ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

1994 TECHNICAL ACCOMPLISHMENTS

SUPPORTING TECHNOLOGY FOR U.S. COMPETITIVENESS IN ELECTRONICS

U.S. DEPARTMENT OF COMMERCE

Technology Administration

National Institute of Standards and Technology
Gaithersburg, MD 20899

NIST

National Institute of Standards and Technology

As part of the Commerce Department's Technology Administration, the National Institute of Standards and Technology (NIST) works to promote U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. NIST carries out its mission through a portfolio of four major programs:

—the Advanced Technology Program, which provides cost-shared awards to industry to develop high-risk, enabling technologies with significant economic potential;

—the Manufacturing Extension Partnership, a network of extension centers and experts providing hands-on technical assistance to smaller manufacturers in adopting new technologies;

—laboratory research and services, which are planned and implemented in cooperation with industry and focused on infrastructural technologies, such as measurements, standards, evaluated data, and test methods; and

—a quality outreach program associated with the Malcolm Baldridge National Quality Award that recognizes continuous improvements in quality management by large manufacturers, service companies, and small businesses.

In fiscal year 1995, NIST is operating on a total budget of nearly $1 billion with about 3,200 staff members at its sites in Gaithersburg, Maryland, and Boulder, Colorado. For further information about NIST, call (301) 975-3058 or e-mail: inquiries@nist.gov (via Internet).

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No wider than the average human hair, this spiral antenna, measuring about 65 micrometers across, is 15 times more sensitive to infrared radiation than comparable lithographed log-periodic antennas. The integrated circuit's range of detected wavelengths is 10 times larger.

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NISTIR 5551

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

Technology Administration
Mary L. Good, Under Secretary for Technology

National Institute of Standards and Technology
Arati Prabhakar, Director

December 1994

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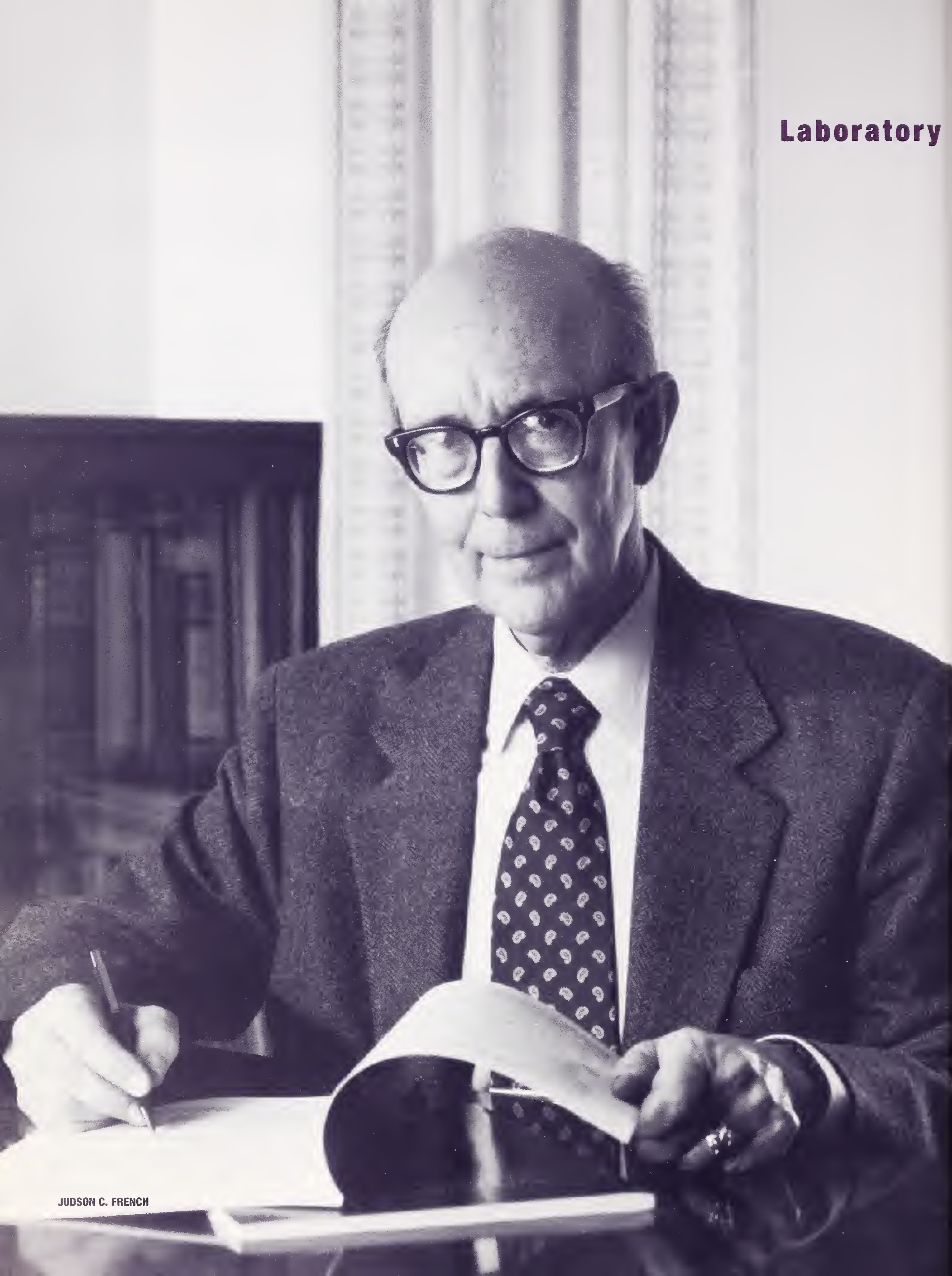


JUDSON C. FRENCH

Director's Message

I welcome your interest in the National Institute of Standards and Technology's (NIST) Electronics and Electrical Engineering Laboratory (EEEL). The purpose of this report is to indicate how our work contributes to the productivity and quality of the electrical and electronics manufacturing industries. We believe that the products and services which the staff has delivered to industry this past year were timely and relevant. By enriching the measurement infrastructure that enables advances in technology in the industries we serve, the direct and indirect benefits of our activities will materially enhance the lives of Americans through better jobs and better information, products, and services. This is our mission, and we take pride and pleasure in performing it well.

As you may know, EEEL provides the fundamental basis for all electrical measurements in the United States and practical measurement services for the electronics industry. We emphasize measurement research and services that are essential to equity in domestic and international trade; to the specification of manufacturing material, equipment, and processes; to manufacturing process and quality control; and to applications supporting the missions of other agencies.

In the next few pages of my message, I've drawn a thumbnail sketch of what we did last year. Before you continue reading, I'd also like to mention where you may find more detailed information about the Laboratory. *Technical Accomplishments* is one of four related publications that we produce to disseminate information about our work. *Measurements for Competitiveness in Electronics* is a description of industry's measurement needs. Our *Strategic Plan* outlines EEEL's broad strategy for meeting industry needs, and the *Program Plan* provides specific technical details of each of the projects designed to achieve our strategic goals. Let us know if you would like a copy of any of these documents.

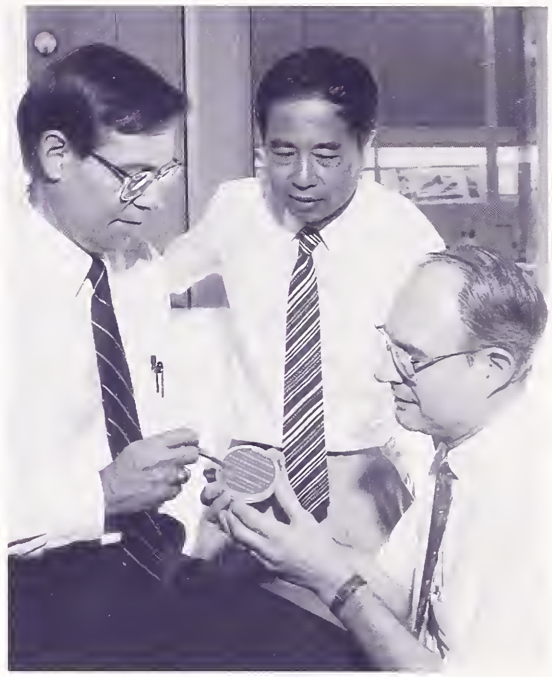
JFrench

Judson C. French, Director
ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

Laboratory Director's Message

EEEL Focuses Closely on Metrology

You may wonder, given the creative scientists affiliated with our Laboratory, why we do not direct our efforts more toward technology development. The answer is simple: the current need for measurement tools is so great that we cannot begin to address them all with our limited resources. Furthermore, other organizations in NIST, such as the Advanced Technology Program (ATP), which will invest approximately $430M in technology development during FY 1995, and other Federal laboratories do have both the mission and the resources for such development. You may be sure, however, that where the possibility exists, we exploit the results of our measurement research and development efforts to provide opportunities for commercialization by industry.



R&D 100-AWARD WINNING TEAM: DONALD NOVOTNY, DE-XIANG HUANG, JOSEPH KINARD

Exceptions Prove the Rules

A good case in point is the development this past year of a thin-film multijunction thermal converter (MJTC) for which NIST won an R&D 100 award. Developed under a Cooperative Research and Development Agreement (CRADA) with an American firm, Ballantine Laboratories, Incorporated, this device represents technology transfer at its best. Thermal converters, which are the most accurate calibration standards for ac voltage and current, also provide a basis for the most precise measurement method for both. The award-winning MJTC results from applying the latest semiconductor processing technology to the fabrication of carefully patterned heater/thermocouple structures and represents a substantive improvement over the electrical performance of the present standard wire thermal converters. Further, it is estimated that MJTCs can be produced with a cost range of $100 to $200 each, depending on the electrical parameters, as opposed to a corresponding range of $150 to $2500 for present standards. Thus, these standards can be built into commercial test equipment, bringing higher accuracy close to the ultimate user in a practical, economic way.

Over time, work such as this has a very significant impact in the marketplace: the greater accuracy, efficiency, and cost-savings realized by such a device enables American electronics manufacturers to design better products, which can be marketed at highly competitive prices to customers who need and find them affordable. The benefits ripple outward from the original target. By the time the impact has subsided, the economy is enhanced through the development not only of better equipment but potentially of more, better-quality jobs.

Reconfiguration Is Key to Flexibility and Responsiveness

Fiscal Year (FY) 1994 has been a very exciting year for the Laboratory in several respects. We are reconfiguring our organization in response to changes in the fields of technology associated with the industry we serve and to be able to meet the challenges posed by emerging technologies.

EEEL has divisions located at the NIST facilities in Gaithersburg, Maryland and Boulder, Colorado. The Electricity Division, which covers the fundamental electrical standards and constants, electronic instruments, video technology, standards for electronic data exchange, and support for the electrical utilities, and the Semiconductor Electronics Division, which covers semiconductor materials, processes, and devices, are located in Maryland.

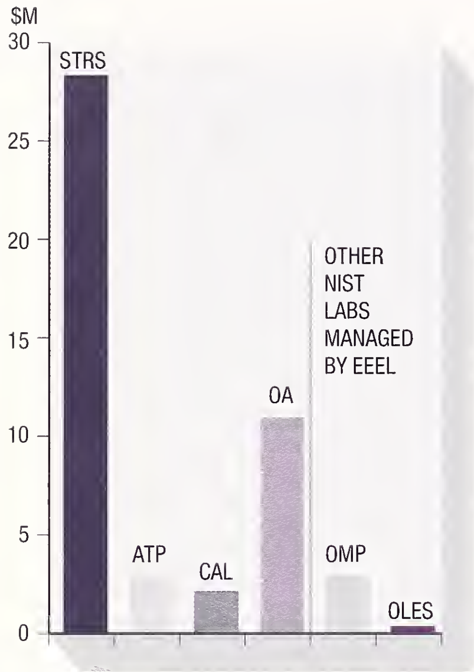
The remaining divisions are located in Boulder, Colorado. The Electromagnetic Fields Division covers microwave and millimeter waves, and electromagnetic interference. The most notable change in EEEL's organizational structure in 1994 involved the formation of a new division, the Optoelectronics Division, to cover fiber optics and optoelectronic devices. Programs on these topics were formerly included within the scope of the Electromagnetic Technology Division. In FY 1994, this Division revised its mission to focus on the technical areas of superconductivity, cryogenic electronics, and magnetics.

In addition to the Laboratory Headquarters, EEEL also has two offices in Gaithersburg, Maryland that matrix-manage NIST-wide programs. The Office of Microelectronics Programs (OMP) leads a unique, growing program which draws on several other Laboratories at NIST to complement EEEL's work in support of the semiconductor industry. At the industry's request, this office is slated for substantial growth. OMP will be managing the planned $25M National Semiconductor Metrology Program, aimed at satisfying measurement requirements of the National Technology Roadmap for Semiconductors. The Program was established in March, 1994 with about $5M in funding; the operating level is intended to be $25M annually within about three years. The Office of Law Enforcement Standards, which is sponsored principally by the National Institute of Justice, will continue to provide technical soundness to tests of products used by American law enforcement officers.

Planning and Resources: Inextricably Linked

And, now, to the resources of the Laboratory because they play a major role in determining our strategy for today and tomorrow. EEEL has, of course, limited resources with which to address the rapidly expanding metrology needs of the electrical and electronics industry as a whole. Taken broadly, this includes the entire spectrum from the electrical utilities to lightwave communications — to the suppliers of materials and equipment to these fields — as well as to the industry's customers. Thus, careful planning and long- and short-term measures of our progress and accomplishments are very important to assure the most effective use of our resources. The means by which we assess our effectiveness range from broad technical area reviews that summarize market issues and industrial measurement requirements, through planning and progress reporting documents, to formal assessments of impact on a national scale. Estimates based on such studies reveal that we can only address about 20% of the services requested by our industrial clients, and emphasize the need for our concentration on measurement technology.

Laboratory Director's Message



FY 1994 RESOURCES

EEEL's Budget

The FY 1994 budget was $44.7M of which $28.4M was internal (STRS) funding. We received an additional $3M to provide key components of the measurement infrastructure required by projects conducted by the electronics industry and sponsored by the Advanced Technology Program (ATP). EEEL has a substantial calibration income of $2.2M, which is 42% of the total calibration fees provided to NIST. The remaining funds, $11M, typically come from other federal agencies.

EEEL received modest expansion funding in FY 1994. The National Semiconductor Metrology Program received $1.5M of which $0.9M funded programs in EEEL. The Microwave program received a $0.5M increase in funding. For FY 1995, the National Semiconductor Metrology Program received a $5.5M increase to bring funding for this area to $10.3M. Of the 1995 increase, $1.4M will fund semiconductor metrology programs in EEEL, with the remainder invested in high priority projects in other NIST laboratories. Our plans are to seek growth in microwaves, semiconductors, fundamental quantum standards, digital imaging, electronic information exchange for automated manufacturing, and high-speed electrical and optical components in FY 1995 to better meet the requirements of our clientele.

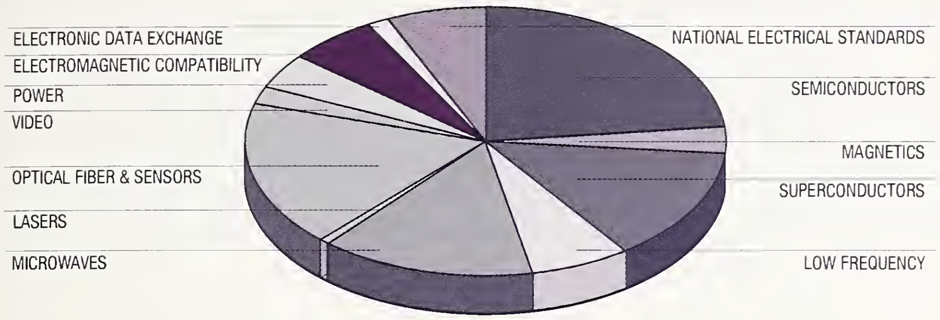
The Issue Is Time: Lack of Funds Equals Attrition

For EEEL, the issue is time. Given the restructuring of the Federal Government as a whole, the sources of other agency funding are decreasing too rapidly to compensate for the slow but healthy increases in internal funding at NIST. As in the past, this year EEEL obtained a significant fraction of its funding from outside sources to support and maintain staffing for our programs. However, the recent slow decline in staff-years-worked, occasioned by limited resources, did not diminish in FY 1994. The Electromagnetic Fields Division accounted for most of this decline with a reduction of total staff from 85 to 73.

In the annual count of staff members made at the turn of each fiscal year, our staff numbered 343, with 69% professionals — 37% of the professionals being at the doctorate level. During the last four years, while total staff declined at the rate of five per year, the number of staff at the doctorate level increased by a little over five per year. In sum, although we are becoming leaner, we are also becoming academically stronger, hiring very high-quality people to carry on EEEL's work.

A Different Perspective on Allocations of Funding

Given our limited resources, the allocation of dollars to programs is based on the bottom line — where the work is expected to have the largest impact. A relatively small allocation of funds for results that allow an important technology to take a significant step forward is money well spent. We attempt to establish priority from an in-depth determination of customer needs and an evaluation of likely social rate of return on our investment.



FY 1994 RESOURCES BY TECHNOLOGY FIELD

Recent economic analysis shows that private-sector investments in R&D provide a social rate of return (90% on average) that is seven times the return on investments in general (e.g., 13% on tangible investments, such as plant and equipment). As a result of the NIST Electronics and Electrical Engineering Laboratory process for selection of projects and transfer to industry of its results, a number of economic studies have shown that its average return on investment is about 200%, over twice the estimated return on private-sector R&D.

Further, this return reflects only the direct benefits of a particular stage or stages studied in a particular industry's economic process (e.g., marketplace transaction cost reductions) and does not take into account additional downstream and other indirect benefits. Industrial officials who participated in the EEEL economic evaluations have said they realized other substantial direct and indirect benefits than those studied, including increased market share, improved product reliability, increased production yields, improved ability to meet customer specifications, improved product features, cost reductions, and stimulation of new directions for company research.

Based on recent correlations between employment growth and gross domestic product (GDP) growth in high-technology industries, and taking into consideration the GDP growth which can be predicted on the basis only of the direct benefits studied, measures of the economic outcome of EEEL work can be derived. As a conservative estimate, considering only the direct and quantifiable benefits, for each \$1M invested in EEEL R&D, an increase in gross domestic product (GDP) of over \$33M and an increase in jobs of over 400 would be predicted.

EEEL Delivers Results

Our success hinges upon the effective delivery of our results. Interactive transfer, with complete description of our results, is crucial if the work is to benefit our customers. The methods EEEL uses for dissemination range from direct meetings and interactions with industry, EEEL-organized workshops and education courses, attendance at conferences, visits to other laboratories, invitations to our facilities, telephone consultations, reports and papers, interactions within professional societies, cooperative research projects, consortia, participation in voluntary standards organizations, and so forth. In a recent five-year period, EEEL has collaborated with or served, in a documented, substantial way, over 2000 different organizations. EEEL delivers results.

We find that our greatest leverage comes from concentration on metrology for materials, processing, and components as opposed to systems. Although we do address generic measurements for systems on occasion, most aspects of systems are more appropriate for industry's own attention. We use long-established criteria to ensure that we only undertake work that our Laboratory is uniquely qualified to perform, not projects that industry, academia, or other laboratories could do equally appropriately.

Laboratory Director's Message

Our Role in These Exciting Times

Our vision is to be the world's best source of fundamental and industrial-reference measurement methods and physical standards for electrotechnology, with a concomitant responsibility to deliver these resources with high leverage to industry and government to facilitate the achievement of national goals. The business we are in is to provide the measurement tools industry needs to provide and prove world leadership in its products. We must respond both to the immediate- and long-range needs of industry and support both with basic research to make sure our work is sound and foresighted.

We are living in exciting times, a statement with special meaning when expressed in Chinese literature. The Chinese characters for crisis and opportunity share a common element. Which of the many technical challenges we face will be of greatest significance? We are committed to the Semiconductor Industry Association's (SIA) request for a National Semiconductor Metrology Program. Where else will we find great impact, perhaps in the field of optoelectronics, or perhaps elsewhere?

The Implementation Plan for the U.S.-Japan Joint Optoelectronics Project was signed by both the United States and Japan on April 25, 1994. We attended the second Joint Management Committee meeting two months later, and agreed upon the steps needed to solicit proposals to serve as the U.S. Broker for this important effort. Reviews of the proposals were begun by the end of the fiscal year. Much is expected of this project, which encourages the development of a broad global view of optoelectronic devices, circuits, and modules and their significance to computing. At home, the Optoelectronics Industry Development Association (OIDA) is developing a technology roadmap somewhat like the semiconductor industry's, though necessarily more complex. The Electronics Subcommittee of the Civilian Industrial Technology Committee of the President's National Science and Technology Council is addressing the need for advances in the electronics industry broadly with other technology roadmaps in view. There are already specific calls for NIST's help in both of these studies. Will all of this lead to new EEEL responsibilities similar to the National Semiconductor Metrology Program?

Consider the attention being given to the environment and the "clean car." Electric vehicles are a matter of great national interest...there is much to be done in electrical engineering and advancing manufacturing of electrical components. Will this turn into a national initiative for EEEL?

Wireless communication has been "rediscovered." It is an important factor in the National Information Infrastructure (NII) and in worldwide markets. Will this have a major impact on our microwave program? Probably! — We are working to anticipate these changes...to be ready.

EEEL Really Makes a Difference

Interesting times, most assuredly. And, tomorrow as well as today, EEEL will continue to really make a difference. It's a matter of record. We have improved the productivity and profitability of companies, large and small. We've stimulated new product commercialization and, in some instances, the startup of new companies. Our work has led to changes in technical practices industry-wide as well as in more localized areas. And, our technical and professional activities influence the actions of others in their technical and policy decisions and actions. I hope that you will find the information included in this report encouraging. On behalf of the staff of EEEL and myself, I thank you for your interest in our Laboratory and its efforts.

he Electronics and Electrical Engineering Laboratory comprises five divisions and two offices. Laboratory Headquarters, the Electricity Division, the Semiconductor Electronics Division, the Office of Microelectronics Programs, and the Office of Law Enforcement Standards are located in Gaithersburg, Maryland. The Electromagnetic Fields Division, the Electromagnetic Technology Division, and the Optoelectronics Division, which was formed in FY 1994, are located in Boulder, Colorado.

The **Electricity Division** maintains and improves the national standards of electrical measurement, and develops stable standards for the dissemination of the units of electrical measure. Another major responsibility of this Division is to realize the electrical units in terms of the International System (SI) and determine the fundamental constants related to electrical units.

The Division is responsible for providing calibration services, and developing and improving the measurement methods and services needed to support electrical materials, components, instruments, and systems used for the generation, transmission, and application of conducted electrical power. In addition, members of this division apply their expertise to selected scientific and technological problems in other areas of NIST research, including research on video technology and electronic product data exchange.

The **Semiconductor Electronics Division** develops and evaluates measurement methods, data, reference artifacts, models and theory, and associated technology to remove market barriers associated with the use of semiconductor materials and with the design, fabrication, characterization, and performance assurance of semiconductor devices and integrated circuits.

The Division conducts research in semiconductor materials and processes, devices, and integrated circuits to provide, through both experimental and theoretical work, the necessary basis for understanding measurement-related requirements for semiconductor technology. By widely disseminating the outcome of their research, especially in the areas of standardized test methods and standard reference materials, as well as by fostering their application, the Division enhances manufacturing productivity and the development, transfer, and exploitation of semiconductor technology for public benefit.

The **Electromagnetic Fields Division** develops and evaluates systems, devices, and methods for the measurement and analysis of radio-frequency electromagnetic fields, signals, noise, and interference. Other areas of investigation within the purview of this Division are the properties of materials for guided and freely propagated fields, including frequency and time-domain representation of electromagnetic fields and their interaction with materials and structures. The Division provides essential measurement and calibration services that enable industry and government to solve important national, commercial, industrial, and military problems, such as evaluating the performance of microwave and millimeter systems, components, and materials used in advanced radars, satellite and mobile communications, and automated test systems.

Assistance is also provided to other agencies to solve measurement-related issues, such as determining levels of nonionizing radiation and solving electromagnetic interference problems. The results of the Division's work are disseminated to industry, universities, and other government agencies to foster effective research, development, manufacturing, and marketplace equity. The Division's principal program areas include microwave and millimeter-wave metrology for continuous-wave transmission-line measurements, noise and dielectric measurements, antenna

EEEL: The Organization

metrology, and fields and interference metrology. These services and associated standards provide a consistent base of measurements to enable contractors in the defense, aerospace, and communications industries to both assemble complete systems and perform the stringent performance assessments which are required.

The **Electromagnetic Technology Division** develops and promotes advanced standards and measurement methods for the magnetics, cryogenic electronics, and superconductor industries and their scientific communities. The Division employs phenomena based on magnetics, superconductivity, and cryoelectronics to create new standards, apparatus, and measurement technology, advancing the state of the art by basic research and the development of requisite materials, fabrication techniques, and metrology.

For the magnetics industry, the Division provides new measurements, instrumentation, imaging, and characterization tools and standards. In addition, with support from theoretical studies and modeling, the Division develops measurement technology to determine basic properties of magnetic materials and structures. The Division collaborates with the magnetic recording industry in the development of metrology to support future recording heads and media with their ever-increasing data density.

For the superconductor industry, the Division uses the unique properties of superconductors to invent and improve measurement methods for electromagnetic signals ranging from static voltages and magnetic fields through audio, microwave, infrared, visible, and x-ray frequencies. This Division leads the international community in setting standards for the measurement of superconductor parameters, and provides the metrology infrastructure needed for the industrial development of both large- and small-scale superconductors.

The **Optoelectronics Division** is committed to providing the optoelectronics industry and its suppliers and customers with comprehensive and technically advanced measurement capabilities, standards, and traceability to those standards. The Division, newly formed in FY 1994, will achieve these objectives by developing and evaluating measurement techniques, and by developing and disseminating reference data, standard reference materials, and components. Providing measurement services and participating in industry-wide efforts toward measurement standardization are also part of this Division's strategy to support the characterization of materials, equipment, and processes as required for design and manufacturing.

In keeping with these activities, the Division conducts basic research, develops new theoretical concepts and models as well as new and advanced devices, components, and associated technology. These actions are designed to further the equitable exchange of products in the marketplace, and the efficient, reliable, and economical application of such products. The Division also provides technical support to other government, industry, and academic organizations.

The **Office of Microelectronics Programs (OMP)** provides integrated circuit manufacturers, materials suppliers, and makers of semiconductor manufacturing equipment with a clear window on the EEEL/NIST organization. OMP offers direct access to an enormously varied range of scientific and technical expertise. In addition, OMP manages NIST's strong working relationship with SEMATECH, the consortium of U.S. semiconductor manufacturers, and with many of its member firms. Research priorities are established on the basis of industry input and the Office's participation in U.S. and international conference and planning activities.

On March 2, 1994, the Secretary of Commerce, Ronald H. Brown, announced that NIST... "is entering into an historic partnership to support the U.S. semiconductor industry with the establishment of the National Semiconductor Metrology Program." The National Semiconductor Metrology Program was called for by the Semiconductor Industry Association to help achieve the goals of the National Semiconductor Technology Roadmap, which charts the industry's technical course through the year 2007 to maintain the U.S. semiconductor industry's global competitiveness. This Program, which will draw on the full range of NIST expertise in semiconductor electronics, manufacturing engineering, chemical and materials science engineering, and fundamental physical science, will be matrix-managed by EEEL's Office of Microelectronics Programs.

The **Office of Law Enforcement Standards (OLES)** supports law enforcement agencies through the development of measurement methods and techniques for testing devices used in such applications as tracking vehicles, speed monitoring, surveillance, and communications. The Office develops minimum performance standards for issuance by the National Institute of Justice (NIJ) as voluntary national standards. The areas of research investigated by this Office include protective clothing and equipment, communication systems, emergency equipment, investigative aids, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic science community.

Its mission is to assist federal, state, and local law enforcement agencies to apply new technology efficiently, effectively, and safely. OLES draws on the technical expertise and resources of all of NIST in its support missions for the National Institute of Justice, which is the research arm of the Department of Justice, and the National Highway Traffic Safety Administration, which is part of the Department of Transportation.

EEEL and Its Customers

EEEL welcomed 752 visitors in FY 1994. Other interactions with our customers included 467 visits to their facilities; many of these visits included technical presentations to the host organization and staff. EEEL staff participated in 176 collaborative projects with industry, including those covered by Cooperative Research and Development Agreements. The work done on many of these projects defines cutting edge technology. The benefits have immediate application for the companies involved, and, downstream, for the economy as a whole. In addition, EEEL is an active participant with industry partners in four consortia. Staff members hold some 260 professional memberships, in addition to 37 memberships held in major standards organizations. Over 60 scientists participated in standards organization activity in FY 1994, often in leadership roles. Seventy-nine guest researchers contributed their efforts to various projects within the Laboratory. Thirteen short courses were conducted by Laboratory personnel for diverse audiences. Staff conducted 26 technical meetings with an aggregate attendance of over 1300. EEEL made major contributions to 51 conferences during this period.

Taken together, such interactions upgrade the metrology infrastructure of the electronics industry at large. The dissemination of the Laboratory's results to U.S. companies, large and small, to universities, and to other laboratories across the nation effectively changes the way people do their work. Equipped with better measurement methods, easier ways to solve problems, more accurate measurement devices, faster, more comprehensive test methods, designers, manufacturers, and researchers move toward their goals with fewer setbacks. Efficient technology transfer enhances progress by sharing best practices and techniques as soon as they are viable.

EEEL staff benefits from such interactions as well. Technology transfer is not a one-way street; new applications spawn new challenges. In order to stay agile as well as robust, it is critical for staff to understand the challenges American companies confront across broad industry lines. The feedback EEEL scientists receive from industry provides the bases for the ongoing modification of the Laboratory's strategy. By staying in close contact with current and potential customers and staying abreast of developments worldwide, EEEL knows best where to focus its resources and efforts in a timely, effective manner.

Eleven patent disclosures were prepared in FY 1994, five patents were issued, and three patent applications were filed. Eighteen patent cases were active at the close of the fiscal year. EEEL staff hold 14 patents under the Technology Development Program.

