ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY • NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

EEEL 1995
TECHNICAL ACCOMPLISHMENTS

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 a portfolio of four major programs:

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

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

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

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

In fiscal year 1995, NIST operated on a total budget of about $885 M with approximately 3,200 staff members at its sites in Gaithersburg, Maryland and Boulder, Colorado. For further information about NIST, call (301) 975-3058 or e-mail: inquiries@nist.gov (via Internet).

COVER:
Omega is the symbol of the Ohm, the basic unit of resistance. It conveys an important aspect of NIST's original charter, the provision of the Nation's primary electrical standards. Information on this aspect of EEEL's work can be found in the section on National Electrical Standards, Page 45.

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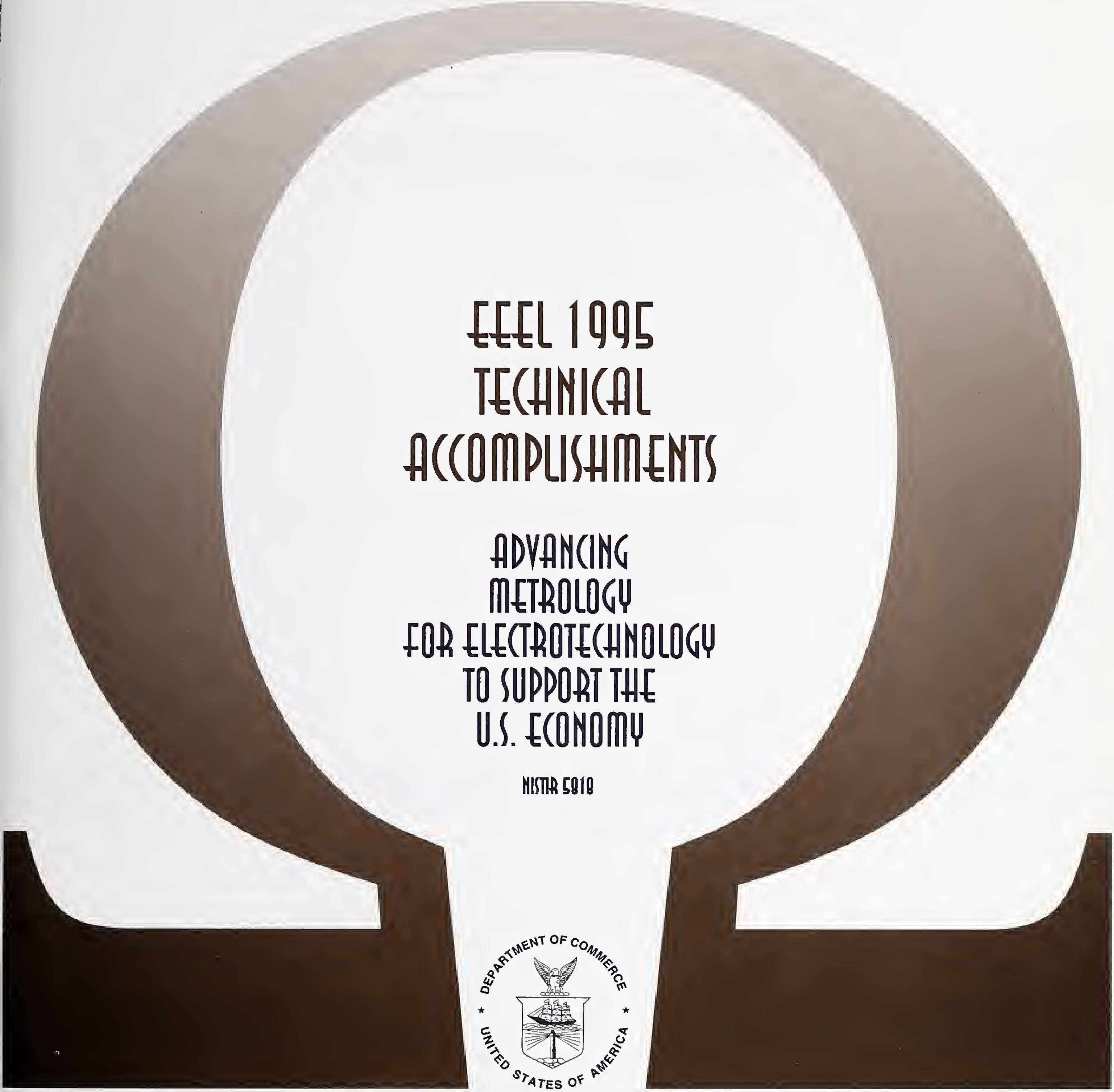

EEEL 1995 TECHNICAL ACCOMPLISHMENTS

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

NISTIR 5818

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

Technology Administration
Mary L. Good, Under Secretary for Technology

National Institute of Standards and Technology
Arati Prabhakar, Director

December 1995

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LABORATORY

NIST continues to be a government organization in which the two phrases "Good enough for government work" and "World's best" frequently mean the same thing. The staff of EEEL has continued to provide U.S. industry with the capability to make electrical measurements that are competitive anywhere in the world. With the Congress and the Administration in significant disagreement regarding the 1996 budget and their respective mandates from the electorate, fiscal year (FY) 1995 ended with significant fiscal uncertainty. I am pleased to report that with respect to our work these past twelve months, the year was one of accomplishment.

SEMICONDUCTOR METROLOGY:
40 YEARS OF WORK

D.G. SEILER, J.C. FRENCH, R.I. SCACE

DIRECTOR'S MESSAGE

Forty Years of Semiconductor Metrology. For example, this year we celebrated a fortieth anniversary of the initiation of our work in semiconductor metrology. As I consider our achievements over that time span, I marvel at how technology, people, and projects change, but the demand for improved metrology has remained unabated.

In 1955, shortly after the transistor was invented, the successful transistor program at NIST was spun off to a separate entity, the Harry Diamond Laboratory. However, given the potential metrology needs for this emerging technology, $30,000 was awarded to fund a continuing program here. The sum was divided among three sections in the Electronics and Electricity Division. Two-thirds of that amount was dedicated to successful projects that disappeared when the services and sections were superseded. The final $10,000 was assigned to me for metrology work.

What Should We Contribute? Since nearly every technical agency in the Washington area had transistor work underway, the challenge was to determine what we could do within our mission that was needed and unique. I soon discovered that most agencies needed help in characterizing their devices and materials — there were no universally available or accepted measurement methods and only a limited number of commercial test sets. Because a focus on measurements was both unique and especially appropriate to NIST, we consulted with two industry associations, the American Society for Testing and Materials and the Electronic Industries Association, to further define a measurement program. Our goal was to define industry's need for NIST services, if such a need existed. Well, the response was immediate and vigorous — Fortune 500 companies argued for the opportunity to define problems and persuade us to solve them "their way."

Who Can Best Define the Problem? Members of each association identified measurements which were important both to manufacturing processes and to product specifications. In each instance, the measurements included great discrepancies for which there was no acceptable resolution. Well, we selected one problem that matched our mission and competence from each organization. Both were successfully addressed with results which were applied industry wide — and these first projects set the tone for the whole future of the program which continues today.

I will not finish the tale, because the task is not complete. But I should note that economic studies on the impact of solving these two problems showed benefits estimated by industry of more than $30,000,000 (more than 100 times the cost of the work) in marketplace transactions alone, and perhaps ten times this amount in manufacturing economies.

LABORATORY DIRECTOR'S MESSAGE

Then and Now: Standards of Excellence

WORKING ON SECOND BREAKDOWN METROLOGY H.A. SCHAFFT

WORKING ON ELECTROMIGRATION METROLOGY H.A. SCHAFFT

I would like to underscore my observation that while technology, people, and projects change, the need for improved metrology persists by highlighting the activities of one of EEEL's staff members, Harry Schafft. Harry, currently a member of the Semiconductor Electronics Division, worked on one of these first problems: the property and potential failure mechanism "second breakdown." For a long time, second breakdown represented a costly problem in power semiconductors. What were principally Harry's methods for characterizing the property were adopted throughout the industry for its power device specifications. His work was also credited with resolving a problem in the main engine control, which was delaying the launch of a space shuttle a few years ago. Today, Harry is providing the industry with expert modeling of the failure mechanism of electromigration, which results from such high current densities that the electron flow moves material and breaks the connection. His electromigration results have been used by at least fourteen companies, including IBM, National Semiconductor, Intel, and Unisys, and an external study has estimated industrial savings already of $26 M in return for the $1.6 M spent on the project.

It goes without saying that Harry's work is an exemplar of the work being done by members of his Division. For lack of space, many other staff scientists credited with historical breakthroughs in this field will remain unsung, but permit me to share with you a statement by the Semiconductor Industry Association that mirrors our longstanding commitment: "Metrology is a key enabler for equipment design and manufacture, for materials production, for generating data for modeling throughout semiconductor manufacturing, and for final test and evaluation. Without satisfactory metrology, the industry will not be able to follow the Roadmap and will cease to be competitive... ." As can be seen in our technical accomplishments, we continue to be dedicated to assuring that this satisfactory metrology is available.

> "We remain grateful for any opportunities to work with your outstanding researchers at NIST and look forward to our continued relationship in technology advancement."
>
> Senior Vice President
> Keithley Instruments, Inc.

We Welcome Your Interest in EEEL

We welcome your interest in NIST's Electronics and Electrical Engineering Laboratory (EEEL). As you may realize, EEEL provides measurement capability of high economic impact focused primarily on the needs of this country's electronics and electrical equipment industries. We do this by providing measurement research and services, principally in our five technical divisions. In the Electricity Division, we honor our original charter, the provision of the Nation's basic, primary electrical standards, and also support electronic instrumentation, the electrical utilities, video technologies, and electronic product data exchange.

In the other divisions, our support encompasses semiconductor electronics, radio-frequency and microwave- and millimeter-wave signals and interference, superconductors, magnetics, and optoelectronics. We also have two offices: the Office of Law Enforcement Standards, which provides technical soundness to tests of products used by law enforcement officers, and the Office of Microelectronics Programs, which administers the National Semiconductor Metrology Program. Each office matrix-manages laboratory work across NIST. More detailed information about each Division and Office can be found in the section entitled "EEEL: The Organization." Examples of the work sponsored by our Laboratory Offices can be found in the section entitled "Programs Matrix-Managed by EEEL."

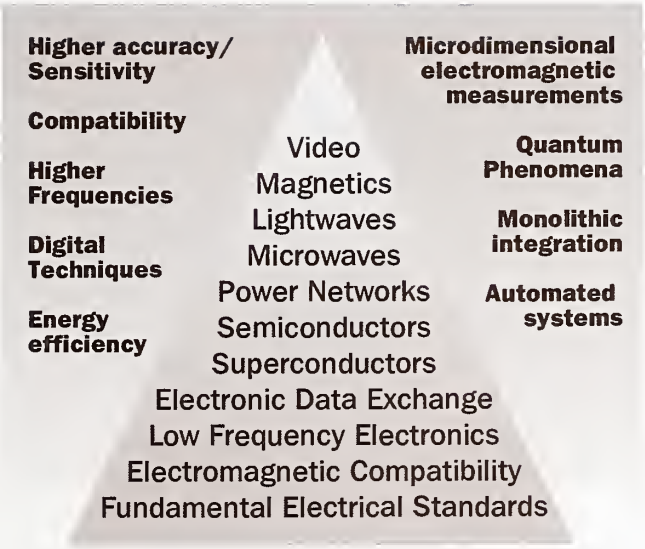
EEEL's Philosophy and Strategy

A thumbnail sketch of EEEL's philosophy or governing principles is perhaps most easily captured in this précis of EEEL's Strategic Plan. The summary of EEEL's Technical Thrusts reflects the priorities established by the Laboratory as well as the organization of this publication. A glance through this document will tell you that our primary focus is measurement.

The sophisticated industry we serve — the fast-moving world of electrotechnology — continues to outstrip the measurement tools available to control its materials and processes and evaluate its products.

Vision:	To be the world's best source of fundamental and industrial-reference measurement methods and physical standards for electrotechnology
Business:	Providing measurement infrastructure for industry and commerce in electronics
Customers:	Electronics industry, its suppliers and customers
Criteria:	Unique research and services with highest quality and highest impact on customers and institutional health
Priority:	Customer-driven, through in-depth determinations of critical needs for today and for tomorrow
Delivery:	Interactive transfer, with complete description, using all effective methods, including customer participation
Evaluation:	Real-time and long-term impact evaluation; both anecdotal and by economically sound methods

EEEL'S PHILOSOPHY



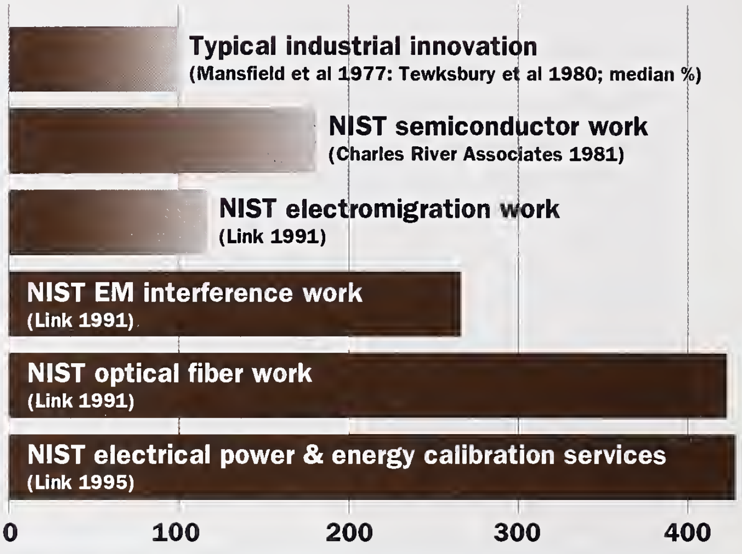
EEEL'S STRATEGY

> "We strongly support and encourage NIST's efforts to produce standards and cooperate with the American Electronics Industry to solve key problems. ... teamwork played a significant part in solving this complex manufacturing problem."
>
> Director
> Global Microcontamination
> Applied Materials, Inc.

LABORATORY DIRECTOR'S MESSAGE

The Difference is Documented

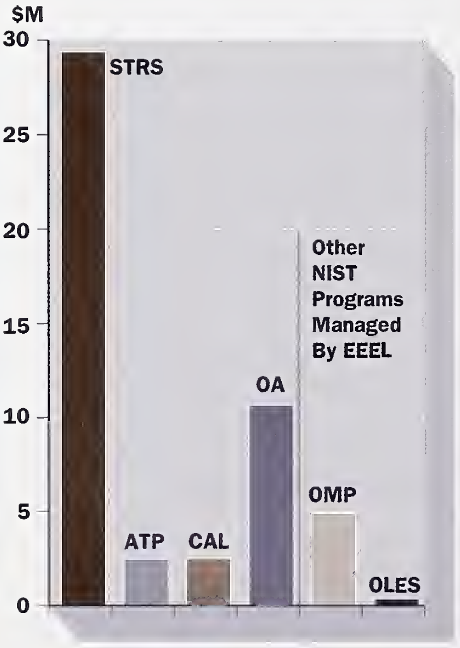
The bottom line is that EEEL really makes a difference to the industries we serve: improving their productivity and profitability as shown by our return on investment data — our median rate of return is well over twice that found for private sector innovation. The impact of our efforts, documented by statements of appreciation and support from industry, stimulates new products and new company start-ups, changes important industry practices, and influences technical and policy actions. Thus, EEEL never lacks exciting and unusual tasks, but given the broad spectrum of problems we are capable of addressing, these tasks must be chosen carefully to maximize return on taxpayers' investment.



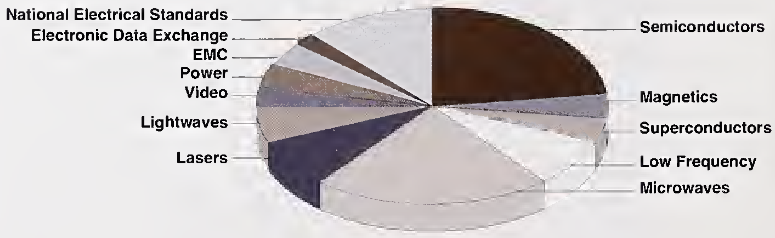
EEEL'S FORMAL IMPACT STUDIES

Resources and Challenges

Our resources comprise a total budget of $46 M of which approximately $30 M is Congressionally-appropriated for Scientific and Technical Research and Services (STRS), and a staff of 322 supplemented by 79 guest scientists and research associates. These resources have a profile in funding and professional staff generally characteristic of all the NIST Laboratories, but we are unique in providing more than 40 percent of all NIST's calibration services, representing an income of $2.1 M. To ensure that we invest our resources wisely, we maintain close interaction with industry during the research selection process and through the course of the research ensuring continuous feedback on our progress, and, finally, by evaluating our actual impact with the assistance of our clients. From the onset, we have committed to making a difference where it counts the most — and to do that, you need to talk to the people grappling with the problems, the people with problems to solve. Because we are neutral, companies trust us with their confidences — often many companies are grappling with the same problems unbeknownst to each other — and we can serve the overall industry well by careful focus and selection.



FY 1995 RESOURCES



FY 1995 RESOURCES BY TECHNOLOGY FIELD

THE WATT EXPERIMENT: DETAIL OF BALANCE WHEEL AND MASS ARTIFACT

The Best is Yet to Come

In the section entitled "EEEL Awards and Recognition," you will note some of the work done in the past year that has been singled out for acknowledgment. We take pride in these accomplishments because they reflect high standards of relevant, practical metrology. As we move toward new frontiers, excitement rises . . . "the best is yet to come." For example, staff in the Electricity Division continue their development of the NIST watt balance. They are exploring the possibility of "reversing" the operation of the balance to measure the kilogram, given that NIST has intrinsic quantum standards for voltage and resistance. Recent progress includes being able to demonstrate sensitivity to 0.1 part per million, implementing a new vertical alignment of the magnetic field, and the design of a new refractometer — all of which will further the goal of being first to realize the electronic kilogram. In this photograph, two critical elements of EEEL's watt experiment are shown: the balance wheel and the working mass standards, the primary standards representing the last mass artifact, which we are hoping to replace with an electrical measurement. In this as in other achievements in metrology, EEEL/NIST expects to reinforce America's leadership as a world-class institute.

Thank you for taking the time to reminisce with me about our past and future work. We welcome your interest in our Laboratory.

French

Judson C. French, Director
ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

EEEL AND ITS CUSTOMER INTERACTIONS

EEEL conducts extensive interactions with people and organizations outside NIST, especially with EEEL clientele. For example, EEEL staff participated in 130 collaborative projects with industry in FY 1995, including those covered by forty-two active Cooperative Research and Development Agreements. The work done in many of these projects addresses cutting-edge technology. Participating companies benefit from direct access to NIST measurement technology, capabilities, and staff. When commercialization occurs as the result of the interaction, the company can benefit quickly; later, the aggregate results often benefit the economy as a whole. As part of this activity, EEEL continued its leadership role in two consortia formed previously by the Laboratory in response to industry needs.

In a new program sponsored by NIST, three members of the EEEL staff were selected to be Industry Fellows. The Fellows were invited by American companies to spend up to a year at their respective sites, contributing to the technical work and becoming familiar with the company's technical and managerial perspectives. Using more traditional channels, 244 members of EEEL staff interacted with customers through participation in professional societies; 66 members held memberships in standards-writing organizations. The standards work involves over 50 EEEL technical experts, who also contributed leadership skills. Further contacts were made with customers through meetings of various types: Laboratory staff conducted 29 short courses and workshops and organized seven major technical meetings in FY 1995. All told, some 2,800 individuals participated in these events. In addition, EEEL provided major input to 63 off-site conferences during the year. Laboratory staff also welcomed 55 guest scientists and 440 visitors in FY 1995, and reciprocated with nearly the same number of visits. The majority of these visits were to customers and, many times, staff were invited to present talks on recent NIST developments to company staff.

Taken together, the results of these interactions provide significant improvements to the measurement base needed by the U.S. electronics sector. Industry benefits through its staff having direct contact with those who are developing the metrology tools. In some cases, the interaction results in the immediate implementation of a NIST-developed method for conducting a measurement that enriches the company's technology resources. In others, the contact can constitute a partnership in which both parties work together to refine a laboratory method for industrial use, or the entire development may be a mutual effort. Another benefit to industry is indirect: measurement problems revealed by our customers become a determining factor in our strategic- and project-planning. This, in turn, improves our capability to respond to the measurement challenges in time to meet their needs. Eleven patent disclosures were prepared in FY 1995, five patents were issued, and three patent applications were filed. Eighteen patent cases were active at the close of the year. The staff holds 19 patents issued since the formation of NIST's Office of Technology Commercialization. The Laboratory served 380 calibration customers, who paid fees of more than $2.4 M. Revenue from the sale of 115 Standard Reference Materials exceeded $131 K. Some 380 copies of software packages developed by EEEL staff were distributed on request. The continuing demand for these services and artifacts demonstrates their importance to industry.

FISCAL YEAR 1995 ACTIVITIES

The Omnibus Trade and Competitiveness Act of 1988 identifies NIST as the Nation's lead laboratory for measurements. This designation confers the responsibility to use NIST's resources to assure that the United States has world class measurement capability to support research and development, manufacturing, efficient commerce, and after-sale support. Meeting this responsibility requires both a leading edge, laboratory-based, research and development program and activities to assure that key needs are identified and the appropriate measurement technology is being developed, the developed measurements are being used, and U.S. measurements are recognized worldwide. Examples of the more significant EEEL activities in both domestic and international areas are presented here.

