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# Emerging Technologies in Electronics ... and their measurement needs

Prepared by the Managers and Staff of the
Center for Electronics and Electrical Engineering

U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
National Engineering Laboratory
Center for Electronics and Electrical Engineering
Gaithersburg, MD 20899

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National Bureau of Standards became the
National Institute of Standards and Technology
on August 23, 1988, when the Omnibus Trade and
Competitiveness Act was signed. NIST retains
all NBS functions. Its new programs will encourage
improved use of technology by U.S. industry.

U.S. DEPARTMENT OF COMMERCE
**Robert Mosbacher, Secretary**
**Ernest Ambler, Acting Under Secretary for Technology**
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
**Raymond G. Kammer, Acting Director**

EMERGING TECHNOLOGIES IN ELECTRONICS

## Foreword

This NIST Internal Report has been prepared by the Center for Electronics and Electrical Engineering (CEEE) within NIST. The report identifies emerging technologies in electronics that CEEE believes will require increased measurement support from CEEE in coming years. The emerging technologies described here are new to the marketplace or are experiencing major technological advances.

This report is an internal planning document. The document is designed to stimulate feedback that CEEE needs to refine its plans for developing measurement capability to support emerging electronic technologies that are important to the national interest. Note that the plans that are associated with "future initiatives" in this document are clearly labeled. They are proposals developed by CEEE. They have not been officially approved by NIST Management or DOC Management. Rather, they represent the current best thinking of CEEE's Management and are subject to review, modification, or deletion by NIST and DOC Management.

The FY 1989 funding projections in this document are estimates, and all funding data are working figures used at the Center level, aggregated in amounts associated with Center analysis of technical work areas, which in most cases do not correspond to amounts in official NIST accounting records, where aggregations may be prepared differently for NIST purposes.

EMERGING TECHNOLOGIES IN ELECTRONICS

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EMERGING TECHNOLOGIES IN ELECTRONICS
Overview

The emerging technologies shown below are those that CEEE believes will require increased measurement support from CEEE in coming years. Also shown are the types of measurement support that CEEE: (1) is providing in its present FY 1989 program; (2) will provide if pending FY 1990 initiatives now before Congress are approved; or (3) will provide if future initiatives proposed by CEEE are ultimately approved. The "Key" at bottom defines the codes used.

| | Present FY 1989 Program | Pending FY 1990 Initiative | Future Initiative |
|---|---|---|---|
| **Semiconductors** | | | |
| Silicon Very Large Scale Integration | M P D | - - - | M P D |
| Silicon Ultra Large Scale Integration | - - - | - - - | M P D |
| Compound Semiconductor Integration | M P D | - - - | M P D |
| **Lightwaves** | | | |
| Optical Fiber Communications | - - D | - - D | M - D |
| Optical Fiber Sensors | - - D | - - - | - - - |
| Optical Information Storage | - - - | - - - | - - - |
| Optical Signal Processing & Computing | - - - | - - - | - - - |
| Lasers | - - D | - - - | - - - |
| **Microwaves** | | | |
| High Performance Components | - - D | - - - | M - D |
| Integrated Circuits | - P - | - - - | M - D |
| Integrated Antennas | - - - | - - - | M - D |
| **Superconductors** | | | |
| High Temperature Superconductors | M P D | M P D | M P D |
| Low Temperature Superconductors | M P D | - - - | - - - |
| **Magnetics** | | | |
| High Density Information Storage | M - - | - - - | M - D |
| High Performance Electronics | M - D | - - - | M - D |
| High Efficiency Motors, Generators, Transformers | M - - | - - - | M P D |
| Non-Destructive Evaluation | M - D | - - - | M P D |
| **Video Technology** | | | |
| High Resolution Displays | - - - | - - - | - - - |
| High Resolution Vision | - - - | - - - | - - - |
| High Definition Television | - - - | - - - | - - - |
| **Smart Systems** | - - D | - - - | - - - |
| **Bioelectronics** | - - - | - - - | - - - |

Key: M = Materials characterization measurements
P = Process control measurements
D = Device characterization measurements

EMERGING TECHNOLOGIES IN ELECTRONICS
Funding Levels

All funds shown below are directly appropriated funds; funds from other agencies are not shown. The first column shows the present FY 1989 levels of funding for related areas of programmatic activity. Those levels are assumed unchanged in future years. The second column shows additional funding for new work in pending FY 1990 initiatives now before Congress. The third column shows further funding in future initiatives proposed by CEEE but not yet approved. The "Key" at bottom defines the codes used.

| | Millions of Dollars | | |
|---|---|---|---|
| | Present FY 1989 Program | Pending FY 1990 Initiative | Future Initiative |
| Semiconductors | | | |
| Silicon Very Large Scale Integration | | | |
| Silicon Ultra Large Scale Integration | 4.2 | 0 | C |
| Compound Semiconductor Integration | | | |
| Lightwaves | | | |
| Optical Fiber Communications | 2.1 | 2.6 | B |
| Optical Fiber Sensors | 0 | 0 | - |
| Optical Information Storage | 0 | 0 | - |
| Optical Signal Processing & Computing | 0 | 0 | - |
| Lasers | 0.3 | 0 | - |
| Microwaves | | | |
| High Performance Components | 2.5 | | |
| Integrated Circuits | 0 | 0 | B |
| Integrated Antennas | 0 | | |
| Superconductors | | | |
| High Temperature Superconductors | 2.8 (N) | 0.7 (N) | A (N) |
| Low Temperature Superconductors | 0.5 | 0 | - |
| Magnetics | | | |
| High Density Information Storage | | | |
| High Performance Electronics | | | |
| High Efficiency Motors, Generators, Transformers | 0.3 | 0 | A |
| Non-Destructive Evaluation | | | |
| Video Technology | | | |
| High Resolution Displays | 0 | 0 | - |
| High Resolution Vision | 0 | 0 | - |
| High Definition Television | 0 | 0 | - |
| Smart Systems | 0 | 0 | - |
| Bioelectronics | 0 | 0 | - |

Key: "A" means less than $5M per year
"B" means $5M to $10M per year
"C" means more than $10M per year

"(N)" means NIST-wide program
"-" means no initiative yet developed

# EMERGING TECHNOLOGIES IN ELECTRONICS
## Initiative History and Technological Trends

For selected elements from the first five categories of emerging technologies listed above, CEEE has developed initiatives to seek increased funding for expanded measurement support in upcoming years. Those initiatives are in various stages of development and processing. The status of each of these initiatives is described below. In addition, for all eight of the emerging technologies listed above, a brief summation is provided of the technological advances that are driving the need for increased measurement support.

### Semiconductors

CEEE has developed an initiative entitled "Advanced Semiconductor Metrology" for an expanded NIST-wide program of measurement support. The initiative addresses materials measurements, process control measurements, and device measurements. The initiative was proposed but not adopted for the FY 1989 budget and the FY 1990 budget. Funding will be sought for this program again in a subsequent year. A description of this future initiative is attached.

Semiconductor integrated circuits are moving to reduced device size, increased integrated circuit density, and increased device speed. In addition, the special capabilities of both silicon and compound semiconductor technologies are being exploited. The measurement capability required to support these technological advances is addressed by the future initiative.

Other major technological advances not addressed by the initiative are on the horizon. Specific examples include: (1) quantum confinement devices made from compound semiconductors that offer 100 times the device density and 1000 times the speed of current devices; (2) diamond semiconductors that can operate at very high temperatures for greater environmental tolerance and reduced cooling problems; (3) semiconductor micromachines; and (4) photocells of greatly improved efficiency.

### Lightwaves

CEEE has developed an initiative entitled "Lightwave Measurement Technology" requiring $10M per year of funding. It focuses on device and materials measurements for optical fiber communications systems. Three pieces of this initiative have been approved by Congress in the budgets for FY 1987 ($0.95M per year), FY 1988 ($0.5M per year), and FY 1989 ($0.4M per year). A request for an additional $2.6M per year is included in the FY 1990 budget now before Congress. Funding for the balance of the initiative will be sought in a future year. A description of the work addressed by the several components of this initiative is attached.

Optical fiber communications systems are moving to (1) higher data rates of 20 gigabits per second at least; (2) improved or new components for local area networks to supplement long-distance lines already in place; and (3) improved components for undersea cables. Measurement support for each of these advances is provided by the proposed initiative.

There are several other emerging lightwave technologies that are beyond the scope of the initiative:

Fiber sensors are now emerging and are exhibiting extraordinary sensitivity, compact size, high environmental toughness, and broadening applicability for diverse measurements. Sensors that measure electrical parameters may become the controlling sources of information in the national power grid. Sensors that measure mechanical parameters, like strain, may lead to smart structures. Smart structures include composite fiber materials with built-in fiber sensors that report on material stresses, aging, or impending failure for applications in aircraft and building structures.

Optical information storage offers high information density, inexpensive removable media, and reduced probability of catastrophic failure.

Optical computing and optical signal processing offer dramatic increases in computing speeds, particularly when employing intrinsic parallel processing through imaging.

Laser technology is advancing rapidly and finding expanded application in industrial processing, medicine, and other fields, in addition to its traditional stronghold of scientific research and development.

## Microwaves

CEEE has developed an initiative entitled "Microwave Measurement Technology". Funding for this initiative will be sought in a future year. This initiative focuses on device and materials measurements. It does not support process control measurements or measurements made inside individual devices to support design. Many of the key measurements made inside devices and some of the needed process control measurements will be addressed by the compound semiconductor component of the comprehensive "Advanced Semiconductor Metrology" initiative noted above. A description of the microwave initiative is attached.

Microwave systems are moving to higher performance levels, higher frequencies, and integrated-circuit form to realize diverse applications including: microwave electronics for high definition television (HDTV), 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 industrial and corporate applications. Ultimately, it will be possible to place an entire microwave system with transmission and reception electronics and phased array antenna on an individual wafer a few inches in diameter for robot vision or automobile collision radar.

## Superconductors

Congress provided NIST with $2.8M per year of funding for high temperature superconductors beginning in FY 1988 prior to receipt of

NIST's first initiative request. The resulting NIST-wide program supports development of materials measurements, process control measurements, and device measurements; it also supports development of superconducting electronic devices with emphasis on measurement applications. For FY 1989 Congress required that NIST allocate an additional $2M of existing funding to high temperature superconductors for one year. The present program for FY 1989, which is operating at the $4.8M level for one year, is described in the attached "Superconductor Program Summary". The FY 1990 budget now before Congress requests an additional $0.7M per year. Those funds will enable NIST to increase its measurement support for the recently discovered second-generation high temperature superconductors whose more complex structures present especially difficult measurement problems. Additional funding will be sought in a future year, but formal plans have not yet been developed. For low temperature superconductors, CEEE presently has no plans to pursue additional funding.

High temperature superconductors promise products for electronics, electric power systems, medicine, transportation, and research. Electronic products include high speed computer chips and sensitive measurement devices for everything from electric current to signals from stars. Electric power products include motors and generators of great power but small size, current limiters, load-leveling equipment, energy storage equipment, and efficient transmission lines. Transportation products include propulsion systems for ships and for levitated trains with speeds over 300 mph (already demonstrated in Japan with the low temperature superconductors). Medical products include powerful magnets for medical diagnostic machines (already a $2 billion per year industry for the low temperature superconductors). Research products include new magnets for fusion research and high energy accelerators. Many other products are known to be possible; others are yet to be conceived. Low temperature superconductors support many of these applications already and will be employed in the new Superconducting Super Collider, a $4.4B project.

Magnetics

CEEE is presently developing an initiative entitled "Advanced Magnetics Metrology". Funding for this initiative will be sought in a future year. The initiative addresses materials measurements and device measurements for the magnetic recording and electronics industries. It also addresses materials measurements, process control measurements, and device measurements for high efficiency motors and generators and other large scale applications. A preliminary draft of this initiative, which will be expanded and refined later, is attached. Other Centers within NIST are developing complementary plans that will likely be integrated at a later date.

Advanced magnetic materials and technologies promise continuing improvements in the density of information storage in magnetic systems. They also promise higher efficiency for motors and generators and higher performance levels for electronic components that require magnetic elements, such as microwave phase shifters based on ferrites. New magnetic technology offers major advances in sensitivity and resolution for electronic systems for non-destructive evaluation (NDE). NDE systems support materials processing and enable evaluation of the integrity of critical structures, such as reactor components, aircraft frames, and building supports, before they fail.

## Video Technology

CEEE has many of the key skills required to provide measurement support for video technology and is now providing some support for selected device technologies for vision systems through its semiconductor program. Also, as part of its microwave initiative, CEEE has included funding for development of measurement support for microwave integrated circuits which will be needed for signal processing for HDTV, among other applications. CEEE has not developed plans to seek additional funding explicitly for video technology. The outcome of the decision by U.S. industry on whether to mount a major effort on high definition television will be a major factor in CEEE's own decision.

Advances in video technology will dramatically affect diverse applications including computer technology, "picture" phones, television, aerospace systems, and automobiles (unobstructed electronic rear view mirrors and electronic maps). Electronic systems capable of processing enormous bandwidths of information in real time will be required to support these displays. High resolution vision systems with broad bandwidth capability will be needed for robot vision, satellites, broadcasting, and many other applications. Flat screen displays will make large screen displays more practical, will widen potential applications, will provide improved display quality, and will ultimately reduce the cost of displays considerably.

## Smart Systems

Smart systems include those employing artificial intelligence, expert systems, neural networks, adaptive electronics, self-calibrating electronics, and a variety of other capabilities. They promise a new generation of electronic instruments. They will be essential to the design, manufacturing, and maintenance of complex systems. CEEE is active in a very limited way in some of these areas but has not yet developed a plan for an expanded program. However, the importance of smart systems to electronics and electrical engineering is a certainty.

## Bioelectronics

New bioelectronic systems offer potential (yet to be assessed) for key advantages relative to conventional electronics: (1) self-assembly - circuits that can be "grown"; (2) small size - 50 nanometer structures, possibly in three dimensions; (3) high computing speed - bioelectronic processes that handle so much information in a single step that even millisecond bioelectronic processes can beat nanosecond electronic processes; (4) high energy efficiency; (5) flexible biological interface - ability to interface directly with biological systems, including man; (6) new sensors - capable of recognizing complex materials or patterns; (7) high reliability; and (8) intelligence - imitation of neural and intelligence patterns of biological systems to perform very complex functions. CEEE feels that it is too early to define an expanded program of measurement support for this emerging field of bioelectronics, but its prospects merit continued close monitoring.

