NISTIR 90-4281

CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING

1990 PROGRAM DESCRIPTION

Ronald M. Powell

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Building 220, Room B-358
Gaithersburg, MD 20899

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Preface

This report describes selected projects of measurement development that CEEE is addressing during fiscal year 1990. The report indicates the directions that these projects will take in the next few years. The report also describes selected accomplishments during fiscal year 1989. Because of the size of CEEE and the scope of its work, only a representative sampling of these projects and accomplishments can be described in a document of this length.

This report also outlines new programs of measurement development that CEEE has defined for future years.

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CENTER FOR ELECTRONICS AND ELECTRICAL ENGINEERING: Overview

Role

The Center for Electronics and Electrical Engineering (CEEE), within the National Institute of Standards and Technology (NIST), provides generic measurement capability in the interrelated areas of electronics, opto-electronics, electromagnetics, and electrical engineering. This measurement capability supports domestic trade, U.S. international competitiveness, and the efficient functioning of the Government. Specifically, CEEE's measurement capability supports:

- industrial R&D toward improved products
- development of manufacturing processes
- quality control
- cost reduction in design, manufacturing, and marketing
- product specification and proof of performance for market transactions
- maintenance
- voluntary industry standards for product compatibility and other aims
- representation of U.S. interests in international standards matters that affect entry of U.S. products to international markets

Two characteristics of NIST are essential to CEEE's effectiveness in contributing to national goals: recognized metrological competence, both nationally and internationally; and an unbiased posture relative to buyers, sellers, and regulators. These characteristics enable NIST to achieve industrial adoption of measurement methods and physical standards of broad benefit to society.

Metrological Products

CEEE develops measurement methods, standard reference materials (SRMs), calibration services, special tests, theoretical analyses, computer models, and generic data. CEEE does not develop prototypes of commercial products, although CEEE's measurement technology is sometimes commercialized by others. CEEE does not promulgate regulations. Rather, industrial organizations and other Government agencies recommend or require the use of the measurement practices and services that CEEE provides.2

CEEE's approach is to determine key industrial needs, conduct responsive R&D, document findings, and deliver those findings to industry and Government. Means of delivery and levels of activity in FY 1989 include: publications (160); talks (202); consultations (1200); standard reference materials (180 sold); calibrations and special tests (5991 tests for more than 350 customers); measurement assurance programs; round-robin measurement intercomparisons; guest workers (58) and research associates (4); training and seminar programs (13 with more than 2000 attendees); participants in professional societies and standards organizations (more than 334); cooperative projects (110); delivery of findings in software form (more than 32); contributions to voluntary industry standards; and consortia in place or forming (6).

Size

For FY 1990, CEEE's estimated cost of operation is $36.5 million, to be provided by a combination of direct funding (50%), funding from other Federal agencies (42%), and reimbursements for calibration and special test services (8%). CEEE's total paid staff as of September 30, 1989 was 361 of which 285 were full-time permanent staff. In addition, CEEE had 58 unpaid guest workers and 4 research associates in FY 1989. Also in FY 1989, CEEE provided about 45% of all of NIST's calibration and special test services, in terms of both numbers of tests performed and dollars charged to customers for those tests.

Organization

CEEE is organized in four Divisions. Table I shows the names of the Divisions, their programmatic emphases, and the percentages they represent of CEEE's estimated cost of operation.

Table I: CEEE's Organization

Division	Emphases	Funding
Electromagnetic Fields	radio-frequency signals and compatibility	33%
Electromagnetic Technology	lightwaves, superconductors, and magnetics	28%
Semiconductor Electronics	semiconductor electronics	18%
Electricity	basic standards, conducted signals, and energy	21%

The programs of the four Divisions are discussed below. For each Division, a brief overview of key factors affecting planning is provided. The overview is followed by a discussion of representative accomplishments during FY 1989 and representative plans for the next one to three years. Because the programs are large and varied, the scope of activity is considerably broader than can be covered here.

ELECTROMAGNETIC FIELDS DIVISION: Radio-Frequency Signals and Compatibility

The Electromagnetic Fields Division provides measurement capability for radio-frequency signals and antennas, with emphasis on microwave frequencies, and for electromagnetic compatibility. More specifically, the Division develops theory, methodology, and instrumentation for measurement of electromagnetic fields and for properties of systems, components, and materials which generate, guide, and control electromagnetic fields. The Division employs 33% of CEEE's total resources. In FY 1989, the Division provided nearly 22% of all calibration and special test services that NIST delivered, on a dollar basis.

Microwave Metrology

The microwave industry served by the Division is the second largest equipment industry in the U.S.; only "computers and their peripherals" is larger. The microwave equipment industry ships about $35 billion of products per year, about one-seventh of all U.S. shipments of electronic equipment, systems, and components. Based on the performance of the overall category of "radio communication and detection equipment", which contains most microwave equipment, the Government buys 48% of all U.S. shipments. DOD dominates the Government share, accounting for 43 of the 48 percentage points. U.S. shipments are expected to grow in real terms by about 5% per year. At the present time, non-DOD purchases not only are larger but also are growing faster. The world market is estimated at 2.1 to 2.5 times the size of the U.S. market.

New or continuing non-DOD Government programs are contributing billions to the demand for new or enhanced microwave services. These programs include: the Department of Commerce's NEXRAD next-generation weather radar stations; the Department of Transportation's National Airspace System Program for new communications and radar systems at 100 U.S. airports; the Department of Transportation's new requirement for on-board wind shear detection systems for U.S. aircraft; and the Department of State's DOSTN worldwide telecommunications network. Emerging programs heavy in microwave equipment include NASA's satellite-based Earth Observing System, now under evaluation.

Viewed more broadly, the growth in the market for microwave systems is driven by the demand for traditional telecommunications and radar services, and by the emergence of new applications. The new applications include: microwave electronics for advanced video technology, for fiber optic communications, and for computer circuitry; vision systems for robots; on-board wind-shear detection systems for airplanes; collision-avoidance radar for automobiles; direct broadcast systems employing satellites; and local communications and radar systems for commercial and corporate applications.

International competition for this expanding market, which is based principally on non-military applications, is intensifying. Both the Europeans and the Japanese are moving quickly to take advantage of the new opportunities. The competition hinges largely on successful pursuit of three major advances in microwave electronics: extraordinary performance levels; integration; and higher frequencies. Extraordinary performance levels are needed to improve speed, signal quality, sensitivity, versatility, and flexibility. Integration of microwave electronic devices with each other, with optoelectronic devices, and with antennas is needed to reduce the size, cost, and weight of microwave systems and to increase their power and versatility. Exploitation of the higher frequencies to 100 GHz, and even to 1000 GHz, is needed to gain access to the additional spectral space and special properties that they offer. All of these advances must be achieved while maintaining high quality and reliability.

Through its interaction with industry, CEEE has identified the new measurement capability required by these advances and has defined a plan for a responsive new program. This plan will meet the broad measurement requirements found critical by several sources: the IEEE Committee to Promote National Microwave Standards (PNMS), the National Conference of Standards Laboratories (NCSL), individual companies, and Federal agencies.

The projects contained within the plan provide measurement support for three important categories of components, as shown in Table II. Projects 1 and 2 cover the frequency range of present interest for both individual components and integrated components. Project 3 covers the frequency range of emerging interest where integrated components will totally dominate.

Table II: New Program for Microwave Measurements

1. Individual Components for 1-100 GHz
2. Integrated Components for 1-100 GHz
3. Integrated Components for 100-1000 GHz

In addition, CEEE has formed a consortium with several microwave integrated-circuit manufacturers and several research laboratories of the Department of Defense to provide selected measurement support for microwave integrated circuits. A similar consortium for microwave properties of materials was attempted but without success; industry felt that such generic work should be supported by Government funding and that NIST's present program was too small anyway to form the basis for a successful consortium.

The Division received 34% of its funding by direct appropriation in FY 1989; nearly all of the rest came from other agencies. The low level of total funding plus the low fraction of direct funding combine to limit the Division's abilities to meet urgent national needs in both the commercial and the Government sectors.

The following sections describe work representative of the Division's present program in microwave metrology and in radiated electromagnetic interference (EMI). Both recent accomplishments and new work that can be conducted with the present level of resources are discussed.