DOMESTIC ACTIVITIES

Work with Industry Segments

Semiconductors

As the semiconductor industry drives toward smaller and smaller feature sizes in increasingly complex circuits with a decreasing cost per function, its manufacturing needs are exceeding current measurement technology. The dynamics of this industry make it extremely challenging for EEEL to assure that NIST provides the correct products in a timely manner. Steps have been taken, under the leadership of Robert I. Scace, to meet this challenge. First, an overview of the NIST program was arranged for representatives from companies that manufacture integrated circuits; from SEMATECH, the research and development consortium of integrated circuit manufacturers; from the Semiconductor Research Corporation, an organization that funds university research in semiconductor technology; and the Semiconductor Industry Association (SIA), the trade association for integrated circuit manufacturers. The interaction stimulated a better linkage between the NIST program and industrial needs.

A second significant activity was the establishment, by the SIA, of a committee to identify the key measurement needs of the industry. NIST was invited to participate in this committee to gain information on emerging needs and to facilitate the transfer of measurement capability from NIST to the industry. The committee was formed and held its first meeting this year. Scace is leading this activity at NIST.

During this year, NIST staff organized and hosted two major workshops for industry and government participants which examined the future of the industry's measurement needs. The workshops covered the unique characterization of silicon integrated circuit development and manufacturing, and compound semiconductor materials and devices.

The first workshop, chaired by David G. Seiler, Chief of the Semiconductor Electronics Division, along with experts from the semiconductor community, including AT&T Bell Labs, Hewlett Packard, Hughes Research Laboratories, Intel, Motorola, Rockwell International, SEMATECH, SEMI, and Texas Instruments, focused on mainstream silicon-based technology. Scientists and engineers from many disciplines related to semiconductor characterization address the key techniques and technologies that will shape the future of silicon-based semiconductors.

The second workshop focused on the significantly smaller but important segment of the industry that works with compound semiconductors — the materials from which semiconductor lasers and light-emitting diodes are made. Such devices may find increased use in wireless communication systems and high-speed circuits. Participants concluded that a road map for the development of this technology is needed. NIST staff, under the leadership of Herbert S. Bennett, has been working with the Electronics Industry Association to see if such a road map can be developed.

Electronics Manufacturing

The National Electronics Manufacturing Initiative (NEMI) is a comprehensive industry-government partnership to expand electronics manufacturing in this country by helping industry manufacture globally competitive products profitably. NEMI was established in 1994.

NIST was among the founding members because we need to understand when the lack of appropriate measurement capability is an impediment to manufacturing. During this past year, the industry has worked to define its needs. Judson C. French led the NIST participation. The initial success of the NEMI effort will lead to coordinated government-industry technical activities during the coming year.

Electromagnetic Interference

As electronic devices and systems become more pervasive throughout our homes, businesses, and industries, there is growing concern that one device will interfere with another. These interferences may range from mildly irritating, for example, when a vacuum cleaner interferes with television reception, or potentially dangerous, which accounts for the requirement that certain electronic devices be turned off as airplanes take off or land. Emissions from and immunity to outside interference is the subject of regulation around the world.

NIST, under the leadership of Motohisa Kanda, hosted a workshop for U.S. industry to determine if the measurement base in the United States was adequate to permit U.S. companies to compete in world markets. The workshop identified a number of problems with measurement accuracy, traceability, and standards. The NIST program has been refocused to address some of the more pressing needs.

Lightwaves

NIST staff, under the leadership of Douglas L. Franzen, has developed a good working relationship with the Telecommunication Industries Association (TIA). The interaction focuses on the activities of the TIA's technical committees which develop voluntary standards for the industry and identify current and anticipated industrial measurement needs. As a result of this interaction, EEEL is developing a series of Standard Reference Materials and test techniques to improve industry's ability to test optical-fiber based telecommunication systems.

Gordon W. Day has led the NIST effort to work with the Optical Industry Development Association (OIDA) in its attempt to develop a road map for the optoelectronics industry in the United States. The OIDA has hosted technical meetings to solicit technical information to support the road map, has drafted a road map, and has circulated the draft for comment to key industry leaders. NIST is contributing to the development so that we can assure ourselves that the measurement capability that we provide will be timely and appropriate.

INTERNATIONAL ACTIVITIES

Cooperation Among World Regional Metrology Groups

One of NIST's responsibilities is to assure that measurements made in the United States are consistent with those made around the world. With this consistency, measurements will not serve as a nontariff trade barrier to the export of U.S. goods. EEEL began two significant activities this year which are intended to help assure the required level of international consistency. The first is the improvement of international comparisons of electrical measurements coordinated by the International Bureau of Weights and Measures (BIPM). The Consultative Committee on Electricity of the BIPM met and decided to attempt to develop a sparse, robust set of electrical measurements that would underpin the mutual recognition of calibrations performed by national measurement laboratories around the world. Robert E. Hebner of EEEL was selected to chair the Working Group that is developing the set of measurements.

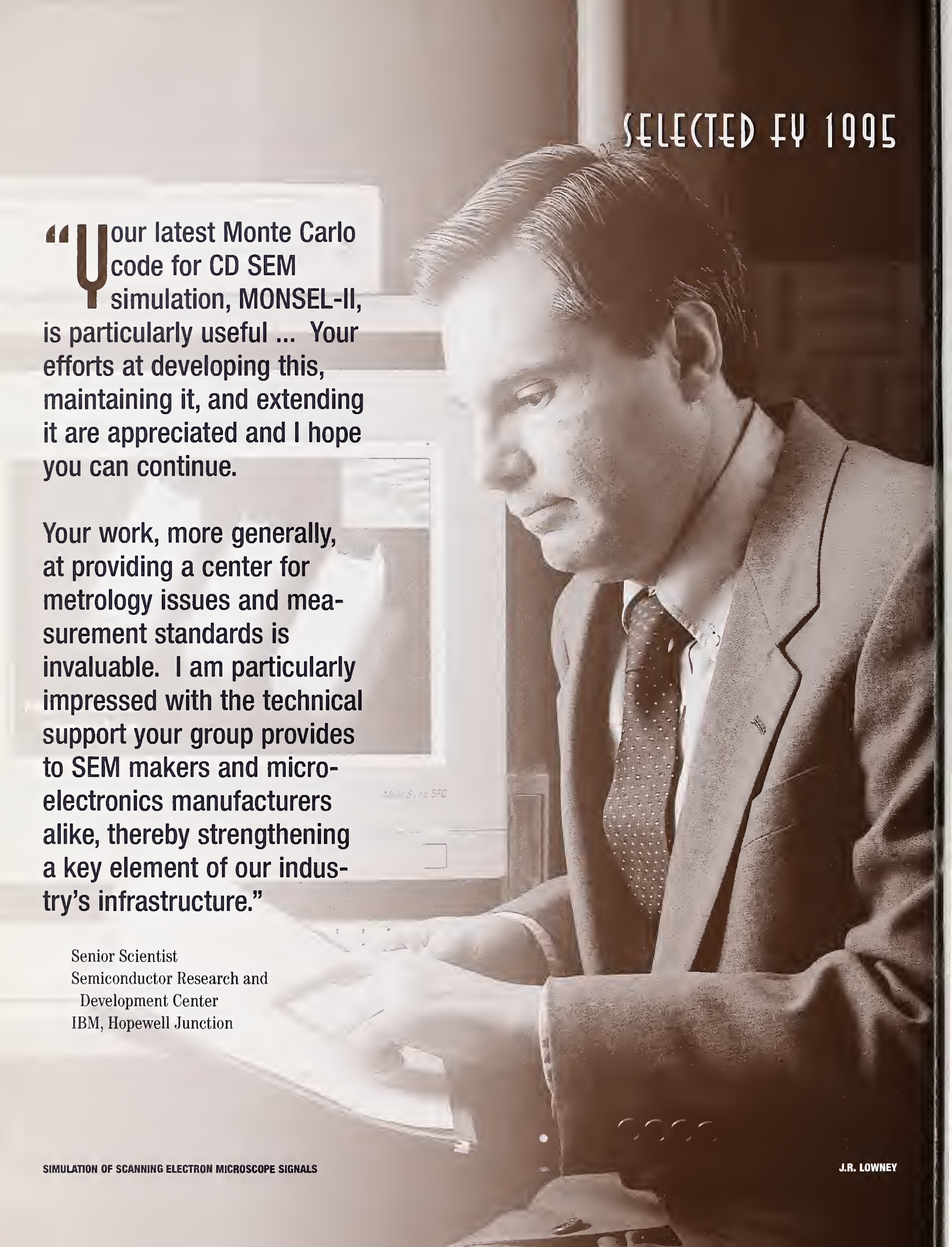
To improve measurements in the Americas, NIST also worked with U.S. industry, the Federal Aviation Administration, and the Organization of American States to sponsor a conference called "Metrology in the Americas." The EEEL contribution to this conference was coordinated by Norman B. Belecki. This Conference attracted about 200 metrologists who developed technical plans to conduct formal comparisons of measurement capability among countries, compared experiences on the level of metrology required for different types and levels of industrial development, and shared experiences on assuring measuring consistency within a country.

These activities are needed to organize and coordinate the necessary measurement comparisons between countries. Comparisons which are being conducted or initiated include:

- Electric power and energy at power frequencies
- Capacitance
- Antenna factor
- Electrical noise measurements
- Comparison of time varying and time invariant signals using thermal converters
- Resistance
- Voltage.

U.S. – Japan Joint Optoelectronics Project

As part of the 1993 U.S.–Japan Agreement on Cooperation in Research and Development in Science and Technology, Judson C. French is leading EEEL's effort to coordinate a bilateral program to advance manufacturing of optoelectronic components. The program arranges for the fabrication, in each country, of advanced designs by university, industrial, or government researchers, and, as such, both stimulates the design of novel optoelectronic devices and strengthens the manufacturing capability.



> "Your latest Monte Carlo code for CD SEM simulation, MONSEL-II, is particularly useful ... Your efforts at developing this, maintaining it, and extending it are appreciated and I hope you can continue.
>
> Your work, more generally, at providing a center for metrology issues and measurement standards is invaluable. I am particularly impressed with the technical support your group provides to SEM makers and microelectronics manufacturers alike, thereby strengthening a key element of our industry's infrastructure."

Senior Scientist
Semiconductor Research and
Development Center
IBM, Hopewell Junction

SIMULATION OF SCANNING ELECTRON MICROSCOPE SIGNALS

J.R. LOWNEY

TECHNICAL ACCOMPLISHMENTS

> "Jerry Lowney's modeling effort is very important. The models will not only help NIST in establishing a line width standard, but it will also help us to understand how our measurement tools interact with our products. ...I strongly encourage your team to continue this modeling effort."
>
> Group Leader
> Measurement Standards Laboratory
> IBM, Essex Junction

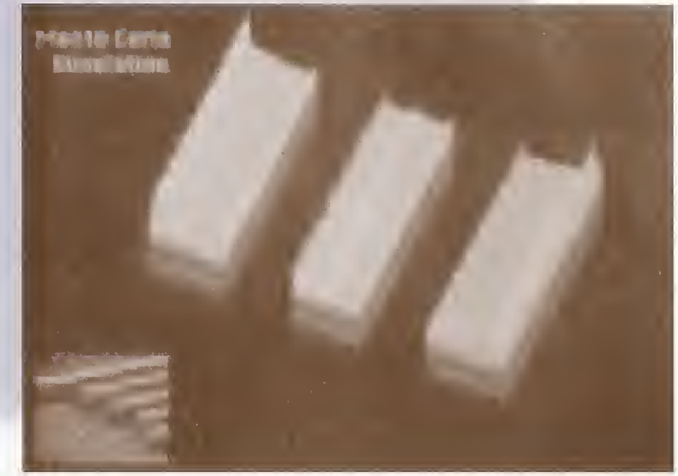
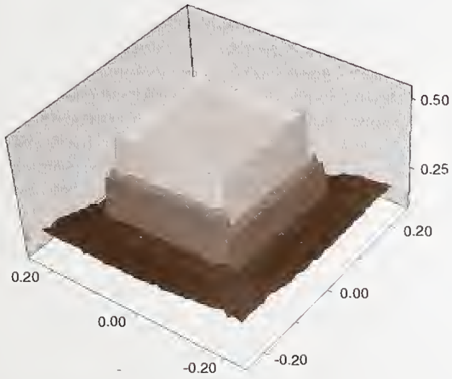


IMAGE OF THREE GOLD LINES ON A SILICON SUBSTRATE

1 SEMICONDUCTORS



SIMULATED BACKSCATTERED YIELD FROM 3D GOLD TARGET ON SILICON (DIMENSIONS IN MICROMETERS)

1.1 Road map goal for length measurement met

The location of an edge in a patterned silicon target has been determined to an uncertainty of less than 6 nanometers from comparisons between simulated and measured backscattered- and secondary-electron signals in a scanning electron microscope (SEM). This achieves, in principle, the goal of the National Technology Roadmap for Semiconductors that the uncertainty in critical-dimension measurements be reduced to 7 nanometers by 2010. Jeremiah R. Lowney of EEEL has completed work on two Monte Carlo codes, which are based on first-principles physics, that simulate the backscattered-, secondary-, and transmitted-electron signals from complex targets in the SEM. Michael T. Postek and Andras Vladar, staff members in the Manufacturing Engineering Laboratory at NIST, have made measurements on a specially made target composed of a 1,000 nanometer step in a silicon substrate in a very-high-accuracy SEM. By overlaying the measured data with the simulation, which predicts the expected signal for a given target geometry, it is possible to determine the position of a measured feature in the target to a low level of uncertainty. This work concludes a five-year collaboration of these researchers that advanced the state of the art in critical-dimension metrology.

Without the simulation, one would not be able to determine the edge location accurately and be forced to use a "rule of thumb." All one could conclude is that the edge occurred somewhere within the region of increased signal. With the simulation, one can determine the edge location visually to within ±3 nanometers, which is a reduction in uncertainty by at least a factor of four due to the modeling. The simulations are produced by Lowney's Monte Carlo

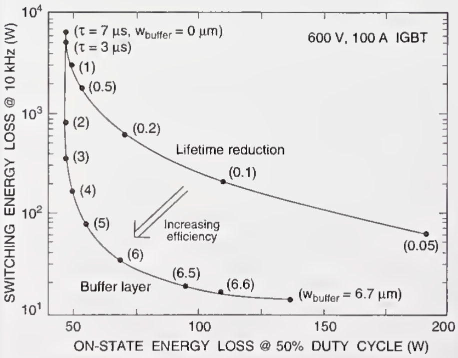
ACCOMPLISHMENTS

> **"It is my view that CD [critical dimension] standards activity for current manufacturing tolerances cannot be successful without a rigorous foundation based upon simulation. Further, the understanding gained through simulation, along the way to standards development, is essential for optimization of equipment reproducibility. It is clear to me that the current simulation program at NIST leads the field and as such must continue to make rapid progress."**
>
> Principal Manufacturing Engineer
> Digital Equipment Corp.

code, named MONSEL-II, which is for two-dimensional target variations. Lowney has written an extension of this code, named MONSEL-III, to compute three-dimensional target features. These codes are being made available to U.S. industry, academia, and other government laboratories. To date, eight laboratories and two universities have obtained the codes.

1.2 NIST power semiconductor model key to industrial circuit design

A NIST mathematical model describing the behavior of insulated gate bipolar transistors (IGBTs) that include a buffer layer has been adopted by a U.S. company for inclusion in their Saber circuit simulator software package. A "bullet proofed" beta version of the model has been qualified and is part of the company's standard product offering.



NIST PREDICTION THAT BUFFER-LAYER IMPROVES IGBT EFFICIENCY

NIST researchers Allen F. Hefner and David L. Blackburn predicted in 1986 that the inclusion of a buffer layer could be used to substantially improve IGBT performance compared to conventional lifetime reduction techniques. Recently, a new class of commercial devices called Ultra-Fast IGBTs has begun to emerge that utilize the buffer-layer concept to optimize device performance, as predicted by the work published earlier by NIST.

Meanwhile, the NIST IGBT model, provided within Saber since 1991, has gained widespread acceptance by the power electronic circuit design community and has been used in the development of numerous new electronic products. In view of the emergence of this new class of advanced buffer-layer IGBT devices, the company worked with NIST through a Cooperative Research and Development Agreement to incorporate the new buffer-layer IGBT model developed by Hefner into their Saber simulator.

The availability of the buffer-layer IGBT model in a widely used circuit simulator will enable circuit designers to better utilize the improved performance of these new Ultra-Fast-type IGBT devices. IGBTs are the preferred devices for most high-power applications such as industrial motor drives, air-conditioning compressors, internal-combustion vehicle electronic ignition modules, and electric vehicle propulsion systems. It is also expected that high-voltage IGBTs will begin to have applications in electric power distribution and railroad propulsion systems. The new model will also enable IGBT device manufacturers to better optimize IGBTs for realistic circuit application conditions using software prototypes for model-based design.

SEMICONDUCTORS

MICROGRAPH OF MICRO-HOTPLATE WITH MICROBRIDGE SUSPENDED OVER ETCHED SILICON PIT

1.3 NIST micro-hotplate device used with gas-sensing applications

Three patents on a micro-hotplate device and its applications have been awarded as a result of a collaborative effort between Michael Gaitan and John S. Suehle of EEEL and Stephen Semancik and Richard Cavicchi of the Chemical Sciences and Technology Laboratory (CSTL). These patents cover the design and use of a micro-hotplate device and its gas-sensing applications with metal-oxide films. In this collaborative effort, EEEL focused on the design, fabrication, and reliability testing of the micro-hotplate devices, and CSTL focused on the deposition and testing of the metal-oxide films.

Micro-hotplates are miniature hotplates, such as those on an electric stove. These devices are building blocks for making micro-chemical sensors on integrated circuit chips. The miniaturization of hotplates allows scientists to change the micro-hotplate temperature very quickly and make and test new sensing materials. The small size of the device also allows scientists to build many hotplates on a single integrated circuit chip. Several micro-hotplate devices can fit on the head of a pin. One class of materials of interest is called metal-oxide films, such as tin-oxide. These materials can be used with the micro-hotplate to sense gases that factories and automobiles produce. Such devices will enable the monitoring of the environment and thus the reduction of chemical emissions. Many companies have expressed a strong interest in using NIST's patents to develop new products for affordable testing of automobile emissions and other types of environmental-monitoring applications.

Micro-hotplates of this type have two distinct advantages over conventional hotplates. The high thermal isolation of this device allows high temperatures on the hotplate structure, a high thermal efficiency so that increasing the power by one thousandths of a watt will raise the temperature by 20 degrees Celsius, and rapid temperature transients from room temperature to 400 degrees Celsius on the order of one thousandth of a second. Secondly, array integration of the heaters with their own individual electronics allows scientists to create a temperature-programmable surface.

ACCOMPLISHMENTS

"Optical E.T.C., Inc. (OETC) has been working with NIST since 1992 to develop the technology leading to a viable thermal-infrared dynamic display device (thermal flat panel display, TFPD), utilizing silicon micromachining of commercial-foundry CMOS devices designed by our respective groups. Through our mutual efforts, NIST and OETC have advanced the technology to a stage adequate to fabricate the first complete demonstration infrared test set for testing infrared sensor and seeker systems.

As a small business, OETC could not have reasonably developed the TFPD technology without the collaboration of NIST personnel and access to the extensive facilities at NIST... In 1994, the GAO selected the NIST/OETC CRADA as one of the top-12 most-effective CRADAs in the nation. The quality of the performance of NIST personnel has been outstanding. In addition, we are pleased to have co-authored a number of papers together and have two accepted for presentation in early 1996."

President
Optical E.T.C., Inc.

A novel application of the micro-hotplate is as a gas analyzer. Electrical contacts on the hotplate allow scientists to measure the electrical conductivity of films. A group of metal-oxide films, such as tin-oxide, exhibit electrical conductivity changes at elevated temperatures in the presence of certain gases. The conductivity response of the metal-oxide films will change as a function of film temperature and film doping with materials such as palladium, in the presence of different gases. By combining the control of temperature and film doping, scientists can change the sensitivity of the gas sensors to various gases. These effects are being utilized to create a gas analyzer chip that can measure gas concentrations of constituent gases in gas mixtures.

1.4 Powerful new technique to measure interface roughness demonstrated

Interface roughness plays an important role in determining the performance of a variety of silicon and compound semiconductor devices. For example, it has been reported in the technical literature that interface roughness decreases the efficiency of compound semiconductor vertical-cavity surface-emitting lasers (VCSELs). It has also been reported that interface roughness degrades transistor performance (switching speed) and transistor reliability (shortened transistor lifetimes). Furthermore, the trend toward more dense circuitry and smaller devices is driving oxides to become thinner, accentuating the effects of interface roughness.

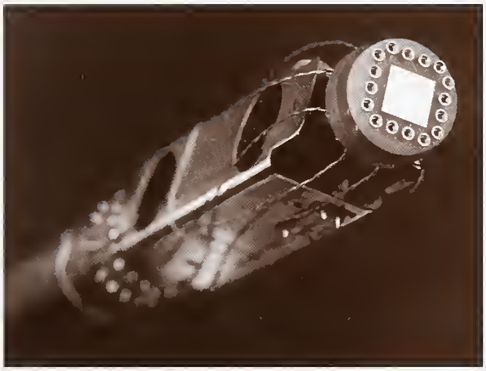
The National Technology Roadmap for Semiconductors predicts that at the turn of the century, gate-oxides will have an effective thickness of approximately 4 nanometers (which corresponds to about 10 atomic layers). In this regime, deviations in the oxide thickness due to interface roughness become increasingly important, because they are a larger percentage of the overall thickness.

