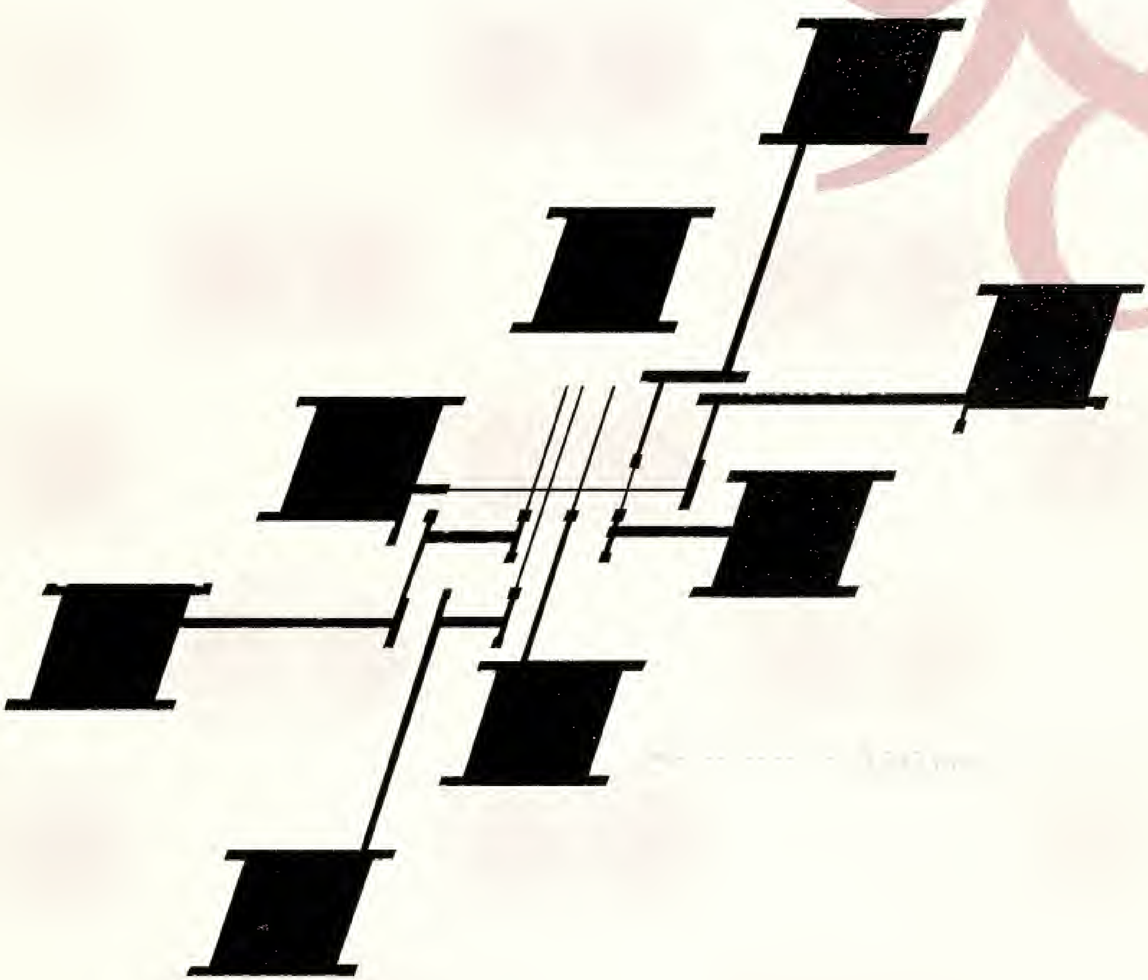
Electronics and Electrical Engineering Laboratory

National Institute of Standards and Technology

NISTIR 6271

EEEL Technical Accomplishments 98



Advancing Metrology for Electrotechnology to Support the U.S. Economy

United States Department of Commerce
Technology Administration
NIST

National Institute of Standards and Technology

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

• Measurement and Standards Laboratories that provide technical leadership for vital components of the nation's technology infrastructure needed by U.S. industry to continually improve its products and services;

• a rigorously competitive Advanced Technology Program providing cost-shared awards to industry for development of high-risk, enabling technologies with broad economic potential;

• a grassroots Manufacturing Extension Partnership with a nationwide network of local centers offering technical and business assistance to smaller manufacturers; and

• a highly visible quality outreach program associated with the Malcolm Baldrige National Quality Award that recognizes continuous improvements in quality management by U.S. manufacturers, service companies, educational organizations, and health care providers.

In fiscal year 1999, NIST is operating on a budget of about $760 million with nearly 3,300 staff members at its sites in Gaithersburg, Maryland and Boulder, Colorado. News and general information about NIST programs and services are available at www.nist.gov, or you can call NIST inquiries at (301) 975-NIST or e-mail: inquiries@nist.gov.

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COVER IMAGE:

EEEL researchers, in collaboration with staff at Sandia National Laboratories and International SEMATECH, are taking advantage of one of nature's rulers to provide a calibration artifact that will enable the semiconductor industry to meet the dimensional requirements for microchips specified in the National Technology Roadmap for Semiconductors. Developing such artifacts is an ever increasing challenge as the critical dimension of microchips shrinks to a few hundred atom diameters. The cover depicts a test structure superimposed over an image of the naturally occurring arrangement of atom pairs in a (110) silicon lattice plane. The structure is patterned in a single crystal of silicon and its critical dimension or smallest feature size is calibrated electrically. This electrical measurement is, in turn, calibrated by counting the atomic planes of the feature in a high-resolution transmission electron microscope (HRTEM) image. The arrangement of atom pairs shown on the cover draws from an HRTEM image provided by Dr. Thomas Headley of Sandia National Laboratories. See page 1.

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

EEEL Technical Accomplishments 98

ADVANCING METROLOGY FOR ELECTROTECHNOLOGY TO SUPPORT THE U.S. ECONOMY

NISTIR 6271

DEPARTMENT OF COMMERCE ★ UNITED STATES OF AMERICA ★

Department of Commerce
William M. Daley, Secretary

Technology Administration
Gary R. Bachula, Acting Under Secretary for Technology

National Institute of Standards and Technology
Raymond G. Kammer, Director

December 1998

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EEEL VISION

To be the world's best source of fundamental and industrial-reference measurement methods and physical standards for electrotechnology.

EEEL MISSION STATEMENT

The Electronics and Electrical Engineering Laboratory promotes U.S. economic growth by providing measurement capability of high impact focused primarily on the critical needs of the U.S. electronics and electrical industries, and their customers and suppliers.

EEEL OUTREACH

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations and cooperates with academia in the development and use of measurement methods and scientific data.

To assure that EEEL understands customers' needs and develops effective programs to meet those needs, close interaction with industry is encouraged. Information is obtained during staff visits to other laboratories, interactions at conferences, visits by others to EEEL, through meetings conducted or attended by staff, and through a wide range of joint activities with industry, such as participation in professional societies, cooperative research projects, and consortia. These information-exchange interactions are so important that they are routinely tracked quantitatively.

Communication Activities

Publications – 220
Software Requests – 297
Talks – 228
Consultations – 2000
Visits – 250
Visitors – 375
Meetings:
Contributors – 41
Attendees – 3000

Joint Activities

Standards Organizations:
Staff Participating – 45
Memberships – 80
Professional Societies:
Memberships – 140
Cooperative Research – 150
Consortia – 6
Guest Workers – 89

Calibration Services

Standard Reference
Materials (SRMs) Offered – 22
SRMs Sold – 236
Sales in FY1998: $233 K
Calibration Service Customers – 300
Fees in FY1998: $1.9 M
Training Courses:
Offered – 9
Attended – ~300

For more technical detail on any of EEEL's projects, please feel free to request the FY1999 Program Plan or a list of EEEL technical publications in your area of interest. A list of current EEEL research projects is included in the Appendix. The list includes two crosswalks: one of the crosswalks identifies the Division or Office conducting each project; the other identifies the program under which the work is performed. EEEL's organization chart is also included in the Appendix, enabling you to contact staff members directly, if you wish.

LABORATORY DIRECTOR'S MESSAGE

J.C. French, Director of EEEL, with A.H. Cookson, Acting Deputy Director of EEEL.

This year marks the twentieth anniversary of NIST's Electronics and Electrical Engineering Laboratory and its predecessor Center for Electronics and Electrical Engineering. Throughout our existence we have maintained our focus on metrology support, providing measurement technology, measurement services, and evaluated data to the nation with the overall goal of improving the U.S. competitive position and quality of life. A specific part of this mission is to provide the fundamental basis for all electrical measurements in the United States.

Our primary clientele are U.S. companies, which collectively have indicated a clear need for our products and services, as have other government agencies and academic institutions. They have done this in many ways including assistance in setting priorities, collaboration in research, participation in consortia, and demonstration of dramatic benefits from use of our results. As just one example, recognizing that NIST support was essential to development of the metrology critical to the industry's further advancement, the semiconductor industry asked Congress to establish the National Semiconductor Metrology Program at NIST. The Program is now receiving some $12 million annually as it grows toward the target level of $25 million. The Program's recent activities are described in the section Programs Matrix-Managed by EEEL.

Over the years, we have learned from our clientele that our contributions have improved industrial productivity and profitability, stimulated new product commercialization and new company startups, changed industry-wide practices, and beneficially influenced technical and policy actions.

Providing comprehensive measurement support to the electrical and electronic sectors is a dynamic target. Our programs must reflect advances in technology and the consequent changes in the requirements of our client community. An example of this type of organizational change is the manner in which we refocused the programs of the former Electromagnetic Fields Division on key radio-frequency advances — including wireless and personal communications and new incentives for achieving electromagnetic compatibility. These developments are now addressed by the Radio-Frequency Technology Division established this year.

We have traditionally sought to measure the impact of our programs, in large part to assure that our process for planning and implementing our research and development is working well. We address this goal not only through a continuous collection of anecdotal evidence and customer expressions of appreciation, valuable as they are, but also through formal econometric impact studies. In our existence as Center and Laboratory, we have contracted seven such studies, which have all shown that the return on investment from our programs is greater — in some cases much greater — than the return on investment from comparable research and development programs in industry. In Fiscal Year 1998, we activated four new studies on the impacts of Laboratory programs in semiconductor power device modeling, near-field scanning antenna metrology, laser and optical fiber power measurements, and Josephson-junction voltage standards. The first two of these are scheduled to be completed in Fiscal Year 1999.

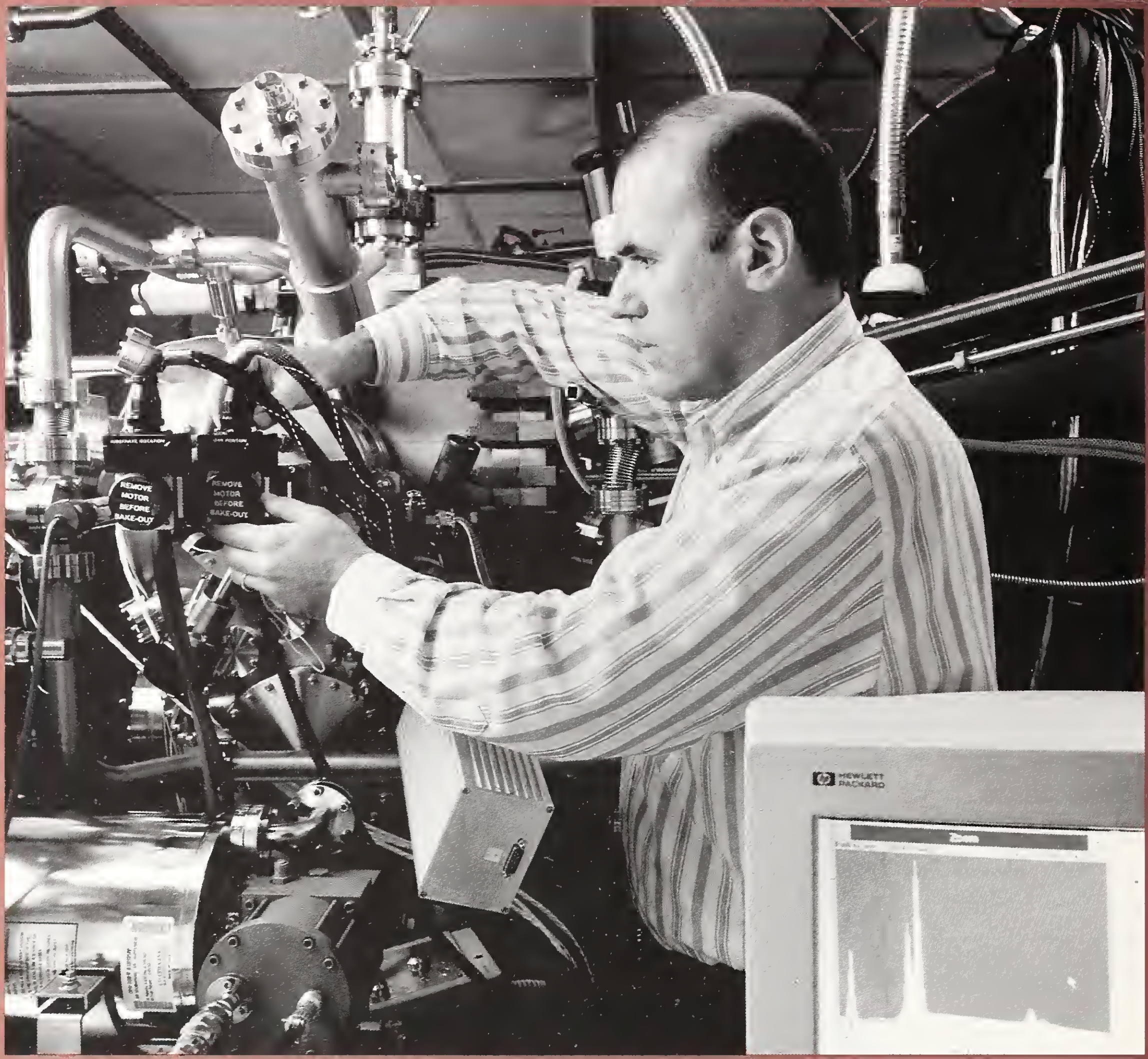
I believe the technical accomplishments described in this twentieth anniversary report provide exciting evidence of EEEL's leadership and effective service as it continues to respond to the needs of industry and to contribute to the scientific community. In the main section, Selected FY1998 Technical Accomplishments, you will find descriptions of work ranging from measurements based on the behavior of single electrons to measurements that characterize entire communication systems. I want to tempt you to explore this collection by presenting here just a small, but I believe impressive, sample of its contents.

- Used the counting of single electrons as the basis for a radically new type of capacitance standard
- Applied "nature's ruler" of crystal atomic lattice planes to directly calibrate semiconductor electrical test structures for critical dimension
- Demonstrated Internet-based remote monitoring of calibration measurements including the ability to adjust instrument settings from NIST and to acquire data in real time
- Provided Standard Reference Materials to support emerging wavelength division multiplexing (WDM) optical fiber communication systems
- Provided industry with its first opportunity to measure contrast in video displays objectively and accurately
- Established the National Wireless Electronic Systems Testbed (N-WEST) to help accelerate the development of wireless technology focusing on Local Multipoint Distribution Service (LMDS)

In closing, I would like to express my appreciation of your interest in EEEL and remind you that I welcome your comments and suggestions.

JCFrench

Judson C. French
Director
Electronics and Electrical Engineering Laboratory



J.G. Pellegrino – Adjusting the sample tilt for *in situ* x-ray emission measurements.

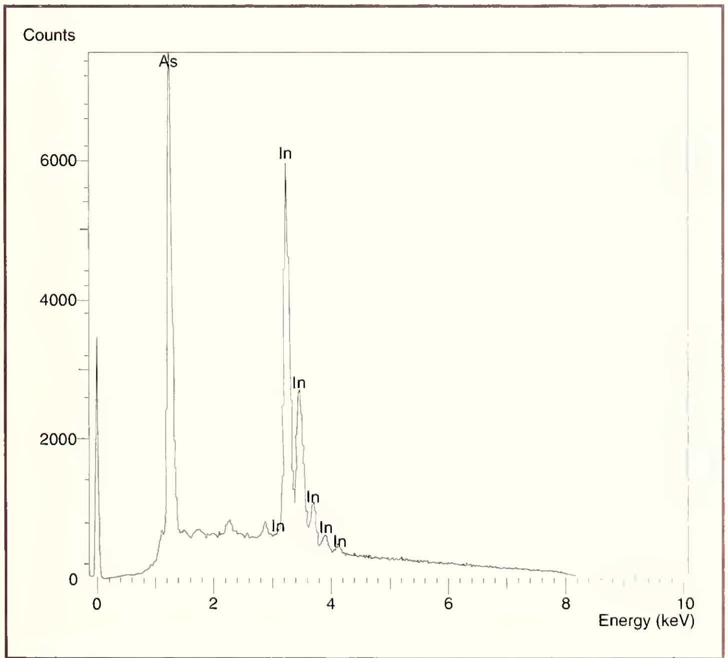
CHAPTER 1

SEMICONDUCTORS

1.1 Direct Feedback for *in situ* Compositional Control of Films

The calibration of semiconductor alloys is a time consuming process, which involves the definition of exacting and reproducible growth conditions. EEEL researcher Joseph Pellegrino has developed a novel *in situ*, x-ray-based technique for directly monitoring the composition of ternary and quaternary semiconductor alloys during growth. The result of this effort is the world's first x-ray emission spectrum acquired during thin film deposition in a molecular beam epitaxy (MBE) chamber. Such spectra provide a direct determination of the mole fraction, even in films as thin as 5 nanometers (nm). The technique is more powerful than other conventional probes that industry uses, such as reflection high energy electron diffraction (RHEED), because it is non-intrusive and non-destructive. Unlike RHEED, the x-ray fluorescence technique does not require a sacrificial sample for instrument calibration.

The Pellegrino probe uses a glancing electron beam as an exciter to stimulate x-rays from the epilayer growth surface. These x-rays are counted and classified by an energy dispersive detector mounted directly on the MBE chamber. The exciter stimulates x-rays from the epilayer growth surface even as the sample rotates. The detector is further equipped with a unique window that is not only transparent to the x-rays, but also capable of cleaning itself as contaminants from the chamber collect at its surface. The window consists of two thin, beryllium metal films, suspended such that the face exposed to the growth ambient can be heated to drive contaminants from the surface. In



Typical gallium arsenide x-ray spectra obtained *in situ* during the growth of a pseudomorphic high electron mobility transistor (pHEMT).

> "NIST's facilities and capabilities in III-V materials research is very impressive. It is just what a fledgling company like ours needs to augment its capabilities and validate its technological and manufacturing methodology."
>
> Leye Aina
> President
> Epitaxial Technologies LLC

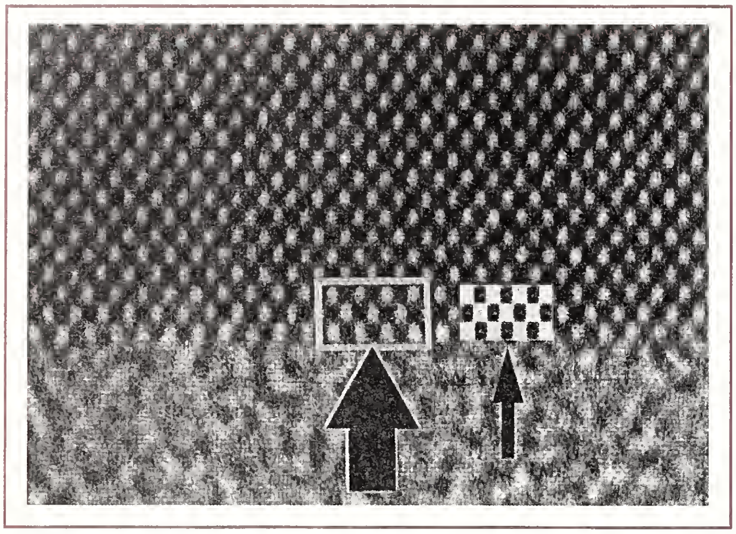
the past, it has been contamination which has prevented altogether the successful implementation of the x-ray technique.

Benefits derived from Pellegrino's direct, *in situ* x-ray probe will include the improved control of composition in compound semiconductor growth, and a significant reduction for industry in expensive post-growth wafer characterization. For the first time, it will be possible to obtain direct feedback for the compositional control of films as they are deposited. This work will enable the improved control of lattice matching in complex heterostructures as well as mole fraction reproducibility in III-V semiconductors that are being used in a variety of opto and cellular-telephone applications.

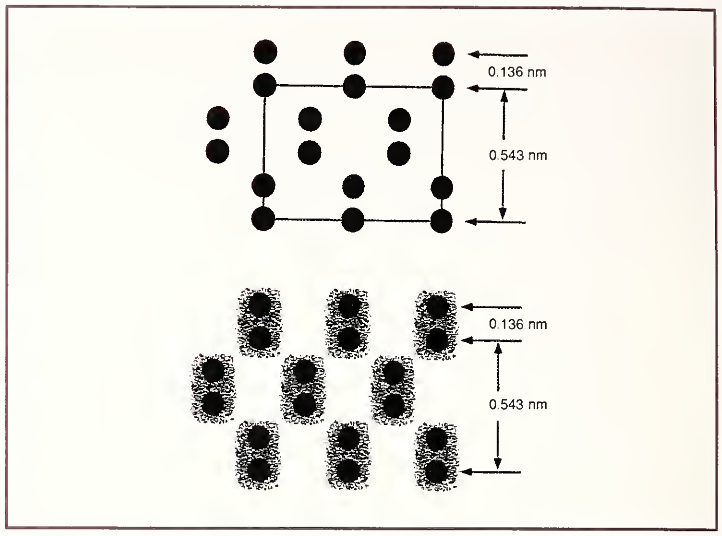
1.2 Reference Features with Linewidth Traceability to NIST Feasible

As the semiconductor industry continues to travel the path mapped by Moore's law, the number of transistors that can fit on a chip is currently doubling every 12 months, and the need for reference materials to calibrate critical-dimension (CD) metrology systems is becoming more acute. Currently, the industry is beginning the transitional task of reducing the size of minimum features to 0.14 micrometer (μm). Staff in EEEL's Semiconductor Electronics Division have been working to develop the metrology necessary to keep pace with industry's need to measure steadily shrinking feature sizes.

In 1994, researchers Michael Cresswell, Richard Allen, and Rathindra Ghoshtagore began a collaboration with staff from the Sandia National Laboratories' Microelectronics Development Laboratory to develop a method to fabricate and certify linewidth reference features. To meet the pressing needs of the semiconductor manufacturers, Cresswell and Allen had to determine a



HRTEM image* of silicon lattice in [110] orientation.



HRTEM image* of lattice-site columns viewed from [110] surface.

way to ensure that the reference features they designed had extremely well-defined sidewalls to provide the means for unambiguous physical linewidth measurements. Without them, any calibration is rendered meaningless by the related measurement uncertainties.

Once the NIST team had theorized the means to produce these reference materials, they worked with their colleagues at Sandia to develop a method to fabricate them. The prototype reference features resulting from this collaboration have the ideally planar and atomically smooth sidewalls needed to permit meaningful calibration. The sidewalls were produced using a lattice-plane selective etch of silicon-on-insulator material, which removed material from different crystal planes in the silicon film at radically different rates. Most importantly, a buried layer of insulator allows the widths of the reference features to be measured with ultra-high precision electrical techniques.

The etching process the Sandia team used reveals reference features with sidewalls defined by (111) lattice planes. The lattice planes provide a built-in ruler with which to measure the dimensions of the features since the features are patterned in a monocrystalline film. Going one step further, the staff of the HRTEM (High-Resolution Transmission-Electron Microscopy) facility successfully generated high-energy electron phase-contrast images of atoms on silicon lattice sites in samples of the project's CD reference materials. The countable (110) lattice planes demonstrate the practicability of tracing reference-feature CDs to a number of known silicon-lattice spacings. Establishing another "first," the staff at the Laboratory was able to obtain sufficient resolution for lattice-plane imaging across the entire 0.5 μm reference feature width – a span of approximately 800 lattice planes. Even more importantly, the collaboration between the NIST team and the Sandia team demonstrates for the first time that it will be feasible to offer reference-feature linewidth certification with NIST traceability to meet the growing demand in the user community.

1.3 Advanced Micromachining Allows More Companies to Manufacture MEMS

NIST and Optical E.T.C. have developed a new silicon micromachining process to fabricate Complementary Metal Oxide Semiconductor (CMOS) MicroElectroMechanical Systems (MEMS). The new process enables companies that do not have on-site IC-fabrication facilities to fabricate CMOS MEMS structures. Such structures vary widely, ranging from micro-heating elements for micro-hotplate gas sensors and thermal flat panel displays to passive microwave components for microwave coplanar transmission lines and power sensors.

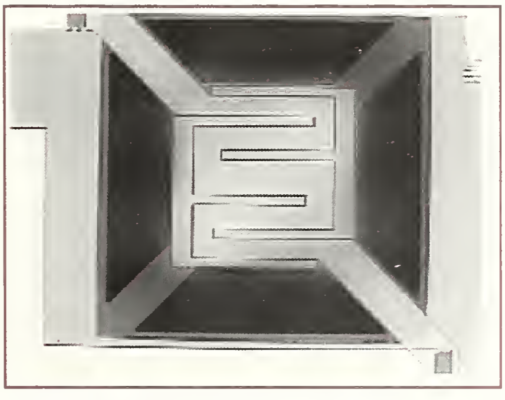
The new process provides improved understanding and control of silicate chemistries in the use of tetramethylammonium hydroxide (TMAH) to anisotropically etch (micromachine) silicon. This process was developed and optimized by extensive laboratory testing in EEEL's Semiconductor Processing Facility. Researchers Michael Gaitan and John Geist found that the new etching process was remarkably sensitive to reagent concentration, and needed extensive laboratory development. A major

*Graphic courtesy of Dr. Thomas Headley, Materials Characterization Department, Sandia National Laboratories.

M. Gaitan – Silicon micromachining CMOS ICs using TMAH anisotrobic etchant.

advantage of this process is that it preserves exposed metallization at wire bond pads over very long periods of etching time which, in turn, means higher yield and increased compatibility with a production environment.

CMOS MEMS are MEMS that are compatible with standard CMOS integrated circuit (IC) technology. These devices are manufactured in commercial IC processes. The IC process creates device structures (precursors) that are then processed into the final MEMS structures. Prior to the development of the TMAH process, Ethylenediamine Pyrocatechol (EDP) was commonly used to post-process CMOS MEMS. The new TMAH process is cleaner, safer, and easier to implement.



CMOS microheating element.