Power and Impedance Standards

The Division is reestablishing its power measurement capability by developing new standards with accuracy comparable to or slightly higher than that of present aging standards, and by automating related measurement systems. The Division is focusing on the region below 18 GHz and on selected frequencies above 18 GHz but below 100 GHz. During this past year, the Division began the evaluation of its rebuilt coaxial calorimeter for power measurements covering 0.1-18 GHz. The Division also continued development of a new waveguide calorimeter for 33-50 GHz (WR-22) based on an isothermal design. This design employs Peltier cooling to reduce time constants and calibration time when used with automated systems. Next, the Division will develop a set of coaxial power transfer standards for use above 18 GHz and will complete the fabrication and evaluation of the isothermal waveguide calorimeter. These design concepts are being used to replace existing waveguide calorimeters in other waveguide bands.

The Division is also developing impedance standards, in two steps: second generation (interim) standards with typically 2.5 times better accuracy than present standards, and third generation standards with typically 12 times present accuracy. The absence of these standards is presently limiting commercial and defense exploitation of advanced measurement equipment whose performance exceeds the capabilities of present standards. During the next few years, the Division will implement key second generation standards, principally at frequencies below 26 GHz. Implementation of the third generation standards will require successful funding of the proposed new program of measurement support. The third generation standards require microinch machining accuracy. This capability is being pursued in collaboration with the Dimensional Metrology Group in the Center for Manufacturing Engineering.

During the past year, the Division further improved the mathematical models used to compute impedance values from physical measurements for impedance standards. The Division also constructed key sets of coaxial impedance standards for 1-18 GHz and evaluated their uncertainties. Next, the Division will extend its theoretical modeling to reflect the effects of connector discontinuities.

Measurement Systems and Services

The Division is developing computer-controlled measurement systems for power, impedance, reflection coefficient, voltage, attenuation, phase shift, and scattering parameters for key frequencies, primarily in the range of 30 kHz to 100 GHz. During the past year, the Division obtained formal internal approval for the documentation for the dual 6-port automatic network analyzer for 0.5-18 GHz coaxial components. The Division also transferred all coaxial power measurements to six-port systems. Among its next projects, the Division will develop automated systems to improve the use of historical data to assess measurement quality and stability.

The Division continues a joint effort with the Electromagnetic Technology Division to determine the feasibility of constructing a cryogenic power detector that promises a factor of five improvement in the accuracy of power measurements. Its completion and broad implementation in the Division's power measurement systems will require the success of the proposed new program.

Integrated-Circuit Metrology

Development of a major program of measurement support for monolithic microwave integrated circuits (MMICs) depends critically on the proposed new program. In the meantime, NIST has begun a small effort with a mix of internal, consortium, and other agency funding. During the past year, the Division installed the equipment required for initial work on the effects of probes on measurements made on microwave integrated-circuit wafers. Using this system, the Division will develop probe and interconnection standards plus related algorithms for removing probe effects from impedance measurements. The Division will also begin planning for power and noise measurements in integrated circuits. A related program on thermal testing for microwave integrated circuits is being conducted in collaboration with the Semiconductor Electronics Division.

Noise

Noise performance ultimately limits the total performance of microwave and millimeter-wave systems. Measurement support requires accurate noise measurement devices (radiometers) and standard noise sources. For the next several years, the Division will continue its development of new cryogenic noise standards, companion radiometers, and noise calibration services with improved accuracy, stability, bandwidth, and ease of use over the range 2-50 GHz. Most recently, the Division completed its 1-2 GHz coaxial radiometer system and initiated special test services. Next, the Division will implement special test services for waveguide systems for 8-18 GHz (WR-90, WR-62) and 40-60 GHz (WR-19). In the longer term, the Division will extend noise measurements to include noise figure of amplifiers.

Pulse Waveform Metrology

The Division is developing capability to measure electrical waveforms with picosecond resolution to support advances in digital switches, computing, communications, and supporting instrumentation. During the past year, the Division transferred its special test services for fast electrical pulse parameters, pulse time delay, and impulse spectrum amplitude to its new Automatic Waveform Analysis and Measurement System (AWAMS), which has been under development for several years. The Division also intercompared its measurement capability with that of a commercial superconducting oscilloscope which is sufficiently fast that it helped the Division reduce by a factor of three the uncertainty in its own measurements. In the next several years, the Division will implement laser-based measurements techniques and supporting national standards that will enable characterizing fast electrical pulses with resolution of 1 picosecond initially and with resolution in the femtosecond domain ultimately.

Scattering and Dielectric Measurements

Inadequate knowledge of the scattering behavior and dielectric properties of materials at microwave frequencies is inhibiting the development of a broad range of electronic components from microstrip antennas to monolithic integrated circuits. The Division is attempting to respond to these needs but can make only a limited response without the success of the proposed new program. During the past year, the Division developed improved algorithms for measurements of materials properties using transmission/reflection methods in coaxial and waveguide sample holders. The new algorithms have enabled an order of magnitude improvement in accuracy of permittivity measurements, precise determination of that accuracy, and capability to measure materials with both higher and lower losses than possible with techniques presently used in industry. Next, the Division will offer measurement services for permittivity up to 18 GHz based on the coaxial holder and will complete a resonant cavity approach that has superior performance for low loss materials, at a single frequency of 10 GHz, and is suitable for evaluating reference materials.

Metrology for Satellites and Earth Terminals

The Division is developing improved measurement capability for monitoring the performance of satellites and earth terminals. This past year, the Division diagnosed software problems and determined accuracies associated with antenna gain and effective isotropic radiated power (EIRP) measurements for earth terminals, contributing to as much as a factor of 10 improvement in the latter. Next, the Division will calibrate probes and standard gain antennas needed to verify the performance of 60-foot antennas used to determine the EIRP of the satellites in the Defense Satellite Communications System.

Antennas

The buyers of antennas want higher levels of performance in order to increase information handling capacity, to gain new frequency and geographical flexibility, and to resolve increasing problems with orbital and spectral crowding. The result has been an increasing demand for antennas with adaptive capability, reduced sidelobes, high polarization purity, multiple beams, shaped beams, and other special characteristics. To meet these demands, new antennas must be made larger and more complex; they must operate at higher frequencies, and they will often require integrated electronics to meet performance requirements at affordable cost. These changes are placing severe demands on supporting measurement science. NIST can address some of these challenges with existing resources but cannot pursue comprehensive measurement development above 26 GHz or for integrated antennas without the planned new program. Funding from other agencies has enabled the Division to address selected measurements above 26 GHz.

The Division continues its development of planar and spherical near-field scanning. For planar scanning the emphasis is on higher frequencies, higher accuracies, broader frequency coverage, more efficient means of data analysis, and continued transfer of near-field measurement technology to industry and Government organizations. During the past year, the Division improved the software used for probe position corrections for planar scanning to enable accuracy levels formerly attained below 30 GHz to be obtained up to 60 GHz. The Division also obtained all of the hardware required for a new spherical near-field range. Next, the Division will complete the first phase of the construction of the spherical range. The Division will also complete the software and theory for identifying errors in the adjustment of individual elements in phased arrays measured with planar scanning.

The Division has successfully promoted broad adoption of near-field scanning by industrial and Government facilities. There are now 35 near-field antenna facilities in the U.S. Nearly all receive measurement support from NIST in one or more of several forms: design consultation, calibrated standards, or software embodying the underlying theory.

Electromagnetic Compatibility

The substantial amount of new electronic equipment put into service in the U.S. each year is greatly exacerbating the already serious problem of electromagnetic interference. Increasingly, measurements of the emissions and immunity of electronic products are becoming a factor in the marketplace. Both national and international regulatory organizations are focusing attention on mandatory standards for EMI immunity and for biological exposure, with far-reaching implications for international trade. Within the U.S., the FCC earlier adopted regulations requiring measurement of the emissions from every electronic product which contains a "clock" (10 kHz or above switching circuit). For DOD, the transportation industry, and the aerospace industry broadly, EMI threatens both malfunctions and loss of life. These concerns have greatly increased the demand for measurements capable of resolving EMI problems.

In response, the Division is addressing key measurement needs falling principally in the frequency range from 10 kHz to 40 GHz and in the power density range from 1 nW/cm^2 to

1 kW/cm^2, where most interfering fields fall. The program has two principal parts: generation and measurement of fields, and measurement support for emissions and immunity testing. EMI measurements are complicated by several characteristics of interfering fields: wide dynamic range and complex spectral content, complex temporal character, and complex field patterns caused by close sources, multiple sources, and scattering.

To enable improved measurement support for resolving the problems of electromagnetic interference, CEEE has developed a plan for a new program. The key projects in that plan are shown in Table III.

Table III: New Program for Electromagnetic Compatibility Measurements

1. Standard Electromagnetic Field Generation
2. Sensor Technology
3. Device/System Emissions
4. Device/System Immunity

The new program would complement the work of the base program described in the following two sections.

