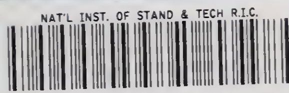
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NISTIR 5483

Electronics and Electrical Engineering Laboratory

Technical Progress Bulletin

J. M. Rohrbaugh
Compiler

September 1994

Covering Laboratory Programs,
April to June 1994
with 1994/1995 EEEL Events Calendar

94-2

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

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

TECHNOLOGY ADMINISTRATION
Mary L. Good, Under Secretary for Technology

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arati Prabhakar, Director

ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY TECHNICAL PROGRESS BULLETIN, SEPTEMBER 1994 ISSUE

INTRODUCTION

This is the forty-seventh issue of a quarterly publication providing information on the technical work of the National Institute of Standards and Technology Electronics and Electrical Engineering Laboratory (EEEL). This issue of the EEEL Technical Progress Bulletin covers the second quarter of calendar year 1994.

Organization of Bulletin: This issue contains abstracts for all relevant papers released for publication by NIST in the quarter and citations and abstracts for such papers published in the quarter. Entries are arranged by technical topic as identified in the Table of Contents and alphabetically by first author under each subheading within each topic. Unpublished papers appear under the subheading "Released for Publication." This does not imply acceptance by any outside organization. Papers published in the quarter appear under the subheading "Recently Published." Following each abstract is the name and telephone number of the individual to contact for more information on the topic (usually the first author). This issue also includes a calendar of Laboratory conferences and workshops planned for calendar years 1994/1995 and a list of sponsors of the work.

Electronics and Electrical Engineering Laboratory: EEEL programs provide national reference standards, measurement methods, supporting theory and data, and traceability to national standards. The metrological products of these programs aid economic growth by promoting equity and efficiency in the marketplace, by removing metrological barriers to improved productivity and innovation, by increasing U.S. competitiveness in international markets through facilitation of compliance with international agreements, and by providing technical bases for the development of voluntary standards for domestic and international trade. These metrological products also aid in the development of rational regulatory policy and promote efficient functioning of technical programs of the Government.

The work of the Laboratory is conducted by four technical research Divisions: the Semiconductor Electronics and the Electricity Divisions in Gaithersburg, Md., and the Electromagnetic Fields and Electromagnetic Technology Divisions in Boulder, Colo. In 1991, the Office of Law Enforcement Standards, formerly the Law Enforcement Standards Laboratory, was transferred to EEEL. This Office conducts research and provides technical services to the U.S. Department of Justice and State and local governments, and other agencies in support of law enforcement activities. In addition, the Office of Microelectronics Programs (OMP) was established in EEEL to coordinate the growing number of semiconductor-related research activities at NIST. Reports of work funded through the OMP are included under the heading "Semiconductor Microelectronics."

Key contacts in the Laboratory are listed at the end of this publication; readers are encouraged to contact any of these individuals for further information. To request a subscription or for more information on the Bulletin, write to EEEL Technical Progress Bulletin, National Institute of Standards and Technology, Metrology Building, Room B-358, Gaithersburg, MD 20899 or call (301) 975-2220.

Laboratory Sponsors: The Laboratory Programs are sponsored by the National Institute of Standards and Technology and a number of other organizations, in both the Federal and private sectors; these are identified on page 31.

Note on Publication Lists: Publication lists covering the work of each division are guides to earlier as well as recent work. These lists are revised and reissued on an approximately annual basis and are available from the originating division. The current set is identified in the Additional Information section, page 27.

Certain commercial equipment, instruments, or materials are identified in this paper in order to specify adequately the experimental procedures. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

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GENERAL INFORMATION

Recently Published

Powell, R.M., **Electronics and Electrical Engineering Laboratory: 1994 Strategic Plan**, NISTIR 5409 (April 1994).

The U.S. electronics and electrical-equipment industries are outstripping available measurement capability with adverse effects on their international competitiveness. Improved measurement support is an essential part of any successful strategy for improving their competitiveness. Among U.S. manufacturing industries, the electronics industry is the largest employer with 1.8 million employees and is virtually tied with the chemical industry for largest shipments of nearly $300 billion (1992). The electrical-equipment industry is also quite large, with shipments of nearly $50 billion (1990). U.S. competitiveness in many fields of electronic and electrical products has been declining. Improved competitiveness will require outstanding performance from manufacturers in every step required to realize a competitive product in the marketplace: research and development, manufacturing, marketplace exchange, and after-sales support. All of these steps are highly measurement intensive. The Electronics and Electrical Engineering Laboratory (EEEL), within the National Institute of Standards and Technology, has identified the principal needs for improved measurement capability and other supporting technology in several important fields: semiconductors, magnetics, superconductors, low frequency, microwaves, lightwaves, power, video, electromagnetic compatibility, electronic data exchange, and national electrical standards. This document describes EEEL's strategic plan for a response to these needs. That response is related to important national goals for a strengthened economy and improved international competitiveness. This plan was developed in consultation with U.S. industry and other NIST Laboratories.
[Contact: Ronald M. Powell, (301) 975-2220]

FUNDAMENTAL ELECTRICAL MEASUREMENTS

Released for Publication

Elmquist, R.E. **Status of the Quantum Hall Resistance RISP**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium, Chicago, Illinois, August 1-5, 1994.

The NCSL Working Group that is developing a Recommended Intrinsic/Derived Standards Practice (RISP) for a quantum Hall resistance (QHR) standard has surveyed a group of standards laboratories to learn where a need for the standard exists. Smaller national laboratories are actively seeking to develop QHR facilities to support industrial needs. U.S. major industrial standards laboratories are suitable sites for the QHR, but few are eager to pursue development due to the perceived difficulty and expense of operating a QHR facility. The development of the RISP will reduce the ambiguity in the planning process. Initial questions about the method of measuring the resistance standard and scaling to the decade levels are addressed.
[Contact: Randolph E. Elmquist, (301) 975-6591]

Kautz, R.L., **Quasipotential and the Stability of Phase Lock in Nonhysteretic Josephson Junctions**.

The principle of minimum available noise energy is used to calculate the quasipotential over the state space of a nonhysteretic Josephson junction driven by an rf bias. This potential surface provides an intuitive picture of the dynamics of phase lock and defines a stability parameter, the activation energy for thermally induced phase slippage, that determines the optimum operating conditions for a proposed programmable voltage standard.
[Contact: Richard L. Kautz, (303) 497-3391]

Kautz, R.L., Benz, S.P., and Reintsema, C.D., **Large-Amplitude Shapiro Steps and Self-Field Effects in High-T_c Josephson Weak Links**.

We demonstrate contiguous Shapiro steps of orders 0 and 1 having amplitudes of 1 mA in a $YBa_2Cu_3O_{7-\delta}$ step-edge junction operated at 38 K. A wide-junction model that includes self-field effects is shown to explain why the observed step amplitudes are smaller than expected from the resistively shunted point-junction model. In spite of their reduced amplitudes, the observed steps are suitable for use in a proposed rapidly programmable

Josephson voltage standard.
[Contact: Richard L. Kautz, (303) 497-3391]

FUNDAMENTAL ELECTRICAL MEASUREMENTS

Recently Published

Eiles, T.M., Martinis, J.M., and Devoret, M.H., **Even-Odd Symmetry Breaking in the NSN Coulomb Blockade Electrometer**, Physica B, Vol. 189-190, pp. 1-8 (1993).

We have measured at low temperature the current through a submicrometer superconducting island connected to two normal metal leads by ultra-small tunnel junctions. As the bias voltage is lowered below the superconducting gap of this Coulomb blockade electrometer, the current changes from being e-periodic with gate charge to $2e$-periodic. We interpret the $2e$-periodic current at low voltages as a manifestation of a sequence of Andreev reflections which shuttles two electrons at a time through the island. This process can only exist if the island favors a state with a definite parity of the number of conduction electrons.
[Contact: Travis M. Eiles, (303) 497-3969]

Ghosh, R.N., Williams, E.R., Clark, A.F., and, Soulen, Jr., R.J., **Cryogenic Precision Capacitance Bridge Using a Single Electron Tunneling Electrometer**, Physica B, Vol. 194-196, pp. 1007-1008 (March 1994).

The electronic charge can be determined by placing a known number of electrons on a calibrated capacitor and measuring the resulting voltage, which leads to a measure of the fine structure constant, α. Single electron tunneling (SET) electrometers with sufficient sensitivity for this application have been fabricated. We report on the design and preliminary results of a capacitance bridge experiment using a SET electrometer to measure two capacitors in a dilution refrigerator. AC measurements of the capacitance ratio have a precision of one part in 10^{-4}, and dc measurements provide information on the leakage rate of the standard capacitors.
[Contact: Edwin R. Williams, (301) 975-4206]

Martinis, J.M., Nahum, M., and Jensen, H.D., **Testing for Metrological Accuracy of the Electron Pump**, Physica B, Vol. 194-196, pp. 1045-1046 (1994).

We have measured the electron leakage rate through a five-junction electron pump. Our observed rate of about 0.3 electrons per second is several orders of magnitude larger than predicted by thermal activation or co-tunneling rates. Our results can be explained by the environmental theory of the Coulomb blockage where noise from the environment causes photon-assisted tunneling.
[Contact: John M. Martinis, (303) 497-3597]

SEMICONDUCTOR MICROELECTRONICS

Silicon Materials

Released for Publication

Rennex, B., ***Standard Reference Materials*: Certification of a Standard Reference Material for the Determination of Interstitial Oxygen Concentration in Semiconductor Silicon by Infrared Spectrophotometry**, to be published as NIST Special Publication 260-121.

A Standard Reference Material, SRM-2551, has been prepared, measured, and certified for the determination of interstitial oxygen number fraction (commonly referred to as the oxygen concentration) in semiconductor silicon. This SRM is intended for calibration of infrared spectrophotometers used to measure the 1107 cm^{-1} interstitial oxygen peak in silicon. Its purpose is to enable its users to improve their measurement agreement. The expanded SRM uncertainty is 0.17% for the low-oxygen specimens, 0.13% for the medium-oxygen specimens, and 0.12% for the high-oxygen specimens. The certifying instrument was a Fourier-transform infrared spectrophotometer which measured the oxygen peak height. Specimens from an earlier international Grand Round Robin (GRR) were used to convert these infrared values to oxygen number fraction (concentration) values. A major source of uncertainty had been measurement drift; this was largely compensated using a control specimen. The remaining sources of uncertainty were instrument reproducibility, nonuniformity in oxygen concentration and thickness over the specimen area, and variation in residual oxygen in the SRM float-zone specimens, each of which float-zone specimens

served as the zero-oxygen reference for a measurement. These sources were combined in quadrature to arrive at the above-quoted 2σ estimate of expanded SRM uncertainty. This SRM uncertainty applies to a "derived" oxygen number fraction which is first measured by an infrared technique and which is then converted to an oxygen number fraction. The oxygen number fraction previously measured in the GRR has a much larger uncertainty than the expanded SRM uncertainty.
[Contact: Brian G. Rennex, (301) 975-2108]

Rennex, B.G., Ehrstein, J.R., and Scace, R.I., **Development of a Standard Reference Material for Measurement of Interstitial Oxygen Concentration In Semiconductor Silicon by Infrared Absorption**, to be published in the Proceedings of the 186th Meeting of the Electrochemical Society, Miami Beach, Florida, October 9-14, 1994.

A Standard Reference Material, SRM-2551, has been prepared, measured, and certified for the determination of interstitial oxygen concentration in semiconductor silicon. Its purpose is to assist users in the calibration of infrared spectrophotometers used to measure the 1107 cm^{-1} oxygen peak. The SRM uncertainty is 0.17% for the low-oxygen specimens, 0.13% for the medium-oxygen specimens, and 0.12% for the high-oxygen specimens.
[Contact: Brian G. Rennex, (301) 975-2108]

Sauvageau, J.E., Burroughs, C.J., Cromar, M.W., and Koch, J.A., **Optimization of ECR-Based PECVD Oxide Films for Superconducting Integrated Circuit Fabrication**, to be published in the Proceedings of the 1994 37th Annual Technical Conference of the Society of Vacuum Coaters, Boston, Massachusetts, May 8-13, 1994.

[See Cryoelectronic Metrology.]

Compound Materials

Released for Publication

Kim, J.S., Seiler, D.G., Colombo, L., and Chen, M.C., **Characterization of LPE HgCdTe Films by Magnetoresistance**, to be published in the Proceedings of the 1994 U.S. Workshop on the Physics and Chemistry of Mercury Cadmium Telluride and Other IR Materials, San Antonio, Texas, October 4-6, 1994.

Magnetoresistance has been shown in the past to be a valuable tool for studying complex energy bands of semiconductors. In this paper, we demonstrate that magnetoresistance can be used as an extremely useful physical quantity to electrically characterize HgCdTe materials, structures, or devices which are of a multicarrier conduction nature. We take advantage of simple relationships between the magnetoresistance, the applied magnetic field, the lattice temperature, and relevant physical quantities in the reduced conductivity tensor scheme.
[Contact: Jin S. Kim, (301) 975-2238]

Richter, C.A., Seiler, D.G., and Pellegrino, J.G., **Mesoscopic Conductance Fluctuations In Large Devices**, to be published in the Workbook of the 22nd International Conference on the Physics of Semiconductors, Vancouver, British Columbia, Canada, August 15-19, 1994.

"Universal" conductance fluctuations are reproducible, aperiodic fluctuations which are due to quantum interference of electron waves passing through an entire device. Here, we report experimental studies of these fluctuations in a variety of millimeter-size GaAs/AlGaAs modulation-doped heterostructure devices. It has generally been assumed that at finite temperatures, quantum interference effects cannot be observed in devices of this large size. We use an ac magnetic field modulation and lock-in amplifier technique to measure the conductance of the devices. This method allows changes in the resistance as a function of magnetic field to be observed and studied in a new size-scale regime where devices have large areas.
[Contact: Curt A. Richter, (301) 975-2082]

Compound Materials

Recently Published

Wang, L., Haegel, N.M., and Lowney, J.R., **Band-to-Band Photoluminescence and Luminescence Excitation in Extremely Heavily Carbon-Doped Epitaxial GaAs**, Physical Review B, Vol. 49, No. 16, pp. 976-985 (15 April 1994).