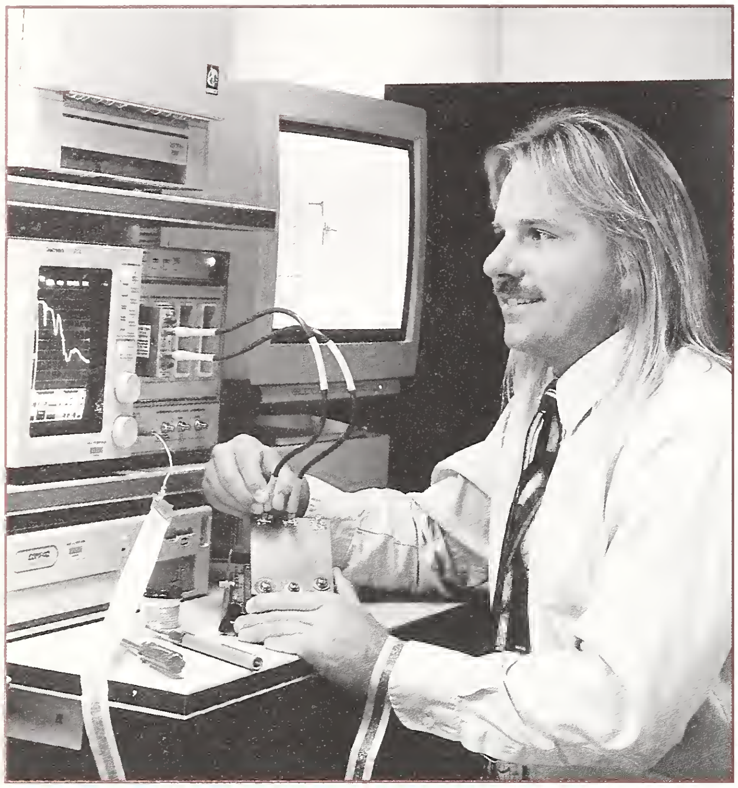
With the successful development of the TMAH process, the Microelectronics Center at North Carolina (MCNC), a provider of MEMS foundry services, agreed to team with MOSIS — Modular Office Systems Integration Software — a provider of IC fabrication services, to provide post-processing of the CMOS MEMS. MCNC had been reluctant to provide this service before the safety considerations associated with EDP had been eliminated. Optical E.T.C. has also agreed to join the partnership to provide a seamless design-to-product fabrication service for CMOS MEMS.

NIST and Optical E.T.C. entered into a cooperative research and development agreement (CRADA) in 1991 to develop CMOS MEMS-based thermal flat-panel display technology. The Department of Defense identified this work as critical to the test and calibration of infrared imaging systems, such as those used in heat-seeking missiles. The CRADA drew on optics and thermal imaging expertise from Optical E.T.C. and CMOS MEMS expertise from NIST. The Department of Commerce recognized this agreement as one of 10 best in the nation in its *Seeds of Commerce* publication.

> "The availability of a service for MEMS substrate etch through MCNC is a significant plus for the MOSIS Service. The MOSIS Service has had an interest in supplying CMOS compatible MEMS capability for some time, but in the past, only designers who have in-house MEMS substrate etch capability were able to experiment with MEMS. With MCNC offering a TMAH based anisotropic substrate etch service, a much larger MOSIS user community will be able to experiment with MEMS."
>
> Vance C. Tyree
> Senior Member of Technical Staff
> University of Southern California
> Information Sciences Institute
> The MOSIS Service

1.4 Power Electronic Interconnect Parasitics Characterized with TDR

Recent experiments at NIST have demonstrated, for the first time, the use of Time Domain Reflectometry (TDR) to characterize the interconnect parasitics of a prototype power converter. The components of this prototype high-power inverter include Insulated Gate Bipolar Transistor



A.R. Hefner – High power IGBT module interconnect parasitics being characterized under realistic application conditions by launching the TDR signal through a stripline test fixture in the configuration of a planar power busbar.

(IGBT) power modules, a busbar, and a high-voltage dc capacitor. The experiments proved that the internal interconnect impedances of the IGBT module can be extracted completely using TDR. Results also indicated that the busbar can be modeled by uniform transmission line segments between connection points, and that the dc capacitor contained a significant series interconnect inductance. Moreover, Semiconductor Electronics Researcher Allen Hefner concluded that the TDR method may also be used to characterize any other power electronics devices or components, such as the interconnects for microprocessor power-supply regulators. Hefner is currently performing simulations and measurements of power converter operation to demonstrate that the major causes of electromagnetic interference (EMI) noise can be identified and that EMI-related performance predictions can be made using the TDR technique together with his widely used physics-based IGBT model.

Without adequate metrology for characterizing interconnects, the electromagnetic wave propagation properties of interconnects are often approximated using analytical or computational methods that do not adequately predict the nonideal behavior of real interconnects. These methods have some fundamental limitations because the physical properties, parameters, and structures of the conductor materials are not generally known, and assumptions must be made in computations. For example, the transmission line properties of structures such as leads or wire bond interconnects inside power device modules or passive components are almost impossible to calculate accurately because they are physically inaccessible after being packaged.

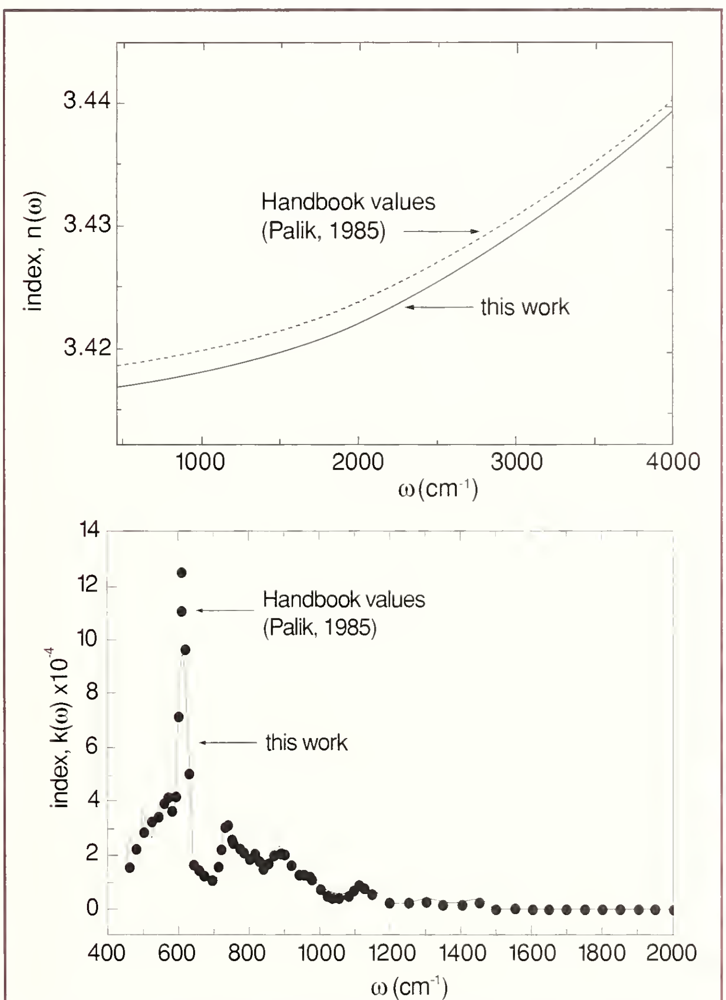
Thus, a measurement-based method such as TDR is critical for the characterization of the transmission line properties of the interconnect parasitics because they cannot be considered as ideal lumped elements (resistors, capacitors, inductors), but must be represented as distributed transmission line elements having transmission line characteristic impedances and propagation delays. In addition, the transmission line characteristics typically are not uniform along the interconnect and must be represented using several transmission line segments having different characteristic impedances and propagation delays. The electrical behavior of module and circuit board interconnects is also becoming increasingly more important in determining the behavior of digital and analog systems due to the increasing speed and power requirements and decreasing operating voltages.

For example, one of the major impediments to the development of the next generation of microprocessor modules is the lack of power-supply stability caused by the interconnects between the microprocessor chip, its power-supply bypass capacitor, and its power-supply voltage regulator. The reason that interconnects are becoming more important for the power-supply stability of future microprocessors is that power requirements have changed; the power-supply voltage has changed from 3.3 V for present systems to 1.1 V for future systems, the voltage compliance requirements have changed from 5% for current systems to 2% for future systems, and the requirement for rate-of-change of power-supply current during power-up has changed from 1 A/ns to 5 A/ns. Given that the characteristic impedance is a key parameter in the present and next generation voltage regulator design, improved interconnect metrology is essential.

This work is a result of the collaboration between NIST (sponsored by The National Semiconductor Metrology Program) and the Virginia Power Electronic Center at VPI&SU (sponsored by the National Science Foundation Center for Power Electronics Systems). The new metrology developed for power electronic interconnect characterization and modeling will lead to a better understanding of the EMI mechanisms. This, in turn, will better the computer-aided design of future power electronic system electromagnetic compatibility (EMC), and result in improved and more cost effective EMI reduction techniques.

1.5 IR Method for Extracting Values of Intrinsic Optical Constants Improves by Factor of 10

Infrared (IR) spectroscopy is a powerful technique that has been used extensively by industry to analyze a variety of materials. This technique is undoubtedly capable of fulfilling many of the materials characterization demands of the semiconductor industry as well, but, up to now, the use of IR probes has been limited by a lack of reliable optical data, models, and test methods. Of these limitations, the most critical is the lack of accurate values for the intrinsic optical constants, $n(\omega)$ and $k(\omega)$, for silicon. It stands to reason that the accuracy with which small concentrations of impurities or the presence of overlayers can be detected is directly related to the accuracy with which the intrinsic properties of the silicon material itself are known. At present, the published values of $n(\omega)$ possess uncertainties* of about one part in 10^3, while the reported values of $k(\omega)$ vary by a factor of 2 or even greater, in some cases.



Comparison of published reference figures and results of this work.

Researchers Paul Amirtharaj and Deane Chandler-Horowitz of the Semiconductor Electronics Division have developed a new iterative method that leads to an improvement of the accuracy of $n(\omega)$ by a factor of 10. Using this method, the accuracy of the $k(\omega)$ values is also significantly improved. Further, their measurements have brought to light a systematic error in the published values of $n(\omega)$, which could be a significant source of error in prior IR analyses.

The method developed by the researchers extracts accurate values for the mid-infrared (450 to 4000 cm^{-1}) optical constants, $n(\omega)$ and $k(\omega)$, of silicon. Two Fourier transform infrared (FTIR) spectra were used: a high-resolution spectrum ($\Delta\omega$ = 0.5 cm^{-1}) yielding a typical channel spectrum, dependent mainly on the sample thickness and $n(\omega)$; and a low resolution spectrum ($\Delta\omega$ = 4.0 cm^{-1})

*All uncertainties are expressed as expanded uncertainties with coverage factor k = 2.

(Right to left) P.M. Amirtharaj, D. Chandler-Horowitz – Examining the optical collimator and sample. The sample is loaded into the Fourier transform interferometer for high-resolution, high-accuracy, mid-infrared refractive index measurements in silicon.

yielding an absorption spectrum, dependent mainly on the sample thickness and k(ω). Independent analyses of each spectrum gave initial n(ω) and k(ω) estimates. The estimated values were then used as the starting point for an iterative fit of the high and low-resolution spectra successively. Colleagues from NIST's Manufacturing Engineering Laboratory provided accurate measurements of the sample thickness. The team's results using the newly developed method are illustrated beside the published values established using traditional methods.

The improved accuracy of the values for the intrinsic optical constants will allow semiconductor manufacturers to further refine the IR spectroscopic analytical limits for impurities and thin insulator layers that will be needed to produce larger and more tightly specified 300 mm wafers. For example, it will be possible to measure the concentration of oxygen impurity in the wafer more accurately now. The enhanced measurement capability resulting from this work also has important implications for reducing feature sizes from the current minimum of 180 nm to 130 nm and below. Important properties of thin SiO_2 insulator overlayers, such as thickness, strain, and/or stoichiometry, can also be measured more precisely than in the past.

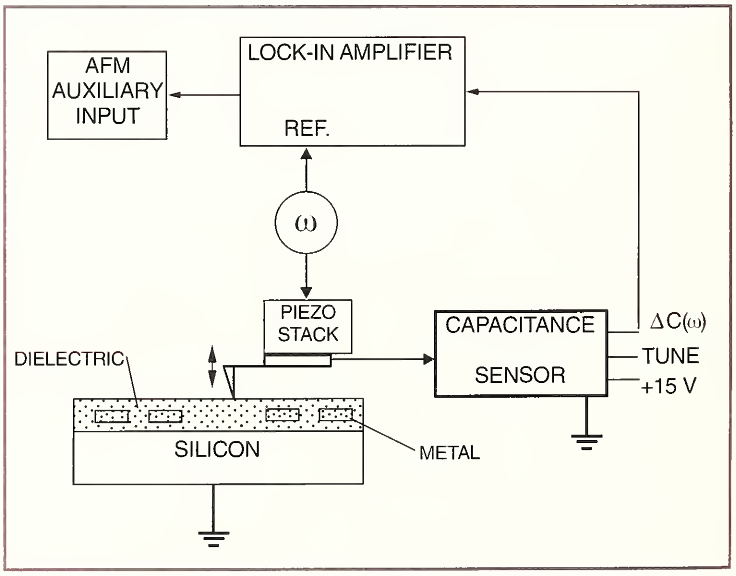
1.6 Intermittent-Contact SCM Mode Measures Overlay Alignment with High Spatial Resolution

The semiconductor industry measures overlay alignment on integrated circuits to improve feature placement and, thus, yield. Currently, optical microscopes are most commonly used to perform these measurements. However, atomic force microscopes (AFMs) have also been used to measure overlay-related surface topography. In the past year, researchers Joseph Kopanski and Santos Mayo have developed a new mode of operating the scanning capacitance microscope (SCM) called the intermittent-contact SCM (or IC-SCM).

The original contact-mode implementation of the SCM was developed for dopant profiling of semiconductors. Contact-mode SCM uses a contacting tip and generates a differential capacitance signal by modulating the depletion region within a semiconductor by means of an ac voltage. In the IC-SCM, the measured SCM signal is the differential capacitance, ΔC (ω), generated by the change in tip-to-sample separation due to the SCM cantilever vertical oscillation at a frequency of ω. IC-SCM is sensitive to the proximity of the tip to a conductor, thus making it possible to image metallization structures buried under planarized dielectric insulating layers. Such a measurement has been used to measure the overlay alignment between two successive levels of metallization on an integrated circuit.

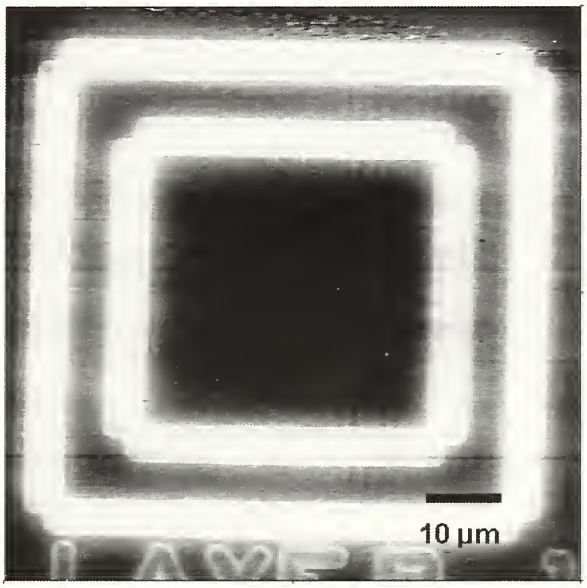
This application represents the first of a new class of scanning probe techniques to electromagnetically characterize metallic overlay test structures. Specifically, IC-SCM enables an AFM-based tool to detect and measure the overlay between both surface and buried metal lines. Among the potential advantages is the fact that AFM-based overlay measurements may not be affected by the same tool-induced shifts that are reported with optically based overlay measurements. Consequently, this technique may be useful for developing a better understanding of the currently used optical techniques. Another application of the IC-SCM being pursued with industrial collaborators is based on its ability to map dielectric constant variations of thin films. Of particular interest are high dielectric constant (high-k) films such as Barium Strontium Titanate (BST). High-k dielectrics have potential uses as the capacitor dielectric in memory chips or as the gate insulator material for next generation transistors with gate insulator thickness equivalent to less than 3 nm of silicon dioxide.

An essential element of the development of the IC-SCM was the computer simulation of measurements, using a commercially available two-dimensional field simulator. Model results predict and explain the distinct behavior of the IC-SCM when it is used to measure the location of buried metal lines that are either electrically grounded or electrically floating with respect to the SCM probe tip. Feedback between the model results and the experimental

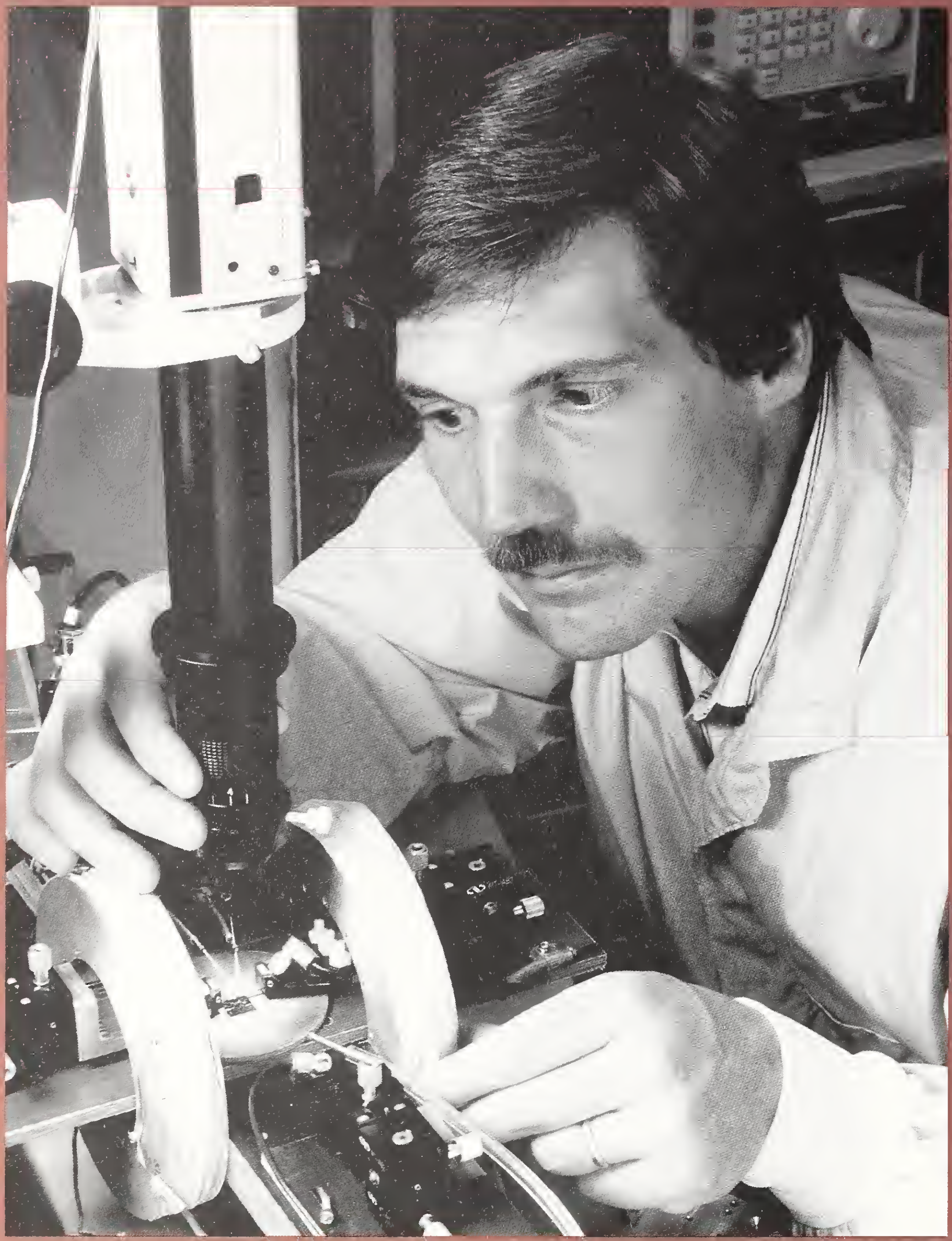


Block diagram of the Intermittent Scanning Capacitance Microscope.

data obtained with an IC-SCM provided a better understanding and optimization of the technique. This work was partially developed under a cooperative research and development agreement between NIST and a consortium of industrial partners.



IC-SCM image of a metal bars-in-bars test structure buried beneath a one-micrometer thick, planarized dielectric layer. The IC-SCM detects the metal lines by sensing the capacitance between the tip and the test structure.



S. Russek – Aligning current contacts and voltage probes on an MRAM test structure to measure its high speed performance.

CHAPTER

2

MAGNETICS

2.1 Sub-Half-Nanosecond Operation of GMR Devices Measured

Ohm's well known law, R = V/I, expresses the resistance of a material as a function of the voltage drop across it and the current flowing through it. The resistance of "magnetoresistive" multilayer composite materials depends additionally on the magnetic states of its component layers. The effect is due to the difference in scattering of "spin-up" and "spin-down" electrons as they flow among the layers, and it can be fairly large in certain materials that exhibit "giant magnetoresistance" (GMR).

GMR in magnetic thin films of nickel-iron and cobalt makes them suitable for use as read heads in the latest hard disks and, possibly, as a new type of nonvolatile magnetoresistive random-access memory (MRAM) for desktop computers. Such devices are being developed by major American electronics firms. The nonvolatility of GMR memory elements is an improvement over current widely used semiconductor memories, which have to be continually refreshed.

An important criterion in evaluating the potential of MRAMs is their switching or write time, their ability to change magnetic state and resistance, and thereby record the 1's and 0's of binary computer code. Equally important is the MRAM's sense or read time. The read operation is similar to that of a disk-drive read head. A fast field pulse is applied. If a sense pulse is observed, the bit is in the 1 state; if not, the bit is in the 0 state.

Using a high speed test structure developed and fabricated at NIST, Stephen Russek and graduate student Shehzaad Kaka of the Electromagnetic Technology Division have demonstrated just how well these giant magnetoresistive films might perform as MRAMs. They measured sub-half-nanosecond operation of GMR devices made at NIST, which is fast enough for future computer memory applications.

The GMR films were composed of two magnetic layers. The thickness of one magnetic layer was 3 nm; the thickness of the other layer was 6 nm. These layers were separated by a non-magnetic spacer layer. In operation, the thinner layer switches at a smaller magnetic field than the thicker layer, allowing the device to change from a parallel to antiparallel to parallel state as the magnetic field from the write line is increased. The change in the overall structure's resistance with magnetic state is as high as 8 percent, a "giant" change compared with ordinary magnetoresistive materials.

Russek and Kaka patterned the films to form devices with line widths of less than a micrometer (between 0.4 μm and 0.8 μm). The development of the test structure, funded by the Defense Advanced Research Projects Agency (DARPA), will allow companies to accurately measure the high-speed performance of their own devices.

The test structure uses microwave transmission lines to sense and write to the sub-micrometer GMR devices. Writing occurs because the current pulses flowing in the transmission lines produce magnetic fields. The devices were written to and sensed using pulses with widths of less than half of a nanosecond (0.46 ns). Sense pulses from the devices were recorded and showed switching times that ranged from 0.3 ns to 0.5 ns.

Russek and Kaka showed that the switching fields increase linearly with the reciprocal of the pulse width: if pulse widths are short, larger fields are required to switch the magnetic state. They also discovered that a minimum in MRAM power consumption occurs at operation speeds near 0.5 ns.

First Set of Magnetic Tunnel Junction Multilayers on 25 μm Polyimide Film

Another type of magnetoresistive sensor is the magnetic tunnel junction in which electrons can jump across insulating spacers depending on the magnetization of magnetic layers. Stephen Russek has fabricated a working set of magnetic tunnel junction imaging arrays for NASA for the nondestructive evaluation of space and aircraft components. Several of Russek's arrays will be integrated into complete imaging test systems. Russek also made the first set of magnetic tunnel junction multilayers on free-standing 25 μm polyimide film. The specimens showed good magnetic response and will soon be patterned to form imaging arrays. Imaging arrays on flexible substrates will be used to visualize flaws in geometrically complicated parts that are not amenable to imaging with planar arrays.

2.2 Pushing Magnetic Data Storage to the Limit

Since 1990, the density of magnetic recording bits in hard disk drives has increased at a compounded annual rate of 60 percent. The cost of mass storage to the consumer has dropped from seven dollars per million bytes in 1990 to three cents today. Modern disk drives now have capacities of several billion bytes. While storage densities have been increasing, so have data rates, at a 40 percent compounded annual rate. Current data rates of 200 MHz will be as high as 1 GHz in five years. These advances in technology are being driven by exponentially increasing demands for the storage and retrieval of multimedia information.

Magnetic bits are written with inductive heads in which current pulses passing through lithographed coils switch the magnetization of a thin, high permeability film in the head. Like a tiny electromagnet, the head, in turn, switches the magnetization of small areas on disk or tape-recording media, thereby recording the binary bit transitions that make up bytes and files. High speed data recording of the near future will require magnetization to switch in times less than one billionth of a second. (A nanosecond is how long it takes light to travel a distance of 30 centimeters.)

Working with the National Storage Industry Consortium (NSIC) in its Extremely High Density Recording project, Thomas Silva, Nicholas Rizzo, Thomas Crawford, and Anthony Kos of EEEL's Electromagnetic Technology Division are addressing questions like: How fast can recording heads write data? How fast can recording media store information? What are the limits to magnetic recording density? The outcome of the NIST research has been the development of several world-class measurement tools and techniques, examples of which follow. The answers could affect an industry with world-wide annual sales of $35 billion.

"Your experiments on very fast switching in magnetic films ... are well designed and incisive. [They are] exactly the right kind of experiments that should be done at an institution like NIST. It advances the science of metrology, and requires facilities, both human and economic, which will coexist in no other kind of institution."

Robert L. White
Director
Center for Research on Information Storage Materials
Stanford University

Magnetic Precession Turns Heads

When magnetic films in heads switch, the process is not direct. Like a child's top, the individual magnetic vectors in a film undergo gyroscopic precession, which impedes fast switching. Thomas Crawford and Thomas Silva have demonstrated proof of magnetic precession as it occurs when thin Ni-Fe films of the type used in recording heads are rapidly switched.

Crawford and Silva were able to coherently control the precessional dynamics by applying two field pulses with an adjustable delay between them on the order of one half ns. The field pulses were generated by current pulses in microwave coplanar waveguides, much as currents generate fields in actual recording heads. The technique uses destructive interference to cancel the two resulting out-of-phase magnetization precessions. Underdamped precessional ringing normally present in thin Ni-Fe converts to critical damping and fast switching. These results have generated great interest among recording-industry leaders, who were concerned that precessional effects could result in deleterious nonlinear transition shifts in disk drive systems.

Team Detects Rotation Times of 200 Picoseconds for 60 degree Rotations

Optical and inductive techniques developed at NIST and the University of Colorado make it possible to measure sub-nanosecond magnetic rotation times in recording head materials. The optical sampling technique known as the second-harmonic magneto-optic Kerr effect (SHMOKE) has measured switching speeds of 300 picoseconds in 50 nm-thick thin film Ni-Fe driven with pulsed magnetic fields. The inductive method, which uses coplanar waveguides, larger field pulses, and samples with larger anisotropy, detected rotation times of 200 picoseconds for 60 degree rotations — five times faster than any previously measured rotation speeds. These measurements of magnetic rotation times in thin film Ni-Fe have unprecedented temporal, spatial, and dynamic resolution.

Characterizing Switching Speed of High Coercivity Media

High coercivity magnetic media may soon present fundamental limits to further increases in areal recording density. As the rise times of head fields decrease below 10 ns, the switching speed of the media may greatly affect the time and field required to write bits. In response to this concern, Nicholas Rizzo, Thomas Silva, and Anthony Kos have developed two experimental techniques to characterize the switching speed of high coercivity media.

Using the first technique, they measure magnetic switching in media over nanosecond time scales using quantitative Kerr microscopy. The team applied nanosecond field pulses to Co-Cr-Ta media that was located over the center conductor of a coplanar waveguide. Then, they quantified the amount of magnetic reversal by measuring the remanent state at zero applied field using the Kerr microscope. They discovered that, below 10 ns, the fields required to switch media get very large due to a crossover to dynamic switching and nonuniformities in the reversal mode.