## Other Developments of Interest to CEEE

Two other major developments are not "emerging technologies" in the usual sense but are of great interest to CEEE. One is the trend toward basing procurement actions on certification of the quality of a manufacturing process rather than on certification of the quality of the final product made by the manufacturing process. This concept is particularly important for complex products whose quality cannot be readily tested. In the semiconductor industry, this trend is referred to as "qualifying processes" rather than "qualifying devices". Accommodating this trend has been an important part of the planning for the initiative on Advanced Semiconductor Metrology and will become increasingly important for other areas of electronic technology. A second trend is the development of universal computer-based descriptions for the design and manufacture of components and systems ranging from transistors to battleships. These universal descriptions lead to a software catalog of standard parts for multiple applications and reduce the cost of the design of new systems, the modification of those systems, and the maintenance of those systems.

ADVANCED SEMICONDUCTOR METROLOGY
Future Initiative
Project Plan

## Introduction

The competitive problems faced by the U.S. semiconductor device and semiconductor manufacturing equipment industries are discussed in the press almost daily. These industries are vital to the U.S. economy, affecting not only the $223 billion electronics industry but the many other sectors of the economy that depend on electronics. Japan and the United States are fighting for the $24 billion worldwide semiconductor device market and the $7 billion semiconductor manufacturing equipment market. Japanese quality and low prices are legendary.

The U.S. still holds a slight technological edge in the areas of ion implantation, thin film epitaxy, and film deposition and etching, but the Japanese have funded strong programs in these areas. The U.S. has lost the lead in optical lithography and in preparation of high quality semiconductor materials and is losing the lead in processing equipment. The Japanese are leading in technologies and their supporting equipment that U.S. companies must possess if they are to compete successfully, and the Japanese are out spending the U.S. industry for capital improvements. These technologies include microwave plasma processing, radiation sources for lithography, electron and ion microbeams, laser-assisted processing, compound semiconductor processing, and three-dimensional device structures. Many significant studies, including the National Research Council's on "Advanced Processing of Electronic Materials in the United States and Japan" (1986), have emphasized the seriousness of the U.S. deficiency in semiconductor manufacturing technologies. This work plan directly responds to this issue by addressing the metrological infrastructure needed for such advanced processing technologies.

## Impact

Semiconductor industry 1985: (millions) [Source: Dataquest]

| | Capital spending | Revenues | Spending/revenues (%) |
|---|---|---|---|
| U.S. merchant firms: | $2211 | $11272 | 20 |
| Japanese firms: | 3346 | 10185 | 33 |

Typical company R&D levels in both the U.S. and Japan are 10 percent of revenues, so each country's industry spends somewhat over $1 billion annually. The long term nature of Japanese research is illustrated by the current Japanese Government funding for microelectronics superlattice devices 1981-1990, $49M; three-dimensional IC's 1981-1990, $55M; and IC's for extreme conditions 1981-1985, $49M. [Source: MITI] Companies at least match this expenditure on these programs.

Microstructures at dimensions below one micrometer form the building blocks for the next generation of semiconductor electronic devices. This work plan is for research and development in microstructure science and technology leading to new measurement techniques and artifacts needed for materials, device, and equipment evaluation and process and quality control. It will enable NBS to develop and deliver essential measurement methods needed to support U.S. companies in their efforts to manufacture competitively semiconductor devices for the 1990's. Key reference data, better models, and improved measurement methods for microelectronics will allow more accurate device design and improved process control by U.S. industry and improve its competitiveness. More reproducible materials processing and higher quality materials can significantly improve yields and lower costs. The transition by industry to submicrometer-scale devices will be aided by NBS contributions. Development of better measurement methods will provide the basis for industrial voluntary standards which assure product compatibility and which support efficient market transactions.

## Summary of NIST Plan

The semiconductor initiative is a NIST-wide effort. The list that follows summarizes the key elements of the plan.

1. Metrology for Advanced Semiconductor Materials and Structures
1.1 characterization of layers
1.2 models for these processes
1.3 spatial variations in layer properties
1.4 properties of the interfaces between layers

2. Metrology for Critical Semiconductor Processes
2.1 patterns and defects in layers
2.2 diagnostics, data, and models for plasma processes
2.3 measurements of patterns in layers
2.4 fundamental information on plasma chemistry
2.5 contaminants in process gases
2.6 fundamental information on plasma physics

3. Metrology for Advanced Semiconductor Devices
3.1 device measurements by advanced beam methods
3.2 device package properties
3.3 models for advanced devices

4. Process Metrology for Advanced Semiconductor Manufacturing
4.1 assessing performance of manufacturing processes
4.2 improved statistical manufacturing process control
4.3 efficient testing of complex circuits

5. Surface structure effects in film growth and properties
5.1 structure at early stages of epitaxial film growth
5.2 physical structure and microcomposition of lithographic structures
5.3 segregation and diffusion at interfaces on an atomic scale
5.4 atomic structure at buried thin-film interfaces
5.5 chemical states at interfaces
5.6 theoretical support for 5

6. Mechanisms in surface processing
6.1 probes for surface-chemical processes
6.2 fundamental mechanisms in electron and photon beam lithography
6.3 structural and topographic surface changes after surface processing
6.4 theoretical support for 6

7. Standard reference data and materials
7.1 measure, compile, and evaluate critical data
7.2 new Standard Reference Materials
7.3 Electronic Materials Data Center

8. Advanced Analytical Techniques for Semiconductor Technology
8.1 high energy analytical techniques
8.2 ultratrace measurements for advanced semiconductors
8.3 microbeam analysis at the nanometer scale

## Details of NIST Plan

The following text describes each element of the NIST-wide plan, using the same section numbers as in the summary above.

### 1. Metrology for Advanced Semiconductor Materials and Structures

1.1 GOALS: Development of electrical and optical techniques for characterizing epitaxial layers and heterostructures to obtain their dimensions, composition, and optical and electrical properties and to evaluate their suitability in high-speed electronic and optoelectronic applications. Fundamental studies of the physics of the initial stages of growth of epitaxial layers of compound semiconductors.

Develop the capability to prepare and characterize epitaxial layers and structures of the highest possible quality. Employ precise optical probes for determining sticking coefficients, adsorption energies, and other information needed for detailed understanding of heteroepitaxial growth. Use highly perfect, well-characterized epilayers to generate reference data for the composition dependence of physical and electronic properties such as bandgap, effective masses, spin-orbit splitting, mobility, impurity state binding energies, heterojunction band offsets, lattice constant, phonon energies, etc. As appropriate, use these specimens as a basis for standard reference materials for properties such as composition, band gap, or lattice constant and for the uniformity of these properties.

MILESTONES

Year 1: Design and construct apparatus for molecular beam epitaxy (MBE) with dual growth chambers suitable for the growth of large gap materials (GaAs/GaAlAs) for digital applications and small gap materials (InSb/HgCdTe) for optoelectronics.

Year 2: Assess the feasibility and relative merit of various optical and x-ray techniques for determining the composition and compositional uniformity of semiconductor alloy epilayers.

1.2 GOALS: Develop generic physical models for submicrometer structures. Complete understanding of the physics of devices and materials is essential for the development of good metrology. Models and computational techniques are important tools for developing that understanding. Develop accurate and computationally efficient methods for describing the effects of small dimensions, abrupt interfaces, and large composition or doping gradients on the electronic and vibrational states of semiconductors. Use these models in the interpretation of experimental data and the refinement of device models.

MILESTONES

Year 1: Determine effects of high doping gradients and bandgap discontinuities on the formation of band tails and impurity bands in moderately to heavily doped semiconductor alloys.

Year 2: Determine the effects of bandgap narrowing on the design and performance of heterojunction optoelectronic devices such as lasers and photodetectors.

1.3 GOALS: Develop methods of surface analysis for evaluating surface properties as a function of process variables and for determining lateral variation of electrical and optical properties of semiconductor surfaces. Provide facilities for in-situ characterization of surfaces during MBE growth. Study growth process and its influence on the optical and electrical properties of epilayers. Surface properties become increasingly dominant as the scale of device dimensions becomes less and less.

MILESTONES

Year 1: Design and construct surface characterization sub-system for MBE apparatus.

Year 2: Design and construct in-situ surface characterization and modification facilities for MBE system.

1.4 GOALS: Develop techniques to characterize the interfaces present in the active regions of devices. These include metal-semiconductor contacts (both ohmic and Schottky), heterojunctions, and other interfaces. Develop sensitive methods based on x-ray absorption and diffraction, electron microscopy and diffraction, and photoelectron spectroscopy to examine the chemical and structural or crystallographic properties of metal-semiconductor and semiconductor-semiconductor interfaces. Correlate the observed interface structure with electrical properties and with the method and conditions of preparation.

MILESTONES

Year 1: Use extended x-ray absorption fine structure (EXAFS) measurements to determine the chemical structure of Pd/Ge "epitaxial" ohmic contacts on GaAs.

Year 2: Compare structural and electrical properties of evaporated Al Schottky contacts with those produced by molecular beam deposition.

2. <u>Metrology for Critical Semiconductor Processes</u>

2.1 GOALS: Develop methods to evaluate the performance of process steps critical to the fabrication of submicrometer structures. Measurement methods required to determine correlations between processing steps and the nature of defects that are unimportant in present processes but which will be important in the future are of concern. Measure and characterize two-dimensional patterning of fine features in lithography, etching, growth, and doping or deposition, including alignment, resists, and light, x-ray, electron beam, or ion beam exposure sources. (See also section 2.3.) Investigate production-worthy metrology for new fabrication procedures that overcome existing material and process constraints, and that eliminate or control random crystallographic and interfacial defects.

The approach will be to develop measurement techniques for evaluating and improving the understanding of the effects of process steps on the properties of the materials and devices fabricated, by measuring physical and electrical parameters such as film thickness, sheet resistance, dopant profiles, contact resistance, interface states and charge trapping, and deep-level defects. This includes measuring uniformity from wafer-to-wafer and batch-to-batch and measuring the numbers and effects of process-induced defects. Also included will be the development of measurement techniques and standard reference materials for controlling critical process steps to optimize or improve reliability, yield, defect density, cost, and throughput. Environmental effects, such as contamination and particulate control, will be a focus. (See also section 2.5.) The new measurement techniques will be in-process, wafer-level, and package-level tools for real-time quality control.

MILESTONES

Year 1: Demonstrate nondestructive measurement methods for quantifying damage induced by plasma and reactive ion etching in submicrometer structures.

Year 2: Develop and test physical and chemical models for the creation of process-induced defects and their elimination or deactivation by gettering and annealing during dry and low temperature (below 900°C) processing steps.

2.2 GOALS: Develop diagnostic tools, chemical reaction data, fluid dynamics models, and end-point detection methods for plasma-assisted film deposition and removal processes. Process models will be developed for plasma-assisted deposition and plasma, reactive ion, and reactive ion beam etching. These models will include both fundamental and applied experiments to understand and characterize the physics and chemistry of reactant absorption, creation of the product molecule or other physical structure, and, for etching, product molecule desorption.

Chemical vapor deposition (CVD), plasma deposition (PD), and plasma etching (PE) are important industrial processes for fabrication of semiconductor devices. These processes involve poorly understood, complex gas-phase reactions which control product quality and reproducibility. Current practice is usually based on empirical optimization of process parameters (e.g. temperature, pressure, gas composition, surface temperature, etc.) to obtain acceptable results without a detailed understanding of the chemistry involved. To exploit fully the capabilities offered by CVD, PD, PE and other processes and to improve product quality and meet new fabrication challenges it is necessary to develop microscopic descriptions of the mechanisms of gas phase as well as surface reactions. This requires diagnostic measurements of gas phase reactants, intermediates, products, and surface species. Laser-based diagnostic techniques (laser induced fluorescence, Raman spectroscopy, etc.) are most suited for detection of gaseous species and for measurement of gas phase kinetics relevant to deposition and etching processes. Tunable laser sources can also be used to improve film uniformity and deposition rates. Laser-enhanced CVD (LECVD) allows the selective photoexcitation of reactants.

LECVD also makes it possible to deposit films with improved dimensional control critical to the fabrication of submicrometer devices. Initial focus of this work will be on silane ($SiH_4$) and chloro-silane reactions. Later, reactions relevant to GaAs, InAs and other semiconductor systems will be investigated.

In CVD and PE, it is also important to understand the effect of energy and species transport on film deposition and removal processes. In these processes, chemical kinetic and transport phenomena are strongly coupled, and large concentration and temperature gradients exist in the reactors. Therefore, modelling of the entire process, with fully coupled kinetic and fluid dynamics, is a necessary tool to develop a basic understanding of the overall process and to optimize the operating parameters to achieve improved deposition and removal rates and film quality. Finally, surface analysis techniques will be developed to obtain composition and chemical state information in a variety of important electronic materials, including Si, GaAs, $SiO_2$, W, Mo, etc. For example, XPS, SIMS and ISS techniques will be used to characterize contaminating layers on films and to determine the appropriate removal temperature. Dynamic SIMS as well as depth-profiling modes of XPS and ISS will be applied to determine the chemistry of internal interfaces, especially the compositional gradients at interfaces. These techniques will be used to correlate film characteristics with changes effected via modification of gas phase reaction parameters.

MILESTONES

Year 1: Demonstrate the feasibility of utilizing laser-based diagnostic techniques for identification of important gas-phase reactions in CVD and PE. Use laser induced fluorescence to detect presence of $SiH_3$, $SiH_2$, $Si_2$, $SiCl_2$ and other intermediates of $SiH_4$ or chlorosilane decomposition.

Year 2: Develop a two-dimensional model for a generic CVD process geometry. This model will be used as a tool to optimize process geometry and operating conditions.

2.3 GOALS: Develop techniques for accurately measuring the critical dimensions of submicrometer features by optical and scanning electron microscopic techniques. Implementation of these techniques in the certification of new and improved feature-size standards and in recommended procedures for use in process verification by the semiconductor industry. The measurement techniques will include effects of the process procedure used to form the feature and the chemistry of the materials composing the feature; i.e. how the physical and chemical properties of the feature interact with the measuring electrical or optical beam.

Accurate measurement of the critical dimensions of microstructures on semiconductor devices is essential to the control of the production process and the attainment of useful yields. The difficulty of making these measurements to the required accuracy is being compounded as the next generation of microcircuits (ULSI) will have feature sizes below one micrometer. It is essential to develop the metrological tools, both theoretical and experimental, to put these measurements on a solid foundation.

For optical measurements we must develop the required electromagnetic models for microstructures whose size is of the order of the wavelength of light, confirm these models by experiment, and build and test an ultraviolet microscope capable of making the measurements to nanometer precision. For scanning electron microscope (SEM) measurements, we must use Monte Carlo calculations to model the electron beam interaction with the sample, detector, and chamber and again confirm the results by experiment with direct interferometry. Finally, in both these cases, the inverse problem must be solved (deducing the feature from the image rather than vice versa), suitable transfer standards must be developed, and the use of these standards in industry established.