Generation and Measurement of Fields

Standard fields are needed for developing and calibrating the probes that are used as transfer standards to maintain measurements of field strength for EMI measurements and other purposes. During the past year, the Division completed development of standard radiating dipoles and monopoles that will be used to evaluate emissions measurement facilities in commercial and DOD facilities. The Division continues its multi-year efforts to develop thermo-optic field probes and all-optical field probes. The thermo-optic probes are relatively insensitive but offer more uniform frequency response than traditional dipole/diode designs, and afford access to high frequencies (110 GHz). The Division continues also its multi-year effort to develop integrated optic probes. These probes are potentially capable of bringing the full electric and magnetic waveforms, phase information included, down to the measurement instrumentation. Thus they are capable of determining the direction as well as the magnitude of interfering fields.

The Division has a critical need for anechoic chambers with extended frequency coverage. The Division's present chamber covers 250 MHz to 40 GHz and thus does not extend downward far enough to reach the 50-100 MHz region in which interfering fields are particularly troublesome. Presently, the Division is limited to the use of an outdoor range for work below 250 MHz. A new chamber covering 30 MHz to 2 GHz is needed, followed by the modification of the present chamber, or a new chamber, to cover 2-110 GHz in order to extend the upper frequency limit as well. These chambers will be constructed if the resources required for the new program described above can be obtained.

Emissions and Immunity Metrology

For EMI emissions measurements, the Division is developing measurement approaches employing enclosed systems (TEM cells and shielded enclosures) and open systems (open-field sites). For immunity measurements, the Division is developing enclosed systems (reverberation chambers, shielded enclosures, and TEM cells), open systems (phased arrays that simulate far-field patterns at near-field distances), and time domain systems. Increasingly, the Division is stressing immunity tests applicable to whole systems, such as entire aircraft, and broadband techniques employing time-domain approaches for efficient testing. During the past year, the Division developed high frequency, broadband (1 kHz-1 GHz) antennas for time-domain EMI testing and prepared a handbook for their operation and maintenance. The Division also evaluated a scale model of a TEM/reverberating test chamber for susceptibility testing. Next, the Division will help the Army implement the test chamber at full size, suitable for whole-vehicle testing. The Division will also develop definitions and measurement techniques for the shielding effectiveness of cables and connectors.

ELECTROMAGNETIC TECHNOLOGY DIVISION: Lightwaves, Superconductors, Magnetics

The Electromagnetic Technology Division develops measurement capability for optical fiber communications systems, optical fiber sensors, lasers, superconductors, and magnetics. The Division also develops superconducting devices and standards for the measurement of electrical quantities. The Electromagnetic Technology Division employs 28% of CEEE's total resources.

Optical Fiber Communications

Optical fibers are the transmission medium of choice for emerging terrestrial communications systems. The 1989 world market for fibers and supporting components was $3.2 billion per year and is growing at about 25% per year. The U.S. accounts for $1.1 billion of this market. Growth of the U.S. market for fiber itself slowed recently as the construction of long-distance lines saturated but is already picking up again as local area networks mature. Growth of the international market will remain at a high level, due to the continued installation of long distance lines in other countries and to the emergence of undersea lines and local area networks.

International competition to supply the world market is intense. The Japanese are on a par with the U.S. in fiber technology and are ahead and gaining in the technology of other key components, such as sources and detectors. The Europeans are proving to be effective competitors, too. U.S. success in the world market will require products of high quality, high performance, and low cost, all highly measurement-dependent aims. The cost of measurement accounts for 20% of the cost of manufacturing optical fiber cable.

In response to the needs of U.S. industry, the Division has been developing measurement support for multimode and single-mode optical fibers for several years now. The Division has also developed a new program of measurement support for the key components and technologies in optical fiber systems. That new program has six projects focused on the topics described in Table IV.

Table IV: New Program for Optical Fiber Communications Measurements

1. Sources, Detectors, Waveguides
2. Modulators, Demodulators, Couplers
3. Hybrid and Integrated Optic Circuits, Materials Characterization
4. Multiplexing, Coherent Communications
5. Switches, Amplifiers
6. Long-Wavelength Fibers, System Performance

To date, Congress and the Administration have provided partial support for the first two of the six projects with funding of $1.95 million per year. NIST Competence funding for the past five years has helped the Division to get started in integrated optics by supporting the development of competence in optoelectronic structures with a special focus on waveguides.

In the area of optical fibers, the Division has contributed to 28 voluntary industry standards in collaboration with the Electronic Industries Association, the Society of Automotive Engineers, the Institute of Electrical and Electronics Engineers, and DOD's Calibration Coordination Group. During the past year, the Division completed a domestic round-robin measurement intercomparison for the geometrical properties of single mode optical fibers and will soon compare results with counterpart international groups. The early results already indicate the need for new supporting reference standards to improve control of fiber diameter for the low tolerances required by the next generation of low loss connectors. The Division also participated in an international intercomparison for optical fiber power measurements. Next, the Division will complete international comparisons for fiber geometry and power, will develop a new national standard for fiber geometry, and will complete work on a new photo-acoustic method for measuring absorption and scattering loss in optical fibers with sensitivities down to 10^{-5} dB.

For supporting components, the Division has developed in-house capability for fabricating high quality waveguides and several waveguide devices to support measurement development, has completed measurement methods for characterizing modulators to 2 GHz, and has developed theory for loss measurements in couplers. Among the upcoming projects will be completion of the development of measurement methods for the uniformity of response over the surface of a detector, and measurement methods for coupler losses, based on the theory just completed. The Division plans to install a chemical-beam epitaxy system in FY 1991.

<u>Optical Fiber Sensors</u>

The market for optical fiber sensors is growing. According to the most recent studies, that market is expected to reach about $1.2 billion per year by the year 2000. At that time fiber sensors will account for about 20% of all sensors, compared to about 5% now. The U.S. is expected to experience a gradually decreasing market share as intensifying foreign competition takes hold.

The Division has developed a plan for increased measurement support for optical fiber sensors used for electromagnetic quantities. The key elements of the planned new program are shown in Table V.

Table V: New Program for Optical Fiber Sensor Measurements

1. Measurement Methods: Polarization, Birefringence, Performance of Multiplexers 2. Reference Materials Data: Birefringence, Magneto-Optic and Electro-Optic Coefficients

During the past year, the Division identified an industrial partner for transfer of the Division's optical fiber sensor technology for electric current; and the Division reached tentative agreement on a cooperative research and development program with that partner. The Division also demonstrated the first current sensor based on the Sagnac interferometer, in cooperation with the Los Alamos National Laboratory. In the coming year, the Division will implement the research and development agreement and will investigate suitable materials for making very small magnetic field sensors with improved sensitivity.

<u>Lasers</u>

Lasers are surfacing in commercial products with world markets of billions of dollars per year. As they do, the U.S. is progressively losing market share in the world commercial market for lasers. In the five years from 1982 to 1987, the U.S. share of the world commercial market fell from 75% to 38%. Japan and Europe picked up the entire difference in roughly equal amounts. Similarly, the U.S. is losing market share in the world commercial market for laser optics. From 1984 to 1988, the U.S. share of that market dropped from 64% to 45%. Laser optics include components such as lenses and mirrors that are critical to laser performance. The intent of other nations is clear; both Japan and Europe have launched programs to advance their competitiveness in the laser technology required for commercial applications of lasers.

Lasers have demonstrated their capabilities in many commercial applications, including these: manufacturing, especially materials processing; research and development; medicine; communications; optical memories, including audio compact disk players, video players, and data storage devices; printing; test and measurement, including environmental sensing; inventory control using barcode scanners; and many other fields.

The world market for lasers and laser-based products exceeds $14 billion per year, and likely by a wide margin. Laser sales themselves are about $2 billion per year. Sales of just three laser-based products account for $12 billion per year: optical memories ($6.6 billion by Japan alone), laser printers ($3 billion), and barcode scanners ($2.5 billion). Sales levels for many other laser-based products are not known but are likely highly significant, especially for manufacturing equipment and medical equipment which consume high dollar volumes of lasers. Japan's ascendancy in the markets for laser-based products is evident. Japan supplies 90% of the world market for audio compact disk players and 85% of the market for low-end laser printers.

Assuring U.S. competitiveness in lasers and laser-based products for commercial applications will require the development of new lasers with new capabilities, higher performance levels, improved quality, and reduced cost. All of these aims are highly measurement dependent. The measurement support required exceeds the capabilities of NIST's present program of laser measurement support. In response, NIST has developed a plan for a new program. The projects within that plan are shown in Table VI.

