NISTIR 5355

Electronics and Electrical Engineering Laboratory

1993 Technical Accomplishments

Supporting Technology for U.S. Competitiveness in Electronics

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U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Electronics and Electrical Engineering Laboratory
Gaithersburg, MD 20899

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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

National Institute of Standards and Technology

The National Institute of Standards and Technology (NIST) promotes U.S. economic growth by working with industry to develop and apply technology, measurements, and standards. It is a major source of technical expertise for U.S. businesses — large and small — seeking to use the latest technologies to improve their products and processes.

Created in 1901, NIST is the nation's premier measurement laboratory. NIST laboratory researchers work with industry to develop new technologies, devise new measurement methods, and provide materials, data, and calibrations for quality assurance. NIST conducts research at the frontiers of science and technology in the following areas: electronics and electrical engineering, manufacturing engineering, chemical science and technology, physics, materials science and engineering, building and fire research, computer systems, and computing and applied mathematics.

Several NIST programs are designed to spur innovation and accelerate the adoption of new ideas and technology by U.S. companies. Through its Advanced Technology Program, NIST provides seed money to help U.S. businesses conduct high-risk research with broad commercial potential.

To assist small and medium-sized manufacturers in modernizing their production capabilities, NIST is building a Manufacturing Extension Partnership that will be made up of Manufacturing Technology Centers, Manufacturing Outreach Centers, the State Technology Program, and LINKS — a support, coordination, and linking/networking infrastructure.

Encouraging industry to improve quality is the goal of the Malcolm Baldridge National Quality Award, managed by NIST in cooperation with the private sector. The award recognizes continuous improvements in quality management by large manufacturers, large service companies, and small businesses.

For more information on NIST programs, call (310) 975-3058.

Table of Contents

Laboratory Director's Message **1**

EEEL Makes a Difference **5**

Long-Term Goals **7**

EEEL and Its Customers **11**

Fiscal Year (FY) 1993 Activities **13**

Workshops 13

Technology Reinvestment Program 14

U.S.-Japan Optoelectronics Project 15

Electronics Working Group 16

NIST-Sandia Agreement 17

Measurements for Competitiveness in Electronics 18

Selected FY 1993 Technical Accomplishments **19**

Microwaves **19**

M1: Planar Transmission Line Characterization 19

M2: Calibration Verification 19

M3: Impedance Parameters of Devices Embedded in Lossy Dielectrics 20

M4: New Calibration Services: Premium Power 21

M5: New Calibration Services: S-parameters 21

M6: New Calibration Services: Power Direct Comparison System 21

M7: New Calibration Services: Noise 22

M8: New NIST Antenna Measurement Range 22

M9: Measurements of Standard Gain Antennas for International Intercomparison 23

M10: Measurements on Permittivity and Permeability on New Materials 23

M11: Round Robin on 7-mm Coaxial Material Measurements 24

Electromagnetic Compatibility (EC) **24**

EC1: Shielding Effectiveness of Airframes 24

Lightwaves (L) **25**

L1: Integrated Optic Laser 25

L2: Laser Beam Profile Measurement Methodology 25

L3: Fiber Geometry SRMs 25

L4: Polarization-holding (h) Parameter Interlaboratory Comparison 26

L5: Wavelength Standard at 1.53 μm Using Trapped and Cooled Rubidium Atoms 26

Superconductors (SC) **27**
SC1: Observation of One Electron in Ten Billion 27
SC2: Productivity and Yield of Josephson Array Voltage Standard Chips 28
SC3: Ongoing Commercialization of NIST Voltage Standard 28
SC4: Record Frequency Response for Josephson Junction 29
SC5: Tuneable Thin-film Resonator Fabricated from High-temperature Superconductor 30
Magnetics (MG) **30**
MG1: Lift-mode Magnetic Force Microscopy (MFM) 30
MG2: Submicrometer Dynamic Measurements of Domains in Magnetic Read Heads 30
MG3: Measurement of Energy Loss in Superconductor Wires for ITER Magnet 31
Semiconductors (SM) **32**
SM1: Electron Density and Hall Mobility of Semiconductor Layers 32
SM2: SEM Data Analysis 32
SM3: Scanning Capacitance Microscope 33
SM4: Electro-Thermal Power System Simulation Methodology Commercialized 33
SM5: Effect of Annealing Conditions on SIMOX Material Defects Demonstrated 34
SM6: NIST/Sandia Collaboration Initiated 35
SM7: Photoreflectance Spectroscopy 35
SM8: Micromachined Semiconductor Devices: MOSIS Fabrication 36
SM9: TCR and Joule Heating Measurement 36
SM10: X-ray Lithography Mask Design 37
SM11: New Electrical Test Structure for Overlay and Feature-Placement Metrology 37
SM12: Faster MOS Oxide Reliability Characterization 38
SM13: Optical Properties of SiO_2/Si Interface Region 38
SM14: MBE Growth and Characterization of Compound Semiconductors 39
SM15: SRM 2551 for Interstitial Oxygen Concentration in Silicon 40
SM16: 14-nm-Thick Oxides Certified as Standard Reference Materials 40
SM17: STM Characterizations in Air on GaAs Junctions 41
SM18: Measurements of Ion Kinetic Energies from Radio Frequency Plasmas 41
Low Frequency (LF) **42**
LF1: Pulse Generator 42
LF2: Commercial Product Derived from Calculable rms ac Voltage 42
LF3: Resistance Step-Down Comparisons 43
LF4: Low Cost/Better Thin-Film Multijunction Thermal Converters 44
LF5: Commercialization of Software Package at $50,000 per unit by Teradyne, Incorporated 44
Video (V) **45**
V1: Videotape of NIST Model for Flat Panel Displays 45
V2: Evaluation of Image-Producing Algorithms 45
Electronic Data Exchange (EDE) **46**
EDE1: Electronic Business Reply Card 46

Programs Matrix-Managed by EEEL 47
Office of Microelectronic Programs (OMP) 47
OMP1: Micromechanical Measurements for Reliability of Electronic Packaging and Interconnects 47
OMP2: Ultraviolet Irradiance Measurement Technology 48
OMP3: Plasma Processing and Chemical Vapor Deposition 48
OMP4: Monitoring the Cure of Thin-Layer Polyimides on Glass Substrates with Photoacoustic Infrared Spectroscopy 49
OMP5: Microelectronics Dimensional Metrology 50
OMP6: Solderability Measurement and Optimization 52
Office of Law Enforcement Standards (OLES) 53
OLES1: Flammability of Mattresses for Correctional Facilities 53

Questions & Answers: Whom Should I Call? 55
EEEL Management Staff 55
Laboratory Headquarters 55
Electricity Division 55
Semiconductor Electronics Division 55
Office of Microelectronics Programs 55
Office of Law Enforcement Standards 55
Electromagnetic Fields Division 56
Electromagnetic Technology Division 56

Appendix A: EEEL Awards and Recognition 57
Institute of Electrical and Electronics Engineers, Incorporated (IEEE) 57
Department of Commerce 58
NIST 60
Other Organizations 61

Appendix B: FY 1993 CRADAs 63

Appendix C: EEEL Organization Chart 67

Laboratory Director's Message

Judson C. French, Director
Electronics and Electrical
Engineering Laboratory

The electronics industry is outstripping available measurement tools to control its materials and processes and to evaluate its products. This is of concern because the electronics industry is the country's largest employer and is one of the two largest manufacturing industries.

The role of the Electronics and Electrical Engineering Laboratory (EEEL) of the National Institute of Standards and Technology is to provide the measurement tools industry must have to provide and prove world leadership in the performance and quality of its products.

During the past year, we have observed a growing industrial need for measurement services from EEEL, continuing technology spin-off from our research, significant impact on our customers, new efforts at outreach influencing Federal-private sector partnerships in planning and implementing significant programs, and unprecedented recognition within the Administration of the significance of the work performed by EEEL. The EEEL is well positioned to fill its role, but a brief review of the primary areas of technical effort indicates the many challenges to be faced:

Fundamental Electrical Standards — Within the United States, EEEL maintains the nation's fundamental electrical standards. An obvious indicator of the challenge to remain ahead of industry's needs is that, for the first time, industry is using quantum techniques on the manufacturing line for quality control; in this case, the voltage standard in the form of the NIST 10-V Josephson voltage array. Our advanced methods to realize the volt and the quantum Hall resistance are both being commercialized.

Microwaves — Our microwave work has substantially changed the standards and practice of the industry and the military. The program is being refocused to provide greater support for wireless communications and electromagnetic compatibility, areas where measurement technology will be needed by the communication, automotive, and electronic industries of the future.

Superconductors — EEEL's portion of the NIST-wide superconductivity program continues to produce exciting and impressive output and has an excellent staff. We are well positioned to support the nascent domestic superconductivity industry.

Recent Achievements

1991 Developed and applied the measurement science needed to evaluate detectors used in weather satellites. Data contributed to the decision to redesign the proposed satellite.

1990 Worldwide, the volt and the ohm were redefined to reflect the accuracy that can be achieved using quantum standards. The redefinition was based, in part, on seven NIST experiments.

1988 A 10-V standard was used for the first time by a U.S. manufacturer for quality control on a production line.

1988 EEEL produced the standard reference material for determining the thickness of a silicon dioxide layer on silicon. Demand within the U.S. semiconductor industry was so great that nearly all were sold as soon as they became available.

1993 Technical Accomplishments

1988 At the request of Congress, NIST performed a special analysis of a digital-audio-tape copy prevention system, found the system to be flawed, and the system was abandoned by the recording industry. An improved system was subsequently developed and adopted.

1987 The world's first 10-V standard based on the Josephson effect was developed.

1986 In response to concerns over possible health effects, the first international standard on the measurement of power frequency electric and magnetic fields was adopted. Significant parts of the standard were based on NIST's investigations.

1980 Developed method to determine the effect of stress on the critical current in superconducting magnets, information which made high-power magnets possible.

Lightwaves — Our optoelectronics and optical-fiber telecommunications program has had a major effect on the optical fiber industry. As the industry matures, our program is shifting attention to measurements for networks and systems and some special components, such as controllable interconnects. We need additional competence to support the optical enhancement of computers through metrology for smart multidimensional interconnects, for example.

Magnetics — Our magnetics work has provided results eagerly adopted by industry in standards and practices and in new commercial products. Current emphasis is working with the industry to improve magnetic information storage, principally through provision of a broad range of sensitive, practical measurement tools and services.

Semiconductors — The semiconductor industry's roadmap for its future clearly emphasizes metrology as important in nearly all of its "show-stopper" technical challenges. The industry has recognized that NIST is the only place in the United States where the broad range of measurements needed for semiconductor processing is routinely and systematically developed. The EEEL is responding by mapping our plans onto the industry's so that we will be suitably responsive.

Power Networks — Service to the power and energy field has a long, continuing leverage and impact. Examples range from the measurement of power and energy for applications such as revenue metering and motor efficiency determinations to the measurement of electric and magnetic fields in the home, business and environment.

Video — The video program is new within EEEL but of great significance as the United States evolves into a new age of information technology. The program presently focuses on display technology and signal processing.

Electronic Product Data Exchange — Improved manufacturing of electronic products requires both an improved physical measurement infrastructure and the information systems to support agile efficient manufacturing. Our small program which assures that general advances in manufacturing information systems are available to electronics manufacturers has already delivered industry-accepted products and is developing a test bed for protocols and new work in electronic commerce.

The use of our work by industry is one of the primary means by which we realize the goals of the laboratory. In fiscal year 1993, several discrete achievements resulting in EEEL/NIST patents were commercialized by industry. The four hardware components and three software products developed commercially will have significant impact in at least two direct ways: increased revenues for the companies that produce them and increased capability for the companies that purchase them. However, commercialization is really a bonus arising from the usefulness of new measurement instruments, which are typically developed to meet internal requirements.

More often, our collaboration with industry in key programs and projects enables our industrial partners to forge ahead on their own to develop and bring new or enhanced products to market more efficiently. From this broader perspective, studies have shown that the economic impact of our technology transfer provides an average return on investment of about 200 percent and ranges up to more than twice that value. In the most conservative terms, by leveraging our very finite resources through long-term interactive relationships with our customers, we achieve more than twice the return of typical industrial research and development efforts.

Of all the technical investigations in which EEEL is involved today, I find the opportunity to link the "mass" unit to a fundamental constant, or well established physical law, to be among the most challenging. Of the seven internationally recognized base units of measurement: length, mass, time, temperature, electric current, amount of substance, and luminous intensity, only the kilogram is still defined as an artifact, the mass of a Pt-Ir block. The consensus around the world is that the testing of physical theories through accurate measurements and the establishment of a consistent set of the fundamental physical constants are essential to the progress of science. Each of the base units of measurement must possess long-term stability at the highest level of accuracy, and this stability is suspect in the case of the mass artifact.

Consequently, we have embraced the goal of tying this last unit to atomic or quantum phenomena, which are essentially immutable. Our prospects are excellent. We have already achieved singular results, strengthening our position in this arena, including a major contribution to the redetermination of the ohm and the volt, and the establishment of the world's best quantum-Hall-effect measurement system. Just as importantly, we have been able to transfer this technology from our laboratory to American companies, enabling them to benefit from increased precision in process manufacturing across industry lines.

Finally, as a world-class laboratory, EEEL recognizes that we learn from others as well as contribute to their development. In a very real sense, our planet is becoming smaller with each day that passes; walls are breaking down and the need to find ways to work together to achieve common ends is increasingly important. During this past year, we came a long way toward finalizing the understandings necessary to undertake a project sponsored by the United States and Japan to further the design and development of advanced computing technologies that combine lightwave and electronic components. As Chairman of the United States contingent, I look forward to the implementation of this venture, which will be a model for U.S.-Japan cooperative research. The specific objectives are to stimulate research and development activity in optoelectronics, provide designers with access to leading-edge fabrication facilities, and encourage effective commercialization. If, as we expect, both nations benefit from joint research in an area likely to yield commercially important technologies, then other cooperative projects will follow.

On behalf of the laboratory staff, I would like to thank you for your interest in EEEL. On the following pages, you will find highlights of some of the technical accomplishments performed in FY 1993 as well as information on each of the divisions in the laboratory, our services, and notable interactions throughout the year.

EEEL Makes a Difference

In 1993, EEEL made a big difference in the lives of people living in the United States. Some of the exciting work accomplished in the laboratory contributed to their health and well-being. Success in other projects contributed directly or indirectly to driving up the economy by making American industry more competitive and the dollar more viable. Measures of the difference EEEL has made over the years have shown substantial increases in industry's productivity and the reliability of its products, new product introductions, new companies formed to commercialize ideas, and substantial market share growth.

And, in many cases, the work done in the EEEL divisions located in Gaithersburg, Maryland and Boulder, Colorado enhanced the quality of our lives in ways we tend to take for granted. Consider for a moment just how we benefited from their work. The metering systems, which are installed in our offices and homes, and provided verifiably accurate indications of power usage throughout the year, were directly traceable to NIST. Communication with others was timely, direct, and clear whether we were 200 or 2 000 000 meters away, using telephones or beepers, facsimiles, or databases networked across the nation. We had windows to events around the world, whether the signals being processed were measured in hertz or terahertz. And, Americans could be secure in the knowledge that we were prepared to respond to friend and foe alike. The Laboratory's work in the area of microwave technology has significantly impacted military as well as industrial practice.

Key to the confidence we feel regarding the infrastructure that supports our lifestyle are standards. Standards are the bedrock that define the parameters of operating systems and equipment. And, the standards that define the calibre of the myriad devices used to harness or channel electrical/electronic energy to better our lives is directly traceable to the work done by the people working in the Electronics and Electrical Engineering Laboratory of the National Institute of Standards and Technology.

Finding ways to cut down the time it takes to execute one or more steps in a process line, without sacrificing an iota of quality, gives American manufacturers an edge. Imagine the impact when you can reduce 8192 measurements to 64. See page 44.

One way to streamline the design and production of video processing components would be to develop software that allowed you to evaluate prototype designs before building the hardware. It can be done. See page 45.

Newly developed composite materials for aircraft provide strength with considerably less weight than conventional materials. But often, the reduction in weight is accompanied by a reduction in shielding from unwanted electromagnetic effects. New techniques to evaluate shielding effectiveness were essential. Now they're available. See page 24.