MILESTONES

Year 1: Ultraviolet microscope fully operational

Year 2: Completion of electron/specimen interaction model

Later: Inverse Optical problem solved
Issuance of SEM linewidth standard

2.4 GOALS: Compile, evaluate, and generate fundamental chemical rates, transport parameters, and collision cross sections applicable to plasma processes and chemical vapor deposition. Develop generic computer model of such processes. Generate and evaluate fundamental rate data needed for modeling low-temperature glow-type electrical gas discharges for use in plasma etching reactors for processing semiconductor materials. Evaluate existing generic computer codes that can be used in modeling of gas-phase chemistry in glow discharges and which can be used for evaluating consistency among existing fundamental data on elementary processes and on observations of gas-discharge phenomena.

MILESTONES

Year 1: Compile data bases for electron collision cross sections, electron transport parameters, and reaction rate constants for fluorinated gases used in plasma etching reactors.

Year 2: Calculate chemical rate constants and electron transport parameters for selected gas mixtures proposed for or used in plasma chemical reactors, and evaluate consistency among electron collision cross sections, swarm, and dielectric strength data for these mixtures.

2.5 GOALS: Develop standards and diagnostic techniques for monitoring input gas streams for moisture and particulate content that provide real-time response and species selectivity. Apply such techniques for on-line measurement and control during the fabrication of submicrometer semiconductor devices and circuits. Develop sensors and particle detection and characterization tools for particulates and contaminants in gases, liquids, and on surfaces.

Moisture and particulates are the most important factors that contribute to device rejection and reduced productivity. Current humidity measurement techniques are limited to concentration levels above 1 ppm. New processes used for fabrication of submicrometer scale devices require measurements of humidity levels below 1 ppm. Measurements at such low concentrations would require development of new techniques utilizing optical methods. One such technique, which will be explored as part of this work, involves the use of a tunable diode laser for multipass infrared absorption measurements. This technique should provide reliable humidity measurements down to about 10 ppb level. The system accuracy and precision would be evaluated using a low dew point humidity generator, which is currently being constructed at NBS.

Particulate contamination has been another critical source of process inefficiency in microelectronics fabrication. This situation is expected to be further aggravated as the dimensions of microstructures are reduced to below a micrometer. Submicrometer particles, either introduced in the input gas stream or generated in some part of the process (such as by homogeneous gas-phase nucleation of $SiO_2$ particles), will represent a major source of device contamination and have to be measured and controlled at each step of the process. These techniques are to be utilized for on-line measurements and real-time control of fabrication processes. Stringent specifications and _a priori_ measurements of these parameters are not sufficient to reduce the rejection rate of semiconductor devices, since moisture and particulates could be entrained in the transfer lines and introduced into the reactor. Therefore, on-line measurements are necessary to ensure high product quality.

MILESTONES

Year 1: Demonstrate feasibility of performing sub-ppm level humidity measurements in a flow system, using infrared laser absorption or other spectroscopic techniques.

Year 2: Demonstrate feasibility of performing single particle measurements in the submicrometer size range, in gas streams typical of those used in microelectronics processes.

2.6 Physics of Plasmas for Semiconductor Processing.

GOALS: Provide useful models to optimize plasma properties for specific semiconductor applications, including deposition, etching and control mechanisms; improve etch resolution via cryogenic plasmas. Predictive models require not only detailed plasma chemistry and kinetics, but also the basic physical properties of the plasma. The most important of such properties include the local energy distributions and densities of the charged particles in the plasma, and the electric field distribution.

MILESTONES

Year 1: Construct a discharge capable of operating over the range of RF frequencies and pressures used for plasma processing. Make preliminary electron and ion density diagnostics.

Year 2: Develop and evaluate methods for determining: charged particle and metastable state densities, electron energy and electric field distributions. Integrate computer modeling with plasma chemists. Begin low temperature development.

3. Metrology for Advanced Semiconductor Devices

APPROACH

The "device technologies" of practical importance in the 1990's will be submicrometer CMOS, high performance bipolar, merged MOS and bipolar, GaAs optoelectronics and microwave devices, and to a limited degree, quantum domain devices. Considering the structures and operation of these devices, two elements of commonality become evident; 1) micro dimensions (i.e., all are microstructures) and 2) high speed operation (ultrafast rise and fall times of signals, high frequency operation, or both). Metrology for these advanced semiconductor devices will require ultrahigh spatial resolution physical, electrical, and thermal analysis tools and ultra-high-speed instrumentation and signal sources deliverable at the chip or package level.

A third element of commonality is packaging complexity. The package serves three basic functions. They are 1) to provide a means for getting signals to and from the circuits/devices, 2) to provide a means of removing the heat generated by the operation of the circuits/devices, and 3) to protect the circuits/devices from the environment. The implementation of these functions for advanced semiconductor devices will require new packaging materials, concepts, and technologies. Ultra-high-speed devices will require innovative methods for getting signals to and from the chip. The power density of ultra-small, high density devices and circuits will require innovative methods and new materials for removing heat from the chip. The new packages must accomplish these functions while not sacrificing their own mechanical integrity. Severe metrological challenges exist to assure that the packaging achieves all of its functions.

3.1 GOALS: Develop methods for determining the critical physical, electrical, and optical properties of advanced semiconductor devices and circuits for wafer and chip level as well as for completed (packaged) devices and circuits.

The industry application of these measurements typically will depend on at which level the measurement is made. Measurements for completed devices are required for specification development and verification and are absolutely critical for the commerce between buyer and seller. Measurements at the wafer and chip level are sometimes used as above, but are usually used for feedback in device design and processing and for device and circuit model development and evaluation.

The critical needs for all levels of measurement will be for signals with ultra fast rise and fall times that are deliverable to and from the package or the chip. This will require active probes, "microwave-like" fixturing and signal propagation. Physical measurements will require submicrometer spatial resolution (horizontal and vertical). These will be accomplished by beam analysis and excitation methods (SIMS, RBS, etc), advanced SEM and STEM techniques, and advanced optical methods. Advanced SEM analysis methods will be developed (both physical and electrical) and expertise in the other physical analysis methods will be maintained to permit the knowledgeable purchase of advanced physical analysis measurements.

MILESTONES

Year 1: Procure and bring into operation ultra high speed device and circuit analysis system. System will consist of commercial instrumentation and NBS fabricated instruments and fixtures.

Year 2: Develop advanced SEM techniques for impurity mapping (horizontal and vertical) with submicrometer resolution.

3.2 GOALS: Develop methods for determining critical device and circuit package related properties, such as signal propagation to and from the "chip", thermal control, and mechanical integrity.

Each of the three major functions of the package will be addressed in this element. Methods will be developed for assessing the capability of advanced devices for removing heat from the active devices and circuits. This will involve a combination of non-invasive infrared mapping methods and electrical characterization. It will also require fixturing in a variety of ambients, including fluid baths, still air, water cooled, and wind tunnels to simulate use conditions. The primary electrical problems are to ensure that the package does not cause distortion in signals to and from the active devices and circuits. High speed network analysis and innovative fixturing will be required to characterize the packages for potential electrical distortion and interference. (See also section 4.3 below.) The mechanical integrity of the package affects all functions of the package, thermal, electrical, and protection. New materials and materials bonding techniques will be required for advanced packages. Models and characterization techniques for the materials and their interfaces will be developed.

A key problem associated with the adhesion of metals to semiconducting substrates is the resulting residual stresses in the components due to thermal expansion mismatch between the metal and the substrate. These stresses can act in three main ways; they can cause the coating to crack or to delaminate from the substrate, or they can combine with stresses already present in the substrate to cause mechanical failure. The first two possibilities will be investigated through the construction of an holographic system to detect residual strains in the coatings. The coatings will be vacuum deposited and studied, in situ, using optical holography.

The mechanical stability of the substrate and its relationship to the pre-existing residual strain in the material before the coating is applied must also be investigated. Indentation tests as well as macroscopic crack growth techniques will be used to determine the susceptibility of GaAs substrates to mechanical and environmentally enhanced failure and to map out regions of residual stresses. These results will be correlated with x-ray topography and infrared microscopy data to determine the relationship between observed residual strains in GaAs wafers and residual stresses leading to failure.

Finally, after a coating is laid on the substrate, it is important to be able to measure the mechanical adhesion between the materials. Thermal waves and indentation techniques will be used to develop a method for measuring the adhesion of the coating to the substrate.

MILESTONES

Year 1: Procure high resolution thermal mapping system. Determine specific materials interface problems for advanced packages.

Year 2: Determine the coating adhesion to the substrate as functions of residual stresses in and hardness of the coating, and of processing variables of the substrate/coating system.

3.3 GOALS: Develop and verify fundamental physical models for phenomena critical to accurate advanced semiconductor device and circuit modeling.

Models based upon sound physical principles impact all areas of advanced device technology. As devices shrink in horizontal and vertical dimensions and employ materials with tailored band structures, classical approximations used in device modeling become invalid and quantum effects become more significant. This transition to more complex domains of operation is made more complex by the high electric fields, high current densities, and large gradients in carrier temperature present in submicrometer devices. The study of these effects requires that a set of models be developed which includes classical hydrodynamic models, modified hydrodynamic models including new physical effects, and Monte Carlo models. Development of these models requires expertise in numerical methods, device physics, and material properties/physics. Device and circuit models will aid in developing the metrology for advanced devices and are used for improving device and circuit designs.

MILESTONES

Year 1: Procure computational facilities required for models for advanced devices.

Year 2: Determine areas in greatest need of physical understanding for modeling submicrometer structures.

4. <u>Process Metrology for Advanced Semiconductor Manufacturing</u>

4.1 GOALS: Develop sophisticated quality control and yield enhancement procedures by combining artificial intelligence, statistical experimental design, and microelectronic test structures for manufacturing semiconductor circuits. Develop new electrical and statistical analysis techniques for assessing reproducibility, performance, and reliability of advanced microcircuits in a manufacturing environment.

Very often, results from a comprehensive test chip program are not used effectively or not used at all because of the quantity and complexity of the data and the lack of available expertise to evaluate the results and make meaningful decisions. The goal of this effort is to apply Artificial Intelligence techniques to process development, manufacturing yield enhancement, and acceleration of technology transfer from the laboratory to the fabrication line of advanced VLSI/VHSIC microelectronic circuits. As a first step, an experimental expert system will be developed at NBS and exercised to demonstrate how such an approach can operate for analyzing selected portions of a VLSI process. In order to provide a data base for this expert system, a test chip and measurement program will be customized to provide data sensitive to various modes of operator, equipment, and process failure associated with replicating submicrometer polysilicon features with optical lithography and reactive ion etching. A knowledge base will be obtained from both test structure results and human experts and which will be compiled into a list of rules. An inference engine running on a small computer will be used to apply the measurement data to the knowledge base. The intended output of the first expert system will be a first-level differential diagnosis of the failure modes prevalent in the lithography process associated with defining a nominal one-micron single-level interconnection system. The experience gained from first expert system and associated test chip will be used as a basis for creating a more comprehensive system/test chip combination aimed at evaluating advanced VLSI/VHSIC process development.

NOTE: In order to perform this, fabrication services of a VLSI/VHSIC manufacturer will have to be secured via collaborative efforts with industry or via DOD involvement.

MILESTONES

Year 1: Develop and evaluate an expert system and selected test structures for characterizing the performance of near-micron lithography processes.

Year 2: Develop and evaluate an advanced deep reasoning expert system for submicrometer lithography system performance evaluation.

4.2 GOALS: Demonstrate value of sound experimental design and statistical process control as an alternative to expensive, after-the-fact procurement testing. Coordinate industry-wide round-robin experiments to improve measurement capability on the factory floor.

Interlaboratory experiments and standardization efforts will allow industry and government to make reliability predictions with greater confidence, promote more effective technical communications, permit sounder product-design decisions, and improve agreement of characterizations by vendor and user. The effort will be two fold: in the characterization of electromigration under pulsed conditions and of time-dependent dielectric breakdown (TDDB) of thin-film dielectrics. In each case, the effort will be designed to establish quantitatively the present status of such characterizations, to identify sources of measurement ambiguity, identify any critically-needed research efforts, and to develop measurement standards in these area, as appropriate.

Measurement deficiencies and ambiguities relative to critical failure mechanisms remain as serious obstacles to improving the performance, quality, and reliability of advanced VLSI/VHSIC microelectronic circuits. Two critical failure mechanisms of such microelectronic circuits are electromigration of the interconnect metallization and TDDB of thin-film dielectrics used in the gates of MOS devices. Serious measurement and characterization gaps exist for the characterization of electromigration under pulsed conditions. In the absence of any consensus guides for current-density limits under pulsed conditions, existing dc guides have been used. A sense of urgency about this measurement deficiency is growing now as advances in the design of microelectronic circuits are creating pulsed current-density conditions in such circuits which exceed these dc limits. At the same time the prediction of the use life of thin-film dielectrics is a "black art". Considerable ambiguities remain in the existing data, the acceleration factors used, the models, and the characterization of dielectrics relative to TDDB.

NOTE: In order to perform this work, fabrication services of a VLSI/VHSIC manufacturer will have to be secured via collaborative efforts with industry or via DOD involvement.

MILESTONES

Year 1: Develop measurement capability for electromigration stress testing under pulsed current conditions; develop and evaluate special test structures for use in both interlaboratory experiments.

Year 2: Design, conduct, and analyze the results of interlaboratory experiments in electromigration and TDDB.

4.3 GOALS: Apply matrix methods to efficient functional testing of integrated circuits, accounting for effects of circuit topology and measurement error. Develop device measurements for very fast rise times. Extend these approaches into the manufacturing process to monitor process variables pertinent to items 4.1 and 4.2 above.

The critical problem of testing complex semiconductor devices will be addressed by extending and applying modeling and mathematical methods previously developed for analyzing the performance of simpler analog, digital, and mixed analog/digital circuits. Because of the large component count and number of circuit nodes contained in advanced ULSI devices and the relatively small number of external connections, it is likely that the use of built-in test circuits and circuit partitioning techniques will be required to develop improved functional tests from which overall performance can be deduced with high confidence. Matrix analysis methods have been shown to be applicable to this class of circuit testing, but are in a very early stage of development. Initial results are extremely encouraging. These methods will take into account the combined effects of circuit topology and measurement errors in estimating circuit component values and in predicting the performance of the circuit over the complete range of operating conditions.

As the dimensions of ULSI circuit components become smaller, the circuits operate faster. In addition, circuits are appearing which have lesser complexity but which are specifically optimized for high-speed operation. These bring the additional problems of measuring their speed and response times. Verifying impulse and step response times on the picosecond and subpicosecond scale with reliable, known accuracy requires new physical standards and related signal processing algorithms.

MILESTONES

Year 1: Development of circuit partitioning algorithms which will allow the extension of earlier analysis techniques to more complex analog circuits. Development of 10-100 picosecond rise time transfer standard.

