Installed a new heat pump on a coaxial microcalorimeter. This is the first step toward providing customer service at 1 mW level.

- Performed 30 calibrations for customers in first quarter; 34 calibrations in second quarter; 36 calibrations in third quarter, and 22 calibrations in fourth quarter. Also provided high power services from 1-400 MHz, 1-1000 kW.

- Developed direct comparison power calibration system for measuring the effective efficiency of Type N thermistor mounts.

- Installed High Power Microwave Measurement System at the Army Primary Standards Laboratory. This system operates from 2 to 1000 MHz at power levels from 1 to 200 watts.

- Completed the development of waveguide transfer standards in WR-10.

- Demonstrated that the DC substitution error with WR-22 superconducting power meter is less than 0.03%.

Project: POWER STANDARDS AND MEASUREMENTS

FISCAL YEARS	94	95	95	97	98
MICROCALORIMETER DEVELOPMENT					
Construct WR-10, -15, -22, -42. [STRS]	—				
Construct microcalorimeter for 3.5 mm and smaller. [STRS, OA]	—	—	—	—	— ⇒
Evaluate WR-10, -15, -22, -42 microcalorimeter. [STRS, OA]	—	—	—		
TRANSFER STANDARDS/CALIBRATION SYSTEMS DEVELOPMENT					
Develop 7-mm coaxial transfer standards <50 MHz. [OA]	—	—			
Evaluate 7-mm coaxial transfer standards < 50 MHz. [OA]		—	—	—	
Develop coaxial power standards 5 MHz to 1 GHz. [OA]		—			
Construct coaxial thermistor standards for DOD and industrial laboratories. [OA]	—	—			
Develop 2.4- and 3.5-mm thermistor standards to 50 GHz. [OA]	—	—	—	—	— ⇒
Build/calibrate 1 GHz reference power meters for Air Force. [OA]	—				

Project: POWER STANDARDS AND MEASUREMENTS (concluded)

FISCAL YEARS	94	95	96	97	98
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]	━━━	━━━			
SUPERCONDUCTING STANDARDS					
Complete feasibility study for WR-22 power standards. [OA]	━━━				
Construct/evaluate device, if feasible. [STRS, OA]	━━━	━━━	━━━	━━━	━━━ ⇒
CALIBRATION/MEASUREMENT SERVICES					
Modify uncertainty statements per NIST guidelines. [STRS]	━━━				
Provide advertised calibration services. [Fees]	━━━	━━━	━━━	━━━	━━━ ⇒
Provide high power measurement services 1 MHz - 400 GHz. [STRS, OA]	━━━	━━━	━━━	━━━	━━━ ⇒

Project: IMPEDANCE, ATTENUATION, VOLTAGE STANDARDS AND MEASUREMENTS

FY 94 Fund Sources: STRS, DOD, Calibration Fees

Staff (6.0 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

Objective: Preserve and improve the NIST physical standards for impedance, reflection coefficient, attenuation, and voltage. Enhance rf/microwave calibration services through continued improvements of standards, measurement systems, and measurement techniques.

Significance: Standards and measurement systems must be improved to realize the potential of modern instruments, and meet the needs of a rapidly advancing industry and technology. NIST standards and services provide the basis for U.S. microwave measurements, and NIST methodology ensures that these standards and services will meet industry's advancing needs. For some time, industry has demanded services for smaller coaxial standards. The physical characteristics of these standards must be determined with smaller tolerances to evaluate mechanical imperfections.

FY 94 Plans

- Modify the low-frequency Twin-T impedance bridge and re-test to determine if errors in original design have been eliminated.
- Design and construct a new drive mechanism for the Mark III Bridge.
- Complete the documentation for thermal voltage converter (TVC) and Micropot Measurement Systems.
- Construct a 30-MHz comparison receiver for the Air Force and develop documentation.
- Convert uncertainty statements for attenuation, impedance, and voltage to comply with the new NIST Policy.
- Provide calibration and measurement services for attenuation, impedance, and voltage.
- Interact with industry and National Voluntary Laboratory Accreditation Program (NVLAP) Office, regarding the final NVLAP technical requirements for calibration laboratory accreditation in attenuation, impedance and voltage.
- Extend capability to measure impedance in Type N coaxial line to 26.5 GHz.

Related Developments

- A new technique to calibrate vector network analyzers (VNAs) below 500 MHz using thin-film resistors has been developed in Germany. This could have numerous applications in 6-port, impedance, and high-frequency voltage metrology, which would undoubtedly impact measurement systems, standards and calibration services.

- A major U.S. semiconductor company has approached NIST to participate in a development and research consortium designed to provide directions and guidelines regarding semiconductor wafer testing at high frequencies. A semiconductor advisory group represented by major semiconductor companies will be responsible for this task.

FY 93 Accomplishments

- Installed a shield around the laser interferometer on the 30-MHz attenuation system.

- Completed the software necessary to control the motor that automatically nulls the 30-MHz receiver.

- Implemented the use of stepping motors on the low-frequency variable capacitors.

- Completed the development of a semi-automated laser micrometer measurement system to measure the diameter of 3.5-, 2.92-, and 2.4-mm airlines.

- Completed the testing and calibration of a low-frequency (10 kHz - 5 MHz) Twin-T impedance bridge. Unacceptable errors were discovered in the traditional design.

- Developed the 30-MHz Linear Measurement System and completed the uncertainty analysis.

- Performed calibrations on 95 customer standards in first quarter; 20 calibrations in the second quarter; 37 calibrations in the third quarter, and 33 calibrations in the fourth quarter.

- Developed preliminary NVLAP technical requirements for attenuation, impedance, and voltage.

- Contributed to final draft of "International Comparison of Low Voltage (0.001 V) in Coaxial Line at 30 MHz."

Project: IMPEDANCE, ATTENUATION, VOLTAGE STANDARDS AND MEASUREMENTS

FISCAL YEARS	94	95	96	97	98
DIMENSIONAL MEASUREMENTS OF AIR LINE STANDARDS					
Complete air gauge automation, quality assurance; new software/graphics: three axis coordination machine. [STRS]	—				
Construct and evaluate the laser micrometer to measure 2.4-, 2.92- and 1.85-mm air lines. [STRS]	—				
IMPEDANCE STANDARDS DEVELOPMENT/EVALUATION					
Investigate alternate Z standards (i.e.; capacitance). [STRS]	—	—	—		
Evaluate E-formed waveguide standards for WR-90, -62, -42, -28, -22, -15, -10. [STRS, OA]	—				
LOW FREQUENCY IMPEDANCE MEASUREMENTS					
Publish report of international comparison of Q-standards. [STRS]	—				
Develop low-frequency impedance measurement system to 5 MHz (Twin-T Bridge). [STRS, OA]	—	—			
Develop Mark III impedance measurement system from 5 MHz to 250 MHz. [STRS, OA]	—	—	—		

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

FISCAL YEARS	94	95	96	97	98
VOLTAGE MEASUREMENTS					
Document thermal voltage converter (TVC) system. [STRS]	▬				
Document micropot system. [STRS]	▬	▬			
ATTENUATION STANDARDS (30MHz)					
Automate 30-MHz WBCO system. [STRS] WBCO standard. [STRS, OA]	▬	▬			
Develop 30-MHz receiver. [OA]	▬				
CALIBRATION/MEASUREMENT SERVICES					
Provide TVC/micropot calibration service. [Fees]	▬	▬	▬	▬	▬ →
Provide low frequency impedance, resistance calibration services. [Fees]	▬	▬	▬	▬	▬ →
Modify uncertainty expressions per new NIST guidelines. [STRS]	▬				

Project: NETWORK ANALYSIS AND MEASUREMENT

FY 94 Fund Sources: STRS, OA, DOD, Calibration Fees

Staff (8.0 staff-years)

Professional	R. JUDISH	R. Ginley*	J. Juroshek*	R. Kaiser
	J. Major*	G. Rebuldela*	M. Weidman*	
Technicians	D. LeGolvan*	N. Martinez	A. Monke*	C. Ondrejka*
	M. Packer*	K. Talley		

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

Objective: Develop and disseminate efficient and cost effective methods for evaluating and validating the performance of vector network analyzers (VNAs). Maintain NIST-developed dual six-ports to support calibration services. Provide traditional calibration services for S-parameters. [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.]

Significance: Vector Network Analyzers (VNAs) are becoming the single most important tool in the microwave research and development laboratory. The procedures to characterize and validate VNAs are not well-established, and the traditional calibration hierarchy is not applicable to S-parameter measurements. The NIST effort to evaluate and validate VNAs is a step toward solving the practical problems to ensure that vector network analyzers can be traceable to national standards.

FY 94 Plans

- Continue the investigation of validation and verification procedures for vector network analyzers.
- Evaluate the stability of a commercial VNA for use in calibration environment.
- Perform measurements to evaluate the stability of a commercial solid state impedance generator for use in VNA calibration/verification.
- Complete the testing, evaluation and documentation of the Air Force (0.25-18 GHz) dual 6-port system.
- Develop a procedure for calibrating dual 6-ports operating from 0.1 - 100 MHz, using discrete one-port standards.
- Provide calibration and measurement services.
- Modify the uncertainties reported in Calibration Reports to comply with the new NIST Policy.
- Re-evaluate and document the measurement uncertainties for all dual six-ports.
- Develop calibration services for S-parameter measurements in 2.4-mm coaxial line.
- Transfer DOS-based check-standard data bases to multi-use UNIX environment.

Related Developments

- Overall demands for NIST microwave calibrations have remained stable despite increasing costs.

- NIST clientele are raising calibration-related inquiries on measurement methodology, traceability, uncertainties, transfer techniques and measurement assurance, suggesting that NIST must develop alternative approaches to conventional calibrations and new ways to transfer expertise.

- Demand for the IEEE Automatic RadioFrequency Techniques Group (ARFTG) measurement comparison program demonstrates a need for alternative and cost-effective measurement services. A modified form of the ARFTG program may provide a technical basis for accreditation.

- Several foreign national and private laboratories have requested to particpate in the ARFTG measurement comparison program (MCP). The United Kingdom (UK) is organizing an ANAMET (an Automatic Network Analyzers users group) club and developing an MCP patterned after ours.

- The IEEE has formed a committee for developing a standard on S-Parameter Measurement and Instrumentation.

FY 93 Accomplishments

- Completed the measurements and modeling for the P287 Connector Committee.

- Completed line-reflect-line-line (LRLL) calibration software for all dual six-port systems.

- Performed analyses for 12 laboratories that participated in ARFTG MCP in first quarter; 6 laboratories in second quarter; 5 laboratories in third quarter, and 10 laboratories in the fourth quarter.

- Performed 65 calibrations for customers in first quarter; 51 calibrations in second quarter; 33 calibrations in third quarter, and 24 calibrations in the fourth quarter.

- Obtained full band coverage (18-40 GHz) and completed a preliminary evaluation on a diode six-port system.

- Performed experiments demonstrating the stability of a solid state impedance generator for use in calibrating VNAs.

- Performed the first calibration of customer devices with 2.92-mm connectors.

- Monolithic microwave integrated-circuit (MMIC) software was modified to work on dual six-port systems.

- Completed the preliminary evaluations of WR-22, -15, and -10 dual six-port systems.

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

Project: NETWORK ANALYSIS AND MEASUREMENTS

FISCAL YEARS	94	95	96	97	98
SIX-PORT DEVELOPMENT					
Complete and deliver coaxial six-port system (2 to 18 GHz) to Air Force. [OA]	━				
Upgrade coaxial six-port (10 to 1000 MHz) system for NIST and Air Force. [OA]	━	━			
VECTOR NETWORK ANALYZER (VNA) CHARACTERIZATION/MEASUREMENT TECHNIQUES					
Develop procedures to evaluate commercial VNAs. [STRS, OA]	━	━	━		
Implement calibration procedures using capacitance standards. [STRS]	━	━			
Develop procedures to verify and validate VNA performance. [STRS, OA]	━	━	━	━	
Develop calibration procedures using lossy two-ports. [OA]	━	━			
Develop calibration/verification procedures using tuneable impedance generator. [STRS]	━	━			

Project: NETWORK ANALYSIS AND MEASUREMENTS (concluded)

FISCAL YEARS	94	95	96	97	98
CALIBRATION/MEASUREMENT SERVICES					
Maintain existing S-parameter calibration service. [Fees]	—	—	—	—	— ⇒
Convert uncertainty expressions to new NIST guidelines. [STRS]	—				
Revise and clarify test reports. [STRS]	—				
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]	—	—	—	—	— ⇒
Develop accreditation requirements. [STRS]	—	—	—	—	— ⇒
Re-evaluate and document uncertainties for all six-port systems. [STRS]	—	—			

Project: MMIC STANDARDS AND MEASUREMENTS

FY 94 Fund Sources: STRS, OA, DOD

Staff (5.0 staff-years)

Professional	D. WILLIAMS	R. Marks	D. Walker	L. Hayden
Technician	J. Morgan			

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

Objective: Improve theoretical and experimental measurement competence, develop standards and on-wafer calibration techniques, and provide support to industry for monolithic microwave intergrated-circuit (MMIC) and related technologies.

Significance: Devices and products based on MMIC technology comprise the fastest growing segment of the international microwave industry. NIST metrology support is critical if the U.S. is to develop commercial MMIC applications and maintain world leadership in this state-of-the-art area.

FY 94 Plans

- Complete development of standard microstrip fabrication process and fabricate microstrip calibration test structures. Determine extent to which characteristics such as via-holes and variations in substrate thickness affect calibration repeatability and the ability to standardize measurements. Continue support and improvement of co-planar waveguide (CPW) standards.

- Finalize calibration verification-technique documentation. Explore implementation of calibration verification techniques, perhaps with the aid of DOD. Expand demonstration experiments beyond MMIC Consortium, if acceptable to Board of Directors. Establish traceability to standard sets developed by National Physical Laboratory (NPL) of United Kingdom. Develop a deeper understanding of fundamental wafer-level measurement problems and problems of establishing traceability with lossy transmission lines.