In the second technique, developed in collaboration with IBM's Almaden Research Center, pulses were again applied to media on coplanar waveguides but a scanning magnetoresistive head was used to quantify magnetic reversal rather than a Kerr microscope. The second technique allowed the team to write actual bit transitions into the media and observe the effect of the high speed pulses. High speed switching was measured as a function of bit density, revealing the effects of the bit demagnetizing fields on the reversal process.

As industry begins to push the limits of magnetic recording, the ability to measure switching speeds of magnetic media becomes important. Both of these techniques are readily transferable to industry and have already engendered interest among industry researchers. This work will serve to quantify the head fields required for high frequency recording in next-generation disk drives.

Thermal Decay of Magnetization: How Long Is Forever?

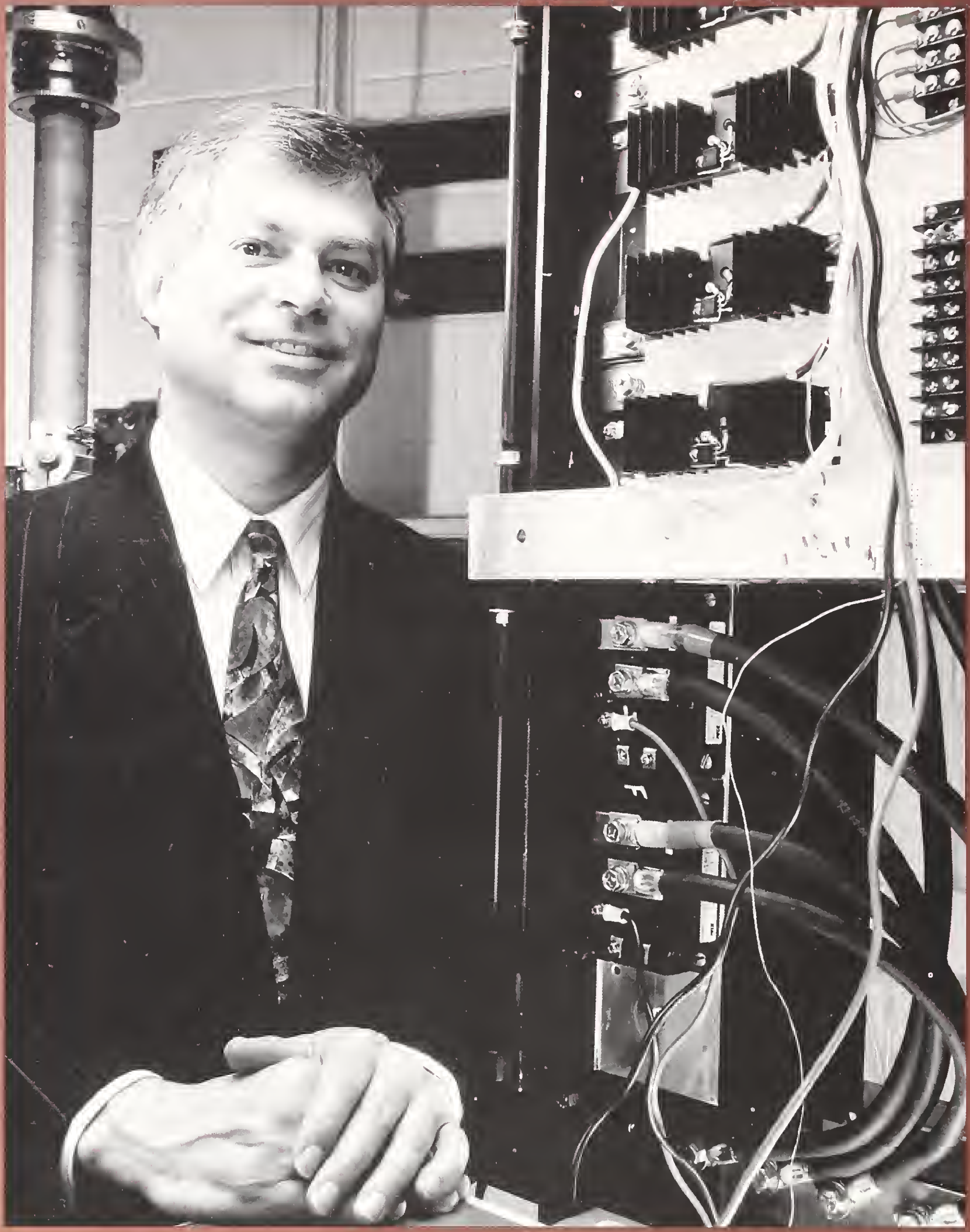
It would be disconcerting, to say the least, if data recorded on magnetic media disappeared overnight. Yet, as bits get smaller and smaller, they might approach the "superparamagnetic limit" where thermal energy is large enough to erase recorded bits. Researchers working on magnetic media often measure the thermal decay of magnetization as a function of time, a parameter called "magnetic viscosity." Typical measurements in a constant applied field often predict a large logarithmic magnetization decay, larger than is actually seen in recorded media.

Nicholas Rizzo and Thomas Silva devised a new, self-consistent technique to simulate magnetic viscosity within bit transitions. They used a vibrating sample magnetometer to measure viscosity while allowing the applied field to decay logarithmically at a rate consistent with the measured magnetization decay. The decaying applied field simulates the decaying demagnetizing field of a broadening bit transition. When the magnetic decay is measured using this technique, the value remains logarithmic in time, but is almost a factor of four smaller than that measured using a constant applied field. These results imply that the standard viscosity measurement is inappropriate when estimating the thermal stability of recorded bits.

Interlaboratory Comparison for Magnetic Thin-Film Head Metrology

The need for standard magnetic reference materials in the hard disk drive manufacturing industry prompted David Pappas, with assistance from Stephen Arnold, Nicholas Rizzo, and Ron Goldfarb, to conduct an interlaboratory comparison of measurements on magnetic thin films. The round robin was sponsored by the National Storage Industry Consortium (NSIC) as part of its *Head Metrology Requirements Roadmap* project.

Twelve laboratories participated in the study, with approximately equal representation from industry, academia, national laboratories, and instrument manufacturers. Nine different magnetic thin-film samples were fabricated at NIST and distributed to the participants. The samples included single-crystal nickel films sputter-deposited on diamond substrates and Ni-Fe films grown on silicon wafers. Measurements from four common magnetometers — induction-field, vibrating sample, SQUID, and alternating gradient force — were included. The interlaboratory comparison revealed the industry's immediate need for consensus standards consisting of Ni-Fe films on MgO substrates and, in the long term, NIST-traceable magnetic thin-film standard reference materials.



L. Goodrich – 500 A current supply used in cryogen-free measurements of superconductors. Supply can provide current waveforms with durations from 30 milliseconds (ms) to 20 seconds (s).

CHAPTER

3

SUPERCONDUCTORS

3.1 NIST Leads International Superconductor Standards Effort

International commerce proceeds most smoothly when trading partners foster agreements supported by clear, consensual standards. For this reason, most industrialized countries encourage their national laboratories and stakeholder industries to participate in the process of setting international standards.

Growing trade in superconducting wire has led to the demand for standards for superconductor measurements. Loren Goodrich and Theodore Stauffer, researchers in EEEL's Electromagnetic Technology Division, assumed leading roles on "Technical Committee 90" (TC90) of the International Electrotechnical Commission (IEC) in the creation of the first international standard on superconductivity. The standard, which was published in 1998, specifies the procedure for measuring dc critical current in multifilamentary copper/niobium-titanium wires, a subject in which Goodrich is recognized as a world-class authority.

As Chair of TC90, Goodrich oversees all of the work undertaken by Committee members. The skills required for this position extend beyond scientific authority to include tact and diplomacy, for the process of creating a standard demands the development of a consensus among all the member countries of the working group. In this case, 14 countries participated in the effort. Goodrich and Stauffer created the first draft of the standard, then addressed all of the comments and suggestions proffered over the next six years, which resulted in nine drafts of the document. In this effort, the revisions often required overcoming language barriers to provide thoughtful explanations of technical details.

The first superconductor standard for TC90, *Superconductivity: critical current measurement – DC critical current of Cu/Nb-Ti composite superconductors,* has become the template for two new critical-current measurement standards for other superconductor materials. The experience obtained from the first standard enabled these standards to move more quickly through the process. Currently, the Committee has seven additional standards at various stages of completion. These standards include several more that are focused on measurement processes and one devoted to the definition of 300 terms commonly used to discuss superconductivity.

In addition to his position as Chair, Goodrich holds many technical positions on TC90, including responsibility for managing the United States Technical Advisory Group (TAG). Representatives from American industries, universities, and national laboratories use this mechanism to provide input to the standards creation process. Assisted by Stauffer, Goodrich informs the U.S. TAG regarding all TC90 activities, encouraging their involvement and support. As the Manager of this Group, it is appropriate for Goodrich to represent American interests in the process; however when acting as Chair, Goodrich properly assigns a Chief Delegate to articulate the positions of the U.S. TAG.

> "As a member of the German National Committee and a member of several TC90/Working Groups, I would like to thank you for your activities as chairman and for your excellent supervision of the meetings and discussions. I would also like to express my thanks for your persistent effort and encouragement to find solutions and agreements during the working group meetings. I am looking forward to our future joint efforts."
>
> Dr. Manfred Thoener
> German Chief Delegate to TC 90
> Vacuumschmelze

First published international superconductor standard.

Guiding Principles for IEC's TC90

- TC90's goals are to facilitate communication, eliminate trade barriers, ensure fairness, and lower the cost of testing.
- Global participation, especially by industry, in every stage of the standards development process increases the degree to which these goals are achieved.
- The wide differences in funding and staffing support provided by industries and nations in a particular standards effort must be resolved in ways that are both constructive and timely.
- Standards should focus only on those parameters that must be specified for the subject products or applications.
- Those conditions under which the applications are fabricated and operated should define the conditions under which the parameters are measured.
- Measurement standards shall not be ambiguous.
- The scope of each standard should be as broad as possible (to include as many products as possible) without compromising the uncertainty of the standard.
- Significant changes to a document in the development process could lead to a standard that is not founded on an interlaboratory comparison.
- The scope of a standard, and the balance between measurement uncertainty and the cost of measurement, are largely determined by the interlaboratory comparison.

Evolution of Measurement Standards for Superconductors

The need for a measurement standard for purposes of trade is often unrealized until two or more laboratories conduct an interlaboratory comparison or "round robin." If the results of such a comparison indicate an unacceptable variance, it is reasonable to infer that the typical laboratory practice for the measurement(s) may be inadequate. More detailed measurement procedures are then established to reduce the variance to acceptable levels – and thence come standards.

The history of domestic and international interlaboratory comparisons of measurements on superconductors continues to indicate that careful measurement methods are needed to obtain consistent results. In some instances, variances have actually ranged from 20 to 50 percent because the measurements are so difficult to perform. Of even more concern is the realization that often there is no available means for practitioners to determine that the measurements are erroneous. Such inconsistencies can lead to many problems, including a tendency to mistrust the results of others, improper claims that stimulate unfair advantage in commerce, and erroneous feedback to manufacturers engaged in the effort to optimize the performance of their conductors.

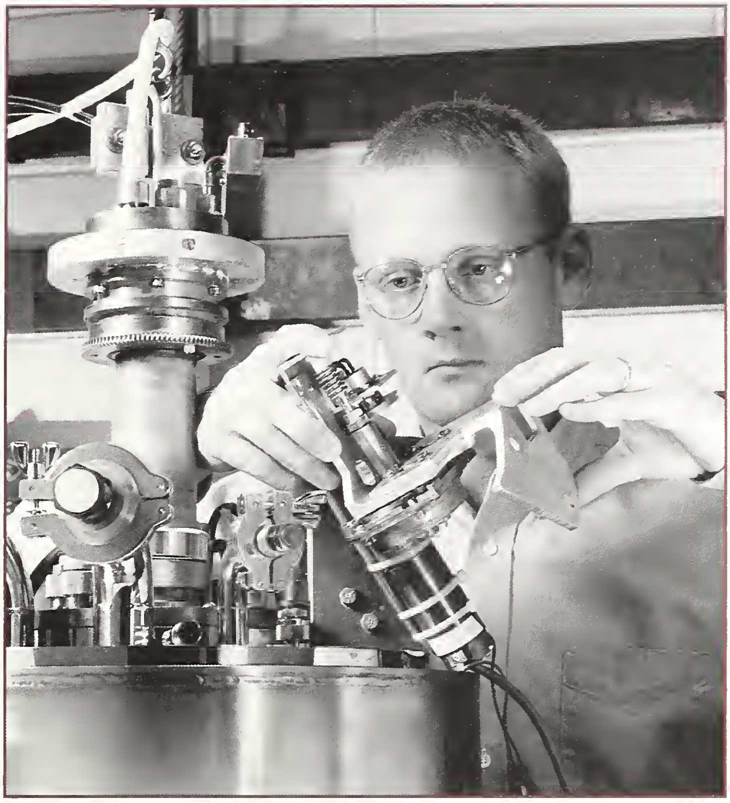
> "This ... work associated with the establishment of international standards for HTS is crucial to the success of the American superconductor industry in a world market where standards efforts are dominated by well-funded European and Japanese participants."
>
> Dr. Alexis Malozemoff
> Chief Technical Officer
> American Superconductor Corporation

Given its mission, NIST plays key roles in many domestic and international interlaboratory comparisons. This experience, coupled with NIST's expertise in metrological research, forms the basis for the critical role NIST plays in the creation of international measurement standards.

Paving the Way for New Types of Standards

At present, superconductor standard measurements that require large transport currents through the sample are done with the sample immersed in a liquid cryogen, such as liquid nitrogen or liquid helium. The liquid cryogen provides the necessary cooling and isothermal conditions for the sample and the apparatus. Stringent control is required because the performance of a superconductor is strongly influenced by its temperature. However, a number of new cryogen-free superconductor applications are being designed to operate in a gas or vacuum environment, rather than in a liquid cryogen. In fact, the operating temperature of these applications often cannot be achieved in a liquid cryogen. Thus, new techniques must be developed to enable precise measurements under these untried conditions. Both Goodrich and Stauffer believe that cryogen-free measurements will become the foundation of the next generation of standards.

Their experience thus far indicates that cryogen-free measurements are much more difficult to perform because precise temperature control is essential as is controlling power dissipation in the conductor during the measurement. Another hurdle to be overcome is the need for custom equipment. Although commercial variable-temperature cryostats are well suited for many low-current, low-power superconductor measurements, they are not adequate for high-current applications. Cryogen-free measurements tend to require custom cryostats and current



T. Stauffer – Preparing for variable-angle cryogen-free critical current measurement.

supplies. Goodrich and Stauffer have designed and built a custom current supply that can provide current waveforms with various durations from 30 ms to 20 s. This range of durations allows for control and detection of sample heating effects. To date, this system has been used to make cryogen-free measurements with currents up to 500 A.

N.M. Oldham – Using an internet-based teleconference to describe test procedures to other laboratories involved in an international comparison of electrical quantities. A digital video camera is used to show the preferred wiring connections for the comparison. Control software and test data are transferred electronically.

CHAPTER 4

LOW FREQUENCY

4.1 First, Viable, Internet-Based, Interactive Test Service Demonstrated

Multifunction calibrators are used to test and verify the accuracy of digital multimeters (DMMs) that are used in a wide variety of industrial applications. In many cases, these calibrators require traceability to nationally and internationally accepted electrical standards. Like DMMs, calibrators operate over a wide range of ac and dc voltage, current, and resistance, and it is virtually impossible to test all available output signals. In the past, several approaches have been devised to test these instruments reliably and efficiently.

One approach is to calibrate them using a few electrical-standard artifacts and rely on 'self-calibration' software in the calibrator to compensate for errors over the entire operating range. Another approach is to calibrate as many points as possible (more than 200) using standard artifacts (zener references, resistors, and thermal converters), and then interpolate between points to estimate uncertainties over the operating range. Most users are more comfortable with the second method but, even with semi-automated systems, it can take a skilled technician up to a week to complete such a test. A third approach, one that is gaining popularity, is to use a transportable DMM which has been characterized using an artifact-calibrated calibrator or 'reference calibrator' maintained at a national laboratory or an accredited standards laboratory. This approach frees most laboratories from laborious artifact calibrations; only those few laboratories with the time and resources need to perform these additional procedures. Traceability is provided through a test report for the transportable DMM.

A new service is evolving at NIST that offers significant value-added benefits to the latter approach. Most significant of these is that a customer's calibrator can be monitored by NIST staff as the test is performed at the customer's site. The new service will employ the Internet to expand present capabilities, making the process not only more efficient and less time consuming but also more collaborative. A customer-owned DMM will be tested using the customer's test calibrator, shipped to NIST where it will be tested using a NIST reference calibrator, and returned to the customer for follow-up tests. An interactive Internet link between NIST and its customers will be established to improve communications, enable rapid transfer of test data, and allow the customer to download test protocols and software for system evaluation.

> SIMnet is a "seed of real hemispheric integration. This is, in fact, a pioneering experiment [that] will set the standard of global acceptance of the Internet as a vehicle for real-time measurements. Through the use of the Internet, distances between national metrology laboratories will become irrelevant."
>
> Sitoo Mukerji
> Director, Office of Science and Technology
> Organization of American States

With both audio and video-capability, NIST will be able to provide real-time consultation and assist with troubleshooting during the test. The customer's 'before' and 'after' data will be sent electronically to NIST where the data analysis will be performed. Once completed, a password-accessible report (that expresses the test calibrator errors and uncertainties in terms of the NIST reference calibrator) may be posted on a NIST web site. In addition, an interactive database of test systems with historical data and instrument modeling should make it possible to predict performance (based on periodic comparisons between the customer's calibrator and DMM), to increase or extend the calibration interval, and to update the test report. If successful, this approach could be applied to many other areas of measurements at NIST and throughout the metrology community.

The development of this Internet-based test service is sponsored and partially funded by the National Advanced Manufacturing Testbed (NAMT) program of the Manufacturing Engineering Laboratory at NIST (www.mel.nist.gov/namt/). To ensure that it addresses the metrology needs of American industry, the program is being conducted in collaboration with a number of industrial and government partners. The work is also closely tied to the Interamerican Metrology System Network (SIMnet), a new program to use the Internet to enhance international comparisons of units within this hemisphere.

4.2 System Defines Four Terminal-Pair Capacitance and Dissipation Factor

Along with the availability of accurate, reasonably priced LCR meters and multi-impedance meters, there comes a demand from the instrument manufacturers for NIST-traceable calibration services to establish and verify the quality and caliber of their products. Ironically, at present,

A.D. Koffman - Using a low-frequency capacitance bridge and a high-frequency network analyzer to measure impedance model components, which are used to predict four terminal-pair (4TP) capacitance and dissipation factor at frequencies from 1 kHz to 10 MHz.

one of the best sources for such calibration services is an American instrument manufacturer; however, its competitors do not wish to avail themselves of the service from this source. Understandably, their preference is to rely upon NIST and other established standards laboratories for the tests that they require.

In response to this need, NIST researchers Andrew Koffman, Bryan Waltrip, and Nile Oldham, with the assistance of guest researcher Svetlana Avramov-Zamurovic, have developed the capability to characterize capacitance and dissipation factor for four terminal-pair capacitors at frequencies up to 10 MHz. Their technique is based on earlier work at NIST (then the National Bureau of Standards, NBS) in the period from 1960 to 1980 and more recent developments at Hewlett-Packard Japan, and requires network analyzer single-port impedance measurements at frequencies from 40 MHz to 200 MHz and precision capacitance measurements at 1 kHz.

A mathematical extrapolation algorithm is used to regress the high-frequency characterization down to 1 kHz to predict the capacitance and dissipation factor in the 1 kHz to 10 MHz range. The instrument-controlling software and the mathematical regression algorithm have already been programmed and a comprehensive uncertainty analysis is near completion. The next step will be the offering of a special test for four terminal-pair capacitors early in FY1999. At present, the team's method is only applicable to air-dielectric capacitors ranging in value from 1 pF to 1 nF. Future work will include extending the method to cover higher-valued capacitors and modifying the procedure to work for capacitors with other types of dielectrics. This work also responds to another need within EEEL's Electricity Division — the need for an accurate reference standard to support the new NIST Digital Impedance Bridge (DIB). The new DIB was designed to replace the aging Maxwell Wien Bridge, which is used to realize the unit of inductance (Henry) at NIST.

CHAPTER 5 MICROWAVES

5.1 N-WEST Addresses Standards and Measurements for Wireless Systems

1998 marked the initiation and rapid development of a new Department of Commerce effort, the National Wireless Electronic Systems Testbed (N-WEST). This project, initiated and directed by Roger Marks of the Radio-Frequency Technology Division, includes as partners NIST's Information Technology Laboratory (ITL) and the Institute for Telecommunications Sciences (ITS) from the National Telecommunications and Information Administration (NTIA).

N-WEST is an experiment. If successful, it will demonstrate how the Federal government can cooperate with industry to accelerate the development and standardization of superior wireless technology. The initial focus is on fixed broadband wireless access (BWA) technology in the millimeter-waves bands, such as the 28-31 GHz Local Multipoint Distribution Service (LMDS) auctioned to the private sector in February and March of 1998. License holders are planning to use these frequencies to deploy rooftop systems as alternatives to optical fiber for high-speed data access for businesses, with the possibility of providing high-speed Internet access to residential customers as equipment prices fall.

> N-WEST is "a very important initiative by the Commerce Department to help jump-start this industry."
>
> Andrew Kreig
> President
> Wireless Communications Association International

Marks envisions the development of a systems testbed for carrying out objective performance measurements under various system configurations. This information will enable industry standards committees to optimize their technical specifications of systems and components. N-WEST went on-line with a web site and a newsletter in April, 1998 and began distributing information and contacting BWA

R.B. Marks – Architect and Director of N-WEST.

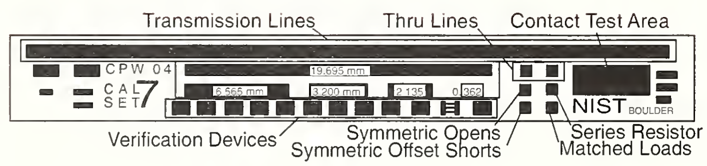
license holders as well as equipment providers. Following an industry strategy session in Boulder during July, N-WEST held a Kickoff Meeting in Colorado Springs in August that attracted 45 participants, many of them key leaders in the BWA industry. By the end of October, 1998, N-WEST had enrolled 43 supporting companies and developed plans to begin standards work within an established Institute of Electrical and Electronics Engineers (IEEE) structure. The Kickoff Meeting was held in conjunction with the IEEE- and NIST-sponsored IEEE Radio and Wireless Conference (RAWCON'98).

RAWCON'98 was chaired by Marks and brought together 300 international representatives for 90 wireless presentations. On-site press reporting of RAWCON'98 and the N-WEST Kickoff Meeting led to significant coverage. To further enhance the N-WEST support base, Marks arranged a September visit to the Canadian Government's Communications Research Centre (CRC) in Ottawa, which the CRC organized as a "Canada/U.S. Meeting on Terrestrial Broadband Wireless R&D." As a result of the meeting, the CRC encouraged Canadian companies to support N-WEST's standardization activities and endorsed the notion of cooperative efforts concerning standardization and testbed activities.

FY1999 should see the creation of both a strong BWA standards committee and an operational testbed facility. Success in the BWA field will likely lead to similar programs for other wireless telecommunications services and, perhaps, extend to wired services as the demand for innovation broadband technologies continues to explode. Additional information about this project may be found at the N-WEST web site (http://nwest.nist.gov).

5.2 World's First Coplanar Waveguide Calibration Sets Available as NIST RM

In a groundbreaking effort led by Radio-Frequency Division researcher Dylan Williams, coplanar waveguide calibration sets fabricated at NIST have become NIST's newest high-frequency Reference Material (RM), NIST RM 8130. These calibration sets give manufacturers a means of verifying the integrity of their microwave on-wafer probing stations using NIST-developed methods for measuring instrument drift, and pre-characterized NIST artifacts.



CPW calibration set diagram. Layout of NIST's Coplanar Waveguide Reference Material.

The RMs, which contain microwave circuitry designed, fabricated, and characterized at NIST, can be used to measure the drift of microwave on-wafer probing stations and to verify that the instrumentation is capable of repeating NIST measurements. The integrity of the test instrumentation and setup is also validated using the RMs. For example, the test procedure identifies unsound connections and other common instrument problems. NIST developed the verification sets with the help of the NIST Monolithic Microwave Integrated Circuit (MMIC) Industrial Consortium. Each RM contains a thru-reflect-line (TRL) calibration set and 12 test structures characterized at NIST. Additional information on this new reference material is available on NIST's High-Speed Microelectronics Project web site (http://www.boulder.nist.gov/micro/).

5.3 New Robust Calibration Technique for Microwave Network Analysis

Vector network analyzers (VNA) have become essential laboratory and factory tools for measuring the performance of radio-frequency electronics devices and circuits for both development and manufacturing. These complex instruments also require very high maintenance, such as daily calibrations, which are often performed using the standards and methods provided by the instrument manufacturers. Given the difficulties inherent in the calibration of these instruments, NIST researchers Roger Marks and Jeffrey Jargon conducted a study that resulted in a substantial contribution to the basic understanding of how network analyzers should be calibrated.

> We at Anritsu greatly appreciate the work you have done...I especially appreciated the paper *Formulations of the Basic Vector Network Analyzer Error Model including Switch Terms* by Dr. Marks. These provided me with some insight as to how I was correcting for the transfer switch. They also shed some light on our VNA hardware. Thank you for your contributions.
>
> Gary Chock
> Program Manager
> Anritsu Company

Initially, Marks formulated a basic vector network analyzer error model and discovered significant limitations inherent in the calibrations implemented in commercial instruments. His findings were published in the Automated RF Techniques Group (ARFTG) Conference Digest (December 1997) under the title *Formulations of the Basic Vector Network Analyzer Error Model including Switch Terms.* Marks and Jargon then quantified the errors in conventional methods by comparing them to a NIST reference calibration. This enabled them to demonstrate how users of high-end vector network analyzers were not achieving the total potential accuracy of their instruments using lumped-element calibrations such as SOLT (short-open-load-thru).

J.A. Jargon – Calibration of a commercial vector network analyzer using the NIST ROBUST SOLT technique.

As a result of their findings, the researchers introduced a new Robust SOLT calibration that provided demonstrably improved accuracy over existing lumped-element methods. This method was published in the 1998 IEEE MTT-S International Microwave Symposium Digest under the title *Accuracy Of Lumped-Element Calibrations For Four-Sampler Vector Network Analyzers.* With Robust SOLT, users of four-sampler vector network analyzers are able to make measurements with higher accuracy in the same amount of time required to use SOLT and without incurring additional hardware costs. Another benefit directly stemming from the new method is that users can calibrate their instruments with fewer standards and still attain the same level of accuracy available with earlier methods.

5.4 Noise-Temperature Measurements on a Wafer or Substrate

The characterization of noise properties of devices residing on a wafer or substrate is an essential ingredient in the design and testing of components that are used in virtually all modern electronic systems, including but not limited to communications systems, home entertainment systems, radar systems, and testing and measurement systems. However, although on-wafer noise measurements are commonly performed in industry, the data obtained are not traceable to any national laboratory, nor is there a process to assure industry compatibility for these measurements.

To address this problem, researchers from the Radio-Frequency Technology Division have been developing the means and methods needed to conduct a study of on-wafer noise measurements and are evaluating approaches that will best support industry needs. The project, led by researcher James Randa, is a cooperative effort between NIST staff, including David Walker, Robert Billinger, and Larry Dunleavy, a former guest researcher from the University of South Florida. To date, the team has successfully completed and verified the theoretical framework and the experimental methods for performing accurate measurements of the noise temperature of a one-port noise source on a wafer or a substrate at microwave frequencies. (Noise temperature is a measure of the noise power available from a given source.) Noise temperatures ranging from about 160 K to 7600 K were produced on a wafer and measured with an uncertainty of about 1.1 percent.