NIST scientist Curt A. Richter has implemented a unique electron transport technique at NIST to measure the roughness of buried interfaces in compound semiconductor transistor devices. This measurement methodology, which is based upon weak-localization effects stemming from the quantum mechanical properties of electrons, allows interface roughness to be quantitatively measured based upon funda-

SEMICONDUCTORS

mental physics; specifically, it is not model dependent. Root-mean-square values of interface roughness have been measured in a variety of high-electron mobility transistors with intentionally rough interfaces, demonstrating that interface roughness can be measured with an uncertainty of less than 0.05 nanometer. While compound semiconductor devices were used to demonstrate this technique, the measurement is being applied to characterize silicon devices.

A custom cryostat was designed and assembled that combines the following capabilities necessary to perform these measurements of interface roughness: crossed magnetic fields, a fine-control tilting-sample-stage, and liquid-helium operation. This apparatus is used to observe weak-localization: a small increase in the device resistance that arises from the quantum-mechanical wave properties of electrons at low temperatures. By probing this resistance increase with crossed magnetic fields, an accurate, quantitative value for interface roughness can be obtained for a given device.



TRANSISTOR ON SAMPLE STAGE

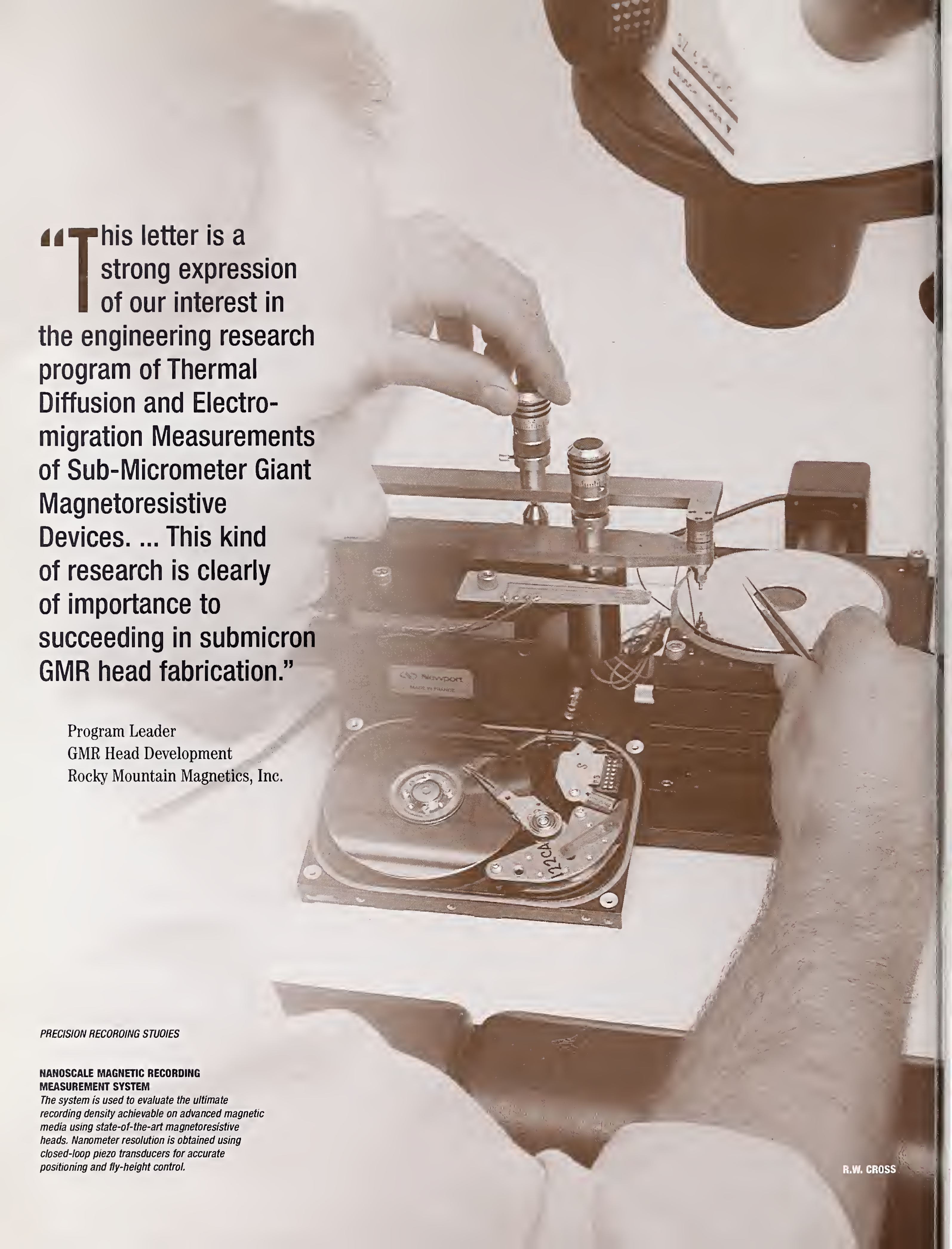
Other techniques that measure interface roughness vary depending upon the physical model used. Because this weak-localization technique is model invariant, it will allow these other metrology tools to be evaluated. Also, because interface roughness is a detriment to many semiconductor devices, and may become more so as device dimensions shrink, its quantitative determination is becoming increasingly important.

LOADING SILICON DEVICE ON TILTING SAMPLE STAGE FOR INTERFACE ROUGHNESS MEASUREMENTS **C.A. RICHTER**

> **"I would like to take this opportunity to thank you for your assistance with my research. The data I have obtained in your lab has provided us… with new insights into the transport properties of our quantum well infrared photodetector (QWIP) structures…"**
>
> Scientist
> Advanced Infrared Technologies Department
> Martin Marietta Laboratories

> “This letter is a strong expression of our interest in the engineering research program of Thermal Diffusion and Electromigration Measurements of Sub-Micrometer Giant Magnetoresistive Devices. ... This kind of research is clearly of importance to succeeding in submicron GMR head fabrication.”

Program Leader
GMR Head Development
Rocky Mountain Magnetics, Inc.



PRECISION RECORDING STUDIES

NANOSCALE MAGNETIC RECORDING MEASUREMENT SYSTEM
The system is used to evaluate the ultimate recording density achievable on advanced magnetic media using state-of-the-art magnetoresistive heads. Nanometer resolution is obtained using closed-loop piezo transducers for accurate positioning and fly-height control.

R.W. CROSS

ACCOMPLISHMENTS

The Magneto-Optic Kerr Effect/Scanning Near-field Optical Microscope (MOKE/SNOM) is one of the first of its kind for the imaging and analysis of recorded "bits" in magnetic media. Near-field optical principles are used to obtain sub-wavelength resolution.

SCANNING NEAR-FIELD MAGNETO-OPTICAL MICROSCOPE **T.J. SILVA**

The plasmon probe, the glass structure for the MOKE/SNOM, supports thousands of tiny silver particles (20-40 nm in diameter) which are used as microscopic probes. By analyzing the polarization of light scattered from the probes when they are within a few tens of nanometers from the sample surface, the shape of magnetic domain patterns can be determined with a resolution exceeding the wavelength of light.

2 MAGNETICS

2.1 How small can magnetic recording heads be?

In its push to squeeze more and more data onto magnetic disk drives, industry is forced to reduce the size of the read heads it uses to extract stored information. A new class of materials exhibiting giant magnetoresistance is under development. Measurements at NIST are helping clarify the problems that must be solved.

Using electron beam lithography, Steven E. Russek, Ralph W. Cross, and Steven C. Sanders created narrow stripes, less than 1 micrometer wide, made of these materials. They drove the same large currents through the stripes that would be used in practical read heads. What they observed were large jumps in electrical response due to magnetic domain switching. These effects are irregular and device-specific. In wider stripes, they are not so pronounced. Before ultra-small commercial devices can be introduced, the measurements indicate that basic problems with domain stabilization must be resolved.

These effects are general properties of a wide class of giant magnetoresistive materials. John Oti compared the experimental data with a micromagnetic simulation. His results qualitatively describe the experimental data and provide insight into the detailed micromagnetic behavior of these films.

2.2 Scanning near-field magneto-optic microscope with 20-nanometer resolution

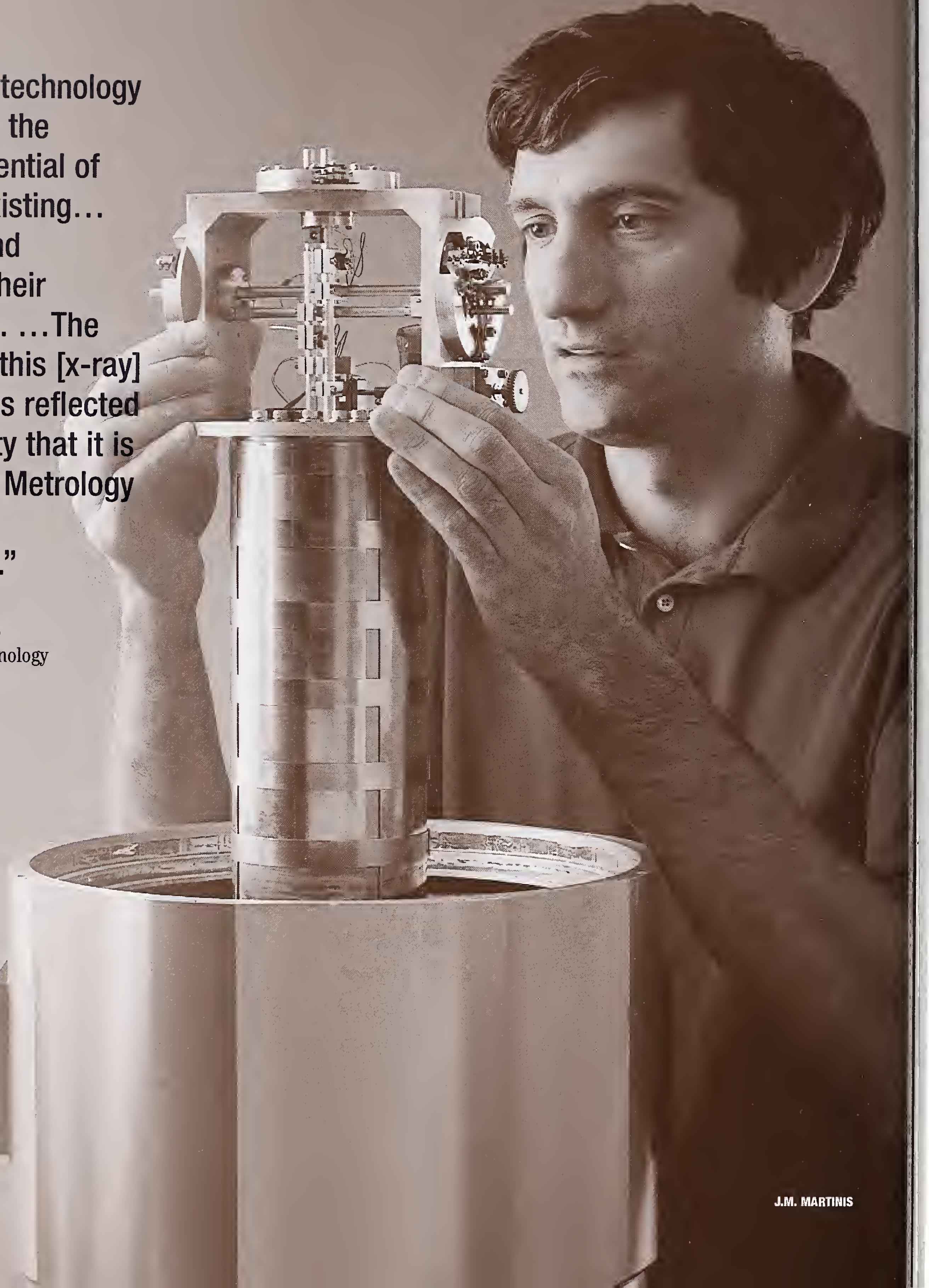
Thomas J. Silva and Anthony B. Kos continued development of the scanning near-field magneto-optic microscope for 20-nanometer resolution imaging of magnetic domains in optically opaque samples. When fully developed, the new microscope will be able to image the ultra-small magnetic structures that are required by the next generation of magnetic disk drives. Such measurement capabilities are important for the magnetic data storage industry as it pushes data densities toward fundamental material limits.

A major advance was made in the software required to operate the Newton-ring interferometer required for the scanning microscope. The interferometer regulates the spacing between the near-field probe (a 30-nanometer silver particle) and the sample surface via closed-loop feedback control of a piezoelectric positioning system. The first version of the control and imaging software has been completed and several images, including some near-field yttrium-iron-garnet images, have been obtained.

Silva, working with University of Colorado Professor Charles Rogers and graduate student Thomas Crawford, found that contrast produced by the second-harmonic magneto-optic Kerr effect is extremely large for metal films of Permalloy, a widely-used soft magnetic alloy of nickel and iron. This is almost three orders of magnitude larger than that measured using conventional magneto-optic contrast for this material. The researchers hope that combining their measurement technique with micromagnetic modeling will provide a unique tool for addressing the magnetic properties of interfaces in thin film systems exhibiting giant magnetoresistance. A better understanding of the magnetic properties of interfaces will greatly aid magnetic data-storage industry engineers in their endeavors to make commercial use of giant magnetoresistance for ultra-high-density read heads.

“…This technology has the potential of replacing existing… detectors and expanding their applications. …The potential of this [x-ray] technology is reflected in the priority that it is given in the Metrology Road Map Supplement.”

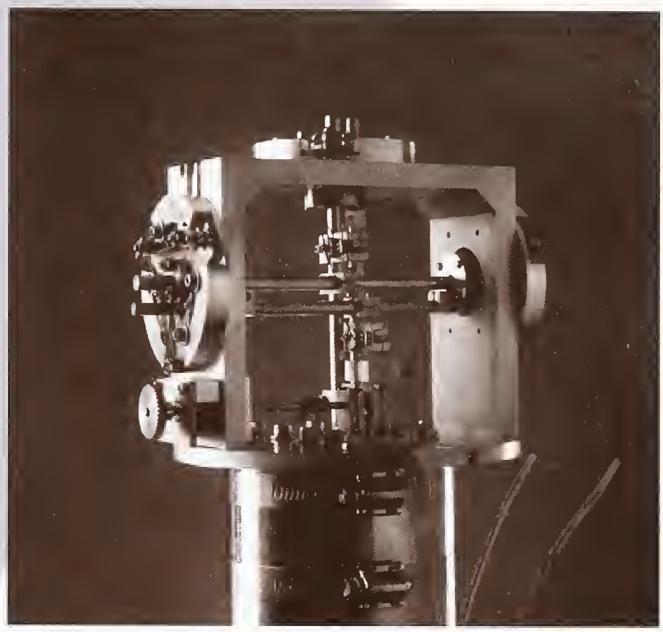
Senior Scientist
Analytical Technology
Infrastructure
SEMATECH



INSTALLING AN ADIABATIC DEMAGNETIZATION REFRIGERATOR IN AN X-RAY DETECTOR (CRYOSTAT INTRUMENT)

J.M. MARTINIS

ACCOMPLISHMENTS



MECHANICAL SUPPORTS OF ADIABATIC DEMAGNETIZATION REFRIGERATOR

3 SUPERCONDUCTORS

3.1 Large-area hot-electron x-ray microcalorimeter

X-rays emitted by excited atoms have energies characteristic of those atoms. Measuring the energy spectrum of x-rays emitted by a material sample provides a chemical analysis of the material, or at least that's what is supposed to happen. One commonly used fast x-ray detector has limited energy resolution which blurs nearby x-rays and confuses the analysis. Another has good energy resolution but such slow counting rates that data collection requires a prohibitively long time.

John M.Martinis, and co-workers Gene C. Hilton, Kent D. Irwin, and Michael Nahum, invented a novel x-ray detector based on sensing temperature rise with a superconducting thermometer. They have demonstrated detectors having energy resolution of 22 electron volts, 6 times better than present fast detectors, while retaining the fast counting rate of present high resolution detectors. Their theory for the detector predicts that, with further development, it can provide a resolution smaller than 1 electron volt.

Their colleagues in industry are excited about possibilities such as the analysis of contaminants in semiconductors. However, the excitement is tempered with a concern about practicality — how the detectors can be practical when they must operate at temperatures below 0.1 kelvin, just above absolute zero. The NIST workers have accepted the challenge and have constructed a compact adiabatic demagnetization refrigerator that houses the detector and mounts on standard x-ray instruments. They are on the verge of demonstrating its use in a standard laboratory environment.

ACCOMPLISHMENTS

> **“The successful VAMAS inter-laboratory comparison of critical currents in BSCCO 2223 High Temperature Superconductor (HTS) has been very valuable to American Superconductor Corporation (ASC). This successful demonstration of the ability of multiple laboratories around the country to consistently characterize the material furnished to NIST by ASC is an acknowledgement of the maturity of the technology and a very necessary step in the path to commercial use… NIST played a key role in this project by ‘pre-measuring’ the samples, managing the routing data collection, and performing expert analysis of the results. This, and similar NIST work associated with the establishment of international standards for HTS, are 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.”**

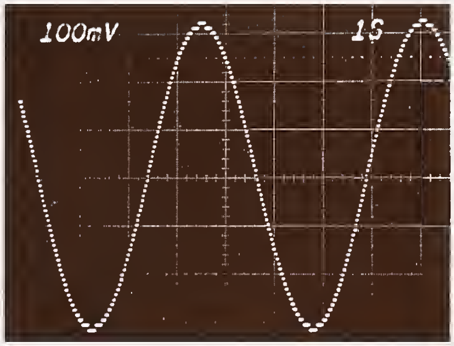
Chief Technical Officer
American Superconductor Corporation

3.2 Programmable voltage standards reach one-third volt

Over the past ten years workers at NIST have provided the United States and many other countries with steady state, i.e., dc, voltage standards based on series arrays of superconducting Josephson junctions. Until now the application of this fundamentally accurate technology to produce time varying, i.e., ac, signals has eluded scientists worldwide.

Clark A. Hamilton and Charles J. Burroughs designed a new voltage standard integrated circuit and demonstrated both ac and dc operation over 4096 levels between -320 and +320 millivolts.

Three important new measurements were made: (1) The chip was used to make linearity measurements of a commercial nanovoltmeter at 1500 points. This measurement is not practical with a conventional Josephson standard. (2) By comparing equal halves of the arrays of junctions on the programmable voltage standard chip, they demonstrated absolute uncertainty of 0.1 nanovolts (28 bits relative to the maximum output of 320 millivolts). (3) A computer was used to send a digital code to the programmable array in order to synthesize a sine wave at the output.



SINE WAVE SYNTHESIZED BY JOSEPHSON D/A CONVERTER

So far the new standard contains just under 10,000 Josephson junctions. Some designs for standards with a 10 volt range could require up to one million junctions. To reduce the size of junctions, Samuel P. Benz recently demonstrated an important breakthrough in palladium-gold barrier superconductor-normal-superconductor (SNS) junctions for this application. SNS junctions also provide much greater stability compared with conventional junctions.

The new standard is a fully programmable voltage reference. It can synthesize fundamentally accurate ac waveforms, and it can perform all of the functions of present dc Josephson standards with greater speed and convenience.

3.3 Year-long interlaboratory comparison of critical current on high temperature superconductor samples completed

Since their discovery in 1986, high-temperature superconductors have attracted the attention of scientists and business people alike. They offer the possibility of carrying electrical currents with essentially zero loss. While cooling with liquid nitrogen (77 kelvin) is required, doing so is vastly more convenient and less expensive than cooling conventional superconductors with liquid helium (4.2 kelvin). With high-temperature superconductors, the magnet system that makes magnetic resonance imaging possible could be much less expensive, allowing more widespread use of this important medical diagnostic tool.

Worldwide, the high-temperature superconductor industry must provide accurate measurements of the properties of its superconducting wires. Loren F. Goodrich and Theodore C. Stauffer completed measurements for a worldwide interlaboratory comparison of critical current measurements on high-temperature superconductor specimens. The critical current is the largest current that the specimen can carry and remain superconducting. This complicated comparison, which took a year to complete, involved five U.S. laboratories in addition to NIST, two specimens from U.S. industry, and data on about 60 specimens at 4.2 kelvin and 77 kelvin. Different styles of specimen mounting and different

SUPERCONDUCTORS

routing patterns among the laboratories were also incorporated.

Preliminary results indicated that this was the first successful comparison on critical currents in high-temperature superconductors. A few small systematic errors and two significant magnetic field errors were discovered.

Not only is NIST leading world activities in actual measurements, but Goodrich is also chairing the International Electrotechnical Commission's Technical Committee 90 on superconductors. This committee was expanded only a few years ago and is drafting internationally agreed-upon standards for use worldwide.