- Explore applications of new technique for determination of the characteristic impedance of planar transmission lines fabricated on lossy or dispersive dielectrics. Explore applications in thin-film characterization. Characterize superconducting transmission lines. Attempt to optimize this technique by exploring effect of reference plane position. Develop and test scattering-parameter calibrations for silicon substrates. Test ideas proposed by an industrial collaborator for de-embedding by removal of probe contact parasitics.

- Continue to assist Noise Project in establishing on-wafer noise-parameter measurement capability. Evaluate on-wafer test structures, including noise diodes, for use in the accuracy evaluation of commercial noise parameter test sets. Structures may be incorporated in CPW standard sets.

- Continue investigation of on-wafer techniques for measuring electromagnetic parameters of advanced electronic packaging such as multichip modules. Set up time-domain measurements system. Complete work under a CRADA to characterize transmission lines with time-domain data. Explore on-wafer time-domain characterization, using microwave calibration techniques. Investigate on-wafer methods to measure the magnitudes of voltages and current.

- Design an experiment to demonstrate how measurement errors affect MMIC designs.

Related Developments

- The development of high-speed digital interconnects for multi-chip module applications requires the centralized expertise and measurement standards that NIST is currently developing in the MMIC program.

FY 93 Accomplishments

- Completed experiments demonstrating the direct measurement of characteristic impedance on lossy substrates.

- Completed the design and began the fabrication of on-wafer noise test structures.

- Demonstrated feasibility of applying microwave-frequency domain-calibration techniques to time-domain instrumentation.

- Completed the design, layout, fabrication, and testing of cryogenic test structures. The Cryoelectronics Group is now fabricating a superconducting version of the structures for a test at 77 K.

- Completed the redesign and the test of the calibration verification procedure at NIST. Tested the technique on-site at three U.S. companies.

- Developed a new calibration technique for accurately measuring the impedance parameters of devices embedded in silicon or other lossy dielectrics.

- Established a CRADA to study the electromagnetic characterization of electronic packaging.

- Developed an accurate lumped-element calibration procedure.

- Tested CPW standards and concluded that standards are usable up to 65 GHz.

Project: MMIC STANDARDS AND MEASUREMENTS

FISCAL YEARS	94	95	96	97	98
S-PARAMETER METROLOGY					
Complete unified measurement theory for planar geometries. [STRS]	━				
Develop de-embedding theory and measurement techniques. [STRS, OA]	━	━	━		
Explore probing technology (fundamental limitations). [STRS, OA]			━	━	━ ⇒
Develop on-wafer measurement support to 60 GHz. [STRS, OA, Fees]		━	━		
Develop on-wafer noise measurements. [STRS, OA]	━	━	━	━	━ ⇒
Evaluate verification of on-wafer measurements. [STRS]	━	━	━	━	━ ⇒
WAFER LEVEL STANDARDS DEVELOPMENT					
Complete development of coplanar fabrication capability. [STRS, OA]	━	━	━		
Develop microstrip and similar multiplane fabrication capabilities. [STRS, OA]	━	━	━	━	━ ⇒
PLANAR FABRICATION FACILITY					
Acquire and install equipment. [STRS, DE]	━	━	━	━	━ ⇒

Project: MMIC STANDARDS AND MEASUREMENTS (concluded)

FISCAL YEARS	97	95	96	97	98
PACKAGING AND INTERCONNECTS					
Explore transmission lines fabricated on thin lossy dielectrics. [STRS]					
Explore and quantify multiple mode propagation. [STRS]					
Apply microwave calibration techniques to on-wafer time domain measurement. [STRS, OA]					
Explore discontinuity characterization. [STRS, OA]					
Quantify coupling and crosstalk. [STRS]					
Develop interconnection standards. [STRS]					
Explore calibrations and measurements for mixed (digital, analog, microwave) systems. [STRS]					
Explore calibrations and measurements for mixed (electrical and optical) systems. [STRS]					
CRYOGENIC PROBING					
Evaluate low-temperature on-wafer probe system (4 Kelvin). [OA]					
Develop high-T_c standards and participate in joint experiments with Cryoelectronics group. [STRS, OA]					

Project: NOISE STANDARDS AND MEASUREMENTS

FY 94 Fund Sources: STRS, CCG, MMIC, Calibration Fees

Staff (7.0 staff-years)

Professional	D. F. WAIT	J. W. Allen	S. Perera	
Technicians	R. L. Billinger	J. L. Rice	J. M. Smith	L. A. Terrell

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

Objective: Develop and disseminate standards and techniques required for accurate measurements of noise (electromagnetic thermal noise) and noise-related parameters, and provide calibration/special test services. Specific needs include standards and automated radiometers in the range 2 to 50 GHz bands and the development of noise figure metrology in the range 8 to 12 GHz band. [Note on waveguide band designations: WR-90 = 8 to 12 GHz; WR-62 = 12 to 18 GHz; WR-42 = 18 to 26 GHz; WR-28 = 26.5 to 40 GHz; WR-19 = 40 to 60 GHz; WR-15 = 50 to 75 GHz.]

Significance: Noise is the ultimate limiting factor affecting the performance of a wide range of microwave/electronic products. Industry needs an accurate noise metrology, based on standards developed by NIST, for evaluating component and system performance and developing improved, more competitive products. NIST noise services support U.S. electronic equipment manufacturers, the communications industry, the radio industry, the satellite broadcast industry, low-noise amplifier technology, and space exploration.

FY 94 Plans

- Develop test services for a Noise Figure from 2-4 GHz.

- Improve the capability of noise temperature measurements in 3.5-mm coaxial line (12-26 GHz). The uncertainty goal is ±150 K.

- Update the uncertainty analysis for all Noise Measurement Services and express per the new revised NIST policy.

- Establish an on-wafer noise-measurement capability.

- Develop a test service in WR-28.

- Provide Noise Calibration Services.

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.

- The metrology laboratories of at least four major U.S. companies have improved their noise measurement capabilities through the employment of cryogenic-standard noise sources fabricated in accordance with the design developed by NIST. The introduction of new NIST calibration services at 1 - 8 GHz and above in 1986 and 1989 resulted in the immediate adjustment of calibration factors of commercial noise sources. Much of U.S. industry accommodated the change and is traceable to NIST.

FY 93 Accomplishments

- Began new Noise Special Test Services in WR-15, WR-42 and 3.5-mm coaxial from 12-26 GHz.

- Installed data base services on the project network.

- Completed the basic design of the amplifier noise radiometer.

- Performed calibrations on four customer standards in the first quarter; three calibrations in the second quarter; one calibration in the third quarter, and seven calibrations in the fourth quarter.

- Established a special test service in WR-62 (12-18 GHz).

Project: NOISE STANDARDS AND MEASUREMENTS

FISCAL YEARS	94	95	96	97	98
IMPROVEMENTS TO SPECIAL TEST/CALIBRATION SERVICES					
Automate the WR-28 waveguide radiometer. [STRS]	——				
Automate the coaxial radiometer. [OA]	——	——			
Develop network/server for data collection. [STRS]	——	——			
Implement real-time statistical control and on-line error analysis. [STRS]	——	——	——	——	—— →
IMPROVEMENTS TO STANDARDS					
Improve ambient standard. [STRS]		——	——		
Develop on-wafer noise source/standard. [OA]		——	——	——	
Develop pseudo-random noise standard. [OA]		——	——	——	——
Develop pressure control and/or temperature sensors for cryogen. [OA]		——	——	——	

Project: NOISE STANDARDS AND MEASUREMENTS (continued)

FISCAL YEARS	94	96	96	97	98
IMPROVEMENTS TO RADIOMETERS					
Improve temperature control. [STRS]	—	—	—		
Develop dual radiometer. [OA]	—	—	—		
NOISE FIGURE METROLOGY-DISCRETE DEVICES					
Characterize noise parameters of a two-port. [OA]	—	—	—		
Develop noise figure measurement procedure. [OA]	—	—			
Provide technical requirements for laboratory accreditation. [STRS]	—	—	—	—	—
Provide special test services. [OA]	—	—	—	—	— ⇒
NOISE FIGURE METROLOGY-INTEGRATED SERVICES					
Develop probe station/deembeding procedures. [OA]	—	—			
Develop noise figure measurement procedure. [OA]	—	—	—	—	
Develop transfer standard. [OA]	—	—	—	—	

Project: NOISE STANDARDS AND MEASUREMENTS (concluded)

FISCAL YEARS	94	95	96	97	98
NOISE FIGURE METROLOGY-INTEGRATED SERVICES (cont'd.)					
Provide special test services. [OA]	━━━	━━━	━━━	━━━	━━━ ⇒
INTERCOMPARISONS/ROUND ROBINS					
Participate in interlaboratory evaluation with U.S. industrial and government organizations and with NIST-counterpart national laboratories. [STRS]	━━━	━━━	━━━	━━━	━━━ ⇒
NOISE DIODE STUDY					
Study effects of environmental factors. [STRS]		━━━			
NOISE METROLOGY SEMINAR/SHORT COURSE					
Give short course to U.S. industry. [STRS]	━━━		━━━		

Project: EMISSION AND IMMUNITY METROLOGY

FY 94 Fund Sources: STRS, Air Force, Army, Navy, OLES, FAA

Staff (10.5 staff-years)

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

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

Objective: Develop and evaluate reliable test methods for electromagnetic emission and immunity of electronic devices, components, and systems. Major challenges are to provide 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.

Significance: Industry and regulatory agencies have requirements for practical yet rigorous measurement techniques in order to characterize and correct electromagnetic interference (EMI) problems. Industry must meet electromagnetic compatibility (EMC) standards to sell products in world market. Industrial clients are both manufacturers of electronic equipment and EMC/EMI test laboratories. NIST research, development, and measurement procedures provide guidelines for the entire EMC/EMI community.

FY 94 Plans

- Extend the theory and measurement techniques for the shielding effectiveness of airframes to include composite bodies, coated window glass, and multiple compartments.

- Analyze and compare narrowband frequency excitation and impulse excitation of reverberation chambers for chamber evaluation and EMC testing.

- Test the NIST software for minimum-phase analysis of linear systems with measured data obtained on dipole antennas and more complicated systems.

- Write a test manual for the evaluation of photoradars that are used for automatic speed measurements by law enforcement agencies.

- Develop improved digital signal processing techniques and software for extraction and waveform analysis of weak signals in noise.

Related Developments

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

- The FAA now requires all commercial airplanes to be tested at 200 V/m for EMI survivability.

- Group members have made contributions to the standards committees of several national and international, professional and industrial organizations, such as IEEE Antenna Propagation Society (AP/S) and EMC Standards Committees, American National Standards Institute (ANSI) Standards Committees, and the American Society of Testing and Materials (ASTM) Committee.

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

FY 93 Accomplishments

- Completed an analysis of EM field penetration through apertures into a lossy cavity with application to aircraft immunity. Demonstrated good agreement of the theory with broadband (1-18 GHz) measurements of shielding effectiveness, cavity Q, and cavity time constant for the NIST scale-model cavity. Performed similar broadband measurements on actual airplanes.

- A theoretical analysis of frequency stirring of reverberation chambers has been completed, and the calculated field uniformity looks promising. The goal is to replace mechanical stirring with faster-frequency stirring.

- Developed a theory for computing the pulse response of minimum phase and non-minimum phase functions from cw amplitude data and developed related software.

- Performed measurements to evaluate the effectiveness of noise excitation of mode-stirred chambers as an alternative to mechanical stirring, and the effect of test signal modulation.

- Successfully designed, fabricated and tested calibrators for photoradars that are used for automatic speed measurements.

- Analyzed crosstalk between microstrip transmission lines and obtained good agreement for frequencies from 50 MHz to 5 GHz.

- Completed a survey of 41 key companies, industrial associates, and government agencies, and ascertained the major EMC-related problems and issues confronting U.S. industry and government today.

Project: EMISSION AND IMMUNITY METROLOGY

FISCAL YEARS	94	95	96	94	98
EMISSION AND IMMUNITY TESTING METHODOLOGY					
Develop electronic mode stirring for reverberating chamber. [STRS, OA]	▬	▬			
Improve electromagnetic interference (EMI) test methods on ground screen. [OA]		▬			
Apply near-field phased array to immunity testing. [OA]			▬	▬	
Improve shielded room measurement methods. [OA]	▬				
ANALYSIS OF EM FIELDS EFFECTS					
Develop time-domain techniques for resonance determination. [OA]	▬	▬			
Analyze EM effects of multiple sources. [OA]			▬	▬	
Analyze effects and characteristics of electrostatic discharge. [Future programs to be determined.]			▬	▬	▬ ⇒
EM FIELDS COUPLING Develop measurement techniques and instrumentation.					
Analyze shielding & reflectivity of materials. [OA]	▬	▬			
Test penetration into systems: connectors; cables. [OA]	▬				

Project: EMISSION AND IMMUNITY METROLOGY (concluded)

FISCAL YEARS	94	95	96	97	98
Study penetration into systems: enclosures; devices. [STRS]	━━	━━	━━		
Use apertured transverse electromagnetic (TEM) cells for shielding effectiveness measurements. [STRS]			━━	━━	
Determine correlation between radiated and conducted EMI. [OA]	━━	━━			
Determine mechanisms for radiated and conducted EMI. [OA]	━━	━━			
Develop sensors for radiated/conducted EMI. [OA]		━━	━━		
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: STANDARD ELECTROMAGNETIC FIELDS AND TRANSFER PROBE STANDARDS

FY 94 Fund Sources: STRS, Measurement Services, Army, Navy

Staff (6.0 staff-years)

Professional	M. KANDA	K. Masterson	D. Melquist	D. Novotny
	R. Orr	J. Randa		
Technician	R. Acker*			

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

Objective: Develop methods and techniques for establishing continuous wave (CW), pulsed, and nonsinusoidal electromagnetic reference fields up to 100 GHz. Current emphasis is in the frequency range up to 40 GHz and at 60 and 95 GHz. Perform research and development on probes and related systems to measure electromagnetic (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.