Heavily carbon-doped GaAs samples with doping levels as high as 4.1 x 10^{20} cm^{-3} were studied by photoluminescence and luminescence excitation spectroscopies. Luminescence and absorption bandgaps were determined, from which the positions of the observed emission spectra, including diffraction and refraction of the luminescence, substrate effects, and lattice contraction in the carbon-doped epilayer, were examined. A first-principles calculation was performed to calculate the density of states, bandgap, Fermi energy, and emission spectrum. Comparison of calculation results with the experiments shows that the theoretical model we use is a good approximation for describing band structure for doping levels higher than 10^{20} cm^{-3}. However, the discrepancy between the measured and the calculated emission spectra indicates that the usual assumptions such as constant momentum matrix elements and quasi-equilibrium distribution of photo-excited electrons in the conduction band may not be appropriate in treating the transition processes in highly degenerate semiconductors.
[Contact: Jeremiah R. Lowney, (301) 975-2048]

Analysis and Characterization Techniques

Released for Publication

Kim, J.S., Seiler, D.G., Colombo, L., and Chen, M.C., **Characterization of LPE HgCdTe Films by Magnetoresistance**, to be published in the Proceedings of the 1994 U.S. Workshop on the Physics and Chemistry of Mercury Cadmium Telluride and Other IR Materials, San Antonio, Texas, October 4-6, 1994.

[See Compound Materials.]

Kopanski, J.J., Marchiando, J.F., Lowney, J.R., and Seiler, D.G., **Scanning Capacitance Microscopy for Profiling PN-Junctions in Silicon**, to be published in NISTIR 5400, abstracts from the Workshop on Industrial Applications of Scanned Microscopy, Gaithersburg, Maryland, March 24-25, 1994.

The NIST scanning capacitance microscope combines an atomic force microscope (AFM) with a high-sensitivity capacitance measurement. A metallized AFM tip, separated by an air gap and oxide layer from a semiconductor, is used to form a metal-insulator-semiconductor capacitor. As the cantilever tip of the AFM is scanned over a semiconductor surface, topography and capacitance are measured simultaneously, permitting capacitance measurements limited in spatial resolution by the tip radius. The RCA videodisc sensor is used for capacitance detection.
[Contact: Joseph J. Kopanski, (301) 975-2089]

Perkowitz, S., and Seiler, D.G., **Optical Characterization In Microelectronics Manufacturing**, to be published in the NIST Journal of Research.

To successfully construct semiconductor devices, the semiconductor industry must measure fundamental material parameters, especially when developing new materials; measure the quality of the material as it is grown; accurately determine the details of thin films, quantum wells, and other microstructures that control or affect device performance; and measure properties of the devices themselves. Properties that need to be determined, therefore, include basic band structure and transport parameters, such as energy gap values and carrier scattering times; the presence and concentration of impurities and defects; alloy parameters; layer thickness; the distribution of materials in complex structures; and many others. This process of determining a wide range of material, structural, and device parameters is called characterization. The semiconductor industry uses many characterization methods which draw on electrical, chemical, and other approaches. Among these, optical characterization techniques, defined as those using electromagnetic radiation from the ultraviolet to the far infrared, stand out because they are nondestructive and require minimal sample preparation since no contacts are needed. These features are of great importance for production use or to examine finished devices. Another benefit is that, unlike electrical methods which require fixed contacts, optical techniques can give two- or three-dimensional maps of properties over the extent of a semiconductor wafer. The six techniques described in this paper (ellipsometry, infrared spectroscopy, microscopy, modulation spectroscopy, photoluminescence, and Raman scattering) were chosen because they are currently or potentially widely used in the industry; they measure a broad array of semiconductor parameters; and they operate in

different regions of the electromagnetic spectrum. The discussion of each technique indicates the basic semiconductor quantities measured, gives the scientific basis of the technique, and indicates how the measurement is made. Illustrative examples from the literature are discussed in detail, showing applications to important semiconductor materials. More information can be obtained from the detailed list of references included. References listed under "General" give a broad overview of the technique, its theory, and practice. Those under "Applications" present further illustrations of how the technique is used for specific problems in real materials, primarily Si, GaAs, AlGaAs, but also diamond, SiO_2, GaAs/Si, InSb, GaAsSb, InGaAs, InGaAlAs, CdTe, HgCdTe, AlAs/GaAs, and HgTe/CdTe.
[Contact: David G. Seiler, (301) 975-2632]

Analysis and Characterization Techniques

Recently Published

Lowney, J.R., Thurber, W.R., and Seiler, D.G., **Transverse Magnetoresistance: A Novel Two-Terminal Method for Measuring the Carrier Density and Mobility of a Semiconductor Layer**, Applied Physics Letters, Vol. 64, No. 22, pp. 3015-3017 (30 May 1994).

The magnetic-field dependence of the two-terminal magnetoresistance that occurs in rectangularly shaped samples can be used to determine both the free-carrier density and the mobility of a semiconductor layer. An approximate equation for the magnetoresistance was derived for variable length-to-width ratio. This technique was used to determine the electron density and mobility of accumulation layers in *n-type* $Hg_{0.8}Cd_{0.2}Te$ *photoconductive infrared detectors* at 6 and 77 K. It should be applicable to a wide variety of fabricated devices and allow significant improvements in processing methods and quality control.
[Contact: Jeremiah R. Lowney, (301) 975-2048]

Device Physics and Modeling

Released for Publication

Albers, J., **A Note on the Calculation and Application of Average Temperatures**.

Electrical and optical techniques are often used to measure the local steady-state temperature of semiconductor device structures. The experimental quantities are actually averages over the region for which the measurement is performed. The calculation of the average temperature is also performed to gain insight into the thermal characteristics of the structure. These calculations have previously been performed using the Kokkas model. In particular, the temperature is calculated at a set of representative points in the area of the measurement. These are then used to construct an approximation to the average temperature. Within the framework of the Kokkas model, the present work shows that the area average temperature can be calculated directly. This obviates the need for point function evaluations of the temperature and the subsequent evaluation of the approximate area average temperature. The direct calculation of the area average temperature should provide for a simpler analysis of experimental data and enhanced insight into the effects of the thermal characteristics on the measured temperature.
[Contact: John Albers, (301) 975-2075]

Lowney, J.R., **Use of Monte Carlo Modeling for Interpreting SEM Linewidth Measurements**.

A scanning electron microscope (SEM) can be used to measure the dimensions of the microlithographic features of integrated circuits. However, without a good model of the electron-beam/specimen interaction, accurate edge location cannot be obtained. A Monte Carlo code has been developed to model the interaction of an electron beam with one or two lines lithographically produced on a multi-layer substrate. The purpose of the code is to enable one to extract the edge position of a line from SEM measurements. It is based on prior codes developed at NIST, but with a new formulation for the atomic scattering cross sections and the inclusion of a method to simulate edge roughness or rounding. The code is currently able to model the transmitted and backscattered electrons, and the results from the code have been applied to the analysis of electron transmission through gold lines on a thin silicon substrate, such as used in an X-ray lithographic mask. Significant reductions in backscattering occur because of the proximity of a neighboring line.
[Contact: Jeremiah R. Lowney, (301) 975-2048]

Richter, C.A., Seiler, D.G., and Pellegrino, J.G., **Mesoscopic Conductance Fluctuations In Large Devices**, to be published in the Workbook of the 22nd International Conference on the Physics of Semiconductors, Vancouver, British Columbia, Canada, August 15-19, 1994.

[See Compound Materials.]

Device Physics and Modeling

Recently Published

Bennett, H.S., and Lowney, J.R., **Physics for Device Simulations and Its Verification by Measurements**, chapter in The IMA Volumes in Mathematics and Its Applications: Semiconductors, Part II (Springer-Verlag, New York, New York, 1994), pp. 34-74.

The motivations for using computers to simulate the electrical characteristics of transistors are discussed. Our work and that of others in the area of device physics and modeling are described. We compare conventional device physics with an alternative approach to device physics that is more directly traceable to quantum-mechanical concepts. We then apply this new approach to quasi-neutral regions, space-charge regions, and regions with high levels of carrier injection. Examples of applying quantum-mechanically-based device physics to energy band diagrams for bipolar transistors are given. The limits for using theoretical results from uniform media in numerical simulations of devices with large concentration gradients are discussed. Calculations of the effective intrinsic carrier concentrations for gallium arsenide and silicon are also given along with published data. In addition, calculations of the mobilities for GaAs that are based in part on quantum-mechanical phase shifts are compared with published data. We then conclude with a discussion of the requirements for verifying and calibrating device simulators for the submicrometer domain.
[Contact: Herbert S. Bennett, (301) 975-2079]

Insulators and Interfaces

Released for Publication

Dahmani, R., Salamanca-Riba, L., Nguyen, N.V., Chandler-Horowitz, D., and Jonker, B.T., **Strain Effect on the Energy Bands of ZnSe Films Grown on GaAs Substrates by Spectroscopic Ellipsometry**.

Room-temperature spectroscopic ellipsometry measurements were carried out on ZnSe thin films grown on (001) GaAs substrates by molecular beam epitaxy for the study of the lattice mismatch-induced strain at the interface. The amplitude of the absorption coefficient at the $E_0 + \Delta_0$ critical point is very sensitive to the strain in the film. The variation in the amplitude of the absorption coefficient is used to estimate the critical thickness for the onset of dislocation generation. Almost complete relaxation of the films was obtained for thicknesses higher than 500 nm. Also, the strain-induced coupling between the valence sub-bands was found to cause additional shifting of the light hole sub-band.
[Contact: Nhan Van Nguyen, (301) 975-2044]

Insulators and Interfaces

Recently Published

Nguyen, N.V., Chandler-Horowitz, D., Amirtharaj, P.M., and Pellegrino, J.G., **Spectroscopic Ellipsometry Determination of the Properties of the Thin Underlying Strained Si Layer and the Roughness at SiO_2/Si Interface**, Applied Physics Letters, Vol. 64, No. 20, pp. 2688-2690 (16 May 1994).

The existence of both the strain and microroughness at the interface of thermally grown SiO_2 films on Si was ascertained unambiguously for the first time by high-accuracy spectroscopic ellipsometry. The dielectric function of the interface was determined by a comprehensive data analysis procedure. By carefully examining the dielectric function obtained by our model, the strain was seen to cause a red shift of 0.042 eV of the interband critical point E_1 compared with the bulk silicon value. The thickness of the interface region was found to be 2.2 nm of which a significant part is due to the strain.
[Contact: Nhan Van Nguyen, (301) 975-2044]

Dimensional Metrology

Recently Published

Kopanski, J.J., Marchiando, J.F., Lowney, J.R., and Seiler, D.G., **Scanning Capacitance Microscopy for Profiling PN-Junctions in Silicon**, to be published in NISTIR 5400, abstracts from the Workshop on Industrial Applications of Scanned Microscopy, Gaithersburg, Maryland, March 24-25, 1994.

[See Analysis and Characterization Techniques.]

Lowney, J.R., and Marx, E., ***Semiconductor Measurement Technology*: User's Manual for the Program MONSEL-I: Monte Carlo Simulation of SEM Signals for Linewidth Metrology**, to be published as NIST Special Publication 400-95.

This user's manual is a guide to the FORTRAN code MONSEL-I which is a Monte Carlo simulation of the transmitted and backscattered electron signals in a scanning electron microscope (SEM) associated with a line specimen with a trapezoidal cross section. The line is deposited on a multilayer substrate. The primary purpose of the code is to determine the actual linewidth from measured SEM signals. However, it can be used for many other purposes such as transmission electron microscopy. Future extensions to model secondary electron signals and multiple lines are planned.
[Contact: Jeremiah R. Lowney, (301) 975-2048]

Dimensional Metrology

Recently Published

Lowney, J.R., Postek, M.T., and Vladar, A.E., **A Monte Carlo Model for SEM Linewidth Metrology**, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Integrated Circuit Metrology, Inspection, and Process Control, Vol. 2196, pp. 85-96 (1994).

A scanning electron microscope (SEM) can be used to measure the dimensions of the microlithographic features of integrated circuits. However, without a good model of the electron-beam/specimen interaction, accurate edge location cannot be obtained. A Monte Carlo code has been developed to model the interaction of an electron-beam with a line lithographically produced on a multi-layer substrate. The purpose of the code is to enable one to extract the edge position of a line from SEM measurements. It is based on prior codes developed at NIST, but with a new formulation for the atomic scattering cross sections and the inclusion of a method to simulate edge roughness or rounding. The code is currently able to model the transmitted and backscattered electrons, and the results from the code have been applied to the analysis of electron transmission through a gold line on a thin silicon substrate, such as used in an X-ray lithographic mask. By comparing the predictions of the code with measured data, it is possible to obtain edge positions to the order of ±10 nm, which is needed for the advanced lithography projected for the year 2000. The uncertainty of this measurement is limited by the sample geometry and surface roughness and not by the measurement process.
[Contact: Jeremiah R. Lowney, (301) 975-2048]

Integrated-Circuit Test Structures

Released for Publication

Allen, R.A., Cresswell, M.W., Ellenwood, C.H., and Linholm, L.W., **The Enhanced Voltage-Dividing Potentiometer for High-Precision Feature Placement Metrology**.

A new, robust, high-sensitivity, electrical test structure based on the voltage-dividing potentiometer principle, and designed for the measurement of the separations of pairs of conducting features, has recently been reported. In this work, the uncorrected measurements had a systematic error in the hundreds of nanometers. Through further measurements and extensive modeling, the systematic error was attributed to asymmetries at the intersections of conducting features in the test structure. In this paper, modified test structures are described that confirm the model and show how these systematic errors can be eliminated.
[Contact: Richard A. Allen, (301) 975-5026]

Integrated-Circuit Test Structures

Recently Published

Cresswell, M.W., Penzes, W.B., Allen, R.A., Linholm, L.W., Ellenwood, C.H., and Teague, E.C.,

Electrical Test Structure for Overlay Metrology Referenced to Absolute Length Standards, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Integrated Circuit Metrology, Inspection, and Process Control VIII, Vol. 2196, pp. 512-521.

This test structure is based on the voltage-dividing potentiometer principle and was originally replicated in a single lithography cycle to evaluate feature placement by a primary pattern generator. A new test structure has now been developed from the single-cycle version and has been used for measuring the overlay of features defined by two different exposures with a stepping projection aligner. The as-measured overlay values are processed by an algorithm which minimizes the effects of nominal random pattern imperfections. The algorithm further partitions measurements of overlay into contributions which derive, respectively, from misregistration of the image fields projected by the two masks and from the drawn misplacement of features on the masks. The numerical estimates of these contributions so obtained from the electrical measurements were compared with those extracted from the same features by the NIST Line Scale Interferometer, providing traceability to absolute length standards. The two sets of measurements were found to agree to within the several-nanometer uncertainty cited for the line scale interferometer's readings alone. The motivation for this work was to compare the nanometer-level distortions, produced by alternative chucking arrangements, of proximity X-ray masks having various support-ring architectures. However, the technique may also be used to evaluate optical aligner tools and to determine image placement quality on optical reticles with traceability to the International Standard of length, the meter.
[Contact: Michael W. Cresswell, (301) 975-2072]

Microfabrication Technology

Released for Publication

Anderson, G.W., Kub, F.J., Papanicolaou, N.A., Katzer, D.S., Modolo, J.A., and Tseng, W.F., **Planar, AlGaAs-Passivated-Base, Heterojunction Bipolar Phototransistors**.