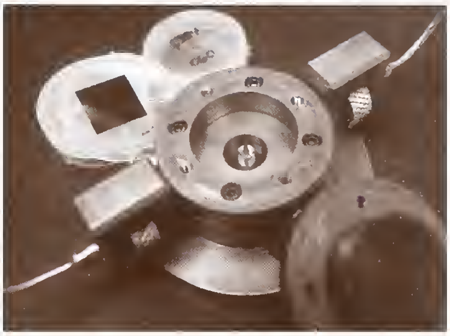
3.4 High-temperature superconductor measurements for wireless communications

High-temperature superconductors (HTS) can be critical elements in microwave components for wireless communications. Their low loss enables them to be made into filters that separate the various calls arriving at a cellular telephone base station. Measurements at NIST are helping develop this new technology and to solve a serious problem. While the superconductors behave superbly with the small incoming signals, they don't yet handle the high outgoing power from the base station.

AUTOMATED MEASUREMENT SYSTEM FOR TESTING MICROWAVE POWER-HANDLING CAPABILITY OF HIGH-TEMPERATURE SUPERCONDUCTOR THIN FILMS

J.A. BEALL

James A. Beall, with assistance from Donald C. DeGroot, Ronald H. Ono, and David A. Rudman, has developed a simple, rapid technique for characterizing the microwave properties of high-temperature superconductor films.



SAPPHIRE DIELECTRIC ROD RESONATOR USED IN HTS SURFACE-RESISTANCE MEASUREMENTS

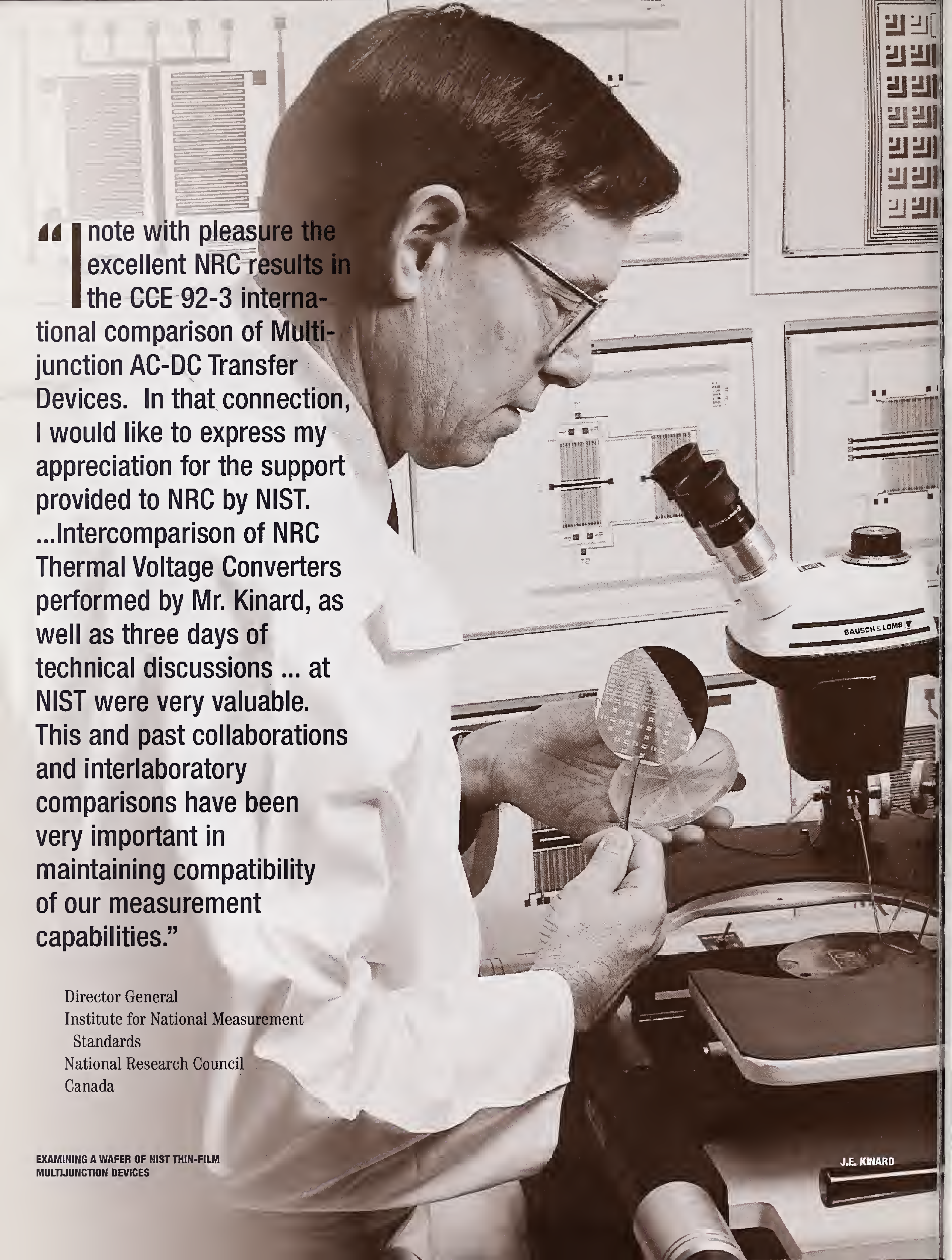
The automated (computer driven) data acquisition system makes pulsed microwave measurements of the power handling ability of superconductor thin films. The pulsed measurement is required to avoid heating the films which distorts the measurement. Films are tested in a nondestructive manner, allowing evaluation before expensive fabrication into finished devices. Moreover, both low-power and high-power measurements of the film surface resistance can be performed in the same test fixture.

The measurement results will be correlated with film deposition parameters, film surface structure, and other electrical measurements in a search for the mechanisms causing increased microwave loss at high power.

The group is working with industry to improve the high-power performance of superconducting films, a necessary step toward their successful introduction into passive microwave devices for wireless communications. One corporate collaborator is already building a copy of the system to use as an in-house process monitoring system. Other corporate collaborators are offering their superconductor films for the program.

"We at STI are actively engaged in the development of high performance, HTS microwave circuits. It has been a pleasure to work with ... research groups which have the interest, measurement expertise and independent status to provide the information we need to help solve generic problems in commercializing these products. ... This is an excellent example of the third party independence of NIST to organize the industry to produce new measurement techniques essential for testing and production. ... Your superconductor research groups at NIST have performed a valuable service to STI and we support this important service being provided to our small but rapidly developing industry."

Director of Operations
Superconductor Technologies, Inc.

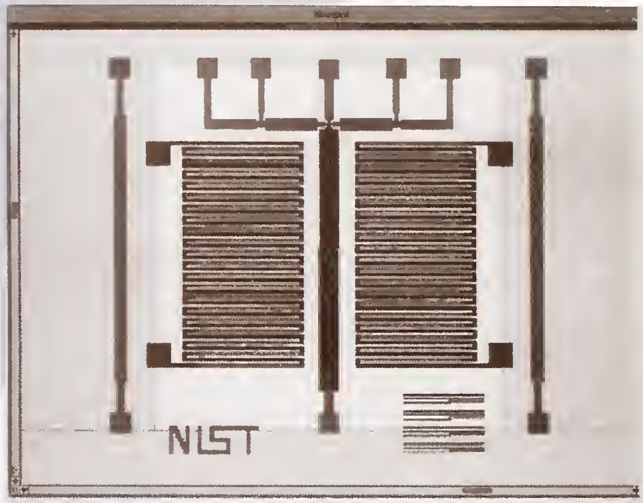


"I note with pleasure the excellent NRC results in the CCE 92-3 international comparison of Multijunction AC-DC Transfer Devices. In that connection, I would like to express my appreciation for the support provided to NRC by NIST. ...Intercomparison of NRC Thermal Voltage Converters performed by Mr. Kinard, as well as three days of technical discussions ... at NIST were very valuable. This and past collaborations and interlaboratory comparisons have been very important in maintaining compatibility of our measurement capabilities."

Director General
Institute for National Measurement
Standards
National Research Council
Canada

EXAMINING A WAFER OF NIST THIN-FILM MULTIJUNCTION DEVICES

J.E. KINARD



INTEGRATED MICROPOTENTIOMETER INCORPORATING A THIN-FILM MULTIJUNCTION CONVERTER

4 LOW FREQUENCY

4.1 NIST thermal converter measurements support industrial instrumentation

AC-DC difference measurements are those in which an alternating current (ac) signal is measured by comparing the heat it dissipates under controlled conditions to that dissipated by a known direct current (dc) signal; when the powers that are dissipated are equal, the RMS value of the ac signal is equal to that of the dc signal. This is significant since there are no physical phenomena which directly produce ac signals of primary standards accuracy — the electrical units are defined and maintained as dc quantities. However, most practical uses of electricity involve ac rather than dc. AC-DC difference measurements, then, are critical for measurements in electronics as are the calibration of meters used for such measurements.

The standards used for ac-dc difference measurements are called thermal converters and consist of a carefully designed load (heater) and some means of monitoring its temperature rise to a high level of precision. The national standards are multijunction thermal converters, so-called because a series of thermocouples are used to monitor the temperature rise in the heater.

These afford measurements with uncertainties smaller than one part per million (ppm) or 0.0001% of the input signal level. Such levels of accuracy are required by industry as the basis for verifying the performance of and adjusting ac voltmeters, the best of which are claimed to have uncertainties of ±10 ppm, and (at a lower level of accuracy) all measurements of electric current, voltage, power, and energy by the utilities.

ACCOMPLISHMENTS

The accuracy, and hence adequacy, of NIST standard thermal converters is verified by measuring the differences between the individual standards, and by carrying out intercomparisons with other national laboratories. This year, in addition to carrying out normal comparisons of standards, NIST participated in four comparisons — each involving different values of voltage or current, and frequency. Three were undertaken bilaterally with laboratories in Germany, Portugal, and Spain, and the fourth was part of an effort involving the laboratories of most of the industrialized nations.

The result of all of this work, carried out by Joseph R. Kinard, Thomas E. Lipe, and Clifton B. Childers, was verification that the national and working standards are performing well within the accuracies claimed for them and adequately enough to support the present needs of U.S. industry. This support comes primarily through calibrations of industrial thermal converters.

The staff also supported industry more directly through cooperative R&D agreements, three of them this year. The first supported work by a U.S. instrument maker to improve industrial measurement capability for ac voltages in the range from 200 to 1000 V. The second was to improve the performance of vacuum thermoelements, the workhorse for industrial ac-dc measurements, so that uncertainties close to one ppm (an improvement of a factor of three to five) are feasible. Such improvements reduce the cost of making measurements and maintaining instrumentation throughout industry, where tens of millions of instruments are employed and must be routinely recalibrated. The third was to apply technology developed by Kinard and his colleagues to an entirely different purpose: the monitoring of sputtering energies in integrated circuit fabrications.

Aside from our partnership in the North American Free Trade Agreement, NIST has a bilateral agreement to provide start-up support to Centro Nacional de Metrologia (CENAM), our counterpart in Mexico. Kinard, Lipe, and Childers provided training and measurement assistance to Dionisio Hernandez Villaseñor this past year. A significant number of calibrations were performed in support of CENAM's primary standards, and a multijunction primary standard was made available for CENAM's use.

4.2 Pulse-energy characteristics of inkjet print-heads evaluated

An assessment was made in the Electricity Division to determine the pulse energy measurements needed for characterizing the print-heads marketed by a well-known instrument manufacturer for use in inkjet printers. The print-head market is huge, and it still has a high growth rate. NIST was contracted by the instrument company to evaluate methods for measuring the pulse energy delivered to such print-heads, with particular emphasis on the method currently used by the company in a recently developed test bed for inkjet print-heads and printers. The results of this evaluation were documented in a report prepared for the company by T. Michael Souders who carried out the experimental analyses required for this project.

Inkjet printers deliver ink to the paper by rapidly heating a small reservoir of ink, causing it to boil and subsequently ejecting droplets through a pinhole-size orifice. Heating of the reservoir is accomplished by rapidly dissipating the energy in a load resistor located in the reservoir, using well-defined electrical pulses. An inkjet print-head contains an array of these orifices, with an integrated load resistor and micro-machined reservoir behind each orifice. The appropriate electrical pulses are delivered by print-head electronics in the printer. Print quality is critically dependent on the amount of total energy delivered by the electrical pulses, which are typically a few microseconds in duration and several volts in amplitude. Accurate pulse energy measurements are considered an important tool for performance improvement research, as well as for manufacturing quality control.

Laboratory measurements confirmed that the test bed used by the company could achieve the desired measurement uncertainty of ±1%, provided that corrections are applied to account for dynamic gain errors of critical equipment. This assessment was made using NIST's recently developed sampling-comparator-based waveform measurement system, in which the overall measurement uncertainties were held to ±0.2%. Periodic NIST calibrations of a pulse-generator transfer standard are being performed to assure that the appropriate dynamic corrections are used, and to provide the company with the desired traceability to NIST standards.

LOW FREQUENCY

VERIFYING AN AC VOLTAGE POINT ON THE MCS M.E. PARKER

4.3 New streamlined test offered for digital multimeters

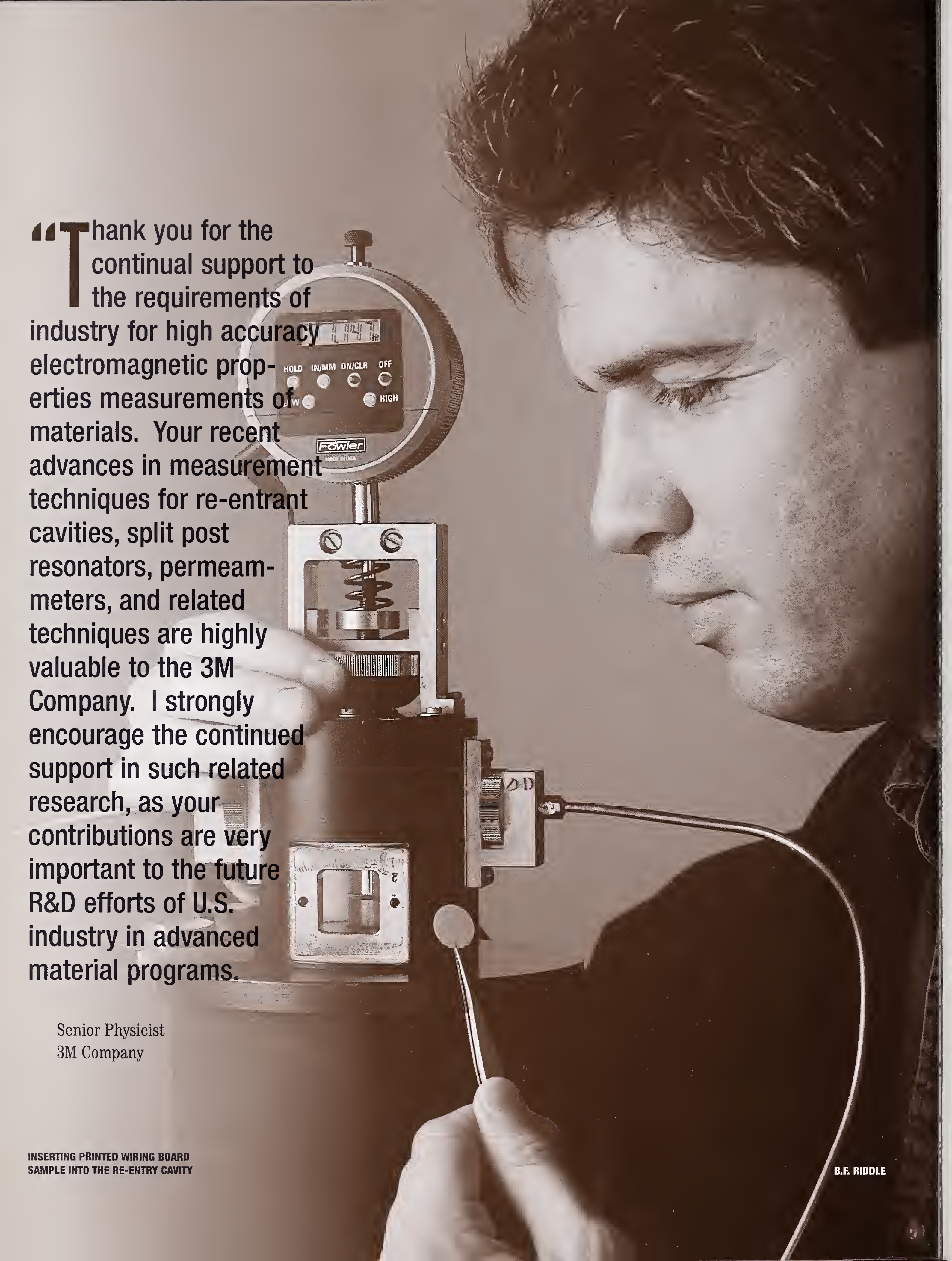
In response to requests from present clientele and potential customers, and as a result of developing a NIST Multifunction Calibration System (MCS), a new 25-point Special Test has been announced (via the NIST Calibration Services Users Guide) for calibrating the most often used ranges of typical precision digital multimeters (DMMs). The cost for this test is about 10% of a more comprehensive multimeter test (entailing as many as 250 test points), and it can be performed with a one-week turn-around time by staff in the Electricity Division.

Nile M. Oldham led the development of the Multifunction Calibration System and associated test capabilities. Mark E. Parker provides the workload testing using the Multifunction Calibration System, including the new 25-point Special Test.

The 25-point test includes four dc voltages, eleven ac voltages, two dc currents, four ac currents, and four resistances.

Precision digital multimeters are being used more often by industrial standards laboratories as transfer standards for dc and ac voltage and current, as well as dc resistance. The resolution and short-term stability of the candidate digital multimeters must be good enough to justify their calibration to accuracies approaching those of laboratory standards, such as Zener-based dc voltage references. The digital multimeter then can be used as a transfer standard for calibrating other less accurate digital multimeters or the outputs of less accurate multifunction calibrators.

Precision digital multimeters are also being proposed as transfer standards for assessing the measurement capability of an organization seeking laboratory accreditation under the National Voluntary Laboratory Accreditation Program (NVLAP), both in terms of proficiency testing and for periodic audits.



“Thank you for the continual support to the requirements of industry for high accuracy electromagnetic properties measurements of materials. Your recent advances in measurement techniques for re-entrant cavities, split post resonators, permeameters, and related techniques are highly valuable to the 3M Company. I strongly encourage the continued support in such related research, as your contributions are very important to the future R&D efforts of U.S. industry in advanced material programs.

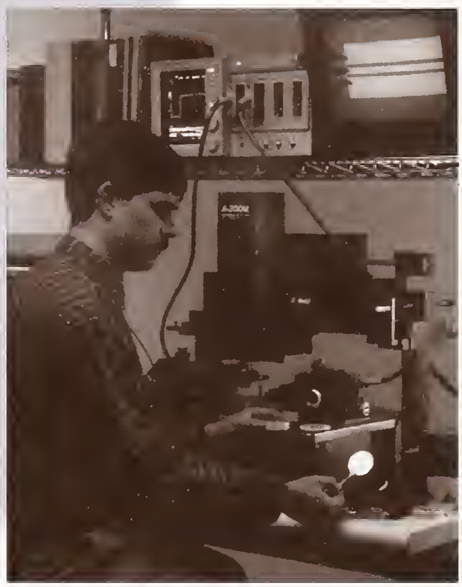
Senior Physicist
3M Company

INSERTING PRINTED WIRING BOARD SAMPLE INTO THE RE-ENTRY CAVITY

B.F. RIDDLE

ACCOMPLISHMENTS

An automated time-domain network analyzer is used with a microwave probe station for on-wafer device measurements up to 20 GHz. Acquisition and error correction software collects time-domain reflection and transmission waveform data for each device. Combining error correction software with automated time-domain techniques provides accurate and cost-effective instrumentation for high-speed microelectronic device and packaging measurements.



CALIBRATED TIME-DOMAIN NETWORK ANALYSIS FOR HIGH-SPEED MICROELECTRONICS **D.C. DEGROOT**

5 MICROWAVES

Sample	Frequency MHz	Relative Permittivity, ϵ'_R	Loss Tangent, tan δ
1	430	2.73 ± 3%	20×10^{-3} ± 10%
2	430	2.77 ± 3%	20×10^{-3} ± 10%
3	400	3.12 ± 3%	4.5×10^{-3} ± 10%
4	450	2.39 ± 3%	0.8×10^{-3} ± 10%
5	375	4.10 ± 3%	19.4×10^{-3} ± 10%

Measurement results for dielectric material samples obtained using the NIST re-entrant cavity. These results are used by the printed wiring board industry to develop and evaluate non-destructive measurements methods for production control.

5.1 Measurements of printed-wiring-board (PWB) materials

Suppliers and end-users of printed-wiring-board materials urgently need better quality control of their shop-floor production methods and have sought assistance from NIST in developing low-cost, faster, more accurate (±3% for ϵ'_R, ±10% for tan δ) and nondestructive techniques for measuring the dielectric properties of PWB materials. In response, EEEL has been providing significant in-house support to an industry "Materials Team" formed by the ATP-supported Printed Wiring Board Consortium. This has involved developing improved frequency- and time-domain measurement methods, as well as evaluating the performance of commercially-available measurement fixtures and instrumentation.

In the frequency-domain work, James E. Baker-Jarvis and William F. Riddle of the Electromagnetic Fields Division have developed improved theory and software for the coaxial re-entrant cavity technique. They also have assessed the method's general accuracy and developed corrections for air-gap errors. Experimental measurements have involved two tunable cavity fixtures operating over the frequency range 80 to 1000 MHz.