Long-Term Goals

EEEL aims to be the world's best source of fundamental and industrial measurement methods, and to provide reference standards that provide high leverage for U.S. industry. Our mission is to deliver these resources to industry, academia, and Government in support of national goals.

EEEL

The Laboratory comprises four divisions and two offices. 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 and the Electromagnetic Technology Division are located in Boulder, Colorado.

Electricity Division

The Electricity Division maintains and improves the national standards of electrical measurement, and develops stable electrical standards for the dissemination of the units of electrical measurement. 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 detection 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.

Semiconductor Electronics Division

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. Research is conducted to provide, through both experimental and theoretical work, the necessary basis for understanding measurement-related requirements for semiconductor technology. By disseminating their results and fostering their application, the Division helps to increase manufacturing productivity and enhance the capabilities of semiconductor technology.

Electromagnetic Technology Division

The Electromagnetic Technology Division develops measurement techniques and standards, and provides calibration services, measurement assurance programs, and reference data for laser and fiber optics technology. As superconductivity and magnetics are clearly identified as sources of new advances in both electrical engineering and electronics, the Division has a prominent role in the NIST-wide programs of research on high-temperature superconductors and magnetic measurements. The magnetics work emphasizes measurement of magnetic characteristics with very fine spatial resolution. Work being done on the unique properties of superconductors, and particularly the Josephson effect, will advance the basic mission of NIST in physical measurements, particularly of fast electrical waveforms and weak electromagnetic fields. The work related to lasers has resulted in a measurement assurance program in laser power, which provides the measurement basis for the procurement of laser systems and the regulation of laser safety by government agencies. The optical fiber work emphasizes a systematic metrology program to enhance the U.S. effort to develop optical fiber transmission systems.

Electromagnetic Fields Division

The Electromagnetic Fields Division conducts basic research and applied research on the interaction of electromagnetic radiation with devices and materials and applies the results of these investigations for the improvement of measurement services. The work emphasizes the development and evaluation of measurement standards needed to characterize the mechanisms and output of electromagnetic sources, receivers, and other passive and active devices. Principal program areas include Microwave/Millimeter Wave Metrology for continuous-wave transmission line measurements, Microwave Metrology for noise, time domain, and dielectric measurements, Antenna Metrology, and Fields and Interference Metrology. These services and associated standards provide a consistent base of measurements to enable customers in the defense, aerospace, communications, and related industries to assemble complex systems and conduct stringent performance assessments of these systems.

Office of Microelectronics Programs

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, such as *MicroTech 2000* and the SIA Roadmap.

The Office of Law Enforcement Standards

The Office of Law Enforcement Standards (OLES) supports law enforcement agencies through measurements and by developing techniques for testing devices used in such applications as tracking vehicles, speed monitoring, surveillance, and communications. Its mission is to assist federal, state, and local law enforcement agencies 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 (NIJ), 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 1000 visitors in FY 1993. Other interactions with our customers included 290 presentations away from the laboratory, and 420 visits to other sites. EEEL staff provided 1710 consultations during the course of the year, as well as in the activities of three consortia. Staff members hold 290 professional memberships, in addition to 90 memberships held in standards organizations. Forty-seven scientists participated in standards organization activity in FY 1993, often in leadership roles. Forty-two Guest Scientists contributed their efforts to various projects within the Laboratory. Eleven short courses were conducted by Laboratory personnel for diverse audiences. Staff conducted 31 technical meetings and attended 900 meetings over the year. Sixty-five members of EEEL's staff made major contributions to conferences during this period.

Taken together, these interactions enabled EEEL staff to develop a realistic, well-founded knowledge of the challenges American companies confront across broad industry lines. This information provides the bases for the ongoing modification of the Laboratory's strategy to implement its mission. By staying in close contact with current and potential customers and staying abreast of developments worldwide, EEEL remains agile as well as robust.

In the electronics industry, being first to get to market means market share. The market is not linear: second-best often means next-to-nothing. Many factors play a role in the leveraging of EEEL's resources but, however they are weighted, the end goal is clear: take the initiatives necessary to anticipate and deliver the results industry will need while the delivery is timely and effective. Within FY 93, EEEL staff undertook 94 cooperative projects with U.S. industry, including cooperative research and development agreements. The work done on many of these projects will define state-of-the-art technology in the years to come.

Laboratory personnel performed over 2200 calibrations, yielding fees of $2.23 million. Revenue from the sale of Standard Reference Materials exceeded $122,000. Requests for software developed by EEEL staff and available to the industrial and scientific community at no cost numbered almost 300. Sixteen patent disclosures were prepared in FY 1993: two were issued and 14 are pending. In terms of technology transfer, EEEL work has led to the commercialization of four hardware components and three software products this past year.

Fiscal Year (FY) 1993 Activities

Workshops

EEEL conducted three workshops this year, each of which afforded industry, as well as the scientific and academic communities, the opportunity to focus on key issues, share ideas, and, in some instances, help to chart the direction that future activities might take. NIST-sponsored workshops have proven to be very valuable for our customers. More often than not, before a workshop is concluded, requests, plans, and commitments are proposed for follow-up sessions.

The **"Workshop on Advanced Components for Electric and Hybrid Electric Vehicles"** was held on October 27-28, 1993 in Gaithersburg, Maryland. The workshop, which was sponsored by NIST, was organized through the Interagency Coordination Task Force on Electric and Hybrid Vehicle Technologies. The Task Force includes members from the Department of Commerce (DoC), the Department of Defense (DoD), the Department of Energy (DoE), the Department of Interior (DoI), the Department of Transportation (DoT), the Environmental Protection Agency (EPA), the Interagency Advanced Power Group (IAPG), the National Aeronautics and Space Administration (NASA), the National Science Foundation (NSF), and the Office of Science and Technology Policy (OSTP).

This workshop focused on the basic research and development required for components critical to the development of electric and hybrid vehicles for the year 2000 and beyond. Emphasis was placed on means to improve the performance, cost, and manufacturability of these vehicles. Participants identified performance requirements, high potential technologies, economic and commercial barriers, and discussed future standards and test procedures. In addition to the overviews by invited speakers from industry, government, and universities, parallel sessions were conducted to enable topical discussions of components for energy storage, energy conversion, electric propulsion, controls and instrumentation, and ancillary systems. The Workshop Proceedings will be published in February, 1994. Over 200 participants registered for this event, and in the questionnaire designed to determine its effectiveness, 90 percent requested a follow-up workshop within a year's time. The next workshop is provisionally scheduled for early in 1995.

The **"Flat Panel Display Measurements Workshop,"** organized in response to industry display needs, was held at NIST on Tuesday, November 16, 1993. Discussions focused on flat panel display (FPD) quality measurement and standards requirements in the explosive FPD industry. The 50 participants represented a wide range of industrial and government interests. Morning sessions were devoted to several invited speakers, who discussed the current standards activities and their future direction. In the afternoon, an open discussion of subjects of interest to the group occurred. There was much concern over the fact that several groups are writing quality-display standards, but are not necessarily talking to each other. Display quality is not even fully specified for color cathode ray tube (CRT) monitors at the present time, so the consensus was that the road to general FPD display quality standards will be difficult, at best.

It was suggested that NIST could serve industry in an important way as a hub or custodian of information regarding the international FPD standards activities. Several action items were suggested and agreed upon, including that NIST would assemble a list (flow chart) of all the standards activities connected with FPDs; NIST will maintain the list and associated information in a format which can be accessed worldwide via e-mail. Two future workshops were also outlined. The second NIST FPD workshop will provide tutorials on all the standards currently applicable to FPDs. The third NIST workshop will provide a forum to permit all standards to be tested in laboratory environments. In conjunction with this third workshop, or in a fourth workshop, equipment difficulties, metrology problems, standard interpretations, and generation of work items to fix deficiencies will be explored.

The **"Computer Modeling of Optical Waveguides and Components: A Hands-On Workshop,"** which was held June 29 - July 2, 1993, at NIST, Boulder, Colorado, attracted 20 participants from various communities, including academia, industry, and government. The thrust of the workshop was very straightforward: disseminate information and techniques that will help the participants to design optical waveguide components. The workshop was cosponsored by the INDO-US Collaborative Program on Integrated Optics. Four analysis tools were treated, each of which was developed under the Collaborative Program. Participants were very enthusiastic about the hands-on laboratory scheduled during the workshop, which allowed them to experiment with working computer code that had been developed over the previous five years.

Technology Reinvestment Program

The Technology Reinvestment Program (TRP), announced by President Clinton on March 11, 1993, is a cornerstone of the Defense Reinvestment and Conversion Initiative. The TRP 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.

Thomas Russell, EEEL's TRP liaison, reports that the project, a cooperative effort involving the Departments of Commerce (NIST), Defense, Energy, and Transportation, the National Aeronautics and Space Administration, and the National Science Foundation, is devoting over 85 percent of its $472 million budget to technology development and deployment activities. The project managers sought broad participation in this effort through an "800" hotline and a series of regional briefings. The TRP elicited 2850 proposals, seeking a total of $8.5 billion in matching funds, from teams consisting of more than 12000 companies, universities, federal research laboratories, and state and local governments in all fifty states and the District of Columbia. Three-hundred technical experts from the participating agencies provided peer review of the submissions. EEEL contributed the greatest number of experts to the NIST contingent.

Most of the proposals aimed toward creating new technologies, with the potential for commercialization in five years. On October 22, 1993, President Clinton approved 41 projects for $140 million in requested Federal matching funds. Final decisions on the remaining awards were scheduled for the end of the calendar year. Planning for the follow-up round of competitions began almost immediately.

U.S.-Japan Optoelectronics Project

In FY 93, 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). Russell announced that the U.S.-Japan Joint Management Committee (JMC) met in Washington, D.C., in December, 1993, to plan implementation of the project to begin in mid-1994. The U.S. JMC members are Judson French (NIST, Chair), Joseph Bordogna (NSF), John Boright (DoS), David Nelson (DoE), and Sven Roosild (ARPA). NIST is responsible for the day-to-day management of the project in the U.S. and co-chairs the JMC.

The ability to prototype is essential for rapid advance in the underlying technology, as experience in silicon-based microelectronics has proven. An excellent 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. The 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 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 central Brokers (either in the United States or Japan), who 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. Funding for the U.S. Broker will be provided by MITI. The U.S. JMC will select the U.S. Broker and determine funding mechanisms for the U.S. users of the project.

French and Russell have targeted time and effort to build bridges to the private sector in the past year. Their efforts included presentations 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 were also 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).

Electronics Working Group

The Electronics Working Group (EWG) of the Federal Coordinating Council for Science, Engineering, and Technology — Committee on Physical, Mathematical and Engineering Sciences (FCCSET PMES) is a key component in government-private sector cooperation encouraged by the Clinton Administration. The EWG is structured to create an area of synergy and cooperation between industry, government, and academia. Its chief aim is to facilitate long-term U.S. leadership in the electronics industry in the face of competitiveness issues such as the consistent, bilateral $20 billion trade deficit with Japan and lags in U.S. market share, growth and production. Competition is increasingly fierce: many countries are competing for dominance of critical technologies, including electronics.

Members of the EWG include the Office of Science and Technology Policy, the Department of Commerce (NIST), the Department of Defense (ARPA), the Department of Energy, the Environmental Protection Agency, the National Aeronautics and Space Administration, the National Science Foundation, the National Security Agency, and, as a nonvoting participant, the Critical Technologies Institute of RAND.

Judson C. French, NIST's EWG member, noted that at the close of the calendar year, the National Science and Technology Council (NSTC) was created by Executive Order to coordinate Administration initiatives that involve several agencies. President Clinton presides as Chairman of NSTC, with Cabinet-level officials charged with overseeing the work done on committees, such as the proposed Civilian Industrial Technology (CIT) Committee to be headed by Dr. Mary Good, Undersecretary of Technology, Technology Administration, Department of Commerce. The EWG became a subcommittee of the CIT. NIST, as represented by EEEL, played a leading role in promoting and developing strategies for the EWG. In FY 1993, the committee reached out to the private sector and proposed the creation of the Electronics Partnership Project, which will be a public-private forum in the electronics domain. In addition, in response to industry requests, the Federal Electronics Inventory Project was created to disseminate information widely. The Inventory will collect and maintain accessible data on electronics-related research and development activities in Federal agencies. A focused Electronics Manufacturing Initiative, which is still in the conceptual stage, is being considered to provide government support for enabling technology and manufacturing infrastructure.

NIST-Sandia Agreement

In 1993, NIST and Sandia National Laboratories agreed on a formal arrangement to cooperate in areas of common activity. The first cooperative area identified was in semiconductor technology. The Semiconductor Industry Association has published a technology roadmap which identifies the technical advances necessary to maintain and increase worldwide market share. In that process, the industry had identified NIST and Sandia programs as important to the industry's success. NIST and Sandia have agreed to coordinate their response to the industry's needs to minimize needless programmatic overlap and to permit a timely response. Joint projects in the areas of lithography, reliability, and packaging have been initiated during 1993.

Measurements for Competitiveness in Electronics

Measurements for Competitiveness in Electronics identifies a major shortfall in U.S. measurement capability that must be addressed to improve the competitiveness of the U.S. electronics and electrical-equipment industries. The report was prepared by six EEEL authors working in consultation with U.S. industry and with other NIST Laboratories to provide a consensus statement of the principal measurement needs. The report serves two primary purposes: to show the close relationship between the U.S. measurement infrastructure and U.S. competitiveness, and to provides the basis for an action plan to correct the measurement shortfall and to advance U.S. competitiveness.

The report addresses both broad measurement issues for high-technology industries and specific measurement needs for individual fields of technology. The broad issues include the role of measurements in the competitiveness of U.S. industry, and the role of NIST in providing measurement support to U.S. industry. The nine fields of technology addressed are semiconductors, magnetics, superconductors, microwaves, lasers, optical-fiber communications, optical-fiber sensors, video, and electromagnetic interference. The report also includes an overview of the U.S. electronics and electrical-equipment industries to provide a context for the discussion.

The report has been reviewed by industry experts in a diversity of companies, has engendered editorial reviews in six industry publications and announcements in a dozen more, and has been generally received as timely and significant. It may be obtained from the National Technical Information Service (Order No. PB93-160588).

Selected FY 1993 Technical Accomplishments

The selection of highlights is representative of our efforts over the past year, and is organized in terms of technology areas. However, all projects are not necessarily represented. As is always the case with research, breakthroughs or advances do not necessarily follow a linear progression or calendar.

Microwaves

M1: Planar Transmission Line Characterization

Dylan Williams and Roger B. Marks developed a breakthrough technique for accurately measuring the characteristic impedance of planar transmission lines. The method, which is applicable to transmission lines fabricated on polymers, silicon, or other lossy or dispersive dielectric substrates, also provides equivalent circuit parameters of the lines (resistance, inductance, capacitance, and conductance per unit length), which in turn contain valuable information on material parameters. Tests indicate that the accuracy achieved using their method exceeds results obtained with other methods available up to now. *Electronic Design* received over 230 requests for reprints of the paper published on this topic in the two months following the magazine's mention of the work.

This technique will have broad application. Planar transmission lines are essential components in applications such as monolithic microwave integrated circuits, printed-circuit boards, and special modules for high-performance computers. As the speed of advanced silicon circuits increases, microwave lines will be required for mainstream silicon as well. Other applications may include the measurement of the dielectric constant and loss tangent of thin dielectrics and the measurement of both normal and superconducting metal parameters.

M2: Calibration Verification

On-wafer microwave measurements play a critical role in the design of the monolithic microwave integrated circuits (MMICs), a technology which promises to replace the costly technology of discrete components in both military and civilian applications, such as personal communication networks and intelligent highways. While the microwave industry has developed numerous calibration techniques, which they hoped would improve measurement accuracy, no rigorous methods were available for actually evaluating the accuracy of these calibrations.

"I am writing to thank Drs. Roger Marks and Dylan Williams for the work they have done in the area of microwave on-wafer probing. I believe that they have significantly contributed to the advancement of this field...As a practicing design engineer, I have used their program DEEMBED extensively...we are primarily interested in the design and development of wafer probes as well as commercial calibration substrates. NIST's DEEMBED program, used with a Vector Network Analyzer, has been our primary, and most accurate, design and analysis tool during the last two years. It would have been difficult to have developed certain products, like CAL93, in the time frame in which they were developed without this software...I have also used the software for measuring the S-parameters of active devices. The ability of the software to give a real impedance, and to extend the usable bandwidth of a given set of coplanar transmission lines, allows us to obtain accurate measurements over a sufficient bandwidth."