Laboratory personnel performed over 4,540 calibrations, yielding fees of $2,137,422. Revenue from the sale of standard reference materials exceeded $100,000. EEEL-developed codes have been incorporated in two commercial software packages this year, and requests for software developed by EEEL staff and available to the industrial and scientific community at no cost exceeded 120. Industry's demand for these services illustrates their importance in terms of product development, quality control, and competitiveness.

Fiscal Year 1994 Activities

U.S.-Japan Optoelectronics Project

Thomas Russell, EEEL's Manager of Optical Computing Cooperative Programs, reported significant progress with respect to United States participation in the Real World Computing (RWC) Program of Japan's Ministry of International Trade and Industry (MITI) in FY 1994. Three major milestones have been achieved since the first U.S.-Japan Joint Management Committee (JMC) meeting to plan implementation of the U.S.-Japan Optoelectronics Project to begin in late 1994. The U.S. JMC members are Judson C. French (NIST, Chair), Sven Roosild (ARPA), David Nelson (DoE), Edward Malloy (DoS), and Joseph Bordogna (NSF). NIST is responsible for the day-to-day management of the Project in the United States.

The Implementation Plan, including Annex I on the protection of intellectual property rights, was agreed to by both the United States and Japan on April 25, 1994. At the second JMC meeting, which was held in Tsukuba Science City, Japan, the JMC confirmed agreement to the Implementation Plan and agreed to plans for signing a Consignment Agreement for transferring MITI funds through NIST to pay for the U.S. Broker. The Consignment Agreement was signed on June 30, 1994. On July 15, 1994, a notice was published in the *Commerce Business Daily* announcing the solicitation for a U.S. Broker for the Project. More than 50 requests were made for the solicitation. Proposals were received on September 15, 1994 and reviews began immediately. The role of the Broker is critical to the success of the Project as each will act as a bridge between the two countries. Users in either the United States or Japan will be able to obtain novel optoelectronic prototypes from suppliers in both countries through the Broker appointed for either country.

The spur for this Project is the understanding that an ability to prototype is essential for rapid advancement in any underlying technology, as experience in silicon-based microelectronics has proven. An early model for such capability is the broker/foundries model, exemplified by the Metal-Oxide Semiconductor Implementation Service (MOSIS), operated by the University of Southern California's Information Sciences Institute (USCISI), and its allied foundries. Parallel optoelectronics activity will be far more complex and challenging because of the variety of technologies involved.

The need for prototyping foundries is even greater in optoelectronics than in microelectronics, because the technology is less mature, and fabrication facilities are limited. Also, few standards have been developed. At present, a single design may depend upon several different materials and fabrication technologies for implementation, and a single fabrication facility typically has a narrowly focused capability in only one technology. Few research groups have the capability to make interconnected and packaged sub-assemblies (i.e. modules). Even the largest of the groups has a limited range of capability, so that a complete prototyping capability does not yet exist anywhere. To develop such a capability will require major advances on several fronts: device, interconnect, packaging, design, and software.

Accelerating the availability of novel prototype optoelectronic devices, circuits, and modules will give users access to leading-edge optoelectronic-fabrication facilities and stimulate R&D activity in optoelectronics for computing in both the United States and Japan; thus, encouraging effective commercialization of optoelectronic devices. Innovative ideas must be testable for them to become practical. In an emerging field such as optoelectronics for computing and processing, only a few innovations will prove to be practical, and tests in actual prototypes are necessary to identify these important developments.

The project will operate through a User-Broker-Supplier model, in which Users submit their designs to either the Broker for the United States or the Broker for Japan. The Broker selected will find appropriate Suppliers. This mechanism will help protect intellectual property rights and aid the development of the field through standard setting and device testing procedures. The U.S. JMC will select the U.S. Broker and determine funding mechanisms for the U.S. users of the project.

The effort to build bridges to the private sector to ensure awareness and understanding of the Project continues. To date, presentations have been made to the Steering Committee of the Optoelectronic Industry Development Association and ARPA contractors, which include industry, universities, federally funded research and development centers, and government laboratories. Meetings have also been held with interested groups, such as the Telecommunications Industry Association, Fiber Optics Division, Board of Directors and the IEEE Lasers and Electro-Optics Society (LEOS). The Project will run for an initial trial period of two years.

Electronics Subcommittee and Materials Working Group

In response to the international challenge to U.S. leadership in the global electronics industry, the Clinton Administration established the Electronics Subcommittee (ESC) under the Civilian Industrial Technology Committee (CIT) of the National Science and Technology Council (NSTC). The ESC has representatives from the Department of Commerce's Technology Administration and from NIST, the Department of Defense (ARPA), the Department of Energy, the Department of State, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, and the White House Office of Science and Technology Policy.

In FY 1994, the ESC has worked with the private sector to create the National Electronics Manufacturing Initiative (NEMI). NEMI is a comprehensive industry-government partnership to improve the manufacturing of electronics in the United States. NEMI's goal is to expand electronics manufacturing in this country by helping industry to meet its goal of manufacturing globally competitive products profitably. The partnership is based on the mutual benefits to be gained by both. Many of our Government's goals will be strongly aided by the electronic industry's success: high-quality jobs will be created in the United States, the U.S. trade position will be improved, electronic systems and components required for the national defense will be ensured, and U.S. citizens will be further empowered in the areas of business, education, and health care.

Judson C. French, the ESC member representing NIST, has devoted significant attention to the realization of NEMI's objectives in FY 1994. French played a leading role in NEMI's effort to identify options for Government action and spur the development of technology roadmaps for U.S. electronics manufacturing. He also participated in the NEMI Workshop on U.S. Electronics Manufacturing, which drew more than 250 attendees from industry, academe, industrial trade associations, and government. Other work with the ESC included assistance in the development of NEMI's taxonomy for Electronics, which was used for the President's National Science and Technology Council's Federal budget crosscut.

EEEL's Thomas Russell was also actively involved in supporting the work of the ESC through the efforts of its Materials Technology Subcommittee (MTSC). The Electronic Materials Working Group (EMWG) on which Russell served was established to support the MTSC in Spring, 1994. Its objectives are to work with industry to identify electronic, photonic, material process, and product technologies that must be addressed to manufacture the next generation of electronic products, and to develop and implement a coordinated national science and technology strategy for investment in these technologies. The Working Group is also expected to provide recommendations for coordinating the efforts of all Federal agencies in electronics, photonics, material processing and manufacturing technologies.

Optoelectronics Industry Development Association (OIDA)

Many believe that optoelectronics is the most significant set of new technologies on the horizon — equivalent to the appearance of semiconductors in the first half of this century. Hailed as the new frontier of the information age, optoelectronics has been identified as an enabling technology that will create markets worth hundreds of billions of dollars and employ more than a million people by the end of the next decade. However, the U.S. domestic industry is not highly competitive across all market sectors. In the early 1990s, it became apparent that strong measures were needed to prevent further erosion of North American industry's share of the market in key segments, including flat panel displays, optical storage equipment, and consumer optoelectronics.

Gordon Day, Chief of EEEL's Optoelectronics Division, has dedicated much time and attention to the Optoelectronics Industry Development Association's effort to develop their Optoelectronic Technology Roadmap, which was realized in FY 1994. As a Roadmap Program Participant, Day was a member of all three OIDA Working Groups, which targeted the communications market, the industrial market, and the military and civil aerospace market. The Groups' objectives were to determine where the greatest market opportunities lay and to identify the key technical barriers associated with them. This information would enable the industry to establish priorities for improving its competitiveness.

Achieving industry consensus for the first time was a key aspect of this work. Without agreement as well as commitment from the industry's manufacturers and users, developing a roadmap and setting strategies to key private and government investment to the areas of greatest opportunity would be meaningless. Over the past two years, the Association has conducted eleven workshops and two national forums to gather the information necessary to develop a strategic vision for the industry for the next two decades (1993-2013).

The Roadmap focuses on improving the competitiveness of the North American industry in displays, optical communications, optical storage, and hardcopy technologies. OIDA believes that most of the recommendations can be funded through refocusing existing optoelectronics programs or through existing industry-driven technology programs.

With respect to flat panel displays, the U.S. has significant technical strengths but Japan controls 95% of the world market. Today, the market is approximately \$5B but it is expected to reach \$20B by the year 2000; as displays are enablers for products with larger markets, the dollar volume of sales for these products is predicted to reach about $260B in 2014.

The market for optoelectronic communications equipment may reach $30B by the next decade but the market enabled by optical communications is even larger. Estimates of $190 to $300B were given in the Administration's Information Infrastructure Task Force report according to OIDA. NIST's core-programs in optoelectronics-related metrology were among those recommended for continued support in the Roadmap..."steps should be taken to strengthen metrology and standards-related work at NIST..." Emphasis was also placed on the continuation of close interactions between program researchers and potential industrial users.

The optical storage equipment industry is dominated by the Japanese in both consumer- and computer-related applications. Although the North American industry is competitive in media (optical disks and tapes), OIDA acknowledges that it is struggling in the face of strong Japanese competition. Roadmap recommendations include industry-government cooperative programs which focus on green, blue, and shorter wavelength lasers; and low-cost manufacturable substrate and media technologies as well as complete optical recording systems that exploit both the lasers and the media. Explicit mention was made of the need to address measurement, testing, and standards issues in this area. The optical storage market is expected to reach $30B by 2013.

Laser printers, imagers, copiers, and scanners make optoelectronics an enabling technology for hardcopy. The Roadmap describes the synergistic relationship between hardcopy and optical communications with an emphasis on high bandwidth communications — improvements in one enable the other. The desire to move images with higher resolution is driving the need for higher-bandwidth communications. Optoelectronics-enabled printers are expected to develop into a $14B market by 2013. With respect to NIST's role in this technology, "OIDA supports NIST initiation of a program to bring together the diverse elements of the industry and appropriate standards organizations to develop agreed-upon and broadly applicable color standards. OIDA also supports research by NIST into related metrology issues and algorithms for incorporation into software for color imaging."

National Technology Roadmap for Semiconductors

The Semiconductor Industry Association (SIA) has announced a new National Technology Roadmap for Semiconductors developed with the cooperation and participation of all aspects of the industry. Included in addition to chip manufacturers were representatives from the semiconductor materials, manufacturing equipment, and device fields, from industry and from government laboratories.

NIST staff were invited to participate in five of the eight Technical Working Groups (TWGs) in the revalidation and updating of the document. The eight TWGs are successors to the original 12 Working Groups (NIST staff participated in these, also) whose workshops and deliberations resulted in the first edition of the Roadmap, widely recognized as authoritatively identifying the steps that industry must take to achieve its objectives 15 years into the future at the year 2007. Semiconductor Electronics Division members Harry A. Schafft, David G. Seiler, George G. Harman, and Loren W. Linholm are participating in the work of the TWGs on Interconnects, Bulk Processes and Materials, Packaging, and Lithography (also known as the National Lithography Committee), respectively. James R. Whetstone, of the Chemical Science and Technology Laboratory's Process Measurements Division, served on the Factory Integration TWG. In addition, EEEL Director Judson C. French worked as a member of the Roadmap Coordinating Group, charged with making sure that the work of each of the TWGs was planned to mesh effectively so as to contribute to the final document.

The SIA has indicated the importance of this activity to the electronics sector in a statement by Craig R. Barrett, Intel chief operating officer and chair of the SIA Technology Strategy Committee: "The industry and government are spending more than $5 billion annually in microelectronics research and development. The roadmap provides us with the necessary blueprint, ensuring that these resources are spent wisely and effectively... The challenge that we have before us is to implement a comprehensive strategy that covers all the critical needs identified by the Technology Working Groups. Since no one entity can shoulder these costs alone, we must work together to ensure that we remain in the forefront of technological innovation."

National Semiconductor Metrology Program Established

The semiconductor industry had strongly urged the Administration and Congress to establish a major metrology program at NIST, and in March the resulting National Semiconductor Metrology Program was announced. Program funding is planned to ramp up over several years to a final level of $25M per year. Industry's backing resulted from the record of useful solutions from NIST coupled with an increasing appreciation on the part of industry leaders of the key role of metrology in advanced competitive products. This program reinforces NIST's role as the nation's lead laboratory for metrology and exemplifies NIST's charter to serve industry

Metrology is one of the pervasive technologies identified in the SIA Workshop Working Group Reports. Measurements are mentioned throughout the workshop publications, frequently as show-stoppers or barriers to progress. The lack of many other measurement capabilities, although not categorized as show-stoppers, pose serious problems as well.

The National Semiconductor Metrology Program, which is matrix-managed by EEEL's Office of Microelectronics Programs (OMP), conducts metrological research and development at NIST; coordinates metrological work among the cooperating Government laboratories; facilitates collaborations, Cooperative Research and Development Agreements (CRADAs), and technology transfer with industry; and acts as the industry's focal point for metrology within government. The newly created Program will also represent NIST in Roadmap management and maintenance, provide technical experts for Technical Advisory Boards (TABs), sponsor workshops to define industry needs and priorities, and work with SEMATECH, SRC, and others to provide continuous improvement in the delivery of needed measurement tools and results.

Critical measurements and measurement techniques are needed for basic understanding, laboratory measurements, and production control. A variety of measurements is needed, including the detection of impurities, fine dimensional accuracy, and materials properties. The Program delivers its products to the industry through direct consultations and cooperative work, publications, lectures, calibration services, special tests on customer artifacts, standard reference materials, and membership on industry standards committees.

Technology Reinvestment Program

The Technology Reinvestment Program (TRP), established by President Clinton in 1993, is designed to stimulate a growing, integrated, national industrial capability that offers the most advanced, affordable military systems as well as the most competitive commercial products. TRP programs are structured to expand high-quality employment opportunities by applying defense and commercial resources to develop dual-use technologies. TRP also provides manufacturing and technology assistance to small firms, and education and training programs that enhance U.S. manufacturing skills and target displaced defense-industry workers.

The Administration's TRP initiative to integrate the commercial and defense sectors in a single, leading-edge technology base is unique in that it is jointly implemented through the collaboration of six Federal agencies: the Departments of Commerce (NIST), Defense (ARPA), Energy, and Transportation, the National Aeronautics and Space Administration, and the National Science Foundation. James Comas, EEEL's TRP liaison, reports that on October 25, 1994, Paul Kaminski, Undersecretary of Defense for Acquisition and Technology, announced the 39 proposals selected for negotiation under the FY 1994 TRP focused competition. More than 230 proposals were submitted for this competition. The authorization for TRP funding requires that all proposals are selected on a competitive basis, and the evaluation process depends on the technical expertise within government agencies, such as NIST. The selection of NIST staff to undertake the review process is based on the areas of expertise required. EEEL staff have been major contributors to the proposal and evaluation process in FY 1993 and 1994.

The 39 proposals selected under the FY 1994 competition include 224 companies, universities, and state and local government organizations, who will receive over \$202M in government funding. Of the 39 selections, 30 are for technology development and 9 are for Manufacturing Extension Centers. All government funding is matched by the participants. Cost sharing of at least 50 percent is a specific TRP requirement in the Technology Development and Manufacturing Extension Center competition, and is a key element in industry and government's commitment to this program. The TRP published an announcement in the Commerce Business Daily on October 21, 1994 detailing plans for the third TRP competition, FY 1995 General Competition. \$250M will be available for projects in the 13 technology development focus areas.

Workshops

Digital video in the national information infrastructure

The core technologies essential to the convergence of the information highway championed by Vice President Gore have only come into being within the past decade. Much must still be done before it will be possible for ordinary citizens to use digital services to access information in their homes from university libraries or museums or medical centers. But, it becomes more possible each day with advances in the fields of electronics, fiber optics, lasers, and digital communications. Work is underway on several fronts to make the vision a reality.

Fiscal Year 1994 Activities

In order to highlight technical issues for industry and government decision makers with respect to Advanced Digital Video in the National Information Infrastructure (NII), a workshop was held May 10-11, 1994, in Washington DC. The purpose of the workshop, which was attended by approximately 190 people from industry, government, and academia, was to define a vision of the role of digital video within the NII, identify the architectural, scaling, and performance issues in realizing this vision, and identify research, experiments, and steps to be taken to resolve these issues.

In collaboration with other industry and government leaders, staff of EEEL's Electricity Division, acknowledged for their contributions to the field of video technology, were able to develop viable definitions of the technical requirements for transmission of digital video information over the National Information Infrastructure and to identify the necessary role the U.S. government must play to facilitate such information transfer.

Third workshop on testing strategies

One of the major costs of bringing highly competitive electronic products to the marketplace is the cost of testing. EEEL staff have successfully developed methods to reduce such costs in the recent past. An efficient and popular means of disseminating the results of the Laboratory's efforts in this area is through workshops.

EEEL staff conducted the third workshop at NIST on Testing Strategies for Analog and Mixed-Signal Products on June 7-9, 1994. Eleven participants from eight different companies and one government laboratory attended the workshop. The application interests of the participants were diverse, ranging from down-hole instrumentation (such as used in oil exploration), to the testing of pacemakers using automatic equipment, to the testing of two-dimensional, charge-coupled arrays. A coincidental follow-up visit to one of the participating companies by the NIST Director attested to the value that industry representatives place on the information gained from such workshops.

The workshop provided the participants with the analytical tools and a comprehensive framework for developing and implementing efficient tests for analog and mixed-signal devices and instruments. The agenda consisted of tutorial material on matrix algebra, lectures on the theory of QR factorization and test-point selection, and the development of accurate device error models using physical, a priori, and empirical approaches, as well as hands-on training in the use of MATLAB™, a commercial software product, to implement the matrix operations needed to develop a given testing strategy.

Benchmarking U.S. Competitiveness to Aid Planning

EEEL has completed an evaluation of methods for computing a balance of trade useful for benchmarking U.S. competitiveness. Presently, different methods are employed within Government and industry. EEEL observes that these methods can lead to very different values for the balance of trade for some merchandise groups. Those differences can even affect whether the balance of trade is positive or negative. EEEL's principal finding is that one method appears to be better than the others for benchmarking U.S. competitiveness, and thus could serve as a standard method.

The purpose of EEEL's study is to provide the methodological basis for using U.S. merchandise trade data as an additional tool for identifying areas of need for NIST services in support of U.S. industry. The trade data can flag and measure decreasing U.S. competitiveness for specific product areas. Such areas may merit closer examination by NIST to determine if they are being adversely affected by the lack of adequate measurement capability or other services that NIST could provide. NIST can then act in response to the discovered needs. These needs may arise in any phase of industry's efforts to realize competitiveness in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support of products.

Trade data are valuable for planning because of their remarkable level of detail and their timeliness. U.S. trade data are reported in more than 15,000 product categories, by U.S. region, by country and of origin or destination, and with only a few months delay. Such timeliness in a data resource of this scope is rare. About 700 of the recorded product categories are devoted to the electronics industry, the focus of EEEL's concern.

EEEL will next employ the best of the methods studied to generate data on the competitiveness of the sectors of the U.S. electronics industry. This effort is part of a broader one in EEEL, focused on integrating economic factors more thoroughly into the planning process.

Implementing Total Quality Management at EEEL

Within the last five years, Research and Development (R&D) organizations have begun to apply the principles of "Total Quality Management" (TQM), known also by a variety of other names, including "Total Quality" and "Continuous Improvement" to their operations. Already an important part of improving the competitiveness of U.S. industry in manufacturing and service industries where processes can be readily analyzed and where measures of improvement are usually fairly straightforward, TQM is now being adapted to the innovative processes that are the hallmark of R&D.

Because EEEL is dedicated to the delivery of quality products and services to our customers, the Electricity Division decided to form a study team to examine what would be required to begin TQM in their laboratories and to devise the best approach to its implementation at all levels of technical, managerial, and administrative responsibility. The finding from the study team was that there are major potential benefits to be derived from a TQM system that is integral with the present leadership structure.

In FY 1994, it was decided that Division projects should be carried out by Quality Improvement Project (QIP) Teams. Training developed specifically for the Division's TQM system will be provided for the various QIP teams on a just-in-time basis. The facilitators for this training will be the study-team members. The team's research on the principles of TQM, and their study of its applications in industry by customers of the Division as well as in research and development firms in the private sector qualifies them for this key responsibility.

The implementation of TQM changes the culture of any organization. NIST is unique in that it has basic research programs as well as national calibration services, and interactions with and transfers of technology to industry. Division management is prepared to accommodate those changes in culture necessary to fully empower staff for problem solving and process improvements.

It is understood that this will enable the Division to take full advantage of the staff's talent and provide staff with an even greater stake in the Division's activities than they may currently have. Staff are also prepared to receive and accept this empowerment, learning to tackle administrative and organizational problems in the ways that R&D problems are traditionally tackled. Given this commitment and the calibre of the Electricity Division staff, the outcome of this pilot study is expected to effect acceptance and the widespread use of TQM throughout EEEL.

New Calibration Services

Support for 2.4 mm coaxial connector devices

The trend in microwave devices in recent years has been toward higher frequencies and smaller sizes. Operating at higher frequencies requires the development of smaller coaxial transmission lines. Today, coaxial transmission lines and devices are available that operate at frequencies up to 50 GHz with 2.4 mm connectors. In order to provide the traceability and calibration support that industry needs in this area, a new calibration service was established for devices with 2.4 mm coaxial connectors. The frequency range for this service is 200 MHz to 50 GHz. Calibration services are provided for S-parameters of 1-port and 2-port devices.

Special tests for high frequency phasemeters

In response to requests from clients for calibrations with increased frequency range and lower uncertainties, new capabilities for testing high-frequency phasemeters and related instruments up to 20 MHz at any desired phase angle have been developed. The improved capability at 5 to 20 MHz has helped to improve the state of the art in making precision length measurements using optical interferometry.

The service makes use of a precision phase meter that uses a dual-channel, 16-bit, 1 million samples per second sampling system, which digitizes both sinusoidal input waveforms over a large number of periods; signal processing is performed in software (with a three-parameter sine-fit algorithm) that provides good estimates of the amplitude, phase, and dc offset to determine phase linearity up to 100 kHz at any phase angle to a basic uncertainty of ±0.003°. For calibrating phasemeters and phase generators up to 20 MHz, a pair of synchronized function generators is used, together with a time-interval analyzer, to determine phase angle linearity between 50 kHz and 20 MHz, maintaining uncertainties from ±0.05° to ±0.25°.

Capacitance measurement assurance program

Following a ten-year lapse, NIST re-established and improved a service in answer to clients' newly emerging needs for support of capacitance measurements at or near state-of-the-art uncertainties. These uncertainties include components caused by transportation and the client laboratory's measurement process which cannot be included in routine NIST calibrations.

The new service, which uses a commercial digital capacitance meter as the transport standard, provides calibration for capacitance standards at both the 100 pF and 1000 pF levels at 1 kHz. In contrast to a normal MAP, where the transport standards are measured by the client laboratory, this capacitance MAP involves measurements performed on "dummy" standards and the client's reference standards by both the meter (transport stan-

Fiscal Year 1994 Activities

dard) and the client laboratory capacitance measurement system. A Technical Note documenting the NIST capacitance Measurement Assurance Program (MAP) service has been prepared.

User/Working Groups

New testing working group created

Currently, there are several existing product data exchange standards for transferring data among automated tools for the design and manufacture of electronic products, and more standards under development. However, there is widespread concern among the industry that these standards are not capable of expressing designs unambiguously, and that harmonization is needed. With the intention of addressing this issue, NIST sent a U.S. delegate to the IEC TC93 held in London, England. At the "Design Automation" meeting, a New Work Item Proposal (NWIP) was submitted to initiate a Working Group on testing for the TC93 suite of standards. The Group's purpose was to develop a strategy for developing test, validation, conformance, and qualification support of IEC TC93 standards. The NWIP was subsequently approved unanimously and the NIST delegate was named its Chair.

Model validation working group

As new semiconductor device types are introduced, new circuit simulator models must also be developed to aid in the design of the electronic systems that use the new device types. The question then arises as to the adequacy of the models. In FY 1994, NIST formed the Working Group on Model Validation. The Group's objective is to establish well-defined procedures for the comprehensive evaluation of circuit simulator models. Such models would provide circuit designers with adequate confidence to use them in the development of new electronic systems and, thus, enable the new devices to be incorporated into products more rapidly.

The group consists of about 120 representatives of the electronics industry having expertise in electronic component design and manufacturing, model development, software development, component characterization, and circuit and system design. Several meetings of the Working Group have been held, and the group has gained the enthusiastic support of its members.

Ion implant users group serves vital part of semiconductor community

Ion implantation is the principal doping technique used in the fabrication of semiconductor device structures. Precise control over the doping species, beam energy, and dose make it indispensable in the manufacture of a wide variety of devices including computer CPUs and DRAMs. It also provides the key for the next generation of very shallow junction structures. The Ion Implant Users Group provides a forum and a network for the implant community. NIST provides the critically needed leadership and organization to ensure its continued growth.

The Group's diverse makeup strengthens the exchange of information and ideas. Its 226 members represent over 100 organizations in 26 states, Canada, and Great Britain. The Group meets on a quarterly basis and recently held its 15th meeting. Topics for the year included Ion Optics, Boron Implantation, Implantation in GaAs and III-Vs, Large Area Implantation and Flat Panel Displays, Argon Aerosol Wafer Cleaning, and Retrofits and Upgrades. A tour of local ion implant factories is often part of scheduled meeting activities.

Selected Examples of Technology Transfer

SRC mentor and video course

The Semiconductor Industry Association Roadmap identifies device and package models including thermal effects as important technical areas in need of development and support to achieve the 15-year goals of the Roadmap. The Semiconductor Research Corporation (SRC) sponsors a research program at the University of Florida with which NIST cooperates to address these needs.

NIST staff assisted faculty at the University of Florida, Department of Electrical Engineering, in teaching an SRC/NTU Satellite video course titled "Physical Circuit Models for Power ASIC Design." Among the topics described in the course were the SPICE implementation of the insulated-gate bipolar transistor (IGBT) model developed at NIST and the electro-thermal models developed at the University of Florida using the methodology first introduced by NIST; both are subjects of the University of Florida Semiconductor Research Corporation contract and have received NIST technical guidance.

The satellite video course was attended by full classrooms at several Semiconductor Research Corporation member company remote sites across the nation. As a result of the interaction between NIST and the Semiconductor Research Corporation program at the University of Florida, the well-known NIST IGBT model has been made available in the widely used SPICE source code and is being evaluated by several software vendors for inclusion in SPICE-based commercial products.

Technology transfer for antenna measurements

NIST continues to be a national resource for industry in the areas of near-field theory and measurements, error analyses, antenna diagnostics, range certification, millimeter-wave measurements and position error correction. Twenty-one registered participants attended the NIST Near-field Short Course which was held in Boulder, Colorado. NIST also presented a course on near-field measurements to McClellan AFB personnel. Lectures were presented at two courses sponsored by California State, Northridge, and Georgia Tech. In addition, NIST hosted the 57th Inter-Service Antenna Group (IGAG), which was attended by thirteen government agencies. By direction of the Secretary of Defense, ISAG is attended by government personnel only and provides a means for discussion of current research, project updates and discussion of technical issues. NIST participation included talks on microwave metrology and providing expertise on current measurement problems. Within the past year, NIST also responded to 46 inquiries about the Planar Near Field Codes for near-field probe position error correction.

International Standards and Intercomparisons

NIST participation in international standards activities helps to protect the interests of U.S. industry so that its products are not excluded from international markets through the adoption of discriminatory standards. International standards may arise as the result of another form of international measurements activity, international intercomparisons. NIST participation in international intercomparisons with counterpart laboratories in other nations validates together NIST's and other laboratories' uncertainty assessments. Collectively, this process provides confidence in the reported results of NIST peer laboratories. In FY 1994, EEEL was involved in several of these international activities.

Comparison in power—WR-22

NIST undertook an intercomparison of power standards with the National Physical Laboratory (NPL) in the United Kingdom in the 33 to 50 GHz band (WR-22). Agreement between NIST and NPL was good: the effective efficiency (η_E) measurements agreed within 0.2% to 0.4% for three mounts at three frequencies and 0.6% to 1.3% at one other frequency. The expanded uncertainty for η_E is 1.6% for NIST and 1.2% for NPL. Reflection coefficient magnitude agreement was typically better than 0.005 with expanded uncertainty of 0.008 for NIST and 0.010 for NPL. The reflection coefficient phase was also well within both uncertainties.

Comparison results on standard-gain antennas

As the pilot laboratory for an international intercomparison on standard-gain antennas, NIST continues to be recognized as the world leader in accurate antenna standards and calibrations. In FY 1994, NIST summarized the results on the gain and polarization measurements of the standard-gain horns used for the international gain comparisons. These antennas were calibrated by national laboratories in Germany, Denmark, France, Australia, England, and NIST at 8-, 10- and 12 GHz. The results of this work were presented at the American Physical Society/International Union of Radio Science (APS/URSI) conference. There is now world-wide interest in a standard-gain antenna intercomparison at 60 GHz.

Round robin on gray-scale method for optical fibers

The gray-scale method is the technique for measuring cladding diameter, core-cladding decentering, and other parameters important to connectorizing fibers. NIST has now completed the international round robin to evaluate the gray-scale method for determining optical fiber geometrical parameters. The results have been documented for a report to be given to the Telecommunications Industry Association (TIA) and the International Telecommunications Union (ITU) (formerly the International Telegraph and Telephone Consultative Committee).

Critical Currents in Superconductors

In FY 1994, NIST constructed two critical-current simulators for Japan's National Research Institute for Metals (NRIM) to be used in an upcoming VAMAS intercomparison, and submitted the latest draft of the Nb-Ti critical-current standard for IEC final voting. NIST also completed plans for the U.S. interlaboratory comparison of critical-current measurements of high-temperature superconductors. Comparisons are now underway among U.S. participants with 60 specimens each of Ag-sheathed Bi-2223 samples from two U.S. wire manufacturers. Similar coordinated interlaboratory comparisons are planned in Europe and Japan.