In the time-domain work, William L. Gans and Nicholas G. Paulter of the Electricity Division used a sampling oscilloscope, operating in a time-domain reflectometry mode, which transmits very short-length pulses

ACCOMPLISHMENTS

"I am writing to encourage the continuation and expansion of NIST's program in the electrical characterization of electronics packaging and interconnections. ... Industry in general lacks the resources to quickly develop the necessary measurement methods and promote them as standards. NIST's involvement is essential to accelerate the process. ... I urge a continuation and expansion of your existing efforts and suggest that it would be of great industry impact."

Principal Engineer
Tektronix, Inc.

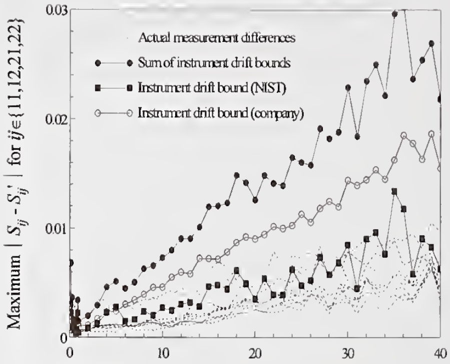
into a parallel-plate transmission line fixture. Time-domain data are then converted to the frequency domain using a Fast Fourier Transform routine.

EEEL measured the complex permittivity properties of a number of printed-wiring-board materials supplied by Team members, using both frequency- and time-domain methods. Results for FR4, a widely-used PWB laminate, were in very close agreement for both techniques (within $< 0.5\%$ for $\in'_{R}$).

5.2 MMIC verification methods

NIST has developed a method for evaluating the accuracy of microwave measurements for monolithic microwave integrated circuits (MMICs). These circuits are key components in low cost wireless networks, global positioning systems, vehicular communications, smart highways, and collision avoidance systems and represent the fastest growing segment of the U.S. microwave industry.

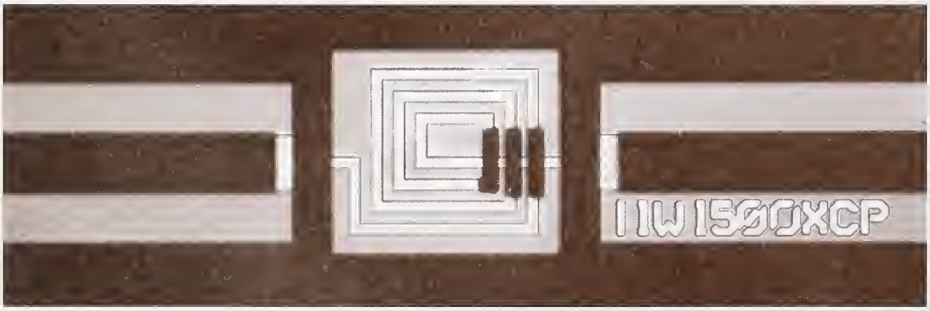
Accurate measurement of MMICs is imperative due to their high frequency of operation and difficulty of design. A consortium of microwave companies, whose members have long been concerned with the accuracy of these measurements, began funding NIST researchers Dylan F. Williams and Roger B. Marks to explore means to determine measurement uncertainty at these high frequencies several years ago. They recently developed a set of calibration standards and procedures for this purpose, some of which industry specialists believe will satisfy the quality system requirements as set forth in the relevant industrial voluntary standard, ANSI/NCSL Z540.



TYPICAL RESULTS OF THE PROPOSED INSTRUMENT VERIFICATION PROCEDURE FOR MEETING ANSI Z540 REQUIREMENTS

The procedures, which were designed to be simple enough to be used in industrial laboratories with commercial equipment, quickly demonstrated their usefulness in a series of on-site tests, identifying both equipment problems and difficulties with calibration procedures. In some cases the tests confirmed that the industry measurements were indeed sufficiently accurate, information unattainable by other means.

In other cases the procedure detected astonishingly high measurement errors, sometimes as high as 70%, which had gone undetected despite complicated and seemingly thorough internal calibration consistency checks. In these cases, the NIST software exceeded the goals of the project. Whether equipment problems, software errors, or poorly defined standards were at fault, special diagnostic capabilities added by Williams and Marks were usually able to identify error sources and suggest remedies.



FLIP-CHIP MMIC

COURTESY OF HUGHES CORPORATION

MICROWAVES

5.3 Flip-chip MMIC characterization

In a direct partnership with industry, NIST has developed and carried out measurements of flip-chip MMIC (monolithic microwave integrated circuit) components and used the results to develop electrical representations useful in computer-aided design software. The work helps provide tools necessary for high-performance design of this promising technology without extensive prototyping.

While the United States leads the world in MMIC technology, primarily due to investments made by the Department of Defense, much of the exploding commercial market in wireless telecommunications has remained off-limits to MMICs due to their high manufacturing cost. The new flip-chip MMIC process promises to offer low-cost production by taking advantage of flip-chip technology, originally developed for packaging advanced computer microcircuits. In this method, finished chips are mounted face-down on a high-tech equivalent of a circuit board.

Flip-chip mounting is compatible with coplanar waveguide circuits, which can offer lower fabrication cost and higher production yield than conventional MMIC processes. However, the design of coplanar waveguide MMICs is hampered by the lack of sophisticated simulation tools. Roger B. Marks and Jeffrey Jargon, teaming with a major U.S. electronics firm in a project sponsored by NIST's Advanced Technology Program, addressed this problem through measurement. They characterized coplanar waveguide components, including transmission lines, metal-insulator metal capacitors, and spiral inductors, using established NIST metrology. They then applied the results to develop electrical representations useful in computer-aided design.

RADIATED FIELD SYSTEM FOR THE NONDESTRUCTIVE EVALUATION OF MATERIALS **R.T. JOHNK**

Trace on screen records reflectivity response of a layered honeycomb composite obtained using synthetic time-domain techniques

Work based on the flip-chip MMIC measurements has been presented at several conferences and received an award for best paper in the RF and Microwaves session at the 1995 International Symposium on Microelectronics. Marks has designed additional test structures, currently in fabrication, to electrically characterize flip-chip packaging effects, including the solder joints which attach the chips.

5.4 Nondestructive time-domain characterization of materials

Honeycomb composite materials are coming into widespread use in the aviation industry. The advantages of these are light weight, high structural strength, and potentially low radar reflectivity for stealth purposes. These materials are widely used in both civilian and military aviation. The need to know the reflectivity response of these materials to radar signals has generated much interest in characterizing the electrical properties of composite materials. Due to the fact that many composite materials are layered and inhomogeneous, the accurate measurement of electrical properties is difficult to perform using conventional test fixtures such as coaxial, cavity, and waveguide fixtures. Conventional measurements require material samples which can be difficult to obtain for layered composites. Also, a nondestructive evaluation system is essential for existing aircraft structural components where the extraction of a core material sample is simply not feasible.

NIST scientists Arthur R. Ondrejka and Robert T. Johnk have developed a time-domain radiated-field measurement system that is capable of extracting the properties of a given inhomogeneous material. The NIST system employs a near-field radar system that illuminates the material under test with ultra-wideband picosecond pulses. By detecting the reflected pulses and applying a suitable signal processing/mathematical optimization procedure, material properties of a given composite material are extracted. The major advantages of this system are speed, the ability to resolve individual layers within a composite material, and the fact that the test procedure is inherently nondestructive. In fact, this system could potentially be used to evaluate structures that are part of actual aircraft. Promising results have been obtained on a test panel made of a layered honeycomb composite material in which the ability to resolve and measure the electrical properties of the various material layers has been clearly demonstrated.

SYSTEM FOR DETERMINING CHROMATIC DISPERSION OF OPTICAL FIBER BY PHASE-SHIFT TECHNIQUES

> “As a manufacturer of optical fiber in the United States and other countries, AT&T places high priority on fiber measurements standardization activities. The ability to succeed in trade and commerce many times depends on the ability to specify and test fiber as well as having good agreement with customers. NIST has played an important role in the fiber optic industry by working with manufacturers in the TIA/EIA groups, sponsoring measurement round robins and providing SRMs.”

Technical Staff
Fiber Measurements
AT&T

S.E. MECHELS

ACCOMPLISHMENTS

DEVELOPMENT OF STANDARD REFERENCE MATERIAL (UPPER BOX)
SRM will support systems for determining dispersion properties of optical fiber, in particular, the zero-dispersion wavelength

6 LIGHTWAVES

6.1 Dispersion in optical fibers

The use of optical amplifiers allows light to travel a greater distance before conversion to an electrical signal. Also, data rates of optical fiber communications systems are steadily increasing. In transoceanic systems, information is being transmitted at rates of billions of pulses per second, over distances of thousands of kilometers. The dispersive or pulse-broadening properties of the fiber are therefore a key to achieving a high level of system performance. Dispersion arises through both chromatic and polarization effects. Chromatic dispersion occurs when different wavelengths (or colors) of light travel at different velocities in the fiber. Polarization mode dispersion results when different polarization states travel with different velocities. Both types of dispersion can occur simultaneously to limit performance.

Representatives of the Telecommunications Industry Association requested that NIST make standard reference fibers available for calibrating test equipment that measures chromatic dispersion. Of particular interest is the wavelength region having least dispersion in the fiber. A goal of 0.1 nanometer was set for uncertainty of the "zero-dispersion-wavelength" in the reference fibers.

The first step toward providing such reference fibers was to develop measurement methods with the precision needed. Steven E. Mechels and John B. Schlager have developed laser-based systems to determine fiber chromatic dispersion. The most accurate of the systems uses a tunable laser modulated at microwave frequencies. Chromatic dispersion is determined by measuring the phase shift of the modulation in the received signal as the wavelength is changed. The zero-dispersion wavelength is extracted from this measurement by curve fitting the data. Because the light source is a laser, the wavelength can be determined very accurately using interferometric methods. The measurement precision of the NIST system is better than 0.006 nanometer for determining zero-dispersion wavelength on 10-kilometer lengths of fiber.

NIST-packaged reference fibers, 10 kilometers long, are currently being circulated in an industry-wide "round robin" (interlaboratory comparison). The fibers are in foam-insulated containers to minimize the effects of thermal fluctuations. The stability currently being achieved for zero-dispersion-wavelength indicates that calibrations can be transferred to other laboratories with an uncertainty consistent with the goals set by industry.

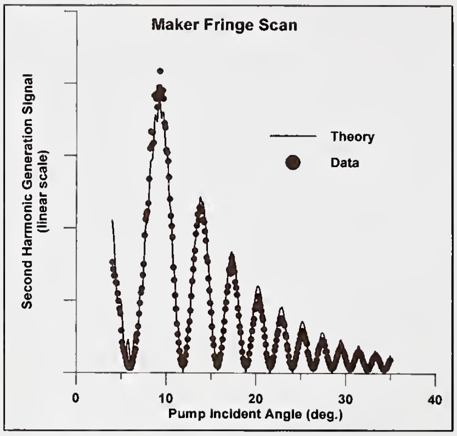
NIST scientist Paul Williams has been studying reference standards and measurement methods for polarization mode dispersion (PMD). He is coordinating a PMD "round robin" among members of the TIA, which has already helped participants identify sources of imprecision in their measurements. The "round robin" also provides a means of evaluating a NIST-developed prototype standard.

Working closely with a major U.S. manufacturer of test equipment, Williams also helped identify and document an apparent disagreement between two of the most widely used PMD measurement methods. Resolution of this issue has important implications in international standards.

6.2 Mapping the uniformity of lithium niobate wafers

Integrated optical devices made in lithium niobate are finding increased use in optical communication systems, optical data storage, reproduction graphics, and optical gyroscope navigation systems. However, improvements in the quality of bulk lithium niobate crystals have not kept pace with demands imposed by the increasing complexity of the applications. Manufacturers of waveguide devices believe that, in order to reduce manufacturing costs in these systems, they need wafer screening procedures that will allow them rapidly to reject defective wafers.

NIST scientists Norman A. Sanford and J. Andrew Aust have applied a technique, called Maker fringe analysis after its inventor, to the uniformity mapping of lithium niobate wafers. In this method, a sample wafer is probed at a wavelength of 1064 nanometers using a laser. Second-harmonic light is generated at 532 nanometers by the nonlinear properties of the sample. The intensity of the generated light is an oscillatory function of the incident angle. The data contained in the envelope and oscillation patterns of the generated light reveal information on material composition of the wafer and the strength of the nonlinear response.



MAKER FRINGE SCAN

Maker fringes from second harmonic (532 nm) light generated in a lithium niobate substrate. Theoretical simulation of the data yields information on material composition and nonlinear response

Repeating these scans in a grid-like fashion over an entire wafer allows the mapping of both linear and nonlinear properties of the wafer. Maps of wafer uniformity with a resolution of two parts in one hundred thousand in refractive index have been demonstrated. This translates into a resolution of one part in ten thousand in the lithium-to-niobium mole ratio compositional variation.

MAPPING THE UNIFORMITY OF LITHIUM NIOBATE WAFERS **N.A. SANFORD**

LIGHTWAVES

The measurement technique is being adopted by a contractor in a manufacturing technology development program.

6.3 A self-calibrating temperature sensor

Sensors made from optical fiber can detect a number of different quantities, including electric current, magnetic field, and temperature. Such sensors are attractive for several reasons, such as their light weight and relative immunity from electromagnetic interference. One of the particular attractions of optical fiber sensors is the ease with which large numbers of sensors can be incorporated into sensor networks. However, testing, maintenance, and recalibration, if done manually in these networks, require substantial labor. Automation can greatly reduce costs.

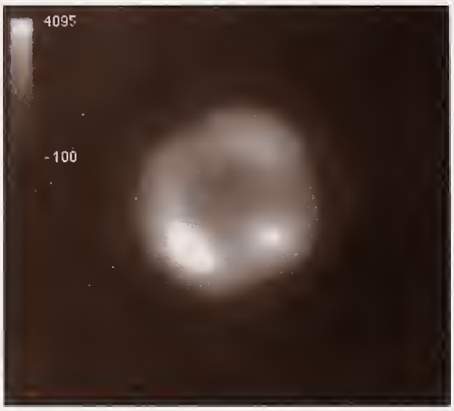
NIST scientist Allen H. Rose, working with industrial scientist Jerry Wyss, demonstrated a computer-controlled optical-fiber temperature sensor that automatically recalibrates itself. This is thought to be the first example of such a device. The NIST-developed self-calibrating temperature sensor is based on the principle that the polarization state of light passing through certain materials changes with temperature. Because this effect depends on the wavelength of the light passing through the material, different laser wavelengths can be used to test the sensor and measure the temperature. If, for example, the amount of light passing through the sensor changes because of a faulty optical connection, the calibration of an ordinary sensor would be lost. But by adjusting the laser to as many as five different wavelengths, this new sensor system can determine the problem and regain the proper calibration. In the demonstration, a 200-fold reduction in transmitted light still permitted recalibration to within about one Celsius degree.

OPTICAL TEMPERATURE SENSOR
NIST-developed self-calibrating optical-temperature-sensor control unit and probe

ACCOMPLISHMENTS

> The NIST approach for laser cavity measurements "will provide the laser industry with standards in an important area that has continued to evade us for almost 30 years. We look forward to working together with NIST in this area for we know you will provide the leadership, neutrality, and methodical work required."

Director
Instruments Division
Auburn Group, Coherent



TWO-DIMENSIONAL IRRADIANCE PATTERN FROM A MULTIMODE VCSEL ACQUIRED WITH THE NIST HIGH RESOLUTION CCD BEAM PROFILE CAMERA

6.4 Vertical-cavity surface-emitting laser measurements

A relatively new type of semiconductor laser, the Vertical-Cavity Surface-Emitting Laser (VCSEL), is starting to be used commercially in applications as diverse as high-speed computer data transmission, laser printers, and displays. These lasers differ from the more common edge-emitting lasers in that light is emitted vertically from the top surface of the semiconductor and has a more nearly circular irradiance pattern. In addition, the lasers can be fabricated in arrays in which large numbers of sources are contained within a small area. To support this emerging technology, NIST scientists have developed new measurement systems for characterizing the output of VCSELs and have made this information available to VCSEL manufacturers and users.

Gregory E. Obarski developed a system for accurately characterizing the intensity noise of VCSELs while certain operational parameters are varied. For example, he can measure the change in noise as he precisely controls the temperature of the laser and its excitation current. This permits more careful design of optical interconnection or optical data storage systems using VCSELs.

Donald R. Larson developed a system to study the speed at which VCSELs can be modulated (i.e., turned on and off). He can also use his system to study VCSEL jitter or timing noise — the relationship between the electrical signal input and the optical radiation output. These speed and timing properties help scientists determine the maximum data rate at which VCSELs can transmit information.

Richard D. Jones established a system for accurately measuring the cross-sectional irradiance patterns and propagation properties of laser beams emitted from VCSELs. This information is used to quantify the beam divergence (i.e., amount of spreading) as well as the size of the beam at the focal planes of focussing optics. The beam profile and propagation properties can be used to determine how well the VCSEL radiation can be coupled into fibers or focussed to small points, as needed, for example, in high resolution printing.

David H. Christensen has provided critical technical expertise to these measurement efforts and has acted as liaison with industry to maximize the useful impact of the NIST measurements. He has also measured the change in emission properties of VCSELs operated in an array as a function of the drive conditions of neighboring emitters. NIST scientists are continuing to expand and improve VCSEL measurement capabilities to meet the evolving needs of industry.

6.5 Wavelength-selective reflectors inside optical fibers

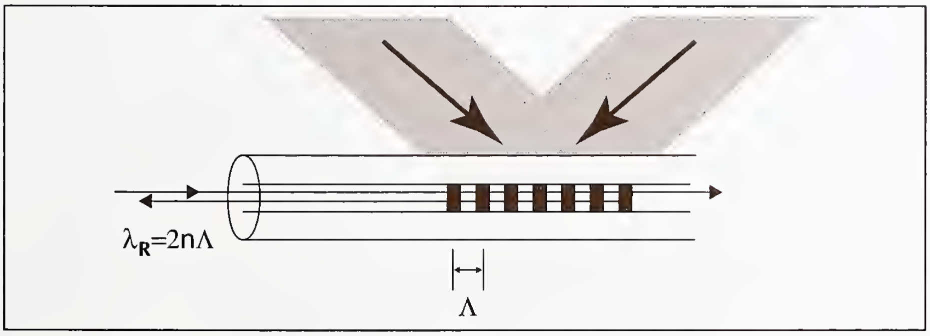
For several years, researchers have known that illuminating optical fiber with an interference pattern of ultraviolet light will create a reflector in the core of the fiber. These reflectors, also known as Bragg reflection gratings or, simply, fiber gratings, are wavelength-selective reflectors.

The ultraviolet light induces a periodic change in the index of refraction in the core of the fiber, and the change remains after the light is removed. But "How long will the change last?" — that is a crucial question which NIST addressed.

The ability to make wavelength-selective reflectors in the core of optical fiber has stimulated the development of many novel fiber devices, such as wavelength filters, fiber lasers, strain sensors, and devices which can correct for chromatic dispersion. Such devices are starting to be marketed by several companies in the United States and abroad. NIST scientists Sarah L. Gilbert and Heather Patrick recently completed a study of the formation of Bragg reflection gratings in optical fiber which sheds new light on the stability of the gratings. Treating the fiber with molecular hydrogen before subjecting it to the ultraviolet light substantially increases its photosensitivity, and speeds the production of the grating.

However, the NIST work showed, in at least one type of fiber, that the stability of the induced index change in hydrogen-treated fiber is substantially less than that for untreated fiber. Gratings written in hydrogen-treated fiber and held at room temperature for six months showed a decrease in the photo-induced index change of 15%, whereas gratings written in the untreated fiber showed no change over the same period. At higher temperatures the difference was even more dramatic; when annealed at 176 degrees Celsius, the photo-induced index change in hydrogen-treated fiber was reduced by 40%, whereas it decreased only 5% in untreated fiber under the same conditions. Thus, NIST has shown that caution should be taken when using fiber gratings made in hydrogen-treated fiber if long-term stability is required.

> **"As a supplier of instruments, I look forward to the day when I can tell our customers we are NIST traceable."**
>
> President
> Photon, Inc.



WAVELENGTH-SELECTIVE REFLECTORS IN OPTICAL FIBER

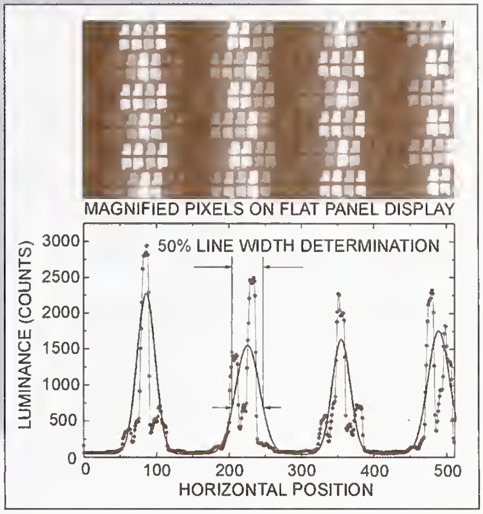
Two interfering beams of ultraviolet light cause a periodic index change in the core of optical fiber. The region is a reflector for light of wavelength $\lambda_R=2n\Lambda$, *where n is the average index of refraction of the fiber core and* Λ *is the periodicity of the ultraviolet-induced index change.*

> “I really appreciate the effort that you put into these comments [review of the International Standards Organization 13406-2.3 flat-panel display standard]. The quality of your work was very high. ...I cannot tell you how useful it is to have help like this. Thank you very much.”
>
> Founder
> Ergonomic Solutions, Inc.