Frank Williams, Microwave Design Engineer, Microwave and Accessories Products, Tektronix, Incorporated

The NIST/Industrial MMIC Consortium, whose membership includes TRW, Cascade Microtech, Incorporated, Texas Instruments, Incorporated, Raytheon Corporation, ITT, and Newark Air Force Base, funded NIST researchers to explore procedures for determining the accuracy of on-wafer microwave measurements. Dylan Williams and Roger Marks proposed a procedure and began testing it in 1992. In 1993, they tested the procedure with the cooperation of personnel in the member laboratories, and quickly demonstrated its usefulness. In some cases, the procedure confirmed that the industry-developed calibrations were indeed sufficiently accurate. This was the first time such information was attainable by any means. In other cases, the procedure detected astonishingly high measurement errors, sometimes as high as 70 percent, which had gone undetected despite complicated and seemingly thorough internal calibration-consistency checks.

Where the test results proved negative, the impact of the test procedure exceeded the goals of the project. The software not only identified the measurement errors, but some special diagnostic capabilities the researchers had added were able to identify error sources and suggest remedies. These diagnostic capabilities led to effective remedies or to the development of alternative calibration procedures for members of the consortium.

Williams and Marks are already looking for ways of opening up these tests to a larger spectrum of the U.S. MMIC industry, for obtaining feedback from the industry on the technique, and for establishing the technique as an industry standard.

M3: Impedance Parameters of Devices Embedded in Lossy Dielectrics

Dylan Williams and Roger Marks have developed a calibration technique that may be the first accurate method of characterizing devices at high frequency on silicon. The technique is expected to have both immediate and long-term applications for microwave metrology. Williams and Marks demonstrated the method in silicon and other lossy dielectrics over the frequency range 50 MHz to 40 GHz, nearly a thousand-to-one bandwidth. Although the technique is probably too complicated to use in industrial settings, it will provide a benchmark against which other more approximate techniques for testing devices embedded in lines fabricated on lossy dielectrics can be compared.

The technology is appropriate for the characterization of microwave devices fabricated on silicon, silicon MMICs, and silicon packaging discontinuities. Also, the method can be extended to both higher and lower frequencies than those demonstrated initially. If the technique could be implemented on time-domain measurement systems, it could be applied to the characterization of high-speed silicon digital devices and circuits.

M4: New Calibration Services: Premium Power

Fred Clague successfully conducted the first effective efficiency measurements on customer reference standards manufactured to NIST specifications and drawings. This premium microwave power calibration service skips one transfer step necessary for ordinary commercial power detectors, allowing an increase in the accuracy of the final calibration. Clague has calibrated 18 standards for three companies and the Department of Defense.

In response to customer requests for reduced uncertainty, Clague used a coaxial microcalorimeter to conduct measurements of newly designed standards originating from the Microwave Metrology group. Clague's measurements verified an uncertainty of 0.4 percent ($2\,\sigma$). Contrasted with the best previous NIST service, this is a reduction in the uncertainty by a factor of three.

M5: New Calibration Services: S-parameters

Microwave calibration services are needed to ensure measurement accuracy by the microwave industry. In response to customer requests, John Juroshek, Manly Weidman, and Raian Kaiser have extended NIST calibration services to devices having 2.92-mm connectors, and begun work to establish a service for devices having 2.4-mm connectors. The group is also evaluating the possibility of using a commercial vector network analyzer for these services. It will offer the opportunity to evaluate cost-effective methods for characterizing and verifying vector network analyzers. This work will be done under a CRADA with the Wiltron Company. The group has also developed a diode-detector dual six-port vector network analyzer operating over the frequency range of 18 to 40 GHz. This device is used to calibrate 1-port and 2-port coaxial devices having 3.5-mm, 2.92-mm, and 2.4-mm connectors.

Work under a CRADA with ATN Microwave, Incorporated, includes evaluating a multi-state two-port device, which is being investigated as an alternate means for disseminating NIST microwave S-parameter measurements. In addition, the group has procured and tested waveguide kits for WR-62 (12.4-18 GHz) and WR-90 (8.2-12.4 GHz) waveguide bands, which they will use to calibrate customer waveguide devices on dual six-port automatic network analyzers.

M6: New Calibration Services: Power Direct Comparison System

Power measurements are one of the basic parameters that must be measured in the microwave industry. Scientists for the Microwave Metrology Group, Manly Weidman, Raian Kaiser, and Dennis LeGolven, have designed a calibration system to measure the effective efficiency of thermistor mounts. This system will result in fivefold reductions in calibration time and in laboratory maintenance time. The reductions in time will carry over to reduced costs for this service.

The new system, which is designed to provide a direct comparison of power, will initially be used for Type-N coaxial power calibrations from 50 MHz to 18 GHz, but coverage may be extended to other frequencies and connector types.

M7: New Calibration Services: Noise

Signal-to-noise ratios are important parameters for characterizing the performance of many electronic systems. In a fundamental way, the amount of noise present limits the amount of data or information that may be transmitted over a communication link, guided or free space.

In response to customers' requests for expanded characterizations in the millimeter-waveguide bands, Sunchana Pucic, working with David Wait and Wayde Allen, has established new special-test services for equivalent noise temperature in the WR-42 (18 to 26 GHz), WR-19 (40 to 60 GHz), and WR-15 (50 to 75 GHz) waveguide bands.

Three new radiometers that use cryogenic primary noise standards were brought on line to replace the older oven standards, which were difficult to operate and maintain. The new equipment has made it possible to reduce the measurement uncertainties by 50 percent and to reduce calibration fees significantly due to a threefold reduction in measurement time.

M8: New NIST Antenna Measurement Range

In support of the microwave industry's immediate need for calibrations and diagnostic measurements on antenna standards up to 3.5 meters in diameter and 100 GHz in frequency, Douglas Kremer and Andrew Repjar established a new antenna facility that includes both a planar scanner and a rotator system. The new rotator system provides pattern, gain, and polarization measurements, as well as cylindrical and spherical near-field measurements. The incorporation of a mechanically-stable mount for antennas of various sizes facilitates the alignment of antennas to tolerances previously unattainable. An evaluation of the new NIST (2.4 x 2.4)-m planar scanner and receiver demonstrated that scanner alignment, knowledge of probe position over the measurement plane, and knowledge of antenna location permits calibrations at millimeter-wave frequencies to 100 GHz.

In FY 1993, Katherine MacReynolds used the new facility to calibrate probes submitted by Near Field Systems, Incorporated for INTELSAT VII and for calibrations of dual-port, circularly polarized antenna standards from 50 to 75 GHz. The facility is also positioned to respond to requests for the evaluation of transmit/receive modules for next-generation phased-array steerable antennas designed for operation at 35, 60, and 94 GHz. The application of this technology is imminent for automatic aircraft landing systems and anticollision radars.

"I am writing to inform you of the outstanding contribution that Carl Stubenrauch and Ronald Wittman have made to the Advanced Communications Technology Satellite (ACTS) Project under the terms of the technical support contract between the NASA Lewis Research Center and NIST.

Much of their work...consisted of investigating possible sources of error arising from the measurement of the ACTS multibeam antenna (MBA), a pair of offset Cassegrain antennas with 50 transmit and 50 receive beams, on a newly constructed GE spherical near-field scanner.

Their efforts led to the discovery of a subtle error in the near-to-far field transformation program used in conjunction with the spherical near field scanner. Correction of this error, in addition to numerous refinements in measurement technique, finally resulted in good agreement between predicted and measured antenna performance and made possible antenna measurements in which we have confidence... I believe their efforts...have been an important contribution to a successful ACTS."

Frank A. Regier, Project Engineer,
Advanced Communications Technology
Satellite (ACTS), NASA

NIST traceability is a common requirement for systems in both the commercial and industrial sectors to verify that performance requirements are met. INTELSAT VII, a communications satellite, which is now in production, will be tested using the planar near-field technique that was invented at NIST. The probes calibrated at NIST will serve as the standards for these tests.

M9: Measurements of Standard Gain Antennas for International Intercomparison

International intercomparisons provide a means for establishing a basis for consistent measurements worldwide. This is increasingly important as high-technology companies develop into multi-national companies. As the pilot laboratory for this international intercomparison, NIST continues to demonstrate world leadership in accurate antenna standards and calibrations.

A group of scientists, including Allen Newell, Carl Steubenrauch, Stan Gilgore, Katherine MacReynolds, and Douglas Tamura, completed the gain and polarization measurements of the standard gain horns used for the international gain comparison. This work constitutes the third NIST calibration of the antennas. The antennas were calibrated at 8, 10, and 12 GHz.

M10: Measurements on Permittivity and Permeability on New Materials

New and cheaper materials are being sought by industry for a variety of electromagnetic applications. In support, NIST responds to industrial requests by providing reliable measurements and accurately characterized specimens. According to an industry spokesman, Richard Geyer's work on an application for the automobile industry is expected to provide potential cost savings of $100 million by eliminating false starts in the production of electronic components using inappropriate materials. The company, Packard Electric, a part of General Motors (GM) Corporation, expects to select material based on Geyer's measurements.

Permittivity and permeability measurements on nine specimens prepared from different mixes of two materials were completed. The specific application involves the optimal material for feed-through filter elements in vehicle wiring harnesses. As the harnesses continue to grow in complexity, the impact of proper selection on cost becomes even more significant. These components will also be an important factor in the development of electric and hybrid-electric vehicles. The search is for the materials best suited to prevent electromagnetic (EM) interference with automobiles' electronic systems. An example of such interference might include an unwanted EM signal that causes a car to stall while moving along a highway.

"For the past two years, NIST and General Motors Packard Electric Division, maker of wiring harnesses for most of the domestic and international autos in this country, together with General Motors Research, have been working together on a CRADA to eliminate electromagnetic interface in our vehicles. G. M. Research invented a novel ceramic material called EMISorb for use in filtered header-connectors for our electrical connections throughout our vehicles. G. M. experienced an unexplained electromagnetic interference problem two years ago and G. M. rushed to NIST for help in this problem. NIST was instrumental in setting up important measurements on one-of-a-kind equipment at your Boulder, Colorado facility..."

Jack G. Simon, Manager, Technology Leveraging, General Motors R&D Center

M11: Round Robin on 7-mm Coaxial Material Measurements

Eric Vanzura and John Grosvenor conducted an 11-laboratory intercomparison that provided a test of industry performance and showed practitioners the significance of a measurement method under development by the American Society for Testing and Materials (ASTM) with NIST leadership. The end result increased the microwave industry's capability for accurate assessment of electromagnetic properties of materials at microwave frequencies.

Having completed the development of software for material characterization using transmission-line measurement methods, the scientists based the intercomparison on a 7-mm coaxial line. They found considerable variation among laboratories, and carried out an analysis, which pinpointed the method used for air-gap correction as a major cause. It was also noted that some variance resulted from the use of differing software packages. After announcing the availability of a new materials software package for permittivity and permeability measurements, which incorporated the air-gap correction, Vanzura and Grosvenor received a significant number of requests (10) from industrial organizations. The availability of the NIST software will further promote uniform measurements through industry and benefit designers and manufacturers of antenna, radome, and microwave devices.

Electromagnetic Compatibility (EC)

"This report appears to add considerably to the knowledge base for a better understanding of the parameters influencing external field transfer/absorption characteristics. It may also provide part of the support needed to justify the reduced High Intensity Radiation Fields (HIRF) levels that are being contemplated by Aviation Rulemaking Advisory Committee (ARAC) for the draft regulatory, advisory and user guide materials."

William Schultz, Vice President, Engineering and Maintenance, General Aviation Manufacturers Association

EC1: Shielding Effectiveness of Airframes

The effects of unwanted electromagnetic energy from sources such as high-power radars on the control, communication, and navigation systems of aircraft is a great concern in the aerospace industry. Equipment in locations formerly shielded by metal structure that has now been replaced by composite structure is also vulnerable. A solution is urgently being sought to support innovations in new-generation transport aircraft, such as the introduction of the glass cockpit, fly-by-wire controls, and full-authority digital engine controls. However, a delicate balance is needed. Testing to overly stringent field-strength specifications is very costly and time-consuming, and it may result in substantial weight penalties in structure.

The work of David Hill, specifically, the theory and measurement techniques for the shielding effectiveness of airframes, with particular emphasis on pulsed fields, addresses this problem. All indications are that it will provide a sound basis for determining realistic levels of withstand fields. To date, Hill has completed an analysis of EM field penetration through apertures into a lossy cavity with application to aircraft immunity. His results demonstrate good agreement of the theory with broadband (1 to 18 GHz) measurements of shielding effectiveness, cavity Q, and cavity time constant.

L1: Integrated Optic Laser

Under a CRADA with Schott Glass Technologies, Kevin Malone and Norman Sanford have developed new integrated optic lasers and amplifiers in neodymium-doped phospate glass. The lasers have been operated operated at 905 nm, 1057 nm, and 1356 nm. The devices will also function as optical amplifiers in the same wavelength ranges. A large fraction of the optical fiber currently installed operates within the 1300-nm optical telecommunications window. Consequently, sources and amplifiers within that wavelength band are extremely important.

The impact of their work may well have significant long-term effects if the lasers and amplifiers are adopted by industry. Based on compatibility with current systems and system costs, a 1300-nm optical communication system could potentially have advantages over 1500-nm systems which are envisioned for both medium-haul communications and local-area networks.

L2: Laser Beam Profile Measurement Methodology

The analysis of parameters such as beam width, divergence, shape, and propagation is essential to matching the laser to its application and for making effective use of lasers. In FY 93, T.R. Scott, working with Richard Jones, conducted and analyzed the results of an interlaboratory comparison to test the current International Standards Organization (ISO) procedure for determining laser beam spatial parameters.

Scott and Jones found a surprising divergence of results among the participants, all of whom were laser instrument manufacturers. As a consequence of this work, which received wide publicity through trade and technical publications, ISO is revising its procedures and definitions of parameters. Just as importantly, the work done by Scott and Jones enables American laser manufacturers to characterize their products with greater accuracy, and provide their customers with a better sense of what they are buying.

L3: Fiber Geometry SRMs

The great information-handling capacity offered by optical fibers has already revolutionized telecommunications. However, U.S. optical fiber manufacturers found themselves at a disadvantage when low-cost connectors which mated with the outer diameter of optical fibers came into use because foreign manufacturers had the possibility of claiming better fiber dimensional control.

Lightwaves (L)

"This collaboration has been of significant importance to Schott Glass Technologies. As you know, Schott has extensive knowledge in the area of glass compositions and has considerable experience in adjusting glass formulation to identify glasses with properties specific to particular applications. This knowledge extends into the domain of active laser glasses; however, since we have no capability to fabricate functioning lasers, Schott cannot, by itself, characterize the active performance of laser glasses.

We rely on collaborations such as our joint CRADA to take our glass formulations and to produce functioning devices for evaluation...The relationship with the NIST Optical Waveguide Laboratory is unique in that the program is focused both on obtaining a fundamental understanding of the science behind these systems and on developing functioning devices which are consistent with the requirements of industry and are thus suitable for eventual commercialization."

Joseph S. Hayden, Ph. D., Manager R&D materials Group, Schott Glass Technologies, Incorporated

"...I would also like to thank you for your efforts and NIST's involvement in this exercise. I would encourage you and NIST to become more involved with definition of the laser diagnostics standards. In my opinion, NIST should have been involved with the ISO standards long ago. It has always bothered me (and others) that the inputs to the ISO standard from the U.S. have come from a committee primarily made up of manufacturers of lasers (LEOMA) and diagnostics equipment. This allows for those on the committee to steer the test specifications in favor of their own products or test techniques or to promote their position in the market place as "measurement experts" because they are on the standards committee. I believe this has happened with the current standards. No one on the committee is a member of an "independent" or "non-biased" organization who can represent the "user" side of the measurement issues. This is why I feel strongly that NIST should become more involved with standards."