Selected FY 1994

PARAMETRIC TEST SYSTEM TO CHARACTERIZE THE WAFER MANUFACTURING PROCESS

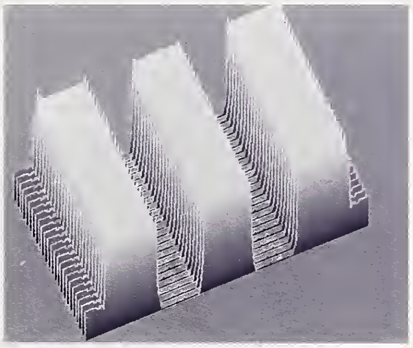
Technical Accomplishments

"These tools are helping to bring power electronics technologies to larger U.S. markets and are putting the United States in a better competitive position....We intend to establish a strong capability in power semiconductors in the United States."

— Director of Operations
for Power Transistors
Power Products Division
Motorola

PARAMETER EXTRACTION FOR THE VALIDATION OF POWER DEVICE MODELS

1 SEMICONDUCTORS



SEM MODELING
The backscattering coefficient as a function of position across three 250-nm wide parallel gold lines on a silicon substrate for a beam energy of 1 KeV.

1.1 Computer modeling of SEM signals

One of the high-priority needs identified by the semiconductor industry through the SIA Roadmap is the ability to achieve accurate measurements of feature sizes down to 0.1 µm. Such measurements require 10-nm resolution. The instrument commonly used for fine-scale measurements is the scanning electron microscope (SEM). However, it is impossible to achieve such quantitative resolution with an SEM without appropriate modeling of the interaction of the electron beam with the specimens being measured.

SEM suppliers provide instruments equipped with a nominal length scale for users to deduce the dimensions of the specimens being studied. The actual SEM image from which the measured dimensions are obtained is a strong function of the measurement conditions and the type of specimen. Thus, any accurate measurement involves simulating the interaction of the electron beam with the specimen for given instrument conditions.

The SIA has identified Monte Carlo modeling as a milestone in achieving improved critical-dimension (CD) metrology. Collaborating with the Manufacturing Engineering Laboratory in response to the SIA, NIST scientist Jeremiah Lowney is developing a series of codes that model SEM signals for various specimen materials and geometries under various measurement conditions. Lowney wrote the Monte Carlo code, MONSEL-I, to model the transmitted and backscattered signals from a line on a multilayer substrate in an SEM to provide the user with the information needed to obtain accurate dimensions.

MONSEL-I has been used to provide a quantitative description of the signals from a gold line on a silicon substrate

On simulation software tools for designers of electronic circuitry:

"I want to let you know how valuable Analogy and its customers have found the IGBT work you have performed over the past several years....I recently conducted a meeting with a major U.S. automotive manufacturer and a major U.S. semiconductor manufacturer who have been using the existing IGBT model in SABER and wish to include buffer layer and dynamic thermal effects in their upcoming simulations."

— Manager
Modeling Research and Development
Analogy, Incorporated

used in CD metrology. An analysis of the computed prediction of the model and the measured data yields the 10-nm resolution needed for advanced integrated-circuit (IC) lithography. A second code, MONSEL-II, has recently been completed, which extends the capability by including simulation of three parallel lines and secondary emission.

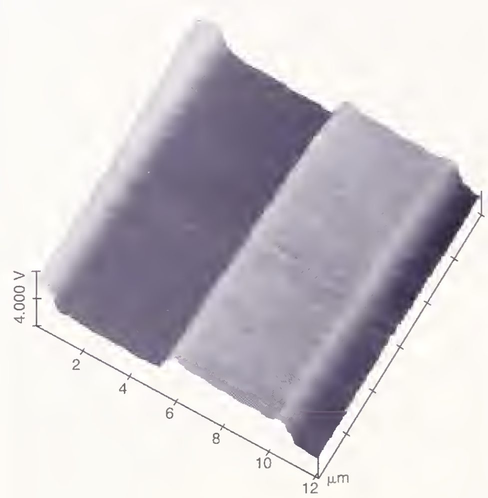
The Monte Carlo codes are being made available to industrial researchers and manufacturers who need to use SEMs for quantitative measurements. The codes are also used at NIST to aid in the production of critical-dimension standard reference materials (SRMs) that can be transferred to industry. Other applications for which the codes are useful include the interpretation of signals from transmission electron microscopy and in the use of electron-beam lithography.

To expedite the transfer of this critical technology, specific interactions are occurring with IBM, Essex Junction, Vermont; AT&T, Murray Hill, New Jersey; Digital Equipment Corporation, Hudson, Massachusetts; Metrologix, Santa Clara, California; Sandia National Laboratories, Albuquerque, New Mexico; and SEMATECH to disseminate results from the code as well as the code itself. NIST is cosponsoring this work with SEMATECH to achieve needed improvements in the accuracy of CD metrology for semiconductor devices.

1.2 Scanning-capacitance microscopy for dopant profiling

The SIA Roadmap has identified NIST contributions as key for advancing the technology needed to profile the dopant distribution across a wafer with a spatial resolution of as little as 10 nm. The measurement methods required must be reliable, nondestructive, and accurate enough to support feature sizes that are shrinking toward 0.1 µm. The scanning-capacitance microscope (SCM) is a promising tool for obtaining dopant profiles in at least two and possibly three dimensions (i.e., depth as well) with the resolution required by industry. Full realization of SCM capabilities requires the instrument to be isolated from electrical noise and from sources of vibration, and requires the development of models of the probe-specimen interaction for a wide range of doping profiles.

NIST scientists Joseph Kopanski, Jay Marchiando, and Jeremiah Lowney have implemented an SCM with improved measurement reproducibility and signal-to-noise ratio. The team has used the instrument to make measurements of the capacitance of pn- and homo-junctions as a function of position and bias which demonstrated excellent resolution and low noise. A computer program has been completed to solve Poisson's equation in three dimensions, so that the capacitance measurements can be related to dopant distribution. SCM measurements and corresponding theoretical calculations must be carried out for a variety of samples to provide the database and experience necessary to calibrate the technique so that quantitative dopant profiles can be obtained. Their



SCM IMAGE
Differential-capacitance image (measured in volts) of lateral p- and n-type regions in silicon. The capacitance sensor clearly delineates the pn junctions.

work constitutes the leading effort to extract quantitative dopant profiles because precision SCM measurements are being interpreted with a comprehensive physical model for the first time.

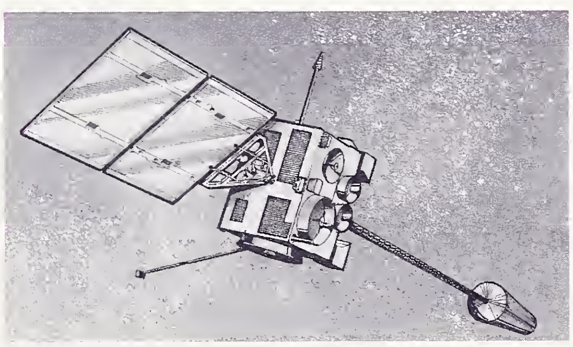
ADJUSTING SENSITIVITY FOR SCM FOR 2-D DOPANT PROFILING

The team has developed a range of working collaborations with industry and SEMATECH to determine the agenda necessary to speed the development of SCM as a practical dopant profiling technique. A CRADA with Digital Instruments Inc., an atomic-force microscope instrument house, to develop commercial applications of SCM is in its second year. The NIST techniques to convert an atomic-force microscope to an SCM have been the basis for similar instruments constructed at Intel, Santa Clara, California, and Digital Instruments, Santa Barbara, California. Site visits have been exchanged between NIST, Intel, and Digital Instruments to make SCM measurements on NIST-produced samples that will help to establish the interlab consistency of SCM. With authors from SEMATECH, Austin, Texas, Kopanski and David Seiler recently published a review of the status of various scanning-probe dopant-profiling techniques. Most recently, a collaboration to model the SCM measurement has begun with Los Alamos National Laboratories.

1.3 Electrical characterization of "GOES" detectors

Three years ago, NOAA asked NIST to undertake a study of the existence and possible causes of the degradation of the performance of mercury-cadmium-telluride infrared detectors being tested for use in its geostationary operational environmental satellites (GOES). These satellites provide a vital link in weather forecasting. NIST's prompt and comprehensive response is credited with a key recommendation not to launch a highly publicized satellite that almost certainly had defective sensors and consequently great potential for causing embarrassment to U.S. technology.

A team of NIST scientists, including David Seiler, Jeremiah Lowney, W. Robert Thurber, Joseph Kopanski, and George Harman, successfully addressed the issues of sensor reliability, fabrication, and testing. Through a series of talks and distributed reports, they furnished the detector suppliers with the improved characterization and testing procedures for their devices that enabled the suppliers to solve the problems within critical deadlines.



GOES SATELLITE

In FY 1994, the team completed their report detailing the improved characterization methods to improve yield for mer-

"I want to thank you for the work Mr. David Berning has done in evaluating the safe operating area of high voltage row drivers we use in our TFEL flat panel displays. David's results confirmed a design issue in one of the drivers that we use in high volumes. His results were shared with the vendor, and as a result we believe the probable root cause has been determined with corrective action taken."

— Principal Engineer
Advanced Technology Group
Planar Systems, Incorporated

"Gallium arsenide...is now being employed for many high volume commercial applications such as lasers in compact disk players, receivers for satellite television reception, and hand held cellular phones....We feel that NIST is in an excellent position to continue to assist the III-V manufacturing community (QED included). A cooperative effort to further develop non-destructive characterization tools would allow the more cost sensitive applications to be successfully addressed....Work has already been done at NIST to address some of these issues....QED would look forward to working collaboratively with you to further address these issues."

— President
Quantum Epitaxial Designs, Inc.

cury-cadmium-telluride photoconductive infrared detectors used in GOES satellites. The areas emphasized were: 1) improved bonding and packaging procedures, 2) magnetotransport methods to monitor the electron density in the surface accumulation layers, and 3) test structures for monitoring critical device parameters after each processing step.

An important aspect of this project is that the results of the work can be applied to the design and manufacture of most types of photoconductive detectors. The team's initial findings were so significant as to warrant expanding the focus to include a study of the mercury-cadmium-telluride detector fabrication process. The measurement tools developed by NIST allowed manufacturers to improve both yield and reliability of these important devices used in many satellite systems.

The experimental and theoretical work performed for this project has also led to improved models and methods for semiconductor characterization in general. For example, the team developed a magnetoresistance-based method to measure the carrier density and mobility of a semiconductor layer that required only two contacts to the device. Previous methods required the complication of four contacts to determine carrier concentration and mobility.

1.4 MBE growth of the InAs system

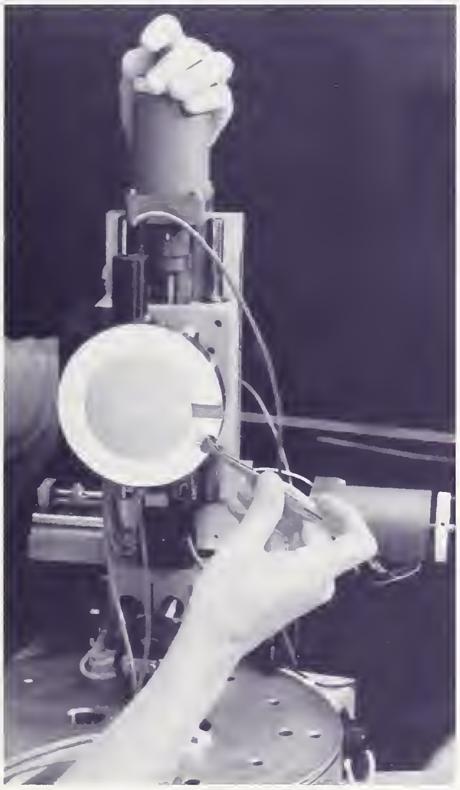
Today, InGaAs is the material of choice for the channel portion of pseudomorphic high-electron-mobility transistors (PHEMTs). These devices are used in both low-noise and high-power microwave devices. The rapidly increasing interest in direct broadcast and cellular phone technologies are such that the compound semiconductor industry has identified the InGaAs PHEMT system as a critically enabling technology.

In a NIST interlaboratory collaboration, researchers Joseph Pellegrino of EEEL and Joseph Woicik of the Materials Science and Engineering Laboratory grew and characterized a series of thin, buried, InAs layers using a variation of the conventional reflection high-energy electron diffraction (more commonly known by the acronym RHEED) techniques to calculate and monitor growth rates. A one-monolayer InAs sample with a cap layer of 2.5-nm GaAs was examined by using an X-ray standing-wave technique at the Brookhaven Beamline Facility. The layer was found to be 74% coherent, but 26% of the InAs was determined to either be on adjacent layers or to have subsequently diffused to more distant layers. Improved growth techniques will be required to achieve the critical thickness constraints for the InAs/GaAs system because after two monolayers, the InAs is expected to be highly defective.

The X-ray standing-wave technique is uniquely capable of quantitatively studying the atomic configurations at these interfaces because of its atomic selectivity and depth of penetration. It is now possible to know the actual atomic site occupation of a buried interface of InAs. Highly significant, this knowledge will lead to better control of the growth of InAs and InGaAs compounds.

SEMICONDUCTORS

A collaboration has begun with Microwave Signal, Inc., Clarksburg, Maryland, to evaluate their material. Other producers of MBE-grown, multi-layer wafers needed for PHEMTs have also expressed interest in information that will enable them to optimize their growth conditions.



ELLIPSOMETRIC MEASUREMENT

1.5 Ellipsometry intercomparison of 10-nm-thick oxide

Thin films of precisely controlled thickness are vital to the microelectronics industry. In many cases, the uncertainty in thickness must be controlled to dimensions on the order of a few layers of atoms for predictable and reliable operation of the devices and circuits manufactured. In order to maintain the required manufacturing control, thickness is conventionally monitored on actual circuits and special test wafers by means of optical methods (such as ellipsometry or reflectometry). In these methods, the thickness and optical properties of thin-film layers are inferred from measurements of the properties of light before and after reflection from the films. The complex optical instruments used in these measurements must themselves be continuously monitored and calibrated using artifacts with thin films of known thickness and optical properties.

Since 1988, NIST has been providing the semiconductor manufacturing industry with artifacts of thin films of silicon dioxide on silicon, which have been certified at NIST as to the film thickness and optical properties using a unique high-accuracy ellipsometer and a detailed and complex measurement scheme. In response to evolving industry needs, the minimum oxide thickness has decreased from 200, 100, and 50 nm available in 1988 to 14 nm by 1993. The demands of industry for even thinner films from NIST created serious questions concerning the possibility of providing such artifacts using the existing procedures, and whether industry was capable of measuring the artifacts with sufficient precision to be useful.

To answer these questions, NIST researcher Barbara Belzer organized an industrial interlaboratory comparison to determine the industry's ability to measure NIST artifacts having thin films with thicknesses as small as 10 nm. Participants in the study included ellipsometer manufacturers Rudolph Research, Flanders, New Jersey; Gaertner Scientific, Chicago, Illinois; and J.A. Woollam Company, Lincoln, Nebraska. Also involved were metrology support laboratories for commercial fabrication

On the fabrication of micromechanical devices using CMOS Foundry processing capabilities:

"I wanted to thank you once again for the time you spent demonstrating EDP etching....Learning this new technique by demonstration, rather than trial and error, most certainly helped us to quickly go up the learning curve of bulk silicon micromachining that is being initiated in association with our new MEMS program here at Xerox."

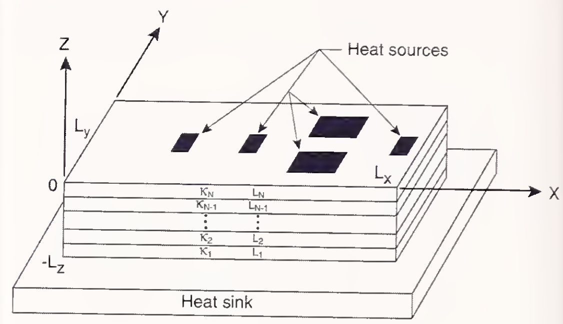
— Researcher
Specialty Microelectronics Processing and Structures
Wilson Center for Research and Technology
Xerox Corporation

lines from IBM, Essex Junction, Vermont; Motorola Inc., Mesa, Arizona; Digital Equipment Corporation in Hudson, Massachusetts; the metrology laboratory at SEMATECH, Austin, Texas; and a commercial standards supplier, VLSI Standards, Inc., San Jose, California.

The results of the study showed that under carefully controlled conditions of measurement and carefully controlled artifact handling, the precision measurement demands of the semiconductor industry for thin-film thickness could be met using the NIST ellipsometric artifacts. As a result, NIST began issuing for sale 10-nm thin-film silicon dioxide on silicon Standard Reference Materials. The study also clearly indicated that if certain metrological guidelines are followed and appropriate methodology is applied, it is possible to meet the projected thickness control requirements for 6.5-nm gate oxides of ±0.3 nm in 1995. Another result of the continuing NIST-industry relationship cemented by this study is an investigation by NIST with the industry into other, possibly more efficient, methods for providing the industry with measurements traceable to NIST without the need for NIST-produced artifacts.

1.6 Thermal model of multilayer microelectronic structures

The operation and reliability of advanced semiconductor-device structures are strongly linked with effective thermal management considerations. Ever-increasing packing densities and total power dissipation levels require the device to dissipate ever greater amounts of the heat which is generated during operation. As a result, device designers need enhanced understanding of the



THERMAL MODELING

effects of geometry, thicknesses, and thermal conductivities on the thermal response of the system. Thermal modeling has met this need.

NIST scientist John Albers has developed a model for the steady-state surface temperature of a multilayer structure. This exact model, TALLML, makes use of a recursion relation technique similar to that used in the analysis of electrical spreading resistance. The model and the associated computer code can be used to compute the steady-state surface temperature of a structure of any number of layers. The model's simplicity allows it to provide surface temperatures quickly and with little effort.

A number of years ago, Albers developed the TXYZ code. This code has enjoyed great popularity among industry and university researchers because of its ease of operation and its extensive documentation. Copies of the code have been requested by over 50 companies and universities. Within NIST, the code has been used for electromigration and oxide studies. The new multilayer model and code serve to complement and extend the TXYZ code and should provide a powerful tool in the understanding of the thermal behavior of modern multilayer microelectronic structures.

S E M I C O N D U C T O R S

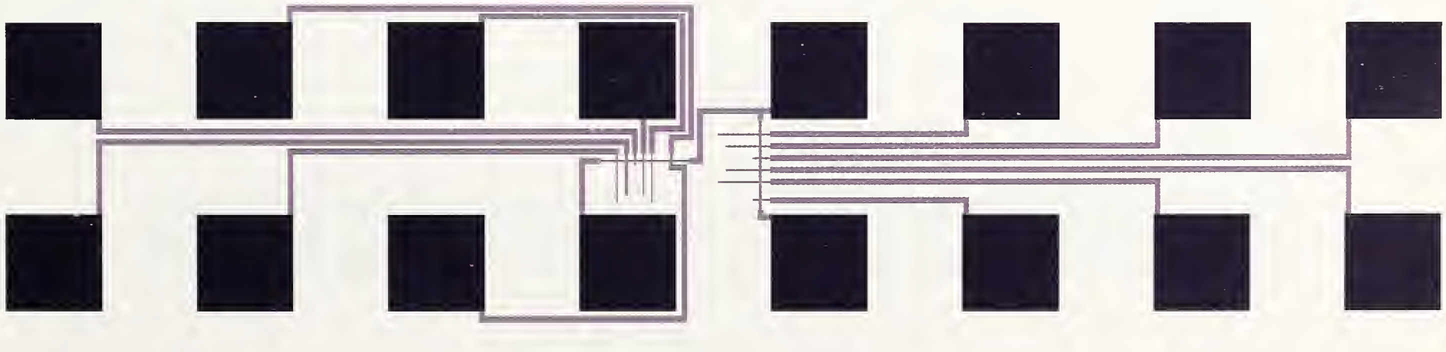
1.7 Hybrid optical-electrical test-structure targets

The fabrication of integrated circuits requires accurate placement of superimposed layers of patterned material. The industry has widely used optically-based metrology for process control almost exclusively in the past, notwithstanding the fact that the uncertainties provided by these methods are too great. As a result, they offer only repeatability to achieve the yields needed for the fabrication of the current generation of devices. But what about tomorrow? Accuracy becomes increasingly important as the critical dimensions of the semiconductor devices being fabricated are reduced in size. Now, a team of NIST scientists has found a technique that provides accurate, as well as precise, in-situ measurements of overlay which could be quickly adopted by industry and attain widespread use for both process control and fabrication-equipment tuning.

The team, consisting of Michael Cresswell, Richard Allen, Loren Linholm, and Colleen Ellenwood, has reported on the design, fabrication, and test of a series of new potentiometer-based electrical test structures that have unique characteristics. Some of the features of the test structures can be read electrically; some can be read optically, and some can be read both optically and electrically. In other words, some of the test structures' electrical features serve also as conventional optically readable, frame-in-frame, overlay targets.

Preliminary data showed that the electrical measurements of overlay agreed with the optical measurements made by the NIST line-scale interferometer to within the uncertainty of that instrument. The electrical measurements thus have traceability to absolute length standards. The dynamic precision for 1000 measurements was found to be 1.5 nm (6σ). These performance levels exceed SIA roadmap goals in overlay-metrology for IC fabrication.

The major advantage of the new hybrid test structure is that it offers a convenient reference with which to check the accuracy of optical instruments at the point-of-use. Through work such as this, NIST is able to transfer the accuracy of new metrology techniques to the ones currently used in the semiconductor industry. This project is being conducted under a Cooperative Research and Development Agreement (CRADA) with Bio-Rad Instruments, Poughkeepsie, New York. Researchers from several industry and government laboratories have expressed interest in assisting in the development of these test structures and in using the resulting test methods once they have been developed. This work will be done in collaboration with NIST scientist E. Clayton Teague of the Manufacturing Engineering Laboratory.



OVERLAY TEST STRUCTURE

"Ground rules of advanced semiconductor devices are reaching dimensions smaller than a quarter of a micrometer. In addition, planarization has become a necessary process step....These advances may drive the development, and dictate the use of novel sensing techniques for profiling and measuring the dimensions of sub-micrometer features. Bio-Rad Semiconductor feels that, by investigating and developing advanced sensing techniques, future needs of the semiconductor industry will be met. Recognizing the expertise of the NIST engineers and scientists, Bio-Rad would welcome the opportunity to work with NIST on such critical development projects."

— Technical Liaison Officer
Bio-Rad Semiconductor

1.8 Patents in electrical overlay and CD metrology

Reference substrates and procedures for the calibration of overlay instruments, consistent with SIA-projected performance requirements, are presently unavailable on a commercial basis. As a result, U.S. overlay-instrument manufacturers agree that this situation may adversely impact IC-fabrication process control during the next several years. The reasons for the unavailability of reference substrates is that the overlay-certification process at NIST is too slow, costly, and time-consuming to serve the level of anticipated demand on a practical basis. However, EEEL has recently been granted patents for new overlay calibration-target designs to facilitate and reduce the cost of the certification process. The latest design, featured in a continuation-in-part patent application, describes a method for electrically certifying overlay-reference substrates for optical metrology. The novel approach transfers the path of traceability to the reticles, from each set of which overlay reference substrates may be mass-produced and certified at acceptable low cost.

NIST has also received a patent for a miniaturized electrical linewidth bridge to provide higher spatial resolution of the widths of features replicated on the wafer-surface for IC-fabrication process control. A separate patent has also been received for a derivative application to enable the electrical certification of graduated scales for optical microscope magnification metrology. The latest related continuation-in-part patent application addresses the traditional problem of feature-sidewall profile uncertainty and its adverse impact on the availability of physical standards for critical-dimension (CD) instrumentation. The new NIST approach replicates features with planar sidewalls of known inclinations and, as in the case of the overlay substrates, uses electrical testing for certification. The commercial significance is that, for the first time, reference materials for both overlay and CD metrology may be mass-produced at relatively low cost and electrically certified by their manufacturer with traceability to NIST standards.

In their patent specifications for overlay metrology, EEEL researchers Michael Cresswell, Richard Allen, Loren Linholm, Colleen Ellenwood, and Michael Gaitan, and Manufacturing Engineering Laboratory researchers E. Clayton Teague and William Penzes describe overlay-metrology target designs to allow calibration of optical instruments through electrical certification of functional overlays. The functional overlays are embedded in multiple-level structures fabricated on a reference substrate. For CD standards, the new approach replicates features in single-crystal materials.

The new electrical structures offer a path leading toward the commercial supply of certified overlay reference substrates at acceptable costs. This work has resulted in a CRADA with Bio-Rad Instruments, Poughkeepsie, New York, and solicitations from other companies.

SEMICONDUCTORS

1.9 Scanning rf impedance for buried-feature overlay metrology

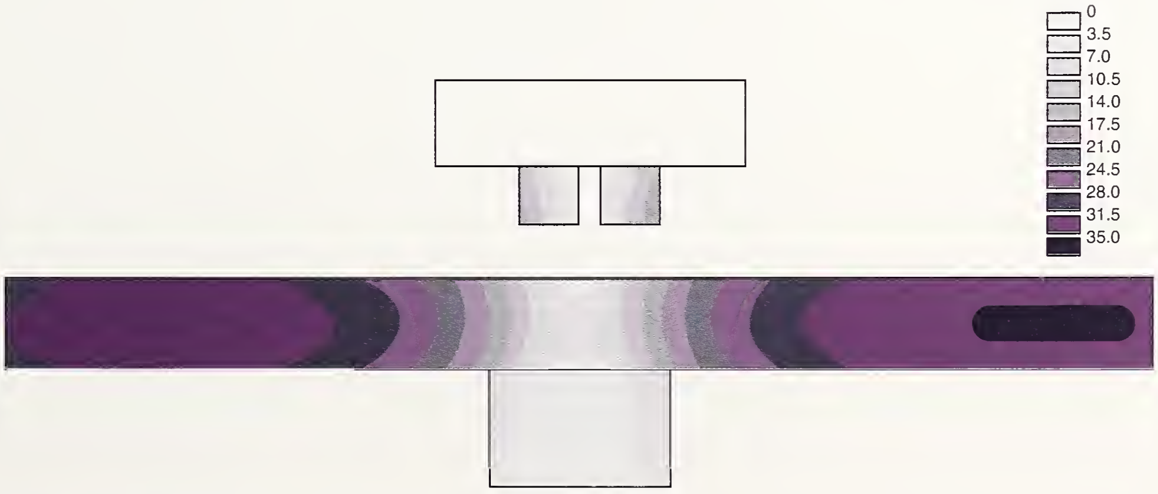
Conventional overlay-metrology instruments are based on the analysis of images produced by laser-beam scattering from features patterned during two lithographic steps. However, the scaling of design rules toward SIA-projected requirements is a growing technical challenge for this approach. One reason is the increasing yield-driven popularity of chemical-mechanical polishing (CMP) for planarization. However, in multilevel interconnect fabrication, CMP severely limits the precision of the measurement of the overlay of patterned resist to pre-patterned features which are unavoidably buried by CMP processing.

In one critical CMP application, the material to be etched, as defined by the resist patterning, is a planarized conducting film, usually of aluminum. The aluminum film obscures buried tungsten-plug reference features from the probe laser beam. The beam therefore relies on locating the shallow indentations in the aluminum film propagated from the location of the plug, but the polishing process tends to obliterate the indentations which serve as essential reference marks. Consequently, in optical-overlay metrology, the feasibility of referencing resist patterns on aluminum films to underlying tungsten plugs is now considered to be very marginal.

EEEL scientists Michael Cresswell, Richard Allen, Loren Linholm, and Joseph Kopanski have proposed and conducted a preliminary experimental investigation of a technique which mimics optical-metrology practice by scanning across a conventional buried frame-in-frame target replicated on the substrate. Instead of attempting to deconvolve the reflected laser-beam image, thereby to extract spatial information as well as providing for the embedded shifts, this alternative technique senses the elements on the reference substrate by a novel means which is being disclosed in a current NIST patent application. Because this new technique appears capable of achieving the spatial resolution previously achieved with pre-CMP technology, several overlay-metrology companies have asked to collaborate in future developments through the CRADA format.

"I had the pleasure of reviewing the document *Realizing Suspended Structures on Chips Manufactured by CMOS Foundry Processes through the MOSIS Service*....This work represents a major first step toward bringing the next generation of MEMS technology out of the laboratory and into mass production. I am very happy to see NIST taking a leading role in this area, and look forward to seeing future contributions from this outstanding research team."

— Professor
Electrical Engineering Department
School of Engineering and Applied Science
University of California, Los Angeles



HIDDEN LAYER METROLOGY
Finite element analysis of eddy-current density distribution-induced semiconductor features.

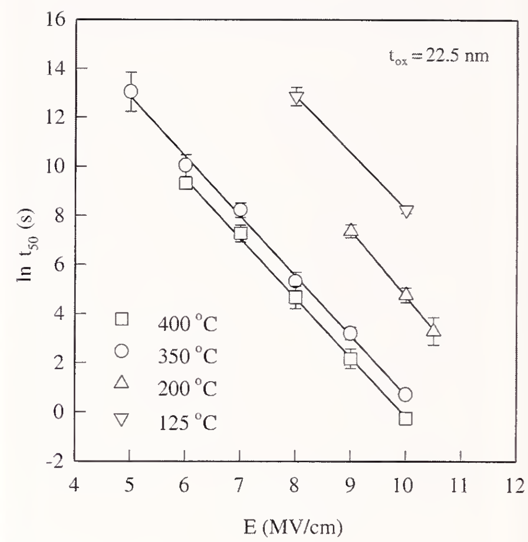
"I am writing this letter in order to acknowledge the fine work of John S. Suehle, who has been involved in a cooperative effort with us here at GE CRD...focused on the measurement of the high temperature (≥350° C) reliability properties of thermally grown thin (≤500Å) silicon dioxide layers.... I want to congratulate John for his work which is extremely important and relevant for quantifying and understanding this important technological subject. This kind of work and cooperative effort is exactly what contributes most to technical progress and helps us determine how to plan future activities and the near term boundaries and feasible goals of a new technology."