Table VI: New Program for Laser Measurements

1. Laser Performance and Quality Measurements
2. Laser Optics Performance and Quality Measurements

The present program of the Division focuses principally on measurements of laser power and energy. With few exceptions, the Division does not have the resources to address beam quality measurements, and the Division does not address at all the development of measurements for the performance and quality of laser optics.

Much of the Division's present program is devoted to responding to industry's call for measurements with greater speed, sensitivity, dynamic range, and accuracy, and broader wavelength coverage.

For power and energy measurements, the Division has constructed and evaluated an improved calorimeter to support microwatt level measurements for the calibration of optical fiber power meters. The Division has also increased the ease of use of its broadband (0.4 to 15 micrometers) low level (1 nanojoule) bolometer standard for routine calibrations. Next, the Division will establish the microwatt calorimeter as a working standard for the calibration of optical fiber power meters; and the Division will incorporate the broadband bolometer standard into a low level laser measurement service as a working standard. The Division will also complete a 500 watt calorimeter as a working standard for 10.6 micrometers. NIST work of this type has reduced discrepancies in the measurement of laser power for selected critical wavelengths and levels by one to two orders of magnitude.

For waveshape measurements, the Division continues its multi-year effort to improve the resolution of measurements of optical waveforms by developing pulse sources with extremely short duration for use in all-optical samplers. Most recently, the Division has successfully observed soliton effects in fiber lasers. Next, the Division will pursue development of very short soliton laser pulses, with subpicosecond durations, that can be used to map out the shape of other fast optical waveforms through all-optical cross-correlation techniques. The Division continues its collaboration with Japan's Nippon Telegraph and Telephone Corporation on development of low cost but high performance methods for measuring repetitive optical waveforms using such all-optical cross-correlation techniques.

Superconductors

The phenomenon of superconductivity enables the fastest, most accurate, and most sensitive measurements possible for many quantities of interest; and it supports the highest current densities achievable in conducting materials. The recent discovery of high-temperature superconductors has intensified interest in these capabilities by reducing refrigeration costs and complexity. Already, the Japanese have predicted worldwide markets of $40 billion per year by the year 2000 for new superconductor products. Diverse applications are in the offing for instrumentation, sensors, computers, communications, medicine, transportation, power systems, manufacturing, and research. However, many practical problems remain to be solved before those applications can become a reality.

Market sizes for products made from low temperature superconductor wire are already significant. The largest is the $2 billion per year market for magnetic-resonance imaging systems, which employ low temperature superconductor magnets. A major upcoming project is the $4.4 billion Superconducting Super Collider, which will also use low temperature superconductor magnets.

NIST's opportunity to provide technical support for the commercialization of high temperature superconductors was greatly improved when Congress provided $2.8 million per year, beginning in FY 1988, for an NIST-wide program. In addition, NIST has developed a plan for a new NIST-wide program focused on high temperature superconductors. The major projects within that program are shown in Table VII.

Table VII: New Program for Superconductor Measurements

1. Measurement Methods for Electrical and Magnetic Characteristics
2. Composition and Structural Analysis
3. Data for Design and Control of Fabrication Processes
4. Development of Superconducting Devices for Measurement Systems

With its present resources, the Division is addressing four major areas: (1) improvements in in-house thin-film fabrication capability to support those applications, (2) application of low and high temperature superconductors to fundamental metrology, (3) development of superconductor measurement methods, and (4) determination of fundamental parameters of superconductors.

The Division is recovering from a fire which destroyed its superconductor clean room in FY 1989. Within two months the Division had established a functional temporary clean room. During this year, the construction of the clean room will be completed, and the rebuilt facility will be put into service. In the meantime, the Division has made major progress in establishing its capability for fabricating all-niobium Josephson junctions. These have greater stability than the lead/niobium junctions that the Division has relied upon to date.

In fundamental metrology, the Division has reestablished its ability to fabricate integrated-circuit voltage-standard chips after the clean room fire. The Division's integrated-circuit voltage-standard chips are now used at nineteen locations. The Division is now focusing on development of voltage standard chips that work at microwave frequencies as low as 10 GHz, compared to frequencies of 70-95 GHz used now. At the lower frequencies, microwave sources of higher power and lower cost are available. The Division is also developing a superconducting kinetic inductance bolometer in collaboration with the Electromagnetic Fields Division and the Radiometric Physics Division. The bolometer offers high sensitivity for microwave and infrared radiation measurements and may enable a factor of five improvement in the accuracy of microwave measurements made with the six-port system upon which NIST relies. The bolometer will next be tested to determine if its fundamental ac losses limit its usefulness. Thereafter, the bolometer will be evaluated in both microwave and infrared measurement equipment. The Division continues its fundamental theoretical and experimental research on superconducting quantized current steps to determine their metrological potential.

The Division is employing low temperature superconductors in diverse measurement applications. Most recently, the Division fabricated a counting analog-to-digital converter with extraordinarily low power dissipation and hopes to demonstrate its performance in the coming year; the device consumes a millionth of the power of a semiconductor converter. The Division has continued its efforts to reduce low frequency noise in superconducting quantum interference devices (SQUIDs), and will next examine the role of different SQUID geometries and different wire bonds in reducing noise.

For high temperature superconductors, the Division is focusing on the preparation of high quality films and the fabrication of Josephson junctions. During the past year, the Division demonstrated a high temperature superconductor bolometer and fabricated squeezable electron tunnel junctions to test approaches to junction formation suitable for yttrium-based and bismuth-based superconductors. The Division also completed a sputtering system for the yttrium-based films. During the coming year, the Division will implement laser ablation processes for depositing superconducting films and will develop patterning techniques which will not degrade the films.

The Division continues its efforts on standard measurement methods and engineering data for practical low temperature superconductor wire. During the past year, the Division selected and evaluated the material for a high critical current superconductor Research Material (4000 amperes) to complement the Division's earlier low current Standard Reference Material (<600 amperes). During the coming year, the Division will complete evaluation of the material and will prepare it and supporting documentation for distribution. The Division has also completed analyses that will allow determining the interfering effects of the self-fields of current leads on critical current measurements. The Division's involvement in critical current measurements retains its international character; in the coming year, the Division will collaborate with major Japanese laboratories to determine sources of errors in critical current and ac loss determinations under the international VAMAS organization (Versailles Agreement on Advanced Materials and Standards).

The Division continues to advance its understanding of a host of important factors that affect the performance or characterization of low temperature superconductors for large scale applications. Paramount among these are stress degradation of the critical current, flux creep, ac losses, and coupling effects among superconducting filaments. During the past year, the Division has made major contributions to the testing and characterization of cable under development for the Superconducting Super Collider. The Division also measured and compared the transverse stress effect in Nb_3Sn samples prepared by competing process technologies. In the coming year, the Division will determine the effectiveness of new calorimetric techniques for alternating current loss measurement. The Division's efforts on measurements of superconducting critical current, including stress degradation, are reflected in the planning and conductor procurement processes of organizations working in fusion energy, high energy physics, and medical imaging. The Division continues to contribute to the development of normal state high current conductors (hyperconductors) by providing both measurement support and phenomenological explanations of anomalous magnetoresistive effects.

In further support of high temperature superconductors, the Division has now developed low resistance contact techniques for the thallium-based and bismuth-based superconductors, to complement its earlier work on the yttrium-based superconductors. The Division has also established an improved criterion for determining the critical current in high temperature superconductors and is observing its adoption by a number of laboratories. Plans for new work on critical current include development of standards for measurement, conduct of a round robin to evaluate the reliability of measurement methods, and publication of a compendium on measurement problems and their solutions. The Division will also expand its program on the effects of grain boundary chemistry on critical current and magnetic susceptibility.

Magnetics

The worldwide magnetics industry encompasses diverse applications, such as magnetic recording, millimeter-wave materials, transformers, motors, generators, and nondestructive evaluation systems. While figures on total market size are lacking, even individual segments are known to be vast. For example, worldwide shipments of magnetic storage devices of all types have been estimated at $40 billion for 1987. Requirements for sophisticated magnetic measurements are on the rise as new high density magnetic recording systems emerge, employing perpendicular media, high coercivity materials, and magneto-optical techniques. Magnetic systems are the subject of intense international competition. DOC, in its 1985 study of disk drives, cited several factors as essential to U.S. competitiveness; three are highly measurement dependent: reduced price, increased quality, and increased performance.

The Division has developed a plan for a new program of measurement support for the magnetics industry. The major projects within that plan are shown in Table VIII.