Significance: Well-defined EM reference fields are necessary for special test measurements, antenna research and development, the evaluation of EM field probes, and the measurement of EM interference (EMI). Commercial antennas and probes are generally unsuitable for metrology purposes, necessitating the development by NIST of probes that can serve as the transfer standards necessary for traceability.

FY 94 Plans

- Validate further the absorber-wall model and use it to develop a model for the low-frequency performance of anechoic chambers used for electromagnetic compatibility (EMC) testing.

- Develop and evaluate the Comité Internationale Spécial des Perturbations Radioélectriques (CISPR) "International" standard dipole that was originally designed by NIST.

- Design, fabricate, and test a simple resistively-tapered dipole (RTD) probe with rf detection. Previous NIST RTD probes have used dc detection.

- Perform testing of EMI shielding effectiveness of commercially available optical fiber bulkhead connector systems.

- Show experimentally that a polarization controller can be used to correct for environmentally induced drift in the optical bias point of a Mach-Zehnder electro-optic modulator, which is used in EM-field probes.

- Characterize the monopole-range radiator, and recheck the stability of the spherical-dipole standard radiator installed in NIST facilities.

- Characterize a 2-cm photonic electric field probe for use in pulse measurements.

Related Developments

- The FCC has announced a policy requiring antennas used in EMI 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.

- M. Kanda is the Vice Chairman of International Commission A of Union Radio Scientifique Internationale (URSI).

FY 93 Accomplishments

- Testing on the 3-loop antenna was completed, and mutual coupling issues were evaluated.

- Completed the basic framework for including the effects of antenna-antenna interactions in monopole calibrations. Made mechanical and instrumentation improvements in all the standard field facilities.

- A (relatively) simple model has been developed for a wall of absorber. The model was compared with a set of measured data, and excellent agreement (±2 dB) was obtained for frequencies up to 600 MHz. The model will be used in characterizing anechoic chambers used in EMI tests.

- The software (named AutoMeasure) for our anechoic and reverberation chambers' measurement systems has been developed and is now fully functional and performing very well. We have succeeded in completely automating standard field calibrations as well as other measurements. The software's features enable us to perform a complex series of measurements without operator intervention. We have also begun an in-depth performance evaluation of the measurement systems and the associated check standard devices using the software.

- A dual-diversity receiver and special antenna array system has been designed and built to limit the spatial environment (and noise) and to correlate low-level signals in a real-time method via computer control. Final system checkout has been completed.

- Repeat measurements have been performed on the spherical dipole in the anechoic chamber, and the test results have been analyzed. Tests of the monopole and further tests of the spherical dipole have also been planned.

Project: STANDARD EM FIELDS AND TRANSFER PROBE STANDARDS

FISCAL YEARS	94	95	96	97	98
STANDARD FIELD GENERATION					
MEASUREMENT SERVICES					
Ground screen site (dipole 25-100 MHz, monopole 30 kHz-300 MHz), TEM cell ($\leq$ 100 MHz), standard magnetic field loop ($\leq$ 40 MHz), anechoic chamber (200 MHz-18 GHz). Measurement services provided on request. [Fees]	━	━	━	━	━ ⇒
ANECHOIC CHAMBER					
Improve measurement capability in the range 250 MHz - 18 GHz. [STRS]	━				
Improve measurement capability in the range 18 - 26 GHz; 26 - 40 GHz. [STRS, DE]	━	━			
Develop measurement capability at 60 GHz; 95 GHz. [STRS, DE, OA]			━	━	
REVERBERATING CHAMBER					
Develop automated system for 18 - 40 GHz range. [STRS, DE]	━	━			
Extend range to 40 - 75 GHz. [DE, OA]		━	━		
Study pulse characteristics of chamber. [OA]	━	━			
Study the effect combination with TEM cell. [OA]	━	━	━	━	

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

FISCAL YEARS	94	96	96	97	98
NEAR-FIELD PHASED ARRAY					
Build for 250 MHz; 750 MHz; 1000 MHz. [OA]			▬		
Develop broadband (octave). [OA]			▬	▬	
STANDARD TRANSMITTING AND RECEIVING ANTENNAS					
Improve narrow band, resonant dipoles. [STRS, OA]		▬			
Implement use of broadband, nonresonant, phase-linear antenna. [OA]			▬		
Refurbish ground screen facility (ground screen cover). [STRS, DE]	▬	▬			
Build new anechoic chamber (larger than the existing one). [STRS, DE]		▬	▬	▬	▬
FIELD MEASUREMENT					
CW ELECTRIC FIELDS ANTENNA DEVELOPMENT					
100 kHz - 18 GHz; 18 - 26 GHz; 26 - 40 GHz. [STRS]	▬				
40 - 75 GHz; 75 - 110 GHz. [STRS, OA]			▬	▬	▬

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

FISCAL YEARS	94	96	96	97	98
MAGNETIC FIELD ANTENNA DEVELOPMENT					
Develop miniature loop antenna (up to 1 GHz). [STRS]		▬			
Develop antenna to measure B and $\dot{B}$ (up to 18 GHz). [OA]		▬			
ANTENNA FOR SIMULTANEOUS E AND H MEASUREMENT					
Develop three-loop antenna system. [STRS]	▬	▬			
Develop one-loop system with electro-optic modulator. [STRS, OA]	▬	▬	▬	▬	▬
PULSED ANTENNA DEVELOPMENT					
Develop broadband antenna (time domain). [STRS, OA]	▬	▬			
Develop active antenna and optically linked antenna. [STRS, OA]	▬	▬	▬	▬	▬
Develop special EM field monitors: environment, dosimeter, nonlinear and/or nonisotropic media. [STRS, OA]	▬				

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS

FY 94 Fund Sources: STRS, NASA, Air Force, Army, Navy

Staff (6.6 staff-years)

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

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

Objective: Provide U.S. antenna manufacturers with a cost-effective means to demonstrate conformance of antenna performance with design specifications. More specifically, develop the theoretical foundations, standards, and associated experimental techniques required for accurate measurements of gain, pattern, and polarization of microwave antennas. Characterize antennas by means of planar near-field scanning and spherical near-field methods from 1 to 100 GHz. Current challenges to be met include reducing gain uncertainties to below ±0.2 dB, implementing probe position error techniques for millimeter wave measurements, determining field uniformity assessment using spherical near-field techniques, and developing and testing adaptive phased array diagnostic methods.

Significance: Spectrum and orbit crowding, and the use of higher frequencies require new generations of antennas. Advanced communication and aerospace systems, including direct broadcast, global positioning, and anticollision systems, employ complex antennas with demanding requirements for gain, pattern and polarization. Accurate antenna measurements are essential for verifying performance, and conventional techniques are often inadequate. While the near-field measurement techniques developed by NIST have already solved many serious measurement problems, new approaches are needed for millimeter-waves, large adaptive arrays, and integrated antennas.

FY 94 Plans

- Update and present the NIST antenna measurement course on site in March, 1994 to industry and academia, and present it off site as needed to industry and other agencies for effective technology transfer.

- Evaluate the new multipurpose extrapolation/cylindrical/pattern/spherical antenna range. Test the facility for spherical and cylindrical near-field measurements.

- Write a report and publish a paper describing 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 x 2.5 m planar scanner and receiver. Measure selected antennas obtained from other agencies or industry, specifically in the millimeter-frequency range. Transfer this technology to industry.

- Complete 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.

- 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. Write a paper for publication.

Related Developments

- 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. He and Ronald Wittmann were also recognized by NASA Lewis Research Center for their contributions to the Advanced Communications Technology Satellite (ACTS) Project.

- The Antenna Measurement Techniques Association (AMTA) recognized Dr. Andrew Repjar and Michael Francis with outstanding service awards. At the AMTA symposium, NIST staff did industrial updates with two U.S. companies. They also consulted with numerous individuals and organizations on antenna measurement problems. These discussions included problems relating to direct broadcast, global positioning, anticollision systems, and probe-position correction methods for near-field scanning.

- 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.

- Dr. Andrew Repjar was elected to the IEEE Adcom of the Antennas and Propagation Society for a three-year term (1993-1995) and serves on the antenna and radar cross section standards committee.

FY 93 Accomplishments

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

- Prepared 15 lectures on antenna metrology for courses presented at the University of California, Northridge and at NIST, Boulder. The latter course was co-sponsored by Georgia Institute of Technology.

- Completed 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.

- Completed first phase of certification process for the new 2.5 m x 2.5 m planar scanner for millimeter-wave antenna measurements. The NIST certification plan for this range has been documented and is available to industry.

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS

FISCAL YEARS	94	95	96	94	98
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]					
Transfer technology to industry. [OA]					
PHOTONIC PROBE SENSOR DEVELOPMENT FOR ANTENNA SYSTEMS					
Develop technology for a prototype photonic probe; evaluate probe on PNF range; determine dynamic range and multiple reflection effects. [STRS, OA]					

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS (continued)

FISCAL YEARS	94	95	96	97	98
PHOTONIC PROBE SENSOR DEVELOPMENT FOR ANTENNA SYSTEMS (continued)					
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]					
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]					

Project: ANTENNA MEASUREMENTS, THEORY AND APPLICATIONS (concluded)

FISCAL YEARS	94	95	96	97	98
TECHNOLOGY TRANSFER					
Document theoretical and measurement developments. [STRS, OA]					
Provide short courses and workshops: compile planar notes; present short courses (PNF). [STRS, OA]					
Participate in IEEE/APS National Distinguished Lecturer Program. [STRS]					
COMPLEX ANTENNAS					
Develop phased-array alignment techniques. [OA]					
Develop characterization methods for advanced millimeter-wave antennas (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 (RCS) AND SPACE SYSTEMS

FY 94 Fund Sources: STRS, JPL, Air Force, Army, Navy

Staff (4.0 staff-years)

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

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

Objective: Develop the standards, measurement techniques, and instrumentation required for measuring critical performance parameters of earth terminals and satellites, and for the absolute calibration of the Air Force Satellite Control Network (AFSCN) metrology earth terminal. Critical parameters include noise temperature (T), antenna gain (G), earth terminal figure of merit (G/T), and satellite effective isotropic radiated power (EIRP). Provide technical support to the Government Range Radar Cross Section (RCS) Measurement Working Group to improve the quality and reliability of range measurements. Evaluate the measurement processes including error budgets, the design and analysis of required artifact standards, and the consultation and support necessary to establish a range certification process.

Significance: Satellite communication is a finely tuned technology requiring accurate measurements of antenna gain, noise temperature, G/T, and EIRP 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.

FY 94 Plans

- Measure gain of AFSCN Camp Parks 18-m antenna for elevations from 5 to 60 degrees, using Cassiopeia A stellar source (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.

- NIST calibration of the moon as a source allows users of the 7 - 8 GHz band to calibrate systems which cannot be calibrated using other radio sources.

- The communications industry currently measures G/T using the sun as a source but results differ between companies. NIST will provide support for solving this problem. A U.S. company has requested NIST ephemeris programs for tracking the sun, moon and other radio sources.

- Improved measurement accuracies will allow enhanced design methods for the antenna and radar cross section community, and reduce retesting of antennas and models, lowering the overall costs. Range improvements have been suggested for four RCS ranges.

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

- Dr. Andrew Repjar received the Antenna Measurement Techniques Association (AMTA) Outstanding Service Award. He also serves on the IEEE Standards Committee which is updating antenna and RCS definition 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 93 Accomplishments

- 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.

- Provided support to JPL in checking out their Clear Aperture Antenna before extensive measurements are made on radio sources.

- Conducted tests to verify proper system operation of the Air Force G/T system which uses the sun as the standard source.

- Prepared error budgets for four radar cross section ranges for the RCS government working group.

Project: METROLOGY FOR ANTENNA, RCS AND SPACE SYSTEMS

FISCAL YEARS	94	95	95	97	98
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]					
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	94	95	96	94	98
RADAR CROSS SECTION MEASUREMENTS					
Visit RCS ranges. [OA]					
Develop plan of error analysis for different ranges. [OA]					
Analyze measurement processes. [OA]					
Evaluate artifact standards. [OA]					
Establish range verification process. [OA]					

Project: SPECIAL TESTS, MEASUREMENTS AND CALIBRATIONS

FY 94 Fund Sources: Calibration Fees

Staff (4.0 staff-years)

Professional	M. FRANCIS	J. R. Guerrieri*	R. L. Lewis*	K. MacReynolds*
	A. G. Repjar*	C. Stubenrauch*		
Technicians	S. Canales*	D. N. Dean*	D. P. Kremer*	D. T. Tamura*

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

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

Significance: 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.

FY 94 Plans

- On behalf of INTELSAT, calibrate four probes for a U.S. company for 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 $1 billion per year. NIST measurement services need to be developed at 75-100 GHz.
- NIST provided special high accuracy measurements of 26 antennas and probes in FY 1993 for industry and government using the near-field, the extrapolation and the spherical probe ranges. These continued

requests are evidence of the need and impact of this service. For example, NIST is planning with industry to measure antenna standards for a commercial world-wide satellite communication system.

- Drs. Andrew Repjar and Carl Stubenrauch are members of the IEEE Antenna Standards Committee and the Antenna Measurement Committee.

- Michael H. Francis received the 1992 EEEL Measurement Service Award.

- Dr. Carl Stubenrauch is Associate Editor of the IEEE Antennas and Propagation Society and Michael Francis is editor of the *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 93.

FY 93 Accomplishments

- Completed probe pattern measurements for the 50-60 GHz dual-port circularly-polarized probes. These probes will be used as NIST standards for commercial and military systems.

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

- Completed 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.

- Calibrated four sets of dual-port cp probes for gain, polarization, and pattern in the frequency ranges: 2.5-2.69, 3.7-4.2, 5.925-6.425 and 12.25-14.25 GHz. These probes will be used by a U.S. company as near-field probe standards in the measurement of INTELSAT VII.