— Leader
SiC Research Team
GE Corporate Research and Development
General Electric Company

1.10 Time-dependent dielectric breakdown model verified

Time-Dependent Dielectric Breakdown (TDDB) of thin silicon dioxide films is a serious failure mechanism in advanced integrated circuits. The dielectric integrity of these films is usually characterized by performing a stress test that accelerates failure by subjecting the device to high temperatures or electric fields. The two competing voltage acceleration models describing TDDB have been a subject of controversy for nearly two decades. Their predictions of dielectric life can differ by several orders of magnitude in time, and it is very difficult to distinguish between the two models for data obtained at stress electric fields above 7.0 MV/cm.

But the controversy may soon be resolved, owing to the work of NIST scientist John Suehle. He has advanced the understanding of time-dependent dielectric breakdown in thin SiO_2 films by verifying the electric-field dependence of the mechanism. Using a novel wafer-level probe station to provide high stress temperatures, Suehle accelerated dielectric failure with temperature so that data could be obtained at lower electric fields. These data verified that TDDB of intrinsic oxides follows a linear electric-field dependence. Suehle's work will enable the development of a physically correct TDDB model. This, in turn, will allow industry more confidence when extrapolating the reliability of gate oxides to operating conditions and predicting the reliability of integrated circuits. A paper describing this work received the Outstanding Paper Award at the 1994 International Reliability Physics Symposium.

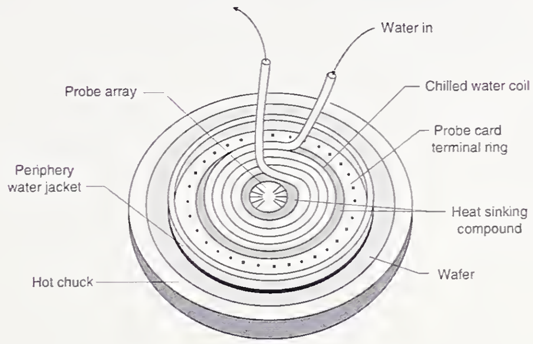


TDDB DATA

Log of the median time to failure [ln t_{50} (s)] plotted as a function of the electric field [E (MV/cm)] for a 22.5-nm oxide. Note that results obtained at fields below 7.0 MV/cm are well described by the linear field model.

The semiconductor industry was so interested in this work that a special interest group (SIG), the Thin Oxide Reliability SIG, was formed to provide a platform for individuals from university, government, and industry to pool resources to make significant advances in the reliability of grown silicon-dioxide films thinner than 35 nm. Current membership includes representatives from National Semiconductor, Salt Lake City, Nevada; AT&T Bell Labs, Allentown, Pennsylvania; Motorola, Scottsdale, Arizona; Sandia National Laboratories, Albuquerque, New Mexico; the University of Maryland, College Park, Maryland; and NIST. The focus of the group is to obtain data from differently processed oxides at a variety of fields and temperatures and develop appropriate models, testing methods, and data analysis procedures. Suehle serves as Chair of the Thin Oxide Reliability SIG.

TDDB Temperature-Controlled Stage



TDDB TEMPERATURE-CONTROLLED STAGE
Water-cooled probe card and test fixture. A water jacket is attached to the top and around the periphery of a standard 10-cm circular probe card.

1.11 Matthiessen's rule to measure thickness of metal films

Accurate information about the thickness and cross-sectional area of metal interconnect lines is essential in the use of accelerated stress tests to assess the reliability of integrated circuits against interconnect failure due to electromigration. Electromigration refers to a failure mechanism in which material in a conducting line is moved as a result of high current densities in this line; if not addressed, the phenomenon constitutes a major barrier to continuing levels of microminiaturization. Accelerated stress tests are widely used in industry and require a calculation of the current needed to achieve the desired current-density stress in the interconnect lines being tested. These calculations are possible only if the areas of these lines are known accurately.

A team of NIST scientists, including Harry Schafft, Santos Mayo, John Suehle, and Donald Novotny of the Electronics and Electrical Engineering Laboratory and Samuel Jones of the Manufacturing Engineering Laboratory, has developed a method for determining the thickness and cross-sectional area of metal interconnect lines that is both accurate and non-invasive. The basis of the method is the use of Matthiessen's rule, which states that the resistivity of a dilute metal alloy is equal to the resistivity of the pure, bulk metal plus a residual resistivity, which is dependent on the additives to the pure metal, but independent of temperature. Means for quantifying the deviation from Matthiessen's rule and thermal expansion effects have been developed, so that by the measurement of the sheet resistance of the metallization at two temperatures, the thickness of the metal film can be determined. Their findings are in agreement with scanning electron microscope (SEM) results within the precision of the SEM. The team's results demonstrate that not just the metal film thickness but also the cross-sectional area of metal interconnect lines can be determined by resistance measurements taken at two temperatures.

This method will also have an impact on process monitoring and control, especially as dimensions continue to shrink. Other methods to measure thickness all have accuracy problems, and none are as straightforward, simple, or quick to perform. A paper describing the results for this work was presented at the 1994 International Integrated Reliability Workshop.

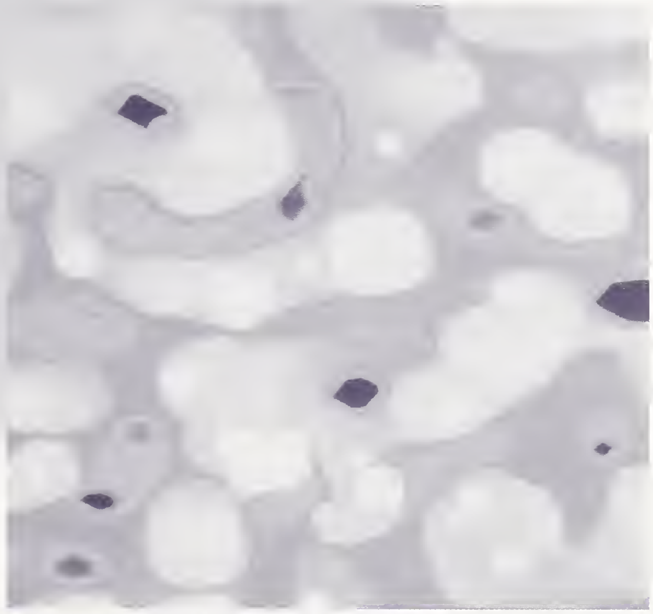
Under a Cooperative Research and Development Agreement (CRADA)—a means of making the Federal Government's research assets more accessible to private companies—an inexpensive, versatile, and reliable technology for dynamic thermal scene simulation is being developed:

"This relationship is in principle what Congress intended....With this type of assistance and motivation, I think we will have a much stronger country."

— President
Optical E.T.C. Incorporated

SCANNED-PROBE MICROSCOPY

Accomplishments



HIGH TEMPERATURE SUPERCONDUCTOR THIN FILM
Image of a $YBa_2Cu_3O_{7-\Delta}$ thin film on an $LaA1O_3$ substrate, taken with an atomic force microscope (AFM). The film was prepared from a fluorinated metalorganic precursor solution which was spun on the substrate, then annealed. The AFM reveals that the film has grown by an island nucleation and growth mechanism.

2 MAGNETICS

2.1 New eddy-current resistivity measurement system

Through their collaboration on this project to apply eddy-current methods to the measurement of resistivity, Anthony Kos and Fred Fickett have provided a much-needed convenient alternative to conventional methods of resistivity measurement, especially for low-temperature measurements. Eddy-current resistivity measurement techniques are typically used for non-standard specimens, such as wire being stressed. For this application, the contacts used in the more common resistivity measuring methods would be subject to damage. This metrology is especially important to applications involving superconducting, magnetic energy-storage devices and fusion machines.

Kos and Fickett have applied modern electronic instrumentation methods to the design of an updated version of a thirty-year-old eddy-current-resistivity measurement system. To provide the needed precision, their system applies a sophisticated computer analysis to determine the eddy-current-decay time constant. Tests conducted on specially prepared copper alloys were successfully compared to conventional four-probe measurements. The new apparatus achieved a factor-of-ten improvement over the older method in the repeatability of the measurement of eddy-current-decay data.

2.2 Hard-disk features characterized

In a continuing effort to provide assistance to the U.S. magnetics recording industry by identifying and resolving problems in component manufacture, Paul Rice and John Moreland have collaborated with Maxtor Corporation, San Jose, California, a U.S. manufacturer of

"The MFM data you provided was useful in two ways. First your measurements of the magnetic field intensity in the vicinity of a recorded bit on a disk has helped us to better understand the writing process of magnetic recording....By developing these concepts further, we anticipate being able to increase track density in disk drives, thus increasing capacity per disk. Second, you measured some disks on which we have found 'nodules'...the problem was one we had never seen before. Your analysis helped us understand that the nodules were in fact a result of a sputtering problem....Once we shared the data with the vendor...we were able to solve the problem very quickly....From your MFM testing, we anticipate learning even more about the writing process of magnetic recording. The data you collect for the different head designs should help to verify (or refute) some of our hypotheses about writing on disks."

— Senior Engineering Manager
Maxtor Corporation

CHARACTERIZING MAGNETIC MEDIA

computer disk drives, to apply lateral force microscopy to the investigation of micrometer-sized sticky or tacky features on the surface of a hard disk.

The features of interest are a few micrometers in extent and twenty to thirty nanometers high, comparable to the disk peak-surface roughness of about twenty nanometers and therefore difficult to image by such common methods as optical or electron-beam microscopy. In lateral-force microscopy, a derivative of atomic force microscopy, the tip is scanned over the specimen. When a variation of friction between the tip and specimen surface is encountered, the cantilever twists slightly, and the twisting is plotted as a function of tip position, imaging the feature.

The importance of being able to characterize these features is underscored by the fact that they can occur on any part of the surface of a disk where the read/write heads can be positioned. Heads already "fly" over disks with separations well below 100 nm. Unless resolved, this problem would present a significant impediment to a design goal of substantial reductions in head flying height, an essential requirement to increase bit storage density in advanced magnetic media.

As recording densities increase, properties such as fringing fields also become more important to the accuracy of magnetic recording. In a related effort, Paul Rice formed a Cooperative Research and Development Agreement (CRADA) with Maxtor Corporation's Read-Head Development Group to apply magnetic-force microscopy and atomic-force microscopy to image the fringing fields and topographies of disk media and thin-film inductive heads.

Rice presented his findings, including correlations of the bit patterns and the fringing fields, in a paper which was presented at the 6th Joint Magnetism and Magnetic Materials/Intermag Conference held in Albuquerque, New Mexico in June, 1994. The paper will be published in the conference proceedings.

Through the recently developed NIST Industry Fellows Program, Rice will take a position at Maxtor Corporation for one year to further pursue these interactions. Two other members of EEEL staff will participate with other companies in this program, which is designed to foster government-industry cooperation in identifying technical trends and opportunities, and to foster the development and use of advanced technology.

MAGNETICS

2.3 Giant-magnetoresistance films characterized

As part of an ongoing program to assist U.S. companies dedicated to magnetic recording technology and manufacturing, NIST scientists Stephen Russek, R. William Cross, Steven Sanders, and John Oti collaborated with the staff of Rocky Mountain Magnetics, Inc. (RMMI) of Louisville, Colorado to fabricate Fe-Ni/Ag giant-magnetoresistance (GMR) films and to measure the dependence of the GMR on annealing conditions. For Fe-Ni/Ag alloys, annealing is necessary to create GMR (the silver has to be driven into the grain boundaries). Annealing can also have other effects, such as changing grain size and tilting the magnetization, which affect the GMR response.

The film sensitivity was found to peak at 335°C for five-minute anneals. The specimen materials were patterned to study high-current-density effects, noise, and transport in submicrometer GMR structures. RMMI intends to produce and test an actual read head from these materials.

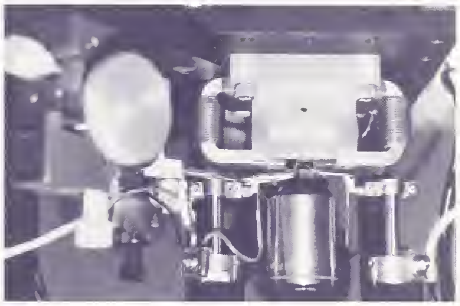
THIN FILM MAGNETIC MEDIA

Using wafers with Fe-Ni/Ag films of different thicknesses prepared by the company and patterned at NIST, the NIST researchers studied the effects of thickness on domain formation in magnetoresistive elements. They were able to determine the effect of annealing on grain size using atomic-force microscopy, and modeled the GMR behavior by varying the grain packing fraction.

2.4 Fabrication and analysis of giant magnetoresistance devices

A recent discovery of NIST scientists Stephen Russek, R. William Cross, and Steven Sanders has had important implications for the use of GMR sensors as read heads for magnetic-storage devices. In response to a request from the National Storage Industry Consortium (NSIC), a consortium of magnetic recording companies, the NIST team has fabricated giant magnetoresistance (GMR) devices with active areas as small as 0.3 µm × 0.7 µm from Fe-Ni/Ag thin films made at NIST, and Fe-Ni-CO/Cu films made at the University of Alabama. In the course of their work, they determined that in structures smaller than 2 µm × 2 µm, magnetoresistance, Barkhausen noise, and 1/f noise follow discrete steps as a function of small applied fields due to the switching of individual magnetic particles.

They also learned that the self-field produced by the drive current can be used to smooth the response for 1 µm and smaller GMR multilayer devices. For such devices, individual magnetic switching events cause jumps and hysteresis in the output near zero applied field. As the current flows through the multilayer, a magnetic field transverse to the current flow is produced that locally aligns the magnetization, which reduces the noise. In the course of their work, the researchers were also able to separate the effect of device heating from that of self-field in GMR read-head test devices. Up to now, it has been known that when a current is sent through the read head, the GMR response decreases. This response may be due to either the magnetic field generated by the current or the (Joule) heating produced by the current. Because the team was able to separate the two effects, it will now be possible for researchers to analyze the nature of the GMR response degradation due to either effect.

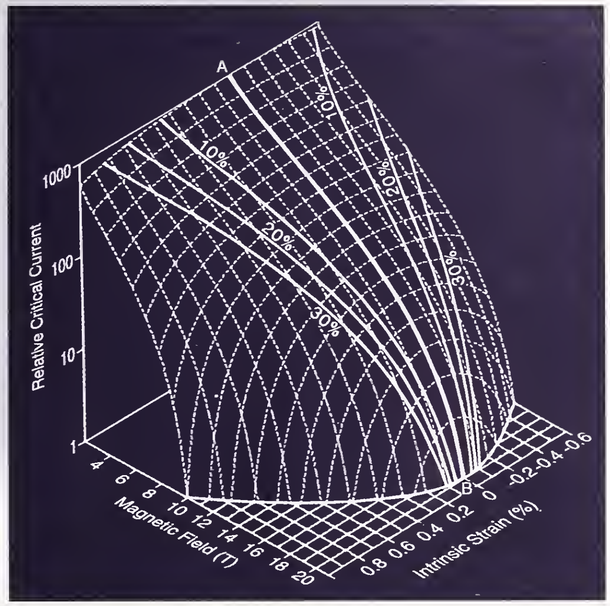


FIXTURE FOR GMR MEASUREMENT

NIST is actively involved in responding to NSIC needs. Investigators within these companies and at universities have sought NIST help in understanding how GMR can be applied in a new type of magnetic sensing. The benefits of this interaction are very significant. The NIST team's findings have resulted in the redirection of some of NSIC's material efforts.

FORMING SUPERCONDUCTOR LAYERS

Accomplishments



MODELING SUPERCONDUCTOR BEHAVIOR

Critical strain surface for commercial Nb_3Sn superconductors at 4.2 K, showing critical current as a function of magnetic field and strain in the superconductor. The conductor behaves as a normal conductor above this surface, but transforms reversibly into the superconducting state below the surface.

3 SUPERCONDUCTORS

DETAIL OF MICROMETER-SIZED IR ANTENNA

3.1 Record performance of HTS bolometer

Although commercial and military surveillance organizations are the prime customers for infrared imaging techniques, commercial markets are developing for U.S. manufacturers. NIST scientists, Erich Grossman, Joseph Rice, and David Rudman have recently invented and implemented an infrared detector that combines a planar lithographic antenna with a high-temperature superconducting microbolometer on a silicon chip. The capabilities of their device, which demonstrated record performance for liquid-nitrogen-cooled thermal detectors, have opened the door to the development of far-infrared imaging arrays based on monolithic integration of these detectors with switching transistors. The work is being extended under a Cooperative Research and Development Agreement (CRADA) with Conductus, Inc. of Sunnyvale, California.

The antenna couples far-infrared radiation into a superconducting strip on a free-standing bridge of yttria-stabilized zirconia created by silicon micromachining. The result of this coupling is to heat the strip, which is held near its sharp superconducting transition at 90 K, yielding a voltage proportional to the infrared power. The minimum detectable power (noise-equivalent power = 9×10^{-12} W/$Hz^{1/2}$) is a factor of two better than the previous record, and the device responds 10,000 times faster, with a time constant on the order of 4 µs.

3.2 HTS junction yields highest beat frequency

Erich Grossman and Leila Vale, of the Electronics and Electrical Engineering Laboratory, have collaborated with Lyndon Zink and Kenneth Evenson, of the Physics Laboratory, to develop the capa-

CRYOELECTRONIC FABRICATION

bility of mixing infrared or visible lasers having great frequency differences. Scientists believe that these mixers will help them relate NIST's time and length standards more accurately. Such mixing provides for accurate measurement of spectral lines having frequencies far removed from the established frequency standards. CO_2 lasers are secondary frequency standards which can be used for this purpose.

This group has succeeded in mixing two 30-THz CO_2 laser signals, using as the mixer a Josephson junction formed from the high-temperature superconductor yttrium/barium/copper oxide (YBCO). Both lasers were first tuned to the same line, yielding beat frequencies from a few MHz up to the free spectral range of the lasers (~80 MHz). One of the lasers was then tuned to a line separated from the first line by 6.9 GHz and a beat note was observed. This was the highest beat frequency observed until that time, and has since been bettered by the NIST team. The work is continuing.

These experiments are similar to a number of classical earlier experiments performed at NIST as part of the IR frequency synthesis effort that precisely measured the speed of light. The group's success with a YBCO Josephson junction suggests that the highly unstable and irreproducible point-contact mixers can be replaced with a completely monolithic device and opens the possibility of much more compact, reliable, and practical IR frequency synthesis systems. High-temperature superconductor junctions should also allow operation to higher frequencies.

3.3 Low-noise performance potential of high-temperature Josephson junctions

Part of EEEL's program to demonstrate high-temperature superconductor applications focuses on measuring the noise produced by the junctions formed from superconducting materials, or the noise of mixers using these devices. This type of measurement is applicable to very-high-frequency receivers, such as are used by aerospace companies for remote sensing.

Erich Grossman and Leila Vale have reported the first direct measurements of the microwave-frequency noise of high-temperature Josephson junctions. They measured (for the lowest-noise device) a maximum available noise temperature of 32 ± 2 K at a physical temperature of 4.3 K, using YBCO step-edge junctions and an ultra-low-noise 1-GHz measurement system.

The peak noise temperature is in agreement (within 1 dB) with published simulations of the ideal resistively shunted junction model. The results imply that such junctions are capable of noise performance that approaches the fundamental quantum limits in millimeter-wave and terahertz detection and mixing applications, and that superconductor applications can be used in very high frequency receivers.

3.4 Electromechanical properties of Bi-based tapes and wires

Scientists Jack Ekin, Steve Bray, and Norman Bergren have provided U.S. superconductor bulk-wire companies as well as superconductor magnet manufacturers with key information regarding the use of experimental material in the development of high-temperature superconductor (HTS) magnets. Ekin, Bray, and Bergren were asked to measure the electromechanical properties of Bi-based bismuth/strontium/cobalt/copper oxide (BSCCO) high-temperature superconductor tapes and wires, including measuring the effect of strain on the critical current of a new Bi-based wire clad with a strong silver alloy instead of pure soft silver. The team cooled the tapes and wires to cryogenic temperatures and measured the strain and critical current concurrently.

SUPERCONDUCTORS

They found that the silver-alloy sheath material has a greater thermal contraction than BSCCO, which places the brittle superconductor in compression on cooling to cryogenic operating temperatures. This gives the conductor increased tolerance for axial strain. The mechanical properties of Bi tapes are recognized as a key engineering design parameter for bulk superconductor devices, particularly magnets and transmission lines.

The team will continue to investigate the electromechanical properties of newly developed products as the need arises. Findings such as these indicate that superconductor magnets made from HTS wire could well supplant conventional superconducting magnets, providing the new materials can be developed to the point where they can withstand the high stress effects and sustain a high critical current in the presence of very strong magnetic fields.

"For many years we, at IGC-AS, have been deeply involved in the development of superconducting materials for High Energy Physics (HEP) and for Fusion Energy Programs. It has been particularly gratifying to find a Group as competent and cooperative as Dr. Fickett's, who are prepared to help American Industry on projects involving superconductors....Drs. Goldfarb and Cross have made very valuable contributions to the National (and International) Fusion programs and to HEP by their work on magnetization and ac losses....Dr. Goodrich has made very careful measurements on the current carrying capacity of our wires which other organizations would have had great trouble in carrying out....Dr. Ekin has carried out investigations on the strain properties of our wires for many years and as he is undoubtedly the world's expert on this type of work, it has been particularly gratifying to have his expertise available to us....In summary, your group at NIST has set a very good example of an important type of cooperation."

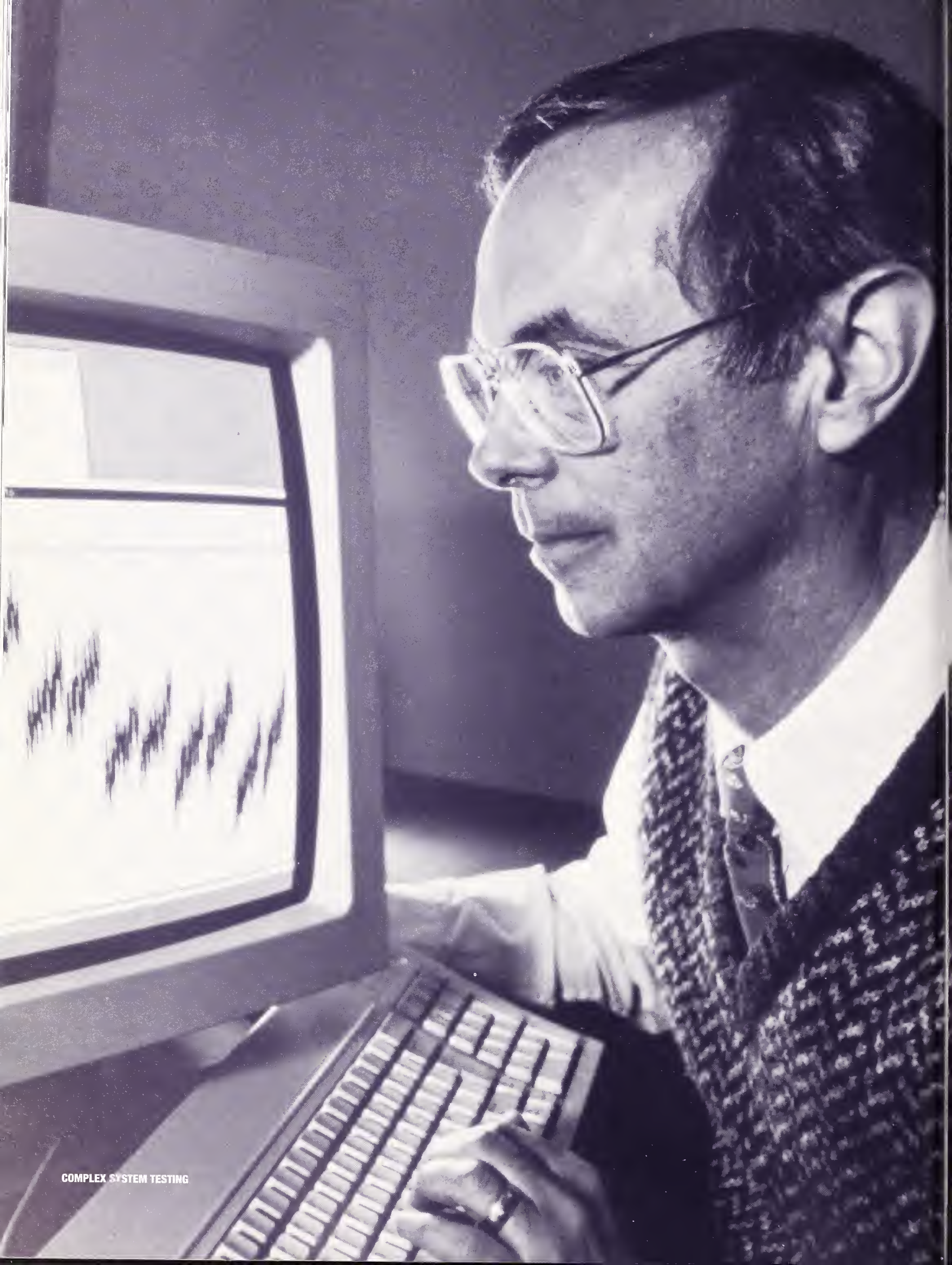
— Manager R&D
Advanced Superconductors, Incorporated
Intermagnetics General Corporation

3.5 Location of critical points in superconductor magnets

Many factors come into play when designing new products with new materials in a developing technology. To move forward, it is essential to characterize the designs and materials modeled in the development process to be sure their operation meets projected specifications. NIST scientists Jack Ekin, a pioneer in developing and understanding the effects of strain on superconductor properties, and Steve Bray collaborated to determine the location of the critical point (which determines when the magnet goes normal) in high- and low- temperature superconductor magnets. Their findings indicate a need to reconsider the applicability of conventional low-temperature superconductor LTS design schemes for high-temperature superconductor (HTS) materials.

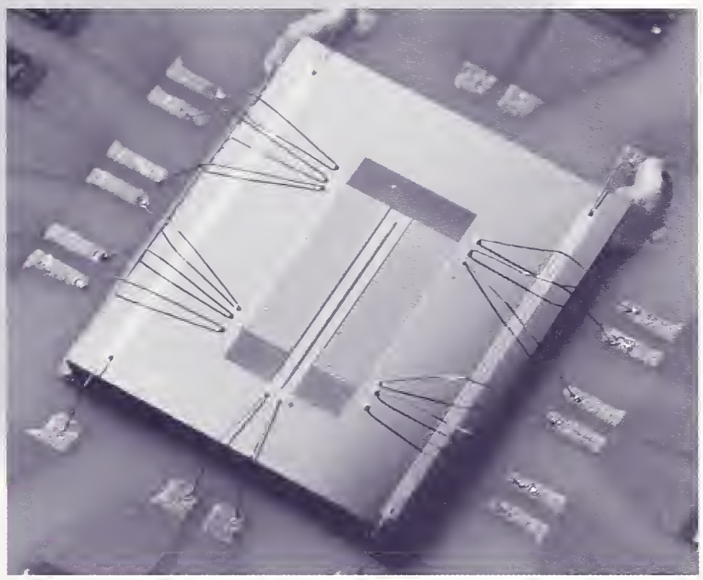
Working with a magnet design associated with low-temperature superconductor materials but constructed of new HTS material, Ekin and Bray measured the critical current of superconducting composite rings as a function of vertical position in the background magnet. Their findings revealed that the critical point in Bi-tape superconductor magnets will be at the ends of the magnet rather than at the high-field position in the middle, as it is for low-temperature superconductor magnets. The coils used in this study were provided through a collaboration among American Superconductor Corporation, the Navy, and NIST.

Ekin and Bray deduced that this is probably the result of the large anisotropy in Bi-tape superconductors. Because the magnet design depends on the location of the critical point, Ekin and Bray's work showed that high-temperature superconductor magnets will probably have to be designed differently.



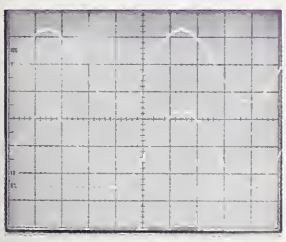
COMPLEX SYSTEM TESTING

Accomplishments



THIN-FILM MULTIJUNCTION THERMAL CONVERTER (MJTC)

4 LOW FREQUENCY



SINE WAVE/DIGITAL SYNTHESIS

4.1 Wideband sampling probes

American industry's need for accurate wideband sampling probes continues to grow. Typical applications include the measurement of electrical voltage, current, phase, power, and impedance in automatic testing systems. Some U.S. companies use this technology in their products; others use sampling comparators to test data converters. Sandia National Laboratories and the Air Force Guidance and Metrology Center have helped to sponsor the work performed by NIST scientists Michael Souders and Owen Laug.

Souders and Laug have developed an improved waveform-sampling probe that is being used as the sensor for a wideband sampling voltmeter. Although developed initially for high-speed time-domain signal sampling, the probe also supports accurate measurement of wideband frequency-domain signals. The heart of the probe is a custom-made analog comparator chip designed by the NIST staff and fabricated in a commercial "foundry." The chip provides a 3 dB bandwidth of 2.5 GHz and a settling-time-uncertainty of 0.1% in 2 ns. For comparison, commercial comparators have bandwidths of about 1 GHz and may take 150 ns to settle with the same uncertainty.

A U.S. patent issued for their probe describes the unique "enabling" technique that reduces the differential thermal effects found in conventional comparators. The probe has also been used with a NIST-designed custom attenuator to make accurate rms voltage measurements in the ±20 V range where the probe-attenuator combination has been shown to have a frequency response (gain flatness) of less than 0.007% (70 ppm) deviation from 100 Hz to 1 MHz, and less than 0.1% deviation for frequencies up to 50 MHz (±2 V range).

4.2 Digital Impedance Bridge

In response to needs for better measurement support for product testing, especially in the instrumentation and electronics components industries, NIST staff have modernized and improved the NIST impedance measurement capability and related calibration services.

NIST engineers Bryan Waltrip and Nile Oldham achieved a major milestone in this effort with the development of a prototype digital impedance bridge (DIB) system capable of automatically measuring any two- or three-terminal impedance in terms of a resistance standard with known frequency and phase characteristics. The bridge has been tested for inductance measurement capability both independently up to 100 kHz and by comparison with the venerable Maxwell-Wien bridge used at NIST to realize the unit of inductance, the henry, up to 20 kHz. The DIB was found to measure two- or three-terminal impedances with uncertainties of 200 to 2000 parts per million, depending on the measurement frequency in the range of 20 kHZ to 100 kHz, the magnitude of the impedance, and the nature of the transfer standard being measured.