RESEARCHER ADJUSTS A REFLECTANCE STANDARD IN FRONT OF A COMPUTER DISPLAY MOUNTED IN AN INTEGRATING SPHERE USED FOR MAKING HIGH-AMBIENT-LIGHT REFLECTION MEASUREMENTS

E. F. KELLEY

ACCOMPLISHMENTS



INVESTIGATION OF LINEWIDTH MEASUREMENTS FOR FLAT-PANEL DISPLAYS

7 VIDEO

7.1 Procedures for analyzing video display performance verified

Cathode-ray tubes are universally used for the display of high-resolution, monochrome, and color gray-scale imagery. However, existing measurement standards for these display devices only provide methods for measuring and evaluating displays targeted for text and graphics applications, and they do not produce sufficient information to adequately differentiate between candidate high performance displays. The goal of establishing such measurement and reporting standards, and promoting their use, is to provide a common language for display users and display manufacturers.

The National Information Display Laboratory (NIDL), a government-funded laboratory at the David Sarnoff Research Center, developed a set of candidate measurement procedures to submit to the Electronics Industries Association for adoption as a voluntary standard. Before submission, NIDL asked that Edward F. Kelley, Paul A. Boynton, and George R. Jones review the proposed standard and implement the measurements in EEEL's Flat Panel Display Measurement Laboratory. A round-robin experiment was conducted in which NIDL performed an analysis of a commercial high-resolution monitor using their procedures, shipped the monitor to NIST for evaluation using NIST's measuring instrumentation and techniques, and compared the two sets of results. Several ambiguities with the NIDL measurement and analysis procedures were revealed. Also, shifts in the monitor characteristics during shipment (particularly convergence) were found to result in measurement differences that exceeded the combined measurement uncertainties.

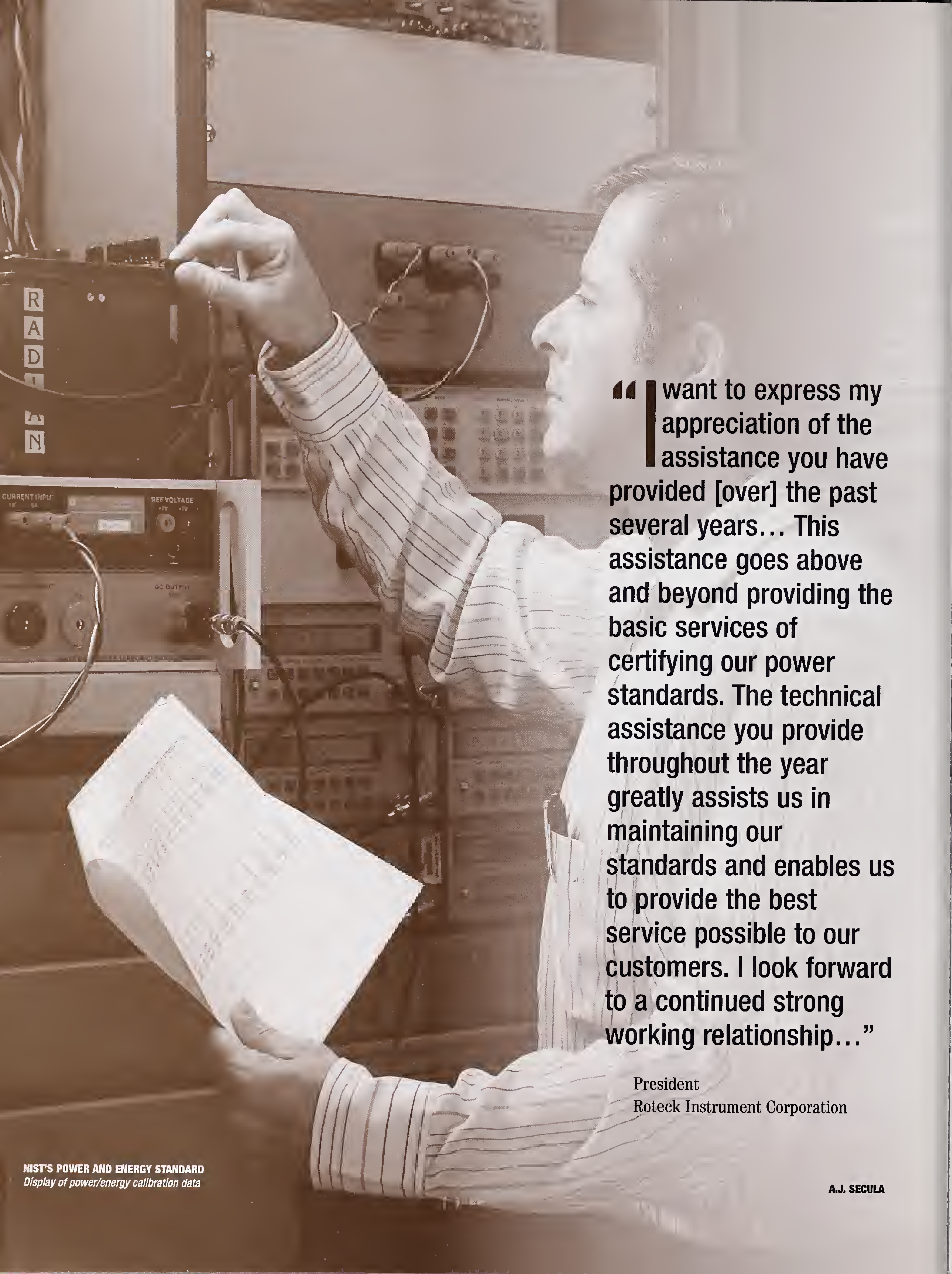
One conclusion of the experiment was that this method demands better transfer standards. Work has begun to develop a more stable and robust transfer standard which will be used in an upcoming international experiment to more fully assess the capabilities of a number of laboratories and measurement methods. Similar measurement standards are needed by industry to competitively characterize the performance of flat-panel displays; these cathode-ray tube measurements will be used as a foundation for present and future work in EEEL for developing flat-panel measurement standards.

7.2 NIST testing leads to redesign of devices for flat-panel display drivers

At the request of a flat-panel display manufacturer, David W. Berning recently investigated a high-voltage integrated circuit that was causing unusually high field failure rates in the driver of the company's display. NIST's measurements on the 250 volt driver showed that the devices did not meet original specifications, and demonstrated the origin of the high failure rates.

The devices were redesigned by the circuit manufacturer to improve the margin of permissible voltages and currents handled by the device (safe operating area, SOA). Follow-up measurements by NIST showed a significant improvement of 10 to 15% in breakdown voltage on the redesigned devices. The manufacturer acknowledged NIST's help: [with the] "testing done by NIST that resulted in the redesigned device with improved SOA and other changes we have made in production procedures, we have made good progress in reducing our failure rates."

Flat-panel displays are a critical component in notebook computers and other portable electronic systems. The flat-panel display driver devices investigated by NIST were responsible for most of the field failures in the manufacturer's electro-luminescence display system. This company is the sole manufacturer of electro-luminescence displays in the United States.



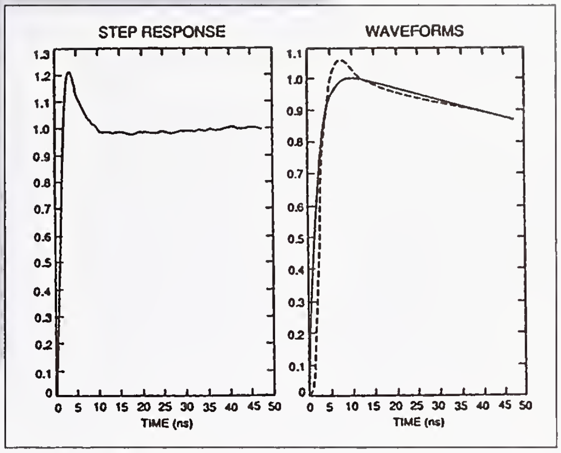
> “I want to express my appreciation of the assistance you have provided [over] the past several years… This assistance goes above and beyond providing the basic services of certifying our power standards. The technical assistance you provide throughout the year greatly assists us in maintaining our standards and enables us to provide the best service possible to our customers. I look forward to a continued strong working relationship…”

President
Roteck Instrument Corporation

NIST'S POWER AND ENERGY STANDARD
Display of power/energy calibration data

A.J. SECULA

ACCOMPLISHMENTS



FAST WAVEFORM CONVOLVED WITH THE STEP RESPONSE OF A SMALL RESISTIVE DIVIDER
Input waveform - (solid line) Output waveform - (dashed line)

8 POWER

8.1 NIST convolution technique used in high-voltage test standard

A convolution technique developed by Gerald J. FitzPatrick and John Lagnese is now included as one of the tests for verifying the accuracies of reference high-voltage dividers in a voluntary standard promulgated by the Institute of Electrical and Electronics Engineers: IEEE Standard 4-1995, "Standard Techniques for High-Voltage Testing."

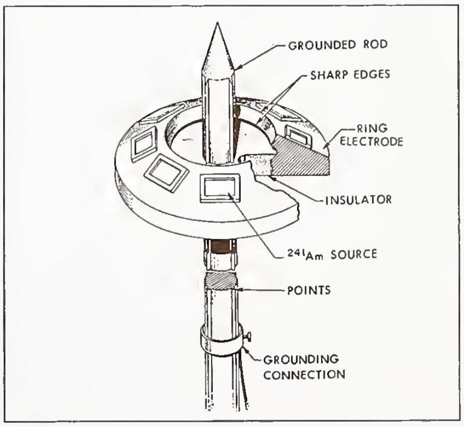
The standard now specifies that the reference divider must be verified by either evaluating parameters calculated directly from the measured low-voltage step response or by estimating errors using the convolution technique. The latter technique is more user-friendly because it calculates the response to a standard lightning impulse waveform and the distortion in the output is seen graphically. Also, the response measurement is performed at low voltage, so no second divider measurement system is required, making it much easier and faster than if the divider also had to be checked at high voltage.

The technique uses a numerical convolution to calculate the output of the high-voltage divider to a low-voltage step together with an analytical waveform of the type to be measured. The check is quickly performed with a digital recorder to measure the response waveform, and a personal computer to perform the calculations. Approved in March 1995 and issued by IEEE in October 1995, the standard is used to ensure international uniformity in the testing of high-voltage impulse dividers used by standards laboratories, industry, and electrical utilities.

8.2 NIST applies expertise in electrical discharges for lightning protection community

At the request of the National Fire Protection Research Foundation (NFPRF), representing the lightning protection community, NIST prepared a report for those interested in assessing lightning protection systems based on the early streamer emission concept. The Foundation turned to NIST as an impartial organization to provide background information on the physical mechanisms of lightning in order to evaluate a proposed standard for early streamer emission devices. The resulting report, "Early Streamer Emission Lightning Protection Systems — Literature Survey and Technical Evaluation," by Richard Van Brunt, Thomas L. Nelson, and Samara Firebaugh incorporates an annotated bibliography of over 300 publications of direct or indirect interest to early streamer emission technology, and a discussion about the state of knowledge concerning the operation and effectiveness of early streamer emission and standard lightning protection devices.

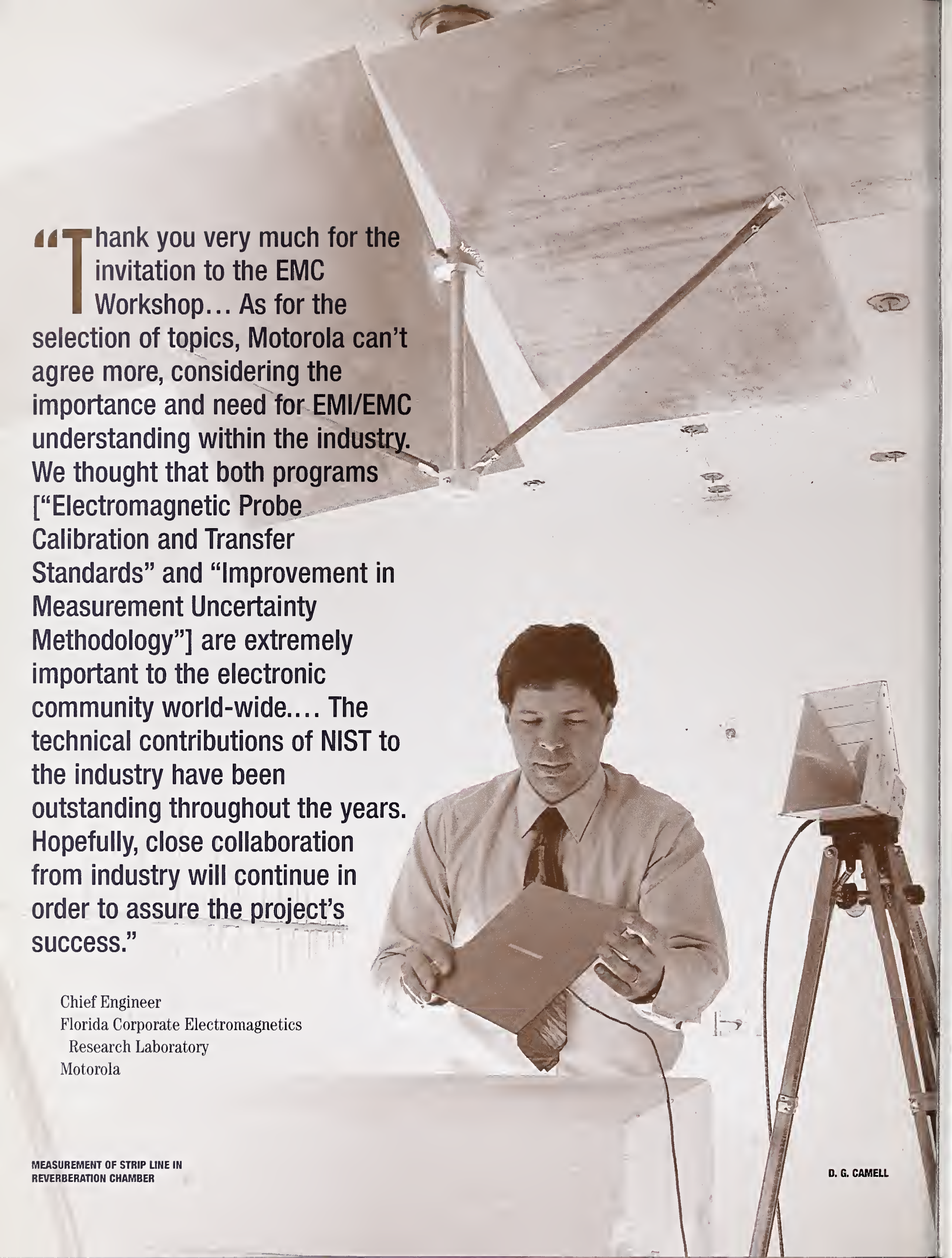
Early streamer emission devices add an ionizing source to a conventional lightning rod or air terminal. The intent is to attract a potential lightning stroke earlier than otherwise by ionizing the air surrounding the end of the lightning rod, thus decreasing the effective distance between the terminal and the electrically charged storm cloud. From the report, it is apparent that a complete understanding of the mechanism of lightning has never been developed. This complicates the evaluation of lightning protection systems, and greatly weakens the basis on which standards can be written. The NFPRF report, issued in January 1995, concluded with recommendations for research in order to elucidate the issues.



EXAMPLE OF AN EARLY STREAMER EMISSION (ESE) LIGHTNING PROTECTION DEVICE - RADIOACTIVE AIR TERMINAL
Published in: Isotopes and Radiation Technology, Vol. 8, No. 2, pp. 178-180 (1970)

"Thank you very much for the invitation to the EMC Workshop… As for the selection of topics, Motorola can't agree more, considering the importance and need for EMI/EMC understanding within the industry. We thought that both programs ["Electromagnetic Probe Calibration and Transfer Standards" and "Improvement in Measurement Uncertainty Methodology"] are extremely important to the electronic community world-wide.… The technical contributions of NIST to the industry have been outstanding throughout the years. Hopefully, close collaboration from industry will continue in order to assure the project's success."

Chief Engineer
Florida Corporate Electromagnetics
Research Laboratory
Motorola



MEASUREMENT OF STRIP LINE IN REVERBERATION CHAMBER

D. G. CAMELL

STRIP-LINE RESONATOR

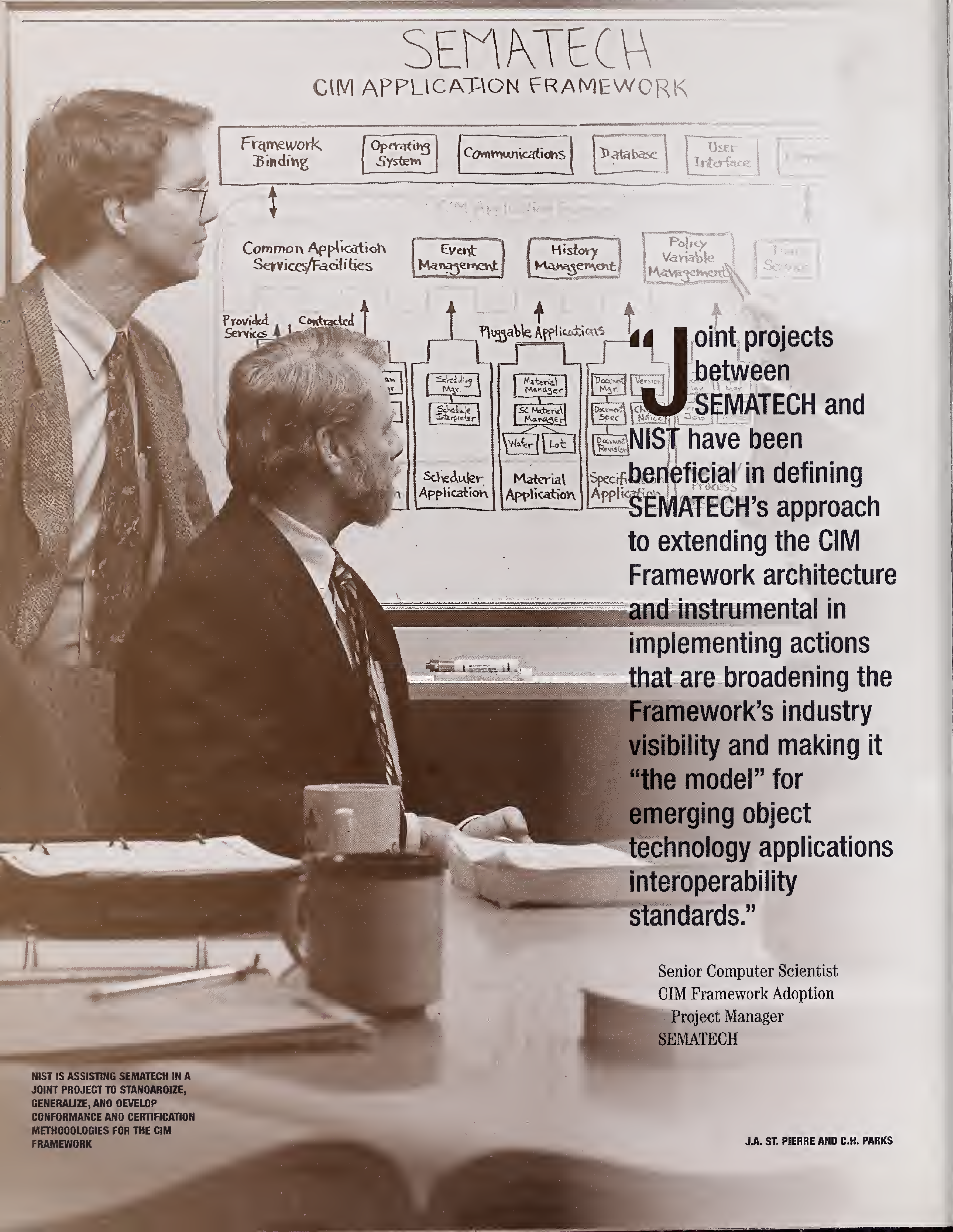
9 ELECTROMAGNETIC COMPATIBILITY

9.1 Printed-circuit-board electromagnetic interference

The density and complexity of electronic systems have introduced an increased potential for electromagnetic interference. Unshielded printed-circuit-boards and integrated circuits can both radiate and pick up electromagnetic interference. The Federal Communications Commission (FCC) limits on radiated emissions from computers cover the frequency range from 30 to 1000 megahertz, and increasing clock rates in digital circuits are likely to result in regulations that cover even higher frequencies. The United States has no radiated immunity requirements, but the European Union regulations for radiated immunity will take effect in 1996.

Industry visits and surveys have indicated a need for better understanding of, and measurement methods for, radiated emissions and immunity of printed-circuit-boards. NIST scientists David Hill, Dennis Camell, Kenneth Cavcey, and Galen Koepke have developed analytical techniques and measurement methods to characterize printed-circuit-board electromagnetic interference. To verify the analysis and measurement methods, they fabricated a microstrip transmission line and compared theoretical and experimental results for radiated emissions and immunity.