Table VIII: New Program for Magnetic Measurements

1. High Density Information Storage
2. Magnetic Sensing
3. Advanced Magnets

During the past year, the Division completed experimental work aimed at defining an effective demagnetization factor for agglomerations of magnetic particles, applicable to the magnetic recording industry and other industries making products from magnetic particles. The Division has also developed a set of 50 precision coils for use in establishing optimal designs for eddy current sensing and for evaluating eddy current techniques as a means of detecting various types of defects. Next, the Division will develop a magnetic force microscope based on its new scanning tunneling microscope. The magnetic force microscope offers high resolution for magnetic domains at a greatly reduced cost compared to other techniques. The microscope will be used to study domain structures in thin-film media important to the magnetic recording industry. The microscope is part of the Division's effort to develop further its competence in magnetic thin films and its understanding of key measurement problems arising in the application of thin films to magnetic storage media and magnetic recording heads.

SEMICONDUCTOR ELECTRONICS DIVISION

The Semiconductor Electronics Division develops measurement capabilities that support the characterization and understanding of semiconductor materials, the development and evaluation of fabrication processes, and the design and evaluation of semiconductor devices. The Semiconductor Electronics Division employs 18% of CEEE's total resources.

Electronics is a top-priority industry in every industrial and emerging nation in the world. Electronic components are integral parts of systems for defense, communications, transportation, medical care, banking, manufacturing, etc. Electronics is the largest manufacturing segment of the U.S. economy, amounting to some $248 billion in 1988 and growing at 11 percent annually. It employs 2 million people. Electronic systems rely heavily on semiconductor devices.

The world market for semiconductor devices is $50 billion. The world market for semiconductor manufacturing equipment is $8 billion. U.S. production of semiconductor devices was $22 billion in 1988 and is presently growing at 25 percent annually. U.S. production of semiconductor manufacturing equipment was $4.6 billion in 1988.

Despite high levels of domestic production, U.S. industry has lost international leadership in sales of semiconductor products; and the situation is worsening. Japan continues to be our major competitor. Japan and the U.S. produced the same amount of semiconductor devices in 1988, about 45 percent of the world market each. But over the past five years, Japan has gained 10 percentage points of the world market at U.S. expense. Similarly, U.S. suppliers of semiconductor manufacturing equipment have watched Japan's share of that market rise 7 percentage points from 24 percent in 1983 to 31 percent in 1988. Fortunately, in 1988 the U.S. still held a 57-percent share of the world market.

The loss of U.S. leadership is reflected most clearly in the production of starting materials for the manufacture of semiconductor products and in the development and implementation of integrated-circuit manufacturing equipment and processes. For example, few U.S.-owned suppliers of the silicon used in integrated-circuit manufacture have survived.

U.S. industry has responded to the challenge through the Semiconductor Industries Association (SIA) by creating two organizations designed to promote U.S. collaboration: the Semiconductor Research Corporation (SRC) and SEMATECH. SRC funds universities to support student training and to conduct research on advanced designs, manufacturing processes, and microstructures for silicon integrated circuits. SRC is operating on a budget of $37 million per year. The funding comes from industrial members ($25 million), Government members ($2 million), and SEMATECH ($10 million). The second organization, SEMATECH, is a semiconductor manufacturing technology center. SEMATECH's goal is to develop generic silicon integrated-circuit manufacturing technology for use by member companies. A key step is the restoration of the viability of U.S. manufacturers of the equipment used in semiconductor manufacturing. SEMATECH will spend $250 million per year for a minimum of five years. The funding will come from several sources: 14 member companies ($125 million per year), DOD ($100 million year), and the State of Texas.

CEEE has a major role to play in assisting these organizations in restoring U.S. leadership because the technological advances that they must pursue are highly measurement intensive. However, CEEE possesses only a part of the financial resources and technical skills required to provide the needed measurement support. Some of the required skills are available from other parts of NIST. To obtain additional funding, CEEE is pursuing three routes. First, NIST is receiving some funding from SEMATECH for work on linewidth measurements, the chemistry and physics of plasma processes, and test structures. About one-third of this funding comes to the Semiconductor Electronics Division and most of the balance falls outside CEEE. Second, CEEE has successfully formed a small Monolithic Microwave Integrated-Circuit Consortium with DOD and some of its contractors for funding measurement development for microwave circuits. Third, CEEE has developed the first phase of a new program plan for additional measurement support. The projects in that new program are shown in Table IX.

Table IX: New Program for Semiconductor Measurements

1. Submicrometer Dimensional Metrology
2. Etching and Deposition Process Measurements, Data, and Models
3. Metrology for Advanced Semiconductor Manufacturing
4. Metrology for Advanced Semiconductor Packaging
5. Metrology for Advanced Semiconductor Materials and Structures
6. Standards for Moisture and Particulates in Process Gases
7. Metrology for Advanced Semiconductor Devices
8. Surface Science for Semiconductor Manufacturing
9. Ultratrace Bulk Analysis for Advanced Semiconductor Devices

In the meantime, the Semiconductor Electronics Division continues to apply its present resources to key measurement problems in selected areas. The Division's directions are guided by industry trends. The most important of these is the push to smaller dimensions and greater numbers of devices in integrated circuits. The reality of the VLSI era, with 1-2 micrometer feature sizes and 10^6 transistors per chip, is giving way to the more ambitious goals of the ULSI era, with about 0.25 micrometers feature sizes and 10^7 transistors per chip. Both VLSI and ULSI circuits are so complicated that they cannot be meaningfully tested after manufacture. Even if such tests could be made, they would be of little value in correcting the manufacturing problems that cause defects. Rather, testing must be applied to manufacturing processes themselves to assure that the integrated circuits they produce are of good quality. The industry refers to this practice as "qualifying processes" rather than "qualifying devices". To qualify processes, both the quality of starting materials and the performance of individual process steps must be verified.

Not surprisingly, the Division has invested the bulk of its resources in pursuit of these two aims. For materials measurements, the Division is determining the quality of starting and preprocessed silicon and compound semiconductor materials; the Division does not have the resources to address measurements of the quality of liquid and gaseous materials. For manufacturing processes, the Division is addressing measurements made on fabricated structures; the Division does not have the resources needed to address measurements of the processing environment itself. The Division also develops measurements to support the design and evaluation of integrated circuits and discrete semiconductor devices.

The Division is especially interested in the development of nondestructive measurement methods, such as optical methods, for characterizing both materials and processing steps (e.g., determining defects and film thickness). Contacting and destructive measurement methods can produce additional unique information. They are often important for comparison with nondestructive methods. Much of the Division's work is focused on the characterization of thin layers, multiple layers, and oxide/semiconductor interfaces. Both silicon and compound semiconductor materials are addressed. For process-related measurements, the Division stresses the use of test structures and expert systems for interpreting the data from the test structures.

The sophistication and scope of the measurement techniques that the Division must develop are increased by several factors. The Division must address: both silicon and compound semiconductors; very high levels of materials purity; very small geometries; sophisticated fabrication technologies like epitaxy, implantation, and SIMOX (separation by implanted oxygen) silicon-on-insulator technologies; complex structures like emerging three-dimensional devices with multiple layers of transistors; and mixed-technology devices such as BIMOS (bipolar/metal-oxide-semiconductor) devices. The broad capabilities required often exceed those available in CEEE. Thus the new program mentioned above is designed as a NIST-wide effort. Both current and near-term projects require participation by other parts of NIST for topics such as linewidth measurements, plasma processing, and packaging.

The following sections describe work representative of the Division's efforts in materials, manufacturing processes, and devices.

Materials

Special measurement methods with high accuracy are required for characterizing the properties of semiconductor materials. Important properties include the levels of dopants, defects, and impurities, and the nature of structural imperfections. Many of these measurement methods also support process development and control.

The Division continues to improve the determination of dopant density in silicon wafers by resistivity measurements. Most recently, the Division demonstrated two-dimensional mapping of resistivity striations and resolved variations as small as 40 micrometers using high density four-probe structures. The Division also continues to support the identification of common impurities in silicon. The Division played a central role in establishing the relationship between infrared absorption and absolute measurements of oxygen in silicon, based on an international round-robin measurement intercomparison, and recently saw adoption of the findings by the ASTM, the Deutsches Institut für Normung (DIN), the Japan Electronics Industry Development Association (JEIDA), and the standards body of the People's Republic of China. In upcoming work, the Division will certify 100 sets of oxygen-in-silicon and carbon-in-silicon SRMs. The Division is also developing measurement support for silicon carbide (SiC) materials which offer high operating temperatures of 650° F. The Division has completed an extensive study of SiC metal-insulator-semiconductor (MIS) capacitor fabrication and will follow with the publication of a summary paper on the fabrication and characterization of SiC MIS structures. This work is important in helping to determine the operating properties of emerging MOSFETs fabricated with SiC.