The NIST staff have also designed and developed a probe for measuring inductors with the DIB, specifically for the calibration of 10-mH standard inductors. The probe consists of a number of programmable ac resistors, each of which can be switch-selected so as to be positioned within a few centimeters of the terminals of the inductor-under-test, thus minimizing the effects of any parasitic impedances.

Recently measurements were made on two special temperature-controlled standard 10 mH inductors from the German national standards laboratory, the Physikalisch-Technische Bundesanstalt, using both the DIB (with the prototype probe) and the Maxwell-Wien bridge. The results between these two measurement systems at 1 kHz agreed to within 0.0005% (5 ppm). This agreement is well within the ±50 ppm standard uncertainty of Maxwell-Wien bridge calibrations at this point.

The importance of this development is underscored by the fact that about 250 impedance standards are calibrated each year at NIST for the support of thousands of commercial impedance meters used throughout the electronics sector. The automated character of the DIB confers great flexibility, and many more data points can be taken than were practical before. The result is that NIST impedance-service customers will be able to get a comprehensive analysis of the standards they submit when the DIB is in full use. These data will include information on drift and on frequency dependence. Other standards laboratories have already shown interest in acquiring information on the DIB design for their impedance measurements.

4.3 HTS cryogenic current comparator

At the Conference on Precision Electromagnetic Measurements, CPEM '94, NIST scientist Rand Elmquist was the first to report on the development of a cryogenic current comparator (CCC) operating at 77 K. The results of his work establish the feasibility of CCC resistance bridges capable of operating at liquid-nitrogen temperatures. These new ratio standards are more stable and introduce significantly lower uncertainties than conventional bridges.

Elmquist's design uses two high-temperature-superconductor bismuth/strontium/cobalt/copper oxide (BSCCO) tubes and an yttrium/barium/copper oxide (YBCO) rf superconducting quantum interference device (SQUID) mounted on a movable probe between the tubes. The two CCC windings consist of 12 turns each of twisted-pair copper wire. The measured CCC sensitivity of approximately 270 $\mu A/\phi_0$ for a single turn results in a current resolution of the CCC of less than 6 nA. The standard uncertainty of the ratio measurement of the CCC is about 0.8 ppm. Elmquist's demonstration of his CCC's performance should pave the way to a significant change in the nature of ratio instrumentation. Present use of cryogenic current comparators is usually restricted to national laboratories because large amounts of equipment and supplies are needed to maintain the temperatures at or below 1 K. Designs modeled after Elmquist's may lead to the implementation of a CCC that can be maintained at temperatures attainable with commercial industrial refrigerators. Such CCCs could be incorporated into measurement instruments for direct industrial applications.

4.4 Standards-quality integrated thin-film thermal converters

In FY 1994, NIST received an R&D 100 award, the 75th in its history, for the work resulting from a collaboration of scientists from EEEL working under a Cooperative Research and Development Agreement (CRADA) with an industry partner, Ballantine Laboratories, Incorporated, Cedar Knolls, New Jersey. The award was presented to Joseph Kinard and Donald Novotny of NIST and Guest Scientist De-Xiang Huang of Ballantine Laboratories for the development of a multijunction ac to dc thermal voltage converter designed to be fabricated with methods developed for microelectronic chips. Thermal converters are the most accurate calibration standards for ac voltage and current, and also produce the most precise measurement method for both.

The team fabricated both thin-film multijunction thermal converters (MJTCs) and integrated micropotentiometers, in which multilayer thin-film MJTCs and output resistors are an integral part of the structure on the same silicon chip. In a traditional converter, the skin effect at higher frequencies cannot be neglected. However, in the multijunction thermal converter devices, the heater and thin-film resistor are so thin that the skin effect contribution from them is negligible.

Multijunction thermal converter accuracies approach those of the best conventional standards, with very low dc reversal errors and small ac-dc differences in the audio-frequency range. As voltage converters, the bifilar MJTCs have ac-dc differences of <1 part per million (ppm) at 1 kHz, <10 ppm from 0.3 to 100 kHz, and <50 ppm at 1 MHz. The overall efficiency and temperature coefficients of film MJTCs improve at temperatures down to 100 K and below.

These thin-film converters result from applying modern semiconductor processing technology to the fabrication of carefully patterned heater/thermocouple structures and represent a substantive improvement over the electrical performance of the usual wire thermal converters. Furthermore, it is estimated that they can be produced with a cost range of $100 to $200 each, depending on the electrical parameters, as opposed to a corresponding range of $150 to $2500 for present standards.

The electronic instrumentation industry is interested in this development which not only will provide a new generation of improved standards, but may also make practical the incorporation of film converters in instruments such as precision multimeters, with the result that their ac performance should approach their dc performance. Also, the new thin-film MJTCs will offer secondary calibration laboratories a combination of technology and performance which closely approaches primary standard capability.

On applying NIST's testing strategies to minimize the number of measurements needed to test complex electronic devices without sacrificing confidence in the test:

"I have looked into the issue of 'Testing Strategies'....In simple terms, this is an approach to reducing test cost. For a 16-bit converter, it is necessary to test 216=64,000 'codes.' By the time you add up multiple passes for noise averaging and temp extremes, the test time is about 100 sec. At 8¢ per sec, this is $8.00 per part. We sell these products for about $25, so you can see that test cost is significant. The concept...is to make a 'model' for the converter and to make selected tests to determine the parameters on the model....We at ADI have been working on this approach for about a year and are moving it into production on two 16-bit ADCs....We hope to reduce the test cost from $8.00 to $3.00. This translates to an annual saving of about $400,000 on these parts alone! This is a pilot project, and if it is successful, we will extend it to other products....I can easily see a cost reduction of several million dollars per year if this approach can be broadly applied to our converter product line."

— Vice President Technology, Semiconductor Division
Analog Devices, Incorporated

4.5 Integrated thin-film micropotentiometers

Integrated micropotentiometer chips are new devices based on thin-film MJTCs. Just as in the case of conventional micropotentiometers, the NIST-developed chips serve as sources of small (millivolt-level) ac voltages for the calibration of ac calibrators, signal sources, and voltmeters. They have been shown to work at frequencies up to 1 MHz with the potential for extension to higher frequencies. These new devices are also suitable as thermal current converters in the 5- to 10-mA range, and as thermal voltage converters at about 1 V. As micropotentiometers at voltages below 100 mV, the new chips have very small ac-dc differences at audio frequencies and only a few tens of ppm up to 1 MHz. As voltage converters and current converters, they have quite small ac-dc differences at audio frequencies and reasonably small values out to 1 MHz. Conventional wire converters are built by hand under a microscope, a dying art, and are subject to electrical overload and mechanical damage to a much greater degree than the NIST chip devices.

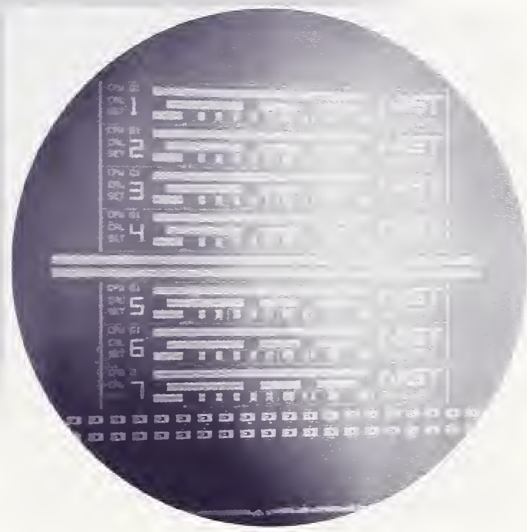
As in the case of the thin-film multijunction converters, NIST scientists Joseph Kinard and Donald Novotny, along with Guest Scientist De-Xiang Huang of Ballantine Laboratories, Incorporated, demonstrated that it is feasible to produce superior replacement devices by applying semiconductor and thin-film fabrication techniques. More than 100 of the new, integrated micropotentiometer chips were produced in FY 1994.

NIST ANTENNA RANGE

Accomplishments

"Engineers in the on-wafer microwave measurement field have long sought a method to quantify S-parameter calibration inaccuracies. A powerful verification technique developed by the National Institute of Standards and Technology (NIST; Boulder, CO) determines error bounds for a working calibration through comparison with the NIST multi-line GaAs through-reflect-line (TRL) calibration....The novel calibration procedure and software package developed by NIST enables calibration verifications to be performed, thus making it possible to demonstrate the traceability of a calibration rather than the traceability of the individual calibration standards."

— "Technique Verifies LRRM Calibrations on GaAs Substrates," *Microwaves and RF*, January, 1994



MMIC IMPEDANCE STANDARD

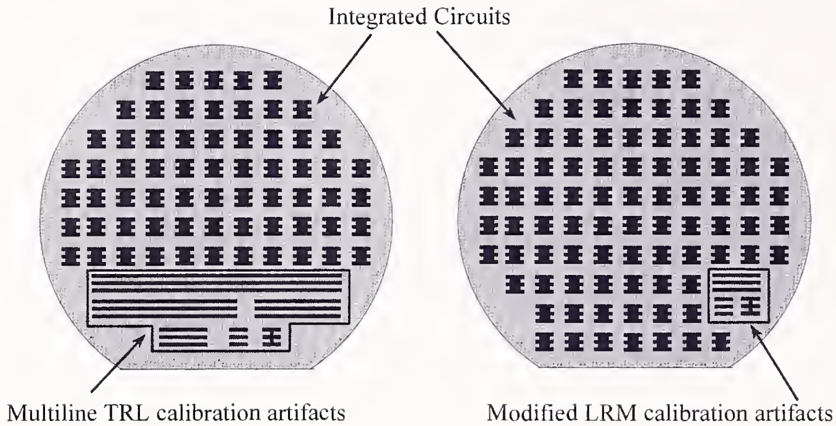
5 MICROWAVES

5.1 MMIC: Line-reflect-match calibration with standards

The fastest growing segment of the international microwave industry incorporates devices and technology based on monolithic microwave integrated circuits (MMICs). Recognized as a potential source of inexpensive commercial microwave products, typical applications for MMIC devices are found in the telecommunications industry, particularly, the emerging wireless communications industry, as well as high-speed computing and computer networks, vehicular communications, smart highways, and collision-avoidance systems.

At present, the microwave industry lacks the accurate on-wafer measurement methods critical to ensure cost-effective product development. NIST scientists Dylan Williams and Roger Marks have provided on-wafer measurement methods that will allow devices to be tested before packaging, or in some instances, before device fabrication is completed. In practical terms, this brings a necessary level of accuracy and practicality to the technology. It will allow commercial manufacturers to use on-wafer probing methods for testing, and, thus, will effectively reduce the need for rework and increase yield on the fabrication line.

MMIC chips require accurate calibrations which can account for the effects of the probe used in the measurements. Calibrations of the highest accuracy require significant and expensive space on the semiconducting wafer. Up to now, the commonly available commercial calibration methods relied on compact calibration sets based on imperfect calibration artifacts. Many engineers had no choice but to use them due to economic constraints. Ignoring the imperfections in the calibration artifacts, they accepted greater measurement uncertainty in order to conserve expensive wafer space.



CONSERVING WAFER REAL ESTATE

Accurate on-wafer measurements require the fabrication of calibration standards on the integrated circuit wafer. Standards for the accurate multiline TRL calibration method, drawn at the left, consume a large area of expensive wafer "real estate." A calibration that is nearly as accurate can be obtained using the modified LRM method, whose compact standard set is sketched at the right. The reduced size allows room for more of the valuable integrated circuits.

Williams and Marks have developed a procedure to characterize imperfect calibration artifacts, which makes it possible to obtain reduced uncertainty with compact calibration sets. The procedure involves two steps: a band-limited calibration and a broad-band calibration. First, an accurate but band-limited calibration is performed which is adequate for characterizing small resistor and line standards. This is achieved with an additional line standard of moderate length. Then, using the knowledge of the artifact's imperfections from the first calibration, the broad-band calibration is performed, which achieves the required accuracy.

This method overcomes the significant additional measurement uncertainty resulting from imperfections in the calibration artifacts and reduces the on-wafer "real estate," the space required on the wafer for the fabrication of a calibration set, to a fraction of that presently required for calibrations of the highest accuracy. A paper describing the NIST methodology, which is applicable to a wide variety of MMICs fabricated with both coplanar waveguide and microstrip transmission lines, won the 1993 Automatic RF Techniques Group Best Paper Award.

5.2 MMIC: Compensation for the substrate permittivity

Until recently, microwave measurements for MMICs required custom calibrations to account for and remove the effects of the probe and launch technique used to contact the devices or circuits being tested. This requirement, in turn, imposed another constraint: all of the calibration artifacts had to be manufactured on the same wafer as the structures to be tested. But, thanks to the efforts of NIST researchers Dylan Williams and Roger Marks, these constraints are no longer binding.

Williams and Marks have developed a model that accounts for differences in coplanar waveguide scattering parameter calibrations for MMICs performed on different wafers. Preliminary work indicates that the model, which accounts for capacitive effects introduced by the substrate permittivity, can be used to correct errors inherent in coplanar waveguide calibrations performed on a substrate that has electrical properties which differ significantly from the wafer on which measurements are performed. The Williams-Marks method only requires that the devices and circuits to be tested are embedded in a standard coplanar geometry.

This new, simple, and straightforward procedure eliminates the need for custom calibration by accounting for the errors of calibrations performed on a different substrate. Furthermore, it suggests methods for achieving traceability to national standards despite significant differences in the electrical properties of the calibration and measurement substrates.

5.3 New NIST antenna measurement range

NIST has created a multi-purpose (extrapolation, pattern, and spherical near-field) antenna measurement range, capable of making fast and accurate measurements of antennas up to 3.5 meters in diameter. The new range operates over a frequency range of 1 to 75 GHz.

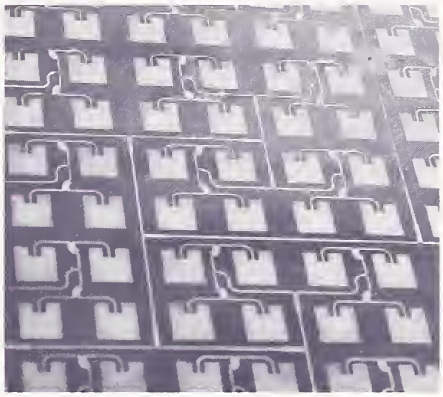
M I C R O W A V E S

A NIST team, consisting of scientists Katie MacReynolds, Nino Canales, and Jeff Guerrierri, has completed their initial evaluations of the range. These evaluations led them to redesign the absorber mounting for the antenna tower to reduce unacceptable multipath errors. A second problem uncovered by the evaluation measurements involved a commercial rotator, which was found to have an inherent resonance that increased probe antenna pattern uncertainties by 0.1 dB. This problem is being solved by a precision alignment of the rotator gears carried out jointly by the manufacturer and NIST.

U.S. industry will benefit in many ways from the new antenna range. In addition to enabling new measurement technology that can then be transferred to industry, users benefit through reduced costs and improved antenna system performance. When measurements are based on NIST standards, and these standards are improved, the quality of the entire national measurement network is upgraded. The enhanced capabilities afforded by the range will permit new calibrations and special measurement test services critical to industry and government laboratories for communication, radar, and other microwave systems. The demand for probe calibrations alone is so large that this range has measurements currently scheduled until August, 1995.

5.4 Element excitations of phased-array antennas

NIST scientists Carl Stubenrauch and Ronald Wittmann have developed software which will allow the accurate alignment and evaluation of phased-array antennas over a frequency range of 2 to 100 GHz. Within this category, U.S. industry is particularly interested in low-sidelobe antennas, anticollision radar antennas, and antennas used in aircraft landing systems. NIST continues to serve as a national resource for new techniques in the areas of planar near-field theory and measurements, scattering matrix theory, spherical near-field theory and measurements, cylindrical and plane polar near-field theory, range certification, millimeter wave measurements and position error correction.



ANTENNA ELEMENT EXCITATION

The software produced by the collaboration of Stubenrauch and Wittmann combines spectrum data acquired for phased-array antennas steered to various angles to obtain a complete spectrum unobtainable from a single-beam position alone. Excitation data computed from this complete spectrum can then be used in adjusting phase shifters to meet design specifications. Measurement uncertainties, steering errors, and various analytic approximations will all introduce errors into the alignment process. Wittmann and Stubenrauch have quantified the effect of these errors to more fully analyze the method, and to recommend possible improvements.

"I would like to take this opportunity on behalf of 3M Company to thank you for the valuable support your research group has provided to 3M. Dr. Jarvis and Michael Janezic have helped two of our key programs with their expertise in dielectric measurements of liquids. It was also a pleasure working with Dr. Geyer, Bill Riddle, Chriss Jones and Eric Vanzura on related techniques for other programs."

— Senior Physicist
Analytical and Properties Research Laboratory
3M Corporate Research Laboratories

5.5 Microwave characterization of HTS materials

A collaboration, now entering its third year, among NIST, the State Department and Jerzy Krupka of the Warsaw Polytechnic Institute of Poland is yielding results that could have a significant impact on the U.S. competitiveness in an area of intense international competition. The collaboration is carried out under the auspices of the Joint U.S.-Polish Marie Sklodowska-Curie Foundation and funded by the U.S. State Department.

Krupka and NIST scientists, led by Richard Geyer, performed ferrite characterization measurements in the 2 to 20 GHz range using a modified form of the Courtney dielectric rod-resonator method. They also characterized high-temperature superconductor (HTS) materials at liquid-nitrogen temperatures, using two dielectric rod-resonator fixtures that operate at 10 GHz and 25 GHz. The HTS materials under test have been obtained from different sources, including NIST's EEEL Electromagnetic Technology Division.

NIST scientists have also been in contact with Jim Hodges, of Illinois Superconductor Corporation, a NIST Advanced Technology Program (ATP) grantee, who is involved in developing thick-film HTS materials for cellular telephone applications. This firm as well as many others are very interested in obtaining NIST assistance in making radiofrequency measurements of the surface resistivity of their materials.

In response, given the international competitiveness aspects, NIST is investigating the feasibility of building a measurement fixture capable of operating at the frequencies of cellular telephony, near 1 GHz. Surface resistance measurements on HTS thin films are needed for developing the design and demonstrating the performance of microwave components, including resonators and delay lines.

5.6 Characterization of thin-film materials

New and lower cost thin-film dielectric materials are being sought by industry for applications, such as shielding. Effective shielding materials are needed to promote electromagnetic compatibility of electronic devices and systems and to protect devices and systems from electromagnetic interference. Devices of particular interest are connectors and printed-wiring boards. For these applications, the automobile industry has estimated potential savings of $100M if better characterization methods were available–for example, for permittivity–to lead to better-performance materials. The measurements of thin-film dielectrics need to be accurately calibrated in the frequency range from 30- to 1000-MHz and traceable to NIST to ensure that these materials perform as intended by designers of devices and systems.

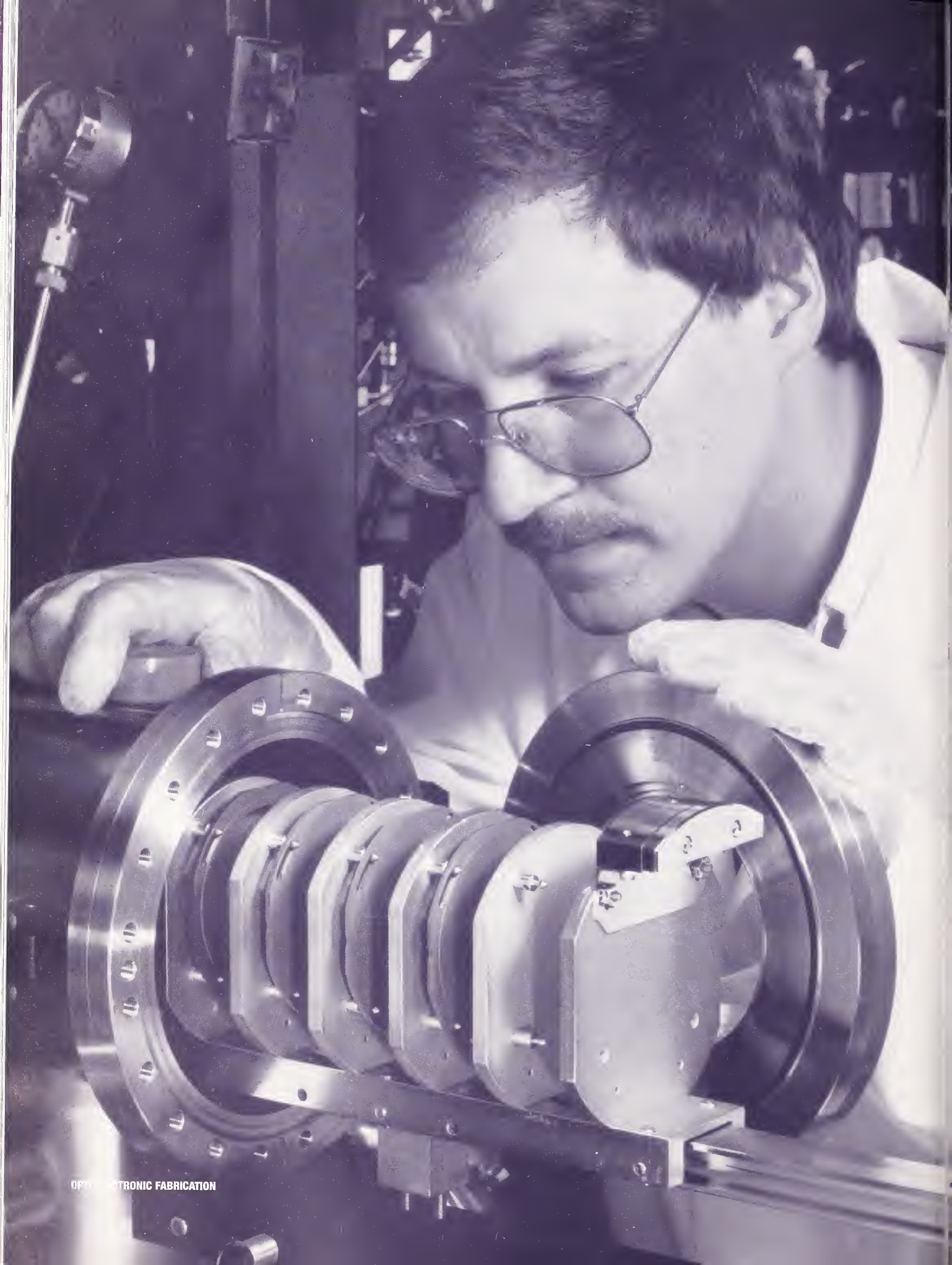
NIST scientists Jim Baker-Jarvis, Mike Janezic, Chriss Jones, and John Grosvenor have developed a new measurement technique for determining the microwave properties of thin lossy polymer films (thickness on the order of 25 μm). These properties include dielectric constant and loss tangent. The technique is specifically useful in the 30- to 1000-Hz frequency range where resonator techniques are not practical. The material-under-test is placed between two flanged sections of 77 mm-diameter coaxial air lines, fed by two tapered 7-to-77 mm diameter transitions. This technique is an extension of an earlier NIST single coaxial probe technique which is not applicable to thin films. The required software has been developed and is now routinely used. Currently, the measurement errors created by the unavoidable presence of air gaps between flanges and film are currently being investigated.

5.7 Radar cross-section measurement uncertainties

In a study of major government facilities, staff of the Electromagnetic Fields Division have identified significant sources of measurement uncertainties encountered in both static and dynamic radar cross-section ranges. NIST principal investigators Lorant Muth, Ronald Wittmann, and Richard Lewis collaborated with many Department of Defense laboratories, including Patuxent River Naval Air Test Center, Holloman Air Force Base, Wright Patterson Air Force Base, the Naval Warfare Surface Center, China Lake, Point Mugu, Radar Target Scatter (RATSCAT) Division, and Eglin Air Force Base in this effort. Radar cross-section is a parameter that defines how easy it is to detect the presence of an object illuminated by a radar beam for a given orientation of the object with respect to the beam. Radar cross-section measurements are used to determine the stealthy performance of aircraft and missiles and other military vehicles; they are now becoming of interest for civilian applications, including air traffic control, highway traffic control, and shipping operations. The Division team developed methods for estimating component uncertainties and for combining these into an overall uncertainty budget. The goal was to provide a reasonable and uniform methodology for evaluating radar cross-section measurements that can be used for both indoor and outdoor test ranges to produce compatible estimates of uncertainty. A benefit of the process is that uncertainty estimation identifies sources of error on which attention needs to be concentrated to improve measurement quality. The team studied and compared alternative methods of estimating uncertainties. The overall uncertainty budget for a specific measurement was developed as a hierarchy of uncertainty budget tables, where the lower-level tables provide the details which are summarized in the upper-level tables. A spreadsheet computer program was developed to facilitate the construction of such a hierarchy of uncertainty tables. A thorough analysis of measurement uncertainty is a first step in the development and implementation of a program for certifying radar cross-section ranges. Additional details can be found in a report entitled *Proposed Uncertainty Analysis for RCS Measurements* (NISTIR 5019).

"It is my pleasure to commend you and your colleagues at the National Institute of Standards and Technology (NIST) for the successful completion of our High Power Microwave Measurement System (HPMMS). This system has been in nearly continuous operation...and we have not experienced a single failure in any component subsystem. The system has proven to be a valuable addition to our high power microwave measurement capability, which as you know, is critical to many of the Army weapons, radars, and communications systems....In closing, I believe your work on the HPMMS has made significant contributions to the state of the art in high power microwave measurement metrology."

— Senior Engineer
Electrical Standards Laboratory
U.S. Army Primary Standards Laboratory Directorate

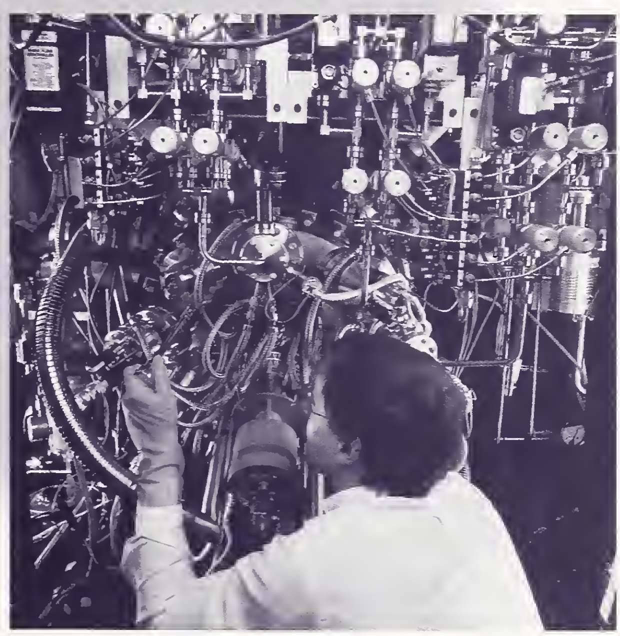


OPT… TRONIC FABRICATION

Accomplishments

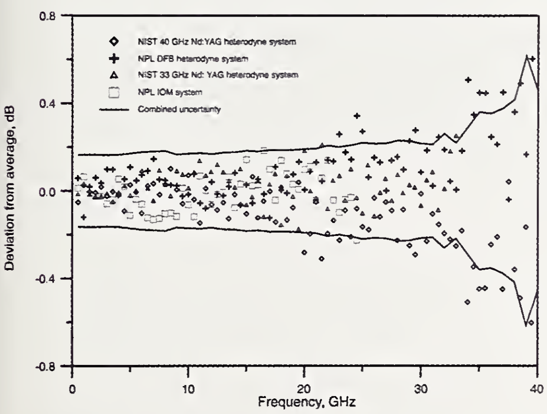
"Honeywell would like to express our appreciation for the contributions that you have made to the waveguide amplifier program. Your expertise in measuring our sample parts combined with your suggestions on how to proceed to the next sample has proven invaluable to the success of our program."

— Principal Developmental Engineer
Military Avionics Division
Honeywell, Incorporated



OPTOELECTRONIC BEAM EPITAXY SYSTEM

6 LASERS



HIGH SPEED OPTICAL DETECTOR MEASUREMENTS

Comparison of frequency response measured by four different measurement systems at NIST and NPL. Detector 3 dB (electrical) bandwidth is 16 Ghz.

6.1 Frequency response comparisons of high-speed detector

NIST scientist Paul Hale, in collaboration with staff of the National Physical Laboratory (NPL), United Kingdom, undertook a comparison of the frequency response measurements of a high-speed optical detector (an InGaAs photodiode) which revealed good agreement between the two national standards laboratories.

For this project, two systems provided by NIST were compared with two NPL systems. Each showed good agreement below 30 GHz ($\pm$0.15 dB at 2σ). However, deviations above 30 GHz (averaging $\pm$0.78 dB) evidenced a possible need to investigate present microwave power calibrations. The results of the collaboration were reported at a Society of Photo-Optical Instrumentation Engineers (SPIE) conference.

Hale has succeeded in modifying the NIST frequency response measurement system to allow high-resolution (300 kHz), reduced uncertainty (below 0.3 dB) measurements on Synchronous Optical Network, (SONET) reference receivers. The system has been used to calibrate three receivers in a special test for industry customers. Hale's work to extend measurement capability to higher and lower frequencies will continue as accurate detector frequency response is critical for characterization of the receivers used in digital and analog optical communication systems.

Initiated in response to the requests of the U.S. communications industry, this program is a first step toward establishing a measurement service or Standard Reference Material for optical detector frequency response. It will also assist in the international effort to provide consistency among national laboratories.