Roger L. Rypma, Vice President, Big Sky Software Corporation

"...Now there remain the issues of providing a standard procedure with an error analysis, comparing different measurement methods (i.e., slits and knife edges versus second moment), and of course providing standard beams to calibrate instruments. The approach you have proposed seems very sound and I am sure will provide the laser industry with standards in an important area that has continued to evade us for almost 30 years.

We look forward to working together with NIST in this area for we know you will provide the leadership, neutrality, and methodical work required."

Lindsay Austin, Director, Instruments Division, Auburn Group, Coherent

"...Our Director of Marketing and Sales...asked NIST to organize a beam measurement round robin... NIST accepted and the results were reported at Optcon '92 in Boston. This effort will, I believe, lead to better beam width measurements in the long run. As a supplier of instruments, I look forward to the day when I can tell our customers we are NIST traceable."

John Fleischer, President, Photon, Incorporated

The critical need for state-of-the-art metrology was conveyed to the Telecommunications Industry Association by urgent requests from members of the U.S. optical communications industry. Responding rapidly to this need, Matt Young developed and certified an optical fiber geometry Standard Reference Material (SRM), which effectively removed the obstacle to producing highly dimensionally accurate American products. In essence, he provided industry with the means necessary to standardize its measurements.

In addition to providing 30 SRMs, which are diameter standards having an uncertainty of less than 40 nm (3 σ) to the NIST SRM office for commercial sale, Young developed a micrometer designed by Theodore Doiren (Manufacturing Engineering Laboratory) for measuring fiber and gage wire diameter for industry use. He and his team also developed an interference microscope and a scanning confocal microscope for accurate measurement of fiber diameter. His contact micrometer work is recognized as having extended the state of the art.

L4: Polarization-holding (h) Parameter Interlaboratory Comparison

In response to a request by the Telecommunications Industry Association (TIA) Fiber Sensor Committee, Rex Craig, working in collaboration with Dingding Tang and Gordon Day, participated in a six-member interlaboratory comparison of measurements of the polarization-holding parameter (h) of high-birefringent fiber. Birefringent material exhibits different indices of refraction for orthogonal linear polarizations of light. When propagating optical signals, the modes are not identical; portions of the signal will get ahead or fall behind and some portion of the signal may be lost. In the best possible scenario, the fiber will maintain its polarization, providing a clear signal from start to finish.

Craig evaluated three coils of fiber, typical of those used in fiber gyroscopes, for the intercomparison. His analysis revealed the need for metrology that would enable industry to implement a single standard: participants' results differed by a worst-case factor of two. Given that polarization holding is an important parameter, Craig's study will form a baseline from which the development of a standard measurement procedure can be evaluated.

> "Spiricon was glad to participate in this hopefully first of a series of round robin tests. We feel any opportunity to improve the beam analysis industry is better for all parties concerned. That any standardization of practices will lead us all to produce better quality products and eliminate confusion. We welcome further chances to work with the staff at NIST and to advance the science of laser beam analysis."
>
> Gregory E. Slobodzian, Engineering Manager, Spiricon, Incorporated

L5: Wavelength Standard at 1.53 µm *Using Trapped and Cooled Rubidium Atoms*

Sarah Gilbert achieved a significant breakthrough in the challenge to construct an ultra-high accuracy wavelength standard to serve the optical fiber communications industry. As part of the development of a reference standard for optical communications, Gilbert successfully trapped rubidium atoms and laser-cooled them to below 1 mK, giving an optical absorption at 1.53 µm having a linewidth less than 10 MHz. This line is used to stabilize the laser.

The width of the line is already narrow enough for the standard, and the methodology of trapping and cooling for this purpose has been demonstrated for potential application to other very narrow rubidium absorption lines at 1.56 and 1.32 µm for complementary standards. Gilbert's work will have important applications for multiplexing, which optimizes the number of signals that can be sent down the same fiber, as well as enhancing the overall efficiency of transmission using optical communications schemes.

Superconductors (SC)

SC1: Observation of One Electron in Ten Billion

There is only one artifact standard left, the kilogram, and the race is on to move this standard toward fundamental, quantum-level standards, such as the electron. Under such circumstances, electric current would ideally be defined as the number of electrons passing a point in a given period of time. John Martinis skillfully argues the merit of efforts to elevate standards to the quantum level. "Artifact standards are located geographically, and require transfer standards to serve the needs of the world population. Quantum standards are essentially laboratory experiments that any laboratory can do. Thus, quantum standards, communicated through technology transfer, will effectively upgrade the quality of measurements in applications around the world."

Martinis is focused on getting to the fundamental level where electrons can be counted: electrons being the quanta of electrical charge. He has confirmed the ability of his newly developed single-particle electrometer to dispense single electrons with metrological accuracy. This charge pump, which operates in the millikelvin range, alternately charges and discharges an ultra-small capacitor with four electrons at high rates. The error rate for charging and discharging exactly four electrons is 0.5 ppm.

In an elegant experiment, Martinis demonstrated that it is possible to observe one electron in ten billion by his detection of the presence of a single excited electron above a condensed ground state of 10^{10} superconducting (paired) electrons. Working in collaboration with Michel Devoret, a Guest Scientist, from Saclay, France, Martinis observed the result at 0.035 Kelvin. This work may signal the development of a new fundamental standard for electrical current.

SC2: Productivity and Yield of Josephson Array Voltage Standard Chips

"Thank you very much for the 1V array you sent us in May. We were also happily surprised to find the NISTVolt software supplied along with the array. This saves us for a great deal of work, and from running the "demo" version, we find it very good. We are also interested in eventual future changes of this software..."

Hans Arne Frøystein, Section Director, National Standards Laboratory, Norway

NIST is the major supplier of Josephson voltage standards, which are used in laboratories throughout the world. Charles Burroughs, working under the direction of Clark Hamilton, has developed a means to improve the productivity and the yield of the development process of 1-V and 10-V Josephson array chips to meet increasing demand. This work was done under a CRADA with Quantum Mechanics, San Diego, California.

With the improved process, 14 chips can be fabricated on a single 3-inch wafer. Burroughs and Hamilton demonstrated the new method, using the NIST niobium trilayer Josephson junction technology and the insulating-layer equipment of Quantum Magnetics. Silicon dioxide deposition equipment recently acquired by NIST now permits the entire process to be done in-house.

The impact of Hamilton's work underscores the close links between metrology and advancements in technology. The Josephson chips are currently in use by manufacturers of precision electronics instrumentation in their own manufacturing control processes. Prior to this capability, these manufacturers were not able to measure, precisely, the accuracy of their own products. One manufacturer documented the fact that until they had access to the standard, they knew they were making "good" products but they couldn't specify just "how good," because they were "better" than their testing capability could measure. Now, when they want to know just how good they are and how they compare to their competition, they can find out.

SC3: Ongoing Commercialization of NIST Voltage Standard

In 1986, EEEL developed a new Voltage Standard based on large series arrays of Josephson junctions. The new standard is much more accurate and easier to use. RMC Cryosystems, Tucson, Arizona marketed the first commercial Josephson Array Voltage Standard in 1988. In 1990, an international agreement defined the volt based on this standard, which was pioneered by NIST. Josephson voltage standards are used in industrial, as well as national and military laboratories because they provide the ultimate in voltage measurement without the need to make comparisons with national standards.

In the last two years, Hamilton has accomplished the technology transfer of EEEL-developed improvements to the original standard, which, in turn, generated three new commercial products:

Hypres, Incorporated, Elmsford, New York is producing the Josephson Series Array Voltage Standard - Model H3660. This 3600 junction superconducting circuit is the key component of a Josephson Voltage standard. When driven with 75 GHz microwave radiation, it generates the quantum voltage levels that are the basis of the SI volt representation.

Custom Microwave, Longmont, Colorado is producing a voltage standard dielectric waveguide probe — a unit that provides the interface between a Josephson voltage standard in liquid helium and the room temperature environment. EEEL originators, specifically, Charles Burroughs and Clark Hamilton, have worked with Custom Microwave to promote the technology transfer. The probe includes low frequency microwave connections and magnetic and radio-frequency interference (RFI) shielding. The use of a dielectric (Teflon) waveguide greatly reduces the consumption of liquid helium - a very expensive cryogen.

Astro Endyne, Boulder, Colorado is producing a Josephson Voltage Standard Automation Unit. This unit is an interface between a PC (personal computer) and a Josephson array chip. It provides all functions required to automate high precision calibrations. Automated calibrations not only save time and expense — they are usually more consistent and accurate.

SC4: Record Frequency Response for Josephson Junction

Erich Grossman and Peter Rosenthal documented the highest frequency response (8 THz) and the highest switching voltage (17 mV) ever obtained in a lithographed Josephson junction. They achieved this result using a lithographed antenna that was fabricated with the junction to measure its far infrared response. Their experiment demonstrates the speed potential for a reproducible element of an integrated circuit and shows that the fabrication process is robust with achievable allowances for manufacturing variation.

Two U.S. companies have already incorporated results from the NIST work in their advanced development programs. The areas in which these results will have direct application include electrical standards, specialized digital circuitry, sensitive radiation detectors, and biomagnetic instrumentation. The latter is used for the detection of very small magnetic fields emanating from the brain and the heart.

"This letter is written to extend a word of appreciation to you and N.I.S.T. for your cooperative effort in establishing Custom Microwave, Incorporated as the manufacturer of Cryoprobe hardware and assemblies. Through your efforts and guidance we have received...orders for Cryoprobe assemblies...Again, thank you for your help."

Mike Larson, Executive Vice President, Custom Microwave, Incorporated

"From 1991 we have been working with our Josephson Voltage Standard. The critical components were bought through RMC, including two chips...tested by you, that are still running very well...I would like to give you my thanks for your splendid development that has provided to many National Laboratories, like us, a very good volt..."

J.M. Balmisa, Head, Electrical Area, Centro Español de Metrologia

"...You may be pleased to hear that our Josephson Junction System is up and running. We took delivery of our first dewar of He on Monday morning and had stable voltage steps by early afternoon...This fairly quick and painless commissioning of a new standard was largely due to your input and assistance..."

Owen Cramer, Project Leader, Laser Measurements Project and Acoustics and Ultrasonics Project, National Metrology Program, CSIR, South Africa

"I took a great interest in your work on High Temperature Superconductor - Normal Metal - Superconductor Josephson Junctions with High Characteristic Voltages. In my opinion, you have achieved high results in a field of HTS Josephson Junction Technology... I research HTS junctions for metrological applications. I carried out measurements of Josphson constant in both bulk and film

HTS junctions but the most accuracy (0.06 ppm) was obtained in bulk junction at 4.4 K. It will be very interesting for me to carry out the precision measurements with your junctions."

A.S. Katkov, Senior Scientific Worker, Mendeleyev Institute for Metrology, St. Petersburg, Russia

Magnetics (MG)

"The magnetic recording industry is experiencing a period where technical advances are pushing storage levels to unprecedented levels. This is being driven in part by the increasing need to store video images, but this would not be possible without continuing improvements in the technology of very small devices. A group at the National Institute of Standards and Technology in Boulder, Colorado, has been active in developing the core measurement needs to support this development. By working closely with the National Storage Industry Consortium they have helped to develop devices incorporating the newly discovered giant magnetoresistive materials. Because the devices are micrometers in size, understanding the complex magnetic behavior requires the development of new instruments capable of probing these dimensions. They have developed an instrument using scanned tips to study the effects produced by reductions in size. A recent discovery has indicated that the fields produced by currents play a strong role in inhibiting giant magnetoresistance effects in the multilayered films. This work is providing crucial support for the development of recording heads in the Ultra-High Density Magnetic Recording Head Project being funded by NIST's Advanced Technology Program."

Dr. James Brug, Technical Manager, NSIC/ATP HEADS Project Manager, Hewlett-Packard Recording Head Technology Project

SC5: Tuneable Thin-film Resonator Fabricated from High-temperature Superconductor

Working in collaboration with the University of Colorado, James Beall has developed a thin-film tuneable 5-GHz resonator incorporating low-loss high-temperature superconductor films and an electrically adjustable capacitor ($Ba_xSr_{1-x}TiO_3$). This is the first demonstration of such a device.

The development of Beall's resonator could have a far-reaching impact on the aerospace industry. Low-loss resonators coupled to antennas have the potential for significantly reducing the size and weight of aircraft and spacecraft antennas.

MG1: Lift-mode Magnetic Force Microscopy (MFM)

To support industry's need for increased storage capability in magnetic reading and recording devices, John Moreland, in collaboration with Paul Rice and Andizej Wadas, has developed a new method of imaging with a scanned probe microscope that significantly increases the sensitivity of the measurement technique.

Referred to as "lift mode" MFM, the method allows immediate subtraction of the topology signal from the MFM signal on a line-by-line scan mode. After the sensing tip is scanned in contact with the surface and the signal recorded, a second scan is made with the tip lifted a small distance above the surface, controlled by the signal from the first scan. Magnetic forces cause deflections of the tip from the prescribed path, and the path difference yields the magnetic image of the surface.

MG2: Submicrometer Dynamic Measurements of Domains in Magnetic Read Heads

With respect to computers, almost all information storage is magnetically based. The industry is making a major push to ensure that a bit of information takes up less space than ever before. In order to measure the higher density, conventional metrology must expand to permit the measurement of smaller and smaller bit sizes. The drive is toward developing greater memory capability for computers of all sizes from lap tops to mainframes.

Until now, available magnetic reading methods were not usable for the high bit densities of new magnetic recording media, and there was no alternative metrology to support the industry. R. William Cross, in collaboration with Anthony Kos and Curtis Thompson, has achieved a breakthrough that can be used to support cutting-edge read-head technology, based on the magnetoresistive (MR) effect.

Cross has developed a scanning four-probe resistance measurement system for studying and measuring the formation and movement of magnetic domains in thin-film magnetic read heads. The voltage taps are microprobes fabricated from beryllium copper with a tip radius of about 0.1 µm, and can be moved independently with a step resolution of 0.05 µm. The scanning system is used to measure local MR responses of the device. From this information, the local magnetic structure is inferred, and the field conditions associated with the formation of domains can be determined.

MG3: Measurement of Energy Loss in Superconductor Wires for ITER Magnet

The International Thermonuclear Experimental Reactor (ITER) project is the largest nuclear fusion energy project ever undertaken. The principle is to emulate the reaction that occurs in the sun, but keep it under control using a magnetic field to confine the ionized gas (plasma). At the core of the project are large superconducting magnets, which are subject to energy losses when their magnetic fields are cycled. If the magnets were to generate too much heat, they would provide an unacceptable load on the cryogenic refrigeration system.

One type of wire to be used in the ITER magnets is a multifilamentary Nb_3Sn made by the "internal tin" diffusion process. The microscopic filaments within these copper-matrix wires have a helical twist, deliberately formed during manufacture. For the past two years, different laboratories have reported different loss values based on magnetic hysteresis measurements. In response to concerns by the U.S. ITER team, Ron B. Goldfarb undertook to verify the conventional methods for measuring hysteresis loss in superconducting wires.

Goldfarb measured the energy loss per unit volume on samples of different geometry using several NIST magnetometers. Traditionally, hysteresis loss is measured on small samples. He discovered that, to get correct values of hysteresis loss, sample lengths must exceed about two twist-pitch lengths. The wire qualification procedure for ITER will be revised to reflect sample length as an important parameter. In subsequent work, Goldfarb and collaborator Kikuo Itoh, of Japan's National Research Institute for Metals, showed that the source of the measurement problem was unintended interfilament contact in this type of superconductor wire.

"I would like to commend Dr. Ron B. Goldfarb and Dr. Loren F. Goodrich, Senior Physicists in the Superconductor and Magnetic Measurements Group, for the work they have performed in support of the U.S. ITER Magnetics R&D program...The competitiveness of U.S. industry in manufacturing high quality superconducting wire is of primary concern to the U.S. participation in ITER because the superconducing wire is the single largest cost element in a device whose total cost is estimated in excess of $5 billion. There is strong international competition for supply of this material. It is therefore imperative that we know quite accurately the physical and electrical characteristics of this material...Dr. Goldfarb has participated fully and enthusiastically in performing ac loss measurements and his work has uncovered a significant source of error when making measurements by various magnetization methods...This has great scientific as well as commercial significance because our contracts with U.S. superconducting wire manufacturers require their product meet a maximum loss specification...It is easy to see the financial implications of basing a product acceptance criteria on a faulty test procedure, but the technological implications could have been catastrophic for the operation of such a costly device. (The errors always underestimated the losses by a significant amount which would have led to not being able to operate the magnets at their design conditions.) We fully expect these efforts and future work at NIST will be quite useful in allowing U.S. manufacturers to be able to test their product, using their own facilities, with greater measurement accuracy and reliability."