Planar GaAs heterojunction phototransistors fabricated in a GaAs/AlGaAs molecular-beam-epitaxial-materials system with an AlGaAs-passivated, 10-nm-thick base and a low emitter-base capacitance have been demonstrated. Electrical contact to the emitter is made by a set of parallel, ohmic fingers. The phototransistors exhibit gain $\geq$20 at 850-nm wavelength optical excitation. These devices have a 3-dB bandwidth of 47 MHz, thus showing promise, upon expected improvement, for large photodetector arrays for optical processing applications requiring 100-MHz bandwidth photodetectors.
[Contact: Wen F. Tseng, (301) 975-5291]

Dhar, N.K., Boyd, P.R., Amirtharaj, P.M., Dinan, J.H., and Benson, J.D., **Self-Aligned Molecular Beam Epitaxy of CdZnTe for IR Focal Plane Arrays**, to be published in the Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), IR Materials Producibility Conference, Orlando, Florida, April 25-29, 1994.

The crystallographic orientation of $Cd_{1-x}Zn_xTe$ ($x \cong 0.045$) grown by molecular beam epitaxy (MBE) on a clean (planar) (100) GaAs surface can be controlled by the proper choice of the GaAs surface stoichiometry. An As-stabilized surface initiates (100)-oriented growth, while the Ga-stabilized surface yields (111)-oriented growth. $Cd_{1-x}Zn_xTe$ ($x \cong 0.045$) MBE layers grown in recesses of shadow-masked-patterned (100) GaAs substrates were found to be in the (100) orientation regardless of whether precursor surfaces were stabilized with Ga or As. The epitaxial layer's orientation and optical properties were determined by backscattered electron channeling and low-temperature photoluminescence measurements, respectively. CdZnTe layers grown in recesses showed improved optical features as compared to the layers grown on planar substrates.
[Contact: Paul M. Amirtharaj, (301) 975-5974]

Microfabrication Technology

Recently Published

Marshall, J.C., Gaitan, M., Zaghloul, M.E., Novotny, D.B., Tyree, V., Pi, J.-I., Piña, C., and Hansford, W., **Realizing Suspended Structures on Chips**

Fabricated by CMOS Foundry Processes through the MOSIS Service, NISTIR 5402 (June 1994).

Chips can be inexpensively fabricated at Complementary Metal-Oxide-Semiconductor (CMOS) foundries through the MOSIS (MOSIS is an acronym for 'MOS Implementation System') Service at the University of Southern California's Information Sciences Institute. MOSIS now supports CMOS-compatible micromachining to realize microelectromechanical systems (MEMS) and devices such as suspended corners, cantilevers, and pixels. The MEMS designs are fabricated through MOSIS on a multi-project wafer, and the user performs a post-processing maskless anisotropic etch. Two new design tiles called 'open' and 'pstop' have been added to support these designs.
[Contact: Janet C. Marshall, (301) 975-2049]

Zincke, C., Gaitan, M., Zaghloul, M.E., and Linholm, L.W., **Test Structures for Determining Design Rules for Microelectromechanical-Based Sensors and Actuators**, Proceedings of the 1994 IEEE Conference on Microelectronic Test Structures, San Diego, California, March 22-24, 1994, pp. 44-50.

We present two test structures for establishing design rules for minimum spacing of a new class of microelectromechanical-based sensors and actuators fabricated through commercial complementary metal-oxide-semiconductor (CMOS) foundries. The microelectromechanical devices are suspended membranes of passivation glass that encapsulates polysilicon and aluminum layers in the CMOS process. The membranes are suspended by anisotropically etching the silicon substrate through openings in the passivation glass. These test structures measure the lateral undercutting and the rotational misalignment of openings in passivation oxide that are used to make the microelectromechanical devices, and give information for the layout, and proximity to circuits of the microelectromechanical devices. Two test structures are discussed, one optical and one electrical, and results for a 2-μm *n*- and *p*-well CMOS process run are presented.
[Contact: Michael Gaitan, (301) 975-2070]

Photodetectors

Released for Publication

Livigni, D., and Li, X., **Spatial Uniformity of Optical Detector Responsivity**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium, Chicago, Illinois, August 1-5, 1994.

A scanning system for measuring the spatial uniformity of the responsivity of optical detectors and methods of quantifying the degree of uniformity are described. Surface plots and contour maps of the measured responsivity are presented along with a statistical treatment. Factors which can affect the accuracy of the uniformity measurement are described, including sampling theorem restrictions and interference artifacts produced when coherent light is used. Examples of these artifacts are presented along with scans of actual Si, Ge, and InGaAs detectors.
[Contact: David Livigni, (303) 497-5898]

Vayshenker, I., Li, X., and Scott, T.R., **Optical Power Meter Calibration Using Tunable Laser Diodes**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium Workshop and Symposium, Chicago, Illinois, August 1-5, 1994.

[See Optical Fiber Metrology.]

Yang, S., Vayshenker, I., Li, X., and Scott, T.R., **Accurate Measurement of Optical Detector Nonlinearity**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium, Chicago, Illinois, August 1-5, 1994.

In this paper, we describe the results of our efforts to analyze and compare by computer simulation three popular nonlinearity methods: (1) superposition method, (2) attenuation method, and (3) differential or ac-dc method. We describe a uniform definition which we used to intercompare the data analysis properties of these methods. Issues, common to these methods or specific to one individual method, that have an impact on the measurement accuracy were studied. Our conclusions are discussed.

[Contact: Thomas R. Scott, (303) 497-3651]

Photodetectors

Recently Published

Hale, P.D., Humphreys, D.A., and Gifford, A.D., **Photodetector Frequency Response Measurements at NIST, U.S. and NPL, UK: Preliminary Results of a Standards Laboratory Comparison**, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Technologies for Optical Fiber Communications, Vol. 2149, pp. 345-346 (1994).

Preliminary results are reported of a standards laboratory comparison. We report the first comparison of high-speed photodiode frequency response measurements up to 40 GHz between NIST and National Physics Lab (NPL) in the 1.3- and 1.5-μm wavelength regions. This comparison is an important step in establishing international agreement on photodiode response measurements, with traceability to international microwave power and dc current standards. Measurements at NIST used a Nd:YAG heterodyne system. NPL used DFB heterodyne and integrated-optical modulator-based techniques. Measurements of a photodiode with nominally 20-GHz optical bandwidth show good agreement with average scatter of $\pm$0.15 dB (2σ) below 20 GHz, and $\pm$0.30 dB from 20 to 33 GHz. The results diverge systematically above 33 GHz, due to calibration of the RF power sensors. Scatter in the data is well represented by the combined uncertainties of the measurement systems up to 33 GHz.
[Contact: Paul D. Hale, (303) 497-5367]

Seiler, D.G., Lowney, J.R., Thurber, W.R., Kopanski, J.J., and Harman, G.G., ***Semiconductor Measurement Technology*: Improved Characterization and Evaluation Measurements for HgCdTe Detector Materials Processes, and Devices Used on the GOES and TIROS Satellites**, NIST Special Publication 400-94 (April 1994).

An extensive study was carried out to improve the characterization and evaluation methods used for HgCdTe (mercury cadmium telluride) photoconductive infrared detectors used in GOES and TIROS satellites. High-field magnetotransport techniques were used to determine the electrical properties of the detector accumulation layers, which partially control their detectivities. Assessments were made of the quality of the bonding and packaging used in detector fabrication, and a list of recommended practices was produced. The applicability of scanning capacitance microscopy and test structures to detector-array evaluation is discussed, and finally recommendations are made for standardized detector calibration. The results of this work have provided new and more refined measurement methods that can be adopted by the detector manufacturers to improve performance and yield.
[Contact: David G. Seiler, (301) 975-2081]

Reliability

Released for Publication

Suehle, J.S., Chaparala, P., Messick, C., Miller, W.M., and Boyko, K.C., **Field and Temperature Acceleration of Time-Dependent Dielectric Breakdown in Intrinsic Thin SiO_2**, to be published in the Proceedings of the 1994 International Reliability Physics Symposium, San Jose, California, April 11-14, 1994.

Time-Dependent Dielectric Breakdown (TDDB) data are presented for 15- and 22.5-nm oxides collected over a wide range of electric fields and temperatures. The results indicate that it is necessary to obtain data over this range to distinguish between the two field acceleration models and to quantify the electric field and temperature dependencies of the thermal activation energy and the field acceleration factor, respectively. We also report on the TDDB characteristics of thin SiO_2 films at temperatures as high as 400 °C and demonstrate the use of these temperatures to accelerate TDDB.
[Contact: John S. Suehle, (301) 975-2247]

Reliability

Recently Published

Suehle, J.S., Chaparala, P., and Messick, C., **High Temperature Reliability of Thin Film SiO_2**, Proceedings of the Second International High

Temperature Electronics Conference, Charlotte, North Carolina, June 5-10, 1994, pp. VIII-15—VIII-23.

We present Time-Dependent Dielectric Breakdown (TDDB) test results for thin SiO_2 gate oxides at stress temperatures up to 400 °C. The data were collected at the wafer level using a specially designed probe station that utilizes a water-cooled probe card and test fixture. It is demonstrated that these oxides exhibit extrapolated lifetimes in excess of 6.3×10^{10} s (2000 years) at 2.0 MV/cm for a stress temperature of 350 °C under positive or negative bias. Our results indicate that the physical mechanism of TDDB does not change significantly up to stress temperatures of 400 °C. It is necessary to obtain data over a wide range of electric fields and temperatures to distinguish between field acceleration models and to quantify the electric field and temperature dependencies of the thermal activation energy and the field acceleration factor, respectively.
[Contact: John S. Suehle, (301) 975-2247]

SIGNAL ACQUISITION, PROCESSING, AND TRANSMISSION

DC and Low-Frequency Metrology

Released for Publication

Huang, D.X., Lipe, T.E., Kinard, J.R., and Childers, C.B., **Ac-Dc Difference Characteristics of High-Voltage Thermal Converters**.

This paper describes a study of high-voltage thermal converters (HVTCs) at voltages above 100 V up to 100 kHz. Techniques for the construction of HVTCs are described, and the effects of aging and dielectric loss on the resistor, changes in the timing sequence of ac-dc difference tests, relay dead-times, warmup times, and voltage level dependence are given.
[Contact: Thomas E. Lipe, (301) 975-4251]

Kinard, J.R., Huang, D.X., and Novotny, D.B., **Integrated Thin-Film Micropotentiometers**.

Integrated micropotentiometers, new devices fabricated with thin-film technology and the micromachining of silicon, have been developed for the accurate determination of ac voltage from 1 to 200 mV up to 1 MHz and with the potential for higher frequencies.
[Contact: Joseph R. Kinard, (301) 975-4250]

Kinard, J.R., Huang, D.X., and Novotny, D.B., **Performance of Multilayer Thin-Film Multijunction Thermal Converters**.

New multilayer, thin-film multijunction thermal converters suitable as high-performance ac-dc transfer standards have been fabricated and studied at NIST. This paper describes their thermal and physical features and the materials chosen to improve performance. Performance data are given over a wide range of frequencies and conditions.
[Contact: Joseph R. Kinard, (301) 975-4250]

Kos, A.B., and Fickett, F.R., **An Improved Eddy Current Decay Method for Resistivity Characterization**.

Eddy-current decay is a unique, nondestructive method for determining the low-temperature resistivity of large samples of pure metal. Furthermore, it is the only means available for measurement of the residual resistivity ratio, ρ(273 K)/ρ(4 K), of samples with shapes that do not lend themselves to conventional four-wire resistance measurement techniques. An improvement to an earlier implementation of the eddy current decay method of resistivity characterization is presented. It involves modernizing the earlier apparatus by the use of a digitizing oscilloscope, commercial curve-fitting software, digital averaging techniques, and modern electronics. Data are shown for high-purity copper cylinders.
[Contact: Anthony B. Kos, (303) 497-5333]

Cryoelectronic Metrology

Released for Publication

Booi, P.A.A., and Benz, S.P., **Characterization of the Emission from 2D Array Josephson Oscillators**, to be published in the Proceedings of the Fifth International Symposium on Space Terahertz Technology, Ann Arbor, Michigan, May 10-13, 1994.

We present experimental results on the emission

from phase-locked two-dimensional arrays of Josephson junctions. We have coupled the emission from 10 x 10 arrays to a room-temperature mixer through a fin-line antenna and a WR-12 waveguide. A single voltage-tunable peak was detected up to 230 GHz. A stripline resonance in the antenna reduced the array's dynamic resistance and thereby the emission linewidth to as low as 10 kHz. We extract an effective noise temperature of 14 K from the linewidth data. When the array's emission was coupled to an on-chip detector junction through a dc blocking capacitor, we detected voltage-tunable emission from 75 GHz up to 300 GHz, and in some circuits emission above 400 GHz. The coherent power spectrum depends primarily on internal resonances.
[Contact: Samuel P. Benz, (303) 497-5258]

De Obaldia, E.I., Berkowitz, S.J., Ludwig, Jr., K.F., Clark, A.M., Skocpol, W.J., Mankiewich, P.M., Rudman, D.A., Roshko, A., Moerman, R., Vale, L., and Ono, R.H., **Evidence of the Coexistence of Oxygen-Related Domains In High-Quality $YBa_2Cu_3O_{7-\delta}$ Thin Films by X-Ray Diffraction and Electrical Measurements**.

High-quality films of $YBa_2Cu_3O_{7-\delta}$ on $LaAlO_3$ have been grown by pulsed laser deposition at oxygen pressures from 25 to 400 mT (3.4 to 54 Pa). X-ray diffraction reveals the coexistence of grains that align with the substrate axes (axial grains) and grains that are rotated by 0.4° from the axes of substrate (diagonal grains). The axial grains have reduced orthorhombicity while the diagonal grains achieve values closer to bulk $YBa_2Cu_3O_7$. The normal state and superconducting properties of the various films can be explained by a simple effective medium theory that considers the axial grains to be highly resistive and nonsuperconducting at 76 K. Using this model, we find that the diagonal grains have intrinsic values $d\rho/dT = 0.58\ \mu\Omega$ cm/K and J_c (0.2T, 76 K) = 1×10^6 A/cm^2.
[Contact: Ronald H. Ono, (303) 497-5081]

Grossman, E.N., and Vale, L.R., **Heterodyne Mixing and Direct Detection in High Temperature Josephson Junctions**, to be published in the Proceedings of the Fifth International Symposium on Space Terahertz Technology, Ann Arbor, Michigan, May 10-13, 1994.