"Paul Hale's frequency response measurements at 1319 nm are very valuable, as he has already gone to higher frequencies, at ten times better accuracy, than anything previously available. Previously, we relied on a loosely-controlled, non-continuing measurement intercomparison to obtain a consensus standard. Paul is now the most significant researcher in the world determined to perfect frequency responsivity standards for the 1319 nm YAG heterodyne laser system....At low frequencies (1 MHz to 3 GHz), we need very high resolution to meet current, critical needs in the telecommunications industry. At high frequencies, we want reliable measurements beyond 50 GHz for new products now being developed....It is also very important to note that Paul's work has been of great help to the American telecommunications industry even though it is work in progress. Rather than wait years for the complete perfection of this work, Paul has been providing intermediate results. Intermediate results are vastly superior to no results at all, and we are greatly benefiting from this work even while it is being improved one step at a time."

— Standards Lab Manager
Hewlett-Packard Lightwave Operation
Hewlett Packard Company

6.2 New system for calibrating optical power meters

Measurement laboratories in U.S. companies involved with optical fiber telecommunications generally use diode laser sources whose center wavelengths differ from the wavelengths commonly used at NIST. Thus, until recently, to apply NIST's calibration results to test meters submitted for evaluation, the meter user had to know the spectral responsivity of the meter as well as the source wavelength. Now, as a result of the efforts of Igor Vayshenker and Xiaoyu Li, NIST can provide its customers with calibration results in a more directly useful form.

Vayshenker and Xiaoyu have constructed and tested an optical power meter measurement system that can calibrate the user's meter at the user's laser source wavelength, or provide the user with spectral responsivity information for the detector used in the power meter.

The scientists developed a wavelength-tunable system to calibrate meters using either collimated-beam or fiber-connector configurations. Their system uses tunable laser diodes that operate in the three fiber optics windows of 850, 1310, and 1550 nm, and have nominal tuning capability of about ±30 nm, providing the capability to perform absolute power calibrations at customer-specified wavelengths or high-resolution spectral responsivity measurements in these regions.

The new system is already being used to perform power measurements on optical power meters as part of special test calibrations, and to perform limited spectral responsivity measurements on optical detectors. It is also being used to perform test reflectivity measurements on specially coated InGaAs detector samples.

6.3 Excimer laser calibration capability developed

In response to numerous requests from the growing number of excimer laser users in industry who require accurate and traceable measurements, NIST researchers Rodney W. Leonhardt and David J. Livigni, working in collaboration

LASERS

with SEMATECH, have established the capability to calibrate power and energy meters used for detecting KrF excimer laser radiation at a wavelength of 248 nm. Measurements in this wavelength region are needed in particular by users and manufacturers of excimer-based semiconductor photolithography systems and by manufacturers and users of all excimer laser measurement equipment. Excimer lasers are widely used in ultraviolet lithography, materials processing, and medical applications such as corneal sculpting. The new capability represents a significant extension of the NIST laser measurement service to ultraviolet laser wavelengths. The measurement system was developed and characterized by the Division with SEMATECH support and consists primarily of standard isoperibol calorimeters along with a calibrated fused-silica beamsplitter. SEMATECH has provided the calorimeters and associated data acquisition system to NIST under a long-term loan agreement, and also provided software support to adapt this system to NIST use.

6.4 First passively Q-switched solid-state waveguide laser

A team of NIST scientists, consisting of Andrew Aust, Kevin Malone, David Veasey, Norman Sanford, and Alexana Roshko, has achieved a breakthrough in the development of a new laser, the first reported passively Q-switched, solid-state waveguide laser. Potential applications for their device include laser radar, sensors, biotechnology, and medicine.

The team's demonstration of the laser established that its output pulses had full-width-half-maximum of approximately 25 ns and peak power of 3 W. The device makes unique use of an organic dye saturable absorber embedded in a thin polymer sheet to accomplish the Q-switching function. As a result, the otherwise passive glass-waveguide laser can be Q-switched without requiring any electronic drive circuits as do other types of waveguide lasers.

Lasers based on the NIST development should be inexpensive and easy to manufacture since the Q-switching function is performed by the passive saturable absorber which can be bonded readily to the waveguide. The device was optically pumped at a wavelength near 800 nm. A passively Q-switched waveguide laser is simpler in operation than commonly used active Q-switching methods, and well suited for many applications. In combination with a laser diode pump, finished laser packages could be quite compact.

The work of this program derives from a Cooperative Research and Development Agreement with Schott Glass Technologies, suppliers of the special glass material used to fabricate the device. The material allows a high-powered pulsed output in the glass.

"Don Larson's frequency responsivity measurements at 850 nm have proven invaluable to us, since Don is presently our sole source in the world for this type of work. We cannot get these measurements at this important wavelength from any other authoritative, independent source....It is also quite significant that Don conducted this as a 'Measurement Intercomparison Program,' not as a NIST calibration service. NIST makes great effort to develop the finest calibration standards in the world, but that process usually takes many years. In the meantime, while American industry is venturing into new technology and in the greatest need of help from NIST, that help often isn't available. HP strongly encourages NIST to develop more intercomparison programs, and more best available interim standards while on the path to those ultimate standards, to significantly benefit American industry during the struggling, early years of a new technology."

— R&D Functional Manager
Hewlett-Packard Lightwave Operation
Hewlett Packard Company

OPTICAL FIBER MEASUREMENTS FOR INDUSTRY

Accomplishments

On the development of Standard Reference Material (SRM) 2520:

"The opportunity to work with NIST on this gave Corning and other American fiber manufacturers a clear competitive advantage."

— Executive Vice President
Corning Incorporated

SRM 2520: OPTICAL FIBER DIAMETER STANDARD

7 OPTICAL FIBER COMMUNICATIONS AND SENSORS

Measured Parameter	Average Measurement Spread (one standard deviation)
Outer Layer Diameter, μm	1.85
Inner Layer Diameter, μm	3.22
Outer Layer Concentricity, μm	0.76
Inner Layer Concentricity, μm	0.79
Outer Layer Noncircularity, %	0.22
Inner Layer Noncircularity, %	0.83
Min. Outer Layer Thickness, μm	2.21
Min. Inner Layer Thickness, μm	1.52
Max. Outer Layer Thickness, μm	2.54
Max. Inner Layer Thickness, μm	1.33
Min. Combined Thickness, μm	1.46
Max. Combined Thickness, μm	1.24

ROUND ROBIN MEASUREMENT COMPARISON

Participants measured 3 different specimens of each of 6 comparison fibers, including 3 standard dual-coated fibers and 3 non-standard fibers. The sample standard deviation is calculated for all measurements on a given fiber and then arithmetically averaged over all fibers, to report the average measurement spread for a given parameter.

7.1 Round robin for optical fiber coating geometry

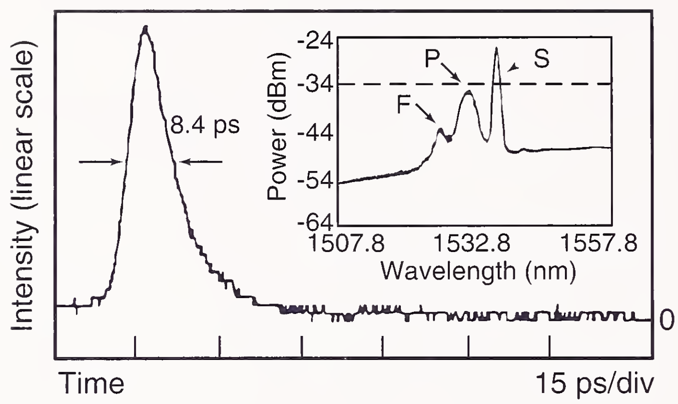
Evidence of EEEL's fulfilling its mission to provide the electronics industry with timely metrology support is the response of NIST principal investigator Timothy Drapela to a request from the Telecommunications Industry Association (TIA) for an evaluation of an industry-wide testing procedure.

Drapela conducted an evaluation of industry test procedures for measuring the geometrical parameters of optical fiber coatings (the outer plastic coating surrounding the fiber), which are important parameters in connector manufacture. He organized a round-robin comparison, stipulating four different optical methods to be used by participants. Over 1000 measurements (12 coating parameters measured on each specimen) from eight laboratories were recorded and analyzed, and reported to the TIA. The results were in good agreement. To simplify the continuation of positive industry practice, NIST is considering the development of a fiber-coating standard reference material, also at TIA's request.

7.2 All-optical sampling with picosecond resolution

Several non-linear properties of optical fiber are of interest in lightwave communications. Among these is four-wave mixing resulting from the optical Kerr effect. NIST scientists Doug Franzen and John Schlager working with M. Jinno, a guest scientist from the Nippon Telegraph and Telephone Corporation, have decided to capitalize on four-wave mixing to demonstrate a sampling technique to acquire high-speed waveforms.

PICO-SECOND RESOLUTION OPTICAL SAMPLING
Optical sampling of 8.4ps pulse with 2.5ps probe pulse using four-wave mixing in a semiconductor optical amplifier showing S, signal; P, probe; and F, four-wave mixing components.



"Tom Scott's work in optical power calibration services has been indispensable to us, since the fundamental measurement of power is a common denominator to nearly every type of fiberoptic test instrument being manufactured. Tom's calibrations form the infrastructure of our business. It sometimes seems easy to shift attention, resources, and money to glamorous research areas but we absolutely cannot neglect our foundations. We have been very pleased with the services Tom and his team have been providing for us, but we need more. In particular, we need spectral responsivity, and dynamic accuracy calibrations."

— Standards Lab Manager
Hewlett-Packard Lightwave Operation
Hewlett Packard Company

One strong advantage of all-optical sampling is its reliance on optical rather than electrical means to achieve high-speed performance. The team used four-wave mixing in a semiconductor optical amplifier to demonstrate all-optical sampling having picosecond time resolution and high signal-to-noise ratio. Also, a high-resolution optical time-domain reflectometer was demonstrated using four-wave mixing as a sampling gate. Millimeter resolution with high sensitivity was achieved on short fiber lengths.

Jinno reported the results obtained by the NIST sampling system at the Optical Amplifier Conference; the findings were also presented at a Conference on Lasers and Electro-Optics (CLEO) workshop.

7.3 High demand for optical fiber geometry SRMs

Matt Young, Timothy Drapela, and Steve Mechels created a standard reference material (SRM) for which there is so much demand that it "sells off the shelf." In FY 1994, the group had to set aside ongoing investigations temporarily to meet an urgent delivery schedule for 15 additional optical-fiber geometry SRMs.

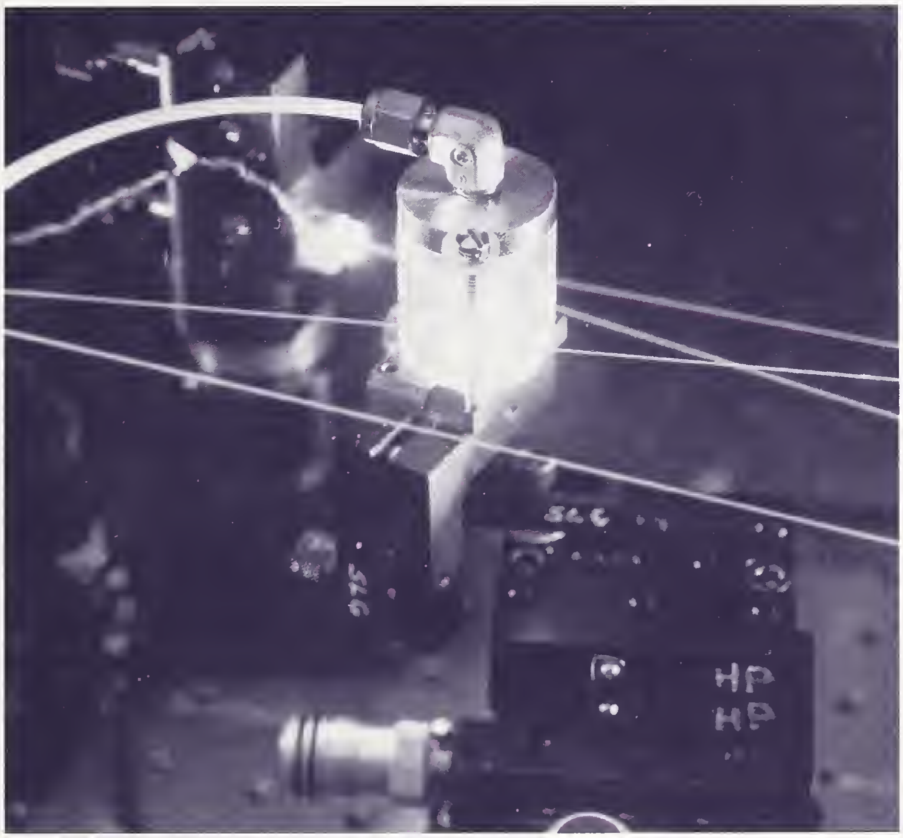
At the heart of each SRM 2520 is an optical fiber whose diameter has been more accurately measured and certified than routinely by any other organization in the world. In the hands of the engineers at an optical fiber plant, an SRM 2520 serves as a calibrated "ruler" by means of which they can adjust the control parameters of the pulling towers used to manufacture fiber. All major U.S. fiber manufacturers are now using the NIST SRM to monitor the uniformity of their own commercial fibers. With SRM 2520, uncertainty in the measurements of fiber diameters now vary within about one-tenth of a micrometer, which is about one fifth of the uncertainty that was available before.

The demand for SRM 2520 continues to increase as the nation's optical fiber networks expand their local-area-networks. This phase of growth, laying optical fibers from major optical cables to individual buildings, homes, and offices, entails large-scale branching and joining of fibers, resulting in higher costs per unit length of fiber installed as compared to long-distance lines, which require far fewer connections to be made. Fibers and connectors with increasingly more exact dimensions are needed to reduce joint loss to acceptable levels. Variation in fiber diameters results in misalignment of the fiber cores, with consequent large signal losses introduced by each connection. Young, Drapela, and Mechels are currently working to develop additional standards to measure the diameters of ceramic ferrules that are used to connect fibers into continuous signal paths.

7.4 Method and standard for polarization-mode dispersion

The success of NIST scientist Paul Williams' investigation into an important effect leading to signal degradation as bandwidth reduction with distance in single-mode fiber has resulted in a collaboration with the Telecommunications Industry Association (TIA) to undertake

OPTICAL FIBER



OPTICAL TRAPPING WAVELENGTH STANDARD

a characterization of polarization-mode dispersion (PMD). As part of the NIST contribution, Williams has completed the development of an artifact that simulates polarization-mode dispersion in long fiber lengths, and established a wavelength-scan measurement system for polarization-mode dispersion in optical fibers.

Williams' wavelength-scan system will be used to characterize the artifact and determine PMD in telecommunication fibers. A round robin with TIA members to evaluate measurements methods for PMD has been started by Williams; two artifacts and a long length of fiber are being measured by TIA participants.

7.5 High-accuracy wavelength standard

In a highly competitive environment, such as the field of optical communications, the gap between metrology development and what's needed on the factory floor is ever-narrowing. The work of a NIST scientist, Sarah Gilbert, and a student from the University of Colorado, Gwenn Flowers, illustrates this point well. Gilbert and Flowers completed a second-generation optical trap for a high-accuracy wavelength standard (0.00001 nm), based on a rubidium transition. The new trap has several improvements which reduce effects of background gas, improve the laser beam uniformity, and improve the response time to changes in rubidium vapor pressure.

"Sarah Gilbert's work on gas absorption cells as wavelength standards shows great promise in a fundamental, essential area of fiberoptic technology....Wavelength and power measurements are the two common denominators for every fiberoptic measurement made, so this is essential work. Present wavelength calibrations are usually performed with a combination of single-line gas lasers, and multiple-line discharge gas lamps. However, there are significant gaps in wavelength coverage with these methods, most notably in the 1550 nm region which is so important for long-haul telecommunication systems (such as underseas cables). Sarah's work with acetylene, ammonia, and other compounds could fill that gap."

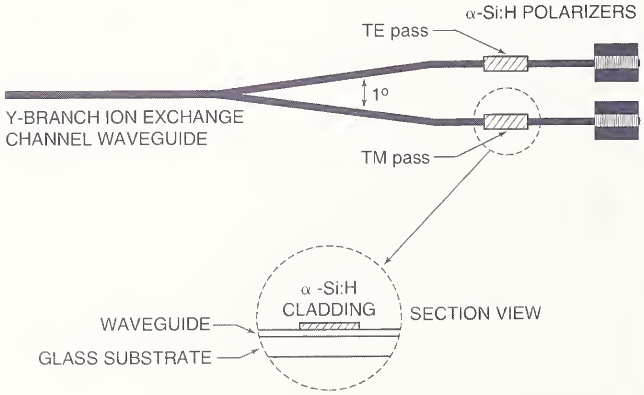
— R&D Functional Manager
Hewlett-Packard Lightwave Operation
Hewlett Packard Company

Accomplishments

At present, their standard serves primarily as a reference for the calibration at NIST of the moderate-accuracy standards (0.01 to 0.001 nm) currently needed by some of the major U.S. companies. However, Gilbert and Flowers report that U.S. industry will require high-accuracy wavelength standards in the near future.

7.6 Optical polarization diversity receiver

David Veasey was the NIST principal investigator of a project which devised a fully integrated optical polarization diversity receiver (PDR). Veasey undertook this project in response to inquiries from U.S. companies involved in two related fields: intelligent vehicle sensor applications and machine tool applications. A Cooperative Research and Development Agreement was established to study possible vehicle sensor applications, which yielded a prototype receiver for the partner firm. NIST co-worker Don Larson and Veasey were awarded a patent for a localized plasma processing technique used in the work. PDRs provide a means for separating the components of an incoming signal of mixed polarizations and are used in sensing and communications applications such as polarimetric optical sensors, machine tool positioning sensors, magnetic read-head positioning systems, optical read-heads for compact disk drives, and coherent communication systems.



OPTICAL POLARIZATION DIVERSITY RECEIVER

The NIST receiver exhibits the advantages typical of integrated optical devices, being small (2 mm by 20 mm), rugged, and easy to fabricate. It consists of a Y-branch waveguide splitter with a one-degree splitting angle, formed by potassium-sodium ion exchange in silicate glass. A hydrogenated-amorphous-silicon cladding is deposited on each branch of the splitter to act as a polarizer. One output cladding is trimmed to a thickness that attenuates the component of guided light having a transverse electric field, while the other cladding is trimmed to attenuate light having a transverse magnetic field. Extinction ratios of 27 dB have been demonstrated. The device is completed with the deposition of metal-semiconductor-metal photodetectors on each of the output waveguide branches following the polarizers. Amorphous silicon claddings are contacted with chrome-gold interdigitated finger Schottky contacts to form the detectors, which have bandwidths on the order of 5 GHz.

7.7 High-speed optical-fiber current sensor

Electric-current sensors made from optical fiber are useful in a variety of industrial and military environments which pose problems for conventional electrical sensors. NIST scientist Kent Rochford has succeeded in designing and constructing a compact high-sensitivity (about 0.7 deg/A), high-speed (about 500 MHz 3dB bandwidth) optical-fiber current sensor based on iron garnet crystals. The new sensor is much simpler to manufacture than a similar sensor built previously at NIST and has a sensitivity-bandwidth product that is about 40 times greater.

Rochford's device exploits coated right-angle prisms to produce the required right-angle reflections without the phase shifts which distort the polarization state. His design requires only half the number of prisms as the first-generation device and is much simpler to assemble.

7.8 Novel iron garnet materials

NIST scientist Merritt Deeter and Guest Scientist Sylvia Milián Bon (University of Twente, the Netherlands) collaborated with personnel at Deltronic Crystal Industries of Dover, New Jersey, to characterize the magneto-optic properties of a large set of novel iron garnet materials. Working under a Small Business Innovation Research (SBIR) Program grant, Deltronic grew over 100 iron garnet compositions tailored specifically for magneto-optic sensing. Measurements made on these materials provide basic materials data for use in the design of a new family of optical-current and magnetic-field sensors.

During the course of their investigation, Deeter and Bon performed frequency response and magneto-optic sensitivity measurements on 24 iron garnet samples, and presented their findings at the 6th Joint MMM-Intermag Conference in June, 1994. The samples exhibited more than an order of magnitude greater normalized magneto-optic sensitivity, about 12.6 deg/A for one sample compared to about 0.14 deg/A for pure yttrium/iron/garnet (YIG). The samples also showed an improved 3dB frequency bandwidth, about 1 GHz for certain compositions as compared to about 700 MHz for pure YIG.

OPTICAL-FIBER CURRENT SENSOR

7.9 Linear retardance standard

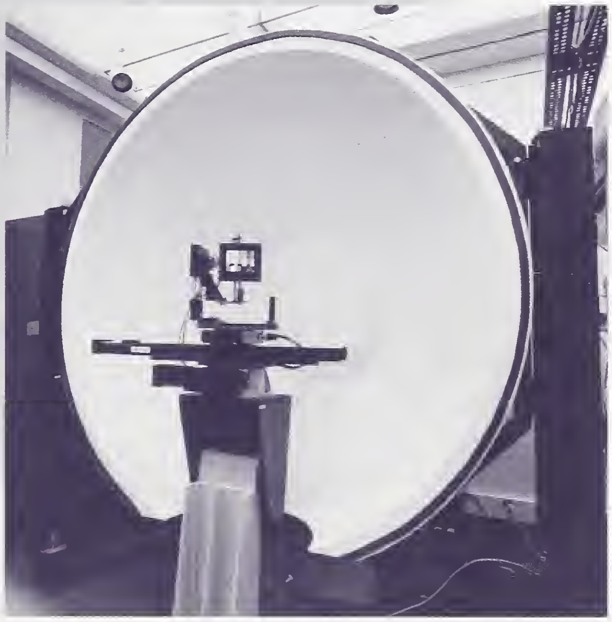
NIST scientists Allen Rose, Kent Rochford, and Paul Williams, working together with Ian Clarke of the University of Sydney, Australia, have completed the design and demonstration of a potential standard for linear retardance at the telecommunication wavelengths of 1.3 µm and 1.5 µm. This program responds directly to the needs expressed to NIST by manufacturers of polarization optics, who require a standard to verify the performance of measurement systems, and by instrument manufacturers who require a calibration standard.

The team's design utilizes total internal reflectance in two rhombs of a special glass to achieve a retardance of about 90° which is stable with temperature and nearly independent of wavelength and angle of incidence. Work on the project continues as investigators test a packaging design for the standard. Once accomplished, NIST hopes to certify the retarder as a Standard Reference Material. Plans are also underway to modify the standard to make it suitable for shorter wavelengths (800 nm).

"Kent Rochford's team has been developing a polarization standard....This is very important work, as no adequate polarization standards presently exist in the world to meet the needs of the American fiberoptic telecommunication industry....In particular, we very much need both standards and recommended procedures for PDL (polarization dependent loss), and PMD (polarization mode dispersion)."

— R&D Functional Manager
Hewlett-Packard Lightwave Operation
Hewlett Packard Company

VIDEO MEASUREMENT LABORATORY



OPTICAL INTEGRATING SPHERE

8 VIDEO

8.1 Flat panel video measurement laboratory

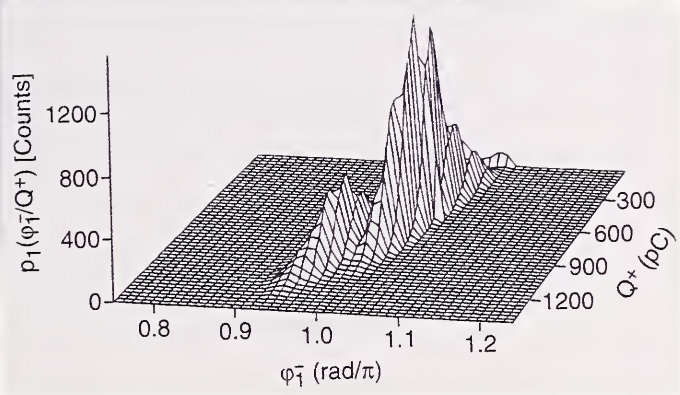
At present, there is no established standard, or industry-wide practice, which would enable U.S. industry to methodically compare flat panel displays being produced by different manufacturers. Subjective evaluations by panels of viewers are no substitute. Manufacturers' use of proprietary measurement practices exacerbates the problem of how to evaluate the state-of-the-art in the development of these components. NIST has been asked to address the challenge of video quality metrics, which if not met will continue to have a deleterious impact on the effort of U.S. industry to regain the lead in a highly competitive environment.

In response, NIST scientists Ed Kelley and Bruce Field have established a laboratory to evaluate flat panel displays both optically and electronically. The outcome of this effort will be the development of a set of industry accepted standards and procedural tests. The results will also contribute to models for predicting display performance.

Investigations in the new laboratory are focusing on colorimetric and electrical measurement and the specification of pixelated flat-panel displays. A variety of photometers, colorimeters, signal sources, signal monitors, and mechanical positioning systems have been adapted, calibrated, and integrated into a versatile automated laboratory capable of characterizing the performance of emissive and transmissive panel displays. Examples of the measurements Kelley and Field are undertaking are uniformity, contrast ratio, gray scale/linearity, viewing angle, and individual pixel characterization.

MEASUREMENTS FOR TRANSMISSION AND GENERATION OF ELECTRICAL POWER

Accomplishments



RELATIONSHIP BETWEEN AMPLITUDE OF FIRST NEGATIVE PULSE AND POSITIVE INTEGRATED CHARGE

Influence exerted by the total charge transferred between two electrodes on the positive half cycle on the phase-of-occurrence of the first negative pulse. The electrodes are separated by an insulator. The influence is due to charge removed from the surface of the insulator by the positive pulses. As can be seen, as the amount of charge removed increases, the first pulse occurs earlier on the negative half cycle.

9 POWER

9.1 Effect of oxygen on electrical discharges in SF_6

The compounds S_2F_{10} and $S_2O_2F_{10}$ are known to be extremely toxic to humans. For those who employ SF_6 as an insulating gas in electric-power systems, the production of these compounds as a result of conditions of use is of major concern. NIST scientists Richard Van Brunt and James Olthoff have studied the effect that common contaminants such as oxygen will have on the formation of these compounds when electrical discharges occur in SF_6. The measurements developed as an outcome of their work provide one of the first indications of the significance of the presence of oxygen on S_2F_{10} and $S_2O_2F_{10}$ formation rates in corona. This work provides the electric utility industry the information it needs to address any safety concerns arising from the use of SF_6 in transmission and distribution systems.

Van Brunt and Olthoff discovered that the production of highly toxic S_2F_{10} from electrical discharges in SF_6 can be significantly reduced with the addition of small quantities of oxygen. The rates for production of S_2F_{10} and of two other species of unknown toxicity, $S_2O_2F_{10}$ and S_2OF_{10} have been measured in both spark and negative glow corona generated using point-to-plane electrodes in SF_6 and SF_6/O_2 mixtures. In pure SF_6, the production rates for S_2OF_{10} and $S_2O_2F_{10}$ are an order-of-magnitude or more below that of S_2F_{10} in both types of discharges. With the addition of 1% O_2, there is a dramatic drop in the S_2F_{10} yield from both discharges with a corresponding increase in S_2OF_{10} yield from the spark and $S_2O_2F_{10}$ yield from the corona. The results can be explained from considerations of the competition among the reactions of SF_5 radicals with SF_5, O_2, and O and the relative degrees of O_2 dissociation in the two types of discharges. A presentation which discusses the results of this work, carried out in conjunction with a consortium consisting of utilities and national laboratories, including Oak Ridge National Laboratory and Hydro Quebec Research Laboratory, was given at the 1994 Gaseous Electronics Conference.

9.2 Model for SF_6 oxidation and decomposition

Richard Van Brunt, of the Electronics and Electrical Engineering Laboratory and John Herron, of the Chemical Science and Technology Laboratory, have developed a "complete" theoretical model for SF_6 chemistry in corona discharges. To date, their zonal plasma chemical model has added significantly to the understanding of how SF_6 decomposes and why the decomposition leads to the formation of certain oxidation by-products.

The model, which is being used to account for the observed oxidation and decomposition of sulfur hexafluoride (SF_6) by negative glow-type corona discharge in pressurized $SF_6/O_2/H_2O$ gas mixtures, yields the dependences of the major stable neutral oxidation by-product concentrations on time, discharge current, and O_2 and H_2O concentrations that are consistent with measured results. In addition, the model allows identification of the predominant sources of oxygen in the formation of the oxygenated species SOF_2, SOF_4, and SO_2F_2, and gives a better prediction of the S_2F_{10} production rate than the earlier model.

The development of the model required determinations and adjustments of numerous reaction-rate coefficients. A detailed sensitivity analysis was performed to determine the relative importance of each of the more than 100 reactions included in the model. Problems of uniqueness that arise because of gaps in the knowledge about important processes that need to be considered were analyzed. A detailed description of the model together with the results from numerous calculations has been prepared for archival publication. Although not totally completed at this time, the model is effectively helping to explain results of recent experiments conducted at NIST and elsewhere.

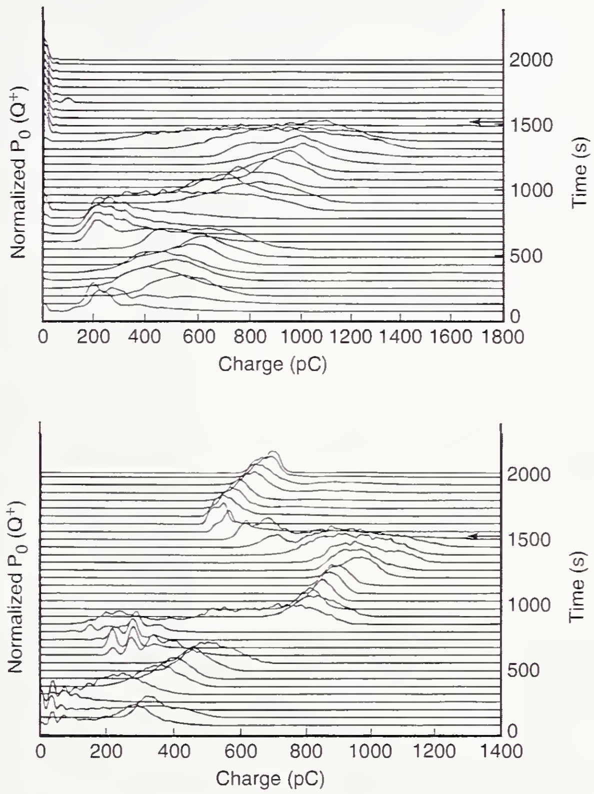
9.3 Digitizer and system for recording partial discharge

Richard Van Brunt and Peter von Glahn have completed the first step necessary to commercialize the stochastic analysis approach applied to the measurement of partial-discharge phenomena. Partial-discharge (PD) measurements are used to monitor the integrity of electrical insulation in high-voltage equipment. Van Brunt and von Glahn have designed, developed, and exercised a new digital partial-discharge recording system capable of real-time recording of continuous PD pulse trains for later off-line computerized stochastic analysis.