The Division continues its support of measurement of thin oxide films. During the past year, the Division certified for sale about 120 SRMs for measurement of film thickness using ellipsometry. Industrial demand for these has been so high that about 150 additional copies will be certified in the coming year. The Division also applied ellipsometry to high accuracy measurements of thin thermal oxides, in preparation for anticipated future requirements for SRMs for even thinner oxides, already requested by industry. Next, the Division will upgrade its ellipsometric capabilities by constructing a spectroscopic ellipsometer that will allow for better measurement support and optical characterization of artificially structured materials, such as those produced with molecular beam epitaxy (MBE). This effort contributes to the Division's long term goal of establishing the capabilities of ellipsometry as a tool for process development and possibly for in-line process control.

The Division continues its efforts to develop powerful measurement tools for structural characterization, supported in part by NIST Competence funding. During the past year, the Division began operation of an X-ray beam line at the Brookhaven synchrotron. The line provides high intensity tunable output. The new X-ray capability, coupled with an upgraded Raman scattering capability at NIST, will be applied to many projects. An example is the development of data to provide the basis for a complete and accurate model of the crystal structure, chemical bonding, and lattice dynamics of strained silicon/germanium alloys. The difference in the energy gap of silicon/germanium alloys, relative to pure silicon, permits the fabrication of heterojunction bipolar transistors which are compatible with silicon-based processing technology and show great promise for high-speed digital and microwave applications; operation at frequencies above 30 GHz has already been demonstrated. The Division has also constructed an optical reflectometer. Reflectometer results have been compared with transmission electron microscopy to demonstrate the effectiveness of the more accessible reflectometer technique for monitoring the progress of annealing in the embedded silicon dioxide (SiO_2) layer of SIMOX. The embedded layer is created by ion implantation, below the top layer of silicon on which devices will be built. It provides improved electrical isolation between those devices in dense VLSI and ULSI circuits. SIMOX structures also show high resistance to degradation of performance from radiation and have other favorable properties.

The Division is providing measurement support for semiconductor photodiodes for accurate measurement of light levels and for charge-coupled devices for sensing images, including those in television cameras. During the past year, the Division developed an "almost completely analytical" model for the performance of photodiodes under specific conditions. The model enables examination of tradeoffs in the design of photodiodes, such as quantum efficiency versus noise, and prediction of the performance of existing photodiodes in specific applications. The model will next be used to verify the accuracy of a sophisticated numeric model for solar cells, augmented with NIST software to extend its applicability to photodiodes. If proven accurate for photodiodes, it will accommodate a wider range of conditions than the "almost completely analytical" model. The Division is also developing an infrared source capable of testing charge-coupled devices with the high performance required to resolve low-contrast images.

Manufacturing Processes

The Division continues to develop its own capability for fabricating sophisticated integrated-circuit structures to support its measurement research and to provide measurement support for process control in industry.

This past year, the Division installed its molecular beam epitaxy (MBE) system for fabrication of III-V compound semiconductor structures for measurement research. In support of effective use of the MBE, the Division determined the optimum flux ratio of arsenic to gallium and/or aluminum and the substrate temperatures for growth of gallium arsenide (GaAs), aluminum gallium arsenide (AlGaAs), and their superlattices. Next, the Division will grow AlGaAs/GaAs structures for high electron mobility transistors (HEMTs) and for studies of the quantum confinement effect. The Division will also fabricate structures for the quantized Hall-effect program and ac-dc thermal converter program, both conducted in the Electricity Division.

The Division launched an ion implantation project this past year with emphasis on developing a theoretical understanding of dopant and damage profiles and on correlating those profiles with optical and transport properties. During this past year, the Division collected, updated, and then verified models for calculation and analysis of data taken with electrical profiling techniques. The Division also calculated one-dimensional data for implantation in multiple-layer structures formed of AlGaAs/InGaAs/AlGaAs using a model adapted from implantation in multiple-layer structures formed of silicon or III-V materials. Next, the Division will calculate two-dimensional data capable of coping with the effects of masks on implantation patterns when implanting silicon and III-V compound semiconductor targets. The Division will also initiate work on a model that addresses the interlayer mixing that occurs at the elevated temperatures at which MBE is conducted and which blurs the desirable sharp boundaries required for multiple quantum well structures.

The Division is developing its capabilities for fabrication of SIMOX structures. This past year, it developed a process for fabricating both n-channel and p-channel transistors in SIMOX material. The Division explored the implantation and annealing parameters necessary for precipitate-free and defect-free material, established the real distinction between annealing in nitrogen versus argon, and proposed a mechanism to explain that difference. The Division also developed a complementary MOS (CMOS) on SIMOX process. The Division next plans to fabricate newly designed test structures in SIMOX wafers that will enable evaluation of the material. The Division will document and disseminate those test structures in the near future.

The Division has also developed the fabrication capability required to make the thermal image resolution patterns required for the low-contrast charge-coupled device testing described above. During the coming year, the Division will develop a suitable process for the fabrication of thin-film ac-dc thermal converters on silicon, discussed further in the section devoted to the Electricity Division.

The Division continues to develop integrated-circuit test structures as a major tool for verifying the performance of fabrication processes and the reliability of circuit elements.

For fabrication processes, the Division is focusing on the analysis of test-structure data using machine learning algorithms and expert systems analyses. The algorithms digest historical data on fabrication processes to derive rules for use in expert systems. The expert systems provide real-time diagnosis of difficulties arising during subsequent processing and generate prioritized lists of candidate corrective actions. During the past year, the Division arranged for additional industrial collaborators to assist in developing and evaluating machine-learning algorithms based on manufacturing data. The Division is focusing especially on the problem of classifying test-structure data in a way that supports expert system analyses. The Division has also evaluated neural networks for classifying data. Neural networks, in this application, are a machine-learning approach to finding the generic set of factors. Those factors are the ones most relevant to evaluation of semiconductor manufacturing processes. Neural networks must find those factors based on imperfect data from the manufacturing floor. In upcoming work, the Division will extract test-structure results from the database of an industrial collaborator and will explore and compare alternative machine-learning techniques for classifying such data. Overall, the Division's efforts in this field resulted in approximately fifty requests for test structure and expert systems reports during the past year.

For reliability determination, the Division is focusing on electromigration degradation. During the past year, the Division discovered a new measurement interference (source of error) for highly accelerated electromigration stress tests. Next, the Division will complete an interlaboratory comparison to establish the bias and reproducibility of an electromigration test method, developed by NIST and adopted as a standard by the ASTM (formerly the American Society for Testing and Materials, now using its initials only). The Division will also present a paper that demonstrates for the first time that the ratio of electromigration damage caused by a pulsed current relative to the damage caused by a steady current is dependent on current density, contrary to present thinking in the industry. The results of the Division's work on electromigration are finding increasing use by industry. In related work bearing on thermal processes that can accelerate electromigration, the Division has reported the first-ever thermal conductivity measurements for thin films of silicon dioxide and has designed a test chip for use in optimizing the measurement procedure. These are critical steps toward a proper characterization of thin-film oxides essential both for the design and interpretation of accelerated stress tests for integrated circuits, and for the design of three-dimensional integrated circuits. In both cases, the integrated circuits experience considerable heating.

Devices

The Division is developing models and measurements to support devices in integrated circuits and power transistors and to improve the reliability of the packages and associated electrical interconnections of semiconductor devices.

For devices in integrated circuits, the Division is conducting theoretical studies of the quantized electron states in silicon and compound semiconductors, with assistance from NIST Competence funding, to understand device performance better. Key tasks include developing measurements for the effects of defects and impurities, and examining radiation and hot carrier effects. The goal is to provide measurement methods and data needed for understanding and designing the devices in integrated circuits. During the past year, the Division calculated the bandgap narrowing that results from high-level injection in silicon and gallium arsenide devices. The Division also demonstrated the use of photo-induced transient spectroscopy (PITS) for characterizing deep levels in SIMOX wafers. Next, the Division will complete the study of PITS and will improve its facility for deep-level transient spectroscopy (DLTS) to enable measurement of deep levels in III-V MBE layers and correlation with growth parameters. The Division will also calculate the majority and minority electron and hole mobilities in gallium arsenide.