We have examined various properties of the high characteristic frequency of $YBa_2Cu_3O_7$ Superconductor Normal metal Superconductor (SNS) Josephson junctions in order to evaluate their performance as low-noise THz frequency mixers. Without far-infrared laser illumination, the microwave frequency noise temperature of our lowest noise device shows good agreement with the predictions of the resistively shunted Josephson model in an applicable region of bias. It has a maximum noise temperature of 36 ± 4 K at a physical temperature of 4 K. When illuminated with a 404 GHz far-IR laser local oscillator and a chopped 77-K blackbody signal, strong modulation of the 1-GHz Intermediate Frequency (IF) noise power is observed. However, certain features of the modulated IF power signal strongly suggest that a large fraction of it is not true heterodyne detection. The spurious component is probably due to direct detection of the broadband hot load/cold load signal.
[Contact: Erich N. Grossman, (303) 497-5102]

Kautz, R.L., Benz, S.P., and Reintsema, C.D., **Large-Amplitude Shapiro Steps and Self-Field Effects in High-T_c Josephson Weak Links**.

We demonstrate contiguous Shapiro steps of orders 0 and 1 having amplitudes of 1 mA in a $YBa_2Cu_3O_{7-\delta}$ step-edge junction operated at 38 K. A wide-junction model that includes self-field effects is shown to explain why the observed step amplitudes are smaller than expected from the resistively shunted point-junction model. In spite of their reduced amplitudes, the observed steps are suitable for use in a proposed rapidly programmable Josephson voltage standard.
[Contact: Richard L. Kautz, (303) 497-3391]

Lachenmann, S.G., Doderer, T., Hoffmann, D., Huebener, R.P., Booi, P.A.A., and Benz, S.P., **Observation of Vortex Dynamics in Two-Dimensional Josephson Junction Arrays**.

Spatially resolved images of the dynamic states of current-biased two-dimensional arrays of $Nb/AlO_x/Nb$ Josephson junctions were obtained using the technique of low-temperature scanning electron microscopy. The arrays were square or rectangular, and the maximum size was 20 x 20. In overdamped arrays, our images at zero or small

applied perpendicular magnetic field combined with model calculations confirm the nucleation of a vortex at one sample edge (or an antivortex at the opposite edge) and its subsequent motion into the array interior. Vortex annihilation due to vortex-antivortex collision was observed to take place in the middle of the array or at the edge opposite to the nucleation edge. These dynamics and the underlying model considerations are similar to that for Abrikosov vortices in the current-induced resistive state of thin film type-II superconductors. The phenomenon of "row switching" is directly confirmed in images of underdamped arrays. The specific rows in the voltage scale at a given bias voltage vary randomly when the current bias is returned to zero.
[Contact: Samuel P. Benz, (303) 497-5258]

Rice, J.P., Grossman, E.N., and Rudman, D.A., **Antenna-Coupled High-T_c Microbolometer on Silicon**.

We describe the first antenna-coupled high-T_c microbolometer operating at infrared wavelengths. This detector incorporates a silicon-micromachined yttria-stabilized zirconia air-bridge at the feed of a planar lithographic antenna to simultaneously minimize the thermal conductance and the heat capacity of the bolometer. At an operating temperature of 87.4 K, the optical responsivity measured using a 300-K blackbody source over a 0.2- to 2.9-THz bandwidth is 2900 V/W, the noise-equivalent power (NEP) is 9 pW/Hz$^{1/2}$, and the time constant is <10 μs. This NEP is nearly a factor of 2 lower than the previous record for a liquid-nitrogen-cooled thermal detector, and the time constant is several orders of magnitude shorter.
[Contact: Joseph P. Rice, (303) 497-7366]

Sauvageau, J.E., Burroughs, C.J., Cromar, M.W., and Koch, J.A., **Optimization of ECR-Based PECVD Oxide Films for Superconducting Integrated Circuit Fabrication**, to be published in the Proceedings of the 1994 37th Annual Technical Conference of the Society of Vacuum Coaters, Boston, Massachusetts, May 8-13, 1994.

A commercial microwave electron cyclotron resonance (ECR) reactor has been optimized for plasma-enhanced chemical vapor deposition (PECVD) of silicon dioxide films at deposition temperatures lower than 150 °C. A spool piece was added to the system, resulting in improved deposition uniformity and lower deposition temperatures. Response surface methodology was used in the ECR system optimization before and after the modification. The response variables were deposition rate, uniformity, index of refraction, film stress, and wet-etch-rate. As a result of the studies, several oxide deposition processes have been developed at ambient temperatures. These processes are presently being used in the superconducting-integrated-circuit fabrication facility at the National Institute of Standards and Technology. The optimization process and results are discussed.
[Contact: Joseph E. Sauvageau, (303) 497-3770]

Wiesenfeld, K., Benz, S.P., and Booi, P.A.A., **Phase-Locked Oscillator Optimization for Arrays of Josephson Junctions**.

An overview of phase locking in two-dimensional (2D) arrays of identical Josephson junctions is presented. General design criteria are discussed for optimization of power and linewidth. A harmonic balance technique is used to derive an analytic expression for the fundamental power as a function of bias voltage for a single shunted tunnel junction with an external shunt resistor having parasitic inductance. A linear stability analysis is performed on the in-phase state of 2D arrays in the absence of any external load. Most excitation modes in the 2D array are damped, leading to stable phase locking between parallel junctions within each row. However, within our theoretical model, no mechanisms intrinsic to the array were found to induce phase locking between rows of junctions. The results of these calculations and their impact on and relevance to the design of phase-locked Josephson oscillators are discussed.
[Contact: Samuel P. Benz, (303) 497-5258]

Cryoelectronic Metrology

Recently Published

Bang, C.A., Rice, J.P., Flick, M.I., Rudman, D.A., and Schmidt, M.A., **Thermal Isolation of High-Temperature Superconducting Thin Films Using Silicon Wafer Bonding and Micromachining**, Journal of Microelectromechanical

Systems, Vol. 2, No. 4, pp. 160-164 (December 1993).

Using a new micromachining technology, thermally isolated thin films of high-temperature superconductor have been microfabricated. The intended application for these structures is in infrared bolometers. A silicon wafer bonding process produces a low thermal mass island of single-crystal silicon on a silicon nitride membrane which provides thermal isolation. The silicon can act as a seed for the epitaxial growth of $YBa_2Cu_3O_7$ on a yttria-stabilized zirconia buffer layer. This paper describes the overall concept of the thermally isolated device, and demonstrates that the micromachined structure can be fabricated with high-quality superconducting films.
[Contact: Joseph P. Rice, (303) 497-7366]

Beall, J.A., Ono, R.H., Galt, D., and Price, J.C., **Tunable High Temperature Superconductor Microstrip Resonators**, Digest of the 1993 IEEE MTT-S International Microwave Symposium, Atlanta, Georgia, June 14-18, 1993, pp. 1421-1423.

We have fabricated and characterized electrically tunable high-temperature superconductor microstrip resonators incorporating $YBa_2Cu_3O_{7-x}$ superconductor and $SrTiO_3$ ferroelectric films. Early versions of these and similar devices were described previously. The resonators consist of two co-linear microstrip line-sections separated by a 5-μm gap. The capacitance of the gap influences the frequencies of the odd-order coupled resonances. Inductively choked dc bias lines are attached to each line section so that a bias voltage can be applied to the gap. When the gap is filled with a ferroelectric material, the odd resonances can be tuned. Frequency shifts of 300 MHz have been observed with a bias voltage of 50 V for resonances at 5.6 GHz and 11.6 GHz. The tunability is independent of temperature from 4 K to 80 K. An upper bound for the loss tangent of the $SrTiO_3$ capacitor is extracted from the resonance Q, and we find $\tan(\delta) < 0.07$ at 4 K. We believe that the Q values are limited by external loading, rather than by losses in the $SrTiO_3$, so the true value of $\tan(\delta)$ is certainly less than our upper bound.
[Contact: James A. Beall, (303) 497-5989]

Booi, P.A.A., and Benz, S.P., **Emission Linewidth Measurements of Two-Dimensional Array Josephson Oscillators**, Applied Physics Letters, Vol. 64, No. 16, pp. 2163-2165 (18 April 1994).

We have coupled emission from 10 x 10 arrays of Josephson junctions to a room-temperature mixer through a fin-line antenna and a WR-12 waveguide. One voltage-tunable spectral peak was detected in the frequency range from 53 to 230 GHz. A stripline resonance in the antenna reduced the emission linewidth from the theoretical value of ~2 MHz at 4 K to as low as 10 kHz. We extract an effective noise temperature of 14 K from the linewidth data.
[Contact: Peter A. A. Booi, (303) 497-5910]

Galt, D., Price, J.C., Beall, J.A., and Ono, R.H., **Characterization of a Tunable Thin Film Microwave $YBa_2Cu_3O_{7-x}/SrTiO_3$ Coplanar Capacitor**, Applied Physics Letters, Vol. 63, No. 22, pp. 3078-3080 (November 1993).

We have fabricated and characterized electrically tunable high-temperature superconductor coplanar microstrip resonators incorporating tunable $SrTiO_3$ ferroelectric thin films. The low-frequency capacitance of the $SrTiO_3$ capacitor is measured directly. High-frequency capacitance and loss information are extracted from the observed resonances and compared with the low-frequency data. Hysteresis loops display an onset of ferroelectricity at 160 K. The spontaneous charge and coercive voltage (at 10 kHz) as a function of temperature are extracted from these loops.
[Contact: James A. Beall, (303) 497-5989]

Han, B., Neumayer, D.A., Marks, T.J., Rudman, D.A., Zhang, H., and Dravid, V.P., **Suitability of Metalorganic Chemical Vapor Deposition-Derived $PrGaO_3$ Films as Buffer Layers for $YBa_2Cu_3O_{7-x}$ Pulsed Laser Deposition**, Applied Physics Letters, Vol. 63, No. 26, pp. 3639-3641 (27 December 1993).

Phase-pure thin films of the $YBa_2Cu_3O_{7-x}$ (YBCO) lattice-matched and low loss tangent perovskite insulator $PrGaO_3$ have been grown in situ on single-crystal (110) $LaAlO_3$ substrates by metal-organic chemical vapor deposition (MOCVD). Films were grown at temperatures of 750 to 800 °C using β-

diketonate precursors $M(dpm)_3$ (M = Pr, Ga; dpm = dipivaloyl-methanate). YBCO films were then grown on the MOCVD-derived $PrGaO_3$ films by pulsed laser deposition (PLD). Scanning electron microscopy reveals that the MOCVD-derived $PrGaO_3$ films have smooth, featureless surfaces. As assessed by X-ray diffraction, the $PrGaO_3$ films grow epitaxially on $LaAlO_3$ with a high degree of (001) and/or (110) plane orientation parallel to the substrate surface, and the subsequent YBCO films of the trilayer grow with a (00ℓ) orientation. Rocking curve and ϕ-scan analyses reveal that the $PrGaO_3$ and YBCO films grow epitaxially. Cross-sectional high-resolution electron microscopy and transmission electron microscopy selected area diffraction confirm that the $PrGaO_3$ and YBCO layers grow epitaxially. YBCO films grown by PLD on the MOCVD-derived $PrGaO_3$ exhibit T_c = 91 K and $J_c = 6 \times 10^6$ A/cm^2 at 77 K in zero field.
[Contact: David A. Rudman, (303) 497-5081]

Rosenthal, P.A., and Grossman, E.N.; **Terahertz Shapiro Steps in High Temperature SNS Josephson Junctions**, IEEE Transactions on Microwave Theory and Techniques, Vol. 42, No. 4, pp. 707-714 (April 1994).

We have studied the far infrared behavior of high-T_c superconductor-normal metal-superconductor microbridges with T_c > 85 K and critical current-resistor products (I_cR_N) as high as 10 mV at 4 K. These are the highest I_cR_N products reported to date for microfabricated Josephson junctions of any material. The junctions were integrated at the feeds of planar log-periodic antennas made from Au thin films. The junctions had dc normal state resistances R_N between 6 and 38 Ω, reasonably well matched to the antenna's estimated RF impedance of 53 Ω. Far infrared laser radiation at 404, 760, and 992 GHz induced distinct Shapiro steps (i.e., constant voltage steps at voltages $n(hf/2e)$, n = 1,2,...) in the current voltage characteristics as well as modulation of the critical current. Steps were observed at voltages up to 17 mV and 6 mV, at temperatures of 9 K and 57 K, respectively. This corresponds to maximum Josephson oscillation frequencies of 8 and 3 THz at these temperatures. These are the first far infrared measurements performed on high T_c junctions. Measurements of the power, frequency, and temperature dependence of the Shapiro steps are presented and discussed in the context of a resistively and capacitively shunted junction model. A value of 4.5 fF for the junction capacitance is inferred from the hysteresis of the slightly underdamped current-voltage characteristics.
[Contact: Peter A. Rosenthal, (303) 497-7212]

Wu, H.-D., Barnes, F.S., Galt, D., Price, J., and Beall, J.A., **Dielectric Properties of Thin Film $SrTiO_3$ Grown on $LaAlO_3$ with $YBa_2Cu_3O_{7-x}$ Electrodes**, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), High T_c Microwave Superconductors and Applications Vol. 2156, pp. 131-140 (1994).

We have fabricated and characterized YBCO ($YBa_2Cu_3O_{7-x}$) microstrip resonators on LAO ($LaAlO_3$) substrates that include thin film STO ($SrTiO_3$) coplanar capacitors to study the dielectric properties of thin film STO. The low-frequency capacitance of the STO/LAO capacitor is measured as a function of temperature and dc bias. We use the observed resonant frequencies to extract the microwave frequency capacitance of the structure and the Q's to determine the microwave losses. A conformal map is developed and used to transform the observed capacitances into dielectric constant values for the thin film STO.
[Contact: James A. Beall, (303) 497-5989]

Antenna Metrology

Released for Publication

Lewis, R.L., Muth, L.A., and Wittmann, R.C., **RangeCAD and the NIST RCS Uncertainty Analysis**, to be published as NISTIR 5022.