In the past year, the combined effort of the team resulted in the design, fabrication, measurement, and characterization of three prototype on-wafer noise sources. The sources use substrate structures and biasing circuitry provided by members of the NIST Industrial MMIC Consortium. The sources exhibit approximately constant noise temperatures, ranging from about 1000 K to about 10,000 K respectively. The reflection coefficients are acceptably small ($\pm$ 0.12) across the frequency range measured (8 to 12 GHz). Some design improvements have been identified for the next generation of noise sources. When the sources are proven satisfactory, they will be used in a round robin with industry.

5.5 First Systematic Uncertainty Procedure for All RCS Measurement Ranges

NIST is providing organizational leadership, technical guidance, and measurement support in a joint government-industry effort to develop a national program to standardize and improve the accuracy of radar cross section (RCS) measurement and calibration procedures. The effort involves devising standard calibration artifacts, determining their measurement uncertainties, and developing a national range-certification process. In order to do this, researchers from the Radio-Frequency Technology Division have been working closely with the RCS community to improve the quality and reliability of RCS measurements for the aerospace industry and government laboratories, and to sustain a superior national capability in this area.

NIST's first major undertaking was to develop a systematic hierarchical uncertainty procedure for identifying

"It is widely recognized that our national measurement capability needs to be strengthened and improved. I wholly support the goals of the RCS Range Certification Project that will establish sustainable and reasonable quality standards and practices for all ranges supporting our nation's investments in low observable technology. It pleases me greatly to see our organizations cooperating so well on these important topics."

Richard R. Paul
Major General, USAF
Commander, AFRL, WPAFB

and quantifying all components of uncertainty for both static and dynamic RCS measurements for any RCS range. After several years of close collaboration with the participating facilities, the theoretical analysis developed by researchers Lorant Muth and Ronald Wittman has led to numerous experiments on RCS ranges and the accumulation of a large collection of data with which to assess RCS measurement uncertainties.

Muth and Wittman have also collaborated with Air Force Research Laboratory (AFRL) scientists at Wright Patterson Air Force Base (WPAFB) to develop a new dual-cylinder single-channel monostatic calibration procedure. A family of four standard cylinders with accurately computed radar cross sections is used to efficiently assess calibration errors at different measurement ranges. In a companion effort, results from various ranges are compared in an ongoing interlaboratory comparison program to assess the overall national capability.

To improve polarimetric calibrations, NIST scientists have also developed a calibration procedure that uses a standard dihedral target rotating about the line-of-sight from the radar to the target. The new measurement and data analysis techniques increase the signal-to-noise and signal-to-clutter ratios, and provide the cross-polarization parameters of the radar system. Researchers have found the data analysis technique especially useful in improving the accuracy of radar cross section measurements on low observable targets; the technique is being tested on data provided by various Department of Defense measurement ranges.

Also, a *Handbook for the Assurance of Radar Cross Section Measurements*, based on the ANSI / NCSL Z540-1 standards document, has been submitted for review to the National Conference of Standards Laboratories. It is expected that the handbook will be adopted by the radar cross section community as the industry standard and, thus, form the basis of a national certification program to be implemented by NIST and an RCS Certification Board.

5.6 Five Improved Techniques Support Industry's Needs to Measure PWBs

Printed wiring circuit boards (PWBs) and substrates, which consist of laminar sheets of low-loss polymer or ceramic dielectric sandwiched between thin copper conductors, are widely used throughout the electronics communications industry. In response to a trend toward higher operating frequencies in both computer and wireless applications, the electronic materials industry is developing new low-cost dielectrics capable of efficiently operating at these frequencies. Researchers James Baker-Jarvis, Michael Janezic, and Bill Riddle of the Radio-Frequency Technology Division are supporting such efforts by developing quick, practical, low-cost, nondestructive techniques for accurately measuring the complex permittivity ($\varepsilon' - j\varepsilon''$) properties of PWB materials.

"On behalf of GE Plastics and the GE Corporate Research and Development (CRD) Center, I would like to thank you for providing an invaluable service in the dielectric characterization of our printed circuit board materials and plastics. The two techniques that you recommended (split post resonator and reentrant cavity method) were implemented at GE CRD and have given us a highly accurate method of characterizing a wide variety of GE materials… ."

Vikram Krishnamurthy
Electrical Engineer
Electronic Technologies Laboratory
GE Corporate Research and Development Center

PWB dielectrics typically consist of laminated layers of a polymer-coated fiberglass weave that exhibit anisotropic dielectric properties; that is to say, the relative permittivity value is different in the plane of the board and normal to it. Most RF designers require data on the normal component of permittivity. However, up to now, existing measurement techniques were unable to provide these data. For example, the widely used standardized test method (IPC-TM-650), which uses a stripline resonator pattern card, cannot resolve the anisotropic properties of such boards — IPC-TM-650 only measures an effective permittivity value.

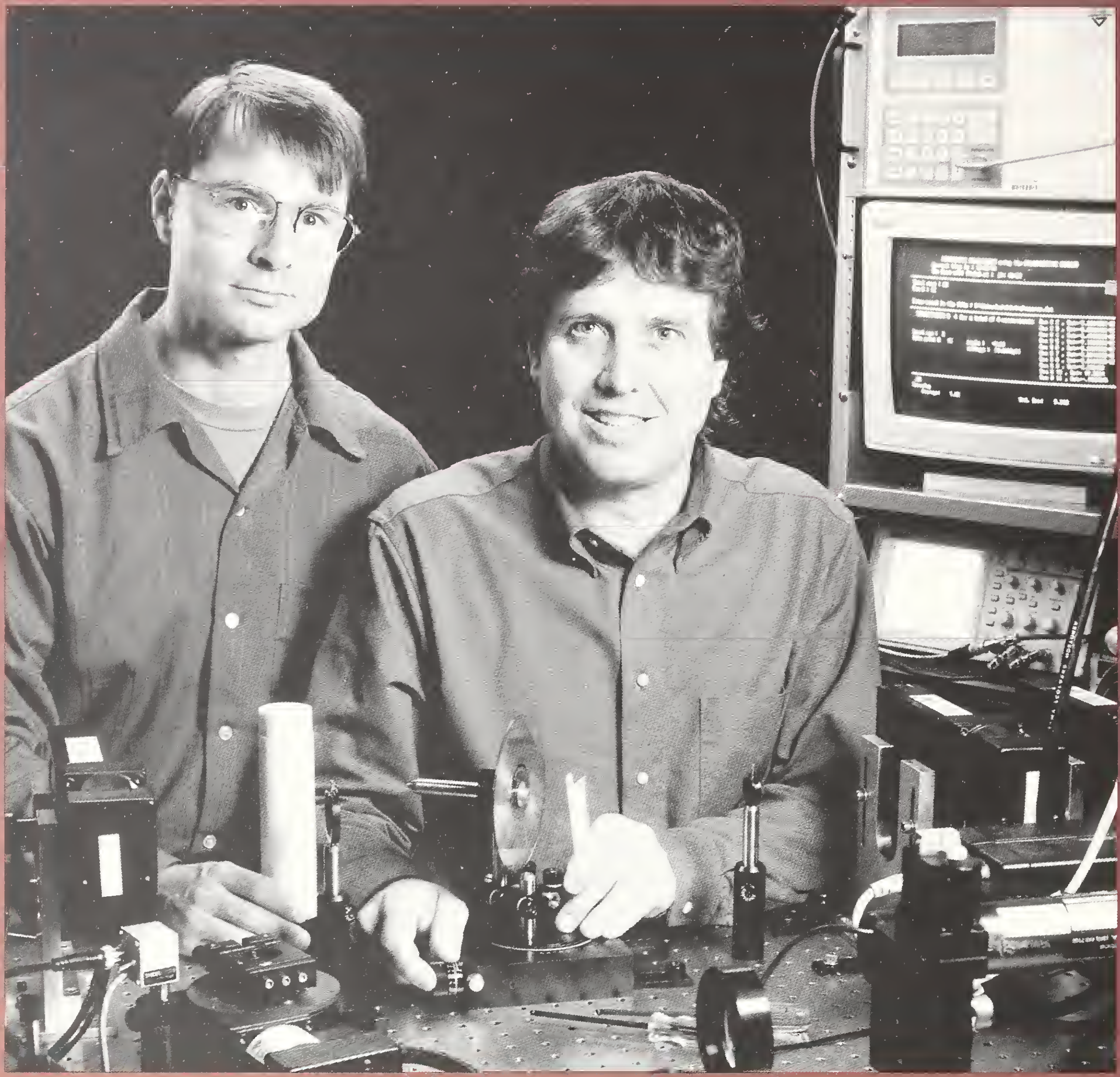
In the past year, EEEL researchers have improved two measurement techniques — the coaxial re-entrant cavity technique and the full-sheet resonance (FSR) technique — which do measure the normal component of permittivity. Baker-Jarvis and Riddle developed an improved mode-matched field solution for the re-entrant cavity geometry that is described in NIST Tech Note 1384. This work resulted in a reduction in measurement uncertainties to ±2% in ε' and ±0.001 in ε''. Further work is planned to support additional fixtures with fundamental resonances of 150, 500 and 1000 MHz respectively, one of which will be used to perform high-temperature measurements.

In the course of their study of the FSR technique, the researchers investigated air-gap errors and compared the NIST measurement data with data derived from equivalent measurements performed in industry. The FSR technique, because of its nondestructive nature, is widely used in industry for measuring ε'; however, it is also used to measure ε'', although it cannot do this with desirable accuracy.

Three other techniques that the researchers focused on are quasi-nondestructive in nature. Each requires the removal of the copper sheets bonded to the PWB conductor. All three yield much better accuracies (±0.5% in ε', ±0.0002 in ε'') but have the disadvantage of only being able to measure the component of permittivity in the plane of the board.

Two techniques, the split-cylinder (Kent) cavity and the split-post resonator, work well for materials known to be isotropic. Rigorous mode-matched field solutions are being developed for these geometries that will yield more accurate data than the approximate solutions proposed by the commercial suppliers of measurement fixtures.

The third technique under study is a semi-confocal Fabry-Perot free-field resonator that is capable of characterizing PWBs at millimeter wavelengths. The team has developed and fabricated such a fixture for operation at 60 GHz (5 millimeter wavelength). Low cost, light-weight compact microelectronics technology is characterized by conductors and devices that are embedded in material structures. The electromagnetic properties of the materials, therefore, are critical to the performance of the end product. The broad range of this and other electromagnetic materials-properties measurement capabilities in the Division's program provide a national resource for advancing modern radio-frequency technology.



CHAPTER

6

(Left to right) S.T. Kreger, K.B. Rochford – Aligning an optical disc (CD) for a birefringence measurement to determine the effect on the optical readout of the disk.

OPTOELECTRONICS

6.1 Optical Disc Birefringence Round Robin Demonstrates Need for Measurement Standards

Optical discs (CDs) are currently the most popular format for music and software distribution and the new higher-density formats (DVDs) are now poised to displace prerecorded videotape. Over the last decade, the pressure to reduce the manufacturing costs of replicated optical discs has led to significant decreases in manufacturing time. Shorter stamping times, in turn, have greatly increased the need for dependable process controls and accurate disc-testing equipment to monitor the manufacturing process and ensure disc quality. To confirm the challenges facing disc manufacturers, Kent Rochford of the Optoelectronics Division, working with replicators and test equipment manufacturers through the Optical Disc Manufacturing Association, coordinated a round robin study to quantify measurement variations within the industry.

Birefringence, or retardance, is an optical property influenced by the replication process that can significantly affect the light beam that is used to read the disc. Birefringence makes the propagation of light dependent on the incident polarization state, and can redirect the beam and enlarge the focused spot so that data readout from the optical disc is degraded. If not held within acceptable levels, birefringence can affect disc playability. Retardance measurements of 20 discs were made by seven round robin participants using a variety of commercial instruments; NIST also conducted measurements on a sample of the discs using an apparatus developed in the Laboratory for this purpose. Considerable variation was observed, even between repeated measurements by the same commercial instrument. The observed measurement variations were large enough to result in the rejection of discs that actually met specification.

Though a large part of this variation was initially attributed to real changes in the measured retardance, additional work at NIST indicated that less than half of the variation could be reasonably attributed to changes in disc temperature, measurement angle, or measurement position. For example, it is difficult to control temperature in a manufacturing environment so the range of temperatures over which discs were measured was considered a major source of variation. NIST measurements showed, however, that the rate of temperature change is much more important than the equilibrium measurement temperature; since round robin measurements were made at thermal equilibrium, temperature was a small source of measurement variation.

From *Metrology for Optoelectronics, An OIDA Workshop Report*, October 1998:
"As a non-commercial organization, with unparalleled technical expertise in its laboratories, NIST has established worldwide recognition and respect in Optoelectronics."

Arpad Bergh
President
Optoelectronics Industry Development Association

To support this effort, Rochford and postdoctoral researcher Stephen Kreger have developed several methods for accurately measuring disc retardance and are working with test equipment manufacturers to develop improved calibration artifacts. This effort is intended to lead to the development of new standard measurement methods and a Standard Reference Material for optical disc birefringence.

6.2 Periodically Poled Lithium Niobate Devices Enable Optical Frequency Chains

Periodically poled lithium niobate (PPLN) devices provide a compact means to generate a wide range of optical frequencies at usable power levels that are, in many instances, impossible to achieve by other methods.

J.A. Aust – Fabricating periodically poled lithium niobate for frequency conversion applications.

J. Andrew Aust, Norman Sanford, and graduate student Jeffrey Mitchell have fabricated and characterized PPLN devices for several NIST projects. Among their collaborators are Leo Hollberg of the Physics Laboratory's Time and Frequency Division and John Hall of JILA, a joint venture of NIST and the University of Colorado. The objective of these collaborations is to synthesize laser frequencies that are linked together to form optical frequency chains and are referenced to well-characterized molecular or atomic transitions. Optical frequency chains are particularly important to NIST's development of future generation time and frequency standards. The ultimate goal of the research is to replace atomic clocks, which operate at microwave frequencies, with optical-frequency-based clocks, which are expected to have much higher accuracies. PPLN devices help achieve this goal by providing an efficient means to phase match during the optical nonlinear frequency conversion process.

PPLN devices are fabricated by applying a DC electric field through a photolithographically defined mask to create a domain grating in the crystal. These devices do not require the strict phase-matching conditions of conventional bulk nonlinear crystals since the domain grating has been engineered to keep the optical pump signals phase-matched with the associated output signal. Another significant advantage of PPLN devices over bulk nonlinear crystals is that one material system may be used to generate output wavelengths ranging from the ultraviolet to the mid-infrared, with only a change in grating period necessary. In nonlinear frequency generation the sum or difference of the optical frequencies of the pump signals determines the frequency of the output signal. With bulk nonlinear crystals only discrete sum and difference frequency generations are allowed, and the choice of the particular nonlinear interaction requires careful consideration of the crystal used, its orientation, and its temperature tuning range to determine if the interaction is even possible.

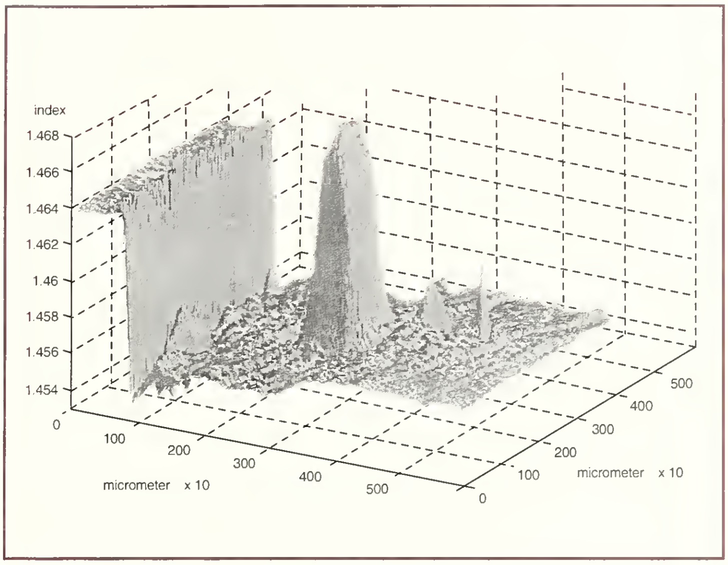
One of the projects to which Aust and Mitchell are contributing is based at JILA and includes researchers from the Primary Time and Frequency Laboratory (Paris), the Bureau International des Poids et Mesures (Sèvres), and the Lebedev Institute (Moscow). Their role in the project is to fabricate PPLN devices needed to implement a Transportable Optical Frequency Standard (TOFS), which will provide a reference in the red wavelength region (633 nm). For the TOFS Project, a PPLN device pumped with 80 milliwatts (mW) of light at 778 nm and 2 mW at 3392 nm produced approximately 0.25 microwatts of 632.8 nm output, greater than 60 times the output from a bulk lithium iodate crystal.

Aust and Sanford are correlating the nonlinear optical properties and materials science issues related to PPLN and investigating the effects of strain and poling conditions on sample quality. Optical characterizations of PPLN are also allowing for the correction of refractive index data for lithium niobate.

Another particularly fruitful collaboration involves Bruce Steiner of the Materials Science and Engineering Laboratory's Ceramics Division, who is performing high-resolution x-ray diffraction imaging of the domain structures. These studies are helpful in determining the best means to manufacture domain-engineered devices. PPLN devices are actively being pursued as a solution to industry needs in the areas of optical data storage, color displays, color printing, medicine, deep-ultraviolet photolithography, and remote chemical sensing. Within the Optoelectronics Division, the devices are being used to generate light with a tunable wavelength near 780 nm for the characterization of multimode fiber used in data communications systems.

6.3 Refracted Near-Field System Provides Unprecedented Resolution

(Left to right) N.H. Fontaine, M. Young – Adjusting the instrument for measuring the index of refraction profile in integrated optical waveguides.

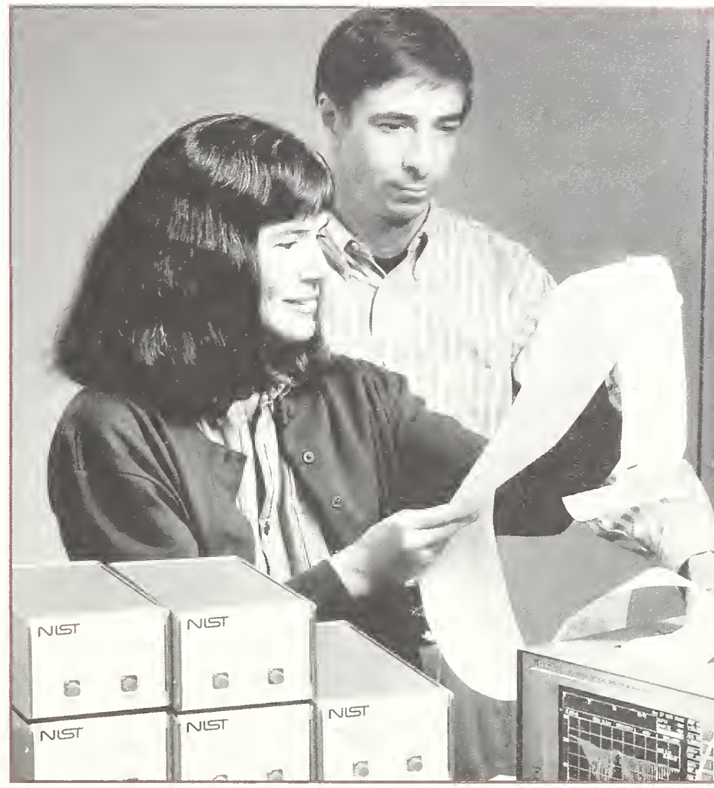


Two-dimensional refractive index profile of a buried-channel planar waveguide measured using the refracted near-field technique.

Norman Fontaine and Matt Young have built and demonstrated a refracted near-field (RNF) system that measures, with exceptional resolution the two-dimensional refractive index profile in both fiber optic and planar waveguides. The RNF technique probes a waveguide with 635 nm laser light focused to a spot on the entrance face of the guide. The waveguide is placed in contact with a material of nearly equal refractive index, allowing light to escape from the side of the guide. Measuring the amount of escaping light gives a precise measurement of the index of refraction at the focal point of the launched light. The accuracy of this technique is generally limited by the uncertainties of the calibration artifacts to about 10^{-3} to 10^{-4}. However, Fontaine is currently able to make measurements with a precision of 4.3×10^{-5}, which is about an order of magnitude better than the resolution achieved in other published RNF results.

Since the lightwave propagation in a waveguide depends on the index of refraction profile within the guide, it is important to have an accurate knowledge of the details of that profile. The RNF technique allows a waveguide manufacturer to verify that the manufacturing process yields the expected profile or to quantify the outcome of a new fabrication technique. For example, this RNF system is currently being used to measure index profiles of ion exchange waveguide structures in order to determine the diffusion coefficient of the dopant ions into the waveguide.

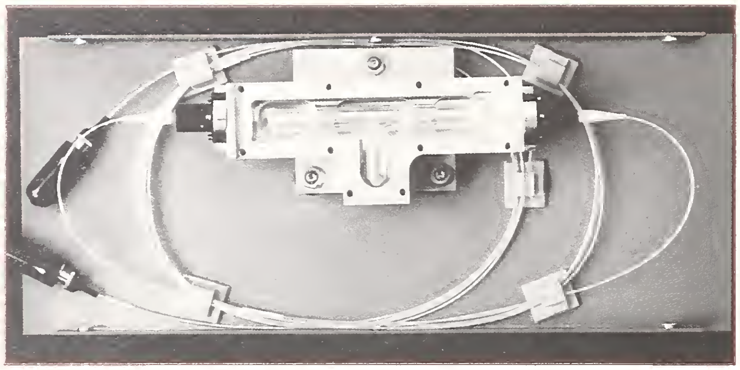
To the waveguide designer, the index profile measurement provides the propagation characteristics of the guide and allows theoretical performance to be compared to measured results. Index profile measurements facilitate accurate waveguide modeling, which in turn improves waveguide performance and manufacturing yield. For example, a particular area of interest among manufacturers is the ability to measure residual strain in the waveguide. Residual strain can affect the index profile or it can alter the polarization of the light; in either case, it will have a deleterious effect on the performance of the device. RNF measurements offer the possibility of mapping the strain-induced birefringence in the waveguide by controlling the polarization state of the input light. The NIST RNF system is currently being modified to allow these measurements as well.



(Left to right) S.L. Gilbert, W.C. Swann – Reviewing the absorption spectra data for SRM 2519 for wavelength standards for the optical communications industry.

6.4 SRMs Enable More Precise Wavelength Calibrations

Optical fiber communication systems are becoming more complex as operators try to push ever more information down the same fibers. New systems are being adopted which expand capacity by using many different wavelengths of light, rather than a single wavelength. This adds many more channels for transmitting information in the optical fiber at the same time. These wavelength division multiplexing (WDM) systems operate in the near infrared 1500 nm wavelength region with channels usually spaced by a few nanometers; channel spacings of much less than



Optical fiber-coupled gas absorption cell inside SRM 2519 for wavelength standards in the 1500 nm wavelength region.

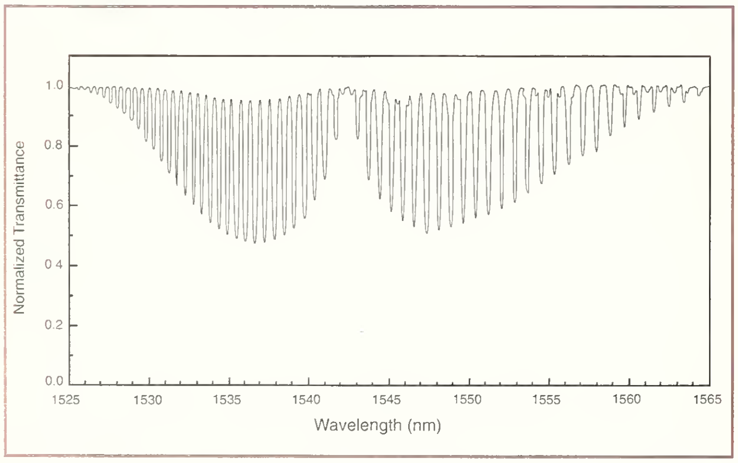
1 nm are anticipated in the future. If one channel's wavelength were to shift, crosstalk could occur between it and a neighboring channel. Thus, WDM systems set stringent requirements for accurate wavelength calibration of equipment and characterization of the wavelength dependence of the optical components used in the systems. Sarah Gilbert and William Swann of the Optoelectronics Division have developed two wavelength references for optical fiber communications.

The wavelength references are now available for purchase from NIST as Standard Reference Materials 2517 and 2519. These references can be used to calibrate optical instruments that characterize system components and measure the channels' wavelengths. This allows manufacturers to control component characteristics so that systems can transmit more information in the same wavelength region.

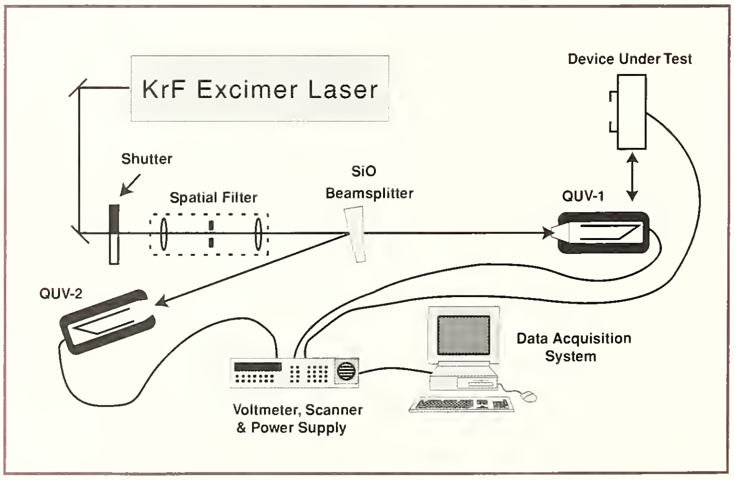
The SRMs are optical-fiber-coupled absorption cells containing a small quantity of acetylene gas (SRM 2517) or hydrogen cyanide gas (SRM 2519). A user-supplied light source can be coupled into and out of the units via optical fiber connectors. The gas molecules have distinctive absorption features in the 1500 nm wavelength region due to their quantized vibrational and rotational motion. Fundamental molecular absorption lines provide references that are very stable under changing environmental conditions and have well understood physical behavior. Acetylene has more than 50 accurately measured absorption lines in the wavelength region from 1510 nm to 1540 nm. Hydrogen cyanide has a similar number of lines in the region from 1530 nm to 1565 nm. To obtain the certified wavelength values for these SRMs, the NIST researchers measured line centers and the small pressure shift due to collisions between the molecules. As a result of these measurements, the SRMs have line centers certified to an uncertainty of 0.0006 nm.

6.5 Improved Excimer Laser Measurements for Semiconductor Lithography

NIST is developing measurement and calibration techniques for the shorter and shorter wavelengths of light needed by the semiconductor industry to fabricate smaller and smaller features in integrated circuits. Several years ago, researchers Rodney Leonhardt and David Livigni of the Optoelectronics Division developed a primary standard laser calorimeter and a calibration system for excimer laser energy measurements at 248 nm. This effort received financial support from SEMATECH, a semiconductor industry consortium. At that time, optical lithography for semiconductor manufacturing using excimer lasers was in the prototype stage. Shortly afterward, the use of 248 nm excimer lasers moved into full production and Division staff were well prepared to provide calibrations to laser energy meter manufacturers as well as end users in the industry. The total uncertainty of these calibrations has recently been reduced by a factor of two to ~ 1% in order to meet customer demands.