Year 2: Development of strategies for evaluating nonlinear analog systems. Development of real-time, single-shot transient software algorithms.

## 5. Surface structure effects in film growth and properties

5.1 GOALS: Characterize film structure at the early stages of epitaxial film growth using forward scattering of photoelectrons and Auger electrons. Metal-semiconductor interfaces, which determine the properties of Schottky barriers, are of particular importance. Measure the structure and bonding of transition-metal atoms to silicon and gallium arsenide single-crystal surfaces. Measure surface segregation and interdiffusion in metal and semiconductor superlattices fabricated by molecular-beam epitaxy. Such properties are critical in ultrathin films where surface diffusion processes are very different from the bulk diffusion mechanisms for macroscopic materials. Finally measure the magnetic properties of ultrathin films.

MILESTONES

Year 1: Design and install new photoelectron spectrometer facility with ion scattering spectroscopy capability and film deposition equipment.

Year 2: Measure film atomic structure for transition metals deposited on silicon and gallium arsenide single-crystal surfaces.

5.2 GOALS: Characterize the physical structure and microcomposition of lithographic structures. Fabricate prototype lithographic structures (metal lines on different substrates; multilayer thin films; ion-implanted semiconductors). Surface measurement techniques with high-spatial resolution such as Auger-electron spectroscopy, secondary-ion mass spectroscopy, and scanning electron microscopy will be used to determine the physical structure and microcomposition of the test materials. New and improved algorithms will be needed to convert the measured signals to the desired quantities.

MILESTONES

Year 1: Specify, procure, and install high-resolution Auger-electron spectrometer and scanning electron microscope.

Year 2: Compare Auger-electron images from prototype test structures with predictions from new algorithms based on electron transport models.

5.3 GOALS: Characterize segregation and diffusion at interfaces on an atomic scale. Deposit metal films on silicon, germanium, and gallium arsenide, and obtain diffusion data by field-ion microscopy with near-atomic spatial resolution. Measure interdiffusion at the low temperatures required for device processing and operation and determine variations of parameters such as substrate geometry and impurity levels. Measure film properties such as nucleation, degree of crystallinity, and defect densities for deposition parameters such as substrate composition and structure, substrate temperature, vapor flux, and vapor purity.

MILESTONES

Year 1: Design and construct film deposition facility on field ion microscope.

Year 2: Determine segregation and interdiffusion at interfaces between silicon and transition-metal films for a range of film-deposition conditions.

5.4 GOALS: Determine atomic structure at buried thin-film interfaces. Use synchrotron radiation at the Brookhaven National Synchrotron Light Source with the techniques of x-ray standing waves (external total reflection and anomalous transmission methods) to measure non-destructively the atomic structure of the interface between thin-film layers. The registry of atomic layers between a substrate and a film is usually desired for high-quality epitaxial films but this has been very difficult to measure without modifying the specimen. Apply the above techniques to III-V and II-VI semiconductor compounds, oxides, and metals to provide the scientific basis for control of manufacturing processes.

MILESTONES

Year 1: Design and construct x-ray standing wave experimental facility.

Year 2: Apply x-ray standing wave technique to characterize nondestructively atomic structure at thin film interfaces between metals and compound semiconductors.

5.5 GOALS: Determine chemical states at interfaces. Use photoelectron spectroscopy with synchrotron radiation to determine the electronic structure and chemical states at interfaces when thin films are deposited on substrates. Deposit metal overlayers on semiconductors and determine the chemical state of reacted layers at the interface. Make prototype structural studies at the monolayer level of epitaxial insulating films.

MILESTONES

Year 1: Design and construct special chambers to perform photoelectron spectroscopy on semiconductor films at Brookhaven National Synchrotron Light Source.

Year 2: Identify chemical states at interfaces between epitaxial insulating films and semiconductor substrates.

5.6 Theoretical support for the above projects:

MILESTONES

Year 1: Develop theoretical methods for calculating the electronic structure of metals and semiconductors.

Year 2: Determine minimum-energy configurations for thin metal films on semiconductor substrates.

6. <u>Mechanisms in surface processing</u>

6.1 GOALS: Develop new optical and spectroscopic probes for characterizing surface-chemical processes during device processing. Use laser beams for surface processing (laser-assisted film growth, generation of radicals at surfaces, photo-carrier-induced chemistry, and fast heating) and as probes to identify chemical species on surfaces under processing conditions. Emphasize the characterization of non-equilibrium dynamics critical for low-temperature processing of semiconductor materials as well as for maintaining non-equilibrium structures during the desired service life of a device.

MILESTONES

Year 1: Design and install experimental chamber and laser equipment to investigate mechanisms of surface reactions.

Year 2: Determine mechanisms of laser-assisted growth of metal films on semiconductor substrates.

6.2 GOALS: Determine fundamental mechanisms in electron and photon beam lithography. Investigate radiation-induced surface reactions that are important for exposure of resists and deposition of films from organometallic compounds. Identify the mechanisms of such reactions and measure their cross sections.

MILESTONES

Year 1: Design and install experimental facility to detect atoms and molecules leaving a surface during lithographic processes.

Year 2: Measure cross sections for electron and photon induced reactions of organometallic resist compounds.

6.3 GOALS: Determine structural and topographic surface changes following surface processing. Use scanning tunneling microscopy, scanning electron microscopy, and standard surface techniques (low-energy electron diffraction, Auger-electron spectroscopy) for characterizing long-range atomic ordering and short-range atomic disorder and defects following surface processing by ion, electron, or photon beams. Determine the mechanisms of these changes and the rates for specific conditions relevant to electronic materials processing. Examine the effects of these surface modifications on other surface processes.

MILESTONES

Year 1: Design and construct scanning tunneling microscope facility for measuring surface topography and defects.

Year 2: Determine changes in surface topography and defects following ion bombardment and effects on surface reactions of semiconductor materials.

6.4 Theoretical support for the above projects.

MILESTONES

Year 1: Develop theoretical methods for investigating molecular dynamics and reactions at surfaces.

Year 2: Calculate mechanisms and rates of prototype semiconductor processing reactions.

## 7. Standard reference data and materials

7.1 GOALS: Measure, compile, and evaluate critical data for (1) electronic and thin film material characterization and (2) chemical reactivity of transients in plasmas and on surfaces.

In (1), obtain data for the following parameters: electron attenuation lengths; matrix effects on elemental sensitivity factors; electron backscattering correction factors; the effects of specimen crystallinity on measured intensities for surface-characterization spectroscopies; and ion sputtering rates. In (2), kinetic and thermodynamic data are required to describe reactions in etching plasmas and on surfaces exposed to the plasmas. Measure, evaluate, and compile these and other important parameters in the form of computer-readable databases for efficient and convenient distribution. Develop improved algorithms for analysis of spectroscopic measurements. Incorporate these algorithms and the new data bases into new expert systems designed to improve the accuracy and efficiency of surface measurements.

MILESTONES

Year 1: Initiate compilations of critical data for characterization of electronic and thin film materials and for chemical reactivity in plasma processing.

Year 2: Produce computer-readable data bases for distribution.

7.2 Fabricate and characterize new SRMs for the calibration of instruments used for surface and interface characterization of electronic materials.

SRMs of the following types are needed: ion-implanted semiconductor materials with known concentrations and depth distributions; oxide thin film materials of known thickness; multilayer metal thin film materials of known thickness; superlattice materials; organic materials; prototype devices with known dimensions for calibration of length scales and spatial resolution of instruments; and multicomponent materials for calibration of instrument sensitivities.

### 7.3 Electronic Materials Data Center

GOAL: Establish a Standard Reference Data program to improve the quality and accessibility of data related to electronics materials. Address the data needs of three significant areas of the semiconductor industry; namely, materials, packaging materials and techniques, and manufacturing processes. The range of properties will include physical, chemical, electrical, magnetic, mechanical, corrosion and optical. Make available high quality scientific and technical data in database formats to help the industry explore new designs, improve the performance of packaged electronic devices and increase process efficiency.

MILESTONES:

Year 1: Establish database of physical, chemical and other data to support modeling of plasma manufacturing processes for electronic materials

Year 1: Establish database of physical, chemical, electrical, mechanical and other properties of silicon and gallium arsenide

Year 2: Establish database for III-V and II-VI compounds of interest

Year 2: Establish database of properties of electronic packaging materials

## 8. Advanced Analytical Techniques for Semiconductor Technology

### 8.1 High-energy radiation techniques

GOALS: New, extremely sensitive technology for the characterization of semiconductor materials and devices is a class of advanced analytical techniques which rely on high energy (MeV) particles in the primary (excitation) and/or secondary (analytical) streams. These techniques include Rutherford backscattering, particle-induced photon emission, nuclear reaction analysis, including hydrogen profiling, and accelerator mass spectrometry. All of these techniques make use of the same basic instrument, a tandem accelerator, with various experimental stations attached. In addition to the analytical techniques, the ion beam can be used for materials modification by high energy implantation and ion mixing. These advanced materials characterization techniques represent the state of the art.

MILESTONES

Year 1: Install and test tandem accelerator and demonstrate state-of-the-art Rutherford backscattering.

Year 2: Demonstrate hydrogen depth profiling by nuclear reaction analysis.

8.2 Ultratrace Bulk Materials Analysis

GOALS: The absolute amounts of impurities that must be determined in semiconductors are beyond the current state of the art. Ultratrace measurements will be applied to the special problems of advanced semiconductors. The existing techniques of Isotope Dilution Mass Spectrometry (IDMS), Inductively-Coupled Plasma with both Atomic Emission Spectroscopy and Mass Spectroscopy (ICP-AES and ICP-MS), Ion Chromatography (IC), and Neutron Activation Analysis (NAA) provide an unmatched combination of analytical tools for addressing this challenge. Capabilities in elemental analysis from ppb to below ppt in favorable cases will be further developed for semiconductor requirements.

MILESTONES

Year 1: Demonstrate quantitative dissolution techniques for the ultratrace analysis of key semiconductor materials and apply them with the appropriate analytical techniques. Where possible, compare these results with a second, nondestructive method.

Year 2: Produce one or more Standard Reference Materials (SRM's) of key semiconductor materials certified for elemental composition of the important ultratrace constituents.

8.3 Microanalysis Techniques at Nanometer Dimensions

GOALS: Semiconductor devices are reaching sub-micrometer dimensions. To perform chemical characterization of these structures and the processing steps necessary to produce them, advanced methods of microbeam analysis will be developed which can perform at the nanometer scale. Two specific techniques at the forefront of sub-micrometer analysis will be developed:

a) Analytical electron microscopy (AEM) provides chemical, morphological, and structural information down to a scale of about 30 - 50 nm with existing instrumentation. The new NBS-NIH Nanometer Analysis Facility, which will be on-line in the fall of 1987, offers the capability to extend the AEM technique to the scale of 1 - 10 nm. The current base of research in quantitative analytical electron microscopy and compositional mapping to the nanometer scale will be given particular emphasis on semiconductor characterization.

MILESTONES

Year 1: Prepare ultrathin semiconductor specimens for analytical electron microscopy and evaluate the practical limit of spatial resolution.

Year 2: With ultrathin specimens, study utility of electron energy loss spectrometry with parallel detection for compositional mapping at high spatial resolution.

b) Secondary ion mass spectrometry (SIMS) can be extended to the scale of 100 nm with high detection sensitivity through the use of pulsed ion beams derived from high brightness liquid metal ion sources in combination with time-of-flight (TOF) mass spectrometry for simultaneous detection of the total mass spectrum. This instrument will be used to explore high sensitivity/high spatial resolution analysis of semiconductors.

MILESTONES

Year 1: Determine detection limits and sensitivity/spatial resolution trade-offs for trace elements of interest in Si and GaAs/GaAlAs under high spatial resolution conditions.

Year 2: Develop quantitative analysis techniques and standards for TOF-SIMS applications to semiconductors.

LIGHTWAVE MEASUREMENT TECHNOLOGY
FY 1990 Initiative and Future Initiative
Project Plan

## Introduction

Optical fibers are the transmission medium of choice for emerging terrestrial communications systems. The current world market for fibers and supporting components is $2.5B per year and is growing at about 25% per year. The U.S. accounts for $1.1B of this market. Growth of the U.S. market has slowed as the construction of long-distance lines has saturated but will pick 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 measurement-intensive nature of this field is reflected in the fact that measurements account for 20% of the cost of manufacturing optical fiber cable.

## Plans

NIST is using existing resources to develop measurement support for multimode and single-mode fibers. NIST is seeking additional resources for measurement development for related components and technologies in three groups, and this Project Plan addresses this expanded effort. Within the three groups are six projects. Each is described individually within this Project Plan.

| Group | Project | Measurement Support For |
|---|---|---|
| Group 1 | Project 1 | sources, detectors, and waveguides |
| Group 2 | Project 2 | modulators, demodulators, detectors |
| Group 3 | Project 3 | switches and amplifiers |
| | Project 4 | coherent communications, multiplexing |
| | Project 5 | hybrid and integrated optic circuits, materials characterization |
| | Project 6 | long-wavelength fibers, system performance |

A minimum of five initiatives will be necessary to fund measurement development for the three groups. Three of these initiatives have already been approved by Congress and are presently providing $1.85M per year of a needed $10M per year of new funding. A fourth initiative is presently part of the FY 1990 Budget of President Reagan, now before Congress. The fifth initiative is still in the proposal stage. The chart below shows the funding associated with each of these sources.

Funding in $M/year

| | Funding Required | Funding Provided | | | Funding Requested | |
|---|---|---|---|---|---|---|
| | | FY 1987 Init. | FY 1988 Init. | FY 1989 Init. | FY 1990 Init. | Future Init. |
| Group 1 | 2.5 | 0.95 | | 0.40 | 1.15 | |
| Group 2 | 2.5 | | 0.50 | | 1.45 | 0.55 |
| Group 3 | 5.0 | | | | | 5.00 |
| | 10.0 | 0.95 | 0.50 | 0.40 | 2.60 | 5.55 |

CEEE chose to apply the funding from the FY 1988 initiative to Group 2 even though Group 1 was not yet fully funded. This decision was taken to enable work to begin on Group 2 earlier than would otherwise have been possible. Thereafter, CEEE returned to applying new funding to the groups in numerical order until each group is fully funded.

The following discussion describes the work that will be undertaken in each of the six projects. Representative planned accomplishments are also shown.

Project 1: Sources, Detectors, and Waveguides

Laser and light emitting diodes are the sources that create the light sent down optical fibers. Detectors capture the light at the receiving end and convert it to an electrical signal for subsequent processing. Waveguides are optical paths embedded in optically active materials. The waveguides channel light in desired directions and to transfer it from one path to another.