The new system, which replaces an existing analog recording system, also supersedes the existing NIST analog PD analysis system [1990 R&D 100 Award winning Stochastic Analyzer for Pulsating Phenomena (SAPP)] because it allows a much more efficient use of available information at a much lower cost. Also, because the new system is much more portable than the SAPP, it is more likely to be useful in factory or field testing of electrical equipment. The system developed by Van Brunt and von Glahn represents the hardware end of a proposed multi-dimensional multi-channel analyzer. Potential customers include instrumentation manufacturers and the electric utilities, which require advanced diagnostic equipment to monitor and extend the useful life of their installed high-voltage equipment.

The Van Brunt-von Glahn recording system consists of a custom two-channel PD digitizer coupled to a new 16-bit parallel digital interface installed in a personal computer. The digitizer is under software control with resulting data being stored in binary files on a computer hard disk. The system allows continuous recording of PD pulses for many hours, and is far superior to present commercially available recording systems in storage capacity alone. Software is being developed that will allow a complete stochastic analysis of the data.

The recorder has already proven useful in the investigation of PD-induced aging of dielectrics and shows promise of providing detailed stochastic signatures that could be useful in development of advanced PD pattern-recognition schemes now being tested in a number of different laboratories.



TIME HISTORY OF POSITIVE AND NEGATIVE INTEGRATED CHARGE DISTRIBUTION

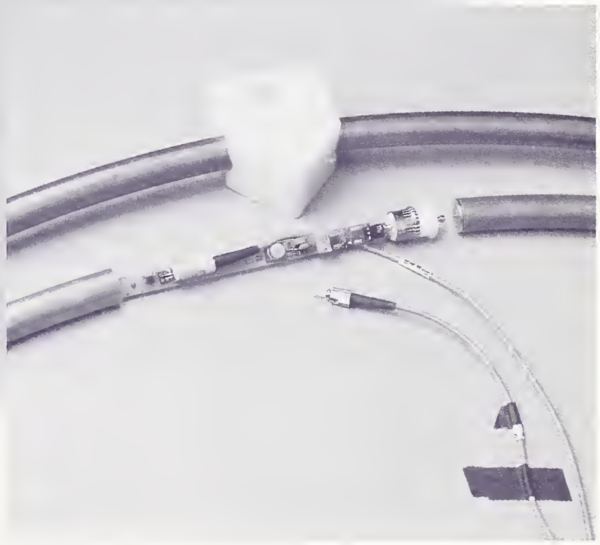
The total charge transferred between electrodes varies over time due to the aging of an insulator separating the electrodes. One set of curves is for charge transferred during the time the ac excitation is positive and the other when it is negative. Each curve plots the probability distribution of this total charge for a 60 s period. All curves are arbitrarily normalized to a maximum of 1.0.

TEST METHODS FOR EM EMISSIONS

Accomplishments

"...to offer our support for your efforts to conduct *in situ* measurements inside anechoic chambers with time domain pulse techniques that will later yield time domain digitized data....Lehman Chambers has developed a 3-D Finite Difference Time Domain (FDTD) computer modeling program for the design and analysis of anechoic chambers for EMC applications. The work NIST is intending to do will further validate our techniques and is of extreme interest to us."

— Program Manager
Lehman Chambers
Paul E. Lehman, Incorporated



ELECTROMAGNETIC FIELD SENSING ELEMENT

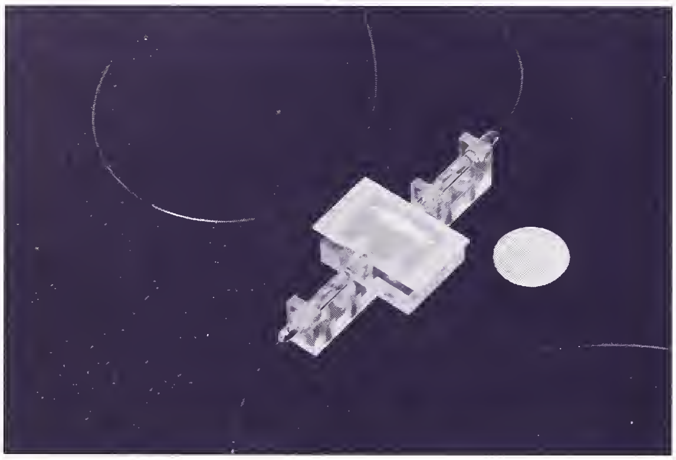
10 ELECTROMAGNETIC COMPATIBILITY

10.1 Three-axis magnetic flux density probe uncertainties

NIST scientists Martin Misakian and Charles Fenimore have carried out computations to improve measurements of power-frequency magnetic fields from localized sources such as home appliances, office equipment, machine tools, and electrical and electronic systems in transport vehicles. This NIST work responds to the increasing concern for possible health effects resulting from exposure to such sources. Since the sources behave more nearly as point sources than as extended sources such as electrical transmission lines, and since there are frequently a number of sources to be considered in a given environment, the magnetic fields experienced can be highly nonuniform, particularly near electrical equipment such as motors, transformers, and heating elements. This situation complicates the measurement of magnetic fields, since there can be a significant difference between the field at one point and at another point only a few centimeters away. The probes that sense fields are typically in the form of circular coils, and the measured flux density is averaged over the cross-sectional area of the coil. Additional measurement uncertainties arise because this value is not necessarily the same as the value of the flux density at the presumed measurement location at the center of the coil.

Misakian and Fenimore calculated the resulting additional uncertainties for a number of coil diameters with the assumption that the magnetic field was produced by a small loop of alternating current, i.e., a magnetic dipole. The magnetic dipole field was chosen because its geometry approximates the field geometry of many electrical appliances. The team calculated additional uncertainties for single-coil probes and for probes having three mutually perpendicular coils.

Accomplishments



PHOTONIC ELECTROMAGNETIC FIELD SENSOR

For three-axis probes, the maximum differences found from the calculations were for the probe positioned in the equatorial plane of the dipole. For all probe positions, the central field exceeded the average field. Misakian and Fenimore were able to show that for distances less than ten probe-radii away from the dipole field source, these differences exceeded 1%. Differences could be as great as 20% for distances less than three-probe radii from the source. The results of the calculations are being incorporated into the draft of an Institute of Electrical and Electronics Engineers (IEEE) standard on instrumentation used for measuring extremely low-frequency magnetic and electric fields, under development at NIST in collaboration with committees in the IEEE Power Engineering Society. Details of the calculation and tabulations of the measurement uncertainties as a function of probe radius and distance from the field source have appeared in two papers published in the *NIST Journal of Research*.

10.2 Shielding and cavity characteristics of airframes

Parents flying off on holiday with small children often wonder why they're asked to be sure that the kids' electronic toys are shut off in the immediate intervals before taking off and landing, and business persons have been known to protest vigorously and demand to know why they are instructed to turn off their computers for the same periods of time. NIST scientists David Hill, Robert Jonhk, Arthur Ondrejka, and Dennis Camell are helping to provide answers to this question and to related electromagnetic/compatibility interference issues that impact the safe operation of aircraft. Several airliners are believed to have responded to uncommanded control inputs as a result of electromagnetic interference and the crash of one transport helicopter has been charged to this cause.

High-intensity radiated fields (HIRF) from high-power sources, such as radars, can affect the control, communication, and navigation systems of aircraft. Carry-on electronics are also a concern as sources of unwanted electromagnetic radiation that couples into control circuits, especially digital circuits. Even low-power emitters can create high fields inside an aircraft compartment, which can be enhanced by resonance effects, as indicated by quality factor (Q) enhancement. Current NIST work will help to determine realistic levels of test fields and practical test methods, such as reverberation chamber testing of systems and components, and respond to aircraft manufacturers' concerns about the high cost of unnecessarily severe test conditions.

In the past year, the NIST team developed both continuous wave (cw) and time-domain measurement techniques for determining the shielding effectiveness, quality factor, and time constant of airplane compartments and obtained data from 400 MHz to 18 GHz for three small (twin engine) airplanes and one large commercial airplane. The team obtained good agreement between cw and time-domain techniques and the earlier theoretical work performed at NIST. Their time-domain techniques permit rapid acquisition of broadband data and time-windowing of data to study the relevant physical mechanisms. The data demonstrated that the electromagnetic environment inside an aircraft can be well simulated by a reverberation chamber.

10.3 Radiated emissions and immunity of PCBs and ICs

Scientists around the world are beginning to investigate concerns that electromagnetic coupling to printed-wiring boards (also known as PCBs), and to components individually, can limit the performance of PCBs and integrated circuits (ICs). However, the basic coupling mechanisms need to be better understood, and emissions and immunity test methods need to be established before this topic can be fully explored. [See previous entry, 5.6 Characterization of thin-film materials.] Current FCC radiated emissions tests do not cover frequencies above 1 GHz, but faster circuitry results in significant radiation (or pickup) at 1 GHz and above. To date, the United States has no immunity requirements or standard test methods over any frequency range.

Following interactions with staff of various concerned companies, NIST scientists David Hill, Kenneth Cavcey, and Robert Johnk studied the effects of electromagnetic coupling by fabricating a representative PCB, analyzing its radiated emissions and reception, and comparing the findings with theory for frequencies from 200 MHz to 2 GHz. The work was facilitated by the use of NIST's reverberation chamber, which is a good candidate for performing fast, accurate, and practical measurements above 1 GHz.

The measurements of radiated emissions and immunity are related by reciprocity, which provides a consistency check on the measured data. The work of this team will improve the understanding of high-frequency radiated emissions and immunity, and lead to further improvements in measurement techniques.

10.4 EMI shielding properties of gaskets

The European Union Electromagnetic Compatibility (EMC) directives, together with the increase in computer clock speeds, which at the same time result in both increased emissions and susceptibility, are creating disturbances in the U.S. marketplace. Regulations of the Federal Communication Commission also pose challenges in the range of 30 MHz to 1 GHz. The market for acceptable gaskets and other shielding materials is growing rapidly, but no definitive, repeatable test methods for assessing shielding performance are available. Gaskets are typically used to ensure continuity of shielding for removable panels and doors. American designers trying to obtain specified shielding levels for their components are frustrated because different measurement techniques give vastly different results (10s of dBs difference) for the shielding effectiveness of the same gaskets.

NIST scientists Motohisa Kanda and Galen Koepke have made significant progress in the past year. Kanda and Koepke surveyed the current methods and fixtures for measuring the shielding properties of EMI gaskets and analyzed the fundamental shielding properties of gaskets. One important goal is to develop methods independent of the material used and independent of whether the material behaves as a conductor or as an absorber. The NIST team found that, although the transfer impedance description of gaskets is independent of the test fixture, the shielding effectiveness is not. To date, they have compared transfer impedance theory with numerous sets of measured data reported in the literature and obtained qualitative agreement. Once these findings have been analyzed and disseminated, designers will be able to compare results of gasket tests by different methods and fixtures.

10.5 Impulse testing of anechoic chambers

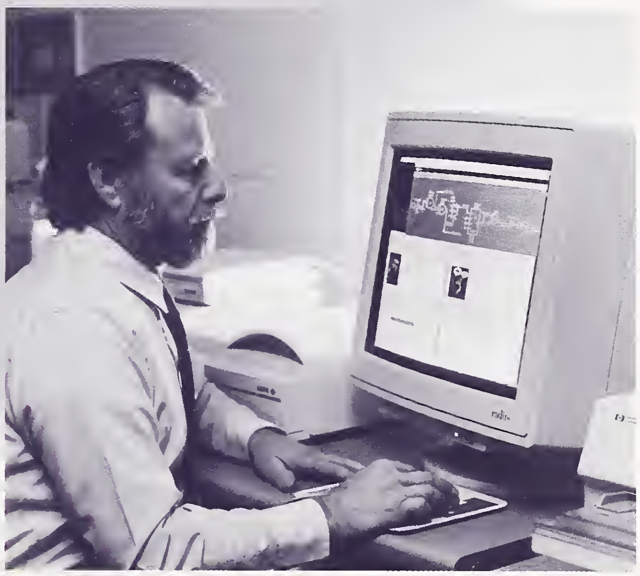
The measurement and modeling of microwave anechoic chambers is of great interest to American industry, particularly if the cost of high-performance anechoic chambers is to be reduced and, for domestic manufacturers of chambers, the challenge posed by foreign manufacturers is to be met. These chambers are used when it is essential to test devices in an environment that is designed to reduce to a minimum, if not completely eliminate, the presence of unwanted signals. That is, the ideal microwave anechoic chamber provides a free-space environment. The number of anechoic chambers used by U.S. industry will increase dramatically with the new 1996 European Union immunity directives that will require U.S. electronics manufacturers to perform tests in anechoic chambers in order to continue to have access to European markets.

In response, NIST scientists Robert Johnk and Arthur Ondrejka have developed a fast, accurate, and low-cost, time-domain measurement system that performs in situ measurements on anechoic chambers for the frequency range from 30 MHz to 5 GHz. While conducting an extensive series of time-domain impulse measurements on the NIST anechoic chamber, Johnk and Ondrejka detected an early-time "glint" phenomenon that might very well explain some anomalies that have been observed but not understood for years.

The data obtained from the late-time response are a strong function of frequency, with simple cavity-like behavior being observed at low frequencies. As the frequency increases, the cavity-like characteristics diminish rapidly. Because of rapid decay characteristics at the higher frequencies, the signal processing algorithm must be modified to capture the early-time data and obtain useful results. The data obtained in this study agree very well with earlier absorber reflectivity measurements obtained at NIST.

ELECTRONIC DATA EXCHANGE

Accomplishments



ELECTRONIC DATA EXCHANGE: CATALOG PAGES LINKED TO APPLICATION DATA

11 ELECTRONIC DATA EXCHANGE

11.1 Electronic business reply card (EBRC) demonstrated

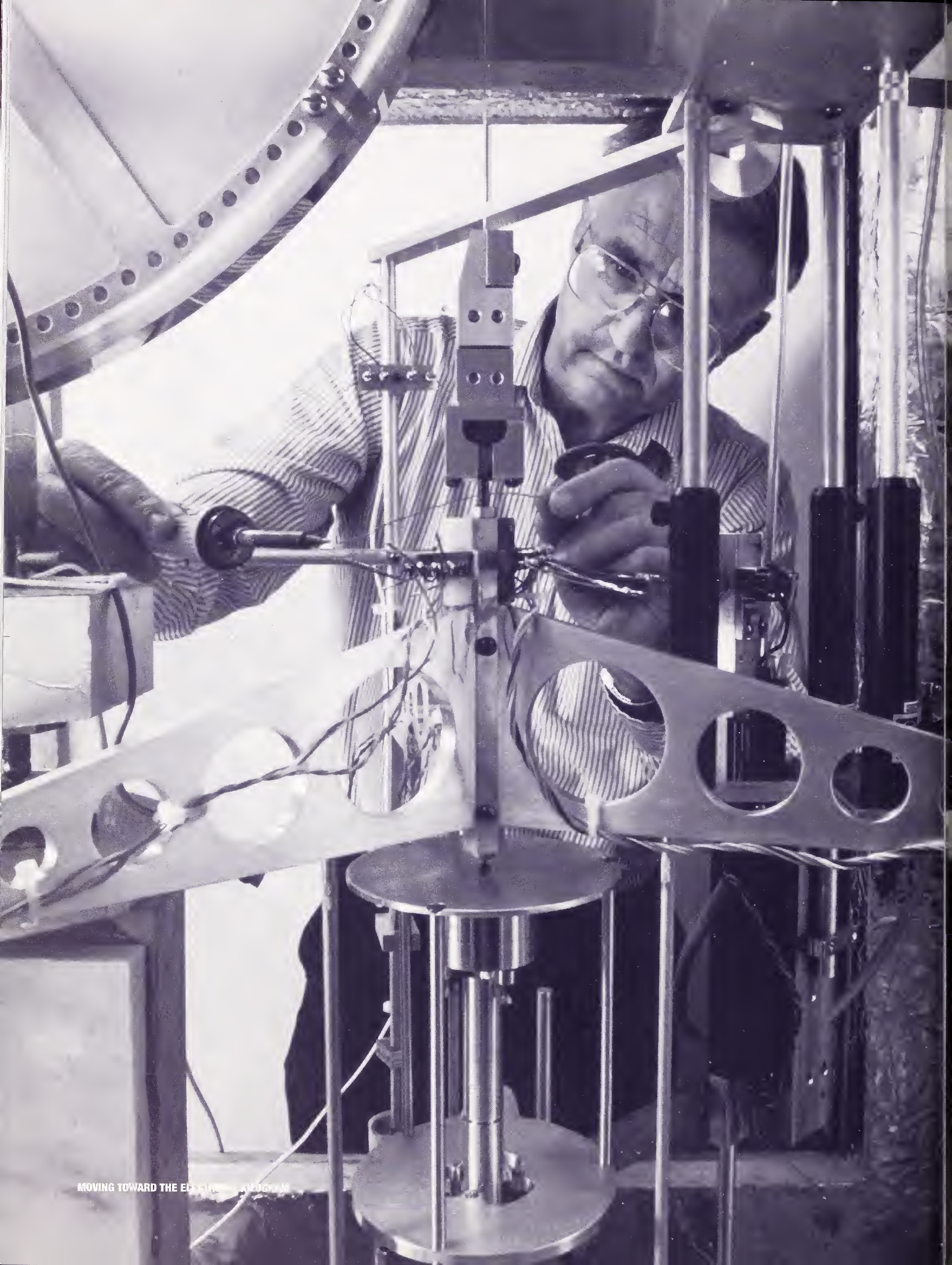
The National Information Highway, or National Information Infrastructure (NII), offers alluring capabilities to industry for the future, and some that it can try out today. Highly efficient, reliable, timely methods of transmitting information between manufacturers and customers is one of the most attractive current offerings.

Electronic Business Reply Cards (EBRCs), one form of which is based on software designed by NIST scientists Barbara Goldstein and Michael McLay to take advantage of the capabilities of the NII, will allow potential customers to request product information, such as electronic component data sheets, from vendors over networks such as the Internet using their personal computers — replacing the mail-in business reply and "bingo" cards found at the backs of trade journals.

Consumers benefit in that it is possible to acquire the desired information almost immediately instead of waiting the number of days typically required to request and receive information through the mail — information that is restricted to what the manufacturer projects the customers will want. Further, customers can query the vendor information using a hypertext structure to determine precisely what it is they want to know at whatever level of detail the manufacturer provides.

The benefit to vendors is significant. There is a very significant cost incurred in their responding to requests generated by bingo cards (some companies have reported costs of $20 per request), and the nature of reply cards draws many unproductive requests with respect to sales. Electronic interactions enable them to make new product information available to target prospects in a much faster and more efficient manner. Contrast the potential weeks required to develop and create printed documentation of new product changes and publish the facts in the industry media, with the potential day or two necessary to revise the on-line information and have it available for immediate dissemination over a network.

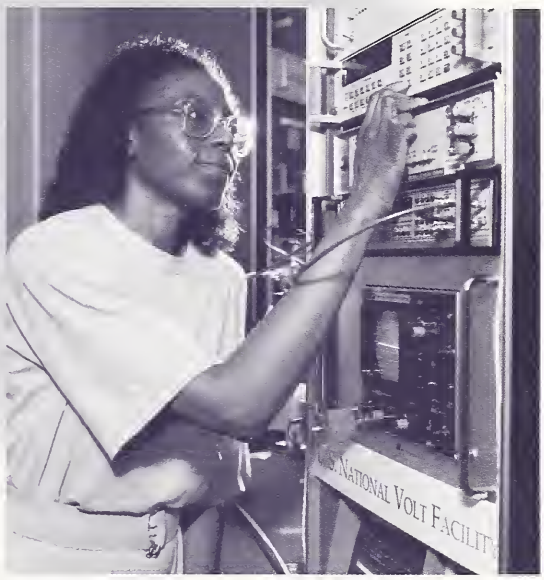
Goldstein and McLay continued to lead the Electronic Business Reply Card (EBRC) demonstration team of the National Initiative for Product Data Exchange/ Electronic Commerce of Component Information project in developing EBRC demonstration software. The software was demonstrated at the Continuous Acquisition Lifecycle and Support (CALS) Expo, November, 1993; and at the Design Automation Conference, June, 1994. Their team also collaborated with Enterprise Integration Technology (EIT), an ASIC/EDA publication to construct an electronic business reply card demonstration of an on-line journal with network links to a breadth of technical information.



Accomplishments

"Measurement of the linearity of HP 3458A digital multimeter's A/D converter, however, remained beyond our grasp until the 10 volt JJ array was made available at NIST's Boulder Laboratories. Initially, we carried several 3458As to Boulder and did some preliminary evaluations using a 10-volt array and system provided by Clark Hamilton....After seeing its value to HP as a measurement tool, we decided to purchase our own 10 volt array and system for use in our lab....On-going support of our 10 volt Josephson array is very important to us in maintaining our leadership in digital multimeters."

— Manager, HP Loveland Standards Lab
Loveland Manufacturing Center
Hewlett-Packard Company



THE NATIONAL VOLT

12 NATIONAL ELECTRICAL STANDARDS

"Thank you again for your time in assisting us with the successful operation of our Josephson Junction. It seems new light has been shed on some of our other standards. We are very pleased with its operation and the new capabilities it provides."

— Metrology Engineer and Senior Metrologist
Metrology Laboratory
Martin Marietta Astronautics

12.1 All-niobium 10-volt Josephson voltage standard chips

NIST is a pioneer in the development of Josephson-junction voltage array standards. In a continuation of the effort to increase the reliability and to improve the performance of these devices, further enhancing their usefulness to metrologists and to the electronics industry, Clark Hamilton and Charles Burroughs have successfully implemented a new fabrication process for chips that achieved both objectives.

Hamilton and Burroughs have fabricated the first all-niobium 10-volt Josephson voltage standard chips and achieved a yield of more than 75%. The fabrication process, in which niobium replaces lead in the wiring, is based on a niobium trilayer structure and results in the replacement of lead connections with niobium connections. This process is more difficult but results in much more reliable chips. The new chips have resolved an eight-year-old problem of flux trapping in the junctions; in addition, the new design incorporates all-gold contact pads, a feature that also increases reliability. This technology is available to interested companies. For example, NIST has transferred the technology for manufacturing both 1-volt and 10-volt Josephson Voltage Standard chips to Hypres, Inc. of Elmsford, New York.

12.2 Josephson-junction sources for ac metrology

The potential impact of Josephson voltage standard arrays to the electronics sector is greater than its use as a reference dc source of unprecedentedly low uncertainty over its entire voltage range, nominally -10 V to +10 V. If arrays of adequate size can be reliably fabricated and suitably programmed, the result will be a device capable of synthesizing ac

"My sincere thanks for the help you gave me in solving a problem with our Josephson Junction array system. I was able to get our system operating again with minimal loss of productivity. Your efforts have been very helpful in transferring technology from NIST to the Fluke Corporation....In any case, it would be difficult to overrate the support you gave me."

— Metrology Engineer
Manager
Verification Tools Division
Fluke Corporation

waveforms having comparable uncertainties, i.e., a quantum-based ac voltage standard.

Clark Hamilton, Richard Kautz, and Charles Burroughs have invented and demonstrated a new type of programmable Josephson-junction array that uses a digital input to rapidly select any one of several thousand quantized output voltages. Their circuit uses a binary sequence of series subarrays of shunted Josephson junctions to make a 14-bit digital-to-analog converter (one junction in the first subarray, two in the second, four in the third ...). With thirteen bias lines, any step number in the range -8192 to +8192, corresponding to the voltage range -1.2 to 1.2 V, can be selected in the few microseconds required to stabilize the bias current. In the initial demonstration, nine of the fourteen bits functioned correctly. When perfected, their circuit will make possible the synthesis of very accurate ac waveforms whose amplitude is directly derived from the internationally accepted realization of the volt.

12.3 High-temperature Josephson junctions for voltage standards

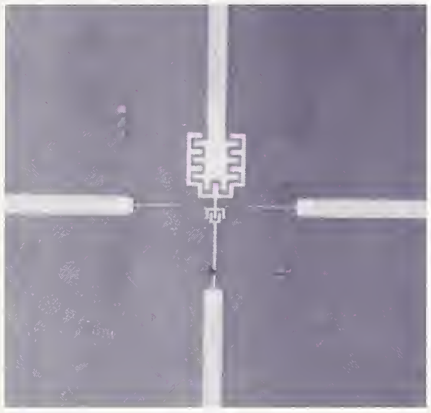
The electronics industry has evinced a long-term interest in the development of commercial superconducting devices and structures, which will be more economical and simpler to maintain than present devices and structures. For example, Josephson-junction voltage array standards are now cooled by liquid helium to near 4 K, a requirement that virtually restricts their use to first-tier metrology laboratories.

Sam Benz, Richard Kautz, Carl Reintsema, and Ron Ono are working together on a long-term project to apply and to demonstrate the potential advantages of high-temperature superconductivity in a variety of measurement situations. A Josephson-junction array standard operating with liquid-nitrogen or closed-cycle refrigeration is an important goal. Toward this end, the NIST team has demonstrated the operation of superconductor-normal-superconductor junctions for voltage standards at 38 K.

This year, they fabricated a single yttrium/barium/copper oxide step-edge junction with a gold barrier, illuminated it with 62-GHz electromagnetic radiation, and found the current-step amplitude of the first quantized voltage step to be 1 mA at 38 K. This current is a value large enough to show that the junction could operate at elevated temperatures without being limited by thermal noise. It is of interest to note that a temperature of 38 K can be reached with closed-cycle refrigeration systems and does not require liquid helium as a cryogen.

SINGLE ELECTRON TUNNELING: ELECTRON PUMP

NATIONAL ELECTRICAL STANDARDS



SINGLE ELECTRON TUNNELING: CAPACITANCE MEASUREMENT

A new long-junction model was formulated which provided an understanding of the results. While construction of an array requires improved junction uniformity, the results obtained with a single junction provide a proof-of-principle for operation of voltage standards at elevated temperatures. Given its significant interest to the scientific community as well, *Applied Physics Letters* has published a paper describing this work. Brought to fruition, this effort will enable more widespread commercial use of Josephson voltage standards, and be ideal for use in the proposed ac array standard.

12.4 Accuracy of electron pump

Work in the field of single electronics offers the potential for further fundamental standards of electrical quantities, a goal being pursued by national laboratories around the world. The pursuit of excellence in this arena is integral to NIST's principal mission.

Ultra-small electronic devices are fundamental to a new class of electronic devices for metrological application. NIST researchers John Martinis and Michael Nahum have performed a detailed experimental and theoretical analysis of factors limiting the accuracy of a single-electron pump operating in the millikelvin temperature range, and demonstrated the successful performance of an electrometer and charge pump. Their work is credited with providing credibility to the development of future metrological devices based on this technology.

In a few years, single-electron devices may make possible capacitance standards and eventually current standards and the determination of a better value of the fine structure constant.

12.5 Single electron tunneling for capacitance bridge

NIST scientists Neil Zimmerman and Alan Clark have demonstrated an important metrological application of single electron tunneling phenomena. The low capacitance leakage demonstrated in their results is essential for future experiments involving electron counting in conjunction with capacitors.

Clark and Zimmerman compared two 0.5 pF vacuum-gap capacitors at cryogenic temperatures in a bridge circuit using a single electron tunneling electrometer as the null detector. An ac bridge (100 to 1000 Hz) using an inductive voltage divider allowed about three ppm resolution for the capacitance ratio. At dc, the precision was limited to about 200 ppm. The leakage resistance of the two parallel cryogenic capacitors was found to be greater than 10^{18} Ω. Zimmerman and Clark believe that they can improve the capacitance measurements — by two orders of magnitude — with a simple redesign of the SET electrometer input capacitance.

"I would like to take this opportunity to inform you of the expansion of our business in the area of superconducting chip holder and cryoprobe fabrication. I would also like to express my appreciation for your assistance in our efforts to become familiar with this technology and to provide it to our customers....High Precision Devices, Inc. is a young company....Our goal is to participate with our customers in the development of prototype or laboratory instrumentation, and then when possible to commercialize those devices that have a commercial potential. With your help, our work in the area of superconducting chip holders and cryoprobes has followed this exact model and we hope it will be a prototype approach that we can use in future similar situations."

— President
High Precision Devices, Incorporated

Programs Matrix-Managed by EEEL

In addition to the laboratory investigations conducted within EEEL, which have been summarized under "Selected FY 1994 Accomplishments," the Laboratory manages NIST-wide programs in microelectronics and law enforcement. The following examples of the matrix-managed work are given to provide a sense of the significance, quality, and impact of the work performed by the cooperating Laboratories within NIST.

Office of Microelectronic Programs

Critical dimension and overlay metrology

Dimensions on the first integrated circuits were relatively easy to measure optically because they were much larger than the resolution limits of good quality microscopes. As the sizes of the features were reduced over the intervening years, problems arose in accurately measuring dimensions that were approaching, and now have about equaled, the wavelength of the light used in the measurement.

The transmission mode of a scanning electron microscope has been shown to be a very effective tool for measuring the sizes of submicrometer features on x-ray masks and for inspection of defects that would be "seen" by x-rays. The feasibility of the technique has been demonstrated for features as small as 0.25 μm on actual x-ray masks, and work is in progress to improve the present accuracy of 10 nm. The electron-beam interaction modeling used to determine the accurate edge position on the mask is currently being modified for use with other electron-detection modes (such as backscattered and secondary electrons).