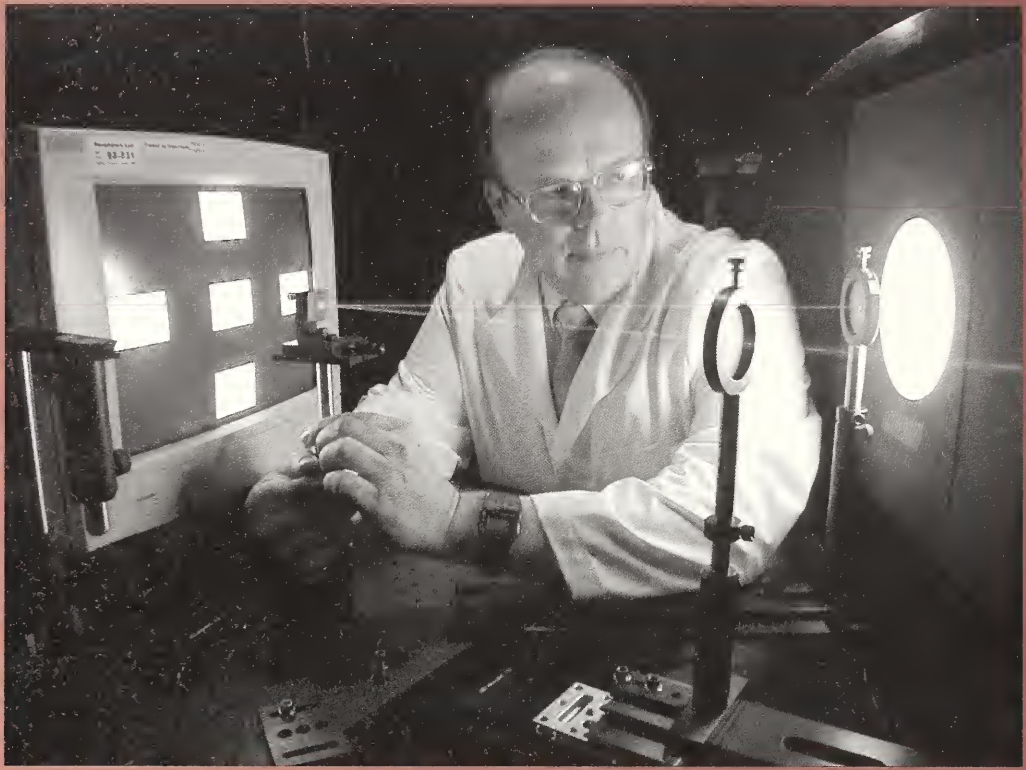
Spectrum of hydrogen cyanide SRM 2519. The center wavelength of each line has been accurately measured.



Measurement system to calibrate laser energy and power meters using KrF excimer laser operating at 248 nm.

The National Technology Roadmap for Semiconductors documents the efforts of the semiconductor industry to reduce the feature sizes of integrated circuits. This requires a shift toward even shorter laser wavelengths in the optical lithography process. Deep ultraviolet lasers, specifically ArF (193 nm) and probably F_2 (157 nm) excimer lasers, will be needed for high-resolution lithography. More advanced laser metrology is necessary for the calibration and support of these optical lithography processes and tools.

Recently, the semiconductor industry has begun prototyping photolithography systems using 193 nm excimer lasers. In response, Optoelectronics Division staff members Christopher Cromer and Marla Dowell have developed a new and unique primary standard laser calorimeter for 193 nm laser measurements that operates in vacuum or with a gas purge. This innovation is necessary because 193 nm laser radiation is absorbed by atmospheric oxygen. The effective date for the provision of calibration services based on this standard is scheduled for the first quarter of FY1999. Future directions for this work include improving the Division's capabilities for the direct calibration of energy density or "dose" meters, improving transfer standards for the dissemination of calibrations to customers with lower uncertainties than are presently offered, and the development of calibration services for instruments using 157 nm lasers.



E.F. Kelley – Using a laser to align the illumination apparatus in preparation for reflection measurements on a computer monitor.

CHAPTER 7 VIDEO

7.1 NIST Leads Development of a New Flat Panel Display Measurement Standard

Flat panel displays (FPDs) are nearly as ubiquitous as the ball-point pen. They are embedded in nearly every form of transportation, in household appliances, office equipment, even childrens' toys. According to the U.S. Display Consortium, the FPD market is projected to increase its current $11 billion revenues to $20 billion by the year 2000.

However, until recently there were no methods available to help answer the question of: "Why does one FPD look so much better than another in a well-lit room?" NIST has led the development of a new standard that helps to answer that question and many others related to FPDs. The Flat Panel Display Measurements (FPDM) Standard, version 1.0, has been published by the Video Electronic Standards Association (VESA). The standard includes measurement procedures for flat panel displays, as well as a tutorial section on photometry and colorimetry intended to help the novice gain familiarity with a difficult system of units by means of worked problems and discussions. The document also contains diagnostic procedures to help ensure that measurements are made properly. The standard provides a basis for good metrology using a wide variety of instrumentation with an emphasis on using the least expensive instruments that will achieve the desired results.

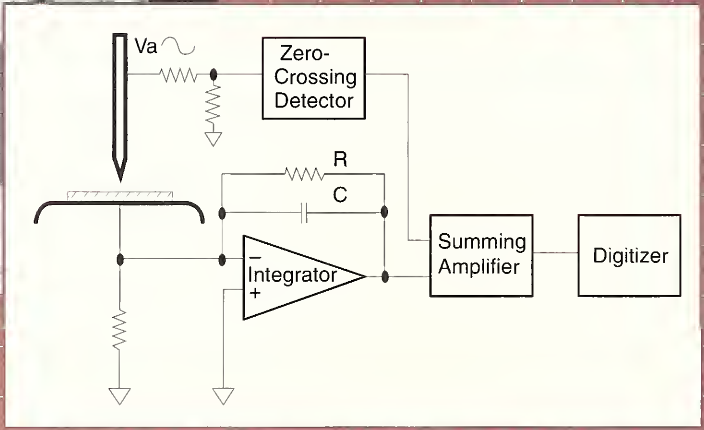
The goal of the FPDM standard is to define display metrology so that everyone around the world will measure the same things the same way. When this occurs, everyone can specify what they want and be able to verify that the end product did or did not meet their specifications. In such a commercial climate, misleading advertisements will prove to be an embarrassment rather than a success because the FPDM standard levels the playing field. Using the standard enables manufacturers of good displays to extol the virtues of their products and allows end-users to verify that the quality of the goods they received matched the specifications of the goods that they ordered.

This standard was developed under the leadership of Edward Kelley of the Electricity Division, who developed a majority of the measurement procedures included in the document. One of these procedures is a significantly improved method for measuring the contrast-ratio (CR) of a flat panel display. This technique, which was published in the May 1996 issue of *Information Display* Magazine prior to the release of the standard, has already had significant industry impact. The key to the new method is its ability to reduce the corrupting effects of "veiling-glare," which were not addressed by previous techniques. In a follow-up discussion with Kelley, Ken Werner, Editor of the magazine recently stated : "Some may even have guessed that veiling glare was the culprit, but that did not give them the tools to separate the measurement artifacts from dynamic system effects. You provided those tools, and there was a *Eureka!* effect. People read your article and said, *Yes! That's the solution.*" Four additional articles on this metrology were commissioned by Werner for the magazine. The most recent article, "The Three Components of Reflection" by E.F. Kelley, G.R. Jones, and T.A. Germer, appeared in the October 1998 issue.

"I recently received from a colleague a copy of VESA's Flat Panel Display Measurements Standard (FPDM)...I'm impressed with the quality of its content and would like to commend you for your excellent work. The display industry was very much in need of this standard – something that would level the playing field and eliminate confusion. Hopefully, the FPD manufacturers will adhere to this standard and play an honest game so that the end user may be able to compare apples to apples and oranges to oranges when it comes to marketing specifications for display devices... ."

Federico Arosemena
Electronics Engineer
Naval Air Warfare Center Training Systems Division

X. Han – High voltage partial discharge cell. Adjusting the amplifier threshold for the detection of a partial discharge pulse from a point-plane discharge cell.



NIST PD detector. The NIST PD detector takes full advantage of the tremendous processing power of currently available, fast, personal computers.

CHAPTER

8 POWER

8.1 NIST Method Permits Complete Characterization of Partial Discharge

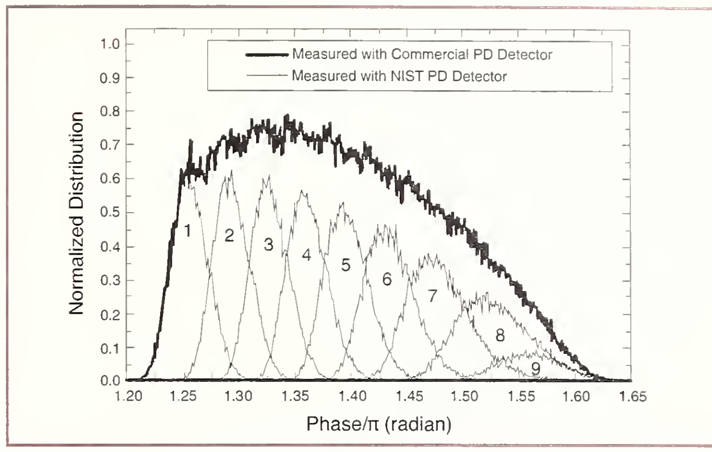
In the past few years, staff on the NIST Dielectric Research Project, including Yicheng Wang and Guest Scientist Xiaolian Han, have developed a digital-detection system for recording and characterizing pulsating partial discharge (PD). The new PD detection system can continuously record all random PD pulses above 1 pico coulomb that occur over extended periods of time, with a maximum average pulse rate exceeding 100 kHz, a minimum inter-pulse time resolution of 3 μs, and a vertical amplitude resolution of 12 bits. The system has several potential applications, including use as a diagnostic tool under ac or dc conditions, for monitoring and assessing the integrity and remaining life of electrical insulation of high-voltage apparatus, and in quality-assurance testing during the design and manufacture of high-voltage electrical components.

The system's design takes full advantage of the tremendous processing power of the currently available, fast, personal computers and the newly available, sophisticated, data-acquisition boards. NIST's new system differs from earlier designs, which detected PD pulse amplitude and time with custom-designed hardware. The new system continuously records the complete electrical waveform that carries the PD pulses and extracts, in real time, the time and amplitude information of random PD pulses in software.

Using this approach for PD detection considerably reduces the development and maintenance cost of PD detection systems and significantly increases system portability. For these reasons, this work may prove to be the crucial development needed to trigger the transfer of digital PD detection and analysis technology from the nation's laboratories to industry. At NIST, the system is being used to study PD-induced aging of dielectric materials, and the correlation between stochastic properties of PD pulses and the degree of PD-induced damage on dielectric surfaces. A copy of the new system has also been made and delivered to the Wright Laboratory, Wright Patterson Air Force Base, where it is used to study and monitor PD-induced degradation of high voltage components used in aircraft.

Partial Discharge Measurements — A Severe Metrology Challenge

Partial discharge is a localized discharge that often occurs at the defect sites of electrical insulation. These sites might be voids or cracks in solid insulation or sharp, metallic points in gas or liquid insulation. Partial discharges are much weaker than the better-known arcing discharges. In fact, the presence



NIST PD detector allows more detailed analysis of PD patterns.

of PD in high voltage (HV) equipment is often concealed because it occupies such a small volume and draws so little current that it does not affect the applied voltage. Consequently, HV equipment can pass HV "proof" tests with PD present because it will not affect the breakdown voltage. Nevertheless, PD can cause degradation of electrical insulation over time, and often is a precursor of the complete electrical breakdown of equipment.

In industry, PD tests, which are guided by national and international standards, are widely used in quality control processes. The applications cover a wide range of products large and small. In addition to HV components, examples range from the manufacture of small capacitors used in televisions to the manufacture of multi-ton generators and transformers. In recent years, the use of PD measurements as a diagnostic tool in power stations and substations to enable preventive maintenance has also increased significantly.

These measurements remain a severe metrology challenge, however, because, in general, PD is a random process. Further, a PD signal is often extremely weak, consisting of a random pulse train. The techniques employed in industry as well as those specified in national and international standards are constantly evolving though. This evolution is possible due to advancements in electronic instrumentation technologies, particularly computer-based digital technologies.

"The NIST-developed Partial Discharge (PD) Analysis System has been in continuous use by the Air Force since its delivery. The expanded capabilities of the system (compared to commercial PD Systems) have proven invaluable for ongoing investigations of corona-induced insulation degradation."

Daniel Schweickart, Project Leader
John Horwath, Electrical Engineer
Wright Laboratories

(Left to right) G.H. Koepke, J.M. Ladbury – Measuring emissions in NIST's reverberation chamber. For electromagnetic compatibility, a device must continue to operate in the presence of external signals (immunity), and must not generate signals that might interfere with other devices (emissions). The sphere, a precision radiator with known characteristics, is being used to compare the capabilities of traditional facilities for measuring emissions with reverberation chambers.

CHAPTER

9

ELECTROMAGNETIC COMPATIBILITY

9.1 EMC Research Advances Understanding of Reverberation Chamber Properties

To say that electronic devices and systems are now an integral part of "everything" is really not much of an exaggeration. Such devices and systems are critical in motor vehicles, aircraft, home appliances, health care equipment, communications, and computers to name a few. Given the relative proliferation of these systems in our homes, workplaces, hospitals, laboratories, test beds, and sources of transportation, consumer safety advocates and product reliability engineers want to understand more about the electromagnetic compatibility (EMC) among these systems and the environments in which they operate. The reason is simple: the intensity of the electromagnetic environment increases as many unrelated systems are required to operate in close proximity to others, and the likelihood of inadvertent changes to critical electrical signals increases due to the electromagnetic environment. Industry must be able to certify their electrical/electronic products for EMC compliance as required by the Federal government and established international standards.

At present, the measurement process for electronic product certification is complex, time-consuming, and costly. To be competitive, industry critically needs new, low cost, efficient methods of performing these measurements. Not only must these techniques be technically correct, they must offer reduced uncertainties. Reverberation chamber techniques, pioneered at NIST, are proving to be an efficient, cost-effective method of carrying out measurements necessary for product evaluation, for susceptibility testing, and for other applications.

At present, NIST is collaborating with the American Automobile Manufacturers Association (AAMA) to transfer improved reverberation technology to the automobile industry. Radio-Frequency Technology Division researchers John Ladbury, David Hill, and Galen Koepke have provided research and technical support to evaluate the effectiveness of reverberation techniques for automobile EMC testing. As a result of this work and knowledge gained from a recent in-depth evaluation of the new reverberation chamber facility at NASA's Langley Research Center, the team has been able to make significant contributions to the understanding of reverberation technology and to facilitate its acceptance by industry.

The research, both theoretical and experimental, led to the identification of the primary sources of error in determining the field parameters in a reverberation chamber. The error sources included antenna effects, inadequate randomization, direct coupling between the antennas, and errors in accepted formulas used to predict the fields. After analyzing the results of several billion measurements in several different reverberation chambers, new measurement and analysis techniques were developed that significantly improve measurement accuracy and reduce uncertainties.

> "I am writing to you to express General Motor's interest in the ongoing research conducted by NIST in the area of reverberation chambers. The technical information generated by this research has helped to increase the understanding of the immense capabilities of this technology, and has, more importantly, helped to inform the electromagnetic community about the benefits this technology has to offer... ."
>
> R. Nelson
> Senior Project Engineer
> General Motors Corporation
> North American Operations/EMC

It is now possible to discern effects in chamber performance on the order of less than ±1 dB, a significant reduction from earlier estimates of ±3 dB to ±6 dB or more. The success of this work raises the possibility of using the reverberation chamber for applications beyond the EMC measurements for which it was originally designed. Related studies could include radio frequency hazard probe calibrations and the evaluation of certain antenna characteristics, such as efficiency. This latest technical information has also been shared with several EMC standards committees, including the International Electrotechnical Commission (IEC), the Radio Technical Commission for Aeronautics (RTCA), and the Society of Automotive Engineers (SAE), that are actively engaged in drafting measurement requirements for reverberation techniques.

Electromagnetic Compatibility (EMC)

What is it?

Electronic systems are compatible if they can operate in their intended electromagnetic environment without suffering or causing unacceptable degradation as a result of electromagnetic interference. (Taken in part from ANSI C63.14-1992) This means that the normal ambient environment should not interfere with

Validating reverberation chamber test methodology. NIST test methodology is experimentally validated jointly by NIST and Navy engineers using a state-of-the-art test vehicle supplied by the American Automobile Manafacturers Association in a large reverberation chamber at Lindgren RF Enclosures, Chicago, Illinois.

the operation of an electronic device, and also that one electronic device should not interfere with the operation of another device.

Why is it important?

Most people associate a lack of compatibility with a noisy radio signal when their computer is on, or a distorted television picture when they are cooking with a microwave oven. These problems are annoying but not life threatening — but if the affected electronic device was not a television but a pacemaker, airbag, missile guidance system, or aircraft navigational system — interference could have disastrous consequences.

What is its impact?

American industry spends tens of billions of dollars to ensure that the problems mentioned above do not happen (yet we still have to turn off our computers on an airplane during takeoffs and landings). This expenditure is spent on research, testing, and specialized hardware that is designed to prevent interference. Due to the large uncertainties involved in evaluating the compatibility of different systems, much of this research is performed to ensure that devices will work in environments that are much more severe than will ever be observed during normal operation.

Why are EMC tests difficult and why do they have large uncertainties associated with them?

Compatibility tests are extremely sensitive to the orientation and layout of a device. Simply changing the positioning of a power cord can change test results by a factor of 10 or more (just as slightly moving an antenna to get better reception in an apartment can produce a picture that is much better). It is not possible to test a device in every possible configuration, so a test must be performed at a small number of representative positions, and then the device must be tested at levels to account for the possibility that the test was not performed in the worst configuration.

What is NIST's role in EMC?

Scientists at NIST are actively researching new measurement methods that are faster, less expensive, and more accurate than previous methods. Reverberation chambers have the potential to address all three of these requirements.

What is a reverberation chamber?

A reverberation chamber is an enclosure in which scientists can create and measure very complex electromagnetic fields that exhibit randomness in the sense that the exact properties of a specific field configuration cannot be predicted but the averages and the variability are very predictable. These chambers have various applications. The current focus is on replicating worst-case electromagnetic scenarios for studying equipment vulnerability. Whereas the current procedure throughout industry is to expose a device to a set of preselected structured environments to assess vulnerability, a reverberation chamber exposes the device to a random selection from all possible environments, thus providing a much more unbiased environment that is characteristic of a real operating environment. Although the environment is random, critical parameters in the electromagnetic environment can be controlled very accurately.

CHAPTER 10

ELECTRONIC DATA EXCHANGE

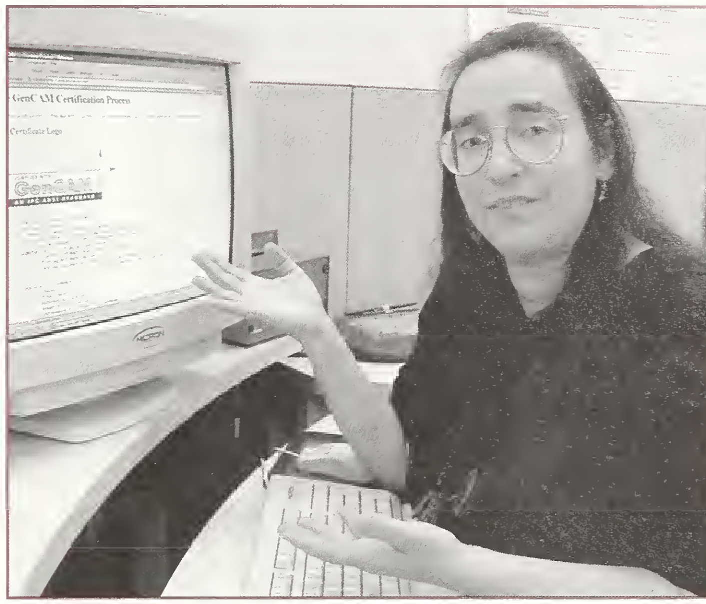
10.1 Testing Software Will Help Reduce $500 M Problem in Electronics Manufacturing Industry

There is a worldwide problem in the electronics industry regarding the transfer of design information to manufacturing facilities. Analysts estimate that this problem costs the industry about $500 M a year. This problem is primarily due to ambiguous data, incomplete data, or misinterpreted data files being transferred from design to manufacturing. Problems resulting from ambiguous data can result in delays in production while ambiguities are resolved or, even worse, the manufacture of products that must be scrapped due to the misinterpretation of the manufacturing data.

> "The industry will be enhanced in their data transfer solutions, thanks to Michael McLay and NIST involvement."
>
> Dieter Bergman
> Director
> IPC

The Institute for Interconnecting and Packaging Electronic Circuits (IPC) has requested NIST's help with this problem. The IPC is a trade association representing over 2300 companies in the electronic interconnection industry worldwide. Its members include printed circuit board designers, fabricators and assemblers. The GenCAM (Generic Computer Aided Manufacturing) standard being developed by the IPC is intended to improve the transfer of design information for electronic products from Computer Aided Design (CAD) tools, to Computer Aided Manufacturing (CAM) tools. GenCAM files may be used to request quotations, to order details that are specifically process-related, or to describe the entire product (printed circuit board and printed circuit assembly) to be manufactured, inspected and tested, and delivered to the customer. GenCam is also able to add information to represent multiple imaging for panel and sub-panel fabrication.

At the request of the IPC, Michael McLay, a member of the Electricity Division, has developed the Compliance Test Module (CTM) software program to support the

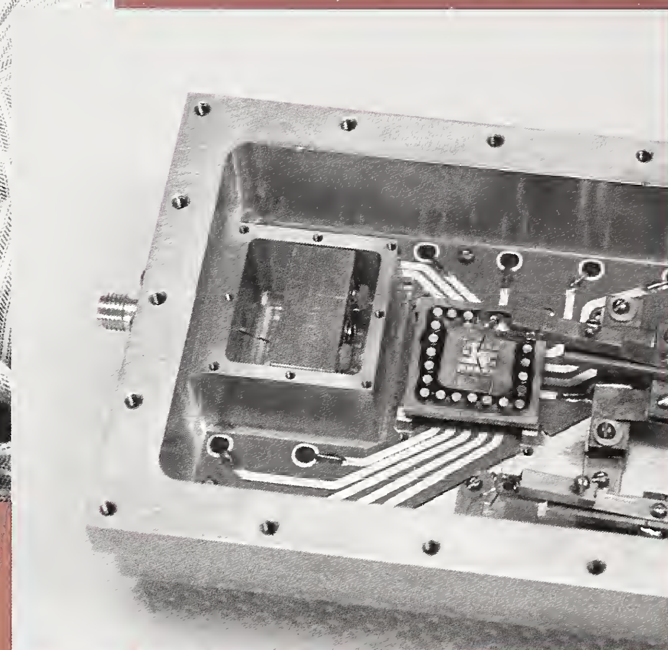


B.L. Goldstein – Demonstration of the web-based GenCAM compliance tool. The tool was developed for the Infrastructure for Integrated Electronics Manufacturing (IIEM) Project.

GenCAM standard under development by the Institute. IPC considers the NIST CTM software a key element in the industry deployment of the GenCAM standard. This view is based on the fact that one of the main problems with GenCAM's predecessors was a lack of strong technical support, especially the existence of conformance testing tools. The lack of conformance tools led to misinterpretations by commercial implementers of earlier standards, which hurt their adoption within the industry. An article on GenCAM in the April 1998 issue of *Printed Circuit Design* magazine stated: "The [GenCAM] CTM will be made available so that the misinterpretation evident in past implementation strategies can be avoided." The first official release of the CTM is scheduled for the first quarter of 1999. At present, the CTM verifies the syntax of the GenCAM file but there are plans to investigate adding semantic testing and testing for a design's "completeness" in the future.

The development of the GenCAM CTM has also contributed to improvements in the GenCAM standard itself. McLay's CTM development work brought to light some ambiguity issues within the standard that were resolved by the development committee, making it a more robust standard. The beta version of the CTM was demonstrated at the 1998 NEPCON that was held March 2-5, in Anaheim, California, and the PCB Design Conference, which was held in Santa Clara, California, on March 23-27.

M. Keller – Mounting the capacitance standard on the dilution refrigerator.



Critical components of a capacitance standard based on counting electrons. The electron pump is located near the center of the figure on a chip surrounded by a square pattern of round posts. The vacuum-gap capacitor is inside a small enclosure on the left. Just above the pump is a needle that can be lowered to allow electrons from the pump to flow onto the capacitor through a small wire (not visible). The box surrounding the components is placed on a dilution refrigerator that cools it to a temperature of 0.04 K.

CHAPTER

11

NATIONAL ELECTRICAL STANDARDS

11.1 Counting Electrons: A New Prototype Standard for Capacitance

American instrument manufacturers count on NIST for the most accurate electrical standards in the world. In response, NIST's Electronics and Electrical Engineering Laboratory routinely pushes measurement technology to its limits — thereby creating and maintaining standards with the smallest uncertainty, or highest accuracy. In so doing, EEEL maintains NIST's reputation as a world leader in electrical metrology. A recent example of significant advances in electrical metrology is a prototype for a capacitance standard, based on counting electrons, which has been pushed to an uncertainty of about 1 part per million (ppm).

Researchers Mark Keller, John Martinis, and Ali Eichenberger, of the Electromagnetic Technology Division, and Neil Zimmerman, of the Electricity Division, created the prototype standard by combining two technologies developed at NIST: the electron pump and the vacuum-gap capacitor. The electron pump, which is a microcircuit, operates at temperatures below 0.1 K, passing and counting individual electrons with an uncertainty of 0.01 ppm. These electrons flow onto the vacuum-gap capacitor, also at 0.1 K. This capacitor has exceptionally low leakage and frequency dependence because it does not contain those dielectric materials which cause conventional capacitors to be less than perfect.

After placing about 100 million electrons onto the capacitor, the researchers measure the resulting voltage across the capacitor. The capacitance is the ratio of the pumped charge to the measured voltage, $C=Q/V$. The imprecision, or lack of repeatability, of the measurement of C is presently less than 1 ppm. With improvements to room-temperature electronics, an imprecision of 0.1 ppm is expected. A comparison of the prototype standard with the best commercial capacitance meter shows agreement well within the 2 ppm calibration uncertainty of the commercial instrument.

A more definitive test of absolute uncertainty will be performed by comparing the prototype with NIST's calculable capacitor, which is the nation's fundamental standard for capacitance. Operating at 1592 Hz, the calculable capacitor allows NIST to provide calibrations with an uncertainty of 0.02 ppm at this frequency. However, at other commonly requested frequencies the uncertainty increases to as much as 2 ppm. If the prototype capacitance standard can operate over a wide frequency range with an uncertainty of about 0.1 ppm, as expected, it will enhance NIST's ability to provide world-class capacitor calibrations.

N.M. Zimmerman – Working at the dilution refrigerator while measuring the vacuum-gap capacitor, which uses a single-electron transistor.

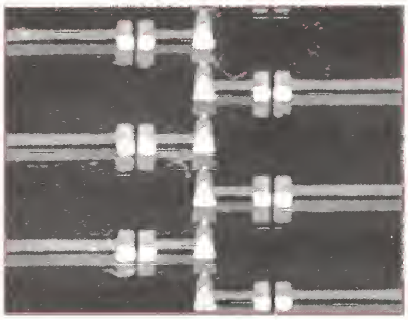
The prototype capacitance standard based on counting electrons is part of the evolution away from artifact standards and toward reproducible, easily transportable standards based on quantized properties of nature. In this case, the quantum property is the electron charge. Since the value of the vacuum-gap capacitor can be determined *in situ* using the electron pump, no artifacts are needed to realize the measurement. When perfected, the prototype standard could function as a primary standard for some laboratories.