Joseph V. Minervini, Acting Head, Fusion Technology and Engineering Division, Plasma Fusion Center, MIT

Semiconductors (SM)

SM1: Electron Density and Hall Mobility of Semiconductor Layers

To relieve some of the quality-control issues that plague the commercial production of mercury-cadmium-telluride (HgCdTe) detectors and similar devices, Jeremiah Lowney, W. Robert Thurber, and David F. Seiler developed a measurement method for determining the electron density and Hall mobility of the semiconductor layers of such devices. The method, which is based on the magnetic-field dependence of the two-terminal magnetoresistance of a rectangular layer, has been successfully used to characterize accumulation layers of n-type HgCdTe photoconductive infrared detectors.

Early in the development process, Lowney carried out a nonlinear least-squares fit to published curves for the magnetoresistance as a function of both the magnetic field and length-to-width ratio. He then determined the electron density and mobility of the top accumulation layers of several differently processed detectors from the fit to the magnetoresistance data at high magnetic field. The method's accuracy was verified by comparing the group's results with those obtained by the device manufacturers using Hall-effect measurements on processed wafers.

By measuring and correlating 20% variations in accumulation-layer density for the different elements of a multi-element detector, the group was able to demonstrate a critically needed method of determining the effects of processing steps on device performance. A very significant advantage to this two-terminal method, as opposed to the traditional four-terminal Hall-effect method, is that it can be applied to small, fabricated devices. This breakthrough is directly linked to EEEL's commitment to provide the necessary measurement expertise to enable the Geostationary Operational Environmental Satellite (GOES) contractors to properly evaluate their HgCdTe infrared detectors.

> "Thank you for the support which NOAA has received from your Laboratory's experts on infrared detector technology...this team has made significant contributions to our Geostationary Operational Environmental Satellite (GOES) Program...and... fundamental improvements to the detector industry as a whole by developing a sophisticated technique to permit the selection of "hot" detectors prior to completing the full production processes."
>
> T.E. McGunigal, GOES Program Manager, NOAA

SM2: SEM Data Analysis

In response to the urgent need to improve critical-dimension metrology for modern semiconductor devices with feature sizes of 0.35 μm and below, Jeremiah Lowney developed a more advanced Monte Carlo computer code to permit the analysis of the data obtained from a scanning electron microscope in either a transmission or a backscattering mode. The objective was to develop a method to interpret the signals that would better relate the measurements to actual specimen dimensions. The electron beam spreads due to scattering as it traverses the specimen, and the collected signals do not correlate easily with the specimen itself.

Lowney's advanced Monte Carlo code allows users to analyze the data to the nanometer level and extract the relevant parameters. In the course of his work, he extensively revised the existing NIST code for analyzing the transmission and backscattering signal as a function of position as the electron beam traverses a lithographically produced line. He also incorporated new features to make the code more accurate and versatile, including a semi-empirical fit to calculated Mott cross sections for elastic electron scattering and a higher order equation for the inelastic scattering due to secondary production. The code also shows the effects of traversing the edge of a trapezoidal line (a plateau in the signal) as well as edge roughness and rounding.

SM3: Scanning Capacitance Microscope

First to incorporate an atomic force microscope (AFM), a product of Digital Instruments, Incorporated, into his design, Joseph Kopanski constructed and tested a scanning capacitance microscope (SCM) for nanoscale profiling of semiconductor p-n junctions. The effectiveness of the instrument was confirmed by the simultaneous acquisition of AFM and capacitance-versus-position images.

This effort is a direct response to the semiconductor industry's articulated need for junction profiling at this scale. A CRADA has been established to facilitate collaboration with SEMATECH and Digital Instruments, Incorporated, the AFM manufacturer. Work will include calibrating and determining the resolution of the SCM. SEMATECH has provided p-n junction specimens, together with Computer Aided Design (CAD) and Secondary Ion Mass Spectroscopy (SIMS) data. SCM data from these samples will provide feedback to improve the results of modeling the SCM measurement by using the ANSYS finite-element package. The end result will be the development of a practical analytical technique for the semiconductor industry. Given the SIA's report stating that no reliable characterization metrology exists for determining two- and three-dimensional doping profiles, this work was assigned a high priority.

SM4: Electro-Thermal Power System Simulation Methodology Commercialized

Working in collaboration with Analogy, Incorporated, Dr. Allen R. Hefner developed an electro-thermal model for the Insulated-Gated Bipolar Transistor (IGBT), which Analogy incorporated into their commercial simulator, SABER. Because of this model, Motorola was able to introduce a new IGBT ignition coil driver concurrently with the release by Analogy of Hefner's electro-thermal model for the device in their SABER simulator. This new product, Electro-Thermal Component Model Software for Circuit and System Simulation, provides electronic system designers with the capability to simulate the dynamic behavior of electronic circuits and systems including the detailed physics of the semiconductor devices and the heat transport throughout the thermal network (semiconductor chips, packages, and heatsinks).

"I'm enclosing documentation for the paper, *Simulating the Dynamic Electro-Thermal Behavior of Power Electronic Circuits and Systems*...by Allen R. Hefner and David L. Blackburn...The reviewers accepted it without any revision, and an industry reviewer said it was the most sensible, useful and professional work he's seen in the field of simulation in power electronic systems."

William M. Portnoy, Professor, Associate Editor, Power Electronics Council, Transactions on Power Electronics, IEEE.

"In an attempt to change the way semiconductor power devices are developed, Analogy, Incorporated and Motorola's Semiconductor Products Sector have signed a $3 million, three-year agreement to deliver analog simulation models before devices are fabricated. The agreement has customers getting 'virtual prototypes'...in lieu of actual samples...Using simulation models will typically shave five months off the development cycle, which for power systems often runs about a year...This is a new paradigm in power electronics."

Electronic Engineering Times, August, 1993

"Motorola's Semiconductor Products Sector will turn to two business units and one of its advanced MOS fabs in an attempt to catch up to Japanese and U.S. competitors in the fast-growing insulated-gate bipolar transistor (IGBT) segment of the power-semiconductor business....Dan Artusi, operations manager of the Power Products Division's bipolar and IGBT transistor lines said that 'We are coming into this market at a time when it is just beginning to take off...We do not intend to compete on price, but rather on performance, specs, and working with specific customers.'"

Electronic Engineering Times, November, 1993

Hefner is the first scientist to demonstrate a methodology for simulating the full electro-thermal behavior of a complex power system. Concurrent simulation of the electrical and thermal aspects of electronic systems is essential for effective computer aided design (CAD) of advanced electronic systems. The new software enables the thermal management considerations (typically one of the most costly aspects of the overall electronic system design) to be incorporated into the traditional electronic circuit design process. The ability to simulate these new devices accurately can reduce the number of design cycles required to develop new electronic products and can significantly reduce the cost of designing new electronic equipment.

SM5: Effect of Annealing Conditions on SIMOX Material Defects Demonstrated

Commercial interest in silicon-on-insulator (SOI) and separation by implanted oxygen (SIMOX) technologies is steadily growing. SOI technology offers combined performance benefits in speed, high-temperature operation, and resistance to ionizing radiation, as well as suitability for integrated-circuit power device fabrication.

SIMOX is a potentially important material system for the future, particularly in terms of ultra-low power electronics for portable systems. However, material defects still impose significant limits on the SIMOX potential. Focusing on one particular aspect of the manufacturing process, Peter Roitman successfully developed a method to investigate defects and dislocations in the annealing process associated with SIMOX material production.

Roitman demonstrated that thermal ramping conditions, including ramp rate, the content of oxygen in the argon environment, and oxide capping, significantly affect the type and density of defects developed during annealing of SIMOX material. His work showed the effects of the annealing conditions on the dislocations, stacking faults, stacking fault pairs, and stacking fault tetrahedra. Both single-implant and triple-implant wafers were included in this important and comprehensive study. Given that SIMOX is the technology of choice for satellite and radiation-hard electronics, as well as a major contender for mainstream integrated-circuit production toward the end of this decade, Roitman's work is a major step forward.

SM6: NIST/Sandia Collaboration Initiated

Robert Hebner, Loren Linholm, and David Blackburn initiated a collaboration between staff within the Semiconductor Electronics Division and counterparts at Sandia National Laboratories. This effort resulted in a series of meetings to identify areas of on-going work and joint resources in which both organizations could quickly respond to meet Semiconductor Industry Association (SIA) goals. Initial areas of joint research include work in sensors, electromigration and stress voiding, reliability modeling, electrical overlay metrology, and measurement standards. Each laboratory has the expertise, equipment, and resources to thoroughly and impartially provide key metrology to the industry. Following EEEL's tradition of working with industry to meet challenges that individual companies lack the resources to solve, Sandia will have much to contribute to this collaboration.

The Memorandum of Agreement signed by the Directors of both Laboratories articulates a decisive move to leverage the strengths of the two institutions, EEEL/NIST and Sandia, toward further helping American industry. Working together, they will respond to the industrial needs represented in the SIA Roadmap, which identifies key components of semiconductor manufacturing that could be helped by federal agencies.

SM7: Photoreflectance Spectroscopy

Deane Chandler-Horowitz and Paul Amirtharaj advanced the state of the art in the measurement of photoreflectance spectroscopy for semiconductor analyses through the use of double-modulation and multiple pump beams. For the first time, the double-modulation technique made it possible to perform accurate measurement of the weak photoreflectance signal in the presence of strong photoluminescence. This technique also permits measurements from a rough surface with significant surface scattering.

The multiple pump procedure allows selective excitation of a single layer, which isolates the source of the spectroscopic signal. This greatly enhances the investigation of complex multilayer semiconductor structures. The power and usefulness of these procedures has been showcased in the study of highly luminescent, multilayer, single quantum-well laser structures grown by Xerox Corporation under an ATP-funded effort. The spectroscopic data provided a detailed insight into the electronic properties of each layer and with respect to strain and interfacial electric fields.

SM8: Micromachined Semiconductor Devices: MOSIS Fabrication

Industry needs the ability to manufacture mechanical-based devices with integrated circuits to make intelligent sensors and actuators. This class of devices, called microelectromechanical systems (MEMS), merges the mechanical world with the microelectronic world. The world market for these devices is growing rapidly. In the automobile industry alone, integrated accelerometers are already offered in some 1993 models for air-bag sensors, and applications are expected for active suspension and braking. Michael Gaitan and Janet Marshall of EEEL, in collaboration with others from MOSIS and Simon Fraser University, Vancouver, BC, have developed a means to significantly boost American industry's ability to design and manufacture micromachined parts in a shorter time-frame and at lower cost.

Essentially, Gaitan and Marshall have devised a means to design and fabricate micromachined devices using commercial CMOS (complementary metal oxide semiconductor) foundries. "Magic," a popular public-domain computer-aided design program for laying out integrated circuits, is the means used to create a unique design layer called "Open." "Open" creates a window through the passivation layer that exposes the bulk silicon surface. By the judicious placement of openings and an anisotropic wet etch that is performed after CMOS processing has been completed, Gaitan and Marshall have created suspended membranes composed of aluminum and polysilicon lines encapsulated in glass. The micromachining step (wet etch) mechanically frees the membrane and creates high electrical and thermal isolation from the bulk silicon substrate. MEMS research at NIST and other places has produced various devices in this class, including thermal flat panel displays, ac-dc thermal converters, gas flow sensors, and micro-hot-plates.

Three patent disclosures related to this work have been filed, and MOSIS announced their official support of this process as a standard CMOS micromachine technology. These results have important implications for the commercial development of micromachined devices, specifically the promise of greatly improved selectivity and reliability of gas sensors that can be manufactured at low cost. A paper entitled "Melding Micromachined Devices with CMOS Foundries" was featured as the cover article in *IEEE Circuits and Devices*.

Optical E.T.C., Incorporated (OETC) entered into a CRADA with NIST over a year ago to explore silicon micromachined arrays of thermal heaters with Dr. Michael Gaitan as the Principal Investigator at NIST. The basic objective of the CRADA was to develop products based on this technology. Although OETC is a (very) small business, it has been able to compete and make significant technical progress in the development of infrared scene simulators, in part, through the outstanding technical interchange and support offered by the CRADA. The overall technical growth and accomplishments in this subject technology have been achieved as a consequence of the cooperative research efforts of OETC personnel and Dr. Gaitan and his colleagues. OETC and NIST are in the process of preparing a comprehensive patent application...We look forward to a continuing productive relationship with NIST.

R. Barry Johnson, President, Optical E.T.C., Incorporated

SM9: TCR and Joule Heating Measurement

Electromigration, a metallization failure mechanism, is of great concern to the semiconductor industry, especially for the reliability assessment of very large scale integrated (VLSI) circuits. An important parameter of accelerated stress tests used to characterize a metal's susceptibility to electromigration is the temperature increase of metal test lines due to joule heating. Accurate knowledge of the metallization temperature is important because the median-time-to-failure is exponentially dependent on the reciprocal of the metallization stress temperature (in Kelvin).

Harry Schafft's work in this area led to the development of EIA/JEDEC Standard JESD33, which was issued in 1993. Schafft's method is used to measure the temperature coefficient of resistance of thin-film metal interconnects used in microelectronic circuits and devices, as well as for determining the joule heating in metal lines subjected to high-current stress tests, and for using a metal line as a thermometer. Engineers concerned with characterizing interconnect metallizations for reliability rely on such standards to measure the temperature rise and identify the stress temperature of a given metal. From there, they can identify stress conditions, from which they can extrapolate to use conditions.

SM10: X-ray Lithography Mask Design

The semiconductor industry recognizes that X-ray lithography offers the potential for higher fidelity feature replication than does optical lithography. Michael Cresswell's work in the engineering of 0.18 μm CMOS-compatible X-ray lithography mask design that undergoes less than 5-nm differential overlay distortion between electron-beam patterning and synchrotron beam-line aligner mounting demonstrates the validity of this technique. The design will be presented to the international lithography community through the Semiconductor Equipment and Materials International (SEMI) organization.

Cresswell's general purpose is to obtain international acceptance of these specifications, or some close derivative of them, in order not to compromise the substantial U.S. investment in this activity. In future work, Cresswell, EEEL's lead scientist on this project, will continue his search for innovative means to support U.S. industry's breakthrough in advanced lithography mask manufacturing quality assurance.

SM11: New Electrical Test Structure for Overlay and Feature-Placement Metrology

In support of the "roadmap" requirements projected through the year 2007 by the Semiconductor Industry Association (SIA), Michael Cresswell developed a new electrical test structure that is based on the principle of the linear voltage-dividing potentiometer. Voltage measurements across pairs of the three parallel voltage taps provide information on their center-to-center spacings. The test structure has been evaluated by reduction-printing its complementary components from two different photomasks onto a resist film covering a conducting film on a quartz substrate. Overlay was determined locally by electrical testing. The electrical measurements were found in all cases to track the corresponding measurements made by the NIST line-scale interferometer by amounts less than the uncertainties attributed to the individual line-scale interferometer measurements.

"Thank you, and your colleagues in the Semiconductor Electronics Division...for leading industry in its closure on the ARPA-NIST-X-Ray Lithography Mask Blank specification. The specification is a key element in ARPA's Advanced Lithography program...NIST's role in securing industry agreement on the specification is much appreciated...Success and encouragement in your venture to derive an international standard from the ARPA-NIST specification under sponsorship by Semiconductor Equipment and Materials International (SEMI)."

David O. Patterson, Program Manager,
Microelectronics Technology Office,
ARPA, DoD

Further, an array of end-tap pairs providing local length references, which were imaged from the first mask, was calibrated as a substrate reference grid, also by the line scale interferometer. A selection of measurements of the separations of the center taps of various potentiometers was made by combining the interferometer-determined locations of the end taps, relative to the grid, with the local electrical overlay measurements. These separations were compared to corresponding measurements made directly by the line-scale interferometer. They also tracked the hybrid-electrical-interferometer measurements by less than the errors attributable to the line-scale interferometer. A potential application of the new test structure is mapping the locations of images projected by a lithographic system onto substrates which have pre-patterned reference grids. Another application is sampling the pattern placement accuracy of 1:1 X-ray lithography masks.