For power transistors, the Division is continuing to provide measurement support for device operation and specification. A key aim is to provide measurements that can nondestructively determine the safe operating conditions of new types of power transistors, including those based on mixed technologies. During the past year, the Division completed a nondestructive test system for determining the limits of failure for bipolar, MOS field-effect transistors (MOSFETs), and insulated-gate bipolar transistors (IGBTs). The IGBTs offer the high current capacity of bipolar power transistors with the minimal control current of MOS devices. The new test system offers twice the voltage level and three times the current level of the previous system plus a productivity increase of a factor of 6 to 10 through use of automated techniques. The Division also developed a test procedure for the safe operating area of MOSFETs. This test procedure is based on the recommendations of the Electronic Industries Association's Joint Electron Devices Engineering Council (EIA/JEDEC) for a test based on current and temperature, rather than on energy, as the cause of failure. During the coming year, the Division will evaluate fully the capabilities and limitations of an IGBT model that it has been developing. The Division will also initiate tests for thermal characteristics of GaAs microwave integrated circuits for the Monolithic Microwave Integrated-Circuit Consortium described in the section on the Electromagnetic Fields Division. The Division's testing capability, technical findings, and test system designs for power devices continue to be sought by industry and Government agencies (e.g., NASA for the space shuttle and space telescope, and DOD for Navy systems).

For packaging, the Division is focusing principally on wire bond reliability. Recent and new courses in the subject have been offered by the Division and are drawing about 100 attendees each. A monograph on wire bond reliability and yield has been completed and has been published. It received many prepublication orders, up to one hundred copies for an individual manufacturer.

ELECTRICITY DIVISION: Basic Standards, Conducted Signals, and Energy

The Electricity Division provides measurement support for systems that transfer signals and energy in conducted form. The Division employs 21% of CEEE's total resources. During the past year, this Division was created by merging CEEE's former Electrosystems Division with the Electricity Division from the National Measurement Laboratory of NIST. The new Division supports both basic and derived electrical units.

The measurements developed by the Division support key U.S. industries, including major portions of the electronic test equipment industry and all of the electrical power industry. The U.S. electronic test equipment industry, with sales of about $7 billion per year, supports the development and manufacture of most of the nation's $248 billion per year of electronic products and many other products as well. The Division's measurement capability supports accurate metering of the nation's entire electrical energy output of $166 billion per year and the evaluation of billions of dollars of new power system equipment each year.

The Division's work is driven by changing and intensifying industrial requirements for (1) greater accuracy over wider ranges of parameters, (2) measurement of arbitrary and pulsed waveforms, not just sinusoidal waveforms, and (3) automation to reduce calibration costs and to support new multi-range industrial systems, particularly automatic test equipment. In response, the Division is developing measurement approaches that have high intrinsic accuracy or that can improve the accuracy that is transferred by shortening the chain of calibration steps. The Division is emphasizing measurement capability that can address both arbitrary waveforms and sinusoidal waveforms with anomalous high frequency components. The Division is focusing increasingly on automated methods of measurement support. To accomplish these aims, the Division is employing powerful digital synthesis and sampling techniques, optical measurement techniques for electrical quantities and dielectric properties, and sophisticated theoretical analyses and modeling.

The following sections describe representative work in each of the areas in which the Division is active.

Fundamental Electrical Quantities and Their Dissemination

At the most fundamental level, the Division maintains the U.S. legal dc ampere, dc volt, farad, and ohm, and measures them in terms of their SI counterparts (International System of Units). Included in this work are the determinations of the values of important constants, especially the gyromagnetic ratio of the proton, the fine-structure constant, and ratios involving the electronic charge and Planck's constant that appear in the mathematical relationships used to determine electrical units. The Division has performed the most accurate realizations of the farad and the ohm values in the world, is an order of magnitude more accurate than the rest of the world for the determination of the gyromagnetic ratio of the proton, and is among the top three in the world for the determination of the absolute ampere. Further, the Division's laboratory is the only one in the world that conducts five related experiments for the determination of electrical units with less than 1 ppm uncertainty (gyromagnetic ratio of the proton, quantized Hall resistance, absolute ohm, absolute farad, and absolute ampere). Thus the Division has the world's best capability for intercomparison and, hence, for assessing potential measurement errors and theoretical anomalies.

During the past year, the Division improved its ability to measure resistances in terms of the quantum Hall effect (QHE). This improvement was accomplished by raising the magnetic field (15.5 tesla) and decreasing the temperature (250 mK) achievable in its quantum Hall apparatus, thus creating flatter quantized resistance steps. The Division also documented and modeled the voltage quantization in the breakdown of the QHE, manifest in instabilities in voltage steps when current levels are too high; further study of the physics of breakdown will follow to better our understanding of this complex phenomenon. The QHE apparatus is NIST's primary standard for resistance. To support this effort, the Division will develop improved QHE test samples in its own laboratory and in collaboration with the Semiconductor Electronics Division and other laboratories worldwide. In related work, improved resistor designs, based on modern materials science, will be evaluated with the QHE apparatus to provide working standards that are more stable than those presently available. Also, a recently completed determination of the SI ohm is to be followed by a new measurement of the farad and subsequent redetermination of the quantized Hall resistance.

During the coming year, an improved determination of the ampere will be made from electromotive force measurements to achieve an uncertainty of 0.01 ppm. A step toward this goal has just been completed with the installation of a superconducting magnet needed to provide the very high forces and high stability required. If successful, this achievement will open the possibility of monitoring the kilogram in terms of electrical units, and perhaps replacing the platinum-iridium mass artifact in Paris with a unit based on fundamental constants. Physical artifacts are subject to change and are vulnerable to destruction. The Division has also tested its measurement system for the gyromagnetic ratio of the proton to determine systematic errors and has uncovered no new error sources. During the coming year, the discrepancy between the absolute ohm experiment and the experiment on the gyromagnetic ratio of the proton will be analyzed.

Division accomplishments in these and related areas led the International Consultative Committee on Electricity to base its recent readjustments of the electrical units very heavily on NIST measurements. The Division, in collaboration with the National Conference of Standards Laboratories, developed and provided guidelines to industry for implementing the adjustments, which were effective worldwide on January 1, 1990. About 7000 copies of the guidelines have been distributed, and more than 400 individuals have been briefed on the changes. The recipients represent virtually all of the nation's high technology companies. Affected are sophisticated electrical measurement instruments involved in research, development, manufacturing, and marketplace exchange for high technology products.

The Division provided 2502 calibrations during the past year for impedance, resistance, and voltage in the low frequency range that is its responsibility (generally below 1 MHz). An increased workload is anticipated in response to the international adjustment in electrical units. To support a high calibration workload and to improve its measurement services, the Division is upgrading equipment, automating systems, and extending the upper frequency ranges of some services. The Division is now using a new bridge for calibration of standard inductors and will soon employ a new automated bridge for some capacitance measurements.

The Division has also completed a new automated system for calibration of standards in the 1000 ohm to 1 megohm range with higher accuracy and efficiency. A totally automated 10-volt system based on the Josephson effect has been developed and compared to the present one-volt system and found equivalent within ±0.1 nanovolts. Next, a fully automated system, for calibrating the 0.1, 1, and 10 dc voltage ranges of digital voltmeters, based on the 10-volt Josephson array, will soon be completed.

The Division has reduced the uncertainties in its multirange ac-dc thermal converters by a factor of two and has made major improvements in the accuracy of its high-frequency converter standards. Techniques for the design and fabrication of thin-film multijunction thermal converters are under development. If successful, this effort will result in new standards superior in frequency response to those now commonly in use and which can be mass produced. In comparison, present standards are handmade in a process far closer to art than science. The Division will also complete a protocol for a Measurement Assurance Program (MAP) for thermal voltage converters and begin a pilot MAP for thermal current converters.

Synthesis and Measurement of Electrical Waveforms

The Division is developing digital synthesis and sampling techniques for generating and measuring sinusoidal and arbitrary periodic waveforms with millivolt to kilovolt levels from dc to 30 MHz. During the past year, the Division extended the capability of its calculable digitally synthesized source (DSS) of "stepped" sinusoidal ac voltage from 8 kHz out to 50 kHz with an uncertainty of ±25 ppm at 7 volts. During the coming year the voltage range will be extended downward to 1 millivolt, and the instrument will be used to verify and enhance the NIST ac voltage calibration services. The DSS provides access to much lower levels than thermal voltage converters which are limited to about 250 millivolts, yet the DSS provides accuracy comparable to the converters. The DSS has already been used successfully as a transportable standard by industry and Government agencies to enable the evaluation of precision ac instrumentation; the DSS is the only instrument capable of performing at its level of accuracy. The Division has also completed the development of a precision transconductance amplifier that enables translating precise voltages into precise currents. It will support new ac current calibration systems.