Micromechanical measurements

Micromechanical material properties and behavior are fundamental to the manufacturability and reliability of advanced integrated circuits and interconnect systems. A NIST effort, led by David T. Read of the Materials Science and Engineering Laboratory, is based on the premise that accurate mechanical property information and experimental verification of the model predictions are prerequisites for useful models of manufacturability and reliability. The program has two main focus areas: mechanical properties of thin films, and high resolution experimental mechanics.

The mechanical properties of thin films differ from those of bulk material because vapor deposition techniques are much different from processes used to produce bulk metals. Standard test techniques for obtaining mechanical properties of thin films have not been established and techniques standardized for bulk materials are not applicable to thin films. A new method for measuring the mechanical properties of thin films has been developed and demonstrated on suspended thin films of aluminum and copper with titanium barrier layers. Progress continues in improving the accuracy of the method, understanding and eliminating the effect of the barrier layers, and reducing the minimum specimen size and understanding specimen size effects. Sandia National Laboratories has produced copper specimen films for mechanical property measurements and tensile specimens are now being prepared for testing at NIST. Mechanical properties of thin films is a proposed topic area for the NIST Metrology Forum, an industry-government-university Cooperative Research and Development Program.

Electron beam moiré has been developed as an experimental technique for examining mechanical displacements within fields as small as 50 μm. The big advantage is the capability to write gratings for which the pitch is not limited by the wavelength of light. Our finest gratings currently have a pitch of 0.1 μm, and have 500 lines. Thermomechanical displacements in cross-sectioned specimens of plated-through-holes have been observed up to 150°C. At present, this technique is being applied to verify finite element modeling of an interconnect structure for a multichip module, in collaboration with the United States Air Force Rome Laboratories and an industrial partner. Additional collaborations are welcome.

Solderability measurements and optimization

As the dimensions of electronic devices decrease in size and surface-mount solder joints replace through-hole connections, new demands are being placed on the soldering process and the mechanical strength of the solder joints. Improved solderability tests and the understanding of solder joint reactions are required to ensure solder joint reliability under these new conditions. Most solder connections currently involve interactions between lead-tin solder and copper wires or pads. The influence of these reactions on solderability measurements is being investigated by a group led by John R. Manning of the Materials Science and Engineering Laboratory. In particular, effects arising from formation of Cu_6Sn_5 and Cu_3Sn intermetallic compounds and non-wettable patches are being measured. To measure unambiguously the solderability properties of the intermetallics, bulk samples of these materials are needed; and, to reproduce material conditions in the solder joints, fine-grained samples are required.

Since Cu_6Sn_5 is not at an equilibrium stable phase at temperatures near the melting point, bulk samples of this alloy cannot be prepared by conventional slow-cooling of the liquid. Moreover, conventional techniques cannot produce fine-grained Cu_3Sn. To avoid these difficulties, NIST developed special rapid-solidification methods for preparing these materials. Tests on these materials showed that the intermetallics provide much poorer wettability for Pb-Sn solder than does copper itself. Thus, these intermetallics, especially when oxidized, can produce non-wettable patches during a soldering operation.

These intermetallic reactions, including measurements of oxidation layers, effects of non-wettable patches on wetting rates, and the influence of these reactions on solderability tests, are being investigated. Moreover, to aid in this process, the phase diagram for this alloy system is being determined. Proper analysis and control of these reactions require knowledge of the ternary Cu-Pb-Sn phase diagram, showing the ranges of compositions and temperatures where the alloy phases of interest are stable.

Plasma processing and chemical vapor deposition

The objective of research at NIST in plasma processing and chemical vapor deposition (CVD) focuses upon development of basic physical and chemical reference data, reference plasma discharge cells, advanced measurement methods as potential process control techniques and for use in validating models of plasma etching, CVD processes, and computational models that describe fundamental thermochemical and kinetics data for chemical system design in CVD reactor modeling. In addition, modeling efforts focus on cluster growth mechanics as a precursor to particulate formation from the gas phase. This research effort, which involves teams of scientists from three NIST laboratories, is led primarily by James R. Whetstone of the Chemical Science and Technology Laboratory.

Accomplishments in the area of RF power measurements in plasma reactors included an evaluation of a beta-test model of a commercial rf probe to measure the power dissipation and impedance of radio-frequency discharges at 13.56 MHz. The probe response was compared with data from an accurate current- and voltage-measurement system designed and implemented at NIST.

The influence of trace amounts of gas-phase oxygen, water, and nitrogen on argon discharges was measured in the GEC Reference Cell, and the concentration levels at which these gases cause significant changes in the electrical characteristics of the discharge were determined. It was also possible to demonstrate as a result of this work that background levels of these gases can be a significant source of irreproducibility in plasma experiments.

In a project dealing with mass spectrometric measurements with application to plasma processing, measurements of the ion energy distributions were taken with a new mass spectrometer system capable of detecting ions sampled through an orifice in the grounded electrode of the GEC Reference Cell. Kinetic energy distributions for Ar plasma over a wide range of plasma conditions were shown to be in agreement with previous data obtained using a different mass spectrometer system, sampling ions from the side of the plasma region.

Work on chemical vapor deposition (CVD) reactor modeling, and particle formation and growth models was also performed during FY 1994. A full two-dimensional model for flow and particle dynamics in an axisymmetric rotating-disk chemical-vapor deposition reactor was developed and validated using experimental data from Sandia National Laboratory. A global particle contamination parameter was identified which specifies the particle size below which no impacts will occur regardless of particle location in the inlet flow to the reactor.

Models of gas phase particulate formation processes focus on the effect of cluster temperature and the characteristic time for particle coalescence as a function of cluster temperature and size. Work was also begun on spatially-resolved, laser-induced fluorescence species concentration measurements in plasma reactors, which will be used to investigate plasma etching chemistries.

Office of Law Enforcement Standards

Police traffic radar devices

Police traffic radar has been used in this country to detect speeding motorists for about 40 years. During that time, radar speed measuring devices have evolved from the original bulky stationary models to the present compact and sophisticated units capable of monitoring the speed of vehicles moving in all directions while employed in either the stationary or moving mode. These technological advances have greatly enhanced the mobility, efficiency, and effectiveness of police traffic radar operations.

Despite the technological advances, highway safety and law enforcement administrators must ensure that radar

Programs Matrix-Managed by EEL

operators receive adequate training, including recognition and avoidance of the electronic anomalies associated with such devices. The National Highway Traffic Safety Administration (NHTSA) has sponsored three programs in OLES which should serve to upgrade both the reliability and credibility of police traffic radar equipment and the quality of operator training.

NHTSA Technical Report No. DOT HS 808-069, issued in January 1994 and entitled "Model Minimum Performance Specifications for Police Traffic Radar Devices," is a revision of DOT HS 807-415, published in May 1989. The principal change in this document is the inclusion of specifications and testing protocols for Ka band radar units. The document has been prepared for a number of audiences interested in police traffic radar, including the legal community and the radar manufacturers.

Electronic police radar calibrator

In order to support the use of cross-the-road radar for speed enforcement in the United States, the Office of Law Enforcement Standards (OLES) has sponsored EEEL's development of an all-electronic Doppler radar calibrator. The calibrator operates at 24.1 GHz (K Band), and provides a standard radar signature that simulates vehicles passing through a radar beam aimed across the road. The simulated signature includes the effect of direction of vehicle travel. This capability is essential for interfacing with the sophisticated signal-processing circuitry in commercially available cross-the-road radar systems and for assessing the accuracy of speed measurement. The calibrator can also be used with conventional down-the-road radar speed-measuring systems that have been widely used by U.S. law enforcement agencies for some years.

Lidar target simulator

Police traffic lidar (light detection and ranging) devices transmit laser pulses, then measure the time of flight of each pulse as it reflects off a target and returns. Time of flight implies distance, and from a series of distance measurements, speed is determined. OLES has developed a target simulator which can present a lidar device with a train of echo pulses at changing delays, simulating the return of pulses from a moving target. The simulator is based on a personal computer and a commercially available programmable delay generator. The software, which can also simulate the effect of a lidar device not being held steady, provides extensive user control via menus and can be configured to accommodate hardware variations. Both government and commercial laboratories have shown interest in using the design and the software.

DNA standard for PCR-based technologies

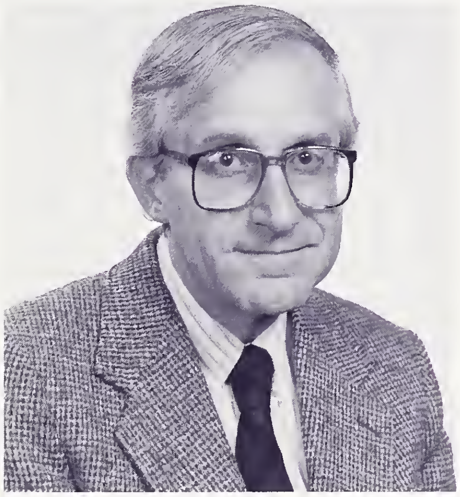
Polymerase Chain Reaction (PCR) technology enables the rapid and efficient amplification of minute quantities of DNA. Depending on whether a DNA profiling technique is used in a forensic, paternity or research setting, the tissue source of DNA can vary. As with all profiling methods, methods for assuring the quality of the analysis are critical to establish confidence and ensure interlaboratory comparability. Two major quality assurance related efforts were pursued during FY94: 1) Validation of SRM 2391 materials and 2) Retesting and certification of SRM 2390, DNA Profiling Standard.

Development of SRM 2391 was initiated with funding by the National Institute of Justice through NIST's Office of Law Enforcement Standards. SRM 2391 is a PCR-based DNA profiling standard developed for the forensic and paternity testing communities. The SRM set includes 1) a standardized allelic ladder for the genetic locus D1S80; 2) a DNA-based molecular size ladder; 3) PCR amplified products for the D1S80 locus; 4) Ten genomic DNA samples; and 5) Two cell lines included as intact cells spotted on Schleicher & Schull type 903 paper, to be used as an extraction standard. The effort focused on validating the proposed components through two extensive interlaboratory studies. Twenty-three private, state and Federal laboratories in the United States and Canada participated in at least one or more of the interlaboratory studies. All proposed components of SRM 2391 were validated in these studies. The studies also revealed that some commonly used methods often gave miscalls in typing. Changes in operations by some of the laboratories to a common format allowed consensus to be achieved in subsequent interlaboratory tests.

EEEL Awards and Recognition

Institute of Electrical and Electronics Engineers (IEEE)

Harry Diamond Memorial Award



MARTIN MISAKIAN

The United States Activities Board of the Institute of Electrical and Electronics Engineers selected *Martin Misakian* as the 1994 recipient of the Harry Diamond Memorial Award. The citation recognizes Misakian's "conception, development, and implementation of measurements of power-frequency electric and magnetic fields, especially your measurement methodology for fields and ion densities near both ac and dc power transmission lines." Misakian's work has put the United States at the forefront of powerline-fields measurement in the world community.

Responding to electric power industry needs and broader issues concerning the siting of powerlines, Misakian developed measurement technology that has become crucial as concerns mount regarding the health effects of electric and magnetic fields from powerlines, household appliances, and office equipment. Misakian led the relevant committees in the Institute of Electrical and Electronics Engineers and in the International Electrotechnical Commission to establish first U.S. and then international standards specifying how field measurements near powerlines should be made. These standards were based on his work. The importance to the United States of the resulting standards is underlined by the nation's increasing dependence on electricity, the consequent installation of ever-more-extensive systems for transmission and distribution, and new concerns for health, safety, and the environment.

Misakian's role has had direct impact on the $190B (1994) U.S. domestic electric power industry and on those seeking to make the crucial determination that there are or are not valid health issues associated with electric power use. Further, Misakian has provided essential guidance on ensuring that field measurements are correctly carried out in bioeffects experiments, through participation in state-directed programs, invited visits to facilities, consultations, and the authorship of two primers for nonspecialists in electrical measurements.

IEEE Fellows

The Board of Directors of the Institute of Electrical and Electronics Engineers (IEEE) selected three members of the Electronics and Electrical Engineering Laboratory for elevation to the grade of Fellow during FY 1994.

Martin Misakian was cited "for contributions to instrumentation and measurement techniques for low-frequency electric and magnetic fields." Misakian has been involved in many facets of the electric and magnetic fields measurement program: research and development of new methods and instrumentation that have been accepted nationally and internationally and documented in 18 archival publications, preparation of two measurement primers for practitioners conducting bioeffects experiments with E and M fields, and service in technical leadership roles in preparation of four national and international metrology-related standards of practice that incorporate techniques developed under Misakian's leadership. As part of his outreach activities, Misakian has visited many bioeffects experiments nationwide in order to verify field measurement procedures and, if necessary, provide guidance to the researchers. Misakian serves or has served on five Government and private panels and committees addressing the effects of electric and magnetic fields.

T. Michael Souders was cited "for advancing the state of the art in characterizing and testing of data converters, waveform digitizers, and equivalent-time sampling systems." Souders has led work at NIST that has provided U.S. industry with needed new metrology tools: precision step generators; measurement, calibration, and testing procedures for current transformers, alternating-current shunts, and precision analog/digital data converters; sampling-type instruments employing data converters; and efficient, analytically rigorous testing strategies that permit manufacturers of electronic components to reduce the number of test points used to characterize a device, in one example, from about 8000 to under 100. NIST testing strategies algorithms are now in use by manufacturers of both test equipment and semiconductor devices. Souders chairs the IEEE committee that developed a consensus standard for waveform recorders; this standard incorporates numerous test methods developed at NIST.

Gordon W. Day was cited "for technical contributions and leadership in lightwave measurements and optical fiber sensors." Day has an international reputation, most recently in the area of optical-fiber sensors. He participated in a team whose electrically calibrated pyroelectric detector won an IR 100 Award in 1975 and led the development of an optical-fiber current sensor which won an R&D 100 Award (successor to the IR 100 Award)

EEEL Awards and Recognition

Excellence in Technology Transfer from the Federal Laboratory Consortium for Technology Transfer for effectively providing the technology embodied in this sensor to the 3M Company. One design of current sensor developed by his team has a minimum detectable current of about 220 $nA/Hz^{1/2}$, several orders of magnitude lower than any previous optical current sensor. Day has been recognized by the Department of Commerce with a Gold Medal in 1974 as a member of a group that carried out precise wavelength and frequency measurements for the methane-stabilized helium-neon laser at 3.39-µm wavelength and a Silver Medal in 1983 as a member of a group that made outstanding contributions to multimode optical fiber metrology that resulted in "significant benefits to the optical fiber industry."

Whitehead Memorial Lecture

The work of *Richard J. Van Brunt* was recognized by IEEE Dielectrics and Electrical Insulation Society through the invitation to deliver the 1994 Whitehead Memorial Lecture. This highly prestigious lecture is only awarded to outstanding experts, and reflects international recognition. The last NIST/NBS (National Bureau of Standards) invitee was John B. Hoffman, Director of the NBS National Measurement Laboratory in 1975. Van Brunt's Lecture, entitled "Physics and Chemistry of Partial Discharge and Corona - Recent Advantages and Future Challenges," is a review of the results of recent experimental and theoretical work dealing with the basic physical and chemical processes in partial discharge and corona. Van Brunt's work at NIST, particularly the results obtained for air, SF6, and SF_6O_2 gas mixtures in point-plane or point-dielectric barrier gaps, has established his reputation as a world-class researcher in this field.

Department of Commerce

Gold Medal

A gold medal was awarded to a NIST team consisting of *Matt Young, Paul Hale, Timothy J. Drapela, and Steve Mechels* of the Electronics and Electrical Engineering Laboratory and to *Theodore D. Doiron* of the Manufacturing Engineering Laboratory "for enabling U.S. manufacturers at their request to produce optical fiber of accurately controlled dimensions and to gain advantage in world markets."

PAUL HALE, STEVE MECHELS, TIMOTHY J. DRAPELA, MATT YOUNG

Responding to the urgent need of U.S. companies, the team developed measurement technology that made it possible for U.S. optical-fiber manufacturers to improve control of fiber geometry to meet the requirements of plug-in connectors. Simplified connectors became necessary when the number of connectors in a system grew large, as in local-area networks. The industry has standardized on a cladding (outer) diameter of 125 µm. The NIST work resulted in a fiber diameter Standard Reference Material (SRM) certified with an uncertainty less than 50 nanometers, together with three evaluated methods for measuring fiber diameter. Major U.S. manufacturers (annual cable shipments worth $890M) have calibrated their fiber-drawing towers with the SRM.

NIST

Bronze Medals

Barbara J. Belzer was "honored for developing and implementing a key NIST-industry intercomparison of semiconductor thin-film measurements determined ellipsometrically." This work defines U.S. baseline performance and establishes a working basis for industry use of a Standard Reference Material (SRM) having an oxide layer 10-nm thick. As devices shrink, accurate control of the thickness of insulating films becomes more challenging and more critical. Industry relies on NIST thin-film oxide SRMs to provide a reliable means for standardizing the required measurements. Belzer's careful attention to specimen stability materially improved the results by minimizing the effects of factors that could have masked the true measurement capabilities of the participants.

James K. Olthoff was "cited for advancing the understanding of plasma processes as applied to semiconductor processing, with special emphasis on plasma diagnostics." He played a critical role in the development of a U.S. research effort involving the use of a reference design of a radiofrequency-discharge cell to provide knowledge needed by the semiconductor industry in applying plasma processing. The industry regards plasma processing to be an essential fabrication technology for advanced microelectronic devices. Olthoff led the EEEL contribution to establishing a world-class laboratory to conduct research on plasma diagnostics, jointly with the Physics Laboratory and the Computer Science and Technology Laboratory. Further, he has led research on measuring ion kinetic-energy distributions of cell plasmas. In addition, Olthoff chairs a committee of cell users, edits a users' newsletter, and has organized special workshops and technical sessions on the cell.

John S. Suehle was "honored for developing a method for testing semiconductor-device oxides at higher temperatures than previously possible." This method has resulted in improved capability for

BARBARA J. BELZER, JAMES K. OLTHOFF, JOHN S. SUEHLE

modeling oxide performance needed by industry and has reduced test times. Device designers need to be able to estimate how long oxide insulator layers in microelectronic devices can resist voltage breakdown in use, which may be years. The reliability of oxide layers had been predicted by subjecting them to high voltage. Suehle's work has demonstrated that subjecting the oxides to high voltage changes the failure mechanism with respect to normal operation and that raising the temperature but not the voltage accelerates the failure without introducing new failure mechanisms.

William P. Slichter Award

ROBERT I. SCACE

Robert I. Scace has been recognized for leading NIST's interaction with the U.S. semiconductor industry. He promoted key contacts with industry and the consortium SEMATECH, pursued and organized continuing interchange with these contacts on his own part and on the part of others at NIST, and demonstrated NIST delivery in response to industry needs. The results were so effective that, once industry leaders recognized metrology's key role in advanced competitive products, they chose to rely on NIST to lead in the development of that metrology: the combination of measurement needs and the record of useful solutions from NIST led the Semiconductor Industry Association to successfully urge the establishment of the National Semiconductor Metrology Program at NIST at a level of $25M per year.

Other Organizations

R&D Magazine: R&D 100 Award

For work resulting from a collaboration of scientists from EEEL working under a Cooperative Research and Development Agreement (CRADA) with an industry partner, Ballantine Laboratories, Incorporated, Cedar Knolls, New Jersey, NIST received its 75th R&D 100 award. The award was presented to Joseph Kinard and Donald Novotny of NIST and Guest Scientist De-Xiang Huang of Ballantine Laboratories for the development of a multijunction ac to dc thermal voltage converter (MJTC) designed to be fabricated with methods developed for microelectronic chips. Thermal converters are the most accurate calibration standards for ac voltage and current, and also produce the most precise measurement method for both.

The award-winning thin-film converters result from applying modern semiconductor processing technology to the fabrication of carefully patterned heater/thermocouple structures and represent a substantive improvement over the electrical performance of the usual wire thermal converters. Furthermore, it is estimated that they can be produced with a cost range of $100 to $200 each, depending on the electrical parameters, as opposed to a corresponding range of $150 to $2500 for present standards. The new thin-film MJTCs will offer secondary calibration laboratories a combination of technology and performance which closely approaches primary standard capability.

Electronic Industries Association (EIA)

EIA recognized the standards work of Douglas L. Franzen with its Engineering Department Distinguished Contributions Award for "significant leadership contributions in fiber optic round-robins leading to widespread agreement of measurement results." Franzen chairs the EIA (now Telecommunications Industry Association) Task Group on Round-Robin Testing. At NIST, Franzen has led a program of test methods development and evaluation in support of lightwave communications. An important aspect of this effort has been the use of interlaboratory trials to evaluate the implementation of selected measurement methods as elements of industrial practice. As a result of the work of Franzen's program, industry has a standardized set of over two dozen test methods for characterizing technologically significant parameters for communications-grade fiber. The existence of this set has promoted marketplace interactions and improved the U.S. competitive position.

Conference on Precision Electromagnetic Measurements: Young Scientist Award

Papers submitted by EEEL's *Bryan C. Waltrip* and *Svetlana Avramov*, a Guest Scientist from the University of Novisad, Novisad, Yugoslavia, have been recognized with Young Scientist Awards by the 1994 Conference on Precision Electromagnetic Measurements. As part of the award, each received a travel stipend to permit them to attend the Conference at NIST Boulder to present their papers. Waltrip discussed the "Design and Performance Evaluation of the NIST Digital Impedance Bridge." Avramov presented the "Audio Frequency Analysis of Inductive Voltage Dividers Based on Structural Models." Both papers highlighted recent Division research to advance the state-of-the-art in impedance measurement and to improve NIST's impedance measurement services in response to evolving industry needs. To qualify for the award, candidates must have fewer than five years of work experience and have played a key role in the research effort described in the paper. Fifteen awards were given this year.

FY 1994 CRADAs

EEEL participated in 34 Cooperative Research and Development Agreements (CRADAs) with industry during FY 1994. Nine CRADAs were in the process of being negotiated during the year and 11 CRADAs were terminated. CRADA participants included large and small companies across the nation. EEEL actively seeks industrial, academic, and non-profit partners to work collaboratively on projects of mutual benefit. Special efforts are made to tailor cooperative programs to the individual needs of research partners. CRADAs typically cover joint research efforts in which both NIST and the cooperating company provide staff, equipment, facilities, and/or funds, in any number of possible combinations for a project of mutual interest. Under a CRADA, NIST can protect confidential or proprietary information exchanged during the project, keep research results confidential, and provide exclusive rights for intellectual property developed. EEEL welcomes industry to collaborate on projects of mutual interest through the CRADA format. A detailed directory of research areas available for cooperative research, entitled Guide to NIST, can be obtained at no cost using fax number: (301) 926-1630.

Harris Corporation: Power Mosfet Development

Vitesse Semiconductor Corporation: Test Chip for High-Density Multilevel Interconnect for GaAs IC Fabrication

Xerox Corporation: Three-Dimensional Structuring of MEMs Transducer Arrays

Center for Research in Electro-Optics and Lasers: Analysis of Lithographic Infrared Antennas

Quantum Magnetics: Voltage Standards

SEMATECH: Semiconductor Technology and Processes

Best Technology, Incorporated: Study of Improved Single-Junction Thermoelements

EPRI, Canadian Electrical Association, Ontario Hydro, Martin Marietta Energy Systems, and Hydro-Quebec: Investigation of S_2F_{10} Production, Detection, and Mitigation

Julie Research Laboratories, Incorporated: Investigation of Methods for Characterization and Performance of Thermal Converters at High Voltage

North American Philips Corporation: Efficacy of Real-Time Image Processing Algorithms

South Carolina Research Authority: Advanced Manufacturing of Electrical Products

Square D Company: A Study of Calibration Techniques for Optical-Current Transducer

Alliance Technologies, Incorporated: Component Libraries for Circuit Simulators

Analogy, Incorporated: Power Semiconductor Devices in Electronic Circuits

Bio-Rad Laboratories, Incorporated, Semiconductor Division: Test Structures to Enable Referencing of Measurements Made by Commercial Optical-Metrology Overlay Systems

Digital Instruments, Incorporated: Development of Capacitance Microscopy

General Electric CRD: Parameter Extraction for High-Power IGBTs

Optical E.T.C., Incorporated: Integrated Dynamic Thermal-Emitter Arrays

RF Microsystems, Incorporated; Naval Command and Control Ocean Surveillance Center: Microwave CMOS Micromachined Power Systems

Zenith Microcircuits Corporation: Utilization of VLSI-Type Test Structures for Enhancing the Manufacturability of SAW Devices

Cascade Microtech, Incorporated: MMIC Consortium

Texas Instruments: MMIC Consortium

U.S. Air Force Base, Newark AFB, Aerospace Guidance and Metrology Center: MMIC Consortium

TRW, Incorporated: MMIC Consortium

ITT Defense Technology Corporation: MMIC Consortium

Tektronix, Incorporated: Transmission-Line Characterization Using Time-Domain Instrumentation

Wiltron Company: Validate Commercial VNA Performance

The Boeing Company: Optical Components

Hewlett Packard Company: Development of Wavelength Calibration Equipment for Optical Spectrum Analyzers and Tunable Diode Lasers

Hewlett Packard Company, Meadowlark Optics: Development of Standard Polarization Components

IMRA America, Incorporated: Rare-earth Doped Waveguide DBR Lasers and Polarization Discriminating Receivers

International Business Machines Corporation: Thin Film for Magnetic Storage Media

Martin Marietta Corporation: Millimeter-wave Components Using High-Temperature Superconductors

Quantum Magnetics, Incorporated: Magnetic Imaging

RMC, Incorporated: Commercial Josephson Voltage Standard

Schott Glass Technologies, Incorporated: Active Glasses for Integrated Optical Devices

Superconducting Core Technologies: Tunable Microwave Devices Using Thin-Film Ferroelectrics

The Regents of the University of Colorado: General Agreement for Collaborative Research in Optical Electronics

Ballantine Laboratories, Incorporated: Thin-film Multijunction Thermal Converters

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

EEE

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Commercial - dial 9-1-301-975-plus extension

BOULDER, COLORADO

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Dial 303-497 plus extension
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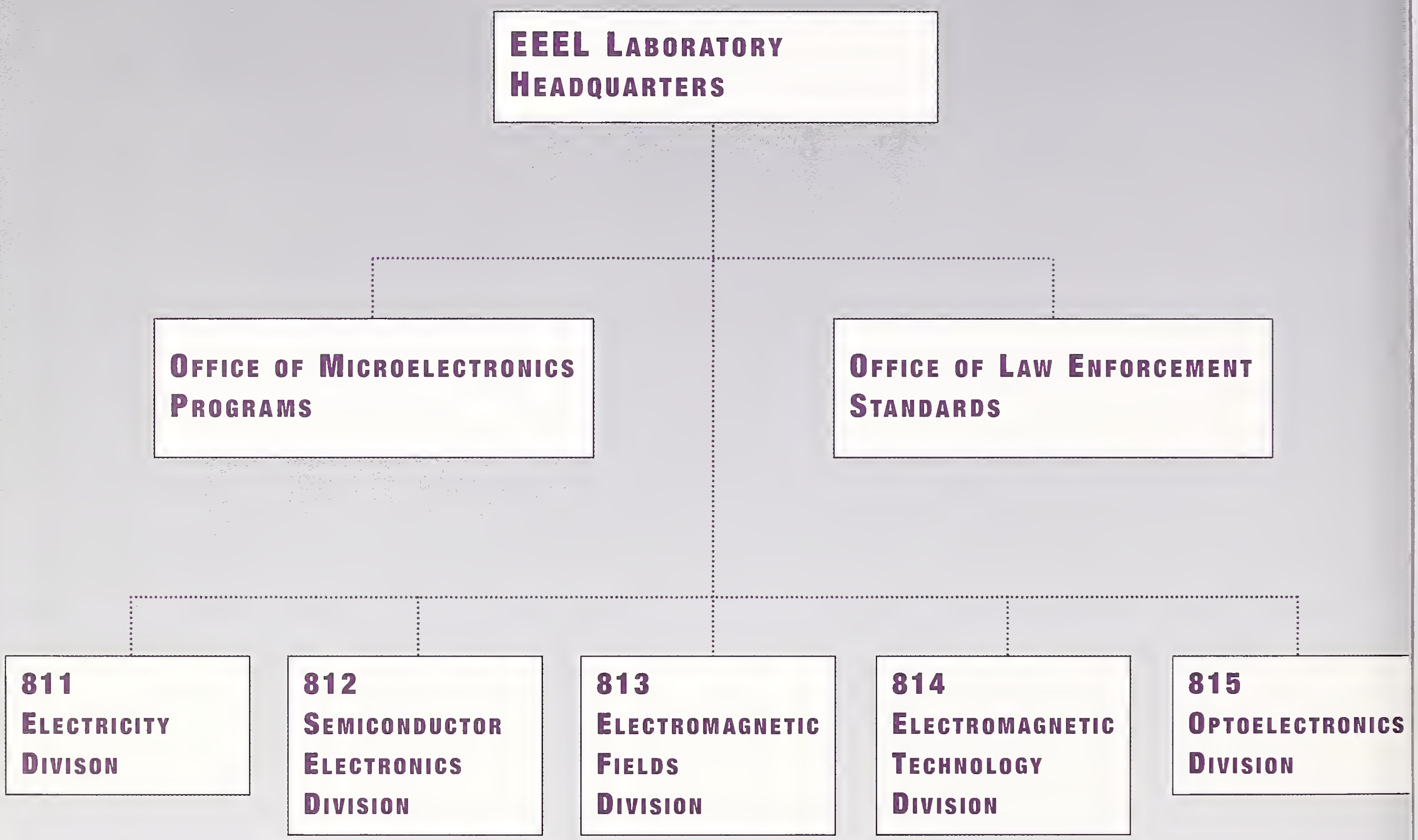
EEEL Executive Structure



Questions & Answers: Whom Should I Call?

Should you wish to contact the management staff of EEEL in either location, telephone numbers and e-mail addresses are provided for your convenience. A complete directory of Laboratory personnel and the EEEL Organization Chart are also provided. We welcome your comments and inquiries.

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December 1994

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. electricity-equipment industry. This report summarizes selected technical accomplishments and describes activities conducted by the Laboratory in FY 1994. Also included is a profile of EEEL's organization, its customers, and the Laboratory's long-term goals.

Keywords

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

Ordering

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