We discuss the salient features of a computer program, RangeCAD, and then translate the program's output into a catalog of radar cross-section (RCS) uncertainties. This specific catalog was developed by NIST to standardize RCS uncertainty computations at the various RCS measurement sites. We check uncertainty estimates generated by RangeCAD against alternative formulations that approximate equivalent uncertainty specifications. Based on this comparison, we conclude that the uncertainty estimates generated by RangeCAD provide realistic values for

the NIST RCS uncertainty analysis.
[Contact: Richard L. Lewis, (303) 497-5196]

Microwave and Millimeter-Wave Metrology

Released for Publication

Clague, F.R., and Splett, J.D., **Developing a NIST Coaxial Microwave Power Standard at 1 mW**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium, Chicago, Illinois, August 1-5, 1994

Some customers of the NIST microwave power calibration service report they are using their calibrated reference standard at a power of about 1 mW rather than 10 mW where the NIST measurement is made. Since the coaxial reference standards accepted by NIST for calibration are dual-element thermistor mounts, they are subject to a dual-element substitution error if not used at the calibration power level. The error differs for each mount. The error is not easily measured, nor is it possible to readily estimate an additional uncertainty for using the mount at a different power. Initial measurements indicate the error can be up to 50 percent of the quoted calibration uncertainty. If the calibration uncertainty does not increase too much, a reasonable solution is to extend the NIST calibration service to powers under 10 mW. This paper briefly describes the present standard and the approach being taken to add the 1-mW capability. Preliminary uncertainty estimates are included.
[Contact: Fred R. Clague, (303) 497-5778]

Marks, R.B., and Williams, D.F., **Microwave Characterization of Printed Circuit Transmission Lines**, to be published in the Proceedings of the National Electronic Packaging and Production Conference (NEPCON East '94), Boston, Massachusetts, June 16, 1994.

This paper reviews the basic methodology for the microwave characterization of printed transmission lines in terms of scattering parameters, impedances, and frequency-dependent transmission line parameters. The focus is on a suite of methods developed at the National Institute of Standards and Technology for the characterization of high-performance electronic packaging and interconnections as well as monolithic microwave integrated circuits.
[Contact: Roger B. Marks, (303) 497-3037]

Laser Metrology

Released for Publication

Young, M., **Lasers**.

A nonmathematical introduction to laser physics for scientists in other fields is given. The introduction includes resonators and amplifiers; Gaussian beams; coherence; and continuous, pulsed, Q-switched, and mode-locked lasers.
[Contact: Matt Young, (303) 497-3223]

Optical Fiber Metrology

Released for Publication

Drapela, T.J., Franzen, D.L., and Young, M., **Fiber Geometry: Results of an International Interlaboratory Measurement Comparison**, to be published in the Conference Digest of Symposium on Optical Fiber Measurements, Boulder, Colorado, September 13-15, 1994.

In an international measurement comparison of fiber geometry measurements, participants showed significantly better agreement, for measured parameters, than in previous comparisons. For cladding diameter measurements, participants who were calibrated by means of a calibration artifact from one of the national standards laboratories, showed significantly better agreement than those who were not.
[Contact: Timothy J. Drapela, (303) 497-5858]

Gallawa, R.L., Kumar, A., and Weisshaar, A., **Symbolic Programming with Series Expansions: Applications to Optical Waveguides**.

We discuss the utility of symbolic computer languages in the context of optical fiber analysis. The symbolic *Map* command, for example, is useful whenever a series expansion approach is used in eigenvalue problems if the basic functions are integrable in closed form. We show how this command allows a simple but accurate evaluation of single-mode fiber parameters in most cases of

practical interest. The *Replacement* command is also demonstrated in tracking the variation of fiber operational parameters as a function of the V-parameter. The savings in CPU time is substantial.
[Contact: Robert L. Gallawa, (303) 497-3761]

Patrick, H., Gilbert, S.L., and Lidgard, A., **Decrease of Fluorescence in Optical Fiber during Exposure to Pulsed or Continuous-Wave Ultraviolet Light**.

We exposed optical fibers to uv light and simultaneously measured the intensity of the 430-nm fluorescence from the fiber core. Two silica glass fibers with different core dopants were investigated: a germanium-doped fiber and a germanium-boron-codoped fiber. The fibers were exposed transversely to pulsed or continuous-wave 244-nm light for times ranging from a few minutes to over an hour. Exposures to pulsed light ranged from 10 to 200 mJ/cm^2 per pulse and with repetition rates of 1 to 50 Hz. Exposures to continuous-wave light ranged from 1 to 35 W/cm^2. For all uv intensities and exposure times, the fluorescence decreased during uv exposure. For a given fiber, the fractional decrease in fluorescence seen from the side of the fiber was dependent only on the total uv fluence. The side-collected fluorescence from the germanium-doped fiber decreased to 60% of its initial value after exposure to 3600 J/cm^2 fluence, while the fluorescence from the germanium-boron-codoped fiber decreased to 40% of its initial value after the same fluence. We compared the temporal characteristics of the fluorescence radiated transversely to the exposed region with that which was collected from the end of the fiber. The temporal characteristics of the fluorescence guided down the core and collected from the end were masked by photodarkening that occurred on the same time-scale. We relate the observed fluorescence decrease to competing theories of its origin and relationship to photoinduced refractive index changes.
[Contact: Sarah L. Gilbert, (303) 497-3120]

Vayshenker, I., Li, X., and Scott, T.R., **Optical Power Meter Calibration Using Tunable Laser Diodes**, to be published in the Proceedings of the 1994 National Conference of Standards Laboratories Workshop and Symposium, Chicago, Illinois, August 1-5, 1994.

We describe a measurement system developed by NIST to calibrate optical power meters using either collimated beam or connectorized fiber configurations. This calibration system uses tunable laser diodes which operate in the three fiber optics wavelength windows of 850, 1310, and 1550 nm. This paper describes standards, techniques, and systems involved in these calibrations.
[Contact: Thomas R. Scott, (303) 497-3651]

Optical Fiber Metrology

Recently Published

Gilbert, S.L., and Patrick, H., **Comparison of UV-Induced Fluorescence and Bragg Grating Growth in Optical Fiber**, Conference Digest of the 1994 Conference on Lasers and Electro-Optics, Anaheim, California, May 8-13, 1994, Vol. 8, p. 244.

We have measured the time dependence of the 400-nm fluorescence of Ge-doped optical fiber illuminated with continuous-wave 244-nm light. Our results differ from previous measurements that used pulsed 242-nm light.
[Sarah L. Gilbert, (303) 497-3120]

Optical Fiber/Waveguide Sensors

Released for Publication

Day, G.W., Deeter, M.N., Rose, A.H., and Rochford, K.B., **Faraday Effect Sensors for Magnetic Field and Electric Current**, to be published in the Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Warsaw, Poland, May 18-20, 1994. [Also given at SPIE Conference in San Diego, California, July 25-27, 1994.]

Recent research at NIST has greatly extended the capabilities of Faraday effect sensors for both magnetic field and electric current measurements. Current sensors using single-mode optical fiber show temperature stability near material limits, and are approaching commercial availability for applications in the power industry. For measuring current at low levels and/or at higher speeds, use of the Faraday effect in iron garnets is showing great promise. Sensors with noise equivalent current of

about 200 nA/√Hz have been demonstrated. In the area of magnetic field sensors, also using iron garnets, several advances, including the use of flux concentration, have led to sensors with noise equivalent magnetic fields in the range of 1 pT/√Hz.
[Contact: Gordon W. Day, (303) 497-5204]

Deeter, M.N., Milián Bon, S., Day, G.W., Diercks, G., and Samuelson, S., **Novel Bulk Iron Garnets for Magneto-Optic Magnetic Field Sensing**, to be published in the Proceedings of the 6th Joint MMM Intermagnetic Conference, Albuquerque, New Mexico, June 20-23, 1994.

We report measurements of the magneto-optic response function and frequency response for three bulk iron garnet crystals grown by a flux technique. The samples were the product of an intensive effort to develop iron garnet compositions with properties specifically optimized for magnetic field sensing. Sensitivity enhancement was achieved through both bismuth substitution (for increasing the saturation Faraday rotation) and gallium substitution (for reducing the saturation magnetization). One sample exhibited a value of magneto-optic sensitivity of 25 °/mT for 1.3-μm light. Frequency response measurements indicate that bismuth substitution actually improves performance (compared to unsubstituted yttrium iron garnet) in contrast with gallium which causes substantial degradation.
[Contact: Merritt N. Deeter, (303) 497-5400]

Rochford, K.B., Rose, A.H., Deeter, M.N., and Day, G.W., **Faraday Effect Current Sensor with Improved Sensitivity-Bandwidth Product**. [A shorter version of this abstract will appear in the Proceedings of the 10th Optical Fiber Sensors Conference, Glasgow, Scotland, October 11-13, 1994.]

We report a new design for a Faraday effect current sensor based on yttrium-iron-garnet that has substantially greater bandwidth than previous designs and is much easier to fabricate. The measured sensitivity is 0.7°/A with a -3 dB bandwidth of 500 MHz, giving an improvement in sensitivity-bandwidth product of approximately 45. A noise-equivalent-current of 840 nA/Hz$^{1/2}$ was measured at 1.8 kHz using difference-over-sum processing. The use of turning prisms with phase-preserving coatings greatly simplifies construction, improves electrical isolation, and increases sensitivity through proximity effects.
[Contact: Kenneth B. Rochford, (303) 497-5170]

Rose, A.H., Ren, Z.B., and Day, G.W., **An Improved Annealing Technique for Optical Fiber**, to be published in the Proceedings of the 10th Optical Fiber Sensors Conference, Glasgow, Scotland, October 11-13, 1994.

We demonstrate that twisting a fiber a few turns per meter before it is annealed largely eliminates the residual linear birefringence. This dramatically improves the yield of annealed coils used for current sensing and makes it possible to use fibers that previously could not be successfully annealed. It is believed that twisting is effective because the residual birefringence is associated with core ellipticity, and this contribution is averaged to near zero by twisting. We also show the temperature stability of sensors made with this new technique.
[Contact: Allen H. Rose, (303) 497-5599]

Veeser, L., Rodriguez, P., Forman, P., and Deeter, M.N., **Optical Wheel-Rotation Sensor**, to be published in the Proceedings of the 10th Optical Fiber Sensors Conference, Glasgow, Scotland, October 11-13, 1994.

We describe a fiber-optic rotation sensor being developed for anti-lock braking systems. The basis of the sensor is the magneto-optic detection of magnetic fields generated by a wheel of alternately magnetized magnets fixed to a wheel of the automobile. Highly sensitive iron garnet crystals serve as the magneto-optic sensing elements. For films with perpendicularly magnetized domains, the domain structure produces diffraction which is magnetic-field-dependent. Exploitation of this effect permits the construction of magneto-optic magnetic field sensors requiring no polarizing elements or lenses.
[Contact: Merritt N. Deeter, (303) 497-5400]

Optical Fiber/Waveguide Sensors

Recently Published

Day, G.W., Lovely, P.S., Whitesel, H.K., and Hickernell, R.K., **Optical Fiber Sensors: Acceler-**

ating Applications in Navy Ships, NISTIR 5018 (May 1994).

The Navy needs new sensors for shipboard machinery monitoring and control, condition-based maintenance, and damage assessment. Our fiber sensors are strongly preferred because of their immunity to electrical disturbances, as well as their potential size, weight, and performance advantages. Despite well over a decade of development and promise, relatively few optical fiber sensors available today can meet the Navy's needs with acceptable performance and cost. This report examines the reasons and recommends strategies to help the Navy achieve its goals.
Contact: Gordon W. Day, (303) 497-5204]

Rochford, K.B., Rose, A.H., Clarke, I., and Day, G.W., **Effect of Semiconductor Laser Characteristics on Optical Fiber Sensor Performance**, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Laser Diode Technology and Applications VI, Vol. 2148, pp. 269-279 (1994).

Optical sensor systems have source requirements that can be significantly different from those of optical communications and other technologies that have generally driven the development of semiconductor sources. In this paper, we examine basic interferometric, polarimetric, and other sensors. Relevant semiconductor source data are reviewed to illustrate the impact of source characteristics on sensor performance. The effect of low-frequency amplitude and frequency noise on sensor precision is described. Errors in sensor calibration due to amplitude and wavelength drifts are discussed. Examples of sensor performance using typical source data illustrate these issues.
[Contact: Kent B. Rochford, (303) 497-5170]

<u>Integrated Optics</u>

Released for Publication

Aust, J.A., Malone, K.J., Veasey, D.L., Sanford, N.A., and Roshko, A., **Passively Q-Switched Nd-Doped Waveguide Laser**.

A passively Q-switched waveguide laser operating at 1.054 μm has been demonstrated in a Nd-doped phosphate glass. The channel waveguide was fabricated by potassium ion exchange from a nitrate melt. Passively Q-switched pulses were achieved by placing a 0.3 optical density acetate sheet containing an organic saturable absorbing dye within the laser cavity. The resulting pulse train consisted of ~25 ns FWHM, 3.04-W peak power pulses. With a 20% transmitting output coupler, cw operation of the laser provided 5.2-mW output power at 1.054 μm for 229-mW-absorbed 794-nm pump power.
[Contact: J. Andrew Aust, (303) 497-3942]

Jinno, M., Schlager, J.B., and Franzen, D.L., **Optical Sampling Using Nondegenerate Four-Wave Mixing in a Semiconductor Laser Amplifier**, to be published in the Proceedings of the Optical Amplifiers and Their Applications Conference, Breckenridge, Colorado, August 3-5, 1994.

Picosecond optical sampling using nondegenerate four-wave mixing in a semiconductor amplifier (SLA) is demonstrated for the first time. High-peak-power probe pulses and electrical gating of the SLA produce an optical sampling signal with high signal-to-noise ratio.
[Contact: John B. Schlager, (303) 497-3542]

Malone, K.J., **Integrated-Optical Devices in Rare-Earth-Doped Glass**, to be published in the Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Critical Review of Optical Science and Technology, CR53 Glass Integrated Optics and Optical Fiber Devices, San Diego, California, July 24-28, 1994.

Many integrated-optical devices have been demonstrated in rare-earth-doped glasses. They can be used as both laser oscillators and optical amplifiers. These devices have been formed by a number of methods including ion exchange and thin-film deposition. These active integrated-optical devices are expected to be important elements in future optical fiber networks. In this paper, a short overview of these devices is given and some notable achievements are discussed. The fabrication of these components is also included, as well as analytical and diagnostic techniques that can improve performance. A discussion of some current

topics in this field concludes this paper.
[Contact: Kevin J. Malone, (303) 497-3289]

Novak, S., Zavada, J.M., and Malone, K., **Using Secondary Ion Mass Spectroscopy (SIMS) to Characterize Optical Waveguide Materials**, to be published in the Proceedings of the Microbeam Analysis Society Meeting, New Orleans, Louisiana, July 31–August 5, 1994.