To provide measurement support for sources, NIST is using funding from the FY 1987 and FY 1989 initiatives to develop measurements for key diode characteristics including pulse width and speed, linewidth to 0.1 part per million (ppm), wavelength to 0.1 ppm, and power output. With additional funding from the FY 1990 initiative, NIST will correlate key aspects of device design with linewidth and will measure linewidth and wavelength to closer tolerances in preparation for the coherent component of the work in Project 4 on Multiplexing and Coherent Communications. NIST will also develop measurements for diode spectral purity, modal noise, threshold current, and stability.

To provide measurement support for detectors, NIST is using funding from the FY 1987 and FY 1989 initiatives to develop measurements for a first set of parameters needed to characterize detectors, including spectral responsivity (sensitivity as a function of frequency), uniformity of response over the detector's surface, and speed and linearity of response. The additional funding requested in the FY 1990 initiative will enable expansion to include measurements for electronic noise in detectors, characterization of detector/amplifier packages, and fabrication of special detectors to enable correlation of key aspects of design with noise performance and sensitivity. Noise measurements are especially important since improved noise performance reduces errors in transmission and enables reduction of the numbers of repeaters (re-amplification stations) along an optical fiber communications line. That reduction in turn reduces the cost and increases the reliability of the line.

To support waveguides, NIST is using funding from the FY 1987 and FY 1989 initiatives to develop measurements and theory for attenuation and mutual coupling in the guides, and measurements for index profile. The additional funding from the FY 1990 initiative will be applied to develop time-domain reflectometry techniques that will enable determining the performance and defects in optical waveguides. Also, NIST will extend its measurement development beyond the present materials supported, glass and lithium niobate, to compound semiconductors.

Finally, the FY 1990 initiative will support construction of a facility for the preparation of optoelectronic materials and devices needed for measurement development for sources, detectors, and waveguides.

FY 1990 Accomplishments (FY 1990 Initiative):

Develop models and a laboratory system to support measurement development for noise in the detectors that receive lightwave signals sent through optical fibers. Noise in detectors is a major factor degrading the performance, and thus the marketplace competitiveness, of fiber optic systems.

Develop a laboratory system for use in developing optical time-domain reflectometry measurements for characterizing the integrated waveguide structures that control the paths of lightwaves in fiber optic systems. Special measurements are needed to support emergence of improved waveguide products.

Project 2: Modulators, Demodulators, and Couplers

Programmatic Description:

Modulators place information on the lightwaves that are sent down optical fibers. Demodulators remove that information at the point of reception. The rate at which modulators and demodulators perform their functions is one of several factors that determine the information handling capacity of a fiber optic system. Couplers join optical fibers together and must transfer light with minimum loss to keep signal strength strong. They require mechanical precision and special optical interface technology to perform their function efficiently.

For measurement support for modulators and demodulators, NIST is presently applying the funding from the FY 1988 initiative to develop measurements for the dominant method of modulation, pulse code modulation. Special emphasis is being given to measurements for characterizing discrete lithium niobate modulators, with focus on modulation depth and modulation speed. The FY 1990 initiative will support expansion to additional types of pulse code modulators: integrated compound-semiconductor modulators, and integrated superlattice compound-semiconductor modulators. Finally, a small amount of additional funding from the proposed future initiative will be used to accelerate the work on pulse code modulation and to enable expanding this project to include coherent modulation for emerging ultra-high-performance systems. This work ties into and supports the coherent component of Project 4 on Multiplexing and Coherent Communications.

For couplers, NIST is using funding from the FY 1988 initiative to support development of measurements for losses in the "passive" couplers for joining both single-mode optical fibers and multimode optical fibers. The FY 1990 increase will enable expanding the work on "passive" couplers to include measurements for bandwidth and coupling geometry. Finally, a proposed future initiative will enable expansion and acceleration of the work on "passive" couplers and later extension to "active" couplers. Active couplers incorporate active devices, such as sources and amplifiers, right into the structures of couplers. The work on active couplers ties into and supports the work in Project 3 on Switches and Amplifiers.

FY 1991 Accomplishment (FY 1990 Initiative):[1]

Develop laboratory system to support measurements of bandwidth degradation by couplers. Couplers must meet rigid requirements for bandwidth preservation to prevent degradation of system performance.

Year 1 Accomplishment (Future Initiative):

Develop laboratory system for characterizing coherent modulators. Coherent modulators must achieve high performance levels to enable coherent systems to achieve high information rates.

Interactions with Industry:

For this project NIST anticipates: industrial research associates, collaborative research projects with industry and universities (e.g., work with Colorado State University, University of Illinois, and Bell Labs on chemical beam methods for sample preparation), contributed samples to support measurement development, and joint standards development with the Electronic Industries Association.

Project 3: Switches and Amplifiers

Programmatic Description:

Optical switches control the passage and direction of signals through an optical communications system. Optical amplifiers restore the strength of weak optical signals that must travel long distances or that must be subdivided many times for the multiple branches of a local area network.

For switches, NIST will focus on measurement of switching times, with resolution to 10 picoseconds initially, and later to 1 picosecond. The speed of switches is one of the key factors limiting the rate of information handling by an optical communications system. After addressing switching time, NIST will develop measurements for other important parameters of switches, such as efficiency and on/off voltages. For amplifiers, NIST will

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[1]Because of first-year costs for equipment and facilities, first-year funding will be focused on Project 1 until the second year when part of Project 2 can be funded also. Thus there is no first-year FY 1990 milestone for Project 2.

focus on measurements of bandwidth and noise first, then gain, heterodyne responsivity, and linearity.

Year 1 Accomplishments (Future Initiative):

Design and build a laboratory system for use in developing measurements of the speed of optical switches, with 10-picosecond resolution. U.S. industry will use this measurement capability to achieve high optical switching speeds. High speeds are essential for high rates of information transfer in competitive optical systems.

Design and build a laboratory system for use in developing measurements of bandwidth, noise, and gain in optical amplifiers. These are the principal parameters that determine amplifier performance.

Interactions with Industry:

For this project NIST anticipates: industrial research associates, collaborative research projects with industry and universities, contributed samples to support measurement development, and joint standards development with the Electronic Industries Association.

Project 4: Multiplexing and Coherent Communications

Program Description:

Multiplexing and coherent techniques enable increasing the amount of information sent through an optical fiber communications system. Multiplexing means combining different optical signals together at the point of transmission for more efficiently handling. That process is reversed at the point of reception where the signals are separated from each other. Coherent techniques enable many different signals, each of which may contain many multiplexed signals, to travel down an optical fiber simultaneously and to be separated readily at the receiving end by tuning, much as a radio or television set tunes. Coherent techniques also enable increasing the signal-to-noise ratio by about 20 dB (100 times better). This improvement reduces the number of repeaters (amplification stations) required in long-distance lines. The reduction of the number of repeaters lowers system costs and increases system reliability. High system reliability is particularly important for planned transoceanic systems since repairs of repeaters will be extremely expensive. Coherent techniques will also be important for local area networks where signal-to-noise ratio will be degraded by repeated subdivision of signals for the multiple branches of the networks.

The performance of a coherent system requires precise control of the frequency and phase of the light in the system. To help achieve this control, NIST will develop absolute frequency standards for use at several wavelengths in the vicinity of 1.3 and 1.55 micrometers. Related transfer standards will be developed to enable delivery to industry. Also, highly accurate measurements for phase noise will be developed. For multiplexers, NIST will focus first on electrical techniques for multiplexing. Then NIST will move quickly to optical techniques using discrete components and finally to optical techniques using integrated-circuit components. Wavelength-division multiplexing will be the key technique addressed. Key parameters that require measurement support include cross-talk, attenuation, coupling efficiency, bandwidth, and polarization.

Year 1 Accomplishments (Future Initiative):

Develop measurement methods for characterizing a key performance parameter (cross-talk) in wavelength-division multiplexers. Multiplexers combine multiple signals together to increase the information handling capacity of optical fiber systems. High performance is essential for competitive systems.

Develop first laboratory implementation of a frequency standard for coherent communications systems operating at 1.3 micrometers. Coherent techniques can improve system performance by providing better noise tolerance. They require better frequency references than are now available before U.S. industry can make them a competitive reality.

Interactions with Industry:

For this project NIST anticipates: industrial research associates, collaborative research projects with industry and universities, contributed samples to support measurement development, and joint standards development with the Electronic Industries Association.

<u>Project 5: Materials Characterization and Integrated-Optic Circuits</u>

Programmatic Description:

Lack of measurement methods and verified data for characterizing electrically active materials is hampering the development and application of new optoelectronic devices. Both discrete and integrated-optic devices are affected, but the need for materials data is especially critical for integrated-optic circuits. This project will develop the measurement methods and data required to meet that need, focusing both on lithium niobate and compound semiconductors. Lithium niobate and glass will be used in discrete components. Compound semiconductors will be used in both discrete components and integrated-optic circuits.

For lithium niobate, measurement techniques will be developed for surface roughness and for electro-optic, acousto-optic, magneto-optic, and thermo-optic properties. For glass, measurement techniques will be developed for attenuation, coupling losses, cross-talk, and switching efficiency. For compound semiconductors, measurements will be developed for attenuation, coupling losses, bandwidth, cross-talk, and switching efficiency.

Year 1 Accomplishments (Future Initiative):

Develop a laboratory system for measuring the electro-optic coefficients of optical materials, as the basis for published reference data for industry. Lack of accurate data on optical materials is retarding U.S. industry's development of both discrete optical devices and integrated-optic circuits.

Develop a first method for attenuation measurement in integrated-optic circuits. Better measurements of attenuation will aid U.S. industry in overcoming present high attenuation levels. These high levels are inhibiting the emergence of powerful, low-cost integrated-optic circuits as competitive products.

Interactions with Industry:

For this project NIST anticipates: industrial research associates, collaborative research projects with industry and universities especially on integrated optics, contributed materials samples and integrated optic devices to support measurement development, and joint standards development with the Electronic Industries Association.

Project 6: Long-Wavelength Fibers and System Performance Measures

Programmatic Description:

Current optical fibers, based on silicon dioxide, have attenuation as low as 0.2 dB per kilometer. New long-wavelength fibers, based on halides, are under development. They offer reduced levels of attenuation levels of 0.001 to 0.002 dB per kilometer. These fibers will operate at wavelengths of 1.8 to 3.0 micrometers, compared to the present 1.3 and 1.55 micrometer wavelengths of silicon dioxide fibers. The new long-wavelength fibers are important to long-distance lines, especially transoceanic lines, since they will reduce the number of repeaters (amplification stations) required by the line. This reduction will increase system reliability and reduce system cost.

As the performance and complexity of optical fiber systems increases, the industry will need more powerful methods for verifying and maintaining that performance. In particular, industry will need objective measures applicable both to sophisticated long-distance lines, including the transoceanic lines, and to expansive local area networks.

For the long-wavelength fibers, NIST will develop special methods for determining their unusually low levels of attenuation. These methods will affect R&D, marketing, and design of systems employing the fibers. As these fibers come into service, NIST will have to provide special methods for characterizing their numerical aperture, spot size, and cut-off wavelength.

For system performance measures, NIST will develop accurate measurements of bit error rates. First, NIST will focus on detailed studies aimed at proper interpretation of "eye diagrams", a sensitive analog technique for qualitatively assessing bit error rates. Later, NIST will development more comprehensive digital techniques that will give precise quantitative assessments of bit error rates in optical fiber systems.

Year 2 Accomplishments (Future Initiative):[2]

Design and build a laboratory system for developing measurements for attenuation in ultra-low-loss fibers operating at long wavelengths (1.8 to 3.0 micrometers).

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[2]Because of first-year costs for equipment and facilities, funding for Project 6 will not begin until the second year.

Design a system for critical measurement and interpretation of "eye diagrams" used for evaluating the bit error rate, a major parameter for characterizing the performance of fiber-optic systems.

Interactions with Industry:

For this project NIST anticipates: industrial research associates, collaborative research projects with industry and universities, contributed samples of long-wavelength fibers to support measurement development, contributed test equipment for systems performance measures, and joint standards development with the Electronic Industries Association.

MICROWAVE MEASUREMENT TECHNOLOGY
Future Initiative
Project Plan

Summary

Microwave systems are critical to the national economy, the national safety, and the national security. The U.S. relies on high performance microwave systems to provide corporate communications, to land airplanes safely, to warn of weather disasters, to conduct international affairs of state, and to defend the nation. In these capacities, microwave systems serve as the eyes of the nation and the backbone of its worldwide communications networks.

The amount of microwave equipment that these and other microwave services require is vast and growing. Present U.S. shipments of microwave equipment are estimated at $35B per year and account for nearly 1/6 of all electronic equipment, systems, and components shipped in the U.S., valued at $223B for 1987. Worldwide shipments of microwave equipment are estimated at $81B per year and are expected to reach $143B per year in the year 2000 (1988 dollars).

The growth in the worldwide market for microwave systems arises from both traditional applications, like those mentioned above, and emerging applications. Emerging applications include: microwave electronics for high definition television (HDTV), 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 industrial and corporate applications.

The nations that will win the expanding worldwide market must successfully pursue three revolutionary changes in microwave electronics: extraordinary performance levels; integration; and higher frequencies.

> Extraordinary performance levels mean improving speed, signal quality, sensitivity, versatility, and flexibility. These improvements are needed to increase information handling capacity and to open new applications areas.
>
> Integration means integrating microwave electronic devices with each other, with optoelectronic devices, and with antennas. Integration is necessary to reduce the size, cost, and weight of microwave systems and to increase their power and versatility.
>
> Exploitation of the higher frequencies means opening frequencies in the region from 30 GHz to 1000 GHz to greater use, or to first use, in order to gain access to the additional spectral space and special properties that they offer.

These changes in microwave technology are just as significant as those that took place in semiconductor technology when integrated circuits replaced transistors and tubes. In fact, that is exactly what is in happening now for microwave technology. These are exciting changes. They will ultimately lead to powerful new products, such as entire microwave systems on individual wafers a few inches in diameter. Each wafer will contain an electronically steerable antenna and integrated electronics for transmission, reception, and

signal processing. Such "microwave systems on a chip" will support robot vision, automobile radar, and other applications.

However, the promises implicit in advanced microwave technology cannot be realized without dramatic improvements in measurement support. NIST has long been aware of the shortfall in its resources to meet industry's measurement needs. Industry executives, through the IEEE's Committee to Promote National Microwave Standards and through the National Conference of Standards Laboratories, have decried the lack of NIST measurement support for industry, have surveyed the needs, and have spelled out the action needed from NIST.

NIST's response is this initiative. NIST proposes to build an expanded microwave measurement technology program in order to provide advanced measurement support for high performance microwave components in three classes: (1) individual components, including antennas, for 1-100 GHz; (2) integrated circuits and integrated antennas for 1-100 GHz; and (3) integrated circuits and integrated antennas for 100-1000 GHz.