Transmission lines are the dominant radiators (or receivers) on printed-circuit-boards because they act like antennas at high frequencies. The measurements were performed in the NIST reverberation chamber (also called a mode-stirred chamber) for frequencies from 200 megahertz to 2 gigahertz. The reverberation chamber is an attractive facility for such measurements because it covers the frequency range of interest and is equally useful for emissions and immunity measurements. Since emissions and immunity measurements are related by reciprocity, the two types of measurements provide a consistency check on the measured data. Reverberation chamber measurements are insensitive to the mounting position and orientation of the test object, and the measurement methods developed in this work are applicable to single circuit boards or entire electronic systems. Additional details can be found in a report entitled "Radiated Emissions and Immunity of Microstrip Lines: Theory and Measurements" (NIST Technical Note 1377).



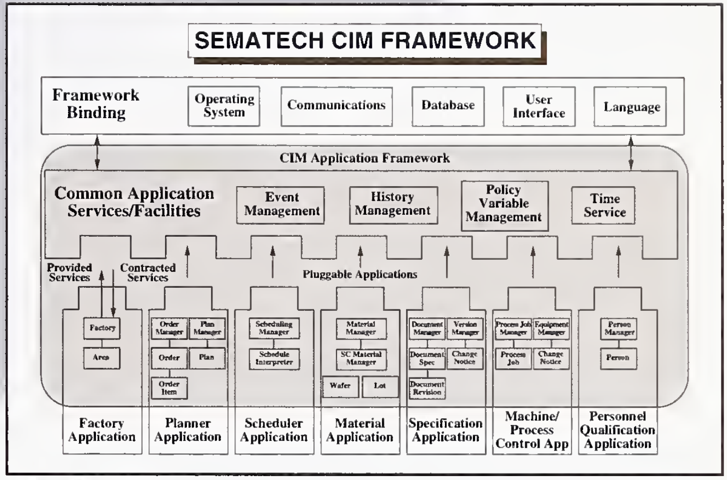
"Joint projects between SEMATECH and NIST have been beneficial in defining SEMATECH's approach to extending the CIM Framework architecture and instrumental in implementing actions that are broadening the Framework's industry visibility and making it "the model" for emerging object technology applications interoperability standards."

Senior Computer Scientist
CIM Framework Adoption
Project Manager
SEMATECH

NIST IS ASSISTING SEMATECH IN A JOINT PROJECT TO STANDARDIZE, GENERALIZE, AND DEVELOP CONFORMANCE AND CERTIFICATION METHODOLOGIES FOR THE CIM FRAMEWORK

J.A. ST. PIERRE AND C.H. PARKS

ACCOMPLISHMENTS



CIM FRAMEWORK
The SEMATECH CIM framework specification describes a software infrastructure aimed at providing a common environment for integrating applications and sharing information within semiconductor manufacturing facilities.

10 ELECTRONIC DATA EXCHANGE

10.1 Road map for reducing semiconductor manufacturing costs developed

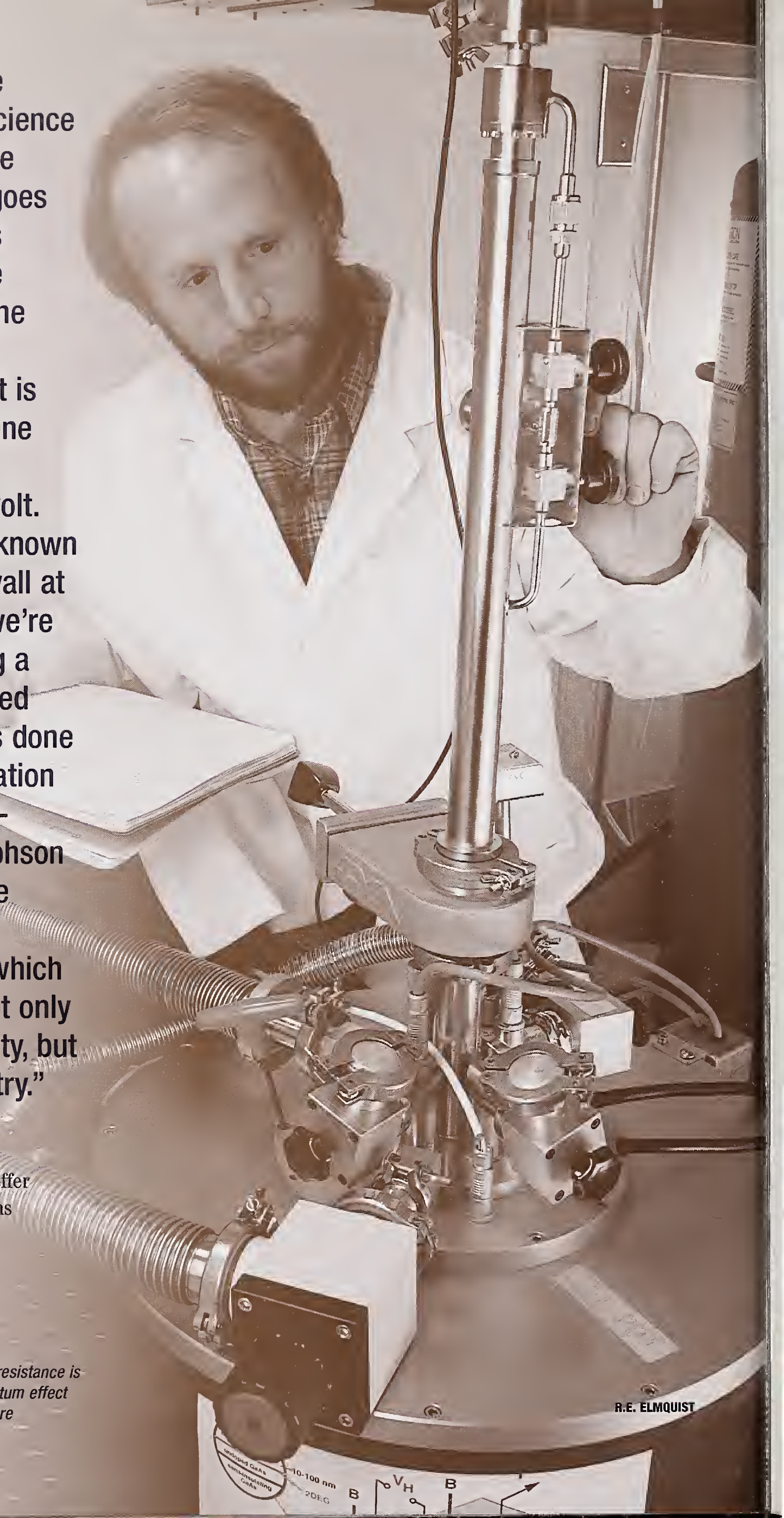
The semiconductor industry reports that as much as 70% of the cost of semiconductor manufacturing software results from in-house activity, mostly through efforts to integrate application software tools from various suppliers. In an effort to reduce these costs, SEMATECH, an industry/government consortium, has developed a Computer Integrated Manufacturing Application Framework based on object-oriented technology. This Framework specifies the interactions among all software components required to operate a semiconductor manufacturing facility, including, for example, software to schedule the use of equipment and personnel, to control manufacturing equipment, and to provide an interface to process planning tools. James St. Pierre of EEEL and Seldon Stewart, a staff member in NIST's Manufacturing Engineering Laboratory, have developed a roadmap for SEMATECH to help define its approach to standardization, generalization, and certification of the Framework. The Roadmap for the Computer Integrated Manufacturing (CIM) Application Framework has been published as NISTIR (5679) and as SEMATECH Technology Transfer Document (95052825A-ENG).

In the report, NIST addresses the problem of how to test object-oriented software to ensure its conformance or compatibility with the software specification (the Framework). Specifically, James St. Pierre (1) conducted a survey of existing certification and conformance testing programs in the electronic design automation industry, (2) performed a cost analysis of relevant programs that were similar in scope, e.g., that represented software with defined interfaces and were tested using "black box" methodologies, and based on these analyses (3) calculated an estimated testing cost of 27 to 30 work-years for the CIM Framework.

The roadmap further documented methodologies to reduce these testing costs. Some recommendations were to: (1) expand the use of formal description techniques in the specification, (2) use a backplane architecture to reduce the cost of software development in application software and potentially to decrease the testing complexity — applications need to be tested for compliance primarily with the backplane, (3) investigate automated test generation through the use of tools, such as those that are being developed for a voluntary standard promulgated by the Institute of Electrical and Electronics Engineers, IEEE-standard 1175, Semantic Transfer Language, (4) make certification not dependent on access to suppliers' source code — source code is most likely proprietary and expensive to analyze, and (5) leverage-off related and fully-tested standards activities such as the Common Object Request Broker Architecture, which provides similar event management and time services functions. The assistance provided to SEMATECH is expected to help decrease the significant costs required to integrate equipment within semiconductor manufacturing facilities, and has resulted in a request by SEMATECH for additional help in developing a specific conformance testing program.

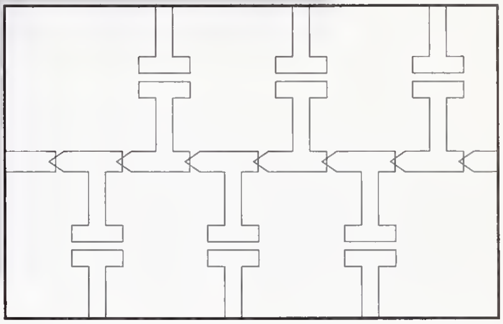
"One of the things one learns early on in science is the integrity of the entire operation and this goes even more so when one is talking about the interface between science on the one side and measurement technology on the other. It is really one continuum. ... One example ... is the establishment of the standard volt. Now, a volt is a very well known unit; it comes out of the wall at 110 volts. And yet what we're talking about is measuring a volt to one part in a hundred million or better. This was done by a very fundamental relation from the field of superconductivity called 'The Josephson Effect.' ... And from it there came a highly accurate measurement of the volt which has made great impact not only on the economics of society, but also on the defense industry."

National Public Radio Interview
with Nobel laureate J. Robert Schrieffer
expressing support for NIST programs



THE NATIONAL OHM
The effect on which this system for determining resistance is based is, like the Josephson effect, another quantum effect and dependent on fundamental constants of nature

R.E. ELMQUIST



SCHEMATIC DIAGRAM OF SEVEN-JUNCTION ELECTRON PUMP

11 NATIONAL ELECTRICAL STANDARDS

11.1 Quantized Hall devices designed to operate at lower magnetic fields

Quantum phenomena provide very precise methods for generating electrical standards, such as the integral quantum Hall effect for resistance. Quantized Hall resistors providing resistance values of 6,453.20175 ohms and 12,906.4035 ohms have found wide acceptance as standards in most national standards laboratories. However, the resistors attain these values only at temperatures close to absolute zero and in very high magnetic fields. These fields can only be produced by very large, expensive superconducting solenoids, cooled in sophisticated cryogenic systems that consume large quantities of liquid helium. The cost of such systems are beyond the means of most commercial calibration laboratories.

NIST scientist Kevin C. Lee is focusing on the development of quantized Hall resistors exhibiting the most desirable resistance value of 12,906.4035 ohms at much lower magnetic fields to permit the use of much smaller, less costly solenoids. The signal-to-noise ratio is twice as large at the higher 12,906.4035 ohm value, and his devices exhibit a constant resistance over a broader range of magnetic field.

Lee prepares the quantum Hall effect devices by alloying contacts to a specially designed heterostructure composed of alternating layers of the semiconductors gallium arsenide and aluminum gallium arsenide. The magnetic field at which the device exhibits a particular resistance value, or plateau, is a function of the design of the heterostructure. By varying parameters such as the density of donor atoms in the AlGaAs donor layer, or the thickness of the undoped AlGaAs spacer layer above the electrically active region, he can make heterostructures that will produce quantized Hall devices that exhibit different resistance values at different values of the applied magnetic field.

This year, Lee designed a heterostructure that produces the 6,453 ohm plateau and the 12,906 ohm plateau at magnetic fields nearly 25% lower than previously required. Since the 12,906 ohm plateau is generally of higher metrological quality, his next goal is to ascertain whether these devices can be made even more useful by operating at higher currents and higher temperatures. Continued success would place such resistance standards within the grasp of commercial laboratories, elevating the level of metrology across industry lines.

11.2 Electron counting with metrological accuracy

In science courses, electric current is defined by how many electrons flow past a point in one second. Capacitance is defined by how much voltage appears across a capacitor when it is charged by a certain number of electrons. EEEL has programs to translate these definitions into standards and measurement techniques. Unfortunately it's very hard to count electrons, and current and capacitance are measured differently.

At least that's how it was before John M. Martinis, with Richard L. Kautz, Mark Keller, Michael Nahum, and Gregory Zimmerli, started work on single electronics in Boulder. By making very tiny quantum mechanical tunnel junctions and operating them very carefully, Martinis can count individual electrons. However, nature conspires to make the task very difficult. The devices must be operated at 0.05 kelvin, very near absolute zero, and shielded from the thermal noise of room temperature components. So far, the team has been able to pump a known number of electrons onto a capacitor, missing only one in two million. The next step is to miss fewer than one in one billion. Neil Zimmerman, their colleague in Gaithersburg, has also been using single electronic technology to compare room-temperature and low-temperature capacitors. With this parallel work, Zimmerman will be able to use the next-generation pump to measure capacitors.

Ultimately, the team wants to count more than ten billion billion electrons in one second — faster than their pump works now. Then, they can measure an important quantity in fundamental physics, the fine structure constant. That better knowledge will in turn improve the accuracy with which other electrical measurements can be made.

PROGRAMS MATRIX-MANAGED BY EEEL

EEEL administers NIST-wide laboratory programs in law enforcement and microelectronics as well as the programs sponsored by our own Laboratory. You will find the descriptions of matrix-managed programs conducted within EEEL in the preceding 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, we provide the following examples.

OFFICE OF MICROELECTRONICS PROGRAMS

Plasma and CVD Process Measurements

Plasma etch and deposition tools used to fabricate modern devices are largely based on empirical and proprietary designs. In the same way that computer modeling has become the basic tool for device and circuit design, eventually process and equipment models will form the working foundations for tool design. There is much technological ground to cover between the present state of the art and that desirable future, but 2D visualization of active species density in plasma is an important and useful step. Scientists in the Chemical Science and Technology Laboratory have developed a technique called Planar Laser-Induced Fluorescent Imaging and applied it to image the spatial density of metastable argon and CF_2 in a variety of plasma gases. These species are important barometers of both energy transfer through gas-phase collisions and polymer formation which often controls etch anisotropy. This work was performed on a standard reference discharge cell platform and has been published to provide relevant data to the modeling community.

Thin Film Profile Measurement Methods and Reference Materials

Ion implantation is a part of the toolbox used in every modern IC fab with boron being one of the most-commonly required species. The physics of boron implant are complex as are the techniques used to measure the resulting concentrations. Efficient multi-location manufacturing requires the availability of a metrological stake-in-the-ground, a Standard Reference Material (SRM). This year, researchers in the Chemical Science and Technology Laboratory released the first boron implant in silicon standard, SRM2137. Judicious choice of parameters used in the construction of SRM2137 make it useful for both implant engineers and laboratory analysts.

Wafer and Chuck Flatness

Since the intricate patterns that define integrated circuits are created photolithographically, the local and global front-surface flatness as well as planarity of the starting wafer are critically important components of the depth-of-focus (DOF) budget. Smaller features defined by short-wavelength optical lithography generally mean smaller DOF budgets; larger wafer sizes needed for cost-effective manufacturing mean tighter requirements on silicon suppliers. The recent drive toward deep ultraviolet lithography and 300-mm wafer diameter has left the industry without a workable metrology method for these parameters. The Manufacturing Engineering Laboratory at NIST has responded by extending a technique well-known to the optics industry to the measurement of 300-mm silicon wafers. In a parallel development, this same team has built and is evaluating a new instrument using infrared transmission interferometry to measure free-standing thickness variations and bow in large wafers.

Improved High Temperature Thermometry

Accurate measurement of temperature is a ubiquitous requirement in the semiconductor industry. The task often falls to the familiar thermocouple. Unfortunately, common alloy thermocouples can become unstable and inaccurate due to phase separation and resulting changes in the Seebeck coefficient of the legs. The modern process environment, particularly fast temperature ramps and strong thermal gradients, exacerbates this problem. A modest effort in the Chemical Science and Technology Laboratory has returned a major practical result — the definition of an elemental thermocouple covering the entire useful temperature range that does not suffer from these issues. This new thermocouple will work with existing instrumentation and shows about a three-fold improvement in accuracy at high temperatures.

Micromechanical Measurements

Modern integrated circuits and multichip modules (MCMs) are often dominated by multiple layers of interconnect wiring. Reliability of that interconnect is related to micromechanical properties, particularly around the via holes that establish vertical connections. NIST researchers in the Materials Science and Engineering Laboratory have pioneered several new techniques for measuring the micromechanical properties of relevant thin films. An electron beam moire technique has been developed and demonstrated to be capable of measuring the small mechanical displacements associated with local strains around a via in a high density multi-chip module interconnect structure.

Moisture Concentration Measurements in Process Gases

The measurement of humidity levels in process gas streams is largely regarded as a critical variable for CFM, the contamination-free manufacture of integrated circuits. Metrological technology for moisture in the range of 10 parts per billion to 500 parts per million has been developed as a two-step process by members of the Chemical Science and Technology Laboratory. In this process, researchers had to generate a reference gas stream that contained the target humidity level, then devise and calibrate an instrument to detect that moisture. A very low temperature saturator, called the Low Frost Point Moisture Generator (LFPG), has been built; its operation is now being verified. An accompanying development, the optical absorption method called a "ring-down cavity" has been demonstrated to have the necessary sensitivity and dynamic range to verify the performance of the LFPG at its low temperature extremes. The ring-down technique has also been shown to have potential for on-line measurement in the semiconductor fabrication (fab) environment.

OFFICE OF LAW ENFORCEMENT STANDARDS

DNA Profiling Standard Is State of the Art

To ensure that DHNA profiling methods are accurate, the National Institute of Justice, through an interagency agreement with the Office of Law Enforcement Standards (OLES), supported the development of DNA testing procedures under the direction of Dennis Reeder of the Chemical Science and Technology Laboratory. Through this effort, the NIST Standard Reference Material (SRM) 2391 was released in June 1995. This new quality assurance standard will help forensic laboratories check the accuracy of DNA analyses carried out with the polymerase chain reaction (PCR). PCR is faster and requires much less DNA than do other methods of DNA analysis.

SRM 2391 consists of 20 components including human cell lines, and PCR-amplified DNA from those cells. Laboratories can perform their own DNA profiles on each of the components and compare their results with certified values from NIST.

Model Minimum Performance Specifications for Lidar Speed-Measurement Devices

Under the direction of A. George Lieberman of OLES, a national performance standard was developed for the lidar devices used by police departments to enforce traffic speed limits in cities and on highways. The document was published as DOT HS 808-214 by the National Highway Traffic Safety Administration (NHTSA) in February 1995 and was immediately adopted by the International Association of Chiefs of Police. The standard establishes a basis for performance testing of lidar devices and provides lidar-based evidence with the reliability and accuracy essential to support speed convictions in courts of law. A big portion of this effort was the development of a target simulator for use in verifying the calibration of lidar speed-measuring devices. The simulator was designed and developed by James A. Worthey of OLES, who also wrote extensive software to create the simulation and record the data.

National Institute of Justice Standard for Autoloading Pistols

The National Institute of Justice Standard 0112.02, Autoloading Pistols for Police Officers, was revised under the direction of Daniel E. Frank of OLES to include the 10-mm Auto and the 40 Caliber S&W cartridge systems and was released in January 1995. As the one piece of equipment that is relied upon most often to protect officers as well as others from harm, it is absolutely essential that a law enforcement officer's firearm be safe and reliable. This standard will help agencies assess the acceptability of any new or reissue autoloading pistols available to the law enforcement community today.

Pepper Spray as a Law Enforcement Tool

As police departments are driven toward less-than-lethal weapons for controlling uncooperative subjects, oleoresin capsicum (OC), or pepper spray as it is more commonly known, is steadily gaining ground as the "weapon" of choice. Unfortunately, quantitative data on the chemical contents of the spray cans being sold are very limited. The question of how to assign an objective index of potency to these sprays has been raised. In order to begin to address the question, the National Institute of Justice (NIJ) is supporting research through the Office of Law Enforcement Standards in this area. The initial study, which was released April 5, 1995 as NIJ Report 100-95, Preliminary Investigation of Oleoresin Capsicum, documents a preliminary investigation into the analytical characterization of OC in order to ascertain the feasibility of determining the concentrations of the pungent constituents. The work was carried out at NIST by Richard G. Christensen of the Chemical Science and Technology Laboratory and Daniel E. Frank of OLES.

EEEL AWARDS AND RECOGNITION

THE INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS (IEEE)

Morris E. Leeds Award

The Institute of Electrical and Electronics Engineers (IEEE) selected *Roger B. Marks* and *Dylan F. Williams* as the recipients of the 1995 *Morris E. Leeds Award* presented at the 1995 International Microwave Symposium in May. The Award was established by the IEEE Board of Directors in 1958 and is presented for outstanding contributions to the field of electrical measurements. Marks and Williams are cited *for the development of measurement methods for accurate on-wafer characterization of monolithic microwave integrated circuits.* The award recognizes their work over the past five years in developing the fundamental theory and principles of on-wafer measurements of microwave network parameters, and for implementing specific calibration methods and measurement validation techniques.