- Measured antenna patterns of 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.

Project: SPECIAL TESTS, MEASUREMENTS AND CALIBRATIONS

FISCAL YEARS	94	95	96	97	98
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]					
Develop minimum scattering probes. [STRS, OA]					

Project: SPECIAL TESTS, MEASUREMENTS AND CALIBRATIONS (concluded)

FISCAL YEARS	94	95	96	94	98
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 94 Fund Sources: STRS, Air Force, SDI, Calibration and Software Fees

Staff (7.0 staff-years)

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

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

Objective: Implement, evaluate, and disseminate measurement methods to determine the complex permittivity and complex permeability of various dielectric and magnetic materials over the RF/microwave spectral range 100 kHz to 100 GHz. Identify and characterize reference materials. Provide standards and measurement services to industry. Implement round robin intercomparisons with industry.

Significance: 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. Accurate characterization data and improved measurement methods, covering a wide spectral range as well as temperature range, are needed 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.

FY 94 Plans

- Complete the development of new algorithms and software for broadband 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 a report on this work.

- Develop the stripline resonator technique for high-precision measurements of dielectric and magnetic reference materials in the frequency range 150-2000 MHz.

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

- Initiate a round robin intercomparison on stripline resonator measurements.

- Develop the use of the 77-mm (3.125") coaxial airline for T/R measurements at frequencies < 1500 MHz. Develop a 2-port technique using 77-mm diameter air-filled adapters for measuring thin films.

- 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.

- Document results of a CRADA effort with two U.S. companies to characterize absorbing materials suitable for use in feed-through filters and to confirm mixing rule predictions.

Related Developments

- NIST has been asked by industry to develop a capability to characterize the microwave performance of high-temperature superconductor (HTS) films, such as YBCO, TBCCO and TLSCCO. The use of such materials in microwave components and circuits appears to be one of the most promising applications for ceramic superconductors.

- The collaborative study of new absorbing composite materials, characterized by NIST using measurements and mixing rule theory, has the potential of saving a U.S. company tens of millions of dollars in costs for integrated filter harnesses.

- Eric Vanzura is completing an ASTM standard procedure for testing materials.

- The round robin conducted using the 7-mm coaxial T/R method for nonmagnetic materials demonstrates the need for accurate measurement techniques traceable to NIST.

- NIST has been asked by the Air Force and industry to develop methods to measure the microwave properties of dc biased magnetic materials.

- Claude Weil gave an invited overview entitled "Dielectric and Magnetic Property Measurements: the NIST Metrology Program" at the Microwave-Absorbing Materials for Accelerators (MAMAs) Workshop held at the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, VA on February 22-24, 1993. The workshop dealt with the application of lossy ceramics.

- Two foreign guest workers are collaborating in EPM project work: Dr. Jerzy Krupka from Warsaw University of Technology, Poland, and Yehuda Kantor from RAFAEL, Israel. Dr. Krupka visited NIST as part of a joint US-Polish Sklodowska-Curie Foundation award.

FY 93 Accomplishments

- Revised EPS_MU_3, the NIST software for material characterization, using transmission line techniques. This version was acquired by nine industrial, three DoD and three academic laboratories.

- Developed full-field models and software for coaxial open-ended probe measurements, including probe lift-off and finite layer thickness. The project is relevant to the non-destructive testing of materials.

- Completed 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.

- Completed first phase of developing the 77-mm transmission/reflection (T/R) system for measuring high permittivity materials from 1-1000 MHz.

- Assembled cryogenic system and performed preliminary tests of a 25 GHz cavity for measuring microwave characteristics of YBCO films at 77K.

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS

FISCAL YEARS	94	95	96	94	98
METROLOGY FOR COMPLEX PERMITTIVITY AND/OR PERMEABILITY OF BULK SOLID MATERIALS, VERY LOW TO HIGH LOSS					
Develop transmission line methods, 100 kHz-18GHz. [OA]	—	—	—		
Optimize algorithms. [OA]	—	—			
Develop high-precision cavity methods for low-loss dielectric materials, 8-11 GHz. [STRS]	—				
Develop special test/calibration services. [Fees]	—	—	—	—	—
Develop metrology methods for inhomogeneous/anisotropic materials. [OA]			—	—	—
IMPLEMENT AND EVALUATE MEASUREMENT METHODS:					
Stripline resonator, 150-3000 MHz; Loaded waveguide, 450-750 MHz. [OA]	—	—	—		
Open-ended coaxial line, 3.5mm. [STRS, OA]	—	—	—	—	—
Large diameter (80 mm) coaxial line. [STRS]	—	—	—		
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]		—	—	—	

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS (continued)

FISCAL YEARS	94	95	96	97	98
MICROWAVE CHARACTERIZATION OF D.C. BIASED MAGNETIC MATERIALS					
Design measurement system. [STRS, OA]					
Construct system after procuring electromagnet and other components. [STRS]					
Evaluate method and reference materials. [STRS, OA]					
RESEARCH AND REFERENCE MATERIALS					
Establish nonmagnetic, low-loss reference standards. [OA]					
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]					

Project: ELECTROMAGNETIC PROPERTIES OF MATERIALS (concluded)

FISCAL YEARS	94	95	96	97	98
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: OPTICAL-FIBER MEASUREMENT SYSTEMS AND STANDARDS

FY 94 Fund Sources: STRS, Navy

Staff (4.5 staff-years)

Professional	D. FRANZEN*	B. Danielson	T. Drapela*	P. Hale*
	S. Mechels*	J. Schlager*	M. Young*	
Technician	R. Juneau*			

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

Objective: Provide the U.S. telecommunications industry with needed optical fiber test procedures and Standard Reference Materials (SRMs). Work through the Telecommunications Industry Association (TIA) to identify specific needs, and with voluntary standards groups to evaluate test procedures. Current challenges include extension of geometry work to include connector ferrules and fiber coatings, and development of special metrology to support chromatic dispersion requirements of high-bit-rate systems and high-resolution needs of optical time domain reflectometers (OTDRs).

Significance: Optical fibers provide long distance digital telephone and data communications and are moving into the local loop. Next-generation systems will operate at higher bit rates; large numbers of connectors and splices will appear in the local loop, requiring fibers and connectors with more exact dimensions to reduce joint loss. Erbium fiber amplifiers projected for use in undersea systems will result in long transmission lengths demanding close tolerances on fiber chromatic dispersion. Next-generation fiber systems will require OTDRs with improved accuracy and resolution. This project provides the measurement base for the U.S. optical fiber industry. Systems developed by NIST provide round robin testing support to the TIA, and U.S. manufacturers make use of NIST SRMs for fiber geometry in order to improve their international competitive position.

FY 94 Plans

- Meet all internal NIST requirements for providing geometry SRMs to industry and supply the NIST SRM Program with a sufficient number for public sale.

- Complete a round robin evaluation of potential TIA measurement methods for connector ferrule geometry; participants include TIA members.

- Complete an international round robin to evaluate test procedures for fiber geometry; test specimens will be prepared by NIST and housed in the SRM containers.

- Develop methods for thread wire diameter measurements required for ferrule inside and outside diameter measurements.

- Develop optical fiber delay line for calibrating the time base of OTDRs and publish results. Develop a high-resolution OTDR suitable for local area networks and determine the standards needed to support such instruments.

- Develop a highly accurate measurement system for determining optical fiber chromatic dispersion in the 1300- and 1550-nm spectral regions. Develop an SRM for chromatic dispersion at 1300 nm and 1550 nm.

Related Developments

- Next-generation optical fiber systems will operate at higher bit rates and move into the local loop to provide service to homes and businesses. Large numbers of connectors and splices will appear in the local loop.

- Undersea communication systems are projected to use erbium optical fiber amplifiers for long transmission lengths; close tolerances on fiber chromatic dispersion will be needed.

- OTDRs have the largest market share for test instrumentation; next-generation fiber systems will require OTDRs with improved accuracy and resolution.

FY 93 Accomplishments

- Delivered the first optical fiber geometry SRMs for cladding diameter to the SRM office in Gaithersburg for commercial sale. The initial delivery of 15 showed exceptionally low values of non-circularity.

- Successfully reconstructed 17-ps laser diode pulses by optically sampling with an erbium fiber laser strobe. This was one of the objectives of a joint NIST/Nippon Telegraph Telephone, Inc. (Japan) effort in optical waveform sampling.

- Completed two connector-ferrule-geometry round robins among TIA members.

- Started the NIST/TIA international round robin to determine single-mode fiber geometrical parameters. Twenty one fibers in NIST SRM holders have been dispersed in three sets to participants in North America, Europe, and Japan. NIST is administering North America while National Physical Laboratory (UK) and NTT are handling Europe and Japan.

Project: OPTICAL-FIBER MEASUREMENT SYSTEMS AND STANDARDS

FISCAL YEARS	94	96	96	97	98
Conduct round robin in chromatic dispersion and develop reference measurement methods. [STRS]					
Develop consensus standards for optical time domain reflectometer. [NAVY]					
Participate in standards committees. [STRS]					⇒
Conduct international round robin for optical fiber geometry. [STRS]					
Work with the International Telegraph and Telephone Consultative Committee (CCITT) to develop standards for optical fiber geometry. [STRS]					
Organize optical fiber measurement symposium. [STRS]					
Supply fiber geometry SRMs to industry. [STRS]					⇒
Develop standards for other optical fiber test instrumentation. [STRS]					⇒
Establish measurement procedures for optical fiber amplifiers. [STRS]					
Investigate and respond to other measurement problems of local area networks. [STRS]					⇒

Project: OPTICAL-FIBER SENSORS

FY 94 Fund Sources: STRS, Navy, NASA, DNA, NSA, LANL, CCG

Staff (8.0 staff-years)

Professional	G. DAY	M. Deeter	K. Rochford	A. Rose
	R. Craig	J. Wyss	P. Williams	
Technician	S. Etzel*	R. Juneau*		

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

Objective: Enhance the competitiveness of the optical fiber sensor industry by providing measurements, standards, and reference data for components and materials used in sensors; provide government and industry laboratories with next-generation sensing technology; utilize expertise acquired in these activities to solve measurement problems in other areas of optical electronics technology. Specific challenges include determination of the fundamental and practical limits to sensor performance, development of new sensor technology for electromagnetic measurements, and the development of polarization components.

Significance: Optical fiber technology brings to metrology many of the same benefits that it has provided for optical communications; particularly significant among these are the relative immunity to electromagnetic interference and reductions in size and weight. Several sectors of the technology are showing commercial success – sensors for position measurement, sensors for use in medicine, optical fiber gyroscopes, and intrusion sensors. Sales of sensors in 1992 are estimated at about $125 million, rising to $1.1 billion in 1999. This project supports the U.S. optical fiber industry through its development of advanced optical sensing techniques and associated metrology.

FY 94 Plans

- Complete development of a standard quarter-wave plate for polarimeter calibration.
- Improve measurement system for determining the polarization properties of optical fiber couplers and other components.
- Develop and evaluate an optical method of measuring dc current.
- Construct and evaluate a pigtailed, high-bandwidth, high-sensitivity current sensor based on the Faraday effect in iron garnets.
- Evaluate the three measurement techniques for polarization mode dispersion presently under consideration as standards.
- Improve performance of self-calibrated temperature sensor to ±2 degree recalibration accuracy.
- Assemble, test, and evaluate operation of high-frequency, high-sensitivity optical fiber magnetic field sensor based on the recently developed magneto-optic flux concentrator.
- Complete report on impediments to commercialization of fiber sensors for shipboard applications.

Related Developments

- Certain areas of fiber sensor technology are showing excellent progress. One medical electronics company is known to be producing 50,000 disposable pressure sensors per year. Another company is producing 5,000 temperature sensors per year. Several companies are producing fiber intrusion sensors; at least one is profitable. The next large passenger plane to be produced in the U.S. will use optical fiber gyroscopes; two Japanese companies are marketing optical fiber gyroscopes for automobiles.

- Commercially available Faraday-effect current sensors for use at high voltage (>100 kV) are now priced competitively with conventional current transformers. One major European supplier to the power industry has indicated that it believes the market for Faraday-effect current sensors will be substantial within a few years and has re-established product development after stopping for nearly a decade. One major Japanese company is expanding its current sensor development work. A U.S. company, using NIST-developed technology, has delivered its first systems to a customer for testing.

- The use of magneto-optic technology for rotation sensing in such environments as automotive transmissions, antilock brakes and aircraft engines is drawing substantial interest. Four companies are known to have development programs.

FY 93 Accomplishments

- Achieved a new record for minimum detectable magnetic field in a Faraday-effect sensor, through the use of flux concentration.

- Completed an interlaboratory comparison of h-parameter measurements in conjunction with the Telecommunications Industry Association.

- Achieved 44-fold improvement in the previous best value of sensitivity-bandwidth product for a Faraday-effect current sensor, using an iron-garnet-based device.

- Developed an improved process for annealing of linear birefringence in optical fiber; allows use of almost any fiber with good yield.

- Constructed and tested first prototypes of a standard quarter-wave plate; stability of 0.1 degree retardance demonstrated over required range of temperature and angle of incidence.

- Developed a method of characterizing the splitting ratio of an optical fiber coupler as a function of polarization state (full range of orientation and ellipticity).