This expanded measurement program will provide the measurement capability needed to accelerate R&D toward new products, to improve quality control during manufacturing, to provide the basis for voluntary industry standards for compatibility and other aims, to support the specification and procurement of microwave products, to improve access of U.S. products to international markets, and to assure U.S. international competitiveness in one of the largest segments of the world market for electronic products.

## Organization of this Document

In this document, the following topics are discussed:

(1) Definition of Microwaves
clarification of terminology

(2) Capabilities and Limitations of Microwaves
technical description of the capabilities and limitations of microwaves, needed for understanding the following material

(3) Microwave Electronics Markets
the size and nature of microwave markets, and the expanded or new services demanded by those markets

(4) Technical Goals for Industry in Response to Marketplace Demands
the technical goals that industry must achieve if its products are to meet the demands of the marketplace

(5) NIST Measurement Support for Industry's Technical Goals
the measurement capability that NIST must develop to enable industry to achieve its technical goals

## Definition of Microwaves

Microwaves are radiated electromagnetic energy just like the radio waves used for radio and television broadcasts, except that microwaves are about 1000 times higher in frequency. Lightwaves are similar to microwaves, but are even higher in frequency, about another 1000 times higher.

### Overview of Frequency Spectrum

| | | |
|---|---|---|
| Megahertz (MHz) = $10^6$ Hz | medium frequency waves | a.m. radio |
| | very high frequency waves | f.m. radio, TV, etc. |
| | ultra high frequency waves | TV, other |
| Gigahertz (GHz) = $10^9$ Hz | centimeter waves | MICROWAVES |
| | millimeter waves | MICROWAVES |
| | sub-millimeter waves | MICROWAVES |
| Terahertz (THz) = $10^{12}$ Hz | infrared light | |
| | visible light | |

Microwaves have frequencies in the range of 1-1000 GHz.[1] Most microwave systems today operate in the range of 1-30 GHz; but frequencies up to 100 GHz are increasingly used, and applications to 300 GHz and even to 1000 GHz are in the offing. Microwaves get their name from the fact that they travel through

[1]The term "microwaves" is sometimes used to represent frequencies in the range of 1-30 GHz. Here "microwaves" will be used to represent all frequencies in the range of 1-1000 GHz. The terms centimeter waves, millimeter waves, and sub-millimeter waves will be used to distinguish among the types of microwaves.

the atmosphere as closely spaced waves. If microwaves could be made visible, they would look like a succession of small ripples, much like the ripples that move across a pond when a rock is dropped in it. The distance from one ripple to another in a microwave is called the wavelength and is usually measured in centimeters or millimeters, hence the terms "centimeter waves" and "millimeter waves," for key portions of the microwave spectrum.

Microwaves are an important part of the frequency spectrum available for our use. This frequency spectrum is limited in capacity because a given frequency cannot be used by two systems at the same time in the same location without mutual interference. The demand for certain frequencies within the spectrum is high, so many conflicts arise. Often these conflicts are international in scope and must be resolved by international bodies.[2]

Communication systems that employ microwaves consist of many electronic components. At the transmission end of a microwave system, electronic devices create and amplify the microwave beam and place information on it. Antennas radiate the beam toward the receiving area. At the receiving end, other antennas capture the incoming beam and other electronic devices remove the information from it. All of these components must work well to preserve the fidelity of the information on the beam. The measurements developed for microwave systems must assure that all functions necessary to accomplish this goal work correctly.

Radar systems work much like communication systems except that they use the same antenna for transmission and reception and they send out a pulsed beam of microwaves, rather than a continuous beam.

Capabilities and Limitations of Microwaves

Microwaves have inherent capabilities and limitations relative to radio waves of lower frequency. The degree to which the capabilities can be realized in real microwave electronics depends on the development of sophisticated microwave technology that is highly measurement intensive.

High information capacity: Microwaves can carry very large amounts of information. This capability is the result of the fact that microwaves have a very high frequency. All radio waves, including microwaves, can carry information in proportion to their frequency. For example, microwaves can carry 1000 times more information than radio waves used for a.m. and f.m. radio. Put another way, one microwave signal can carry all of the program material of 1000 a.m. radio stations simultaneously. This high information capacity is important both to telecommunications applications and to signal processing applications.

Line-of-sight transmission: When microwaves are radiated by antennas, they travel in a straight, line-of-sight manner. This is true because microwaves, unlike radio waves of lower frequency, pass right through the ionosphere,

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[2]The World Administrative Radio Conference meets every four years under the aegis of the International Telecommunications Union to make the frequency allocations, and the International Frequency Registration Board keeps track of the allocations.

which is the electrically charged atmospheric layer surrounding the earth. For this reason, microwaves cannot work their way around the globe by bouncing back and forth between the earth and the ionosphere, as radio waves of lower frequency can do. Instead, microwaves must be relayed along the surface of the earth from one microwave tower to another, or they must be transmitted to satellites that retransmit them downward to desired locations or that relay them to other satellites for retransmission downward. This line-of-sight characteristic is a limitation for some applications. For other applications, it is an advantage: it helps prevent interference among different microwave systems operating on the same frequency.

Highly focused: Microwaves can be focused into narrow beams much more easily than radio waves of lower frequency. In this sense microwaves approach the characteristics of light; light is readily focused by reflectors like those in flashlights. Because microwaves can be focused, their energy can be delivered to small nearby receiving antennas or to entire geographical areas, such as entire states, from remote satellites. Also, because of focusing, two or more microwave beams can be directed to adjacent areas without mutual interference, even if they operate on the same frequency. This characteristic improves efficiency in the use of the microwave portion of the frequency spectrum.

Small antennas: The high frequencies of microwaves reduce the size of the antennas needed to achieve a given degree of focusing. This fact reduces the cost of microwave systems and increases the diversity of applications that they can serve. For example, the relatively small size of microwave antennas makes them suitable for roof-top mounting for corporate communications systems. The size advantage also facilitates mobile applications in automobiles, airplanes, satellites, and space vehicles. The size reduction is particularly important for the design of highly focused antennas, since antennas with high focusing are larger than those with less focusing at a given frequency. Even very highly focused microwave antennas can be tolerable in size (several meters); antennas with comparable focusing at lower frequencies would be impossibly large.

Atmospheric interactions: The higher frequencies of the microwave family (the millimeter-wave and sub-millimeter-wave frequencies) interact more with the atmosphere than do radio waves of lower frequency. This interaction limits the distances over which these microwaves can travel through the atmosphere, a problem for some applications. For other applications, this interaction is an asset: it enables the use of microwaves to sense weather conditions that radio waves of lower frequency cannot "see"; and it enables limiting a transmission to a controlled distance to reduce unwanted reception by nearby users or unwanted interference with them when they are operating on the same frequency. This characteristic is particularly important when using millimeter waves for local applications such as local communications systems or local radar systems for monitoring moving objects. In free space, atmospheric interactions are not a problem, even for satellite-to-satellite communications, since satellites orbit well above the atmosphere.

Metal/earth interactions: Microwaves interact more sensitively with conducting objects, including the earth, than do radio waves of lower frequency. Therefore, they are effective for radar, navigation, guidance, and remote sensing (geological, agricultural, and weather sensing).

High spatial resolution: The higher frequencies in the microwave spectrum provide high spatial resolution. High resolution is particularly important for radar systems since it allows them to "see" objects more clearly and thus to identify them more accurately.

Optoelectronic technology: Microwave technology can be integrated with optoelectronic technology to provide powerful capabilities that are not achievable by either technology alone. For example, microwave technology is now being used to place information on lightwaves in experimental optical fiber systems. This new approach has produced the highest information rates yet achieved in optical fiber systems.[3] Conversely, optical fibers show promise for use in large microwave antennas; and embedded optical waveguides show promise for use in integrated microwave antennas and in microwave satellite systems.

Note in the above discussion that microwaves are repeatedly associated with smallness: small waves, measured in centimeters and millimeters; small antennas; and fine scales of resolution for radar. All of these characteristics derive from the high frequencies of microwaves. However, as noted earlier, the special properties of microwaves can only be fully exploited with sophisticated microwave technology, and that technology is very measurement intensive.

## Microwave Electronics Markets

### U.S. Outlook

U.S. shipments of microwave equipment are estimated at $35B for 1988.[4] Microwave equipment represents nearly 1/6 of all U.S. shipments of electronic equipment, systems, and components, valued at $223B in 1987.[5] Only one other equipment category has greater shipments: computers and their peripherals.

Most microwave equipment falls in the category "radio communications and detection equipment" (SIC Code 3662)[6]. For this reason, the performance of

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[3]"Lasers" in Fiber Optic News, page 4 (April 4, 1988). The potential for microwave electronics in fiber optic systems is further discussed by Jeff Montgomery and John Ryan, "Leap Seen for Microwave Fiber-Optics", Microwaves & RF, Vol. 26, No. 6, p. 53 (June, 1987).

[4]Microwave equipment shipments are not tracked as an independent data category in the current Standard Industrial Classification (SIC) System of the U.S., so the exact levels are difficult to determine. The figure shown here is based on an estimate that U.S. shipments represent about 95% of those for North America as a whole. The North American production is estimated as $36.8M for 1988 by Jeff D. Montgomery of ElectroniCast Corporation in "Microwaves to 2013", Microwave Journal, Vol. 31, No. 9, pp. 259-272 (September, 1988).

[5]1988 Electronic Market Data Book by the Electronic Industries Association Marketing Services Department, p. iii.

[6]SIC means Standard Industry Classification System.

this category provides the best documented estimator we have of the outlook for U.S. shipments of microwave equipment. U.S. shipments of all equipment in this category were valued at $54B in 1987 and are expected to grow at 4% in 1989 and at 5% per year for the following five years in real terms (exclusive of inflation), according to the Department of Commerce.[7] If these rates of growth are applied to the microwave content of U.S. shipments ($35B in 1988) through 1994, and if the 5% rate continues rate continues to the year 2000, then the following levels of microwave shipments in constant 1988 dollars will result:

Projected Growth of U.S. Microwave Equipment Shipments

| | | Billions of Dollars | | |
|---|---|---|---|---|
| | | 1988 | 1994 | 2000 |
| Constant 1988 dollars | (no inflation) | 35 | 46 | 62 |

The enormous size of U.S. shipments of microwave equipment reflects the broad range of services that microwave systems already provide: communications; navigation; radar; guidance; remote sensing (geological, agricultural, and weather); electronic warfare; test and measurement; industrial applications; consumer applications; and others. The demand for new or emerging services will keep the shipments of microwave equipment high. Examples of new or emerging services include: on-board wind shear detection systems for airplanes; improved radar systems for weather forecasting; collision avoidance radar systems for automobiles[8]; low-power high-speed communications systems for local environments[9]; local radar systems for monitoring and controlling moving objects[10]; vision and control systems for robotics; high speed computer circuits; signal processing for high speed fiber optic communications systems; signal processing for high definition television (HDTV); and local bypass facilities for corporate communications.[11] Other new or emerging applications

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[7]1989 U.S. Industrial Outlook of the U.S. Department of Commerce, pp. 27-1 to 27-3.

[8]West Germany is in the lead. AEG Ag has announced imminent introduction of an integrated circuit chip containing a millimeter-wave receiver, with a projected cost as low as $15, suitable for communications systems and automobile radar.

[9]Japan's Key Technologies Research & Development Center is investing 45 million yen to develop this flexible new communications product for frequencies from 10 kHz to 1000 GHz.

[10]Japan's Key Technologies Research & Development Center is investing 120 million yen in developing remote monitoring and control systems using millimeter waves capable of handling 100 units of moving objects in natural environments within 2 kilometer radius to assure safe functioning.

[11]The facility bypass networks bypass local public telephone networks to achieve one or more aims: "reduce costs, improve service quality, and offer greater security, reliability, and service flexibility". They are usually implemented with microwave systems since installation of custom cable systems

require satellites. Examples include: television receive-only systems associated with direct broadcast satellite (DBS) service[12]; satellite mobile systems; direct business use of satellites for video programming; and end-to-end facility bypass networks. The last two are already major industries. Many of the others have the potential to become so.

U.S. Government Purchases

Of the $54B of equipment in the category "radio communication and detection equipment" (SIC Code 3662), $26B or 48% was purchased by the U.S. Government. Of that $26B, $23B or 43% of the $54B, was purchased by the Department of Defense, according to the Department of Commerce.[13] These figures provide the best documented estimators we have of the fraction of microwave equipment purchased by the Government.

While the DOD is expected to remain the largest Government purchaser of microwave equipment, other Government agencies are increasingly involved in making, stimulating, or approving major uses of microwave equipment. The Departments of Transportation, Commerce, and State, and the Federal Communications Commission and the National Aeronautics and Space Administration provide examples:

> The Department of Transportation (FAA) is currently participating in a $5-6B procurement of microwave equipment to upgrade the microwave systems at 100 U.S. airports. The new systems include: (1) communications systems for exchange of information between airplanes and control towers; (2) landing systems for aircraft; (3) radar systems for monitoring weather; and (4) radar systems for monitoring the movement of airplanes in the air and on the ground.[14]
>
> The Department of Commerce is the principal partner in a related three-agency $0.5B procurement for NEXRAD, the next generation of weather radar. By the mid 1990s, 175 NEXRAD systems are slated for installation.[15]

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is too expensive and far less flexible. The Department of Commerce indicates, in a review of studies of the subject, that "16-29 percent of large-volume telephone company customers are bypassing their local telephone companies". End-to-end facility bypass networks bypass both local and long distance lines of public telephone networks. 1988 U.S. Industrial Outlook of the U.S. Department of Commerce, p. 33-3.

[12] Japan is in the lead.

[13] 1989 U.S. Industrial Outlook of the U.S. Department of Commerce, p. 27-1.

[14] Information provided by the FAA. The system is described in the National Airspace System Plan, Federal Aviation Administration, U.S. Department of Commerce (June, 1988). A discussion of the new system appears in "Why Tomorrow's Skies will be a Whole Lot Safer", Business Week, pp. 99, 102 (September 5, 1988).

[15] Performance, Unisys Defense Systems Issue, p. 5 (Spring/Summer, 1988).