SM12: Faster MOS Oxide Reliability Characterization

More often than not, being able to reduce the time it takes to bring a product to market effectively increases the product's competitiveness because it can be produced less expensively. John Suehle recently provided semiconductor manufacturers with such a boost, using wafers provided by National Semiconductor.

All integrated circuit manufacturers must characterize the reliability of their thin dielectric films. Until now, the characterization procedure was considered prohibitive owing to the excessive time required to perform the tests. Suehle developed a high-temperature wafer probing station which demonstrates that oxide breakdown tests can be conducted at temperatures as high as 400 °C or more without any deviation from the characteristics observed at the lower, more commonly used, stress temperatures of 200 °C and below.

Suehle's work greatly reduced the time necessary to perform oxide breakdown tests. For example, the time required is over two orders of magnitude less when testing parts at a field of about 9 MV/cm at 400 °C rather than 200 °C. Also, the results of this study have demonstrated for the first time that MOS-based technologies are reliable for high-temperature applications above 200 °C. As information about Suehle's results spread, more and more interested manufacturers called to inquire how their companies could benefit from this advanced capability.

> "I am writing this letter to acknowledge the fine work of John S. Suehle who has been involved with us here at GE CRD. Specifically, our joint effort has been focused on the measurement of high temperature reliability properties of thermally grown thin dioxide layers. The purpose of the work was to determine the feasibility of making MOS devices and ICs operate reliably at these temperatures...Since we here at GE are interested in utilizing SiC devices in high temperature control systems and had obtained a WPAFB contract to develop SiC high temperature microelectronics, it was paramount that the high temperature reliability characteristics of MOS structures be determined...This investigation showed for the first time the feasibility of long term very high temperature MOS reliability. Since our results using either Si or SiC samples are identical, the feasibility of high temperature SiC CMOS may be possible, whereas before it was not thought to be...Again, 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 the 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."
>
> Dale M. Brown, Program Manager,
> Silicon Carbide Technology Program, GE

SM13: Optical Properties of SiO_2/Si Interface Region

Nhan Nguyen achieved an advance in the quantitative understanding of the optical properties of the SiO_2/Si interface region by conducting accurate spectroscopic-ellipsometry measurements and by developing an analysis that, for the first time, provides comprehensive accounts for strain and microroughness. Results show the presence of strain and microroughness at the interlayer observed from the red-shift of the critical point E and the low magnitude of the dielectric function.

Such advances support the semiconductor industry's crucial need to understand the optical properties of the interface region between thin SiO_2 films and silicon substrates, and ensure the ability to continue the accurate measurement of oxide film thicknesses as they evolve. Nguyen's work will provide a more accurate model for ellipsometer manufacturers to use in the software developed to determine the thickness of SiO_2 films, as well as assisting the development of thinner SiO_2-film standard reference material (SRM) artifacts.

SM14: MBE Growth and Characterization of Compound Semiconductors

Vertical integration is a major concern for people working on integrating optoelectronic capabilities (light detection and light generation) of III-V and II-VI material with the very large scale integrated circuits (VLSI) capabilities of silicon. As dimensions get smaller, the role played by interfacial sharpness and precisely engineered band-gaps will become more important.

Working in collaboration with the Army Research Laboratory, Fort Belvoir, to examine alternative substrate materials for mercury-cadmium-telluride (HgCdTe) infrared detectors, Joseph Pellegrino produced and characterized high-quality gallium-arsenide-on-silicon (GaAs/Si) heterostructures. He employed a variety of thermal-stress-relieving techniques during growth, resulting in the production of epitaxial layers of GaAs on Si with measured half-width-at-half-maximum of 240 arc seconds. This material compares favorably with current state-of-the-art GaAs/Si material of 180 to 200 arc seconds. The monolithic integration of III-V devices with silicon circuits is being vigorously pursued to incorporate photonics and high-speed electronic devices with advanced silicon technology. The results of this work will also contribute to the vertical integration of II-VI infrared detectors with the VLSI capabilities of silicon.

Pellegrino demonstrated the influence of GaAs buffer-layer thicknesses on the interface quality of subsequently grown low-order AlAs/GaAs superlattices through a unique combination of X-ray diffraction, photoreflectance, and spectroscopic-ellipsometry techniques. His results indicate that buffer layers having thicknesses less than 100 nm are not beneficial to the superlattice interface sharpness; smoother interfaces were obtained in samples with buffer layers of 250 nm and greater. This work contributes to the precision fabrication of short-period superlattices used for all compound devices based on optical and electrical confinement effects.

To support the semiconductor industry's ability to grow epitaxial layers of atomic-scale heterostructures with well-defined layer thicknesses and interfaces for carrier confinement and transport purposes, Pellegrino conducted high-resolution X-ray diffraction measurements of the single monolayer aluminum arsenide-gallium arsenide (AlAs/GaAs) superlattices fabricated by the Semiconductor Electronic Division's molecular-beam epitaxy (MBE) facility. His results indicate the advantages of each method. The samples grown by migration-enhanced epitaxy (MEE) are more highly strained and have more tilt than the same superlattice structures grown using the interrupted-growth technique. The results also show that the MEE technique produces a more abrupt superlattice interface.

SM15: SRM 2551 for Interstitial Oxygen Concentration in Silicon

Brian Rennex developed Standard Reference Material (SRM) 2551 to enable industry to make quick, nondestructive, inexpensive infrared measurements of interstitial oxygen, a critical parameter in integrated circuit fabrication. Interstitial oxygen concentration must be tightly controlled for optimal impurity gettering and enhanced mechanical strength of the silicon wafers.

Rennex achieved a precision of 0.15 percent (2σ), which meets projected industry requirements into the next century and also represents an improvement of an order of magnitude over previous capabilities.

SM16: 14-nm-Thick Oxides Certified as Standard Reference Materials

Ellipsometry is a critical metrology tool in the silicon manufacturing industry, especially for the control of many thin- film processes. Current gate oxide thickness can be as thin as 7 nm, and ultrathin standard reference materials are currently needed. In FY 1993, a team led by David Blackburn and Barbara Belzer, with additional expertise provided by Nhan Nguyen in the development of ultra-thin oxides, produced the world's first standard reference material (SRM) for thin film SiO_2 on Si at a thickness of 14 nm. The NIST thin-film research team has also produced 10-nm ultra-thin oxides, whose certification is pending the results of a NIST-initiated interlaboratory comparison study.

NIST's leadership in this area will establish a baseline of ellipsometric capability, raise the metrology level of the industry, and eventually provide the much-anticipated 10-nm ultra thin oxide-on-silicon SRMs, as well as speed the development of SRMs in the 5- to 7-nm thickness range. Participants in the inter-laboratory comparison study include SEMATECH, Motorola, Incorporated, IBM, DEC, Rudolph Research, Gaertner Scientific, VLSI Standards, J.A. Woollam Company, Incorporated, and NIST. Given that the SIA Roadmap has identified the area of robust gate dielectrics as a critical concern, the metrology of their development is a constant challenge for all phases of their growth. Standards are required to support this metrology.

SM17: STM Characterizations in Air on GaAs Junctions

Scanning Tunneling Microscopy (STM) techniques are playing a very significant role in evolving technologies, such as nanoelectronic device fabrication and characterization. Scanning Tunneling Spectroscopy (STS) is of fundamental importance for STM characterizations because it probes the local electronic state density of a surface, providing information that is essential for the interpretation of STM image contrast.

Wen Tseng and John Dagata (Manufacturing Engineering Laboratory) characterized gallium arsenide (GaAs) junctions in air using the STM. The junctions were electrically doped over the range of p and n between 10^{15} and 10^{19} cm^{-3}. They developed a novel method of electrical characterization on non-metallized materials and showed for the first time: that meaningful STS spectra of GaAs surfaces can be obtained in air; that the passivating layer, consisting of a stable, ultra-thin oxide, allows the STM tip to probe the bulk electrical properties of the semiconductors; and that quantitative doping information can be extracted from the STS data.

SM18: Measurements of Ion Kinetic Energies from Radio Frequency Plasmas

For a layman, it is hard to imagine a need to improve techniques for a manufacturing process that accommodates millions of devices in one square centimeter, but the problem is real and James Olthoff, working with Richard Van Brunt and Svetlana Radovanov, has taken a significant step toward developing the metrology needed to solve it. Olthoff successfully managed to quantify the kinetic energies of ions from radio-frequency discharges in argon, helium, and hydrogen as well as in mixtures of these gases. He obtained these values using a reference parallel-plate discharge cell with well-characterized electrical parameters.

In the semiconductor industry, the kinetic energy of ions is a key parameter in determining the etching rates of materials exposed to ionized gases (plasma etching). Ions play an important role in the anisotropic (one-directional etching) process that relies on the accelerated bombardment of ions perpendicular to the surface of the semiconductor material. Anisotropic etching minimizes undercutting, producing finer, well-defined features — critical attributes given devices measured not in micrometers, but in nanometers. An understanding of the energies and identities of the bombarding ions is essential for manufacturers, who are attempting to develop new etching methods, and to modelers, who are trying to simulate these methods. Olthoff's work is the first step toward developing instruments capable of monitoring these energies in real time as part of the plasma diagnostics needed for manufacturing control.

Low Frequency (LF)

LF1: Pulse Generator

Reference pulse generators are used in the measurement of settling performance, step and impulse response, and frequency response of digital instruments, such as digital oscilloscopes, waveform recorders, and A/D converters. Fast, accurate pulse generators are important reference standards, and Owen Laug has developed a pulse generator with a novel current source design that enables it to achieve a pulse amplitude stability of 100 ppm. Laug's instrument consists of a time base that employs a 10-MHz crystal reference, a control unit, and a remote head in which the output pulse is developed. Selectable repetition rates of 0.001-, 0.01-, and 1.0-MHz, duty cycles of 10 to 90 percent in 10 percent increments, and delays (between trigger output and pulse output) of 0, 100, 200, and 300 ns are provided.

Laug found the measured time base jitter, relative to the trigger output, to be approximately 6 ps rms. He found the transition duration of the pulse to be approximately 190 ps, with the pulse settling to 0.3 percent of its final value in 2 ns. The baseline and topline levels can be provided as outputs to provide dc reference levels. This model will be further evaluated in an upcoming round robin, which includes NIST and industry laboratories.

LF2: Commercial Product Derived from Calculable rms ac Voltage

Technology transfer is the basis for three new products developed by Guildline Instruments, Incorporated: the Guildline AC Voltage Reference - Model 7410; the Wide Band Transconductance Amplifier - Model 7620; and the Wideband Shunt, which was developed in conjunction with the amplifier. With each product, Guildline credits the National Institute of Standards and Technology (NIST) in its product literature.

Nile Oldham and Paul Hetrick developed the digital waveform synthesis technology that makes it possible to generate the 16 waveforms that are stored in the AC Voltage Reference's nonvolatile memory. By measuring the dc level of each of the steps used to generate the waveform, it is possible to compute the rms value of each waveform to an uncertainty of 10 ppm (2 σ) below 1 kHz. The commercial instruments not only provide the most stable and accurate rms voltage commercially available — but further enhance the U.S. competitive position.

Guildline's Wide Band Transconductance Amplifier - Model 7620 and the Wideband Shunt are designed to meet the ever increasing need for calibration of state-of-the-art current devices at levels up to 20 A rms at frequencies up to 1 MHz. A U.S. patent was granted to Owen Laug on the basis of the amplifier's unique design, which enabled it to source currents up to 35 A rms at 100 kHz with short term instability of less than 25 ppm. The combination of output current and frequency exceeds previous state of the art by a factor of 15.

The commercialization of the wideband shunt was incidental to the development of the amplifier. For NIST engineers, it was just a simple device they developed to do a job — for Guildline, it was another state-of-the-art device that enhanced their offering to the public. Originally consisting of 100 off-the-shelf resistors arranged in a ring formation with the wires pulled through a central opening, it was designed to verify the accuracy of the amplifier. Guildline's product literature offers it as the 7320 series of AC high-stability, non-inductive, four terminal resistive current shunts.

In terms of the larger picture, the U.S. patent issued to Oldham on the digital wave form synthesis work represents an improved method of independently deriving a low-frequency AC voltage standard, which can then be tied to a dc standard, such as the Josephson array. More than 20 NIST digitally synthesized source (DSS) instruments have been ordered for use in Department of Energy National Laboratories. Together, Oldham, Hetrick, and Laug not only advanced the state-of-the art, they facilitated the technology transfer that traditionally upgrades the metrics industry-wide.

LF3: Resistance Step-Down Comparisons

NIST calibrates approximately 500 standard resistors per year for industry and other government laboratories. In order to upgrade NIST technology to better serve industry, Ronald Dziuba and Rand Elmquist developed a cryogenic current comparator that will provide significant advantages for calibration customers. Their comparator is automated and provides greater accuracy. Also, the number of steps required to perform procedures is fewer, although each is more complex. The cryogenic comparator will supercede the Hamon ratio boxes traditionally used for resistor calibrations.

To verify the validity of the cryogenic option, Dziuba and Elmquist carried out two step-down comparisons from the National Ohm to working standards. Both Hamon devices and NIST-developed cryogenic current comparators were used to scale from the i=4 step of the quantum Hall resistor to 100-ohm and 1-ohm working standards.

The results agreed with the working standards predicted values within 0.02 ppm and closed with negligible error. The good closure is indicative of the agreement in scaling between the traditional Hamon ratio boxes and the cryogenic current comparators. This agreement is on the order of 0.000 ± .003 ppm (1 σ).

Cryogenic current comparators are simpler in operation than Hamon devices and their use for resistance scaling and the maintenance of working standards is expected to reduce calibration costs for NIST customers as well as provide higher quality results. NIST-calibrated standard resistors are used in support of quality assurance and research activities throughout industry.

LF4: Low Cost/Better Thin-Film Multijunction Thermal Converters

Joseph Kinard and Donald Novotny, working on a CRADA with Di-Xiang Huang of Ballantine Laboratories, Incorporated, successfully completed a production run of thin-film multijunction thermal converter chips that represents a substantive improvement over the electrical performance of the present standard wire thermal converters with a significant cost reduction.

Given the corresponding range of $150 to $2500 for present standards, these results will almost certainly lead to the incorporation of thin-film converters in high performance calibration instrumentation. Further, their incorporation into such applications will result in a significant metrological improvement, specifically, that the audio frequency ac performance of these instruments will consequently approach their dc performance.

LF5: Commercialization of Software Package at $50,000 per unit by Teradyne, Incorporated

$50,000 per package can seem a very small sum when contrasted with the $1.5 million investment in testing equipment generally required to perform quality control procedures on integrated circuit production lines. So, Teradyne, Incorporated, Boston, Massachusetts, quickly received orders for their Advanced Precision Converter Library, which is designed for use with the Teradyne A520 Mixed Signal Test Station. IC manufacturers never really see the EEEL-developed linear error modeling technique in all of its statistical elegance. The windows-oriented software isolates the user from the mathematical burden of the underlying process.

More importantly, it isolates the manufacturer from the otherwise punishing cost of testing. Data converters make high demands in terms of test time and cost. For converters of 12 or more bits, test costs can account for 50 percent of the product sales price. Consider a 13-bit A/D converter: 8192 measurements were typically used to fully characterize the part until Michael Souders and Gerard Stenbakken announced the impact of their testing strategies. They were able to demonstrate that these types of converters could be characterized with only 64 measurements — amazing reductions in test time and cost. The U.S. semiconductor industry relied on EEEL to respond to the technological challenge of minimizing testing costs while achieving smaller defect rates even as IC designs grew more complex.

Video (V)

V1: Videotape of NIST Model for Flat Panel Displays

The flat panel display (FPD) industry is experiencing explosive growth and has great potential to touch many aspects of our lives. From aeronautics and cockpit displays to automobiles and dashboard displays, from workstations and home computers to wall-sized displays for home entertainment and information systems, flat panel displays have the potential to surround us with inexpensive and compact color imagery as the information highways open up.