Project: OPTICAL-FIBER SENSORS

FISCAL YEARS	97	96	96	97	98
Develop and refine measurement techniques and standards for the characterization of high-birefringent optical fiber. [STRS]	—	—			
Develop measurement techniques for determining the polarization properties of optical fiber components. [STRS]	—	—	—		
Develop and evaluate measurement techniques for polarization mode dispersion of optical fiber and other components used in communications. [STRS]	—	—	—		
Determine and disseminate data on the magneto-optic, electro-optic, and stress-optic properties of materials. [LANL, STRS]	—	—	—	—	
Develop standard polarization components for use in instrument calibration. [CCG/NAVY]	—	—	—		
Explore performance limits of optical fiber current and voltage sensor technology. [NASA, STRS]	—	—	—		
Explore sensitivity, speed, and stability limits of sensors based on the Faraday effect in iron garnets. [NSA, DNA, STRS]	—	—	—	—	
Develop and demonstrate techniques for making optical fiber sensors self-testing and self-calibrating. [CCG, NAVY]	—	—			
Examine generic sensing technologies that offer potential performance and cost benefits. [NAVY]	—	—	—	—	

Project: INTEGRATED OPTOELECTRONICS

FY 94 Fund Sources: STRS, ATP, Army, Air Force, Boeing, IMRA, NSF

Staff (13.5 staff-years)

Professional	R. PHELAN	A. Aust	D. Christensen	R. Gallawa
	R. Hickernell	J. Hill	E. Johnson	D. Larson
	J. Lehman*	K. Malone	M. McCollum	G. Obarski
	N. Sanford	D. Veasey		
Technician	None			

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

Objective: Develop advanced metrology needed in integrated optoelectronics (IOE) for the optical communications, optical information processing, and emerging optical computing industries. Specific challenges include development of planar waveguides and vertically integrated optoelectronic structures that will facilitate the development of advanced metrology, the determination of material reference data, and the creation of new standards.

Significance: Intense research and development efforts are in progress to use efficiently installed and future optical fiber cables by taking advantage of the enormous bandwidths available and by multiplexing the signals. Economical distribution of high-quality signals to a large number of customers will require IOE components. Optical storage, reprography, and displays are major industries that are becoming increasingly dependent on IOE components. If optical computing is to become a viable alternative to purely electronic computing, the evaluation and a greater development of the IOE components for computing will be required. Optical interconnects require IOE devices. This project supports the IOE industry through metrology development, standards, and reference data; many ATP programs in IOE need this project's expertise for support and evaluation.

FY 94 Plans

- Evaluate *in situ* spectral reflectometry for real time monitoring of the growth of periodic structures.
- Determine methods to measure rare-earth ion solubility and diffusion rates in waveguide structures.
- Determine methods to nondestructively measure the dimensions of ferroelectric domains in waveguide structures.
- Determine linewidth and stability measurement techniques for distributed Bragg reflector waveguide lasers.
- Develop measurement schemes to determine required complex index of refraction data of AlGaAs quantum well materials to design optimal device structures.
- Perform photoluminescence modeling and measurements to obtain the data required for nondestructive evaluation of vertical III-V structures.
- Assemble a system to evaluate the improved accuracies of the electrically calibrated pyroelectric detector.

- Create, evaluate, and deliver spectral reference standards to the Air Force standards laboratory.

- Extend the operation of the electro-optic sampling system to 1.30 and 1.55 μm.

- Measure the relative intensity noise (RIN) of laser diodes at reduced temperatures to determine the practical limits of RIN measurements.

- Design a system for a broad-range tunable laser source based on tunable semiconductor lasers.

- Determine the potential for 0.1% uniform InGaAs reference detectors.

Related Developments

- A Japanese company is reported to be using lithium niobate external modulators in its 10-Gbit/s lightwave systems to avoid chirping problems of laser diodes.

FY 93 Accomplishments

- Developed a new integrated optic laser, made from neodymium-doped glass, that operates at three wavelengths – 905-, 1057-, and 1356-nm. Materials were furnished by a company through a CRADA.

- Developed integrated optic 30 dB polarizers for both transverse magnetic and electric polarizations, demonstrating the utility of the localized plasma etching process for which a NIST patent has been formally requested. This is a crucial step in the development of an integrated optic polarization diversity detector for which there are many uses.

- Completed the optoelectronic device fabrication facility. Installed and made operational necessary equipment, including the large vacuum system.

- Designed, installed, and operated a liquid nitrogen storage tank and continuous feed system, which provides a reliable and less expensive source of liquid nitrogen and pure, dry nitrogen for the chemical-beam epitaxy (CBE) system and optoelectronic device facilities. It allows for extended periods of operation of the CBE with less consumption of liquid nitrogen.

- Completed a general-purpose optical spectrum acquisition and analysis package, applied to comparative microphotoluminescence measurements and simulation of vertical-cavity semiconductor structures, and correlated with reflectance spectroscopy measurements. Collaboration with Yale University demonstrated the applicability of the measurement technique for studying spatially varying composition profiles in semiconductor epilayers.

- Demonstrated the capability to make spectral reflectometry measurements while growing GaAs/AlGaAs layers in the CBE, a significant step in developing the *in situ* growth metrology. Real-time monitoring indicates the potential for creating mirrors with accurately determined center frequencies with significantly fewer tries.

- Confirmed the University of Illinois theory of GaAs/AlGaAs quantum-well refractive index by measuring the reflectance of distributed quantum well structures, and co-authored a paper with the Illinois group.

- Established procedures for making zinc diffusion in lithium tantalate that allow for high-differential-index waveguide structures with low loss, as part of a CRADA. Established that the process produces high-quality waveguides in $LiTaO_3$, which should yield much lower thresholds for the waveguide lasers. This was a significant step required for the development of waveguide lasers.

Project: INTEGRATED OPTOELECTRONICS

FISCAL YEARS	94	95	96	97	98
Develop *in situ* growth metrology for III-V compound semiconductor structures. [NSF, STRS]	—	—			
Develop metrology to evaluate materials and device structures for waveguide lasers. [IMRA, Boeing, ATP]	—	—	—	—	—
Develop metrology to evaluate III-V compound, vertically integrated, periodic structures. [STRS]	—	—	—	—	
Develop electrically calibrated pyroelectric detector as transfer optical power measurement standard, with order of magnitude improvement in accuracy. [Air Force]	—	—			
Develop theory required to support metrology of IOE devices. [STRS]	—	—	—	—	—
Develop metrology for evaluating maximum speeds of operation of sources, detectors, and modulators at wavelengths needed by industry. [STRS]	—	—	—	—	—
Develop the metrology to evaluate noise of laser diodes. [STRS]	—	—	—	—	
Develop metrology to evaluate spectral properties of laser system components. [Air Force, Army, STRS]	—	—	—	—	—
Participate in standards committees. [STRS]	—	—	—	—	— ⇒

Project: MEASUREMENTS FOR SOURCES AND DETECTORS

FY 94 Fund Sources: STRS, Air Force

Staff (4.5 staff-years)

Professional	D. FRANZEN*	S. Gilbert	T. Drapela*	P. Hale*
	A. Sanders*	J. Schlager*		
Technician	R. Juneau*			

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

Objective: Provide the optical communications industry with practical measurement techniques and standards for optical detectors and sources needed in optical telecommunications systems. Of specific interest are methods to characterize optical fiber lasers and amplifiers, and methods to characterize and provide wavelength standards for laser diodes. Challenges will be to develop metrology systems for determining frequency response of detectors to 40 GHz and for the accurate acquisition of high-speed optical waveforms.

Significance: High-bandwidth measurements are particularly needed to support high-performance systems and components that can take advantage of the potential bandwidth of installed optical fiber cables. More-sophisticated transmitters and receivers will allow an increase in channel capacity by several orders of magnitude through higher bit rates and wavelength division multiplexing. This project supports the development of the next generation of optical telecommunication systems.

FY 94 Plans

- Develop high-accuracy wavelength standard. Lock single-frequency erbium fiber laser to laser-cooled rubidium.

- Extend coverage of laser heterodyne system for measuring detector frequency response to 40 GHz and start industry-wide round robin to evaluate measurement methods.

- Investigate frequency-domain phase-response measurement techniques to 40 GHz.

- Complete the comparison of frequency-response measurements with NPL, required for international traceability.

- Construct a prototype multi-wavelength standard (1300 nm and 1550 nm) for calibrating optical spectrum analyzers.

- Improve NIST ability to sample by optical means optical waveforms of interest to high-bit-rate systems.

Related Developments

- A Japanese company has advanced high-speed system technology with a field trial of a 10-Gbits/s system.

- A major U.S. company has expressed an interest in upgrading existing installed dispersion-unshifted fiber systems by using erbium fiber amplifiers and dense wavelength division multiplexing at 1550-nm wavelength. This course of action will create a need for new wavelength standards.

- Direct modulation of laser diodes at 25 GHz has been reported by a U.S. company.

FY 93 Accomplishments

- Successfully trapped and laser-cooled rubidium atoms to below 1 mK, yielding an optical absorption linewidth of less than 10 MHz. This was the key technical challenge in building an ultra-accurate wavelength standard for optical fiber communications in the 1.5-μm region.

- Used uv laser light to write a Bragg grating inside the core of a single-mode optical fiber, achieving a reflectivity of over 90%. This is comparable to state-of-the-art values reported by other laboratories.

- Constructed and documented a laser heterodyne system for measuring detector frequency response to 30 GHz. Developed a fast detector package to transfer high-speed detector calibrations to outside laboratories.

Project: MEASUREMENTS FOR SOURCES AND DETECTORS

FISCAL YEARS	94	96	96	97	98
Develop high- and moderate-accuracy wavelength standards at 1300 nm and 1550 nm to support needs of optical communications industry. [Air Force, STRS]					
Complete high- and moderate-accuracy wavelength standards for laser diodes. [Air Force, STRS]					
Develop methods to characterize optical fiber lasers and amplifiers. [STRS]					
Establish advanced heterodyne system for measuring frequency response of detectors to 40 GHz at 1300 nm and 1550 nm. [STRS]					
Establish transfer standard for short impulse response duration of detectors. [STRS]					
Develop measurement methods for sampling fast optical waveforms in support of lightwave communications. [STRS]					

Project: LASER POWER AND ENERGY MEASUREMENTS

FY 94 Fund Sources: STRS, Newark AFS, CCG/AF, CCG/Navy, Calibration Fees

Staff (8.5 staff-years)

Professional	T. SCOTT	R. Jones	R. Leonhardt	X. Li
	D. Livigni	W. Case*	J. Lehman*	A. Sanders*
	I. Vayshenker*			
Technician	R. Juneau*	D. Keenan	I. Tobias	

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

Objective: Provide calibration and measurement assurance services for the laser power and energy industries, as needed for safety regulation, engineering, optical telecommunications, and acceptance testing. Specifically: develop calorimeters for optical fiber power, providing 1% accuracy at 1 μW; develop calorimeters and provide measurement services for excimer lasers (1% accuracy at 1 J), carbon dioxide lasers (1% at 1 kW), and Nd:YAG lasers (1% at 300 W); develop linearity measurement capability for fiber power meters.

Significance: Lasers constitute a large and growing market: laser sales are $2 billion per year, and the worldwide market for laser-based products, such as optical memories, laser printers, barcode scanners, and telecommunications exceeds $14 billion. Lasers are found in nearly all segments of the industrial community. Excimer lasers are widely used in ultraviolet lithography, materials processing, and medical applications; the FDA is expected soon to approve excimer lasers for corneal sculpting. High power Nd:YAG and CO_2 lasers are used increasingly in industrial and medical systems. This project provides essential laser power and energy measurement services to the laser and telecommunications industry for quality control and the regulation of safety.

FY 94 Plans

- Develop high-power Nd:YAG laser calibration capability at a wavelength of 1.06 μm.
- Develop 10.6-μm measurement capability at 1 kW for calibration service.
- Complete optical fiber power round robin and present results at National Conference of Standards Laboratories meeting.
- Incorporate uniformity, linearity, and spectral responsivity measurements into the optical power measurement service program; document entire optical power measurement service program.
- Build two excimer laser calorimeters to be used as NIST national standards for excimer laser measurements.
- Design, construct, and implement tuneable laser source systems for optical fiber power calibrations at the three nominal wavelengths of 850-, 1300-, and 1550-nm.
- Conduct second phase of laser beam profile round robin with beam profile system manufacturers.
- Deliver a system for calibrating optical fiber meters for Army.

Related Developments

- The use of high-power Nd:YAG lasers for industrial welding and cutting has increased dramatically this past year. NIST has recently had several urgent requests for high-power (>300 W) measurements and standards at 1.06-μm wavelength because of discrepancies of 30% or more at industrial laboratories.

- The expanding use of excimer lasers for industrial and medical purposes has increased the need to develop and provide national laser power/energy traceability at all three of the following wavelengths: 193-, 248-, and 308-μm.

FY 93 Accomplishments

- Completed construction of optical fiber power measurement system for AF primary standards laboratory at Newark AFB, OH. This system will allow them to calibrate optical fiber power meters with and without fibers/connectors attached.

- Completed an analysis of the data acquisition software and hardware used by the laser calibration laboratory at the AF primary standards laboratory. The results of this effort are documented in a report being submitted to the AF to help them improve their laser measurement capability.

- Completed initial set of intercomparison measurements on a silicon "trap" detector on loan from the Radiometric Physics Division. This was the initial step in a thorough intercomparison process being conducted between the Boulder and Gaithersburg optical power laboratories to formally confirm the agreement between the particular standards being used.

- Designed, built, and delivered two-level NdYAG laser radiometers to Navy Corona. These radiometers are improved low-level instruments and will be used to calibrate Navy laser rangefinders.

- Presented invited talk "Beam Analysis Round Robin" at SPIE conference in Boston, MA.

- Chaired the "Laser Measurements Working Group" at the 1992 IEC TC-76 Laser Safety Conference in Rotterdam, Netherlands.