The Department of Transportation (FAA) is requiring that wind shear detection systems be installed on 3600 jetliners within four years. While costs vary with the type of aircraft, an estimate of $50,000 per aircraft has been mentioned leading to a total cost of $0.2B.[16] FAA is not specifying the technology to be used; the marketplace will decide. Microwave radar, laser radar, and passive infrared systems are the primary candidates for forward looking detection.[17]

The Department of State has issued a request for proposals for a new worldwide telecommunications network that will cost up to $0.7B. It will contain a mix of microwave and fiber optic communications technologies and computers.[18]

The Federal Communications Commission has just approved the launching of 23 new communications satellites, valued at $4B.[19]

The National Aeronautics and Space Administration, in cooperation with the National Oceanic and Atmospheric Administration of the Department of Commerce, is actively evaluating the merit and design of an Earth Observing System, composed of four to six satellites to monitor long-term changes in the earth's atmosphere, magnetic field, geology, etc. The project is collaborative with Japan and the European Community. U.S. costs for the system would be $2B to $4B over ten years. The system would rely critically on advanced microwave and optical equipment.

World Outlook

The world market for microwave equipment is estimated to be 2.1 to 2.5 times the size of the U.S. market alone.[20] If we assume the median value of 2.3 and

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[16]"Wind-Shear Devices to Be Required on Jets", Washington Post, p. A19 (September 27, 1988).

[17]FAA and NASA are jointly investing $24.8M over five years (beginning in 1987) to stimulate development of advanced wind shear detection systems in their Forward Looking Technology Program. The systems are described in Airborne Wind Shear Detection and Warning Systems: First Combined Manufacturers' and Technologists' Conference, Federal Aviation Administration, U.S. Department of Transportation, and National Aeronautics and Space Administration (January, 1988).

[18]The project is described in Department of State Telecommunications Network, Request for Proposal by the U.S. Department of State (October, 1988).

[19]"FCC Okays $4B in Satellite Launchings", Electronic Engineering Times, p. 38 (January 16, 1989).

[20]Again, good figures are lacking, but estimates can be made based on estimates of world market sizes for categories containing a lot of microwave equipment. Dick Anderson, Vice President and General Manager of the Microwave and Communications Group of Hewlett-Packard, has provided one of those estimates in a talk at Test and Measurement Trends and Technologies -

a real growth rate of 4% for 1989 and 5% for the following five years, identical to the pattern projected by DOC for the next six years for the U.S. alone, and if the 5% rate is further assumed to apply to the year 2000, then the following levels of microwave shipments in constant 1988 dollars will result:

Projected Growth of World Microwave Equipment Shipments

| | Billions of Dollars | | |
|---|---|---|---|
| | 1988 | 1994 | 2000 |
| Constant 1988 dollars (no inflation) | 81 | 106 | 143 |

The U.S. is not penetrating the rest of the world market well. For example, U.S. exports in the category of "radio communication and detection equipment" (SIC Code 3662) were only $4.5B in 1988. Imports were higher at $5.0B, yielding a negative balance of trade and an export/import ratio of 0.9. Japan supplies 48% of all U.S. imports in this category, four times the contribution of any other country. Only 9% of U.S. exports in this category go to Japan.[21] In summary, the U.S. has a lot to gain by better penetration of the world market, and a lot to lose by increased penetration of its own market.

Current data on the performance of other countries in the world market for microwave equipment are difficult to obtain, but data for 1981 for telecommunications equipment indicate the strength of the chief competitors of the U.S.: Japan, Canada, and Europe. In that year, the U.S. still had a favorable balance of trade with an export/import ratio of 1.3. The table below shows that the competing nations achieved higher export/import ratios than the U.S. while maintaining high absolute levels of exports. Since 1981, the U.S. export/import ratio has declined to 0.9, as noted above.

1981 Telecommunications Equipment Trade Data[22]

| | Amount Exported, Ratio (re: 1.0 for U.S.) | Export/Import Ratio |
|---|---|---|
| U.S. | 1.0 | 1.3 |
| Japan | 1.4 | 19.8 |
| Canada | 2.2 | 2.1 |
| Europe | 4.6 | 3.8 |

Competing factors will affect the growth of the world market for microwave equipment. On the one hand, the demand for the services of microwave systems is rising, especially as new applications are identified. On the other hand,

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Editorial Seminar, sponsored by Hewlett-Packard (April 6, 1988).

[21] 1989 U.S. Industrial Outlook of the U.S. Department of Commerce, p. 27-2.

[22] "The Telecommunications Industry", U.S. Department of Commerce, International Trade Administration, p. 21 (April, 1983). Focuses on SIC Code 3661 only.

the cost of microwave equipment will fall if microwave integrated circuits and integrated antennas can be successfully developed. These cost reductions will be significant (factors of 100). As a result, the first nations to successfully commercialize microwave integrated circuits and antennas will gain a tremendous advantage in both the U.S. market and the international market for microwave products. The cost reductions, in turn, will inevitably open larger markets for microwave products.

The Japanese are among the nations that are pushing hard to develop microwave integrated circuits, driven almost exclusively by consumer applications. They are highly interested in direct broadcast satellites, mobile radio transmission systems, high-data-rate optical transmission systems, and signal processing for high-definition television (HDTV).[23] The Japanese have proven their ability to be competitive in telecommunications components. According to a recent NSF/DARPA assessment of Japan's telecommunications technology, "The components it [Japan] introduces into the market are increasingly the most advanced in technical characteristics and quality and the lowest in cost. Japan is verging on international market dominance at the components level."[24]

The Europeans are driving hard, too, with a special emphasis on telecommunications applications of microwave technology. They have become major standard setters in this field.

Impact of Optical Fibers

The emergence of optical fiber systems will affect the demand for microwave equipment but in a limited manner only, for two reasons. First, the demand for communications services is so high that all available means of transmitting data will be needed. Second, the emergence of optical fibers affects primarily one type of microwave service: point-to-point communications between areas of high population density. For other types of services, microwave technology will continue to dominate and expand: point-to-point communications services for areas of low population density; point-to-multipoint communication services in all areas; mobile communication services for land, sea, air, and space; sensing, including geological, agricultural, and weather sensing; radar; navigation; guidance; electronic warfare; industrial applications; and consumer applications. These microwave services require one or more of the characteristics that cable technology cannot provide:

| | |
|---|---|
| area coverage: | communications, sensing, radar, navigation, guidance, electronic warfare, consumer applications |

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[23] Far East Scientific Bulletin 11 (1) of U.S. Office of Naval Research, p. 112 (January-March, 1986).

[24] JTECH Panel Report on Telecommunications Technology in Japan - Final Report by the Japanese Technology Evaluation Program, sponsored by the National Science Foundation and the Defense Advanced Research Projects Agency, p. xi (May, 1986).

movement: communications with satellites or mobile vehicles including automobiles, aircraft, ships, and spacecraft; radar

flexibility: communications, electronic warfare

microwave energy: industrial, medical, and consumer applications

"Flexibility" requires clarification. It takes several forms: (1) Microwave systems can be set up quickly without the need to resolve the difficult right-of-way problems that arise when laying cable. (2) Microwave installations are less sensitive to variations in the terrain than cable installations. (3) Satellite and terrestrial microwave systems can be reconfigured readily to serve different geographical areas and new users. (4) Satellite systems can serve vast areas of low population density just as easily as small areas of high population density. Because of this flexibility, microwave systems can serve in both permanent installations and temporary installations such as those used for emergencies.

While optical fiber technology does compete with microwave technology for some communications applications, the more salient relationship between the technologies is complementary or even symbiotic.[25] For example, microwave systems will provide "local area" delivery for signals carried across the country by optical fibers, particularly when mobile subscribers are involved. In fact, microwave and optoelectronic technologies will gradually merge as optoelectronic technology takes on functions in microwave systems and microwave technology takes on functions in optical fiber systems. Together, they will provide levels of performance that neither can achieve alone.

Technical Goals for Industry in Response to Marketplace Demands

To meet the demand for expanded and new microwave services and to compete internationally, U.S. industry must pursue three technical goals for microwave systems:

Goal #1: Improved performance
Goal #2: Reduced cost, size, and weight
Goal #3: Improved access to higher frequencies

To achieve Goal #1 of improved performance, industry must pursue higher information density, improved signal quality, and expanded versatility and flexibility:

Higher information density can be achieved by increasing the information capacity of existing systems and by enabling a greater number of systems to operate without mutual interference in a given region. These advances are highly important because crowding is becoming increasingly serious as additional terrestrial systems come into use. In space, crowding will

[25] "The Evolving Symbiosis of Optical Fiber, Satellites", Washington Post, pp. H-1 and H-5 (August 21, 1988). Also, "Personal View: Systems Integration" by George Heiter, AT&T Bell Laboratories, Microwaves & RF, p. 126 (May, 1988).

become of special concern in 1990 when existing satellite capacity is expected to saturate.[26] Only limited space is available in the valuable geostationary orbit.[27] To enable satellites to operate without mutual interference, high performance antennas with low side lobes must be developed.[28] Also, higher frequencies must be used to provide additional spectral space. Finally, the information capacity of microwave frequencies already in use and of existing optical fiber systems must be increased by developing advanced microwave signal processing electronics.

Improved signal quality is needed to maintain low data error rates, especially as information capacity is increased. Improved signal quality is also needed to improve the sensitivity of microwave systems so that they can serve wider applications in communications, radar, and sensing. Such improvements will require improved fidelity in the microwave signal processing circuits for both digital and analog signals.

Expanded versatility and flexibility will also be required. They can be achieved by developing microwave systems that can operate on many different frequencies simultaneously and that can serve many different geographical areas simultaneously through electronically steered antennas.

To achieve Goal #2 of reduced size, weight, and cost of microwave components, miniature individual components and integrated components will be required for virtually all microwave frequencies. These components will be important for all applications but especially so for mobile, air, and space applications.

To achieve Goal #3 of improved access to the special capabilities and spectral space of the higher microwave frequencies, new electronic technologies capable of efficient performance will be needed. Both the 30-100 GHz range and the 100-1000 GHz range, where microwaves take on quasi-optical behavior, must be addressed.

NIST Measurement Support for Industry's Technical Goals

To support industry in pursuit of the above three technical goals, NIST must provide industry with a broad spectrum of advanced measurement capability. This measurement capability is needed to support research, development, manufacturing, voluntary industry standards for compatibility and other goals,

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[26] 1988 U.S. Industrial Outlook, p. 31-4.

[27] The geostationary orbit lies over the equator and is about 23,000 miles high. It is the only orbit which permits satellites to revolve about the earth in such as way that they remain positioned over the same point on the earth all of the time. This "stationary" position enables them to provide continuous service to the locations beneath them. To place more satellites in this orbit, the spacing between them must be reduced, increasing the problems of mutual interference with adjacent satellites.

[28] Antennas with low side lobes have minimal radiation off to the sides. Such antennas reduce mutual interference between adjacent satellites in orbit or between adjacent ground stations on earth.

specification, procurement, maintenance, acceptance of U.S. products in domestic and international markets, and international competitiveness broadly.

The urgency of this need has been stated in unqualified terms by U.S. industry:

> U.S. industry executives have joined together under the auspices of the Institute of Electrical and Electronics Engineers to form the Committee to Promote National Microwave Standards. The Committee members, which include company chief executive officers and chairmen of the board, have issued a report stressing the urgency of the measurement needs, decrying the weakening position of the U.S. compared to its competitors, spelling out the specific measurement problems, and urging resolution of them by NBS/NIST.[29]
>
> The National Conference of Standards Laboratories (NCSL), operating under the guidance of member executives of major U.S. high technology companies, surveyed 400 organizations (346 industry, 61 government, and 4 universities) to determine key measurement needs. NCSL found a serious shortfall in NBS/NIST measurement support for microwave technology with adverse effects on major sectors of U.S. industry. The report spelled out the measurement problems and urged resolution by NBS/NIST. It also noted the negative effects of inadequate measurement support on national goals, such as productivity improvement, quality improvement, and international competitiveness, among others.[30]
>
> Industry trade articles have highlighted the urgency of the need for expanded microwave measurement support from NBS/NIST for many years,[31] noting, for example:
>
>> "The NBS struggles under a woefully meager budget to research measurement technology and supply measurement services to support the measurements revolution of the '80s and the '90s. Truly an impossible task."[32]

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[29] The PNMS Report - Microwave Metrology in the U.S.A. by the Committee to Promote National Microwave Standards, an ad hoc committee sponsored by the IEEE Microwave Theory and Techniques Society (November, 1987).

[30] Report by the National Measurement Requirements Committee of the National Conference of Standards Laboratories, Sections 1 and 3 (Revision 2, April 1987). The findings of the original survey were published in 1983 and were updated in this latest 1987 revision.

[31] Jim Fitzpatrick, "NBS and Microwave Metrology -- Growing Concern within the Industry", Microwave System News, p. 43 (May, 1984). John L. Minck, "A (Modest) Proposal to Establish a National Bureau of Microwave Standardization", Microwave System News, pp. 67-71 (May, 1986). John Minck, "Some Significant Things That Have Happened to RF in the Last 10 Years", RF Design, pp. 29-34 (October, 1988).

[32] John Minck, "Some Significant Things That Have Happened to RF in the Last 10 Years", RF Design, pp. 29-34 (October, 1988).

The measurement capability that NIST must develop to address these concerns is outlined below in three projects. Each project corresponds to a key group of components that requires improved or new measurement support. Following the outline, the specific work that NIST must carry out for each project is described.

Projects of the Microwave Measurement Technology Initiative

1. Individual Components for 1-100 GHz
   1.1 Electronic Devices
   1.2 Antennas

2. Integrated Components for 1-100 GHz
   2.1 Integrated Electronic Circuits
   2.2 Integrated Antennas

3. Integrated Components for 100-1000 GHz
   3.1 Integrated Electronic Circuits
   3.2 Integrated Antennas

The order of the three projects above indicates the order in which NIST will fund measurement development if initiative funding becomes available. Since the most immediate needs are in the 1-100 GHz range, that range is addressed before the 100-1000 GHz range.

1. Individual Components for 1-100 GHz

The new measurement methods needed for individual components must embody major advances over those currently available. These advances are summarized in the list below and are explained more fully in the paragraph that follows:

Higher accuracy: typically ten times greater

Susceptibility to automation: manual measurement methods too slow for sophisticated new microwave systems

Continuous frequency coverage: not just selected frequencies

Broader interface compatibility: new microwave interfaces for miniature components and new optoelectronic devices

The new measurement methods must be typically ten times more accurate to support emerging high performance systems. They must be susceptible to automation since modern systems are so complex that they cannot be efficiently characterized with today's manual measurement methods. The new measurement methods must operate over broad, continuous frequency ranges to support new systems with greater frequency flexibility; in the past, measurements at key fixed frequencies sufficed. The new methods must support a broader range of interfaces for two reasons: new miniature microwave components, with new types of interfaces, are being introduced to cut the size, cost, and weight of microwave systems; and new optoelectronic devices will be interfaced with microwave devices. For example, optical fibers will likely replace metal waveguides in key roles in satellites and antennas. The fibers are lightweight, low cost, and flexible and do not interfere with microwave beams. They may serve as signal interconnections within satellites or as controlling lines within powerful phased array antennas, among other applications.[33]

The individual components that require improved measurement support may be divided into two groups: (1) electronic devices that generate, process, and transport microwaves without radiating them, such as signal sources, amplifiers, detectors, waveguides, coaxial cable, and connectors; and (2) antennas that transmit and receive the microwaves. The measurement needs of these two classes of components are described below.