Secondary Ion Mass Spectroscopy is used to analyze optical waveguides in $LiNbO_3$ and glass. Diffusion profiles are measured as well as cross-sectional images of waveguides.
[Contact: Kevin J. Malone, (303) 497-3289]

Integrated Optics

Recently Published

Christensen, D.H., Hickernell, R.K., Schaafsma, D.T., Pellegrino, J.G., McCollum, M.J., Hill, J.R., and Rai, R.S., **Correlation of Optical, X-Ray, and Electron Microscopy Measurements on Semiconductor Multilayer Structures**, Proceedings of SPIE (The International Society for Optical Engineering, P.O. Box 10, Bellingham, Washington 98227-0010), Spectroscopic Characterization Techniques for Semiconductor Technology V, Vol. 2141, pp. 177-188 (1994).

Techniques based on optical, X-ray, and electron microscopy measurements are applied to characterize a wide variety of semiconductor multilayer structures. Bragg mirrors serve as valuable test structures for evaluating the epitaxial uniformity of crystal growth systems. Careful characterization of half-wave-spaced single quantum wells provides a method for determining their complex refractive indices using reflectance spectroscopy. Comparison of cross-sectional microphotoluminescence to surface-normal photoluminescence, combined with these characterization techniques, allows studies of spontaneous emission in microcavities and elucidates the difficulties with using surface-normal photoluminescence to determine the alloy composition of the mirror layers. The application of these characterization methods to visible-wavelength AlGaAs mirrors, 485 to 720 nm, enables the development of these mirrors for uses such as optically tailored substrates and visible surface-emitter or detector arrays.
[Contact: David H. Christensen, (303) 497-3354]

Kumar, A., and Gallawa, R.L., **Bent Rectangular Core Waveguides: An Accurate Perturbation Approach**, Microwave and Optical Technology Letters, Vol. 7, No. 6, pp. 281-285 (April 20, 1994).

We discuss a method of evaluating the effective indices of quasi-modes of a bent rectangular core waveguide taking into account the correct dielectric constant of the corner regions, which is ignored in earlier methods. At small bend curvatures and low V values, the corner regions contribute much more to the effective index change than the bending itself.
[Contact: Robert L. Gallawa, (303) 497-3761]

Kumar, A., Gallawa, R.L., and Goyal, I.C., **Modal Characteristics of Bent Dual Mode Planar Optical Waveguides**, Journal of Lightwave Technology, Vol. 12, No. 4, pp. 621-624 (April 1994).

Modal characteristics of bent dual-mode planar optical waveguides are obtained. The bending-induced changes in the modal power distribution is found to be quite different for the two modes. Surprisingly, unlike the fundamental mode, bending causes the fractional modal power for the second mode to increase in the inner core-half and to decrease in the outer core-half of the waveguide. Interestingly, this leads to a decrease in effective index of the second mode due to bending at sufficiently high V-values.
[Contact: Robert L. Gallawa, (303) 497-3761]

Schaafsma, D.T., Christensen, D.H., Hickernell, R.K., and Pellegrino, J.G., **Comparative Photoluminescence Measurement and Simulation of Vertical-Cavity Semiconductor Laser Structures**, Proceedings of the Materials Research Society Conference, Boston, Massachusetts, November 29–December 3, 1993, Vol. 326, pp. 483-488 (1994).

We present comparisons of photoluminescence (PL) data for various vertical-cavity surface-emitting laser (VCSEL) and distributed quantum well structures taken with the pump beam (and the collection path) in two different configurations: normal to the

surface of the sample; and perpendicular to a cross section of the epitaxial layers. We demonstrate that the cross-sectional PL (XPL) technique can resolve individual features in the structures, and that the surface-normal PL (NPL) spectra are perturbed by the multilayer mirrors in the VCSELs. We elucidate a potential method for transforming between the NPL spectra and the non-perturbed XPL spectra and evaluate the sensitivity of this method to various measurement as well as material parameters. This simulation technique is well-suited to wide parametric variations of the dispersion curves for the complex dielectric constant of the materials, the pump field distribution, and the depth profile of the gain medium.
[Contact: David T. Schaafsma, (303) 497-7281]

Veasey, D.L., Larson, D.R., and Veigl, I., **Waveguide Polarizers Processed by Localized Plasma Etching**, Applied Optics, Vol. 33, No. 7, pp. 1242-1244 (1 March 1994).

We developed a downstream localized plasma-etching process that permits *in-situ* monitoring of light throughput in a semiconductor-clad channel waveguide as the semiconductor thickness is trimmed. Hydrogenated amorphous silicon films are deposited on ion-exchanged channel waveguides by plasma-enhanced chemical vapor deposition. We then employ the localized plamsa-etching process to maximize accurately the extinction ratio between transverse electric and transverse magnetic polarizations propagating in the clad waveguide. We achieve polarization extinction ratios of greater than 30 dB for both TE-pass and TM-pass polarizers.
[Contact: David L. Veasey, (303) 497-5952]

Complex System Testing

Recently Published

Koffman, A.D., and Souders, T.M., **Application of the NIST Testing Strategies to a Multirange Instrument**, Proceedings of the Measurement Science Conference, Pasadena, California, January 27-28, 1994 (unpaged).

A new modeling and test point reduction technique for analog and mixed-signal devices has been developed at the National Institute of Standards and Technology. This technique has been applied as a case study to a manufacturer's thermal transfer standard for potential use in testing and calibration. An empirical model is formulated using complete test data from many devices collected from several production runs. The model is then algebraically reduced using singular value decomposition and QR decomposition. Once the final reduced model is obtained, it is used to test devices which are measured only at a reduced set of test points. The model allows accurate prediction of device behavior at all other test points. Techniques for optimal model size selection are discussed. Device modeling results are presented and compared to complete test data.
[Contact: Andrew D. Koffman, (301) 975-4518]

ELECTRICAL SYSTEMS

Power Systems Metrology

Released for Publication

Morrison, H.D., Chu, F.Y., Eygenraam, M., Sauers, I., and Van Brunt, R.J., **Decomposition of SF_6 and Production of S_2F_{10} in Power Arcs**, to be published in the Proceedings of the 7th International Symposium on Gaseous Dielectrics, Knoxville, Tennessee, April 24-28, 1994.

Sulfur hexafluoride (SF_6) gas was decomposed in four power-arc tests at the Ontario Hydro Research Laboratory. The decomposed gas was subsequently analyzed by infrared absorption spectroscopy, mass spectrometry, gas chromatograph, and gas chromatography involving cryogenic gas enrichment to determine the concentrations of the gaseous by-products SOF_2, SF_4, SO_2F_2, and S_2F_{10}. In all cases, SOF_2 and SF_4 were found to be the predominant by-products. The SOF_2 concentration was always more than 10^3 times greater than that of S_2F_{10}. Considering that S_2F_{10} is only 160 times more toxic than SOF_2, it can be concluded that the toxicity of arc-decomposed SF_6 is governed by SOF_2 and not S_2F_{10}.
[Contact: Richard J. Van Brunt, (301) 975-2425]

Magnetic Materials and Measurements

Released for Publication

Cross, R.W., Russek, S.E., Sanders, S.C., Parker, M.R., Barnard, J.A., and Hossian, S.A., **Size and Self-Field Effects in Giant Magnetoresistive Thin-Film Devices**.

Giant magnetoresistance was measured as a function of device size for patterned NiCoFe/Cu and NiFe/Ag multilayers. For the NiCoFe/Cu films, antiparallel alignment of the spins between layers was achieved through interlayer exchange fields by setting the Cu thickness to 2.3 nm. The normalized maximum change in resistivity $\Delta\rho/\rho$ was 8% for most of the samples. For the NiFe/Ag films, antiparallel alignment was achieved through magnetostatic coupling, not exchange fields, by setting the Ag thickness to 4.4 nm to eliminate interlayer exchange. The maximum $\Delta\rho/\rho$ for the NiFe/Ag films was 4.5%. Saturation fields for the exchange-coupled films were much larger than for the magnetostatic-coupled films. The films were patterned into stripes with Au current leads for size-effect measurements. The height of the stripes varied from 0.3 to 16 μm, and the track width varied from 0.7 to 16 μm. Discrete switching events were observed for both materials at the small device sizes. Self-field and heating effects due to the applied current were investigated for the different device sizes. The effect of the self-field produced by the applied current was separated from the thermal contribution and was found to reduce the response by over 32% for a current density of 1.1×10^7 A/cm^2.
[Contact: Ralph W. Cross, (303) 497-5300]

Fickett, F.R., **Measurements and Standards for Magnetic Properties**, to be published in the Proceedings of the Symposium on Advances in Measurement Techniques and Instrumentation for Magnetic Properties Determination, Cedar Falls, Iowa, May 20-21, 1994.

Standards are seldom talked about except in highly specialized technical conferences, but they underlie much of what we accept as truth in all our measurement activities. In the world of commerce, they are much more in evidence because large amounts of money may hang in the balance. In this paper, I discuss the need for standards, types of standards, how new standards become proposed and developed, how they are used to guarantee measurement accuracy, the concept of traceability, and future challenges in the field. The subject is general, but the emphasis is on the field of magnetics. I also discuss magnetic measurements specifically related to standards or that have potential for standards applications.
[Contact: Fred R. Fickett, (303) 497-3785]

Rice, P., Hallett, B., and Moreland, J., **Comparison of Magnetic Fields of Thin-Film Heads and Their Corresponding Bit Patterns Using Magnetic Force Microscopy**.

We have used dc-mode magnetic force microscopy to image the magnetic fringing fields of several thin-film heads and the bit patterns written with these heads. The images were taken with Si_3N_4 tips coated with 10-nm Fe and 5-nm Au. The heads and disks are typical industry standards. The heads had a variety of pole piece configurations. A large track separation was used so that the erase bands could be thoroughly studied. We were surprised to discover magnetic fields that correspond to layers in the alumina overcoat near the pole pieces. The magnetic force microscope images of the bit pattern show a definite twist at the track edge that points toward the trailing pole piece. We also observed disk magnetization patterns, at frequencies too high to be read by the head, that remained after an ac erase procedure.
[Contact: Paul Rice, (303) 497-3841]

Magnetic Materials and Measurements

Recently Published

Coffey, M.W., **Deformable Superconductor Model for the Fluxon Mass**, Physical Review B, Vol. 49, No. 14, pp. 9774-9777 (1 April 1994-II).

Outstanding difficulties in a deformable type-II superconductor model for the fluxon inertial mass per unit length μ_d are resolved. An identity for the inertial mass, valid for an arbitrary quasiparticle fraction when the ionic displacement field is irrotational, plays a critical role in the analysis. This approach avoids previously employed approximations, leading to qualitatively different results, including a fluxon mass which properly vanishes at the transition temperature and which has a greatly reduced magnitude. A framework for the solution of the elasticity equation for an isotropic superconduc-

tor is presented and the close relation between μ_d and the ionic strain field is shown.
[Contact: Mark W. Coffey, (303) 497-3707]

Rice, P., Moreland, J., and Wadas, A., **DC Magnetic Force Microscopy Imaging of Thin-Film Recording Head**, Journal of Applied Physics, Vol. 75, No. 10, pp. 6876-6800 (15 May 1994).

With the use of a new form of magnetic force microscope (dc MFM), magnetic force images of a thin-film recording head have been made. Using dc MFM, atomic force microscope images are presented of the surface topography and magnetic forces taken simultaneously, allowing direct correlation of magnetic fields to the pole pieces. Magnetic force images of the head at typical head-to-disk spacings are presented. The tips used for these images had two different magnetic coatings.
[Contact: Paul Rice, (303) 497-3841]

Oti, J.O., Russek, S.E., and Sanders, S.C., **Magnetic and Magnetoresistive Properties of Inhomogeneous Magnetic Dual-Layer Films**, Journal of Applied Physics, Vol. 75, No. 10, pp. 6519-6521 (15 May 1994).

Magnetic and magnetoresistive properties of sputtered Co alloy dual-layer films are compared with micromagnetic simulations. The simulations elucidate the details of the switching behavior of the dual-layer films as a function of the interlayer exchange and magnetostatic interactions. The simulations have led to a conceptual understanding of the coercive field splitting caused by the interlayer interactions. A calculation of the anisotropic magnetoresistance (AMR) has been included in the simulations. The AMR provides a second independent macroscopic quantity (in addition to the average magnetization) which can be measured and compared with the micromagnetic simulations. The AMR is more sensitive to the micromagnetic structure perpendicular to the applied field and is a better test of the accuracy of the micromagnetic model. The simulations fit well to the measured AMR data on CoNi-Cr-CoNi dual-layers.
[Contact: John O. Oti, (303) 497-5557]

Superconductors

Released for Publication

Coffey, M.W., **Critical Currents in a Continuum Model of the Mixed State**, to be published as NISTIR 5021.

A novel view of the critical current density in type-II superconductors is presented. Although primarily concerned with soft samples, those lacking dense bulk inhomogeneities, the model lends insight into the current-carrying ability of both soft and hard materials. The model stems from a phenomenological theory of the mixed state, in analogy to the vortex state of a rotating superfluid. Special attention is paid to the role of the boundary conditions on electromagnetic fields and densities, and on the role of surface pinning of vortices. Experimental verification of aspects of the model is mentioned, and further experiments or re-analysis of some existing data were suggested. More technical material concerns anisotropic superconductors, such as the high-T_c cuprates, and a quantitative discussion of the characteristic depth for vortex bending is included.
[Contact: Mark W. Coffey, (303) 497-3703]

Coffey, M.W., **Effect of Superconducting Phase Fluctuations Upon Surface Reactance**.

The effect of superconducting phase fluctuations upon the radio frequency surface reactance is discussed. A Langevin approach is used to find the mean square phase fluctuation in a Josephson-coupled layer model of 3D superconductors in the Meissner state. The fluctuation effect on the penetration depth λ is estimated in both classical and quantum limits, and its relevance to microwave measurements is discussed.
[Contact: Mark W. Coffey, (303) 497-3703]

Sanders, S.C., Russek, S.E., Clickner, C.C., and Ekin, J.W., **Insulating Boundary Layer and Magnetic Scattering in $YBa_2Cu_3O_{7-\delta}$/Ag Interfaces over a Contact Resistivity Range of 10^{-8} to 10^{-3} Ω-cm^2**.