Project: LASER POWER AND ENERGY MEASUREMENTS

FISCAL YEARS	94	95	96	94	98
Design and develop a cryogenic calorimeter. [STRS, Navy]	━━	━━			
Complete round robin in optical fiber power meters. [STRS]	━━				
Document microwatt calorimeter standard and upgrade power measurement services to ±0.1%. [STRS, CCG/Air Force, Newark AFS, CCG/Navy]	━━	━━			
Provide calibration and MAP services. [Calibration Fees]	━━	━━	━━	━━	━━ ⇒
Upgrade uncertainty of laser power measurement services to ±0.3%. [STRS]	━━	━━	━━		
Develop a calorimeter standard for excimer lasers at 248 nm. [STRS]	━━				
Establish measurement services for excimer lasers. [STRS, Calibration Fees]	━━				
Participate in standards committees. [STRS]	━━	━━	━━	━━	━━ ⇒
Develop system for M-squared laser beam profile measurement. [STRS]	━━				
Implement special test measurement for tele-communication wavelength region. [STRS]	━━	━━			
Conduct round robin in linearity for optical fiber power meters. [STRS, CCG/Navy]	━━	━━			
Design and develop linearity system for fiber power meters and detectors. [STRS, CCG/Navy]	━━	━━			

Project: SUPERCONDUCTING METROLOGY

FY 94 Fund Sources: STRS, CCG/Army, URI/Navy, Stanford University, ATP, Air Force

Staff (6.6 staff-years)

Professional	C. HAMILTON	C. Burroughs	S. Benz	P. Booi
	M. Cromar*	R. Harris*		
Technician	G. Wallace*	M. Crews*		

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

Objective: Support industrial need for in-house absolute voltage standards and calibration, and manufacturing control of precision electronic instrumentation. Provide a superconductive basis for ultra-high-speed signal sampling, ultra-low-noise magnetic detection, and millimeter-wave sources. A specific challenge is to develop an ac voltage standard based on the Josephson effect with potential accuracy greater than that of thermal converters.

Significance: Superconductive technology allows voltage standards and sensitive magnetic flux measurement at the fundamental performance limit. No other technology is capable of this performance. Most of the major national standards laboratories in the world depend on NIST for voltage standards. Moreover, advances in electronics for fundamental scientific research, telecommunications, radar, and data processing will demand higher speed measurement than is now possible. This project is designed to meet future needs in an area of prime NIST responsibility by providing standards and establishing measurement techniques to support new developments in industrial, military, and scientific technology.

FY 94 Plans

- Design, fabricate, and test circuits for a rapidly programmable voltage source. Goal is to make a fully functional chip with 14 bits of resolution and a range of ±1.2 volts.

- Provide NIST certification for commercial suppliers of Josephson voltage standard chips and act as a second source whenever commercial suppliers cannot provide the required devices. Collaborate with industry to maintain U.S. dominance of market for all Josephson voltage standard systems and components. More than 35 national, commercial, and military standards laboratories worldwide rely on NIST Josephson voltage standard chips. Four U.S. companies are using NIST chips to evaluate and improve commercial products. Using NIST designs, five U.S. companies have developed and marketed new products to support Josephson voltage standards

- Participate in a consortium to demonstrate technology for a superconductive workstation. Oversee design and construction of standardized ultra-high-speed test station which will be implemented at NIST and by the consortium. Participate in testing of chips which are being developed.

- Develop two-dimensional arrays of Josephson junctions as narrow-linewidth, broadly-tunable millimeter-wave sources in the range 60-600 GHz.

- Consult with participants in the University Research Initiative superconductive electronics project (SUNY Stony Brook, University of Rochester, Berkeley). Provide NIST-developed technology for cryoprobes, hardware, and software for automated testing as needed.

- Develop low-temperature magnetometers (SQUIDs) tailored to needs of Stanford Gravity Probe-B program. Report effects of junction size and type and effects of SiO_2 insulation on low frequency excess noise. Incorporate Josephson arrays as switchable isolators in the SQUID input circuits. Evaluate SQUID array amplifiers as followers for very-low-noise SQUIDs.

Related Developments

- As a result of a technology transfer program with NIST, a U.S. company now supplies the 1-volt chips marketed as a NIST Standard Reference Material.

FY 93 Accomplishments

- Successfully tested the rapidly programmable Josephson voltage standard being developed to synthesize ac waveforms with a calculable rms value to high precision. The programmable array of Josephson junctions achieved 9-bit resolution with a sampling rate of 1 kHz and has the potential to become a new ac voltage standard, possibly supplanting thermal converter standards.

- Improved productivity and yield of both 1-volt and 10-volt Josephson array voltage standard chips so that all outstanding orders could be satisfied. Shipped 20 devices based on purchase orders totaling $235K.

- Developed an ultra-high-speed chip mount and cryoprobe for superconductive integrated circuits with a participant in ATP-sponsored work. Analyzed the margins of a single flux quantum circuit that an ATP-funded company had proposed, and delivered a report showing that the margins were only ±3%, suggesting that the proposed design will not work.

- Fabricated 80 chips on a single 3-inch wafer containing over 50 different SQUID devices and a 100-SQUID amplifier. This represents a major advance that allows the fabrication of many engineering variations of a circuit in only one fabrication run.

- Eliminated possible source of excess low frequency noise in SQUIDs, by experimentally verifying that washer layers of niobium exhibit the same noise as when the layers are made of lead.

- Assisted a company to develop a new automation unit for Josephson voltage standards, based on the NIST design. The company has sold five units to date.

- Coupled coherent power from 2D arrays of Josephson junctions to room-temperature electronics. The emission linewidth is as narrow as 20 kHz and is tunable over the range 67 to 230 GHz.

Project: SUPERCONDUCTING METROLOGY

FISCAL YEARS	94	95	96	97	98
Develop all-Nb voltage standard chip. [CCG/Army]	—				
Provide advice to standards laboratories. [STRS]	—	—	—	—	— ⇒
Assist private commercial U.S. firms in system and chip development. [STRS]	—				
Participate as full partner in consortia to demonstrate superconductive workstation. [ATP, URI/Navy]	—	—	—	—	—
Develop LTS SQUIDs for Stanford Gravity Probe-B program. Study effects of junction size and type, and effects of SiO_2 insulation. [Stanford University]	—	—	—	—	—
Develop 2D Josephson arrays as microwave sources. [Air Force]	—	—			
Fabricate practical devices with Nb junction technology. [STRS]	—	—	—	—	— ⇒
Develop 14-bit programmable voltage standard. [STRS]	—	—			

Project: CRYOELECTRONIC METROLOGY

FY 94 Fund Sources: STRS, ONR

Staff (3.5 staff-years)

Professional	J. MARTINIS	R. Kautz	M. Nahum	A. Steinbach*
	R. Harris*			
Technician	G. Wallace*	M. Crews*		

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

Objective: Develop a new generation of ultra-small cryogenic devices offering unprecedented performance for electrical standards and metrology.

Significance: Ultra-small electronic devices are fundamental to a new class of electronic devices for metrological application. The demonstrated performance of an electrometer and charge pump at NIST gives credibility to future metrological devices based on this technology. In a few years the single-electron devices may produce a better value of the fine structure constant and, eventually, charge and capacitance standards in integrated-circuit form. This project is designed to meet future needs in an area of prime NIST responsibility by providing standards and establishing measurement techniques to support new developments in industrial, military, and scientific technology. Practical results of this project may include X-ray detectors having energy resolution 100 times better than achieved today.

FY 94 Plans

- Develop detailed physical understanding of charge pump noise sources which limit accuracy to 0.5 ppm in five-junction pumps.

- Fabricate and test seven-junction pumps for reduced errors.

- Perform initial tests of a capacitance standard.

- Evaluate energy resolution of superconductor-insulator-normal metal (SIN) X-ray detectors. If SIN X-ray detectors achieve only 50-eV energy resolution, they may allow major improvements in chemical analysis using scanning electron microscopy and X-ray fluorescence.

- Collaborate with Brown University and the University of California at Berkeley on SIN far-infrared detectors.

- Prepare white papers and proposals describing extended research by the Cryoelectronic Metrology Group involving low-temperature devices, which are non-superconducting.

Related Developments

- Researchers at Saclay, France and elsewhere are actively pursuing single-electronics for its scientific and potential technological interest.

- Next year, Competence funding for this project will expire. The Division is committed to the continued funding of this project and the coordination of this work with the fundamental electrical standards work being conducted elsewhere in EEEL.

- The two-stage SQUID amplifier with a 30-ns rise time has attracted interest from the U.S. industrial community for its potential application to nuclear magnetic resonance systems and small-antenna systems. NASA considers it appropriate for a variety of uses.

FY 93 Accomplishments

- Measured an error rate of 0.5 ppm for the electron pump. This rate is a factor of 1000 lower than all other electron pumps but still much higher than the theoretical predictions. Identified the noise source as being due to 1/f charge fluctuations and developed a strategy (7-junction pump) to achieve metrological accuracy.

- Showed that the critical current of two series-connected ultra-small Josephson junctions can be modulated by applying charge to the "island" connecting the junctions.

- Designed a novel bolometer whose thermal isolation is based on electron/phonon mismatch and whose thermometer is an SIN junction. Has demonstrated noise-equivalent-power of 3×10^{-18} W/$\sqrt{\text{Hz}}$ at 0.1 K, making it the most sensitive IR detector ever.

- Detected pulses from X-rays and phonons with the hot-electron microcalorimeter, in extension of the infrared capability of the bolometer. Showed by calculations that as an X-ray detector, the bolometer is 50 times better than current X-ray detectors; as a phonon detector, it is 1000 times better than current phonon detectors. Submitted a patent disclosure on "Microcalorimeters for X-ray Detectors."

Project: CRYOELECTRONIC METROLOGY

FISCAL YEARS	94	95	96	97	98
Demonstrate charge pump accuracy to 1 part in 10^9. [STRS, ONR]	—	—	—	—	—
Develop low-leakage capacitors. [STRS]	—	—	—	—	—
Perform initial experiments to measure fine-structure constant. [STRS]		—	—	—	—
Demonstrate prototype capacitance standard. [STRS]	—	—			
Develop metrological standard for transport to Electricity Division. [STRS]		—	—	—	—
Develop scanning Coulomb blockage electrometer. [STRS]	—	—	—		
Measure energy resolution in SIN X-ray detector. [STRS]	—				

Project: DETECTORS AND THERMAL CONVERTERS

FY 94 Fund Sources: STRS, NASA, ONR, SDIO

Staff (4.6 staff-years)

Professional	D. McDONALD	E. Grossman	M. MacDonald	J. Sauvageau
	R. Harris*	J. Koch*		
Technician	G. Wallace*	M. Crews*		

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

Objective: Develop devices to measure electromagnetic fields with more accuracy and sensitivity than is available from conventional devices.

Significance: The physical foundation of this NIST work is the use of superconducting inductors, coupled to a SQUID, as a fundamental measurement device. The temperature dependence of inductance provides the world's most sensitive thermometer (with sensitivity of a few parts in 10^9) for power measurements. This kinetic-inductance thermometer can be the basis for power standards at audio, radio, microwave, and infrared frequencies, as well as for the visible, ultraviolet, and X-ray portion of the spectrum. Used in a different mode, it can be a sensitive detector of ionizing (pair breaking) radiation. Both direct and heterodyne detectors are anticipated.

FY 94 Plans

- Complete fabrication, testing, and installation of a kinetic-inductance fixed-point device in the national standard radiometer.

- Design and fabricate an initial kinetic-inductance-based ac/dc thermal converter for the audio-frequency- and radio-frequency ranges. Use of cryogenic thermal converters provides NIST with a technology for calibrating the improved thermal converters that industry is developing for the market place.

- Begin development, in collaboration with Optical Electronic Metrology Group, of an improved power meter for fiber optics, based on high-temperature superconductivity (HTS).

- Design, fabricate, and test a THz heterodyne mixer based on HTS step-edge Josephson junctions.

- Optically characterize room temperature Nb microbolometers in the 1 to 30 THz range.

- Characterize 4-K niobium photoinductive detectors.

Related Developments

- Radiometry spans the spectrum from audio to X-ray frequencies and is the most widely used technology for primary calibrations across the electromagnetic spectrum. Other Agency funding is ending for both this project and the users of the national standard radiometer. Sustained funding is essential if NIST is to maintain a superior technology in order to determine the limits of commercial radiometers.

FY 93 Accomplishments

- Accepted delivery, installed, and tested a new SiO_2 Electron Cyclotron Resonance, plasma enhanced, chemical vapor deposition system. Fabricated good-quality Josephson-junction test circuits using SiO_2 deposited in the ECR reactor. The system was also used in a wet-etching process suitable for the kinetic inductance thermometers.

- Characterized room temperature niobium detectors; found them to be as good as any other room temperature detectors.

- Completed rebuilding of the national standard infrared radiometer. Performed tests (continuing) to characterize performance; measurements of the dc substitution error were satisfactory.

- Micromachined the first silicon thermal isolation structures to allow about two orders of magnitude improvement in radiometer sensitivity at 6 K. These structures will also be used at 0.1 K for X-ray detectors.

- Fabricated the first kinetic-inductance fixed-point thermometers, using the design model of the previously fabricated differential thermometers as a guide. Deficiencies in that model were discovered and a new model was developed appropriate to the fixed-point thermometers.

- Submitted an invention disclosure on antenna-coupled room temperature detectors, which is entitled "Niobium Microbolometers for Far-Infrared Detection."

Project: DETECTORS AND THERMAL CONVERTERS

FISCAL YEARS	94	95	95	94	98
Develop infrared standard radiometer. [SDIO]	━━━━				
Develop antenna-coupled detectors for infrared focal plane array. [ONR]	━━━━				
Develop antenna-coupled ambient temperature detectors. [STRS]	━━━━	━━━━			
Design and characterize infrared heterodyne receiver. [NASA]	━━━━	━━━━	━━━━	━━━━	
Provide prototype cryogenic ac/dc converter. [STRS]	━━━━	━━━━	━━━━		
Develop improved fiber optic power meter using HTS materials. [STRS]	━━━━	━━━━	━━━━		

Project: HIGH-TEMPERATURE SUPERCONDUCTING FILMS AND ELECTRONIC DEVICES

FY 94 Fund Sources: STRS, NASA, ARPA

Staff (8.7 staff-years)

Professional	M. CROMAR*	D. RUDMAN	J. Beall	D. deGroot
	T. Harvey	R. Ono	C. Reintsema	L. Vale
	R. Harris*	J. Rice*		
Technician	G. Wallace*	M. Crews*		

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

Objective: Exploit the properties of high-temperature superconductors (HTSs) for more convenient precision measurements and standards. Develop the basic science, establish the technology, and create HTS devices for metrological and commercial use, and transfer this technology to commercial manufacturers.