The Calculable Capacitor

A. M. Thompson and D. G. Lampard first envisioned the cylindrical calculable capacitor in 1956. This device is constructed so that its capacitance depends only on one shielding electrode whose displacement can be accurately measured by laser interferometry. Thus, the calculable capacitor links an electrical unit, the farad, directly to a mechanical unit, the meter. Such links are important because the principle that mechanical and electrical forces are equivalent is one of the foundations of metrology.

The Electron Pump

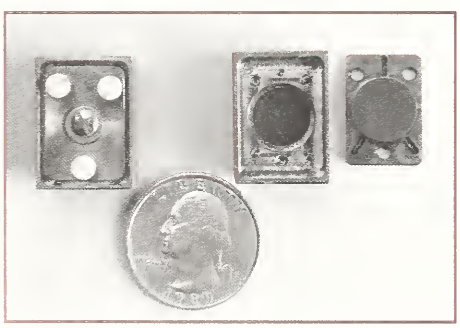
The electron pump designed at NIST consists of a chain of 1 μm metal islands separated by thin oxide layers. It requires significant energy for an electron to move from one island to the next by tunneling through the thin oxide. When the pump is cooled to a temperature of about 0.1 K, electrons are trapped on the islands by this energy barrier. However, the energy barrier can be manipulated by applying voltages to gate electrodes near each island. When the gate voltages are pulsed in sequence, a single electron can be moved from island to island and passed from one end of the chain to the other. NIST researchers have built a pump with seven junctions that passes electrons with only one error in 100 million cycles.



Electron pump

The Vacuum-Gap Capacitor

The vacuum-gap capacitor developed for the prototype standard must meet several important criteria, including no measurable time dependence (drift) or frequency dependence of the capacitance value. Most important of the electrical characteristics is that it must have extremely low electrical leakage; a lower bound for the leakage has been measured at 10^{19} Ω (a world record). In addition, it must be able to operate at very low temperatures; thus, it is constructed of a special grade of copper, suitable for low temperatures, along with sapphire standoff balls, which have excellent thermal conductivity at low temperatures. The next (and final) stage in the evolution of this standard capacitor is to design one which meets the same electrical criteria, while having a tunable capacitance value.



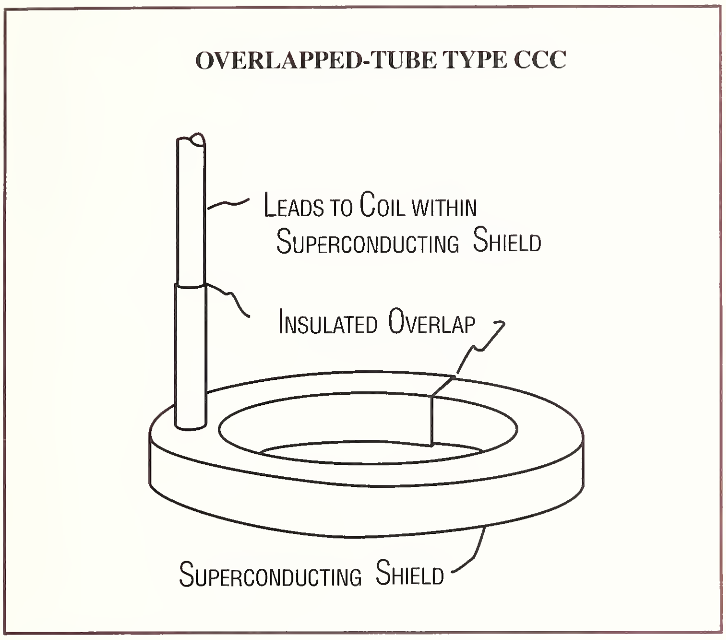
Vacuum gap capacitor: (left to right) complete assembly, grounded shell, and electrode, including three standoff sapphire balls.

R.F. Dziuba – Connecting a customer's standard resistor in NIST's automated 10 kΩ calibration system. The 10 kΩ working standards are verified periodically against the QHR using the CCC measurement system.

11.2 CCC Bridge Provides Most Accurate Resistance Ratio Scaling in World

The electrical resistance calibrations provided by NIST's Electronics and Electrical Engineering Laboratory cover an immense range: seventeen orders of magnitude — from 10^{-4} ohm shunts to 10^{12} ohm thin-film resistors. To further improve critical calibration services, Electricity Division staff Randolph Elmquist, Lisa Scott, and Ronald Dziuba, recently built and installed a cryogenic current comparator (CCC) bridge for maintaining the most stable NIST working standards used at key resistance levels. Maintaining these working standards requires that metrologists accurately transfer values that are based on the National Ohm by steps, or ratios, of 10 or 100.

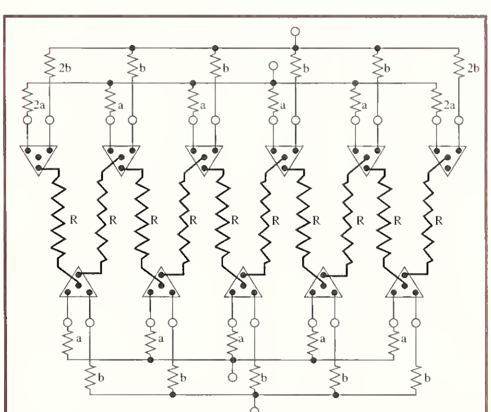
The team's new CCC bridge uses superconducting quantum interference device (SQUID) technology, and presently provides the most accurate method of resistance ratio scaling in the world. The CCC method of scaling provides a direct link from standards calibrated against the quantized Hall resistance (QHR) to working calibration standards at 1 ohm and 10,000 ohms. The new method is faster, less risky, and reduces the uncertainty associated with the previous method, which used Hamon bridges or network devices, by a factor of three.



Toroidal CCC in the form of an overlapping superconducting shield containing various ratio windings. This nearly ideal magnetic shielding provides ratio uncertainties of one part in 10^9 or better. This CCC contains eight ratio windings with a total of 808 turns within a shield of outer diameter of 4 cm.

(The assigned uncertainty of the Hamon method, even at only 2×10^{-8}, was a major component for calibrations at 1 ohm and 10,000 ohms.)

These improvements are due in large part to the fact that the CCC bridge method determines a ratio of 100 by a one-step process instead of a two-step process. Also, in the Hamon process, uncertainty accrued from the bridge measurements and from the mechanical contacts that formed the series and parallel junctions of the Hamon network. The junction connections had to be made very precisely in order for the devices to give accurate resistance ratios. Finally, some Hamon devices used toxic, mercury-wetted contacts, which demanded more time for cautious and careful handling.



Series-parallel buildup transfer resistor or Hamon standard. The standard is configured in the parallel mode. The ratio between the series and parallel connections is 100:1.

With CCC scaling, the Division can provide reduced uncertainties and faster turn-over in calibrations for the most demanding customer applications. About one-third of the resistance calibration workload at NIST is made up of highly stable and precise 1 ohm and 10,000 ohm resistors. When improvements are made at these key levels, the results are transferred to industry, resulting in better reliability in instrumentation and manufacturing processes.

11.3 A Giant Step toward Establishing a Quantum-Based Definition for the Kilogram

As reported in FY1997, the realization of the SI Watt can be used to monitor the artifact SI base unit of mass, the kilogram. During FY1998, Electricity Division researchers Edwin Williams, Richard Steiner, David Newell, and P.T. Olsen have completed one version of the experiment and reported a value for the SI Watt and for the Planck constant, *h*, which is a direct result. The new value for *h* ($6.62606891 \times 10^{-34}$ J-s), which has an uncertainty of

New facility and vacuum system designed to allow monitoring of the kilogram at the 10 parts per billion level. Researchers E.R. Williams and D.B. Newell (upper level), and R.L. Steiner (lower level) are aligning the vacuum system and superconducting magnet below.

87 parts per billion, is a factor of ten better than their previous result. Establishing the new value also improved the accuracy of values for related fundamental constants (including electron mass, proton mass, elementary charge and Avogadro's number) and paved the way for a quantum-based definition of mass.

The experiment, referred to as the Watt Balance experiment, used a moving-coil watt balance — an apparatus with a kilogram mass balance connected to an induction coil in a magnetic field. First, the group moved the coil vertically to generate approximately 1 V, measuring its velocity and exact voltage. Next, they measured a current sent through the coil to create an upward magnetic force that exactly balanced the downward force of gravity on a 1 kg mass. By combining these measurements and using the Josephson and quantum Hall effects, the researchers could extract the value of h. These results have recently been published (Phys. Rev. Lett. 81, 2404, 1998). Richard Steiner presented the results in July, as an invited speaker, at the Conference on Precision Electromagnetic Measurements (CPEM) held in Washington, DC. Also at CPEM, David Newell presented the designs and detailed the progress anticipated for the next generation of the experiment. The team's goal is to improve the uncertainty of the experiment by an order of magnitude. This accuracy will allow practical monitoring of the artifact kilogram and lead to a new quantum-based definition for the kilogram.


C. Hamilton – Assembling a Josephson integrated circuit for the voltage standard.

Regarding the National Conference of Standards Laboratories Interlaboratory Comparison (ILC) for the dc volt, which was coordinated by EEEL
"...the participants found this ILC to be efficient, and the data analysis to be fair and timely. We greatly appreciate NIST's contributions to the ILC97 and plan to use this as the model for the 1999 ILC."

William Quigley
President Elect
National Conference of Standards Laboratories (NCSL)

11.4 NIST Delivers: The Portable Voltage Standard

Until recently, laboratories that needed to calibrate their local primary voltage standards had two choices: they could send their standards to NIST or they could install their own Josephson voltage standard calibration system — an undertaking that is equivalent to gearing up to the accuracy of the National Volt. Neither choice was trouble-free.

However, those constraints disappeared when researchers Clark Hamilton and Charles Burroughs of the Electromagnetic Technology Division collaborated with staff from Sandia National Laboratories to develop a compact, fully automated, portable voltage standard. The new standard is easily shipped by overnight courier and can be assembled and operated in less than an hour. More importantly, accuracy is not sacrificed for convenience. The portable calibration system has an uncertainty of better than two-one hundredths of a part per million (0.02 ppm), which is fully equal to the accuracy of the entire installed laboratory system.

The portable system consists of a cryoprobe for cooling the voltage chip, which has 20,208 superconducting Josephson junctions, an electronics package that is 13 centimeters tall and 48 centimeters wide, and a notebook-computer controller. The total mass of the system is only 21 kilograms. The system's built-in software contains complete diagnostics and a variety of options for fully automated measurement and data analysis. System users need only supply a standard liquid-helium storage Dewar.

The first of these new systems is circulating among 10 National Aeronautics and Space Administration (NASA) centers where it brings an improvement in uncertainty of more than an order of magnitude. A second system, recently delivered to Sandia National Laboratories, is being tested in preparation for circulation among

Department of Energy laboratories. The researchers' future plans include a further reduction in size and mass, and the addition of a compact cryocooler.

One Great Standard Deserves Another

A new, programmable Josephson voltage standard (PJVS) system, which was developed by Clark Hamilton, Charles Burroughs, Todd Harvey, and Samuel Benz of the Electromagnetic Technology Division, has been demonstrated in the NIST Watt Balance experiment. The PJVS can be rapidly programmed to any voltage in the range +1.1 V to -1.1 V and is ultra-stable and noise resistant. Using this new voltage reference is expected to reduce significantly the uncertainties associated with voltage measurements in the Watt Balance experiment.

The characteristics of the PJVS are an excellent match for the voltage reference needs of the experiment. The Josephson circuit is a segmented array of 32,768 superconductor-normal-superconductor junctions. The application of computer-controlled bias currents on 13 input lines allows digital control of the output voltage.

The new system's stability and noise immunity allow it to be directly connected to the experiment. In a preliminary trial, the new standard worked correctly in both force and velocity modes. Work is now underway to optimize the system's controlling electronics by incorporating them into a convenient and reliable instrument that can be permanently integrated into the experiment.

11.5 Developing a Definitive AC Voltage Standard

Researchers Samuel Benz, Charles Burroughs, and Clark Hamilton of the Electromagnetic Technology Division are developing a definitive ac voltage source based on arrays of pulse-quantizing Josephson junctions. This source uses a long digital code of up to 8,000,000 bits to represent the desired waveform, typically a sine wave. When the pulse code is applied to a series array of Josephson junctions, the pulse amplitudes are quantized and multiplied to produce a waveform that is the summation of billions of quantum pulses. A knowledge of the pulse code, the number of junctions in the array, and the clock frequency is sufficient to compute the output voltage waveform.

Recent improvements — including the acquisition of a 12 billion bits-per-second pulse code generator, improved input bandwidth, and the use of a bipolar input waveform — have increased the maximum voltage range of the instrument to 52 mV peak to peak, more than an order of magnitude increase. Present evaluations of the accuracy of the synthesized sine waves are based on measurements of harmonic content. At a typical frequency of 3.5 kHz, all harmonics are at least 66 dB below the fundamental, indicating a worst-case root-mean-square (rms) voltage error owing to harmonic generation of less than one part per million. The next generation of system improvements is expected to yield kilohertz and megahertz frequency waveforms with amplitudes up to 100 mV and a rms uncertainty of less than one part per 10 million.

PROGRAMS MATRIX-MANAGED BY EEEL

The Electronics and Electrical Engineering Laboratory administers NIST-wide laboratory programs in microelectronics and law enforcement as well as the programs sponsored by this Laboratory. Descriptions of matrix-managed programs that are conducted within EEEL are to be found in the Accomplishments section of this document. Additionally, to offer a sense of the significance, quality, and impact of the matrix-managed work performed by other cooperating laboratories within NIST, the following examples are provided.

OFFICE OF MICROELECTRONICS PROGRAMS (OMP) — NATIONAL SEMICONDUCTOR METROLOGY PROGRAM (NSMP)

Measuring Thermal and Hygrothermal Expansion Coefficients in Polymer Thin Films

Staff of the Materials Science and Engineering Laboratory have developed an instrument to measure the out-of-plane thermal and hygrothermal expansion coefficients of polymer thin films used in electronic and opto-electronic packaging.

Given the wide temperature ranges and humidity conditions to which polymer thin films are subjected during manufacture and use, their behavior needs to be measured to qualify materials as having the necessary reliability goals.

A technique based on a capacitor cell has been developed which is insensitive to sample thickness and has been operated successfully down to film thicknesses of 2 µm. Careful calibration of the resulting instrument, including compensation for the dielectric constant of the ambient air for temperature, pressure, and humidity, allows measurements of total film thickness accurate to 2 parts per million.

The previously existing metrology standard measurement, using the thermal mechanical analyzer, was limited to films of 25 µm or greater, and accuracies down to 10 to 30 nm, or 400 parts per million for the thinnest films using this technique. The NIST staff responsible for the development of this instrument have applied to the Institute for Interconnecting and Packaging Electronic Circuits for acceptance of this procedure as a standard. Further development activities underway using x-rays will allow even more sensitive measurements on films less than 1 µm thick.

New Measurement Services

Instruments developed under two National Semiconductor Metrology Program (NSMP) projects are now mature enough to provide measurement services for the public. The instrument known as the Calibrated Atomic Force Microscope (C-AFM), was developed by the Manufacturing Engineering Laboratory. It is a three-dimensional measuring machine with the following properties:

	x	y	z	
Range of travel	50	50	5	µm
Displacement resolution	1.2	1.2	0.004	nm
Measurement uncertainty	0.1	0.1	0.6	percent

Measurements are traceable to the wavelength of light. Initial services are being offered as special tests on nano-engineered grids and other references used to ensure the accuracy of dimensional measurements critical to semiconductor processing. These include tools for pitch measurement (distance from right-side to right-side or from left-side to left-side of adjacent lines or similar features on a chip) or for step height measurement.

The second instrument, which was developed in the Chemical Science and Technology Laboratory, is a Low Frost-Point Generator (LFPG) of gas streams containing precisely known amounts of water vapor. LFPGs are needed to calibrate instruments for measuring the moisture content of high-purity gas streams such as those used in integrated circuit manufacturing. The LFPG works by passing the gas stream over the surface of ice held at a temperature within the range of minus 5 degrees to minus 101.6 degrees Celsius.

By very closely controlling the temperature (within 0.002 degrees Celsius), gas streams with compositions between 4 parts of water vapor per thousand parts of gas and 3.4 parts per billion parts of gas can be produced with a precision of better than 0.04 percent. This precision is made possible by exacting temperature control and the fact that the physical properties of water are very well known. Thus, the performance of the LFPG can be established by calculations based on sound physical principles, and the uncertainties and limitations of most other approaches to this measurement can be avoided. Suitably stable commercial hygrometers are now being accepted for calibration.

Other measurement services previously developed on NSMP projects include ultraviolet light meter calibration at 248 nm; mass flowmeter calibration; laser power and energy calibration at 248 nm; x-y grid plate dimensional calibration; and optical flatness calibration. In addition, several Standard Reference Materials are also available. These include SRM 473 — optical linewidth, SRM 2134 — arsenic implant in silicon; SRM 2137 — boron implant in silicon; SRM 2531-2536 — thin film (SiO_2) thickness; SRM 2541-2547 — silicon resistivity; SRM 2551 — oxygen in silicon; and the Reference Material 8090, SEM magnification reference.

SEM Monitor Wins 1998 R&D 100 Award

An R&D 100 Award has been given to a computer-based system for monitoring the performance of scanning electron microscopes (SEMs). Operating in very nearly real time, the monitoring system provides assessment of the instrument's performance and clear indications for optimizing it. Developed by the Manufacturing Engineering Laboratory in cooperation with a private company, and with partial support from SEMATECH, the SEM Monitor provides a simple, qualitative, and quantitative framework for monitoring an SEM's resolution, astigmatism, and image quality both over time for a single instrument or compared with other instruments.

The system analyzes the imaging of finely-detailed objects by computing a two-dimensional Fourier transform of the image. A properly-tuned SEM will produce an image containing excellent detail, as reflected in strong high-fre-quency components in the image details. The system analyzes the Fourier information and interprets it in terms readily understood by the operator. The SEM Monitor has been commercialized by the industrial partner in this work.

New CRADAs Developed with SEMATECH

Semiconductor manufacturing is a global business. To a very large extent, semiconductor device manufacturers equip their plants with those processing tools that they judge to be the "best of breed." The tools may come from anywhere in the world. This was not always the case. When SEMATECH was founded in 1987, one of its objectives was to restore the United States to a leadership position in the industry. While this change has taken place, due in part to the efforts of SEMATECH, such a national focus is no longer seen by the integrated circuit manufacturers that own SEMATECH as appropriate to their present and future global interests.

NIST and SEMATECH have had a Cooperative Research and Development Agreement (CRADA) governing their technical relationship since 1990. This has allowed NIST to undertake certain metrology development projects needed and supported by SEMATECH that might not otherwise have been undertaken and enabled NIST to have a much closer technical relationship with SEMATECH and its member companies.

On April 1, 1998, SEMATECH established a subsidiary, International SEMATECH, that includes five foreign-based companies among its participants as well as the U.S.-based firms that own SEMATECH. A new CRADA has been established with the new company and a nearly identical one is in place with SEMATECH to replace the previous CRADA that expired at about the same time. Both CRADAs define NIST's technical work done under their provisions to be public domain. This greatly simplifies the intellectual property aspects of the agreements as well as some of the legal requirements that arise because of the participation of foreign-based companies. The arrangement allows NIST to continue to participate in a mutually beneficial relationship that is appropriate to the realities of this thoroughly global industry.

Optical Properties of Lens Materials for Deep Ultraviolet Lithography

Extremely accurate determinations of the indices of refraction, dispersions, and temperature dependencies of lens materials are essential for deep ultraviolet lithography exposure tools used in the manufacture of next-generation integrated circuits. Staff in the Physics Laboratory have recently completed measurements of these three parameters for fused silica and calcium fluorite from a variety of sources, using an upgraded temperature controlled precision refractometer, to an accuracy of 7 parts per million for the indices and to 0.1% for the dispersions and to 10% for the temperature dependencies of the indices, at 193 nm.

A Fourier transform interferometric spectrometer is being assembled to refine the index measurements further to one part per million, and to extend the wavelength down to 157 nm. This work, performed in collaboration with MIT Lincoln Laboratory and SEMATECH, supports the development of the infrastructure required to apply 193 nm laser emission for making 0.18 μm and smaller integrated circuit feature sizes, consistent with the National Technology Roadmap for Semiconductors (NTRS) target date of 2001 for commercial production of these chips. In addition, it supports exploration of the feasibility of extending optical lithography down to 157 nm.

Polarized Light Scattering Instrument Improves Sensitivity to Small Wafer Defects

Light scattering is often used to detect defects and particles on silicon wafers. However, the signals from "killer" defects and particles are becoming smaller as the design rules are being reduced. In fact, current light-scatter techniques are barely able to detect particles that are a problem at the 180 nm scale.

Researchers in the Physics Laboratory have developed and built a new instrument which uses the polarization of light scattered by an artifact to identify and classify that artifact. The instrument incorporates twenty-eight separate detection systems spread out over the hemisphere, each with a polarizer and a detector. The signals are recorded as the incident light polarization is rotated, yielding information that can help identify the source of the light scattering.

A patent application has been filed for a specific design of this instrument, for which each polarizer is aligned to eliminate the scattering signal from microroughness. Since light scattered by microroughness obscures the small signals scattered by particles, this design will substantially improve the sensitivity of a light scattering instrument to defects and particles. In addition to its usefulness in process inspection of silicon wafers, the design is expected to be valuable for identifying and characterizing defects in optical components, disk storage materials, and film coatings.

OFFICE OF LAW ENFORCEMENT STANDARDS (OLES)

Choose to Survive

The document, *Choose to Survive – A Guide to Standards and Tests for Ballistic Resistant Vest Performance and Reliability*, is primarily intended as a guide for law enforcement officers and purchasing agents who are responsible for procuring ballistic-resistance vests for law enforcement departments. Using a layman's terms, the text provides explanations of the statistical terminology that is commonly used by manufacturers to express the ballistic performance of their vests, thus allowing customers to easily compare one armor to the next. Without this assistance, customers lacking an understanding of the technical issues or vocabulary might otherwise end up comparing apples to oranges.

Forensic Sciences: Status and Needs — NIJ Report 600-98

To assess the current state of forensic laboratories, the National Institute of Justice (NIJ), the Office of Law Enforcement Standards (OLES) and the American Society of Crime Laboratory Directors (ASCLD) held a joint workshop, *Forensic Sciences Summit: Roadmap to the Year 2000*, March 5-6, 1996, at NIST. Its purpose was to determine the current status and needs of forensic laboratories. The proceedings and recommendations from the workshop are published in this report.

Supercritical Fluid Extraction in Hair Drug Testing

NIJ Report 601-98, *Evaluation of Analytical Methodologies for Non-Intrusive Drug Testing: Supercritical Fluid Extraction in Hair Drug Testing*, documents the results of an investigation of supercritical fluid extraction (SFE) as an environmentally friendly alternative to currently used wet chemical procedures in hair drug testing. SFE was found to be superior to existing wet chemical methods. Extraction times for the SFE method were 30-40 minutes as compared to the several hours to one-day intervals required for currently used liquid extraction methods.

Full Scale Room Burn Pattern Study — NIJ Report 601-97

One method fire investigators use to determine the cause and origin of fire is the study of patterns or "indicators" left on building components or building contents by the fire. Previous studies have shown that some traditionally used indicators have little or no technically defensible basis. In order to study the patterns or indicators produced by fires, full scale experiments were conducted using test rooms furnished as residential bedrooms. This report describes the experiment, setup, measurement results, and the post fire inspection of the rooms.

Development of New Measurement Apparatus for Handcuff Testing

The classic mass-produced steel handcuff, little changed over the last 90 years, is used for arrests and for prisoner transport. Corrections and police officers would now like to see this design improved so that fewer prisoners are able to pick the lock or otherwise break free of the cuffs. The typical lock mechanism has only two moving parts plus a spring and the ratchet that is part of the actual cuff. OLES research is providing data and calculations as a basis for possible changes to the formal handcuff standard, and to stimulate improvements in the cuffs on the market.

The research to support changes must include detailed issues of material strength, dimensions and so forth. In support of this goal, a new force-torque apparatus was assembled, combining some basic parts that were on hand with new computer hardware and new programming. A research contract was let to a firm that has experienced mechanical engineers and a variety of measuring equipment, and the OLES force-torque apparatus was loaned to the contractor. Although initially intended as the torque-recording device in one potentially destructive test, it was also used in other non-destructive tests, such as measuring the torques exerted with the key in normal operation. This apparatus enables OLES to collect handcuff data as needed, and may also be useful for other applications in the future.

Explosives Detection Report

The feasibility of discovering a hidden explosive by detecting the very weak electromagnetic fields emitted by the timing device of its electronic detonator is one of several investigations administered by OLES as part of the NIJ Domestic Counter Terrorism Program. The theoretical foundation for this study is provided by NISTIR 5072, *Spherical-Wave Characterization of Interior and Exterior Electromagnetic Sources*, published December 1997.

Since timing devices radiate at frequencies below 2 MHz, corresponding to wavelengths greater than 150 m, the report shows these devices can be treated as small quasi-static electric and magnetic dipole radiators. The report also shows that the masking effects of external (noise) sources can be treated by extension of the spherical near-field scanning solution. Experiments are currently underway to verify these predictions and to point to optimum detection schemes.

NIJ Battery Guide

Batteries are commonly used by law enforcement agencies for powering an endless list of items including: flashlights, night vision equipment, laptop computers, camcorders, automotive starter systems, portable communications equipment, and radar and lidar devices for traffic speed control. As a result, batteries have become a major expense for police departments.

To help buyers better understand battery terminology and be able to match the appropriate batteries to their applications, the Office of Law Enforcement Standards has prepared a new guide for publication. NIJ Guide 200-98, *New Technology Batteries Guide*, provides an introduction to battery fundamentals, types, performance and economic trade-offs, selection criteria, handling and maintenance

NHTSA Radar Calibrator

OLES supported the development of a portable calibrator that is designed to simulate the radar reflections of vehicles passing on streets and highways. The device, described in NIST Technical Note 1398, *Portable Calibrator for Across-the-Road Radar Systems*, May 1998, will be used to evaluate the effectiveness of photoradar devices which distinguish vehicular type (i.e., car, truck, or motorcycle) and determine direction and speed of travel. The calibrator, designed under an interagency agreement with the National Highway Traffic Safety Administration, can also be used with conventional down-the-road radar devices and would be particularly useful for testing proposed direction-sensing moving radar devices.

DEPARTMENT OF COMMERCE
Gold Medal

John Martinis, Gene Hilton, Kent Irwin, and David Wollman

This team from the Electromagnetic Technology Division is recognized for producing a radical new x-ray detector, demonstrating its performance, and developing the resulting microanalysis system to the point of commercialization. The detector and system is expected to revolutionize x-ray microanalysis and meet critical industry needs in the $80 billion U.S.-semiconductor market as well as in other industries. The team has used the system to identify particulate contamination as small as 100 nm in diameter on silicon wafers. Industry praise for the work includes citation of the x-ray microcalorimeter as an example of important progress toward meeting industry metrology goals by the SEMATECH President and CEO. The National Semiconductor Metrology Roadmap cites improved identification of small particles and defects as one of the most critical metrology needs.