We have measured interface transport in thin-film $YBa_2Cu_3O_{7-\delta}$/Ag interfaces having resistivities ranging from 10^{-8} to 10^{-3} Ω-cm^2. Analysis of the interface I-V data indicates that tunneling is the predominant transport mechanism even for the *in-*

situ interfaces having contact resistivities of 1 to 5 $\times 10^{-8}$ Ω-cm^2. Zero-bias conductance peaks having full-width-at-half-maximum values of 3 to 5 mV and normalized amplitudes of 4 to 22% are also observed for the entire range of interface resistivity. The similarity of the zero-bias conductance peaks among these widely varying interfaces suggests that the interface transport is governed by the same mechanism in each case. These conductance peaks are analyzed in the framework of the Appelbaum-Anderson model for tunneling assisted by magnetic scattering from isolated magnetic spins in the interface.
[Contact: Steven C. Sanders, (303) 497-5096]

Xi, J.-H., Zheng, G.-G., Grishin, A.M., Moon, B.M., Rao, K.V., and Moreland, J., **Novel YBCO and YBCO/YBO Multilayer Films by Bias-Masked "On-Axis" Magnetron Sputtering**.

In-situ $YBa_2Cu_3O_{7-x}$ (YBCO) films have been fabricated on $SrTiO_3$ (001) and $LaAlO_3$ (001) substrates by "*on-axis*" biased-rf magnetron sputtering in Ar-10% O_2 at pressures as low as 3 x 10^{-2} mbar. When a biased-copper mask is introduced between the substrate and the target, the negative oxygen ion-resputtering effect has been almost eliminated. The surface morphology and physical properties of the obtained films are greatly improved on applying a *positive* dc substrate bias with respect to the grounded deposition chamber. By this approach, superconducting YBCO films with transport critical current as high at 10^6 A/cm^2 and low normal-state-resistivity are obtained. STM/AFM analyses of the films with the best superconducting properties reveal a spiral columnar growth mechanism.
[Contact: John Moreland, (303) 497-3641]

Superconductors

Recently Published

Moreland, J., Clark, A.F., Soulen, R.J., and Smith, J.L., **The Superconducting Energy Gap of Bulk UBe_{13}**, Physica B, Vol. 194-196, pp. 1727-1728 (March 1994).

The superconducting energy gap, **Δ**, of bulk UBe_{13} was measured as a function of temperature. Junctions were made by breaking a narrow region of a specimen in a vacuum and repositioning the broken ends to form a mechanically adjustable break junction point contact. We concluded that the $2\Delta(0)/k_BT_c = 4.2$ by fitting the data to the BCS form assuming a T_c of 0.80 K.
[Contact: John Moreland, (303) 497-3641]

Other Electrical Systems Topics

Released for Publication

Belecki, N., Cookson, A., Secula, A., Stenbakken, G., and Von Feldt, R., **Implementation of Total Quality Management in the Electricity Division**, to be published as a NISTIR.

A Task Team was formed in the Electricity Division to consider the most effective way of implementing Total Quality Management (TQM). The five-person team, with representatives from the management, professional, technician, and secretarial staff, made a series of visits and meetings with four external companies, a research laboratory, and two consulting firms, as well as held discussions with the NIST Office of Quality Programs and the Chemical Science and Technology Laboratory. The discussions are summarized under the headings of TQM Structure, Team selection, Task selection, Measures, Awards, Communications, Training, When introduced, Critical Factors for success, and Lessons learned.
[Contact: Norman Belecki, (301) 975-4221]

LAW-ENFORCEMENT STANDARDS

Released for Publication

Frank, D.E., **Police Personal Body Armor: What Do We Know? What Do We Need to Know? What Would We Like to Know?**, to be published in the Proceedings of the 1994 Personal Armour Systems Symposium, London, England, June 24, 1994.

In the process of assisting the Office of Technology Assessment (OTA) review of the National Institute of Justice (NIJ) body armor standards, a thorough examination of the basis for the standards was undertaken. In most cases, it was found that there was a firm experimental basis for decisions. Where data did not exist, NIJ used a best engineering

judgment approach, and OTA agreed that the standards are working. In this paper, the points of engineering judgment are reviewed and a call issued for international cooperation on gathering data to fill the gaps in the body armor community's collective knowledge.
[Contact: Daniel E. Frank, (301) 975-2757]

PRODUCT DATA SYSTEMS

Released for Publication

Goldstein, B.L.M., **Electronic Commerce for the Electronics Industry**, to be published in the Proceedings of the 1994 Electro International Conference, Boston, Massachusetts, May 10-12, 1994.

This paper discusses the potential impact of an electronic marketplace on the electronics industry, the enabling technology needed to effectively migrate current business practices to take full advantage of such a highly networked environment, a few of the organizations participating in the creation and promotion of these technologies, and some of the challenges to migration.
[Contact: Barbara L. Maia Goldstein, (301) 975-2304]

Parks, C., **Demonstration: World Wide Web for Distribution of Users Group Information on Internet**, to be published in the Proceedings of the 1994 IDEF Users Group Spring Conference, Richmond, Virginia, May 23-26, 1994.

Internet is rapidly becoming the primary means of communication among millions of people including individuals, academia, government, and commercial organizations. This demonstration is an experimental use of an Internet "hypermedia document server and reader" facility to present information about the IDEF Users Group. Should the Users Group adopt the World Wide Web as one means for distributing information, the demonstration files are available for modification and hosting on a server so as to be available on the network. The Users Group demonstration includes links to the NIST FIPS documents on IDEF0 and IDEF1X which are now available for access.
[Contact: Curtis Parks, (301) 975-3517]

VIDEO TECHNOLOGY

Released for Publication

Fenimore, C., Field, B.F., Frank, H., Georg, E., Papillo, M., Reitmeier, G., Stackhouse, W., and Van Degrift, C., **Report on the Workshop on Advanced Digital Video in the National Information Infrastructure**, May 10-11, 1994, Georgetown University Conference Center, Washington, DC, to be published as a NISTIR.

A workshop was held to highlight technical issues for industry and government decision makers with respect to Advanced Digital Video in the National Information Infrastructure (NII). The purpose of the Workshop was to: (1) define a vision of the role of digital video within the NII; (2) identify the architectural, scaling, and performance issues in realizing this vision; and (3) recommend the research, experiments, and steps to be taken to resolve these issues.

This summary by the Program Committee reports on some of the important ideas expressed by the speakers and the conclusions reached by the breakout groups, and the recommendations from the Workshop as a whole. The reader is referred to the unedited Breakout Group Reports and speakers' slides, in Part 2 of the Report, for more details.
[Contact: Charles Fenimore, (301) 975-2428]

Kelley, E.F., Field, B.F., Jones, G.R., and Boynton, P.A., **Display Modeling and an Active Matrix Liquid Crystal Display Model on a Video Supercomputer**, to be published in the Proceedings of the Society for Information Display International Symposium, San Francisco, California, June 12-17, 1994.

An active-matrix liquid crystal display (AMLCD) is simulated on a cathode ray tube display driven by a video supercomputer, the Princeton Engine. The supercomputer permits the use of real-time video in conducting human factors visualization tests. The display model produces a representation that visually matches an actual AMLCD display for a wide range of viewing angles.
[Contact: Edward F. Kelley, (301) 975-3842]

ADDITIONAL INFORMATION

New NIST Standard Reference Material

SRM 2551, a calibration standard for interstitial oxygen in silicon is now available. This SRM was prepared for the qualification and calibration of infrared spectrometers used by the industry to determine oxygen concentration in silicon.

The SRM is issued as sets of four pieces of silicon, each double-side polished 2.5-cm squares of 2-mm thickness. The four silicon pieces are: a float-zone reference specimen and low-, medium- and high-level oxygen (Czochralski-grown) specimens with oxygen levels on the IOC-88 scale from approximately 16.5 to 26.5 ppma. Each SRM set was individually certified using an FTIR instrument that had been modified to maximize measurement reproducibility by significantly reducing sample mounting and interchange effects. Redundant measurements were taken to improve measurement statistics and control samples were utilized at two levels to monitor and correct for instrument drift effects. The FTIR instrument itself was calibrated against a master set of specimens retained from the Grand International Round Robin from which the IOC-88 oxygen conversion factor was derived.

The 2-sigma uncertainty of certification for these SRM sets ranges from 0.17% at the low oxygen level to 0.12% for the high oxygen level. This uncertainty is a measure of the equivalence of the oxygen values of each SRM set to the Grand Round Robin master set and therefore to each other SRM set. (The uncertainty of absolute oxygen levels as measured in the Grand Round Robin is not incorporated in the SRM certificate.) Use of the SRM will enable infrared test stations to determine their own specific conversion factor between infrared absorption and interstitial oxygen level rather than assuming that all instruments operate with the same conversion factor. This will enable significant improvement in oxygen measurement control and equivalence of measurement station values throughout the semiconductor industry.

While the full benefits of these exceptionally small uncertainty values may not be immediately realizable by all infrared test systems without tightened measurement procedures, the SRM is expected to fully support the measurement requirements for improved oxygen control that are projected on the National Technology Roadmap for Semiconductors.

The price of each SRM set is $507.

To order, contact Standard Reference Material Program, (301) 975-6776. For technical information, contact Brian Rennex, (301) 975-2108.

Lists of Publications

Smith, A.J., **Metrology for Electromagnetic Technology: A Bibliography of NIST Publications**, NISTIR 5008 (September 1993).

This bibliography lists the publications of the personnel of the Electromagnetic Technology Division of NIST during the period from January 1970 through publication of this report. A few earlier references that are directly related to the present work of the Division are also included.
[Contact: Annie Smith, (303) 497-3678]

Lyons, R.M., and Gibson, K.A., **A Bibliography of the NIST Electromagnetic Fields Division Publications**, NISTIR 5009 (September 1993).

This bibliography lists publications by the staff of the National Institute of Standards and Technology's Electromagnetic Fields Division for the period from January 1970 through July 1993. Selected earlier publications from the Division's predecessor organizations are included.
[Contact: Kathryn A. Gibson, (303) 497-3132]

Meiselman, B., **Electrical and Electronic Metrology: A Bibliography of NIST Electricity Division's Publications, NIST List of Publications 94** (January 1994).

This bibliography covers publications of the Electricity Division, Electronics and Electrical Engineering, Laboratory, NIST, and of its predecessor sections for the period January 1968 to December 1993. A brief description of the Division's technical program is given in the introduction.
[Contact: Katherine H. Magruder, (301) 975-2401]

Walters, E.J., **Semiconductor Measurement Tech-**

nology, 1990-1993, NIST List of Publications 103 (January 1994).

The bibliography provides information on technology transfer in the field of microelectronics at NIST for the calendar years 1990 through 1993. Publications from groups specializing in semiconductor electronics are included, along with NIST-wide research now coordinated by the NIST Office of Microelectronics Programs which was established in 1991. Indices by topic area and by author are provided. Earlier reports of work performed during the period from 1962 through December 1989 are provided in NIST List of Publications 72.
[Contact: E. Jane Walters, (301) 975-2050]

Availability of *Measurements for Competitiveness in Electronics* [First Edition], NISTIR 4583 (April 1993).

This document is the successor to NISTIR 90-4260, *Emerging Technologies in Electronics ...and their Measurement Needs* [Second Edition]. The new *Measurements for Competitiveness in Electronics* identifies the measurement needs that are most critical to U.S. competitiveness, that would have the highest economic impact if met, and that are the most difficult for the broad range of individual companies to address. The document has two primary purposes: (1) to show the close relationship between U.S. measurement infrastructure and U.S. competitiveness, and show why improved measurement capability offers such high economic leverage and (2) to provide a consensus on the principal measurement needs affecting U.S. competitiveness, as the basis for an *action plan* to meet those needs and to improve U.S. competitiveness.

Copies of this document are available as Order No. PB93-160588 from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161, at (800) 553-6847 or (703) 487-4650.

Abstract – Measurements are used to determine the values of hundreds of important quantities in the electronics industry. Representative quantities are the widths of the interconnections within semiconductor integrated circuits, the attenuation of lightwaves in optical fibers, and the signal power from microwave satellite antennas. Measurement capability is a fundamental tool used to build the nation's high-technology products. As such, it is part of the national infrastructure for the realization of these products.

Measurement capability is critical to research and development, manufacturing, marketplace entry, and after-sales support of products. Thus, measurement capability affects the performance, quality, reliability, and cost of products. The result of this pervasive impact is that the level of U.S. measurement capability places an upper limit on the competitiveness of U.S. products.

At present, U.S. industry is experiencing a major shortfall in the measurement capability needed for competitiveness in electronic products. This document identifies the measurement needs that are most critical to U.S. competitiveness, that would have the highest economic impact if met, and that are the most difficult for the broad range of individual companies to address. The measurement needs are reviewed for nine important fields of electronics, including semiconductors, magnetics, superconductors, microwaves, lasers, optical-fiber communications, optical-fiber sensors, video, and electromagnetic compatibility. These fields of electronics underlie more than $300 billion of electronic and electrical products manufactured in the U.S. each year.

This assessment provides the framework for an action plan to correct the shortfall in U.S. measurement capability in electronics and to advance U.S. competitiveness.

Guide – The compiler of the document provided an introductory guide to its organization and content. Because EEEL believes that a number of *TPB* readers will be interested in the information presented in the various chapters, the contents of this guide are reproduced below (page numbers of chapter summaries are included to provide a measure of the extent of the treatment):

This document contains 12 chapters, divided into two groups. The first three chapters are introductory in nature and are relevant to all of the following chapters. The remaining nine chapters address individual fields of electronic technology. Each chapter begins with a two-page summary that provides ready access to the major points made in

the chapter. These short summaries are found on the pages identified below. By selecting from these summaries, you can quickly access information on the subjects of most interest to you.

Introductory Information – Chapter 1, Role of Measurements in Competitiveness (page 3); Chapter 2, NIST's Role in Measurements (page 21); Chapter 3, Overview of U.S. Electronics and Electrical-Equipment Industries (page 31).

These three chapters introduce the subject of measurements and provide an overview of the products of the U.S. electronics and electrical-equipment industries.

Chapter 1, **Role of Measurements in Competitiveness**, shows why measurements are a fundamental part of the infrastructure of the nation. Chapter 1 also sets measurements in the context of the many other important factors that affect competitiveness.

Chapter 2, **NIST's Role in Measurements**, indicates the circumstances under which Government assistance to industry in the development of measurement capability is appropriate in pursuit of a strengthened national economy.

Chapter 3, **Overview of U.S. Electronics and Electrical-Equipment Industries**, introduces these industries through an overview of their major product lines. This chapter shows the various ways in which the products of these industries are commonly classified and how those classifications relate to the structure of this document.