Significance: The potential impact of HTS on electronics is enormous, but a practical technology must be developed to realize it. Progress on HTS thin-film technology has been rapid, setting the stage for the fabrication of devices to determine the most promising opportunities for this technology. The Group has developed all the components required for HTS integrated circuits and is beginning work on specific devices. This project is part of a nationwide research and development effort to reach that goal.

FY 94 Plans

- Develop tunable microwave components based on HTS films and ferroelectric capacitors.
- Develop microwave testing and measurements for HTS films and devices in collaboration with the Electromagnetic Fields Division.
- Improve superconductor-normal-superconductor (SNS) step-edge Josephson junctions in both single and array configurations.
- Develop HTS microbolometers on silicon substrates. Characterize their response and evaluate them for metrological and commercial applications.
- Characterize HTS Josephson junctions as terahertz mixers.
- Characterize the shape of microwave-induced steps in HTS Josephson junctions and evaluate their potential as elements of a Josephson voltage standard.

Related Developments

- Several U.S. companies are marketing HTS products, including HTS SQUIDs on a chip, thin films, interconnects, and microwave components.

FY 93 Accomplishments

- Fabricated step-edge HTS SNS Josephson junctions and SQUIDs over a ground plane, perhaps the first such in the world. Properties of the junctions are similar to junctions grown directly on the substrate. Remarkably, the spread in critical currents in the Josephson junctions was smaller than in junctions fabricated directly on a substrate.

- Fabricated a record-setting high-I_cR_n junction coupled to a lithographed far infrared antenna. Measured the response of the antenna-coupled junction to radiation from a far infrared laser. Observed constant-voltage steps at voltages corresponding to 8 THz, a world record in lithographic junctions.

- Made and demonstrated the first thin film tuneable 5-GHz resonator using low-loss HTS films and an electrically adjustable capacitor ($SrTiO_3$). Applications include small-antenna systems.

- Demonstrated that high-quality YBCO films could be fabricated on a new insulating layer ($PrGaO_3$) on a $LaAlO_3$ substrate.

- Determined the effect of normal metal overlap on the resistance of SNS step edge devices, and found that reducing the overlap length to below a few micrometers greatly increases the device resistance without significantly reducing the critical current. This transfer effect was successfully modeled.

- Demonstrated phase locking between two HTS step-edge SNS junctions at frequencies up to 1.06 THz and temperatures up to 35 K.

- Measured the microwave surface resistance of HTS films with a dielectric resonant-cavity technique. The facility for the measurement was developed in the Antenna and Materials Metrology Group of the Electromagnetic Fields Division, and the results were consistent with those made using the Taber resonator technique at the University of Colorado. The dielectric cavity should be easier to use and is potentially more accurate.

Project: HIGH-TEMPERATURE SUPERCONDUCTING FILMS AND ELECTRONIC DEVICES

FISCAL YEARS	94	95	96	97	98
Improve *in situ* film growth by laser ablation. [STRS]	—	—			
Investigate new film/substrate combinations. [STRS]	—	—			
Develop multilayer technology. [STRS]	—				
Develop Josephson effect devices. [STRS]	—	—	—	—	—
Investigate microwave characteristics and applications of HTS. [ARPA]	—	—			
Fabricate HTS integrated circuits. [STRS]	—	—	—	—	— →
Develop practical circuits and devices. [STRS]	—	—	—	—	— →
Develop HTS devices at highest possible frequency. [STRS]	—	—	—	—	— →
Develop HTS microbolometers. [STRS, NASA]	—				

Project: SUPERCONDUCTOR STANDARDS

FY 94 Fund Sources: STRS, DoE

Staff (4.5 staff-years)

Professional	L. GOODRICH	F. Fickett*	R. Goldfarb*	J. Ekin*
	L. Cooley	A. Srivastava*		
Technician	T. Stauffer			

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

Objective: Promote the competitiveness of the U.S. superconductor wire and other superconductor component manufacturing industries, as well as the superconductor materials development industries, by providing superconductor standards, reference materials and devices, and round robin testing, and by participation in organizations such as ASTM and international standards organizations. Parameters of particular interest to industry are critical current, critical field, and ac loss.

Significance: The present diversity of measurement methods results in large uncertainty in superconductive critical current of large conductors. Design of large magnet systems requires 5% uncertainty or less. Large cable conductors have new problems in degradation of current caused by the cabling. High-temperature superconductor (HTS) materials represent a new and difficult challenge in measurement science; their approaching commercialization requires rapid development of acceptable measurement methods. This project addresses these problems by establishing standards and measurement methods; its international standards activities protect U.S. interests in international trade.

FY 94 Plans

- Determine a sampling and distribution pattern for the International Thermonuclear Engineering Reactor (ITER) interlaboratory comparison on Nb_3Sn critical-current (I_c) measurements. Recommend a standard sample holder and cryostat interface design for ITER tests. Fabricate and test the standard sample holder and cryostat interface design. Measure the $I_c(H,T)$ of each of the four Nb_3Sn wires for the ITER interlaboratory comparison.

- Provide leadership of national (ASTM, IEEE) and international (VAMAS, IEC) standards activities in superconductivity by directing U.S. coordination and participation in standards setting and in interlaboratory comparisons.

- Develop critical current standards for bulk high-temperature superconductors including measurement methods, superconductor simulators, and HTS reference devices. Maintain calibration of hybrid simulators, and promote simulator availability to U.S. superconductor manufacturers and international testing programs.

- Complete testing of the NIST high-current variable-temperature critical-current measurement system. Interact with U.S. manufacturers and national laboratories to develop the NIST device as the primary precision measurement system in the 20- to 76-K region.

Related Developments

- International competition in the superconductor industry, even for supplying U.S. government projects, is fierce. The competition underscores the need for standards and education in the measurement of the superconducting characteristics of HTSs.

FY 93 Accomplishments

- Ongoing work in the VAMAS collaboration has resulted in five U.S. laboratories responding to a questionnaire "Characterization and Evaluation of HTS," on future VAMAS activity. NIST finished editing the final report (340 pre-print pages) on the Nb_3Sn critical-current interlaboratory comparison for the VAMAS program for publication. VAMAS began an interlaboratory comparison of H_{c2} measurements using NIST SRM-1457 as a way to check magnetic field calibrations at a high field. NIST H_{c2} data at 4.02 K were analyzed and submitted to VAMAS; interlaboratory results, showing a variation of 0.55%, were presented at the VAMAS meeting at ICMC.

- The VAMAS collaboration to develop Reference Devices of BSCCO/Ag tapes continued with a visit to NIST by Dr. Yuyama of NRIM, during which 55 runs were made on 12 test samples. Critical current measurements were repeatable to 4%.

- Measured the energy loss per unit volume of superconductor wire samples of different geometries, in connection with a problem in the ITER project. Using several magnetometers, found that sample lengths must exceed two or three twist-pitch lengths to get accurate volume hysteresis losses. Designed, constructed, and tested a new critical-current probe for ITER magnet round-robin measurements; NMR calibration of the 52-mm-bore magnet showed 4 mT-to 6 mT-anomalies in the calibration; critical-current data for the interlaboratory comparison were made on the NbTi SRM and on the Nb_3Sn wire manufactured in the United States.

- Sent a 50-A superconductor simulator to a U.S. company and assisted with the evaluation of their measurement system using the device. Following the evaluations, created a custom design of a superconductor simulator for them that simulates high mutual inductance between the sample and the voltage taps. Generating a mutual inductance of about 100 mH to handle 5 A and 50 A required that two simulators in separate boxes be made because of the large inductors. This inductance also creates protection problems for the voltmeter since current spikes or open circuits could easily burn out a voltmeter.

- Sent a 95-page mailing to the 37 people on the U.S. Technical Advisory Group for IEC/TC-90 to get their input on the US national position (vote and comments) on five New Work Item Proposals from WG-2 (Superconductor Measurements). This mailing also informed the new WG-3 (Electronic Characteristics Measurements) of NIST activities.

- Developed a methodology for producing HTS reference specimens that removes the possibility of sample changes due to environmental effects and variability in the making of electrical connections.

Project: SUPERCONDUCTOR STANDARDS

FISCAL YEARS	94	95	96	97	98
Determine sampling and distribution pattern for ITER international intercomparison of Nb_3Sn I_c measurements. Recommend, fabricate, and test standard sample holder and cryostat interface design. [DoE]	—	—	—		
Participate in international intercomparisons of critical current and ac loss measurements. [STRS]	—	—	—	—	— ⇒
Support national standards activities by coordinating U.S. interlaboratory comparisons. [STRS]	—	—	—		
Provide leadership of national (ASTM, IEEE) and international (VAMAS, IEC) standards activities in superconductivity. [STRS]	—	—	—	—	—
Develop critical current standards for bulk HTS, including measurement methods, superconductor simulators, and HTS reference devices; promote availability to U.S. manufacturers. [STRS]	—	—			
Complete variable-temperature, high-critical-current measurement system; interact with U.S. manufacturers and national laboratories to develop device as primary precision measurement system in 20-76 K region. [STRS]	—	—			

Project: CONDUCTOR SYSTEMS

FY 94 Fund Sources: STRS, DoE, ICA, Army, Navy/DTRC

Staff (4.0 staff-years)

Professional	F. FICKETT*	S. Bray	L. Dulcie*	R. Cross*
	J. Ekin*	A. Kos*	C. Thompson*	
Technician	N. Bergren			

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

Objective: Provide the superconductor magnet and related industries with needed measurement methods on superconductor and non-superconductor materials to support the design, construction, and operation of large superconducting and other systems. Specifically emphasize materials and systems in commercial and near-commercial use, such as NbTi and Nb_3Sn multifilamentary conductors; developmental materials such as Nb-based intermetallics; and low-resistivity normal conductors used in engineering applications.

Significance: The International Thermonuclear Engineering Reactor (ITER) program continues as the world's largest fusion-energy effort; the Relativistic Heavy Ion Collider will require 0.55 million meters of superconducting cable; tens of thousands of superconducting magnets are in use in laboratories throughout the world; and the growing medical field of magnetic resonance imaging is a major new market. Practical low-temperature superconductors are complex composite materials, and high-temperature superconductor (HTS) materials are even more complex. This project provides a common base for interaction among system designers, system manufacturers, and materials manufacturers. The unique NIST capabilities are also requested for other electrical measurements in support of industry.

FY 94 Plans

- Develop data base on properties of silver to support its uses in conjunction with HTS practical conductor development. Publish a wall chart of appropriate properties.

- Measure transverse compressive stress effects in Nb_3Sn cable structures with emphasis on strand crossover behavior. Measure axial strain effect on critical current in experimental compound superconductors at very high magnetic fields. Determine effect of conductor shape and cabling configuration on strain effects.

- Re-establish eddy current resistivity measurement capability for low-temperature bulk samples.

- Evaluate and improve the non-intrusive tow conductivity measurement system and expand the existing tow conductivity data base. Evaluate means of accurately measuring the resistivity of submicron-diameter fibers with short lengths.

- Perform critical current measurements on model wires and full-scale candidate conductors for Navy applications. Measure fatigue effect in Superconducting Composite Rings (SCCRs) and measure residual resistivity ratio of SCCRs before and after fatigue testing.

- Complete project to determine the behavior of conduction electrons in conductors where the scattering mean free path is significantly limited by conductor dimensions.

Related Developments

- Small superconducting magnetic energy storage systems for power quality are now commercially available. They use liquid helium technology. Larger systems are being designed.

- Development of wire and tape from HTS materials continues; lengths suitable for some magnets are available, but overall critical current (at field) needs improvement before most large-scale applications can be considered.

FY 93 Accomplishments

- Collaborated with a U.S. company to find material-related ways of reducing the proximity-coupling contribution to ac loss in NbTi ultra-fine multifilamentary conductors with different matrix materials. Found that proximity coupling could be controlled by using different amounts of Mn and Si in the Cu matrix. Results gave larger filament spacing for coupling onset from that reported in the literature. The twist pitch of the conductors was identified as the cause for the difference.

- Completed evaluation tests of candidate conductors for the MIT 1-GHz nuclear magnetic resonance (NMR) magnet project. Measurements were made to 23.5 T and strain-effect was measured at 1.8 K. Analyzed and sent data on the transverse-axial stress comparison in Nb_3Sn to MIT for use in a finite element calculation of the three-dimensional stress interaction in a monofilament Nb_3Sn conductor. This information is needed for the selection of a conductor for the construction of the 1-GHz NMR spectrometer. Two Nb_3Sn candidate conductors for a 45-T hybrid research magnet were measured for the National High Magnetic Field Laboratory to determine the critical-current dependence on axial strain.

- Chaired meetings on the final development of the eddy current probe evaluation standard under development for the Army. Input from various DoD agencies and the Aerospace Industrial Association is being incorporated into the standard. Measurements at NIST of a number of industry-provided probes were completed. The probes did not meet the minimum specifications of the standard.

- Completed a fatigue test on a NbTi Superconducting Composite Ring (SCCR). The SCCR was mechanically fatigued at 5 T and 75% of I_c for 2000 cycles without quenching, but quenches during a second test in which the strain amplitude was increased, which more closely resembles the actual operating conditions of a magnet, indicates that 100% reliability may not be achievable for these coils under the simulated operating conditions.

- Tested Nb_3Sn conductors for electrical response to axial strain in magnetic field for the engineering test study of the ITER. The results are needed especially to interpret the measurements being conducted on coil-wound samples, which show a spring-back problem.

- Prepared and examined new Army fiber samples (degradable metal-coated glass and polypyrrole, diameters down to 200 nm) with the scanning electron microscope to determine diameter and coating quality and measured resistance per unit length of the degradable fibers. Set up and tested the Army's duplicate resistivity measurement system, and converted the separate long- and short-fiber systems to a single unit by modifying the hardware and software.