R.B. MARKS AND D.F. WILLIAMS

Although their focus was originally on monolithic microwave integrated circuits, recently Marks and Williams have been applying their results to metrology issues in the microelectronics packaging and telecommunications industries. NIST calibration and measurement software based on the Marks and Williams methods is now widely used in industry and academia. Comments from individuals who supported their nomination included: "landmark microwave circuit theory...the first truly important advance in microwave circuit theory in the past 50 years," ... "unusual and outstanding, requiring deep insight and understanding on their part, in addition to being of wide practical applicability to the field of microwave measurements," ... "particularly struck by the thoroughness of their analysis and the supporting practical work... they have shown unusual leadership in this emerging area."

Additionally, *IEEE's Automatic Radio-Frequency Techniques Group (ARFTG)* recently acknowledged the *outstanding contributions in the development of on-wafer calibration and measurement methods* made by *Roger B. Marks* and *Dylan F. Williams* by the presentation of its *Automated Measurement Technology Award.* ARFTG is an independent professional society that is affiliated with the Institute of Electrical and Electronics Engineers Microwave Theory and Techniques Society as a conference committee. The ARFTG Award is given for significant contributions which advance the field of radio frequency/microwave measurement.

The measurement methodology developed by Marks and Williams enables accurate electrical characterization of MMIC devices required for applications such as on-board radar for vehicle separation, information highways, and personal and wireless communications. Among their accomplishments are the development of a waveguide circuit theory that extends the classical theory of electromagnetic waveguides to include lossy and open waveguides typical of integrated circuits; development of accurate on-wafer calibration schemes; development of methods to measure the complex characteristic impedance of printed transmission lines on gallium arsenide; development of simple-measurement-based methods for verifying accuracy; and development of calibration techniques for measuring the characteristic impedance of lossy and dispersive substrates typical of electronic packaging and silicon integrated circuits.

IEEE Fellows

The Board of Directors of the Institute of Electrical and Electronics Engineers selected three members of the Electronics and Electrical Engineering Laboratory for elevation to the grade of Fellow during FY 1995.

Alan F. Clark was cited for his *contributions to superconductivity research, development of accurate characterization methods for superconductors, and development of related industry standards.* Beginning in the early 1980s, Clark led the development of accurate characterization methods for bulk superconductor materials, especially for superconductors in wire form to be incorporated in cables for magnets, and was instrumental in achieving the adoption of these methods by research, development, and production communities as superconductivity became a practical component of electrical engineering. He is responsible for the first NIST Standard Reference Material related to superconductivity, for critical current, and his contributions are credited with promoting the acceptance of a superconducting magnet in a routine medical diagnostic tool in the form of magnetic resonance imaging, now a $2 B industry.

Clark became Editor of the IEEE Transactions on Applied Superconductivity in 1994 and served as Chairman of the Editorial Board for this journal from 1989 until his appointment as Editor. For the same period Clark chaired the IEEE Superconductivity Committee, supported by ten IEEE societies and assigned to promote applications of superconductivity in the electrical and electronics engineering communities. He is a Fellow of the American Physical Society and a previous recipient of the Department of Commerce Silver Medal.

Additionally, Clark has also been elected a *Full Member of the International Academy of Electrotechnical Sciences* for *major contributions in the development of world applied superconductivity.* Clark received his honorary diploma in a ceremony at the 1994 Applied Superconductivity Conference. The *International Academy of Electrotechnical Sciences* is a nongovernmental association of scientists from the United States, the Confederation of Independent States (the former USSR), the United Kingdom, Germany, Switzerland, Italy, France, Japan, Austria, and Korea, with the objectives of "consolidating electrotechnical scientific efforts across international boundaries, encouraging the development of designs and products applying electrotechnical sciences, and developing international scientific education and exchange of the new technologies."

Clark A. Hamilton was cited *for developing the Josephson voltage standard and other novel superconducting circuitry.* Hamilton is one of the co-inventors and principal developers of the Josephson voltage standard. Operating at either 1 volt or 10 volts, these superconducting devices consist of series arrays of Josephson junctions, elements which connect frequency with voltage through a fundamental constant. The 10-volt arrays use over 20,000 junctions and are the most complicated superconducting circuits in actual use, though operation as a standard is relatively simple. The Josephson voltage standard is now the worldwide accepted standard of voltage. Some 35 laboratories throughout the world have standards built in Hamilton's laboratory. The standards can also be found in industrial laboratories where they are used in manufacturing control and assessment of the accuracy of precision electronic equipment.

Most of Hamilton's career at NIST has been devoted to the design, fabrication, and testing of superconducting microcircuits for a variety of ultra-high-speed and high-accuracy applications. He has been the principal investigator on many contracts for the development of superconducting high-speed A/D converters, counting circuits, and analog sampling devices.

Among his accomplishments are the demonstration of a 6-bit A/D converter with a 100-ps conversion time and a counter with a bandwidth above 100 GHz. Hamilton also helped to develop a pyroelectric radiometer that won an IR-100 award for NIST. In addition to the distinction of being appointed a NIST Fellow, Hamilton's contributions have merited numerous awards, including Department of Commerce Gold and Silver medals. His current work includes the development of an ac Josephson voltage standard, based on rapid switching between many thousands of voltage steps in an array of junctions.

Hamilton has also been selected to receive the *1995 IEEE United States Activities Board Electrotechnology Transfer Award* for *providing services that collectively have resulted in the practical introduction of a new voltage standard based on Josephson-junction arrays into industry and the general metrology community of measurement systems.* This award honors individuals whose contributions in key government or civilian roles led efforts to effectively transfer or apply federal- or state-sponsored development in advanced electrical, electronic, and computer technologies to successful commercial sector opportunities.

Richard J. Van Brunt was cited for his *research in electronegative gases and the stochastic properties of partial discharges.* Van Brunt has led a nationally important program of gaseous dielectrics research at NIST that has resulted in new fundamental physical-chemical and compositional data and associated measurement methods, needed and used by the U.S. electric power industry for advanced, efficient high-voltage electrical insulation systems and by industries dependent on plasma processes, such as the plasma etching of semiconductors. In one aspect of the work, he has provided intellectual leadership of a government-industry consortium to evaluate the effects of his laboratory discoveries in operating power systems.

Van Brunt was able to confirm quickly that the extremely poisonous gas S_2F_{10} could be formed in operational systems insulated with the gas SF_6, which is increasingly used in transmission and distribution equipment. He then developed a method sensitive enough (part per billion level) to show that S_2F_{10} can be present in commercially produced SF_6. Van Brunt has proven how even minute electrical discharges in insulating systems can form toxic byproducts and cause aging of the insulating material. Such aging can lead to catastrophic system failure. He is first to invent a method for measuring the effect of one event in a pulsating series of events on following members of the series; the resulting data for electric discharges in an insulating system provide identification of likely failure sites. His analog "stochastic analyzer for pulsating phenomenon" was recognized with an R&D 100 Award in 1990 and has been followed by the development of a new digital instrument. In the past year, Van Brunt has also been appointed a NIST Fellow.

EEEL AWARDS AND RECOGNITION

THE AMERICAN PHYSICAL SOCIETY (APS)

The Membership of the American Physical Society selected one member of the Electronics and Electrical Engineering Laboratory for elevation to the grade of Fellow during FY 1995.

APS Fellow

The American Physical Society has named *Edwin R. Williams* a Fellow of the Society for *excellence in measurement research leading to an upper limit of the rest mass of the photon and precision determinations of the gyromagnetic ratio of the proton and the fine structure constant, and for leadership in highly accurate realizations of the base electrical units, the ampere, volt, ohm, and farad.* Williams' achievements cover a range of precision metrology.

An example is the determination of proton gyromagnetic ratio (γ_P), important because a measure of this fundamental physical constant yields an accurate determination of the fine-structure constant. Among other occurrences, γ_P enters into the Nobel-prize-winning experiments (Dehmelt, Kinoshita) on electron anomalous moment to provide one of the most stringent tests of quantum electrodynamic theory.

To make his experiment yield the most accurate determination to date, Williams had to invent and develop a number of measurement methods, including: a magnetic method to measure the center positions of wires forming a solenoid 2-m long with 0.03 μ_m uncertainty, a method to compensate such a solenoid without using additional windings, a method for determining leakage current between adjacent coils of the solenoid, improved methods for measuring the nuclear magnetic resonance frequency at low magnetic fields, and a method to measure the susceptibility of the soil beneath his experiment.

At present Williams' chief concerns include the Watt balance and its prospective transformation into an "electronic kilogram" and the application of single-electron-tunneling (SET) to metrology. With respect to the latter, he has worked with a group at the Service de Physique de l'Etat Condensé, CEA-Saclay (France), where he was a member of a team that is credited with the first observation of single-electron oscillations in small islands using an SET transistor as a detector. Williams has been previously awarded Department of Commerce Gold and Silver medals.

DEPARTMENT OF COMMERCE

Silver Medals

The Silver Medal Award, the second highest honor awarded by the Department of Commerce, is bestowed for "meritorious contributions of unusual value to the Department or the Nation."

Michael W. Cresswell is recognized for *spearheading the effort to develop a U.S. standard for a mask ring for use in X-ray lithography.* These systems are needed for submicrometer fine-scale lithography, the key to new generations of advanced microelectronic devices. The standard promotes further U.S. commercial development by allowing U.S. firms to capitalize on their world leadership in X-ray lithography.

Joseph R. Kinard and *Donald B. Novotny* are cited for *the development of a new class of ac-dc thermal voltage converters of enhanced performance.* The team applied semiconductor thin-film fabrication technology to the challenge of producing a multijunction device. The concept led to a collaboration with Ballantine Laboratories and was recognized by a 1994 R&D 100 Award to both organizations for implementing thin-film multijunction converters. These devices offer accuracy comparable to that of existing primary standards.

Roger B. Marks and *Dylan F. Williams* were cited for *development of methods and basic theory enabling industry to make on-wafer measurements at required accuracies of wireless and other monolithic microwave integrated circuit (MMIC) chips.* Their work has removed serious barriers to the commercial exploitation of MMIC devices for civilian uses, including wireless communications, intelligent transportation systems, and information superhighways.

NIST

Bronze Medals

The Bronze Medal Award, the highest honorary recognition available for Institute presentation, recognizes work that has resulted in more effective and efficient management systems as well as the demonstation of unusual initiative or creative ability in the development and improvement of methods and procedures. The Award is also given for scientific accomplishment within the Institute.

John Albers is cited for *development of the TXYZ code now used widely by the semiconductor industry for predicting the thermal behaviour of multilayer structures found in most devices.*

J. ALBERS, E.J. WALTERS, E.F. KELLEY

Responding to semiconductor industry needs, Albers developed and made available to users — more than 60 to date — a computer program that enables the calculation of the steady-state temperature distribution of microelectronic chips and packages. Designers require the thermal characteristics of devices to avoid thermally caused degradation and failure; the best device in the world is useless if its chip overheats. For his program, Albers chose a Fourier-series solution of the steady-state, heat-flow equations for the general case of a rectangular three-layer structure with multiple heat sources on the top surface. TXYZ provides for the calculation of the temperature at any set of points in this structure.

E. Jane Walters is recognized for *key, sustained contributions to the Semiconductor Electronics Division,* especially in the areas of information collection, organization, and dissemination. With initiative, skill, and diligence, Walters coordinated brochures and exhibit materials, and established information databases that have enabled the Division to respond rapidly to numerous inquiries about its programs as well as to satisfy formal reporting requirements. Walters also set up systems for tracking the technical status of projects, and for editorial control and tracking of Division publications, materially contributing to their quality.

Edward F. Kelley is cited for *design and implementation of a versatile laboratory for assessing the quality of flat-panel displays and providing domestic industry with methods for evaluating competing displays.* At present, standards for characterizing these displays are either non-existent or inadequate for providing meaningful comparisons between similar displays produced by different manufacturers or between displays based on different technologies. The facility created by Kelley provides a firm metrological basis for the development of measurement procedures for immediate use by industry and for incorporation into future standards. Government and industry groups are already seeking NIST's help in developing display quality standards.

OTHER ORGANIZATIONS

John Mungenast International Power Quality Award

François D. Martzloff has been awarded the first *John Mungenast International Power Quality Award.* Martzloff was selected by an awards committee composed of power electronics industry leaders. Power Quality Assurance Magazine and UtiliCorpUnited Energy One established the Award to recognize outstanding contributions in the field of Power Quality engineering; the Award is named in honor of John Mungenast, a recognized supporter of research in power electronics.

FEDERAL LABORATORY CONSORTIUM (FLC)

Matt Young has been awarded the *FLC Award of Merit* for *Excellence in Technology Transfer.* Young led a small group that developed an artifact standard for optical fiber diameter measurements. The standard, which is accurate within less than one-tenth of one micrometer, is needed in order to make relatively lossless connections between communications fibers. Major North American manufacturers have purchased the standard and have used it to recalibrate their instruments. An Executive Vice President of Corning said in reference to the development of the Standard Reference Material 2520: "The opportunity to work with NIST on this gave Corning and other American fiber manufacturers a clear competitive advantage."

FY 1995 CRADAs

EEEL participated in 42 cooperative research and development agreements (CRADAs) with industry during FY 1995. 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.

Alliance Technologies, Incorporated: Component Libraries for Circuit Simulators

Analogy, Incorporated: Power Semiconductor Devices in Electronic Circuits

Ballantine Laboratories, Incorporated: Thin-film Multijunction Thermal Converters

Best Technology, Incorporated: Study of Improved Single Junction Thermoelements

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

Cascade Microtech, Incorporated: MMIC Consortium

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

Digital Instruments, Incorporated: Development of Capacitance Microscopy

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

General Electric CRD: Parameter Extraction for High-Power IGBTs

Harris Corporation: Power Mosfet Development

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

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

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

International Business Machines Corporation: Thin Film for Magnetic Storage Media

ITT Defense Technology Corporation: MMIC Consortium

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

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

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

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

Quantum Magnetics, Incorporated: Voltage Standards

Quantum Magnetics, Incorporated: Magnetic Imaging

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

RMC, Incorporated: Commercial Josephson Voltage Standard

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

SEMATECH: Semiconductor Technology and Processes

South Carolina Research Authority: Advanced Manufacturing of Electrical Products

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

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

Texas Instruments: MMIC Consortium

The Boeing Company: Optical Components

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

TRW, Incorporated: MMIC Consortium

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

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

Wiltron Company: Validate Commercial VNA Performance

Xerox Corporation: Three Dimensional Structuring of MEMs Transducer Arrays

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

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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 Electromagnetic Fields Division, the Electromagnetic Technology Division, and the Optoelectronics Division, which was formed in FY 1994, are located in Boulder, Colorado.

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

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810 LABORATORY HEADQUARTERS

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2228	HORMUTH, James A., Exec. Officer

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ADMINISTRATIVE SUPPORT - BOULDER

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4258	LIEBERMAN, A. George
5128	WATERS, Nathaniel E.
3396	WORTHEY, James A.

The **Office of Microelectronics Programs (OMP)** provides integrated circuit manufacturers, materials suppliers, and makers of semiconductor manufacturing equipment with a clear window on the EEEL/NIST organization. OMP offers direct access to an enormously varied range of scientific and technical expertise.

In addition, OMP manages NIST's strong working relationship with SEMATECH, the consortium of U.S. semiconductor manufacturers, and with many of its member firms. Research priorities are established on the basis of industry input and the Office's participation in U.S. and international conferences and planning activities.

The National Semiconductor Metrology Program, which was established in 1994 and draws on the full range of NIST expertise in semiconductor electronics, manufacturing engineering , chemical and materials science engineering, and fundamental science, is managed by OMP.

The **Office of Law Enforcement Standards (OLES)** supports law enforcement agencies through the development of measurement methods and techniques for testing devices used in such applications as tracking vehicles, speed monitoring, surveillance, and communications. The Office develops minimum performance standards for issuance by the National Institute of Justice as voluntary national standards. 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.

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

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.

811.00 ELECTRICITY DIVISION

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2402 ENGLER, Hans (GR)
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2412 LAUG, Owen B.
2438 WALTRIP, Bryan C.

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2406 SOUDERS, T. Michael (PL)
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2419 BELL, Barry A.
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4245 MOORE, Theodore P.
4243 SECULA, Andrew J.
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4238 SIMS, June E.

Thermal Transfer Standards and Measurements
4250 KINARD, Joseph R., Jr. (PL)
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4251 LIPE, Thomas E., Jr.

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4244 TILLETT, Summerfield B.

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4443 KIM, Jinhee (GR)

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4228 NEWELL, David B. (PD)
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2737 FitzPATRICK, Gerald J.
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3517 PARKS, Curtis H.
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4124 ST. PIERRE, James A.
4229 McCALEB, Michael R.

SEMICONDUCTOR ELECTRONICS DIVISION

The **Semiconductor Electronics Division (SED)** provides leadership and participates in developing the semiconductor measurement infrastructure essential to improving U.S. economic competitiveness. The Division's primary focus is on mainstream silicon; other programs respond to industry measurement needs related to compound semiconductors, power devices, and silicon-on-insulator devices. SED plans and implements its programs in cooperation with the semiconductor industry and its suppliers and customers to address critical needs. By achieving goals such as those outlined in the National Technology Roadmap for Semiconductors, a silicon roadmap SED participated in developing, the Division effects a significant impact on industry.

SED program areas include optical and electrical characterization metrology, metrology for nanoelectronics, in-situ metrology, scanning probe metrology, MBE compound semiconductor growth and characterization, focused ion-beam lithography, superlattices and heterostructures, interface properties, quantum nanostructures, model validation for model-based design, power semiconductor devices, device and package electrical and thermal metrology, silicon-on-insulator metrology, silicon integrated circuits, thin-film process metrology, metrology for process and tool control, reliability metrology for interconnects and dielectrics, test structures, and microelectromechanical systems (MEMS).

812.00 SEMICONDUCTOR ELECTRONICS DIVISION
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2097 HARMAN, George G., NIST Fellow
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2050 WALTERS, E. Jane, Lead Editorial Assistant
2296 ROHRBAUGH, Janet M., Editorial Assistant

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GL = GROUP LEADER
GR = GUEST RESEARCHER
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.01 MATERIALS TECHNOLOGY
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4706 MILANOVIC, Veljko (GR)
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2073 ZINCKE, Christian A. (GRF)

ELECTROMAGNETIC FIELDS DIVISION

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

Assistance is also provided to other agencies to solve measurement-related issues, such as determining levels of nonionizing radiation and solving electromagnetic interference problems. The results of the Division's work are disseminated to industry, universities, and other government agencies to foster effective research, development, manufacturing, and marketplace equity. The Division's principal program areas include microwave and millimeter wave metrology for continuous wave transmission line measurements, noise and dielectric measurements, antenna metrology, and fields and interference metrology. These services and associated standards provide a consistent base of measurements to enable contractors in the defense, aerospace, and communications industries to both assemble complete systems and perform the stringent performance assessments which are required.

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3132 LYONS, Ruth Marie, Secretary
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3557 REEVE, Gerome R.
5284 DeLARA, Puanani L., Property Officer

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5593 PITTMAN, Earle
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5048 TALLEY, Ken

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3166 NOVOTNY, David
3309 ONOREJKA, Arthur R.
3737 JOHNK, Robert T.

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5766 KOEPKE, Galen H.
3214 CAMELL, Oennis G.
5332 MEOLEY, Herbert W.

EMI Measurements & Standards
3472 HILL, Oavid A.
5372 LADBURY, John M.

.08 ANTENNA AND MATERIALS METROLOGY

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Near-Field Antenna Techniques
3732 DEAN, David N.
5873 FRANCIS, Michael H.
3302 BASSETT, Oavid N. (PT)
5196 LEWIS, Richard L.
3471 MACREYNOLDS, Katherine
3927 STUBENRAUCH, Carl F.
3694 TAMURA, Douglas T.
3863 GUERRIERI, Jeffrey R.
5702 CANALES, Seturnino, Jr.

Dielectric Materials Properties
5305 WEIL, Claude M.
5852 GEYER, Richard G.
5621 BAKER-JARVIS, James R.
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ELECTROMAGNETIC TECHNOLOGY DIVISION

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

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

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

814.00
ELECTROMAGNETIC TECHNOLOGY DIVISION

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3678	MAORIO, Michael, Property Officer
5068	SIMMON, Mary Jo, Cler. Asst.

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GL =	GROUP LEADER
GR =	GUEST RESEARCHER
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PL =	PROJECT LEADER
PT =	PART TIME
S =	STUDENT

.01 MAGNETIC RECORDING METROLOGY

5097	RUSSEK, Stephen E. (PL)
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.02 MAGNETIC INSTRUMENTS & MATERIALS CHAR.

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7305	LIDU, Sy-Hwang

.04 MICROSTRUCTURAL ANALYSIS FOR ELECTRO-MAGNETIC TECHNOLOGY

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7320	STORK, Frons (GR)

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5052	REINTSEMA, Carl D.

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Abstract

The Electronics and Electrical Engineering Laboratory (EEEL), working in concert with other NIST Laboratories, is providing measurement and other generic technology critical to the competitiveness of the U.S. electronics industry and the U.S. electricity-equipment industry. This report summarizes selected technical accomplishments and describes activities conducted by the Laboratory in FY 1995. Also included is a profile of EEEL's organization, its interactions with customers, and the Laboratory's long-term goals.

Keywords

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

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