American industry's ability to exploit and improve flat panel displays can be improved by modeling their performance. Toward this end, Edward Kelley developed a model of a flat panel display. Kelley's model uses a video supercomputer, the Princeton Engine, to emulate on a CRT (cathode ray tube) how the flat panel display would appear. The model, which uses an electrooptical Kerr effect to simulate the responses of individual pixels, enables viewers to investigate the effects of viewing angle, crosstalk between pixels, and resistance between the connections of the elements that form the screen. Display manufacturers are very interested in taking advantage of Kelley's work for it enables them to model and view the performance of a candidate FPD prior to even manufacturing a prototype.

V2: Evaluation of Image-Producing Algorithms

Under a CRADA with Philips Laboratories, Bruce Field, working with Stephen Herman of Philips, has developed a means to evaluate software prototypes of video-processing hardware. The software effectively eliminates the need to physically build the hardware to evaluate its performance, and shortens the development time by eliminating the need to make hardware changes. Modifying software can be done so much faster than hardware modifications.

The Princeton Engine offers the capability of developments in imaging through real-time processing capability, accepting and producing a variety of video images. Manufacturers could achieve significant cost savings in development by fully exploring the ramifications of their designs in software prototype before going to production. The CRADA enables Philips to use the Princeton Engine, a video supercomputer, to evaluate video processing algorithms in real time. The Laboratory is open to industry researchers for collaborative research.

Electronic Data Exchange (EDE)

EDE1: Electronic Business Reply Card

The replacement of paper transactions with electronically transmitted information provides powerful advantages to the potential buyer and reduces the costs incurred by the potential seller. The full implementation of the electronic marketplace could revolutionize the way in which all commercial transactions occur.

Michael McLay and Barbara Goldstein have provided engineers with a hands-on introduction to the concept of electronically transferring electronic component product data, through their participation in the industry-government Electronic Commerce of Component Information program. Goldstein led a demonstration team which displayed an electronic business reply card at the 1993 Design Automation Conference, and is building upon its success for future demonstrations. The work of McLay and Goldstein is demonstrating the kinds of interactions that are made possible by the electronic marketplace and are guiding the electronics industry toward standard-based solutions for electronic commerce.

Programs Matrix-Managed by EEEL

In addition to the technical programs conducted by EEEL, whose accomplishments have been summarized above, the Laboratory manages NIST-wide programs in microelectronics and law enforcement. The laboratory investigations conducted within EEEL in these two areas have been accounted for in the descriptions above. 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 (OMP)

Materials Science and Engineering Laboratory

OMP1: Micromechanical Measurements for Reliability of Electronic Packaging and Interconnects

Micromechanical material properties and behavior are fundamental to the manufacturability and reliability of advanced integrated circuits and interconnect systems. Accurate mechanical property information and a physically realistic understanding of the behavior of specific material interfaces are prerequisites for useful models of manufacturability and reliability.

The "Micromechanical Measurements for Reliability of Electronic Packaging and Interconnects" project, led by David T. Read, currently has two research efforts in progress: mechanical properties of thin films and microscale experimental mechanics. A method for measuring the mechanical properties of thin films is being developed. The guiding principles are to test materials as they are used in electronic devices and to develop methods for obtaining unambiguous property data. Sample fabrication routes typical of those used in the electronics industry are selected. Specimen sizes equal to the size of components in electronic devices are the ideal.

A procedure for preparing and tensile-testing suspended thin films has been developed, and has been demonstrated on suspended thin films of aluminum and copper with titanium barrier layers. Because multiple specimens from a single wafer can be tested, this technique produces an amount of data sufficient for statistical characterization. Such data are appropriate for input to analytical models of device behavior. However, improvements in accuracy and in specimen characterization are needed.

Electron-beam moiré has been developed as an experimental mechanics technique for examining displacements within fields as small as 50 μm. Load transfer among fibers in fiberglass under tension has been examined quantitatively in individual glass fibers 8 μm in diameter. Thermomechanical displacements in cross-sectioned specimens of plated-through-holes have been observed up to 150 °C. Improvements are needed in writing finer gratings on the specimens, and in making the finest gratings larger. Our current finest gratings have a pitch of 0.1 μm. Die-attach specimens will be studied, to show further applicability of the method.

An analytical electron microscope (AEM), with a replacement value in the neighborhood of $1 million, was installed in our laboratory this year, and represents a major improvement of our capabilities. A lithography mask has already been made with specimens down to 20 μm wide. The instrument will be used to characterize the thin-film specimens, enabling determination of local chemical composition, crystal structure, grain size, and defect density. Such specimen characterization will allow informed comparisons of the mechanical properties of films from different sources. This characterization will be essential to making the measured mechanical property data useful to industry.

Physics Laboratory

OMP2: Ultraviolet Irradiance Measurement Technology

This project, led by C. L. Cromer, was designed to develop a spectroradiometer for use in deep ultraviolet (DUV) semiconductor lithography. The instrument was designed to measure the radiant power at the wafer plane. This was needed to help provide better control in the manufacturing of semiconductor wafers.

Two additional spectroradiometers with improvements that greatly increase measurement accuracy have been developed. Both spectroradiometers were completed and calibrated. The calibration was carried out relative to standard tungsten and argon arc light sources, and checked by the use of a standard detector.

Chemical Science and Technology Laboratory

OMP3: Plasma Processing and Chemical Vapor Deposition

Improved process models and sensors are critical to achieving 0.12-μm feature sizes for manufacturing equipment. The predictive models required will be based on semi-empirical-to- fully-fundamental methods by the beginning of the next century. These rely heavily upon a knowledge base describing the basic physical and chemical mechanisms occurring in etching and deposition reactors.

To advance plasma processing techniques, a reference discharge cell, such as the Gaseous Electronics Conference (GEC) rf Reference Cell now being tested in numerous laboratories, is used to calibrate diagnostic measurements, test chemical kinetics models processes, and learn about the inherent physical characteristics of the discharge that control limitations on reproducibility.

Other achievements during the year included:

Observed experimental evidence that low pressure plasmas in the GEC reference cell are sensitive to electrode surface conditions. Determined that a surface layer containing oxygen is formed on the aluminum electrode surface, and that this process can be reversed . Demonstrated that electrical measurements can be used to monitor the kinetics of the development and removal of this oxygen-rich surface layer.

Evaluated 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 was mounted on a GEC reference cell and a comparison was made between the probe readings and data from the current and voltage measurement system designed and implemented at NIST. The comparison proved useful in identifying and bounding measurement errors and in defining the optimum ranges of operation of both measurement systems.

Measured ion energy distributions with a new mass spectrometer system capable of detecting ions sampled through an orifice in the grounded electrode of the GEC rf Reference Cell. Kinetic energy distributions for argon 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 ion from the side of the plasma region.

Modeling of gas phase particulate formation processes has resulted in determination of thermodynamic equilibrium properties of silicon atom clusters up to 480 atoms and kinetic properties of cluster growth up to 960 atoms over the temperature range 600 to 2000 K. Bulk and surface energy contributions are determined as a function of temperature and size. Kinetic properties show the effect of cluster temperature on atomic mixing rates and the characteristic time for particle coalescence as a function of cluster temperature and size.

Materials Science and
Engineering Laboratory

OMP4: Monitoring the Cure of Thin-Layer Polyimides on Glass Substrates with Photoacoustic Infrared Spectroscopy

Polymers are widely used in electronic packaging to provide low dielectric constant films which insulate the metal conductors. Among the requirements for such a film are that it should: (1) initially be tractable so that the film can be deposited on a substrate, (2) cure to become inert to the solvents and conditions used in the depositing of successive films, (3) adhere to the substrate, to previously deposited inert films, and to the metal conductors, (4) have anisotropic thermal expansion so that adhesion to dissimilar materials such as substrate and metal conductors can be accommodated, (5) be strippable if reworking is necessary, (6) planarize rough structures, (7) be stable at temperatures which allow soldering to be carried out, and (8) be relatively unaffected by environmental factors such as humidity.

Three commercially available polyamic acid solutions were cured in thin-layer form on glass under various conditions. The resultant polyimides, characterized as flexible, semi-flexible and semi-rigid, have, in that order, increased potential for undergoing physical ordering when on a substrate. After being cured, the layers were examined on the substrates using photoacoustic spectroscopy (PAS) in a step-scan, time-sliced mode. The PAS spectra contain time-weighted contributions from different depths in the layer. An algorithm was devised to quantify differences between sets of time-weighted spectra from different specimens. The resulting numerical index indicates the extent to which the two specimens differ over their "thermal depths." Different polyimides can easily be distinguished from one another and the effect of small differences in curing can be discerned.

Manufacturing Engineering Laboratory

OMP5: Microelectronics Dimensional Metrology

The Microelectronics Dimensional Metrology Group, led by R.D. Larrabee, completed an X-ray mask linewidth project sponsored in part by a client company, completed an interlaboratory study of the utility and use of a new lithographic SEM magnification standard, organized and ran two workshops: one on optical modeling for metrological applications, and the other on improving user/vendor relations in the litho-metrology arena.

The feasibility of using transmission mode SEM meaurements for use in submicrometer metrology on X-ray masks having been established by the Group earlier, the client company provided funds to modify our metrology SEM to accommodate X-ray masks of their design and to test theoretical predictions for the optimum way to detect the transmitted electrons. The optimized system was successfully demonstrated, and the company purchased a custom designed SEM using the principles developed under this project. We collaborated with the supplier of this SEM to assure that our design principles were realized in this custom design. The project was completed with delivery of five X-ray mask standards and the publication of a detailed report of the project in the NIST Journal of Research.

A comprehensive interlaboratory study was completed to evaluate the utility and use of a new lithographically defined SEM magnification standard designated SRM 2090. Over 40 instruments from over 30 companies were included in this study. The accumulated data set was analyzed and the results published in the NIST Journal of Research. These results clearly showed the need for calibration of the metrology SEMs used in the micrometer and submicrometer range of dimensions, and confirmed an almost universal tendency for industrial SEMs to contaminate samples. Thanks to our collaborators at one company, a nondestructive way was found for cleaning standards of this contamination.

The utility of the new standard was best illustrated by the request of many participants to keep the samples or to retain them longer than we had specified in order to use them for comparison of different SEMs. With utility thus demonstrated, we are now buying artifacts for SRM 2090 to be calibrated in the metrology SEM.

The third annual optical modeling workshop was organized by our group, but held in connection with the annual SPIE Microelectronics Symposium held in San Jose, California in February, 1993. This series of workshops was conceived by our Group for the purpose of bringing together all the people in this field for the purpose of comparing not only their approaches to the problem, but also their results. This is a "theoretical round robin" approach wherein the participants all modeled the same structures and compared results. The initial efforts were sufficiently successful in revealing programming errors and poor assumptions that two additional workshops have now been held to extend the initial work to more useful structures and structures that more completely exercise the models. The results of these workshops have been reported in papers at the following year's SPIE meeting. However, the greatest value of the workshops is not the papers, but the informal feedback given to the participants throughout the year regarding how their modeling results compared to others. A similar workshop for SEM modeling is being organized by our group for March 1994 and will be held in connection with a popular meeting for those concerned with the use of scanning electron microscopes.

A second workshop, organized by our group and held in connection with the February SPIE Microelectronics Symposium, was on improving the relationships between the users and suppliers of the metrology tools used in microlithography. Predictably, more problems were identified than solutions but, perhaps for the first time, both users and vendors talked to each other freely and without hesitation. Perhaps the most novel concept presented was that of "shared responsibility" where both the user and the supplier share the responsibility for instrument performance over the life of the instrument from design to its being scrapped. These and other topics discussed at this workshop are summarized in NISTIR-5193.

OMP6: Solderability Measurement and Optimization

An understanding of the factors determining the solderability of electronic components and printed wiring boards is becoming critical as U.S. industry switches to surface mount devices. The surface mount geometry places new demands on the soldering process itself and on the mechanical strength of the solder joints. The small size and the geometry of surface mount components limit visual inspection of the solder joint and make rework of improperly soldered connections difficult; good first-pass solderability is, therefore, an important industrial goal. These same performance demands will be placed on any Pb-free solders used to replace Pb-Sn alloys. Even with present device technology and Pb-based solder alloys, poor solder joints and their rework are estimated to cost industry $0.5 billion to $1 billion per year.

The impending legislation on the removal of Pb from solder alloys makes it imperative that new solder alloy systems be developed that meet high manufacturing and performance standards, as well as environmental standards. Under the leadership of the National Center for Manufacturing Sciences (NCMS), an industrial/government consortium has been organized to investigate candidate Pb-free systems. NIST and NCMS have signed a CRADA describing NIST participation in this $8 million research and development program. In addition to NIST, members include IBM, AT&T, Rockwell, Texas Instruments, Ford, GM-Hughes, GM-Delco, Motorola, Microfab, United Technologies Research Center, Rensselaer Polytechnic Institute, and Sandia National Laboratories.

The solderability measurement and optimization project, led by J.R. Manning, is designed to develop measurements and test techniques and scientific guidelines that U.S. manufacturers can use (1) to evaluate components for solderability before committing them to production, (2) to monitor soldering conditions in-line in order to meet the high performance and reliability requirements now demanded for surface mount solder joints, and (3) to develop new Pb-free solder alloys that meet stringent manufacturing, performance, and environmental requirements.

Accomplishments during FY 1993, included the following:
Analyzed the importance of test factors in the wetting balance solderability test using statistically designed experiments.

Designed a new accelerated aging test with independent control of temperature and water vapor pressure to (1) amplify minor defects in the surfaces which lead to solderability defects at the ppm level; and (2) simulate component solderability after storage. A processing model has been generated that relates aging variables to solderability as measured by the wetting balance test.

Determined the key parts of the ternary phase diagram for the Sn-Ag-Bi system, a candidate Pb-free alloy system, through thermodynamic calculations, differential thermal analysis, and solidification experiments. The phase diagram predicts the equilibrium phases which will occur for any temperature proposed for soldering.

Analyzed the effect of interfacial reactions, including interfacial diffusion and dissolution, on the wetting and spreading of Sn-Bi solder as measured by the area-of-spread technique for assessing solderability.

Collaborated with the National Center for Manufacturing Sciences (NCMS) in developing the research and manufacturing assessment program for consortium for the development of Pb-free solder alloys.

Office of Law Enforcement Standards (OLES)

OLES1: Flammability of Mattresses for Correctional Facilities

Building and Fire Research Laboratory

As recently as a decade ago, full scale testing was required to evaluate the flammability characteristics of mattresses. Under a contract supported by Lawrence Eliason, Director of OLES, a project was set up to establish requirements for the fire safety of mattresses.

This project was conducted in collaboration with NIST Building and Fire Research Laboratory, Fire Safety Engineering Division, and the California Bureau of Home Furnishings and Thermal Insulation (BHFTI). The study responded to the concerns of the National Institute of Justice (NIJ) Detention and Corrections Committee of the Technology Assessment Program Advisory Council (TAPAC). Their concern focused on whether the effectiveness of flame retardant treatments of institutional mattresses decreased through use.

The BHF heat-release-rate (HRR) data from full-scale burn tests was correlated with the bench-scale burn tests conducted by NIST. An examination of the data for non-propagating and propagating fire regimes for mattresses resulted in the development of an NIJ performance standard for the flammability of mattresses for detention and correctional facilities use. The standard was based upon HRR limits as determined through the valid and cost-effective bench-scale burn tests designed at NIST.

Questions & Answers: Whom Should I Call?

EEEL Management Staff

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, is also provided in Appendix C. We welcome your comments and inquiries.

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Appendix A: EEEL Awards and Recognition

Institute of Electrical and Electronics Engineers, Incorporated (IEEE)

George G. Harman received the highest award of the IEEE/CHMT Society and ECTC, the ECTC Sustained Distinguished Contributions Award. Harman was cited for long and exceptional contributions as Chairman of the CHMT Nominations Committee and the Awards and Fellows Committees, as well as his outstanding service to the ECTC and to the VLSI Packaging Workshop.

Robert A. Kamper, Director of the National Institute of Standards and Technology's Boulder Laboratories and Chief of the Electromagnetic Technology Division within the NIST Electronics and Electrical Engineering Laboratory, received the prestigious IEEE Harry Diamond award.

Cited for distinguished technical contributions in the field of electrotechnology while in U.S. Government Service, Kamper pioneered the application of superconducting quantum-mechanical principles to engineering measurements. As a result of Kamper's work, the United States is now the recognized world leader in precision voltage determination. NIST Superconducting Josephson-junction array voltage standards are used by major U.S. companies to improve competitive position through the validation of new instrumentation concepts and to achieve unprecedented quality control.