Project: CONDUCTOR SYSTEMS

FISCAL YEARS	94	95	96	97	98
Investigate transverse stress effects in experimental superconductors at high fields. [DoE]	■	■	■		
Perform tests and evaluations of conductors for DoE. [DoE]	■	■	■	■	
Evaluate magneto-mechanical characteristics of developmental candidate conductors and composite coils for Navy ship propulsion. [Navy/DTRC]	■	■			
Investigate stability of practical superconductors. [STRS]	■	■	■	■	■ ⇒
Develop data on properties of silver and silver alloys. [STRS]	■				
Develop apparatus for using microwave resonance in superconductor characterization; fabricate 10-GHz strip line resonators to study microwave contact resistance. [STRS]	■				
Develop system to measure electrical properties of conducting fibers; apply atomic force and scanning tunneling microscopies to evaluate fiber structure and properties. [Army]	■	■			
Determine size-limited behavior of electrons; measure effect of conductor purity on size-effect limited resistivity. [ICA]	■				
Measure strain effect on critical current in compound superconductors at very high magnetic field; determine effect of conductor shape and cabling configuration on strain effects. [DoE]	■				

Project: MAGNETICS

FY 94 Fund Sources: STRS

Staff (8.0 staff-years)

Professional	R. GOLDFARB*	J. Oti	P. Rice	T. Silva
	R. Cross*	F. Fickett*	A. Kos*	J. Moreland*
	S. Russek*	S. Sanders*	C. Thompson*	
Technician	J. Field			

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

Objective: Provide the magnetic recording industry and other industries using magnetic materials with advanced techniques for measuring and imaging magnetic information-storage materials. A significant challenge is to develop a basic understanding of the magnetic properties of materials and structures to correlate with further development of the various scanned-probe microscopies and other instruments for studying the microscopic magnetic properties of materials.

Significance: Magnetic measurements in the $52 billion worldwide magnetic information-storage industry are an ongoing source of disagreement. The advent of thin-film magnetics has resulted in further measurement problems. The rapid increase in magnetic recording density requires development of microscopic measurement techniques. This need is affirmed by an industrial survey and continuing industrial interactions. This project responds to the major U.S. industrial needs for basic magnetic measurements.

FY 94 Plans

- Apply scanned probe microscopy methods to measurement of nanoscale magnetic systems, concentrating on those systems that hold promise for magnetic recording. Develop techniques to image magnetic signatures below the 1-μm limit and down to at least 10 nm.

- Develop micromagnetic models of unbiased giant magnetoresistance (GMR) and anisotropic magnetoresistance (AMR) sensors subjected to any combination of uniform external fields, self-fields of current contacts, point-source fields, and fields produced by other sources of interest. Implement an electron scattering model for calculating GMR and AMR responses in multilayer and granular sensors.

- Image the magnetic field structures of magnetic recording heads using magnetic-force-microscopy and attempt high-resolution imaging of domain walls on magnetic garnet. Develop methods for imaging of permaloy domain structure and apply to commercial memory elements.

- Use the magnetoresistance scanning system to measure the effect of local field excitations on magnetoresistive (MR) response in MR thin films. Record two-dimensional MR profiles and corresponding magnetic profiles of MR elements. Determine the field and field-angle dependence of the first domain-wall nucleation field and the annihilation field, and compare to theory.

- Use the NIST multipurpose high-temperature superconductor (HTS) measurement rig to measure resistivity and magnetic susceptibility simultaneously as a function of temperature, field, and current. Determine the effect on intergranular properties in HTS bulk samples and intrinsic properties in thin films. Investigate the difference between magnetic and transport critical current determination.

Related Developments

- Rapid advances in magnetic recording make the need for dependable measurement technology on the submicrometer level more pressing. The bit density of conventional magnetic recording continues to increase dramatically. New optical recording technologies may once again challenge magnetic systems.

FY 93 Accomplishments

- Completed experimental and theoretical work to investigate the bulk properties of well-characterized dual-layer Co/Ni media. Limitations of the model were investigated and the coercive field splitting for small Cr separation layer thickness was successfully modeled. Additional theoretical studies of dual-layer magnetic CoNi-X-CoNi and Co-X-Co films, done in concert with the film fabrication and characterization efforts, suggest that interlayer magnetostatic interaction is primarily responsible for coercive field splitting in the CoNi-X-CoNi films.

- Demonstrated that it is possible to do conventional noncontact magnetic-force microscopy (MFM) using a thin-film Ni tip developed for tunneling-stabilized MFM. The tips can be used in the laser detection scheme provided in a commercial instrument and may be of the type preferred for these measurements.

- Set up the Hall probe magnetometer to measure both the electrical and magnetic properties of a YBCO superconductor. Susceptibility and J_c were measured simultaneously as a function of temperature and field. The measurements highlight differences between the two-dimensional magnetic measurement and the one-dimensional electrical measurement.

- Developed a technique of magnetic force microscopy termed "lift mode" MFM. The method allows immediate subtraction of the topology signal from the MFM signal on a line-by-line scan mode, thereby significantly increasing the sensitivity of the measurement technique. Used the lift mode system to successfully image the magnetic field of commercial thin-film recording heads.

- Made a series of magnetization measurements on soft magnetic steel; found significant variations in saturation magnetization, suggesting material nonuniformity. Based on the relationship found between liquid-helium and room-temperature measurements, recommended changes to commercial specifications regarding required measurement temperature.

- Began work on GMR *granular* films for recording-head applications, for which vast improvements in signal-to-noise characteristics are possible. In collaboration with University of Alabama Magnetics Institute, measured size effects and self-field effects in patterned read-head devices made from granular Cu/NiCoFe thin films exhibiting GMR.

- Designed and constructed a toroid magnetometer to measure iron samples. The system requirements were: (1) low-frequency operation (5-10 mHz), (2) high magnetic field (0.3 T), and (3) variable temperature (4 K to room temperature).

Project: MAGNETICS

FISCAL YEARS	94	95	96	97	98
Use multipurpose HTS rig to measure resistivity and magnetic susceptibility, and effect on intergranular properties. [STRS]	▬	▬			
Provide consultation on ac loss behavior of conductors for new particle accelerators and fusion energy. [STRS]	▬	▬	▬	▬	▬ ⇒
Measure effect of local field excitations on magnetoresistive response in thin films; study first domain-wall nucleation field and annihilation field. [STRS]	▬	▬			
Develop coercivity measurements; determine effect of magnetic relaxation; evaluate types and coercivity ranges of potential SRMs. [STRS]	▬	▬	▬		
Conduct fundamental studies of practical magnetic materials and new materials of current interest. [STRS]	▬	▬	▬	▬	▬ ⇒
Develop practical micromagnetic measurement system and scanning tips. [STRS]	▬	▬			
Improve precision and accuracy of tunneling-stabilized magnetic force microscopy. [STRS]	▬				
Apply scanned probe microscopy to study of new recording systems. [STRS]	▬	▬	▬		
Develop measurement technology for magnetic recording. [STRS]	▬	▬	▬	▬	▬ ⇒
Publish monograph on magnetic measurements. [STRS]	▬	▬	▬		
Provide experimental demonstration of multilayer magnetic film model, including AMR and GMR effects. [STRS]	▬	▬			
Develop industrial collaborations in the area of magnetic recording. [STRS]	▬	▬	▬	▬	▬

Project: SUPERCONDUCTOR STRUCTURE AND PROPERTIES

FY 94 Fund Sources: STRS, DoE, ARPA, Navy

Staff (7.5 staff-years)

Professional	F. FICKETT*	M. Coffey	A. Roshko	R. Thomson
	L. Dulcie*	J. Ekin*	J. Moreland*	S. Russek*
Technician	C. Clickner			

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

Objective: Provide the superconductor materials development industry with essential understanding of both low-temperature and high-temperature superconductors, particularly under conditions typical of superconductor applications, and determine applicability of existing measurement techniques to emerging materials. Challenges include determination and control of the mechanisms responsible for flux pinning and the factors affecting growth morphology, with an aim toward enhanced critical current.

Significance: High-temperature superconductivity is one of the major technological advances in recent times. This project makes use of the Group's recognized expertise in conventional superconductivity measurements to contribute to the new measurement problems associated with the high-temperature superconductor (HTS) materials. Major thrusts are application of emerging measurement technologies such as scanning-tunneling microscopy (STM) and atomic-force microscopy (AFM), to superconductor evaluation and transfer of this information to industry.

FY 94 Plans

- Construct ultra-high vacuum STM with new scanner and test at low temperatures; measure I/V curves of superconducting fullerenes using the system.

- Fabricate very thin YBCO films using laser growth on $LaAlO_3$, MgO, or $SrTiO_3$ substrates. Measure transport critical current density and characterize other superconducting properties. Investigate the surface morphologies of the YBCO film surface for submicrometer features.

- Determine pinning mechanisms in film and bulk HTS and optimize fabrication process for high critical current density. Upgrade deposition and analysis systems.

- Determine the suitability of the YBCO/Au/Pt/Al multilayer system as an interface to silicon by measuring contact resistance after oxygen annealing. Develop an effective method of depositing a dielectric layer, necessary for the contact measurement, that is compatible with 400 °C oxygen anneals. Fabricate a test structure using photolithography.

- Determine activation energies, surface barriers, pinning potentials, and mechanism of intergranular flux pinning in HTS and investigate how flux structure influences the transport current capability. Measure the anisotropic intergranular coupling properties and lower critical fields of oriented HTS.

- Develop a model of type-II superconductor behavior in the mixed state in linear response to circularly polarized radiation. Compare results of the model to theories of type-II superconductor response in the mixed state at very high frequencies. Explore possibilities of a nonlinear response theory for circularly polarized radiation.

- Design and fabricate high-quality contacts to HTS films down to 2 µm. Develop and optimize both in-situ and ex-situ contact processes. Develop characterization methods for contact losses in microwave applications.

Related Developments

- Commercial HTS products are now appearing. A commercial-size electric motor has been demonstrated. Designs are being prepared for HTS-based underground power transmission cables that will be direct replacements for existing power lines.

FY 93 Accomplishments

- Completed an extensive series of surface degradation studies on YBCO films. Electrical contacts made to degraded films exhibited very high and usually unacceptable electrical resistance. Surface resistance of 13 chips with over 100 devices was tested after varying exposure times in air and CO_2. Reflection high-energy electron diffraction and STM analyses were used. Completed a preliminary passivation study to determine if the YBCO/Au/Pt/Al multilayer system could withstand a 400 °C Ar anneal; found that a 50-nm layer of MgO over the entire chip protects the YBCO from losing significant oxygen during the Ar anneal.

- Discovered the common existence of particulate structure on the surface of HTS films by using atomic force microscopy and STM techniques on the same sample. Collaborated with the National Renewable Energy Laboratory on a project where these "sand" particles are studied with scanning Auger spectroscopy and X-ray photoemission spectroscopy.

- Collaborated with a commercial firm to perform STM measurements on BaKBiO thin films sputtered onto four different substrate materials. The films have a woven structure of many needle-shaped grains. The size and aspect ratio of the grains changed on the different substrates. Company personnel were surprised by these images and are working to improve the smoothness of their films.

- Developed a test chip pattern and used it for analysis of Pt and Pt-Au buffer layers for super-semiconductor contact fabrication. Completed analysis of two anneal curves on thin-film YBCO/Ag interface contact resistivity, and completed the first phase of a contact resistivity degradation study of YBCO as a function of air and chemical exposure. Both studies are integral steps needed in the development of superconductor contacts for the multichip module program.

- Developed a quantitative theoretical treatment of transverse thermomagnetic effects in HTS materials, with potential applications to HTS cuprates and bismuthates, layered organic superconductors, and multilayer structures.

- Completed a nanolithography study for identifying methods of using the STM to modify the surfaces of YBCO thin films. Five techniques were developed – milling, electron beam damage, vaporization, electrochemical etching, and causing oxygen electromigration. Each process is quite distinct and has different strengths and weaknesses. Work is continuing on refining several of the techniques for use in producing very small controlled structures for Josephson junctions and extremely small SQUIDs.

- Applied theory of radio and microwave frequency response of coupled vortex and superconductor systems to analysis of transmission and reflection data from YBCO films. The phenomenological theory incorporates effective mass anisotropy and accounts for two-fluid effects in addition to nonlocal vortex interaction, and has been used to model the surface impedance of uniaxially anisotropic type-II superconductors.

Project: SUPERCONDUCTOR STRUCTURE AND PROPERTIES

FISCAL YEARS	94	95	96	97	98
Develop data base on critical parameters of new superconductors. [Navy]	▬	▬	▬	▬	▬ ⇒
Develop model of type-II behavior in mixed state for response to circularly polarized radiation, and analyze at very high frequencies. [STRS]	▬	▬			
Extend low-resistance contacts to new superconductors, large currents, and high magnetic fields. [STRS]	▬	▬	▬		
Develop low-resistance contacts between HTS and semiconductors. [DoE]	▬				
Apply magnetic force microscope to flux lattice imaging. [STRS]	▬				
Determine flux pinning mechanisms in films and bulk conductors. [STRS]	▬	▬	▬	▬	
Determine effects of grain boundary structure, chemistry, crystallography, and microstructure on properties of HTS. [STRS]	▬	▬	▬	▬	▬ ⇒
Investigate superconductor properties of thin and thick films. [ARPA]	▬	▬			
Construct UHV STM with new scanner and test at low temperatures; measure I/V curves of superconducting fullerenes, using this system. [STRS]	▬				
Fabricate very thin YBCO films using laser growth on a variety of substrates and measure properties; investigate film surface for nanoscale features. [ARPA]	▬	▬			
Fabricate *ex situ* contact chips; evaluate surfaces with RHEED before and after exposure to air; study after cleaning and regrowth. [STRS]	▬	▬			
Examine structure and composition of HTS materials by STEM, TEM, AES, or SIMS. Study morphology of thin films by SEM, STM, and AFM. [STRS]	▬	▬	▬		