The Division continues to advance its capabilities for the precision digital synthesis of waveforms for the measurement of power. During the past year, the Division participated in a mutually beneficial international intercomparison of power measurements at frequencies out to 5 kHz. The comparison enabled calibration of a special high frequency wattmeter, circulated by NRC-Canada. The comparison also enabled the Division to discover an error source in its audio-frequency power bridge, which has much higher frequency capability than those in other international standards labs (20 kHz versus typically 1 kHz). The errors are understood and will be eliminated during the coming year. The Division is also developing an high resolution sampling waveform measurement capability, based on a commercial 16-bit instrument, that will enable evaluation of the power bridge to 20 kHz and other measurement systems to 200 kHz. The long-range goal of this effort is to provide routine calibration support from 50 Hz to 10 kHz with uncertainties as low as 10 ppm for tests at power frequencies and with uncertainties no higher than 1 percent for special tests on waveforms with frequency content up to 200 kHz.

The Division is improving its ability to measure voltage and current at high levels with high accuracy and convenience. As part of this process, the Division has developed a second power and energy calibration system that complements the capabilities of its earlier system (240 volts, 5 amperes) with higher levels of output (700 volts, 100 amperes). The Division will also continue to explore optical methods of current measurement through modeling and investigation of possible measurement approaches in collaboration with the Electromagnetic Technology Division.

The Division continues its work on the development of measurement support for data converters and waveform recorders, with an emphasis on a precision sampling voltage tracker (SVT) for measurement of the rms voltage of repetitive arbitrary waveforms. The instrument has already demonstrated performance over the range 1-200 MHz with uncertainties comparable to those of thermal voltage converters but with much wider dynamic range (15 mV-1 V rms). The performance of the SVT is limited by its commercial analog comparator. The Division is modeling the comparator and will create a new design based on that model in the coming year. If this effort is successful, an IC manufacturer will be sought to implement the design at an accessible cost. A lower frequency version of the SVT system operating over the range 100 Hz to 1 MHz with a target uncertainty of 10 ppm will follow.

Complex Electronic Systems

The Division continues its work on strategies for identifying the minimum number of tests required to assure the performance of complex electronic systems that would otherwise be too complicated to test in a cost-effective manner. The work requires developing mathematical models, formulating test algorithms, and selecting key test points. The Division's efforts are motivated both by industrial needs and by its own need for methods of maintaining its complex calibration systems.

During the past year, the Division completed a study on the limitations of linear modeling and developed a capability for modeling second order sensitivities of linear and nonlinear circuits in the time domain. The Division also developed and evaluated an efficient test strategy for a 13-bit switched-capacitor analog-to-digital converter. It successfully predicted the linearity errors of all 8192 codes with measurements made at only 64 codes and with accuracies comparable to those achieved by testing all codes. Next, the Division will begin development of the basis for test strategies using adaptive, empirical modeling, and robust estimation. The Division will also continue its collaborative efforts with industry on empirically-based strategies for testing analog-to-digital converters. When fully developed, the Division's methodology will further production line testing for multiple purposes, including: assuring proper functional performance; trimming or adjusting devices; or, with extensions, diagnosing soft faults (those short of complete component failure). The Division is focusing principally on analog circuit elements since they are the critical front end of most measurement systems. Extension to combined analog/digital circuits will follow in future years.

Pulse Power Measurements

The Division continues its development of measurement methods for pulse power electrical quantities in support of fusion research, space power sources, nuclear weapons simulations, lightning mitigation, and other applications.

The primary focus is on pulses with durations of one millisecond to one nanosecond, voltages above ten kilovolts, and currents greater than ten kiloamperes. During the past year, the Division developed a new approach to the evaluation of the step response parameters of pulse power systems. The Division also expanded its previous assessment of the measurement needs of space power systems. During the coming year, the Division will provide guidance on proper techniques for measurement of high voltage impulses used in lightning simulation, and it will evaluate high voltage impulse dividers for use as transportable standards in support of a proposed revised international standard on high voltage measurements.

Power Quality Measurements

Power quality issues are complicating both proper use of electricity and its accurate measurement. The Division has embarked on a small program focused both on developing measurement techniques for characterizing the quality of ac power, and on improving mitigation techniques with emphasis on surge protection. During the past year, the Division instituted a power quality program at NIST itself, complete with monitoring instruments. The Division also demonstrated techniques for detecting incipient defects in power cables based on pulses from partial discharges. In upcoming work, the Division will emphasize measurements to determine the reliability of metal-oxide varistors subjected to repeated overvoltages. A major effort will be made to catalyze industry views on the surge environment and on effective approaches to mitigation.

Electric Fields and Ions

The Division continues to develop measurement methods for ac and dc electric and magnetic fields and for ions near dc transmission lines. In general, dc lines are more economical than ac lines for transmission over distances greater than 400 miles, due to the reduction of reactive effects. Earlier work on ac electric and magnetic fields has led to national and international standards for measurement. These efforts support meaningful study of the bioeffects of power lines by the nation's researchers in government and industry.

During the past year, the Division worked with the Institute for Electrical and Electronics Engineers in developing a new draft IEEE standard for measuring dc electric fields and ion-related parameters near dc power lines. The Division also completed a manuscript describing the optimum experimental configurations for studies of the biological effects of power-frequency ac magnetic fields. Next, the Division will continue its work with the IEEE on the dc standards, and it will prepare guidance on the measurement of power-frequency ac magnetic fields in residential and occupational environments.

Dielectric Materials

The Division continues to develop data, models, and measurement techniques that enable improvements in the development and safe use of liquid and gaseous dielectrics for electrical insulation. Insulating materials are being placed under increasing electrical stresses as the demand for the delivery of more power in existing rights-of-way leads to the use of higher voltages in transmission systems.

As part of its support of measurement for liquid insulation, the Division has compared electro-optic and resistive divider methods for measuring voltage impulses. The Division has also completed studies of the effects of pressure on partial discharges in n-hexane, which serves as an idealized medium for study and which is also a component in some insulating materials. Next, the Division will extend its work on n-hexane to include study of the growth and initiation of partial discharges. The Division will also develop instrumentation and experimental methods for detecting the light emitted just before and during partial discharges to determine its value in the study of breakdown in insulating liquids. The overall goal is to provide fundamental materials data and measurement methods that can be used to determine what can and cannot be done to improve liquid insulation.

To support the study of gaseous insulation, the Division continues to provide data and models that describe the physical chemistry of the formation of degradation products in sulfur hexafluoride (SF_6) insulation. The high dielectric strength of sulfur hexafluoride enables downsizing power lines and power system components in substations where space is at a premium, but sulfur hexafluoride's degradation products can be corrosive and toxic, motivating much of the Division's recent work. During the past year, the Division measured the production rate of S_2F_{10}, a toxic breakdown product, using a new chromatographic technique and correlated the results with theoretical predictions. The Division took the first steps needed to develop a consortium for further investigation of the S_2F_{10} problem. The Division also applied for a patent on its new method for measuring the stochastic behavior of pulsating partial-discharge phenomena. In the coming year, the Division will extend its work on S_2F_{10} production and will prepare a review of the rates of fundamental gas-phase reactions that are needed in developing plasma-chemical models for SF_6; the results will be compared with the prediction of models. The Division's work supports studies of insulation failure and also use of pulsed discharges for starting high-power arc lamps and other applications. The work also provides a technical basis for future NIST efforts supporting chemical diagnostics and controls for plasma processing of electronic circuits.

Automated Electronic Manufacturing

Neutral "product data exchange specifications" are needed to simplify the design, manufacture, documentation, procurement, and support of modern electronic components and systems. A national effort to develop such specifications is underway; that effort extends to structural as well as electronic systems. To further development of the electronic specifications, the Division has organized a forum to bring together interested participants and will next sponsor workshops. The Division will define more clearly NIST's role in this process and will plan, with NIST's Center for Manufacturing Engineering, the development of an Electronic Manufacturing Research Facility as a test-bed for future electronic manufacturing concepts.

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This report describes the work of the Center for Electronics and Electrical Engineering (CEEE) at the National Institute of Standards and Technology. The report focuses on selected projects of measurement development that CEEE is addressing during fiscal year 1990. The report indicates the directions that these projects will take in the next few years. The report also describes selected accomplishments during fiscal year 1989. Because of the size and scope of CEEE's work, only representative projects and accomplishments can be covered in a document of this length.

The fields covered by this report are microwaves, electromagnetic compatibility, optical fiber communications, optical fiber sensors, lasers, superconductors, magnetics, semiconductors, fundamental and derived electrical quantities, complex electronic systems, electric power, and automated electronic manufacturing.

This report outlines new programs of measurement development that CEEE has defined for future years in eight of the above fields: microwaves, electromagnetic compatibility, optical fiber communications, optical fiber sensors, lasers, superconductors, magnetics, and semiconductors.

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