Silver Medal

Edward F. Kelley

Edward F. Kelley is recognized for his invention and development of new methods for characterizing video displays and his effective introduction of these methods to industry, in part through spearheading the development of the standard recently issued by the Video Electronics Standards Association, *Flat Panel Display Measurements Standard Version 1.* Kelley is a member of the Electricity Division. Owing to his work, industry is able, for the first time, to make these important measurements with confidence in their accuracy.

NIST
Applied Research Award

John Martinis, Gene Hilton, Kent Irwin, and David Wollman

This Gold Medal award-winning team produced a radical new x-ray detector requiring scientific and technological breakthroughs in detectors, superconducting electronics, and cryogenics; demonstrated its performance; and developed it to the point of commercialization. Industry interest is so strong that the process of licensing NIST patents has drawn highly competitive responses from all applicants. Detailed negotiations have begun. This interest derives largely from the semiconductor industry's conviction that the detector will revolutionize x-ray microanalysis. At the core of the system is the sensor, based on a microcalorimeter that converts an x-ray photon into heat and accurately measures the energy of the heat pulse with a resolution of a few electron volts.

Bronze Medal

Kent B. Rochford, Allen H. Rose, Paul A. Williams, and Chih-Ming Wang

This group of researchers is recognized for raising the state-of-the-art in optical polarization measurement to meet industry needs, and the concomitant development of theoretically grounded practical measurement methods and standards for determining the polarization characteristics of optical components. Included in the team's work is a full response to the demanding requirements of the optical communications industry for means to determine the polarization characteristics of optical fiber. One example of their accomplishments is the development of an artifact standard to calibrate instruments used to measure the polarization characteristics of light. This work represents an order-of-magnitude improvement over previous approaches. Rochford, Rose, and Williams are members of the Optoelectronics Division. Wang is a member of the Information Technology Laboratory.

Richard A. Allen

Richard Allen has provided reliable measurements that are used by several consortia to transfer NIST electrical test structure metrology to industry. Allen is a member of the Semiconductor Electronics Division. This metrology responds to needs identified in the Semiconductor Industry Association's National Technology Roadmap for Semiconductors and provides dimensional measurements in support of lithography. The most recent consortium drew the active participation of some 18 U.S. companies and was sufficiently successful that industry asked for a follow-up consortium. This success is due in no small part to the confidence that participants could place in the NIST measurements guided by Allen and to the metrology expertise he applied to consortium operations.

Barbara Goldstein

Barbara Goldstein has been the driving force in recruiting very strong industry support and participation in the NEMI Factory Information Project, especially through her leadership of the Technology Implementation Group (TIG). NEMI, the National Electronic Manufacturing Initiative, is an industry-led, private-public partnership fostering the development of the worlds' best electronic manufacturing supply chain. Goldstein is a member of the Electricity Division. Under her guidance, the TIG established a testbed that has demonstrated plug-and-play operation, a concept that calls for hardware and/or software to be "plugged" into a manufacturing environment and to "play" immediately in concert with other equipment rather than causing protracted and costly interfacing problems.

Denise Prather

Denise Prather has provided enhanced administrative and logistics support for the Electricity Division's calibration services, materially improving the responsiveness of these services and earning many plaudits from their clientele. Prather serves as Division Calibration Services Administrator, a position created four years ago by increasing the level of duties and responsibilities of the position that she had ably filled for the preceding decade. She has had outstanding success in coping with this major expansion in every aspect of her work, in particular the addition of analytical duties requiring expertise in the individual calibration processes and the continuous exercise of good judgement.

AMERICAN PHYSICAL SOCIETY Fellows

Ronald F. Dziuba

The Council of the American Physical Society has elected Ronald F. Dziuba Fellow of the Society "for exceptional contributions to the realization of the ohm, the use of the quantum Hall effect as the primary resistance standard, and professional support to the metrology and scientific communities." Dziuba, a physicist in the Electricity Division, received a Department of Commerce Gold Medal as a member of the NIST team that made essential contributions to the 1990 international adjustment of electrical units. He later received NIST's Allen V. Astin Measurement Science Award for outstanding contributions to the NIST resistance calibration service, including the design and implementation of four automated measurement systems covering eight decades of resistance values with uncertainties unmatched elsewhere in the world. Dziuba is widely recognized as a pioneer in the development of the cryogenic current comparator, which can be used for the extremely precise comparison of resistances at arbitrary ratios (i.e., not restricted to decade values). The shielding techniques he developed make possible ratios known to 1 part in 10^9, vital for the successful application of the quantum Hall effect.

John M. Martinis

The Council of the American Physical Society has elected John M. Martinis Fellow of the Society "for experimental investigations into the fundamental quantum behavior of low-temperature electronic devices." Martinis, a physicist in the Electromagnetic Technology Division, has brought uncanny insight to the challenges of low-temperature physics. He is one of the inventors of the x-ray microcalorimeter recognized this year by a Department of Commerce Gold Medal and by the NIST Applied Research Award. Martinis also spearheaded world-leading experiments in single-electron tunneling behavior, culminating in the successful demonstration of the first seven-junction electron pump. The performance of this device — it counts electrons with an accuracy of fifteen parts per billion — confirms the feasibility of new fundamental electrical standards. The primacy of this work has been recognized by all the principal laboratories investigating similar experiments. One application of the new electron pump and its developments is the creation of a new capacitance standard.

In other work, Martinis has studied and used superconducting amplifiers known as SQUIDs. SQUIDs constitute the most sensitive detectors of magnetic fields known, and are therefore desirable for a number of scientific and medical applications. Martinis realized that a barrier to greater SQUID use was the matching transformer between the SQUID and its room-temperature amplifier, an arrangement requiring the use of complex readout electronics. To address this problem, Martinis designed and fabricated a series array of 100 SQUIDs having much higher bandwidth and response than conventional SQUIDs and sufficient output voltage change that the output can be directly coupled to room-temperature electronics. Martinis applied this device in testing a then new theoretical prediction in mesoscopic physics: that metallic resistors at low temperatures can exhibit shot noise but have a current noise spectral density one-third the standard prediction. This work is important because noise constitutes a fundamental limit for fine-scale experiments, and a better understanding of the mechanisms producing noise provides clues for reducing it. Martinis confirmed the theoretical predictions by measuring the current dependence on noise in a number of silver resistors having a range of lengths from 1 μm to 100 μm. Use of the SQUID array provided small enough measurement uncertainties for reliable results.

INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS
Fellows

Douglas L. Franzen

The Board of Directors of the Institute of Electrical and Electronics Engineers has elected Douglas L. Franzen a Fellow of the Institute "for contributions to optical fiber characterization procedures." In response to industry requests, Franzen has led NIST efforts to develop more than two dozen national standards for characterizing fiber that have materially contributed to the competitive position of the U.S. lightwave communications industry. Until his recent retirement, Franzen served as Leader of the Fiber and Integrated Optics Group in the Optoelectronics Division. Franzen has authored or co-authored more than 50 technical papers ranging from presentations of forefront research to handbooks on optical fiber characterization that are regarded as standard references in the field. He presented an invited short course on fiber measurements at the annual Optical Fiber Communications Conference for seven years, and in 1980 he helped found the biennial Symposium on Optical Fiber Measurements and continues to serve as its General Chair. In other recognition of his contributions, Franzen recently was elected Fellow of the Optical Society of America "for technical contributions and leadership in optical fiber measurements" and has received the Department of Commerce Bronze, Silver, and Gold Medals and NIST's Applied Research Award. Franzen has also received the Nippon Telegraph and Telephone Corporation Director's Award for collaborative work that resulted in an innovative all-fiber optical sampling device for measuring the waveform of picosecond-risetime optical pulses.

Loren W. Linholm

Loren W. Linholm has been elected Fellow of the Institute of Electrical and Electronics Engineers (IEEE) for "initiating and guiding the development of innovative microelectronic test structure-based measurement techniques, and associated parametric test-instrumentation procedures for monitoring advanced semiconductor wafer-fabrication processes and tools." Linholm is the leader of the IC Technology Group in the Semiconductor Electronics Division.

The fabrication process of integrated circuits (ICs) on semiconductor wafers is becoming increasingly complex, and new tools are being regularly introduced to perform those processes. Linholm's most significant contribution is innovation in electrical test structure metrology for monitoring the fabrication of ICs on semiconductor wafers. His innovations enabled the process-monitoring function to meet the challenges presented by the increased density of devices and the complexity of manufacturing tools that powered the enhanced performance of modern integrated circuits. Computing power provided by advanced semiconductor microprocessors and memories is the lifeblood of the modern economy. The National Technology Roadmap for Semiconductors specifically identifies the importance of continuing the enhancement of the metrology functions to which Linholm has made his significant contributions. The process-development and monitoring functions that have benefited from Linholm's innovations are particularly important because accurate information concerning the linewidths, overlay, and contact resistance being generated by the semiconductor manufacturing line is a prerequisite of competitiveness. He has achieved outstanding results in his own original research, has led a team of researchers with significant technical accomplishments, and has been a leader in organizing the test structure community into a recognized technical discipline through conferences and forums.

OPTICAL SOCIETY OF AMERICA
Fellows

Gordon W. Day

The Board of Directors of the Optical Society of America has elected Gordon W. Day Fellow of the Society "for contributions and leadership in optoelectronic measurements." Day has had a distinguished career at NIST and its predecessor NBS since 1969, culminating in his current position as Chief of the Optoelectronics Division. Early in his career, Day participated in the effort to measure the frequency of the methane-stabilized helium-neon laser in terms of the frequency of the primary cesium standard. With that accomplished, and an independent measurement of its wavelength in terms of the (then) primary length standard, a 100-fold improvement in the accuracy of the determination of the speed of light was achieved. In addition, the stage was set for a redefinition of the meter, which occurred in the early 1980s. Day then became involved in the development of detector-based radiometry. Among the results of that work was the Electrically Calibrated Pyroelectric Radiometer which has been manufactured and sold as a laboratory standard since 1976. Other developments included the development of inexpensive pyroelectric detectors based on the polymer PVF_2, which made low cost infrared intrusion detectors possible, and the development of spectrally-flat reference detectors for the spectral characterization of detectors.

Day was one of the founders of NIST work on optical fiber measurements that contributed to the development, verification, and dissemination of over two dozen measurement techniques that are now standards in the optical fiber industry. He is a co-originator of the biennial Symposium on Optical Fiber Measurements, which continues as an important forum for the dissemination of research results in this technology. Day also founded the NIST work on optical fiber sensors; his own research focused on the use of optical techniques for the measurement of electrical quantities — current, voltage, electric and magnetic fields. Under his direction, the work resulted in several new sensor technologies that led to substantial improvements in the state-of-the-art and world records for sensitivity. Day has written or coauthored over a hundred papers and two patents.

Matt Young

The Board of Directors of the Optical Society of America has elected Matt Young Fellow of the Society "for developing reference standards enabling U.S. manufacturers to control optical fiber, ferrule, and coating diameters." Young, a physicist in the Optoelectronics Division, led the development of critical measurement technology to aid U.S. optical fiber manufacturers who needed better fiber geometry measurements, especially with the advent of low-cost plug-in style connectors (ferrules). The great information-handling capacity offered by optical fibers had already revolutionized telecommunications over long distances creating "information highways" and replacing many coaxial cables, microwave links, and satellite channels. Previously fibers were coupled together in variations of a labor-intensive process that aligned fiber cores for maximum transmission of light. When the ferrule-type connectors were introduced, the demands on fiber geometry exceeded the capability of industry to measure parameters such as the diameters of the fiber core that mate with the inner diameter of the ferrules. Responding rapidly to an urgent industry request, the NIST work resulted in an SRM that is available for industry to standardize its measurements and two methods — scanning confocal microscope and contact micrometer — for measuring fiber diameter. The work of the NIST team extended the state-of-the-art to provide industry with needed practical measurement uncertainties of 40 nm and market advantage. All U.S. manufacturers of optical fiber use the NIST SRM as a basis for adjusting the operation of the pulling towers used to draw fiber from blanks. Young has also made significant contributions to multimode optical fiber measurements of attenuation, index profile, and numerical aperture and quantified the use of scratch-and-dig standards for optical surface quality. Young's recent work has been recognized with a Department of Commerce Gold Medal. He was also awarded a Silver Medal for his earlier work on optical measurements.

MEDAL OF THE PHOENIX

Loucas Christophorou

Loucas Christophorou, a researcher in the Electricity Division, has received the Medal of the Phoenix from the President of Greece. This award is the highest honor bestowed upon civilians by the Greek government and was conferred on Christophorou for exceptional contributions to science. The Greek Ambassador to the United States presented the award to Christophorou at a ceremony in the Greek Embassy.

Christophorou's professional scientific career spans 35 years, most of which was spent at Oak Ridge National Laboratory and the University of Tennessee, where he made world-recognized contributions to the areas of atomic, molecular, and nuclear physics. Christophorou has been a member of the Electricity Division since January 1995, where he leads projects related to gaseous dielectrics and to plasma diagnostics, including chemical and physical data of interest to the semiconductor industry.

G.G. Harman, world's foremost authority on wire bonding in microelectronics, signs a copy of the second edition of his book for J.C. French, Laboratory Director.

EUROPEAN PACKAGING AWARD

George G. Harman

George G. Harman was the first recipient of the new European Packaging Award, conferred at the Third European Conference on Electronic Packaging Technology and the Ninth International Conference on Interconnection Technology in Electronics, held in Nuremberg, Germany in June. Harman is a NIST Fellow in the Semiconductor Electronics Division. An all-European committee chose Harman to receive the award because of his outstanding achievements in the development of wire bonding. It is a signal honor for a European organization to confer a major award on a non-European the first time the award is given. In further recognition, Harman was asked to present a four-hour "Honour Tutorial" at the Conference. His topic was Advanced Wire Bonding.

Harman has received the NIST E.U. Condon Award for publications excellence and the Department of Commerce Gold and Silver Medals. A former President of the International Society for Hybrid Microelectronics (now International Microelectronics and Packaging Society, IMAPS) and a fellow of IMAPS and of the Institute of Electrical and Electronics Engineers, Harman has founded and provided leadership for a number of conferences and other activities in the packaging field and has presented numerous invited seminars worldwide. The author of the first and second editions of the popular NIST handbooks on wire bonding in microelectronics, Harman is generally considered to be the world's foremost authority on the subject.

INFRARED INFORMATION SYMPOSIA (IRIS)

David G. Seiler

David G. Seiler, Chief of the Semiconductor Electronics Division, recently received the IRIS award "in recognition of his distinguished participation in the activities of IRIS as Chairman of the Infrared Materials Specialty Group (IMSG)." IRIS works with both the Department of Defense and NASA to sponsor meetings that provide forums where representatives of industry, government, and academia can present, discuss, and evaluate improvements in the quality of infrared materials and in the capability of infrared detectors.

Under Seiler's leadership IMSG conducted meetings to provide opportunities for the presentation, discussion, and dissemination of information on the exploration, development, and use of materials for military, optical, and electro-optical devices and systems operating in the optical (defined as ultraviolet to millimeter-wave) spectrum. Topics of interest for IMSG include materials characterization and screening methods, optical materials (e.g., infrared windows, nonlinear optical materials, opto-electronic and photonic materials, binary optics and applications, microlensing), detector materials (extrinsic and intrinsic semiconductors, superlattices, quantum wells and dots, substrates, influence of material quality on detector performance, new growth techniques), and processing issues (*in situ* analysis and growth control, noninvasive, noncontact evaluation).

NATIONAL ELECTRONICS MANUFACTURING INITIATIVE (NEMI)

Judson C. French

The National Electronics Manufacturing Initiative, Inc. has invited Judson C. French, Director of the Laboratory, to sit as the government ex-officio member of its Board of Directors. NEMI identifies itself as an industry-led, private-public partnership that brings together the largest electronic equipment manufacturers in the United States, their key suppliers, consortia/associations, government agencies, and universities to foster development of the world's best electronics manufacturing supply chain. NEMI's goal is to help its members to become global leaders in volume electronics manufacturing. The Board of Directors has operational responsibility for the organization. It approves strategy, plans, and budgets, reviews the performance of NEMI projects, and establishes committees and appoints chair people. The seven-member Board is made up of decision-making officials from its participating organizations. Ex-officio members of the Board have a non-voting status. The bylaws also explicitly identify one of the four ex-officio members as being a government official involved with the electronics industry. Prior to French's appointment, this position was filled by the Director of the Electronics Technology Office at the Defense Advanced Research Projects Agency (DARPA).

NIST was involved from the outset in the development of NEMI, which was first conceived in 1994 as a government-industry partnership by the Electronics Subcommittee (ESC) of the President's National Science and Technology Council. French was the NIST representative on the ESC and, working with the other ESC members, played a key role in formulating the ESC activity which evolved into NEMI. The ESC had representatives from industry, associations, and nine government agencies. In 1996 NEMI was privatized by the participating electronics firms and now works with government agencies and universities to provide input and guidance on the R&D needs for the electronics manufacturing infrastructure. French's service on the Board will ensure that NIST will continue to have access and insight into U.S. electronics manufacturing and better enable NIST to work with this industry.

AUTOMATIC RADIO-FREQUENCY TECHNIQUES GROUP (ARFTG)

Robert M. Judish

Robert Judish, Leader of The Microwave Metrology Group in the Radio-Frequency Technology (formerly Electromagnetic Fields) Division was elected Vice-President of ARFTG at its 50th Conference held in Portland, Oregon late last year. ARFTG is an independent professional society affiliated with the IEEE Microwave Theory and Techniques Society (MTT-S) as a conference committee. ARFTG's primary interests are in computer-aided microwave analysis, design, and measurement. ARFTG holds two conferences a year, one in conjunction with the MTT-S International Microwave Symposium, and a second in late Fall. Specific duties assigned to the vice-president include monitoring and coordinating all ARFTG committee activities, maintaining the Executive Committee handbooks, and assuming the duties of the President when the President is not present. By custom, the vice president of ARFTG is expected to serve for two years and then serve as president for a further two years.

Judish has been an ARFTG member since 1983 and has served on the Executive Committee since 1989. He chaired the Standards Committee until election as vice president. In 1995, Judish conceived and developed the ARFTG short course on microwave and RF measurements that is co-sponsored by NIST. The success of this course led to the formation of the ARFTG Education Committee, which Judish chaired for its first year. He remains a member of that Committee.

ANTENNA MEASUREMENT TECHNIQUES ASSOCIATION (AMTA)

Michael H. Francis

Members of the Antenna Measurement Techniques Association (AMTA) have elected Michael H. Francis to a three-year term on the AMTA Board of Directors. Francis is a member of the Radio-Frequency Technology Division. As part of his duties, he will serve as the AMTA Technical Coordinator for 1998. Functions of the Technical Coordinator include reviewing papers and publishing the annual AMTA Proceedings, organizing the technical sessions for the annual symposium, and judging the student paper competition. AMTA is an international association of approximately 400 antenna measurement scientists and engineers from industry, universities, and international government laboratories.

Roger B. Marks

Roger B. Marks received the Best Technical Paper award at the 50th ARFTG Conference held late last year. Marks is the founding coordinator of the N-WEST activity and a member of the Radio-Frequency Technology Division. His paper, *Formulations of the Basic Network Analyzer Error Model Including Switch Terms*, explained and contrasted the two commonly used parametric characterizations of vector network analyzers (VNAs). Calibrating a VNA is predicated on the fact that its internal computer relies on a conventional error-model description. Through his paper, Marks has provided a useful contribution to the microwave community by relating the conventional error models to a more physical counterpart, the error-box formulation, which previously has been the province of those developing VNA calibration methods.

Appendix

TABLE 1: EEEL PROGRAMS AND THEIR PROJECTS

PROGRAMS	PROJECTS
OFFICE OF MICROELECTRONICS PROGRAMS	National Semiconductor Metrology Program
SEMICONDUCTORS	Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Metrology for Simulation and Computer-Aided Design Metrology for Process and Tool Control Gate Dielectric and Interconnect Reliability Metrology Micro-Electro-Mechanical Systems (MEMS) Plasma Chemistry - Plasma Processing
MAGNETICS	Magnetic Recording Metrology Magnetic Instruments and Materials Characterization Nanoprobe Imaging for Magnetic Technology
SUPERCONDUCTORS	Superconductor Interfaces and Electrical Transport High Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
LOW FREQUENCY	AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems
RADIO FREQUENCY	High-Speed Microelectronics Metrology Nonlinear Device Characterization Power, Voltage, and Impedance Standards and Measurements Network Analysis and Measurements Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems

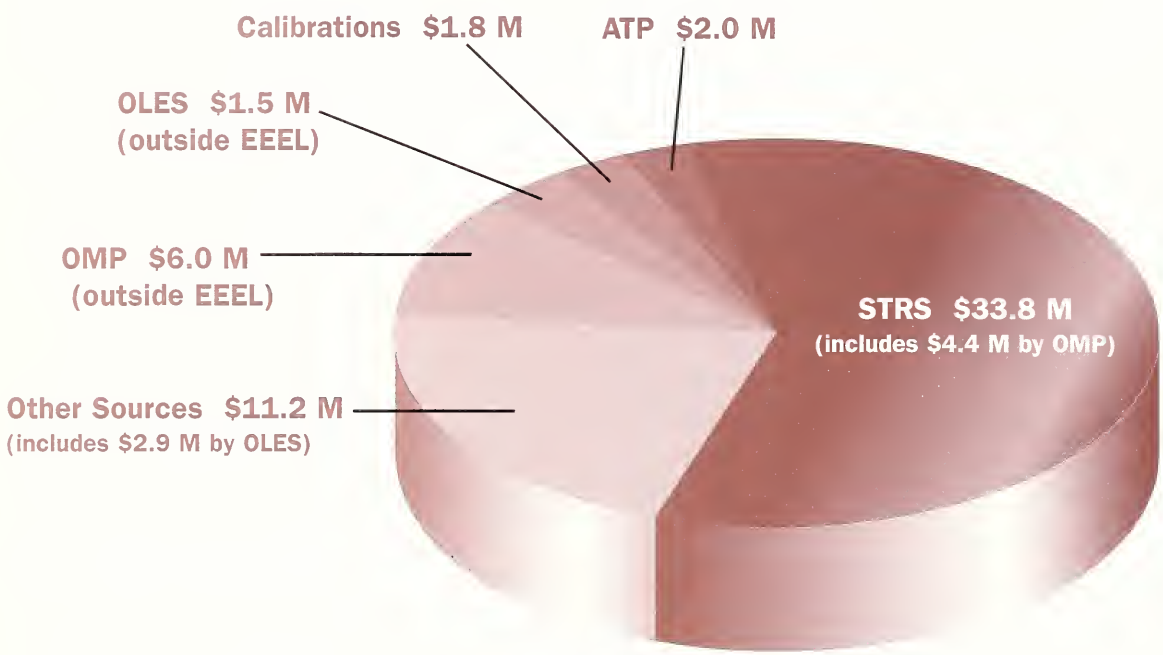
PROGRAMS	PROJECTS
OPTOELECTRONICS	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
VIDEO	Video Technology
POWER	Dielectrics Research Metrology for Electric Power Systems
ELECTROMAGNETIC COMPATIBILITY	Standard EM Fields and Transfer Probe Standards Emission and Immunity Metrology Electromagnetic Properties of Materials
ELECTRONIC DATA EXCHANGE	Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
NATIONAL ELECTRICAL STANDARDS	Ohm and Farad Realization and Dissemination Quantum Voltage and Current
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

TABLE 2: EEEL ORGANIZATIONS AND THEIR PROJECTS

ORGANIZATIONS: OFFICES AND DIVISIONS	PROJECTS
OFFICE OF MICROELECTRONICS PROGRAMS	National Semiconductor Metrology Program
SEMICONDUCTOR ELECTRONICS DIVISION	Metrology for Nanoelectronics Optical Characterization Metrology Scanning-Probe Microscope Metrology Thin-Film Process Metrology Metrology for Simulation and Computer-Aided Design Metrology for Process and Tool Control Gate Dielectric and Interconnect Reliability Metrology Micro-Electro-Mechanical Systems (MEMS)
ELECTRICITY DIVISION	Plasma Chemistry - Plasma Processing AC-DC Difference Standards and Measurement Techniques Waveform Acquisition Devices and Standards Waveform Synthesis and Impedance Metrology Measurements for Complex Electronic Systems Video Technology Dielectrics Research Metrology for Electric Power Systems Ohm and Farad Realization and Dissemination Quantum Voltage and Current Infrastructure for Integrated Electronics Design Infrastructure for Integrated Electronics Manufacturing
RADIO-FREQUENCY TECHNOLOGY DIVISION	High-Speed Microelectronics Metrology Nonlinear Device Characterization Power, Voltage, and Impedance Standards and Measurements Network Analysis and Measurements Noise Standards and Measurements Antenna Measurement Theory and Application Metrology for Antenna, Radar Cross Section and Space Systems Standard EM Fields and Transfer Probe Standards Emission and Immunity Metrology Electromagnetic Properties of Materials

ORGANIZATIONS: OFFICES AND DIVISIONS	PROJECTS
ELECTROMAGNETIC TECHNOLOGY DIVISION	Magnetic Recording Metrology Magnetic Instruments and Materials Characterization Nanoprobe Imaging for Magnetic Technology Superconductor Interfaces and Electrical Transport High Performance Sensors, Converters, and Mixers Josephson Array Development Nanoscale Cryoelectronics High-T_c Electronics Superconductor Standards and Technology
OPTOELECTRONICS DIVISION	Dielectric Materials and Devices Semiconductor Materials and Devices Fiber and Discrete Components Integrated Optics Metrology Optical Fiber Sensors Optical Fiber Metrology High Speed Source and Detector Measurements Laser Radiometry
OFFICE OF LAW ENFORCEMENT STANDARDS	Enabling Technologies for Criminal Justice Practitioners

EEEL FY 1998 Resources



The funds used to operate the Electronics and Electrical Engineering Laboratory are derived from several sources. Scientific and Technical Research and Services (STRS) funds are provided by Congress for programs at NIST. Calibration funds are received for performing calibration services for industry and government. Other funds may be obtained from a variety of sources, including other Federal agencies, non-Federal government organizations, cooperative research and development agreements (CRADAs), and NIST internal calibration and standard reference material development funds. The Office of Microelectronics Programs (OMP) and the Office of Law Enforcement Standards (OLES) funds are used to support NIST Laboratories external to EEEL.

EEEL FY 1998 CRADAs

EEEL participated in 19 cooperative research and development agreements (CRADAs) with industry during FY1998. CRADA participants included large and small companies across the nation. EEEL actively seeks industrial, academic, and non-profit partners to work collaboratively on projects of mutual benefit. Special efforts are made to tailor cooperative programs to the individual needs of research partners. CRADAs typically cover joint research efforts in which both NIST and the cooperating company provide staff, equipment, facilities, and/or funds, in any number of possible combinations for a project of mutual interest. Under a CRADA, NIST can protect confidential or proprietary information exchanged during the project, keep research results confidential, and provide exclusive rights for intellectual property developed. EEEL welcomes industry to collaborate on projects of mutual interest through the CRADA format. A detailed directory of research areas available for cooperative research, entitled *Guide to NIST*, can be obtained at no cost using fax number: (301) 926-1630.