Francois D. Martzloff received the Power Engineering Society Recognition Award: Working Group on Surge Characterization in Low-Voltage Circuits.

Harry A. Schafft received the 1992 Wafer Level Reliability Workshop plaque of appreciation.

Four members of EEEL's staff were elected Fellows of the Institute of Electrical and Electronics Engineers by the IEEE's Board of Directors:

John W. Adams was cited for contributions to the development of standards for measuring the electromagnetic shielding effectiveness of planar materials.

David L. Blackburn was cited for contributions to the understanding and characterization of the electrothermal properties and related failure mechanisms of power semiconductor devices.

Robert E. Hebner was cited for the development of optical and electro-optical techniques to measure the electric behavior of dielectric liquids.

Harry A. Schafft was cited for contributions to the reliability of semiconductor devices and for the development of test methods for improving quality control.

Three staff publications were given "Best Paper" awards by the IEEE.

Department of Commerce

Gold Medal

The NIST High-Temperature Superconducting Films and Electronic Devices Project team was awarded a Department of Commerce Gold Medal for providing the United States with world leadership in the burgeoning field of superconducting electronics by setting three records:

- Fabrication demonstrating a production-compatible method for practical integrated circuits incorporating high-temperature superconducting elements and interconnections

- The highest frequency response —8THz— in a lithographed Josephson junction, showing the speed potential for a reproducible element of an integrated circuit (as opposed to a special one-of-a-kind point-contact device)

- Highest switching voltage of any microfabricated Josephson junction, showing that the fabrication process is robust with achievable allowances for manufacturing variation.

U.S. manufacturers immediately incorporated results from the NIST patent-applied-for technology in their development programs.

Team members, all from EEEL's Electromagnetic Technology Division, were James A. Beall, Michael W. Cromar, Erich Grossman, Richard E. Harris, Todd E. Harvey, Nancy A. Missert, Ronald H. Ono, Joe P. Rice, Peter A. Rosenthal, David A. Rudman, and Leila R. Vale.

Silver Medal

Allen R. Hefner received a Department of Commerce Silver Medal for his development of the first physics-based electrothermal model of a power semiconductor device. These devices are used to control the flow of electric power. Dr. Hefner modeled an insulated-gate bipolar transistor (IGBT), the control device of choice for many applications but especially for motors, which consume some 60 percent of the $186 billion worth of electricity generated in the United States each year. Hefner worked with industry to incorporate his model into commercial simulation software that provides circuit and system designers with a powerful tool for developing energy-efficient products, such as hybrid-drive and electric vehicles, machine tools, and appliances. Hefner's work on the IGBT provided manufacturers with the means to provide customers with a model for a power device based on their specific requirements. The customer can then carry out the preliminary design of the intended circuit based on the model and recommend changes in its design to optimize it before production.

Robert A. Kamper, Director of the National Institute of Standards and Technology's Boulder Laboratories and Chief of the Electromagnetic Technology Division within the NIST Electronics and Electrical Engineering Laboratory, received a Department of Commerce Silver Medal for his exceptional, resourceful, and dedicated service as Director of the Boulder Laboratories. In this position, he has developed rapport among the Department of Commerce agencies sharing the site and between these agencies and the City of Boulder. Negotiated acceptance of the Department's Boulder site development plans on the part of the community was testimony to Dr. Kamper's effectiveness in his role. Characteristically, his style consistently reflects a reasoned approach in emotionally charged issues. Extremely well-regarded for his ability to meet challenges with equanimity and a nonconfrontational attitude, Dr. Kamper's skillful leadership and negotiations led to agreement on the construction of a new NOAA building as well as the proposed NIST Advanced Technology Laboratory.

NIST

Bronze Medal

Three members of the EEEL staff received Bronze Medals from the National Institute of Standards and Technology:

Sarah Gilbert received a NIST Bronze Medal for her work on high-accuracy wavelength standards. The work, which was based on novel techniques using laser cooling and excited-state absorption in atomic rubidium, produced absorption linewidths as narrow as 7 MHz near 1530 nm. Dr. Gilbert locked a single-frequency erbium fiber laser to the rubidium resonance. EEEL has played a significant role in the development of cooling and trapping methodology, and this wavelength standard is one of the first applications for trapped neutral atoms. The optical fiber communications industry required the moderate-accuracy and high-accuracy wavelength standards in the 1300- and 1500-nm regions to support existing commercial technology. Such applications include practical methods of laser diode evaluation, and support of new technology aimed at providing the capacity required by information highways, specifically, methods such as wavelength division, multiplexing, and coherent transmission.

The team of *Michael Gaitan* and *Janet Marshall* has developed and successfully demonstrated procedures that enable micromachine designers to fabricate micromachine devices using a commercially available standard process, followed by an in-house custom etching step that requires only simple, inexpensive etching equipment. The modifications carried out by Gaitan and Marshall added two layers to the MOSIS complementary metal oxide-semiconductor (CMOS) process to define a region to be micromachined by customers upon receipt of their MOSIS chips. These layers, the open layer and the etch-stop layer, define a region of bare silicon, which is to be exposed to the post-processing etchant; and define an ion-implanted frame around the open layer within which the etched silicon is confined. The team also modified the computer-aided design software to recognize the two levels. There is great excitement in the U.S. for the potential offered by micromachined parts, given that a single silicon chip can incorporate both the micromachine and an integrated circuit. Parts proposed to date include electric motors, gear trains, lever mechanisms, and in-vivo surgical tools, in addition to the thermal targets, specifically, the ac-to-dc thermal converters, standard sources of electromagnetic radiation, and chemically specific sensors under development at NIST. Dr. Gaitan and Ms. Marshall have made it possible for a wide range of government and university researchers to enter the micromachine arena through the MOSIS foundry service, the University of Southern California (USC) silicon integrated-circuit fabrication service.

Other Organizations

Andrew G. Repjar received the Antenna Measurement Techniques Association (AMTA) Outstanding Service Award.

Peter Roitman was named by the Naval Research Laboratory to receive an Alan Berman Research Publications Award, the equivalent of a "best paper" award for the Laboratory. The award recognized the 'technical clarity and literary merit' in the paper on radiation-induced charge trapping in a variety of silicon-on-insulator materials.

Robert I. Scace received the SEMI Karel Urbanek Memorial Award. Scace, Director of the Office of Microelectronics Programs, was cited for his "leadership, dedication, and long-term service to SEMI and the semiconductor industry in the area of technical standards". Scace has been associated with SEMI's standards program since 1975, when it involved some 30 volunteers and had not published any standards. He has assisted significantly in the establishment of the institutional framework, staff, and procedures that now support over 50 technical committees and 2700 volunteers in Europe, Japan, and North America. Scace was one of the principal architects of SEMI's international standards development approach, which produces needed standards promptly and avoids unnecessary development of competing, nationally oriented standards that can become non-tariff trade barriers.

Appendix B:
FY 1993 CRADAs

EEEL CRADAs In Effect In FY 1993

DIVISION	RESEARCH PARTNER	PROJECT TITLE
ELECTRICITY	BALLANTINE LABORATORIES, INCORPORATED	THIN-FILM MULTIJUNCTION THERMAL CONVERTERS
	BERKELEY RESEARCH ASSOCIATES, INCORPORATED	CHARACTERIZATION OF THE AURORA FACILITY OIL SWITCH
	BEST TECHNOLOGY, INCORPORATED	STUDY OF IMPROVED SINGLE JUNCTION THERMOELEMENTS
	EPRI, CANADIAN ELECTRICAL ASSOCIATION, ONTARIO HYDRO, MARTIN MARIETTA ENERGY SYSTEMS	INVESTIGATION OF S_2F_{10} PRODUCTION, DETECTION, AND MITIGATION
	ILLINOIS TOOL WORKS, INCORPORATED	PHOTO-DECOMPOSITION OF SULPHUR HEXAFLUORIDE
	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
SEMICONDUCTOR ELECTRONICS	ALLIANCE TECHNOLOGIES, INCORPORATED	COMPONENT LIBRARIES FOR CIRCUIT SIMULATORS
	ANALOGY, INCORPORATED	POWER SEMICONDUCTOR DEVICES IN ELECTRONIC CIRCUITS
	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	MICROWAVE CMOS MICROMACHINED POWER SENSORS

EEEL CRADAs In Effect In FY 1993

DIVISION	RESEARCH PARTNER	PROJECT TITLE
ELECTRO-MAGNETIC FIELDS	SOLID-STATE MEASUREMENTS, INCORPORATED	PROTOTYPE CAPACITANCE-VOLTAGE (C-V) ANALYSIS EXPERT SYSTEM
	ATN MICROWAVE, INCORPORATED	DEVELOPMENT OF MULTI-STATE PROGRAMMABLE TUNER FOR MICROWAVE CALIBRATION TRANSFER
	CASCADE MICROTECH	MMIC CONSORTIUM
	GENERAL MOTORS CORPORATION, PACKARD ELECTRIC DIVISION	DEVELOPMENT AND EVALUATION OF A LOSSY FILTER DESIGN
	ITT DEFENSE TECHNOLOGY CORPORATION	MMIC CONSORTIUM
	RAYTHEON COMPANY	MMIC CONSORTIUM
	STRATEDGE CORPORATION	ELECTROMAGNETIC CHARACTERIZATION OF CERAMIC ELECTRONIC PACKAGING INTERCONNECTS
	TEXAS INSTRUMENTS	MMIC CONSORTIUM
	TRW, INCORPORATED	MMIC CONSORTIUM
	WILTRON COMPANY	VALIDATE COMMERCIAL VNA PERFORMANCE

EEEL CRADAs In Effect In FY 1993

DIVISION	RESEARCH PARTNER	PROJECT TITLE
ELECTRO-MAGNETIC TECHNOLOGY	THE BOEING COMPANY	OPTICAL COMPONENTS
	HEWLETT PACKARD COMPANY	DEVELOPMENT OF WAVELENGTH CALIBRATION EQUIPMENT FOR OPTICAL SPECTRUM ANALYZERS AND TUNEABLE DIODE LASERS
	HEWLETT PACKARD COMPANY/MEADOW LARK OPTICS	DEVELOPMENT OF STANDARD POLARIZATION COMPONENTS
	HONEYWELL, INCORPORATED	GAIN AND LOSS MEASUREMENTS OF ERBIUM-DOPED WAVEGUIDES
	IMRA AMERICA, INCORPORATED	RARE-EARTH DOPED WAVEGUIDE DBR LASERS AND POLARIZATION DISCRIMINATING RECEIVERS
	MARTIN MARIETTA CORPORATION	MILLIMETERWAVE COMPONENTS USING HIGH TEMPERATURE SUPERCONDUCTORS
	QUANTUM MAGNETICS	VOLTAGE STANDARDS
	RMC, INCORPORATED	COMMERCIAL JOSEPHSON VOLTAGE STANDARD
	SCHOTT GLASS TECHNOLOGIES, INCORPORATED	1.3 MICROMETER SILVER ION EXCHANGE INTEGRATED OPTIC LASER

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813
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LEGEND
* = ALSO SERVES DIVISION 813
CON = CONSULTANT
CU = CONTRACT WITH UNIVERSITY
CP = COOPERATIVE EDUCATION PROG.
FH = FACULTY HIRE
FTT = FULL TIME TEMP.
GRF = GRADUATE RESEARCH FELLOW
GL = GROUP LEADER
GS = GUEST SCIENTIST
N/F = NIST FELLOW
PD = POSTDOCTORAL APPOINTMENT
PL = PROJECT LEADER
PT = PART TIME

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5409 MECHELS, Steve
6353 PATRICK, Heather (WS-CU)
3223 YOUNG, Matt
7723 JINNO, Masahiko (GS)
3223 BRILLIANT, Nathan

Optical Fiber Sensors
5204 DAY, Gordon W. (PL)
5170 ETZEL, Shelley M. (WAE)
5400 DEETER, Merritt N.
5599 ROSE, Allen H.
3805 WILLIAMS, Paul
5170 ROCHFORD, Kent
3359 CRAIG, Rex
7612 MILIAN BON, Silvia (GS)
3941 CLARK, Ian (GS)

Laser Measurements
3651 SCOTT, Thomas R. (PL)
3439 JONES, Richard
5583 KEENAN, Darryl A.
5162 LEONHARDT, Rodney W.
3621 LI, Xiaoyu
5898 LIVIGNI, David J.
5253 TOBIAS, Iris L.
3394 VAYSHENKER, Igor
5393 YAANG, Shao (CTR)

Optical Communication Device Metrology
3696 PHELAN, Robert J., Jr.(PL)
3942 AUST, Andy J. (FTT)
3354 CHRISTENSEN, David H.
3761 GALLAWA, Robert L.
3455 HICKERNELL, Robert K.
3370 HILL, Jim R.
3234 JOHNSON, Eric G.
3440 LARSON, Donald R.
3654 LEHMAN, John H.
3289 MALONE, Kevin J.
5167 McCOLLUM, Mark J.
5747 OBARSKI, Gregory E.
5239 SANFORD, Norman A.
5952 VEASEY, David L.
7554 KETTERL, Joseph (GS)
7281 SCHAAFSMA, David (Wk. Study-CU)

.03 CRYOELECTRONIC METROLOGY

3776 HARRIS, Richard E. (GL)
3988 McCARTHY, Sandra E., Secretary

SQUIDs
5375 CROMAR, Michael W. (PL)

High Temperature Superconducting Devices
5375 CROMAR, Michael W. (PL)
5989 BEALL, James A.
3340 HARVEY, Todd E.
3762 ONO, Ronald H.
5052 REINTSEMA, Carl A. (CTR)
3988 KIMMINAU, Kristi (CU)
3988 HUBER, Martin E. (GS)
3418 WALLACE, George H.
5081 RUDMAN, David A. (PL)
5121 VALE, Leila R.
7366 RICE, Joe P. (PD)
3988 BECK, Heather (CU)
3988 BORCHERDT, Lisa (CU)
7212 DeGROOT, Donald C. (PD)

Ultra High-Speed Devices
3740 HAMILTON, Clark A. (N/F) (PL)
5258 BENZ, Sam P.
3906 BURROUGHS, Charles J.
5049 CREWS, Maggie S.
5910 BOOI, Peter (GS)

Single Electron Devices
3776 HARRIS, Richard E. (PL)
3391 KAUTZ, Richard L.
3597 MARTINIS, John M.
5430 NAHUM, Michael (PD)
5913 WELTY, Rick (GS)
3988 PRICE, John (GS)
5844 STEINBACH, Andy (CU)
3988 KOPROWSKI, Brian (H.S. Stu)

Radiation Detectors
5113 McDONALD, Donald G. (PL)
5102 GROSSMAN, Erich
3770 SAUVAGEAU, Joseph E.
7064 KOCH, Jonathan
3988 VALDEZ, John (CU)
3988 MACDONALD, Michael (CU)
5911 KAPLAN, Todd

.05 SUPERCONDUCTOR & MAGNETIC MEASUREMENTS

3785 FICKETT, Fred R. (GL)
5477 CORWIN, Ruth, Secretary

Superconductor Measurements
5441 CLICKNER, Cameron C.
5448 EKIN, John W.
3143 GOODRICH, Loren F.
3641 MORELANO, John
5631 BRAY, Steven L.
5344 BERGREN, Norman F.
5097 RUSSEK, Steve
5420 ROSHKO, Alexana
3840 SRIVASTAVA, Ashok (CU)
3777 STAUFFER, Theodore C.
3141 THOMSON, Ruth E. (PD)
5096 SANDERS, Steve (PD)
7747 COOLEY, Lance (PD)
5097 KIRCHENBAUM, Leif (CU)
3143 MEDINA, Troy (CU)
5345 PEDERSON, Adam (CU)
5420 TROTT, Katie (CU)
3143 WIEJACZKA, Julie (CU)

Magnetic Measurements
3650 GOLOFARB, Ronald B.
5300 CROSS, R. William
5300 FOSTER, Steve
5333 KOS, Anthony B.
5557 OTI, John (PD)
3703 COFFEY, Mark (PD)
3841 RICE, Paul

Conductor Measurements
5206 THOMPSON, Curtis A.
5606 DULCIE, Laura L.
5300 NGUYEN, Phuong X. (CU)

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 1993. 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

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