Fields of Technology – Chapter 4, Semiconductors (page 53); Chapter 5, Magnetics (page 95); Chapter 6, Superconductors (page 129); Chapter 7, Microwaves (page 147); Chapter 8, Lasers (page 183); Chapter 9, Optical-Fiber Communications (page 217); Chapter 10, Optical-Fiber Sensors (page 303); Chapter 11, Video (page 339); Chapter 12, Electromagnetic Compatibility (page 381).

Each of these chapters contains four basic types of information:

Technology Review: The field of technology is reviewed to highlight and explain the special capabilities that make the technology important. This review introduces the technical concepts that are necessary for understanding the sections that follow.

World Markets and U.S. Competitiveness: The economic significance of the field of technology is highlighted through use of national and international market data for major products that employ the technology. Available information on the U.S. competitiveness is described.

Goals of U.S. Industry for Competitiveness: The goals that U.S. industry is pursuing to improve its competitiveness are discussed so that they can be related to requirements for new measurement capability supportive of the goals.

Measurement Needs: The new measurement capability that U.S. industry will need to enable it to achieve its goals is described. This discussion emphasizes measurement capability that is needed widely in U.S. industry, that will have high economic impact if provided, and that is beyond the resources of the broad range of individual U.S. companies to provide.

[While the assessment of measurement needs in this document is wide ranging, not every field of technology important to the electronic and electrical-equipment industries has been covered. NIST plans to expand this assessment in future editions to include additional fields.]

The order in which chapters appear is intentional: the technologies on which most other technologies depend are introduced first. Thus, the chapter on semiconductors appears first because most electronic technologies depend on semiconductor materials. In contrast, the chapter on video is located near the end because it depends on nearly every other technology discussed earlier.

Chapters 4, 5, and 6 of this document describe the measurement needs arising from three important materials technologies that underlie current and emerging electronic and electrical products. These chapters also describe the measurement needs of components and equipment based on these materials and not discussed separately in other chapters.

Chapter 4, **Semiconductors**, addresses both silicon and compound semiconductors and their use in components, including individual (discrete) electronic and optoelectronic devices and integrated circuits. Semiconductor components are central to all modern electronic products from consumer products to supercomputers.

Chapter 5, **Magnetics**, focuses on both magnetic materials and the components made from them. Magnetic materials are second in importance only to semiconductor materials for electronic products and play a central role in electrical products. This chapter also addresses the measurement needs of selected equipment critically dependent on magnetic materials, including magnetic information storage equipment, electrical power transformers, and others.

Chapter 6, **Superconductors**, examines superconductor materials and addresses both present and emerging applications of these materials in electronic and electrical products.

Chapters 7 through 11 describe the measurement needs associated with selected technologies of importance to U.S. competitiveness for current and emerging products.

Chapter 7, **Microwaves**, describes the highest-information-capacity radio technology. Microwave electronics provide the basis for modern and emerging wireless communications systems and radar systems. Included are new personal communications services with both local and worldwide access, intelligent vehicle-highway systems, and advanced audio and video broadcasting systems, among others.

Chapter 8, **Lasers**, addressed the single most important component for emerging lightwave systems used for manufacturing, medicine, communications, printing, environmental sensing, and many other applications.

Chapter 9, **Optical-Fiber Communications**, describes the highest-information-capacity cable technology. It provides the basis for national and international information highways of unprecedented performance and broad economic impact. Optical-fiber systems will be linked with microwave systems to interconnect mobile and portable users and to backup cable systems.

Chapter 10, **Optical-Fiber Sensors**, focuses on an emerging class of sensors that offers outstanding performance for a broad spectrum of applications in manufacturing, aerospace, medicine, electrical power, and other areas.

Chapter 11, **Video**, emphasizes advanced, high-performance systems, such as high-definition television, which offer, for the first time, simultaneous access to high-resolution, smooth motion, and great color depth. The chapter notes the potential of full-power implementations of video technology in interactive networked environments. The chapter contains a special focus on flat-panel displays.

Chapter 12, **Electromagnetic Compatibility**, describes the special challenges that the U.S. faces in maintaining electromagnetic compatibility among the many new products of electronic and electrical technologies. Such compatibility is essential if the full potential of all of the above technologies is to be realized without debilitating mutual interference.

Appendices -- The three appendices provide definitions of the U.S. electronics and electrical-equipment industries. These definitions were used in preparing much of the economic information in the report.

Appendix 1 describes the Standard Industrial Classification System that the U.S. Government uses for collecting data about U.S. industry. This appendix also lists publications in which the U.S. Government reports data on U.S. shipments.

Appendix 2 provides a definition of the U.S. electronics industry in terms of the Standard Industrial Classification System.

Appendix 3 provides a definition of the U.S. electrical-equipment industry in terms of the Standard Industrial Classification System.

1994/1995 Calendar of Events

August 16-19, 1994 (Boulder, Colorado)

Laser Measurements Short Course. NIST, in cooperation with the University of Colorado and industry, is offering this Short Course which will emphasize the concepts, techniques, and apparatus used in measuring laser parameters. Topics to be presented are: optics for laser measurements; attenuation techniques; laser operation; basic laser power/energy standards; laser power/energy measurement techniques; optical fiber power measurements; transfer standards; beam profile measurements; diode lasers; laser measurements for optical communications; statistics and error analysis; laser safety; and detectors. The Course will include a visit to the NIST laser measurement laboratories.
[Contact: Thomas Scott, (303) 497-3651]

September 13-15, 1994 (Boulder, Colorado)

Symposium on Optical Fiber Measurements. Sponsored by the IEEE Lasers & Electro-Optics Society, the Optical Society of America, and NIST, the Symposium will provide a forum for reporting the results of recent measurement research in the area of lightwave communications, including optical fibers.
[Contact: Douglas L. Franzen, (303) 497-3346]

September 22-23, 1994 (San Jose, California)

Particles, Haze, and Microroughness on Silicon Wafers. Co-sponsored by NIST, ASTM, and SEMI, this conference will address particle generation in process tools, advances in scattering techniques, and relationships between haze, microroughness, and particle detection and identification. [Contact: Robert I. Scace, (301) 975-4440]

October 27, 1994 (Gaithersburg, Maryland)

Ion Implant Users Group Meeting. One of the topics to be discussed will be Atomic and Electrical Profiling of Ion Implanted Layers. Additional topics will be announced at a later date.
[Contact: John Albers, (301) 975-2075]

January 30—February 2, 1995 (Gaithersburg, Maryland)

International Workshop on Semiconductor Materials Characterization: Present Status and Future Needs. Papers will be presented in all relevant fields of interest to materials characterization in semiconductor device manufacturing, growth, processing, diagnostics, in-situ, real-time control and monitoring, etc. All relevant semiconductor materials will be addressed: Group IV elements, Group III-V compounds, Group II-VI compounds, IV-VI compounds, and others. The Workshop is sponsored by the Advanced Research Projects Agency (ARPA), SEMATECH, and NIST. Other co-sponsors are expected.
[Contact: David G. Seiler, (301) 975-2074]

April 28, 1995 (Andover, Massachusetts)

Ion Implant Users Group Meeting. This will be the first of regularly scheduled yearly meetings of the IIUG in the Boston area because of the size and interest of the New England membership. Topics to be discussed will be announced at a later date.
[Contact: John Albers, (301) 975-2075]

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National Highway Traffic Safety Administration;
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Nuclear Regulatory Commission
Various Federal Government Agencies

NIST SILICON RESISTIVITY SRMs

In response to needs of the semiconductor industry, NIST's Semiconductor Electronics Division provides silicon bulk resistivity Standard Reference Materials (SRMs) through the NIST Standard Reference Materials Program. A new class of resistivity SRMs is being introduced to respond better to users' requirements.

The first NIST (then NBS) resistivity SRMs were fabricated from crystal 50 mm (2 in) in diameter. These wafers represented various combinations of crystal growth process, crystallographic orientation, and doping, each combination chosen to give the best expected wafer uniformity for a given resistivity level. Each wafer in every set was individually measured and certified. Some of these sets are still available until the supply is exhausted (see table).

The Division is now certifying single-wafer resistivity standards at approximately the same resistivity values as were available in the earlier sets. These new SRMs are fabricated from crystal 100 mm in diameter, intended to provide improved compatibility with newer end-use instrumentation. In response to user comments, the new SRMs will be more uniform in both thickness and resistivity, will have reduced uncertainty of certified value due to use of an improved certification procedure using a four-point probe, and will be measured and certified at additional measurement sites for better characterization of wafer uniformity at its core. The additional measurements needed to qualify the improved SRMs will make them more expensive on a per-wafer basis than the earlier sets.

NIST SILICON BULK RESISTIVITY STANDARD REFERENCE MATERIALS

DATE UPDATED: 8 AUGUST 1994

Note: Problems in producing and certifying new SRMs have resulted in substantial delays. The first to become available, for 10 and 180 ohm · cm, are not likely to be ready until 1995.

NOMINAL RESISTIVITY (ohm · cm)	OLD SRMs	AVAILABILITY	NEW SRMs	ANTICIPATED AVAILABILITY
0.01	1523 (one of set of two wafers)	limited supply	2541	to be announced
0.1	1521 (one of set of two wafers)	limited supply	2542	to be announced
1	1523 (one of set of two wafers)	limited supply	2543	to be announced
10	1521 (one of set of two wafers)	limited supply	2544	to be announced
25	1522	set of three wafers no longer available	2545	to be announced
75	1522		2546 (100)	to be announced
180	1522		2547 (200)	to be announced

The above table will be updated in future issues to reflect changes in availability. Every effort will be made to provide accurate statements of availability; NIST sells SRMS on an as-available basis. For technical information, contact James R. Ehrstein, (301) 975-2060; for ordering information, call the Standard Reference Materials Program Domestic Sales Office: (301) 975-6776.

International Workshop on Semiconductor Characterization: Present Status and Future Needs

January 30—February 2, 1995
Gaithersburg, Maryland, U.S.A.

The International Workshop on Semiconductor Characterization: Present Status and Future Needs will be held Monday, January 30 through February 2, 1995, at NIST in Gaithersburg, Maryland. The Workshop provides a forum to present and discuss critical issues, problems and limits, evolving requirements and analysis needs, future directions, and key measurement principles, capabilities, applications, and limitations. It will be comprised of formal invited presentation sessions, poster sessions for contributed papers, and panel sessions. Invited sessions are planned on:

- Si Process Development and Manufacturing — The Drivers
- Analytical Technology and Metrology Requirements for Beyond 0.35 μm Technology
- Process and Characterization Issues
- Above-Si Processing
- Critical Analytical Methods
- Si and Compounds: In-Situ; Real-Time Diagnostics, Analysis, and Control
- Frontiers in Compound Semiconductors

Contributed poster papers are solicited on new breakthroughs and major improvements in measurement techniques for silicon or compound semiconductors. Authors are requested to submit a one-page abstract by September 23, 1994 to the Conference Contact below. An author's kit will be mailed following paper acceptance.

Sponsors: The Advanced Research Projects Agency, SEMATECH, National Institute of Standards and Technology, Army Research Office, U.S. Department of Energy, National Science Foundation, and SEMI.

Conference Chair: David G. Seiler, NIST

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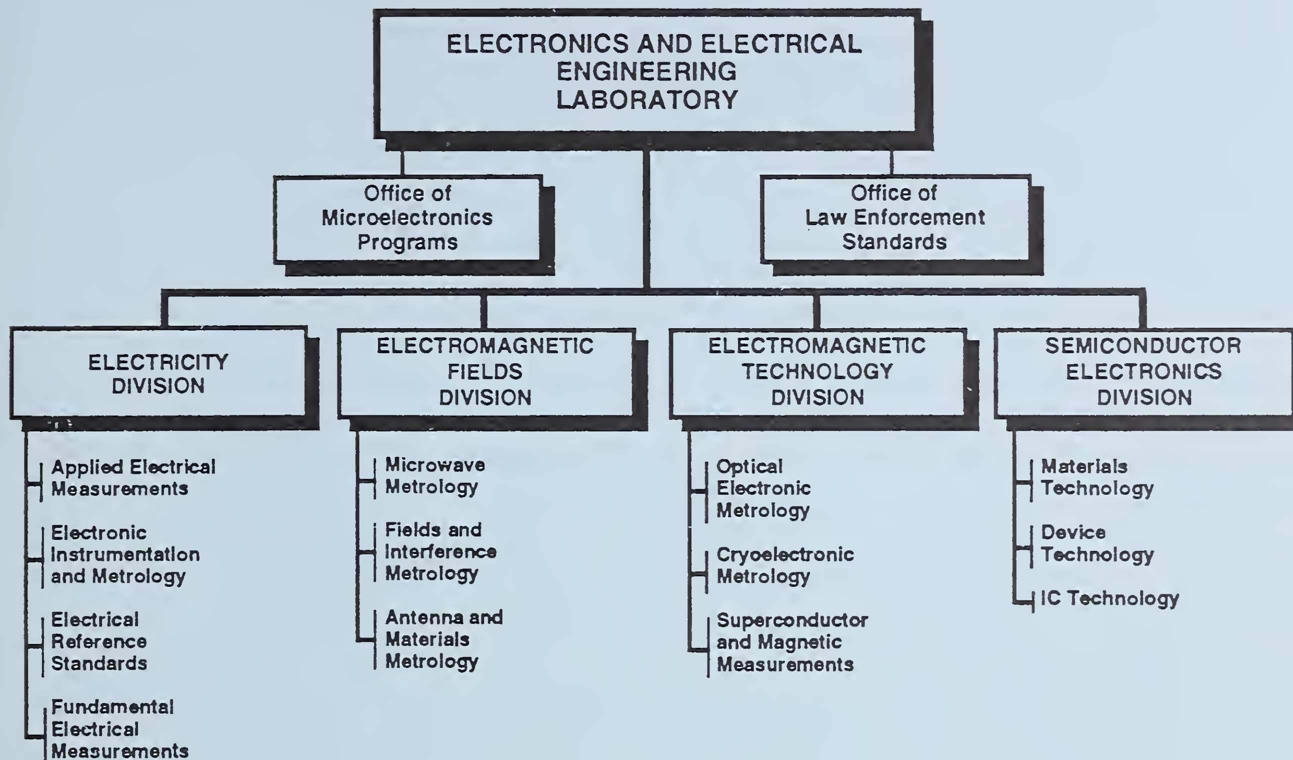

KEY CONTACTS

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Electromagnetic Technology Division (814)	Acting Chief, Dr. Richard E. Harris (303) 497-3776

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