EEEL FY 1998 CRADAs

ORGANIZATION	PROJECT TITLE
Astralux, Inc.	Processing of GaN Devices
Crystal Technology, Inc.	Analysis of Lithium Niobate Wafers
Cascade Microtech, Inc.	MMIC Consortium
Digital Equipment Corporation	Dielectric/Silicon Interface Property Measurements on Digital Transistors
Environmental Optical Sensors, Inc.	Absorption Cell Technology
Hewlett Packard Company	MMIC Consortium
Hughes Aircraft Company	MMIC Consortium
ITN Energy Systems	Infrared Microantenna-Coupled Diodes for a Flexible Integrated Power Pack
Northstar Photonics	Eye-Safe Q-Switched Solid State Lasers
RF Microsystems (NRAD)	Microwave CMOS Micromachined Power Systems
Schott Glass Technologies, Inc.	Rare-Earth-Doped Waveguide Laser Structures and Photosensitivity in Bulk Glasses
Science Applications International Corporation (SAIC)	HIDE-Low-Cost Microengineered Functional IR Materials
Texas Instruments	NIST Scanning Capacitance Microscopy Image-to-Dopant Profile Software and Metrology Techniques Consortium
Texas Instruments	Magnetic Force Microscopy and Scanning Potentiometry of Thin Film Devices
Texstar, Inc.	Optical Fiber Electric Field Sensors
The Regents of the University of Colorado	General Agreement for Collaborative Research in Optical Electronics
TPL, Inc.	Development of GMR Arrays for NDE Applications
TRW, Inc.	MMIC Consortium
U.S. Air Force Base, Newark AFB	MMIC Consortium

Note: In addition to the CRADAs identified above, EEEL's Office of Microelectronics Programs negotiated CRADAs covering projects NIST-wide with SEMATECH and International SEMATECH.

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813 ELECTROMAGNETIC FIELDS DIVISION

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815 OPTOELECTRONICS DIVISION

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812 SEMICONDUCTOR ELECTRONICS DIVISION

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814 ELECTROMAGNETIC TECHNOLOGY DIVISION

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*Acting Deputy Director of NIST during FY1998
**Serving as EEEL representative in the NIST Program Office during FY1998

EEEL: The Organization

The Electronics and Electrical Engineering Laboratory comprises five divisions and two offices. Laboratory Headquarters, the Electricity Division, the Semiconductor Electronics Division, the Office of Microelectronics Programs, and the Office of Law Enforcement Standards are located in Gaithersburg, Maryland. The Radio-Frequency Technology Division, the Electromagnetic Technology Division, and the Optoelectronics Division are located in Boulder, Colorado.

810 LABORATORY HEADQUARTERS

2220 FRENCH, Judson C., Director

2220 PALLA, Jenilie C., Secretary
2220 HEBNER, Robert E.*
2220 COOKSON, Alan H., Acting Deputy Director
2220 FIELD, Bruce F.**
2220 SACCHET, Linda L., Secretary
2220 MAYO-WELLS, J. Franklin, Staff Asst.

2220 POWELL, Ronald M., Scientific Asst.
2665 RUSSELL, Thomas J., Mgr., Optical Computing Coop. Prog.
5267 SURETTE, JoAnne M., Information Specialist
2228 HORMUTH, James A., Exec. Officer
2220 THOMASSON, Brenda L., Secretary

ADMINISTRATIVE SUPPORT - GAITHERSBURG

2227 HAMILTON, Darlene J., Admin. Ofr.
2229 JOHNSON, Margie I., Admin. Ofr.
2230 GREENHOUSE, Marilyn T., Admin. Ofr.
5633 MURPHY, Joan S., Admin. Ofr. Asst.

ADMINISTRATIVE SUPPORT - BOULDER

3813 ANDRUSKO, Gaynel K., Admin. Ofr.
3514 GLAZE, Terry L., Admin. Asst.
3812 SCHUMP, Jeanne, Admin. Ofr.
5342 McCOLSKEY, Kathy, Admin. Ofr.
5123 DERR, Linda S., Admin. Asst.

OFFICE OF MICROELECTRONICS PROGRAMS

4400 KNIGHT, Stephen, Acting Director
4400 SETTLE-RASKIN, Alice, Secretary
2040 GRAVATT, Cary, Assoc. Director
4400 MARTINEZ, Joaquin V.

*Acting Deputy Director of NIST during FY1998
**Serving as EEEL representative in the NIST Program Office during FY1998

OFFICE OF LAW ENFORCEMENT STANDARDS

2757 HIGGINS, Kathleen M., Director
2757 FATAH, Alim A.
4258 LIEBERMAN, A. George
2757 LYLES, Sharon E.
5128 WATERS, Nathaniel E.
3396 WORTHEY, James A.
2756 LEACH, Marilyn A.
8071 RICE, Kirk D.
8073 LORD, Carter K.

The Office of Microelectronics Programs

The Office of Microelectronics Programs (OMP) matrix-manages a NIST-wide program responding to the measurement requirements of the semiconductor industry. It provides integrated circuit manufacturers, materials suppliers, and makers of semiconductor manufacturing equipment with a clear window on the entire NIST organization. OMP offers direct access to an enormously varied range of scientific and technical expertise.

In addition, OMP manages NIST's strong working relationships with SEMATECH and the Semiconductor Research Corporation, two consortia of American semiconductor manufacturers, and with their many member firms. Research priorities are established on the basis of industry input and the Office's participation in domestic and international conferences and planning activities. The National Semiconductor Metrology Program (NSMP), which was established in 1994, draws on the full range of NIST expertise in semiconductor electronics, manufacturing engineering, chemical and materials science engineering, and fundamental science. NSMP is also managed by the Office of Microelectronics Programs.

The Office of Law Enforcement Standards

The Office of Law Enforcement Standards (OLES) supports criminal justice agencies through the development of measurement methods and techniques for testing devices used in such applications as tracking vehicles, speed monitoring, surveillance, communications, and counterterrorism efforts. The Office develops minimum performance standards for issuance by sponsoring agencies as voluntary national standards. Its mission is to assist federal, state, and local criminal justice agencies to apply new technology efficiently, effectively, and safely. OLES draws upon the technical expertise and resources of all of NIST in its support missions for the National Institute of Justice (NIJ), the research arm of the Department of Justice, and the National Highway Traffic Safety Administration, which is part of the Department of Transportation.

The areas of research investigated by this Office include clothing, communication systems, emergency equipment, investigative aids, protective equipment, security systems, vehicles, weapons, and analytical techniques and standard reference materials used by the forensic science community. In the past fiscal year, OLES has focused on supporting NIJ and criminal justice agencies in identifying those standards that are high priority requirements for providing direct support in counterterrorism efforts. In the year to come, the task will be to focus on expanding existing standards and testing programs to include selected counterterrorism technologies and equipment.

811.00 - ELECTRICITY DIVISION

2400 ANDERSON, William E., Chief

2400 SCHMEIT, Ruth Ann, Secretary
2439 GREENBERG, Joseph, Spec. Assistant
4223 BELECKI, Norman B.
2868 CHANDLER, Joseph W., Computer Network Supp.
4941 DORSEY, Roy W., Div. Calib. Shpg.
4221 PRATHER, Denise, Div. Calib. Serv. Admin.
2404 MARTUCCI, Robin J., Secretary (PT)

.02 ELECTRONIC INSTRUMENTATION AND METROLOGY

2419 BELL, Barry A. (GL)
2402 GREEN, Kathy H., Secretary

Automated Measurements for Voltage, Current, Phase, Power, and Impedance

2408 OLDHAM, Nile M. (PL)
4237 CHANG, Y. May
2412 LAUG, Owen B.(Ctr)
4237 MARTIN, Richard K. (S)
2441 PALM, Robert H. Jr.
2413 PARKER, Mark E.
4244 TILLETT, Summerfield B.
2438 WALTRIP, Bryan C.
2438 YAMAWAKI, Masao (GR)

Waveform Acquisition Device Standards and Test Methods

2406 SOUDERS, T. Michael (PL)
2437 LARSON, Donald R.
2412 LAUG, Owen B.(Ctr)
2441 PALM, Robert H., Jr.
2414 ROY, Sandip (S)

Thermal Transfer Standards and Measurements

4250 KINARD, Joseph R., Jr. (PL)
4247 CHILDERS, Clifton B.
4251 LIPE, Thomas E., Jr.

Calibration and Testing Strategies

2440 STENBAKKEN, Gerard N. (PL)
4518 KOFFMAN, Andrew D.
2406 SOUDERS, T. Michael

Optoelectronic Technology

2405 PAULTER, Nicholas G., Jr. (PL)
2441 PALM, Robert H., Jr.

.04 FUNDAMENTAL ELECTRICAL MEASUREMENTS

3722 KELLEY, Michael H. (GL)
4219 LIVINGSTONE, Sharon D., Secretary

Resistance Standards and Quantum Hall Effect

6591 ELMQUIST, Randolph E. (PL)
4249 CAGE, Marvin E.
4239 DZIUBA, Ronald F.
4240 JARRETT, Dean G.
4225 JONES, George R., Jr.
4236 LEE, Kevin C.
4224 MATTHEWS, John (GR)
4245 MOORE, Theodore P.
4243 SECULA, Andrew J.

Capacitance

6591 ELMQUIST, Randolph E. (PL)
4246 JEFFERY, Anne-Marie
4745 LaDUCA, James R. (S)
4231 LEE, Lai H. (Ctr)
4246 SHIELDS, John Q. (GR)
4232 SHIELDS, Scott H.

Voltage Standards and Josephson Effect

4226 STEINER, Richard L. (PL)
4238 SIMS, June E.
4691 TANG, Yi-hua

Single Electron Tunneling

4226 STEINER, Richard L. (PL)
4219 LOBB, Christopher (GR)
4270 MARTIN, Stuart B. (CP)
4219 SOULEN, Robert (GR)
4219 WELLSTOOD, Frederick (GR)
5887 ZIMMERMAN, Neil M

Watt, Ampere, and Gamma P

4226 STEINER, Richard L. (PL)
4228 NEWELL, David B.
4206 WILLIAMS, Edwin R.

.05 ELECTRICAL SYSTEMS

2403 OLTHOFF, James K. (GL)
2403 MAHON, Sylvia M., Secretary

Dielectrics

3955 STRICKLETT, Kenneth L.
2432 CHRISTOPHOROU, Loucas
3775 HAN, Xiaolian (GR)
2425 VAN BRUNT, Richard J. (GR)

Power and Energy

2986 NELSON, Thomas L.
2417 PETERSONS, Oskars (Ctr)
3956 SIMMON, Eric D.
4688 SNIDER, Lisa
3955 STRICKLETT, Kenneth L.

Pulse Power Technology

2737 FitzPATRICK, Gerald J.
3956 SIMMON, Eric D.
6658 PITT, James A.
2403 WILLIAMS, Derek D. (S)

Electric and Magnetic Fields

2426 MISAKIAN, Martin

Power Quality

2409 MARTZLOFF, Francois D.

Plasma Processing

2403 OLTHOFF, James K. (PL)
2432 CHRISTOPHORU, Loucas
4631 SIEGEL, Ralph B. (GR)
4278 WANG, Yicheng

.06 ELECTRONIC INFORMATION TECHNOLOGIES

4124 ST. PIERRE, James A. (Act. GL)
4222 FROMM, Sharon L., Secretary

Video Technology

3842 KELLEY, Edward F. (PL)
3014 BOYNTON, Paul A.
3063 CHANG, Raymond (S)
2428 FENIMORE, Charles P.
3828 LIBERT, John M.
2077 ROITMAN, Peter

Infrastructure for Integrated Electronic Program

4124 ST. PIERRE, James A. (PL)
4478 ANG, Jeremy C. (S)
3644 BRADY, Kevin
4478 EKPERIGIN, Tuoyo O. (S)
2304 GOLDSTEIN, Barbara
4479 KUTA, Michael J. (S)
4099 McLAY, Michael J.
4229 McCALEB, Michael R.
4284 MESSINA, John V.
3517 PARKS, Curtis H.

Infrastructure for Integrated Electronic Manufacturing

2304 GOLDSTEIN, Barbara (PL)
3644 BRADY, Kevin
4479 McBRIDE, Anthony C. (S)
4099 McLAY, Michael J.
3517 PARKS, Curtis H.
4124 ST. PIERRE, James A.

The Electricity Division

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

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

812.00 - SEMICONDUCTOR ELECTRONICS DIVISION

2074 SEILER, David G., Chief

2054 MAIN, Brenda P., Secretary
2079 BENNETT, Herbert S., NIST Fellow
2068 BLACKBURN, David L., Assignee to Semiconductor Res. Corp.
2242 BUCK, Laurence M., Computer Facility Mgr. (Property Officer)
2097 HARMAN, George G., NIST Fellow
5466 McBRIDE, Duncan, ComSci Fellow from NSF
2050 SECULA, Erik M., Lead Editorial Assistant
2296 ROHRBAUGH, Janet M., Editorial Assistant
2048 LOWNEY, Jeremiah R. (GR)
2054 OETTINGER, Frank F. (GR)

.01 MATERIALS TECHNOLOGY

8009 SHAFFNER, Thomas J. (GL)
2053 HUFF, Barbara J., Secretary

Metrology for Compound Semiconductor Manufacturing

2123 PELLEGRINO, Joseph G. (PL)
3241 GAJEWSKI, Donald A.
5329 GUYER, Jonathan
2087 MONK, David H.
2081 SMIRL, Arthur L. (GR)
5291 TSENG, Wen F.

Optical Metrology for Semiconductor Manufacturing

5974 AMIRTHARAJ, Paul M. (PL)
6582 BALCHIN, Gregory A. (GR)
2084 CHANDLER-HOROWITZ, Deane (Laser Safety Officer)
2108 RENNEX, Brian G. (PT)

Scanning Probe Microscope Metrology

2089 KOPANSKI, Joseph J. (PL)
2238 KIM, Jin S.
2088 MARCHIANDO, Jay F.
2067 THURBER, W. Robert

.03 DEVICE TECHNOLOGY

2071 HEFNER, Allen R., Jr. (GL)
2056 CROWE, Cheryl D., Secretary

Processing in the Semiconductor Processing Laboratory (SPL)

2699 NOVOTNY, Donald B., SPL Mgr.
2095 KREPPS, Guilford L.
2094 RUSSELL, Raymond G.

Metrology for Simulation and Computer-Aided Design

2071 HEFNER, Allen R., Jr., (PL)
2075 ALBERS, John
2069 BERNING, David W.
6586 BOUCHE, Sebastian (GR)
5193 SHEN, Bruce (GR)
4745 TU, Cheng B. (GR)
2055 ZHU, Huibin (GR)

.04 IC TECHNOLOGY

2052 LINHOLM, Loren W. (GL)
2052 WILKES, Jane M., Secretary
2236 ELLENWOOD, Colleen H., CAD Facility Mgr. (PT)

Metrology for Process & Tool Control

2072 CRESSWELL, Michael W. (PL)
5026 ALLEN, Richard A.
4446 GHOSHTAGORE, Rathindra N. (GR)
2182 GUILLAUME, Nadine (GR)
5623 OWEN, James C.
2820 OYEBANJO, Olanrewaju (GR)

Gate Dielectric and Interconnect Reliability Metrology

2247 SUEHLE, John S. (PL)
5420 AFRIDI, Muhammad (GR)
2111 CHEN, Yuan (GR)
2078 EDELSTEIN, Monica D., Safety Officer
5466 HEAD, Linda (Ctr)
2045 MAYO, Santos
2234 SCHAFFT, Harry A. (PL)
2241 SCHUSTER, Constance E.
4723 VOGEL, Eric

MicroElectroMechanical Systems

2070 GAITAN, Michael (PL)
5484 GEIST, Jon (GR)
4739 HOPCROFT, Matthew (GR)
2049 MARSHALL, Janet C. (PT)
4706 MILANOVIC, Veljko (GR)
4796 OZGUR, Mehmet (GR)
4710 SMEE, Stephen A. (GR)
2239 ZAGHLOUL, Mona E. (FH)
2073 ZINCKE, Christian A. (GRF)

.05 THIN-FILM METROLOGY

2060 EHRSTEIN, James R. (GL)
2081 ROACH, Ramona, Secretary

Thin-Film Process Metrology

2060 EHRSTEIN, James R., (PL)
2248 BELZER, Barbara J.
2044 NGUYEN, Nhan Van
5373 PERKINS, Mike (GR)
2082 RICHTER, Curt A.
2065 RICKS, Donnie R.

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GL = GROUP LEADER
GR = GUEST RESEARCHER
GS = GRADUATE STUDENT
N/F = NIST FELLOW
PD = POSTDOCTORAL APPOINTMENT
PL = PROJECT LEADER
PREP = PROFESSIONAL RES. EXPERIENCE PROG.
PT = PART TIME
S = STUDENT
WS = WORK STUDY

Semiconductor Electronics Division

The Semiconductor Electronics Division provides leadership in the development of the semiconductor measurement infrastructure essential to improving U.S. economic competitiveness. The Division provides measurement methods, physical standards, and supporting data and technology; any associated generic technology; and fundamental research results to industry, government, and academia.

The Division's primary focus is on mainstream silicon but its programs also respond to industry measurement needs related to compound semiconductors, power devices, and silicon-on-insulator devices. The Division plans and implements its programs in cooperation with the semiconductor industry, its suppliers, and its customers to assure that the critical needs of the community are being addressed. To enhance its effectiveness, the Division collaborates and partners with industry, academia, other government agencies, and standards organizations.

813.00 - RADIO-FREQUENCY TECHNOLOGY DIVISION

3131 FRIDAY, Dennis S., Chief
3132 LYONS, Ruth Marie, Secretary
3037 MARKS, Roger B., Wireless Testbed Program
5284 DeLARA, Puanani L., Property Ofr.
3753 HEWITT, Paula M., Measurement Services
3302 SANDERA, Sharon L., Editorial Assistant
3302 BASSETT, David N., Secretarial Aid

.01 RADIO-FREQUENCY ELECTRONICS GROUP

3380 JUDISH, Robert M. (GL)
5755 RIVERA, Susie, Secretary

High Speed Microelectronics

3138 WILLIAMS, Dylan F. (PL)
5491 KAISER, Raian
3015 MORGAN, Juanita
4034 PADILLA, Allen (PREP-S)
3447 REED, Kristopher (PREP-S)
5490 WALKER, David K.

Power, Voltage, and Impedance

3609 FREE, George M. (PL)
5871 ALLEN, J. Wayde
5778 CLAGUE, Fred
3524 ONDREJKA, Connie
5593 PITTMAN, Earle S.
3939 SHERWOOD, Glenn V.
3365 VORIS, Paul

Noise

3150 RANDA, James P. (PL)
5737 BILLINGER, Rob
5958 JONES, Chriss A.
3280 TERRELL, L. Andrew
3610 WAIT, David F. (GR)

Non-linear Devices

7212 DeGROOT, Don (PL)
3596 JARGON, Jeffery

Electromagnetic Properties of Materials

5305 WEIL, Claude M. (PL)
5621 BAKER-JARVIS, James R.
5852 GEYER, Richard G.
5533 GROSVENOR, John H., Jr.
3656 JANEZIC, Michael D.
5752 RIDDLE, Bill F.

Network Analysis

5362 JUROSHEK, John (PL)
3634 GINLEY, Ronald A.
3210 LeGOLVAN, Denis X.
5249 MONKE, Ann F.
5231 PACKER, Marilyn E.
5048 TALLEY, Kenneth E.

.02 RADIO-FREQUENCY FIELDS

5703 REPJAR, Andrew G. (GL)
3321 HAAKINSON, Edit, Secretary

Near-Fields Antenna Techniques

5702 CANALES, Seturnino, Jr.
5873 FRANCIS, Michael H.
3863 GUERRIERI, Jeffrey R.
3471 MacREYNOLDS, Katherine
3927 STUBENRAUCH, Carl F. (GR)
3694 TAMURA, Douglas T.

Standard EM Fields and Transfer Probe Standards

3214 CAMELL, Dennis
3737 JOHNK, Robert T.
5320 KANDA, Motohisa
3756 MASTERSON, Keith D.
5332 MEDLEY, Herbert W.
3168 NOVOTNY, David

EMC Measurements & Facilities

3995 CAVCEY, Kenneth A.
3472 HILL, David A.
5766 KOEPKE, Galen H.
5372 LADBURY, John M.

Antenna Systems Metrology

3603 MUTH, Lorant A.
3326 WITTMANN, Ronald

Radio-Frequency Technology Division

The Radio-Frequency Technology Division provides national metrology support for the measurement of the fundamental properties of devices, components, materials, and systems essential to the advancement of radio-frequency (RF) technology and for the measurement of RF electromagnetic (EM) field properties necessary to characterize EM emissions and environments. Its focus, the radio-frequency spectrum, is the broad region of the electromagnetic spectrum between the audio and the infrared.

The Division's programs are dedicated to fundamental theoretical and experimental research to advance the science and practice of the measurement of free-space, bounded and guided EM fields, and the characteristics of RF devices and systems. Its major activities include developing physical standards and test and measurement methods, and providing calibration and special-test services, standard reference materials and standard reference data to clients. In addition, the Division collaborates with industry, academia, and other government agencies to provide expert technical support that enhances national commercial and military competitiveness.

814.00 - ELECTROMAGNETIC TECHNOLOGY DIVISION

3776 HARRIS, Richard E., Chief
3678 BRADFORD, Ann G., Secretary
5068 SIMMON, Mary Jo, Cler. Asst.

.01 MAGNETIC RECORDING METROLOGY

3374 PAPPAS, David (PL)
5477 CORWIN, Ruth, Secretary
3381 ARNOLD, Stephen (GR)
3841 RICE, Paul
3141 THOMSON, Ruth Ellen

.02 MAGNETIC INSTRUMENTS & MATERIALS CHARACTERIZATION

3650 GOLDFARB, Ron (PL)
3701 CRAWFORD, Thomas (PD)
3997 KABOS, Pavel (GR)
7365 KAKA, Shehzu (PREP)
5333 KOS, Tony
5206 RIZZO, Nick (PD)
5097 RUSSEK, Steve
7826 SILVA, Tom
5477 YEE, Gordon (GR)

.03 NANOPROBE IMAGING FOR MAGNETIC TECHNOLOGY

3641 MORELAND, John (PL)
3188 LOEHNDORF, Marcus (GR)

.05 SUPERCONDUCTOR STANDARDS AND TECHNOLOGY

3143 GOODRICH, Loren (PL)
3777 STAUFFER, Ted

.06 SUPERCONDUCTOR INTERFACES AND ELECTRICAL TRANSPORT

5448 EKIN, Jack (PL)
5631 BRAY, Steve
5441 CLICKNER, Cam
3722 COLLINS, Tim (Ctr)
5345 SESSELMANN (GR)
7894 XU, Yizi (Ctr)

.07 JOSEPHSON ARRAY DEVELOPMENT

3740 HAMILTON, Clark (PL)
5258 BENZ, Sam
3906 BURROUGHS, Charlie
3340 HARVEY, Todd
3988 McCARTHY, Sandy E., Secretary

.08 NANOSCALE CRYOELECTRONICS

5081 RUDMAN, Dave (PL)
5344 BERGREN, Norm
7644 CHERVENAK, Jay (PREP PD)
3148 COVINGTON, Mark (PD)
5606 DULCIE, Laura
3418 EICHENBERGER, Ali (GR)
5679 HILTON, Gene C.
3402 HUBER, Martin (Ctr)
5911 IRWIN, Kent
3391 KAUTZ, Dick (GR)
5430 KELLER, Mark
3597 MARTINIS, John
3988 NAM, Sae Wao (NRC PD)
3021 RABIN, Michael (NRC PD)
7457 WOLLMAN, Dave

.09 HIGH PERFORMANCE SENSORS, INFRARED DETECTORS, AND MIXERS

5102 GROSSMAN, Erich (PL)
7064 KOCH, Jay
5052 REINTSEMA, Carl
3114 NOLEN, Shalua (PREP PD)

.10 HIGH T_c INTEGRATED CIRCUITS

3762 ONO, Ron (PL)
5989 BEALL, Jim
7900 BOOTH, Jim
5049 CREWS, Maggie
7213 SKIMAKAGE, Hisashi
5121 VALE, Leila
3988 WILLIAMS, Christine (WS)

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GL = GROUP LEADER
GR = GUEST RESEARCHER
GS = GRADUATE STUDENT
N/F = NIST FELLOW
PD = POSTDOCTORAL APPOINTMENT
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PREP = PROFESSIONAL RES. EXPERIENCE PROG.
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Electromagnetic Technology Division

The Electromagnetic Technology Division develops and promotes advanced standards and measurement methods based on cryogenic phenomena, especially superconductivity, and on magnetics. The Division creates new standards, instruments, and measurement technology, advancing the state-of-the-art by basic research and the development of requisite metrology, lithographic fabrication techniques, and materials. The output is used broadly in the semiconductor, instrumentation, superconductor, and magnetic data storage industries as well as others.

815.00 - OPTOELECTRONICS DIVISION

5204 DAY, Gordon W., Chief
5202 CLARK, Alan F., Deputy Chief
5342 SMITH, Annie J., Secretary

.01 SOURCES AND DETECTORS

3651 SCOTT, Thomas R. (GL)
3842 SKINNER, Dorothy L., Secretary
3741 CASE, William E. (Ctr)
3052 CLEMENT, Tracy S. (PT)
5620 CROMER, Christopher L. (PL)
7455 DOWELL, Marla L.
5367 HALE, Paul D. (PL)
3439 JONES, Richard D.
5583 KEENAN, Darryl A.
3654 LEHMAN, John H.
5162 LEONHARDT, Rodney W.
3621 LI, Xiaoyu
5898 LIVIGNI, David J.
5747 OBARSKI, Gregory E.
3696 PHELAN, Robert J., Jr. (Ctr)
3789 SIMPSON, Philip A. (Ctr)
5253 TOBIAS, Iris L.
3394 VAYSHENKER, Igor
5342 ZHANG, Zhuomin (Ctr)

.02 FIBER AND INTEGRATED OPTICS

3805 WILLIAMS, Paul A. (Act. GL)
5187 METZ, Sara E., Secretary
5858 DRAPELA, Timothy J.
3346 FRANZEN, Douglas L. (Ctr)
3296 GARCIA, Jose (GR)
3250 KALRA, Punit S. (PREP)
5409 MECHELS, Steven E.
3542 SCHLAGER, John B.
3223 YOUNG, Matt (PL)

.03 OPTICAL COMPONENTS

3120 GILBERT, Sarah L. (GL)
3842 SKINNER, Dorothy L., Secretary
3359 CRAIG, Rex M.
7463 DYER, Shellee D. (PREP PD)
7630 ESPEJO, Robert J. (PREP)
3287 ETZEL, Shelley M. (PT)
7630 FEAT, Nicolas (GR)
7728 GILL, Erin M. (PREP-GS)
5342 HUBBARD, Margaret A. (PD)
7367 KREGER, Stephen T. (PD)
5170 ROCHFORD, Kent B.(PL)
5599 ROSE, Allen H.
7381 SWANN, William C.
7630 WEST, John W. (PREP)

.04 OPTOELECTRONIC MANUFACTURING

3455 HICKERNELL, Robert K. (GL)
5187 METZ, Sara E., Secretary
3942 AUST, J. Andrew
5069 BERTNESS, Kristine A.
3354 CHRISTENSEN, David H.
3289 FUNK, David S. (PREP PD)
3234 HAYS, Scott (PREP GS)
7368 KNOPP, Kevin J. (PREP GS)
7955 MIRIN, Richard P.
7300 PETERS, Phil M. (GR)
5420 ROSHKO, Alexana
5239 SANFORD, Norman A. (PL)
7948 SILVERMAN, Kevin L. (PREP-GR)
7953 SUMAN, Christopher C. (PT)
5952 VEASEY, David L.

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GL = GROUP LEADER
GR = GUEST RESEARCHER
GS = GRADUATE STUDENT
N/F = NIST FELLOW
PD = POSTDOCTORAL APPOINTMENT
PL = PROJECT LEADER
PREP = PROFESSIONAL RES. EXPERIENCE PROG.
PT = PART TIME
S = STUDENT
WS = WORK STUDY

Optoelectronics Division

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

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

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 FY1998. Also included are profiles of EEEL's organization, customer interactions, and long-term goals.

Keywords

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

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