### 1.1 Electronic devices

NIST must develop new measurement methods for determining critical microwave quantities in individual electronic devices. The most critical measurement needs correspond to the two functions that a microwave system must perform to convey information from one location to another: (1) transfer microwave power efficiently, and (2) preserve signal fidelity while doing so.

Power transfer measurements

| | |
|---|---|
| power | Determines power levels throughout a microwave system. |
| impedance | Enables components to be interconnected compatibly, with minimum power loss. |
| attenuation | Determines power loss within a component. |

Signal fidelity measurements

| | |
|---|---|
| waveshape | Enables evaluation of signal quality throughout a system and determination of performance of signal sources, amplifiers, modulators, detectors, and electronic switching devices. |
| noise | Enables minimizing electronic noise to optimize information throughput and to reduce errors in transferring data in a microwave system. |

Noise measurements serve as an example of the problems currently faced by industry. Noise is the single most important characteristic of microwave amplifiers and amplifying components (transistors); premiums are charged and

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[33]Phased array antennas contain many radiating elements. By controlling the strength and phase of the signal emitted by each element, the array can be made to produce diverse and well controlled radiation patterns to serve special needs. For example, phased array antennas can be designed to illuminate receiving areas of diverse shapes, or to reduce of unwanted side lobes (radiation off to the side of the antenna) that could interfere with adjacent microwave systems. The "phase" of an element determines the moment at which the alternating microwave signal fed to it goes through its maximum value, relative to the corresponding moments for the signals fed to the other elements.

paid for good noise performance. Noise performance affects the sensitivity and information capacity of systems. Yet present noise measurement capability is not adequate to characterize the noise performance currently being achieved in modern products, so manufacturers and buyers cope constantly with inadequate tools for product development, specification, and evaluation. As a result, manufacturers have repeatedly sought NIST assistance in resolving this problem. NIST must develop methods for measuring noise that are far better than those currently available and that are suitable for adoption as standard methods industry wide.

NIST must also develop measurement methods for determining the microwave properties of materials. The quantities for which measurement methods and data are required are these:

<u>Materials measurements</u>

| | |
|---|---|
| permittivity | Determines the electrical properties of the materials. |
| permeability | Determines the magnetic properties of the materials. |
| uniformity | Determines the degree of uniformity (homogeneity) of materials properties throughout the material. |
| anisotropy | Determines the degree of uniformity of materials properties as a function of angular orientation. |

The performance of microwave components is very sensitive to the microwave properties of the materials of which they are made. That sensitivity is particularly important in the design of the "substrates" (similar to the circuit boards of conventional electronics) that provide the waveguide channels that interconnect individual microwave electronic components. Unfortunately, most existing data on the microwave properties of materials are based on measurements made many years ago on conventional materials at frequencies below 10 GHz. Few data exist for frequencies above 10 GHz, and practically no data exist for newer materials.[34]

## 1.2 Antennas

For antennas, NIST must develop measurement methods that can provide greater accuracy, improved susceptibility to automation, broader frequency coverage, and better control of the radiation pattern of antennas. Such measurement capability will enable antennas to deliver stronger signals to receiving stations, to work in close proximity to other antennas without mutual interference, and to serve applications requiring greater sensitivity and versatility. The phased array antenna is a key example of the type of powerful modern antenna requiring improved measurement support.

---

[34]NIST surveyed industry's measurement requirements for microwave materials and described the urgent needs in its "Summary Report on Measurements and Standards Requirements for Materials Used in Electromagnetic Applications: Results of a Limited Survey" (February, 1985). Everything from substrates, to protective antenna covers (radomes), to microwave integrated circuits is affected. For example, better materials measurements are essential to the success of the automated design and manufacturing processes that produce microwave integrated circuits; these circuits, in turn, can cut the cost of microwave electronics by factors up to 100.

The measurements required fall into two classes: (1) antenna measurements, and (2) materials measurements. The initiative must address antenna measurements for 26-100 GHz[35] and materials measurements for 1-100 GHz.

Antenna measurements

| | |
|---|---|
| gain | Determines how successfully an antenna can focus its power in the forward direction, toward the intended receiving antenna. |
| pattern | Determines focusing performance of an antenna in all directions, essential for illuminating the desired receiving area and for reducing stray radiation that can interfere with adjacent systems. |
| strength | Determines strength of the microwave beam from a transmitting system. |
| polarization | Determines a special property of an antenna that allows it to send two non-interfering signals on the same frequency to double its information handling capacity. |
| bore sight | Determines how closely an antenna radiates in the expected direction. |
| natural signal source characterization | Enables use of the sun, moon, key planets, and stars as natural signal source standards for evaluating and maintaining the performance of earth terminals and satellite microwave systems while in service. |

NIST will also develop measurements for the properties of microwave materials used with antennas, with a special emphasis on materials used for protective covers (radomes) for the antennas. The microwave properties of these materials are not well understood, especially at frequencies above 10 GHz; yet those properties significantly affect the performance of antennas. The key parameters that must be measured for antenna materials are these:

Materials measurements

| | |
|---|---|
| permittivity | |
| permeability | |
| uniformity | |
| anisotropy | |
| transmissivity | Determines how well the material passes microwave power. |
| reflectivity | Determines the amount of microwave power reflected by the material. |

[35]Development of measurements for antennas (non-integrated) below 26 GHz is supported by existing NIST resources.

## 2. Integrated Components for 1-100 GHz

Increasingly, microwave systems will be built in integrated form to reduce size, weight, and cost. Integration will take two principal forms:

> Integrated electronic circuits: integration of microwave electronic devices, like signal sources and waveguides, onto a common substrate along with associated optoelectronic devices
>
> Integrated antennas: integration of the elements of an antenna onto a common substrate along with associated electronic and optoelectronic devices

Integration poses difficult measurement challenges for several reasons:

> Minimal measurement ports: Input and output ports of electronic devices within integrated circuits are not readily accessible. In individual components those input and output ports provided convenient locations for attaching measurement devices.
>
> Measurement probe sensitivity: Circuit elements are closer to each other, so measurement probes are more likely to disturb the circuits that they measure.
>
> Materials sensitivity: The performance of circuits made in integrated form is even more sensitive to materials properties than the performance of circuits made from individual components.
>
> Multiple technologies and interfaces: The incorporation of optoelectronic technology in integrated microwave circuits and antennas leads to an especially complex mix of technologies and interfaces.

These differences necessitate new definitions for measured quantities, new measurement methods, and new physical standards to support those measurement methods.

### 2.1 Integrated electronic circuits

The integration of microwave electronic devices is pursued for reasons similar to those that motivated the integration of conventional semiconductor devices. However, the structures required, the materials employed, and the types of devices used all differ. Also, microwave integrated circuits operate at 1000 times the frequency of most semiconductor integrated circuits (GHz versus MHz), making the performance of the microwave circuits much more difficult to measure. In particular, they are much more sensitive to the presence of measurement probes.

To date, the lack of measurement methods suitable for microwave integrated circuits has hampered the design of integrated circuits and the development of fabrication processes for making them. Measurement problems in microwave integrated circuits are so critical that major manufacturers estimate that 80-90% of the cost of the resulting devices is associated with testing.

There are four classes of measurements that must be developed to support microwave integrated circuits. They can best be distinguished by the locations at which the measurements are made:

<u>(1) Inside devices</u>: measurements internal to the electronic devices within the integrated circuits, to support their design and fabrication

<u>(2) Input/output ports of devices</u>: measurements at the input and output ports of the electronic devices within integrated circuits, to determine the overall performance of the devices and to establish how well they transfer microwave signals to interconnecting waveguide channels

<u>(3) Inside waveguide channels</u>: measurements to determine the performance of the interconnecting waveguide channels themselves

<u>(4) Inside materials</u>: measurements to characterize the microwave properties of the substrates and other starting materials used to make both the electronic devices and the waveguide channels within the integrated circuits.

Measurement development for category (1) will be adequately supported by NIST's Advanced Semiconductor Initiative if all parts of that initiative are funded. Measurements for categories (2), (3), and (4) will require support from this Microwave Measurement Technology Initiative.

For categories (2) and (3), NIST must develop new measurements for the following quantities:

<u>Power transfer measurements</u>

power
impedance
attenuation

<u>Signal fidelity measurements</u>

waveshape
noise

These are the same quantities applicable to individual electronic components, but the measurement methods required are entirely different. Because of the small scale of integrated circuits and the proximity of all of their components, special measurement methods will be required to access the internal workings of the integrated circuits and to prevent interference with their operation during the measurement process. If some interference occurs, it must be minimized. Corrections for any remaining interference must be made based on theoretical calculations. Special contacting electrical measurement techniques and non-contacting optical measurement techniques must be developed to accomplish these aims. Also, special test structures must be developed that can be built right into commercial integrated circuits to facilitate measurement.

For category (4), NIST must develop measurement methods and supporting physical standards for the following properties of the materials used in microwave integrated circuits:

<u>Materials measurements</u>

permittivity
permeability
uniformity
anisotropy
transmissivity
reflectivity

Lack of data on the microwave properties of materials is severely impairing the design and manufacture of integrated circuits. Such data are essential for systems used in automated manufacturing and computer-aided design since these systems depend on materials of known and uniform properties. As noted above, most existing data on the microwave properties of materials are based on measurements made many years ago on conventional materials at frequencies below 10 GHz. Few data exist for frequencies above 10 GHz, and practically no data exist for newer materials.

The materials properties of interest must be measured as a function of temperature and humidity to simulate true conditions when in use. They must be measured as a function of composition to support design and manufacturing processes. They must be measured as a function of frequency to support wideband (frequency flexible) applications.

## 2.2 Integrated antennas

Integrated antennas are one of the most promising of emerging microwave technologies. They are panels, either flat or curved, which contain embedded metallic radiating elements that look much like the wiring patterns in an integrated circuit. Integrated antennas may contain thousands of elements, especially when configured as phased array antennas.[36] Integrated antennas can be very large (many meters in size) or very small (a few centimeters in diameter, fabricated directly on the surface of a single semiconductor wafer). Integrated antennas will contain electronic devices built right into them. These devices will serve as small transmitters and receivers. Each transmitter or receiver may be associated with individual radiating elements or with groups of elements within the antenna. The elements in an integrated

[36]The integrated phased array will be a powerful type of antenna. Its radiation pattern and direction of radiation will be electronically controlled, without physical motion of the antenna. The control is accomplished by adjusting the strength and phase of the signal radiated by each element within the antenna. In some configurations, each element of the antenna will have its own transmitter and receiver. In other configurations, each element will have its own phase shifter but will share its receiver or transmitter with several other elements. In still other configurations, groups of elements will have a single phase shifter; and many groups, or even all groups, will share a common transmitter or receiver.

antenna may be controlled by optoelectronic devices.[37] The elements may contain built-in signal processing circuits.[38] Some new antenna designs are so complicated that they cannot be economically constructed without integration.[39]

Integrated antennas offer several advantages over conventional antennas:

<u>Reduced size, cost, and weight</u>: Embedding the elements in an insulating substrate reduces the structural complexity of an antenna considerably.

<u>Adaptable shapes</u>: Integrated antennas can be shaped to conform to the skin of a vehicle, such as an airplane, satellite, or spacecraft, and thus can meet the special aerodynamic and structural requirements of those vehicles. They can also be shaped to conform to the surfaces of buildings for aesthetic or practical reasons.

<u>Sophisticated designs</u>: Integrated antennas can be implemented as phased arrays, the most versatile of emerging antenna types. Phased arrays can transmit in many directions without being physically moved (electronic steering). Both the direction of transmission and the shape of the radiation pattern can be changed virtually instantly. This capability enables a single satellite with such an antenna to serve many different geographical regions on a time-shared basis by sending its signal to one location after another in rapid succession.

Integrated antennas can be driven by multiple small low power transmitters, built right into them. They do not require the traditional single high power transmitter. The use of multiple transmitters eliminates the need for a complex network of microwave waveguides within the antenna to carry microwave power to the antenna elements from a central transmitter. The result is a considerable reduction in weight. Also, because the transmitters for the individual elements are low power, they can employ low cost semiconductor signal sources, rather than the expensive and often short-lived microwave tubes that are required by high power central transmitters. Integrated

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[37] Optical waveguides embedded in a phased array integrated antenna may be used to control the relative strengths and phases of the signals transmitted by the individual elements of the antenna. Relative to metallic waveguides, which would otherwise be used for such control, the optical waveguides are lighter and will not interfere as much with the radiation pattern of the antenna.

[38] For example, the information received by each element of an integrated receiving antenna may be converted to digital form by its own semiconductor electronics, located right at the antenna element. The resulting digital data from each antenna element can then be brought out of the antenna on light beams carried by optical waveguides. This approach results in a much lighter antenna than possible when microwave signals themselves must be brought out through multiple metallic waveguides.

[39] The individual faces of an active array may contain as many as 5000 active transmit/receive devices and thus may not be practical to implement in any form other than an integrated form.

antennas may be controlled with optical signals fed through optical waveguides. Optical waveguides are desirable because they are non-interfering; thousands of such signals will be required to control a complex integrated antenna.

To support integrated antennas, NIST will develop measurements for overall antenna performance and for the performance and interaction of individual antenna elements within the integrated antenna. The principal quantities that must be measured are these:

<u>Overall antenna measurements</u>

| | |
|---|---|
| gain | |
| pattern | |
| polarization | |
| bore sight | |
| noise | Determines the noise contributed by the integrated antenna which now contains the transmission and reception electronics and must be evaluated as a whole. |

<u>Antenna element measurements</u>

| | |
|---|---|
| diagnostics | Determines which elements of the antenna are not working correctly. |
| coupling | Determines the effects of the coupling between closely spaced elements on antenna performance. |
| phase | Determines how the signals from the individual elements track in relation to each other. |
| strength | Determines how well the strengths of the signals from the individual elements track with each other. |

The new measurement approaches required will be especially challenging for several reasons:

<u>No single input/output port</u>: Integrated antennas do not have a single point of microwave power input or output which can provide a reference for measurements. New definitions for quantities such as gain and noise will be necessary, along with new measurement approaches.

<u>Different transmit/receive performance</u>: Integrated antennas will not perform exactly the same way in transmission and in reception, as conventional antennas do; so separate measurements must be made for each of these modes. The differences arise from the fact that different built-in electronics will be activated for reception versus transmission. Also, in some cases, different radiating elements within the antenna will be used for each mode.

<u>Large size</u>: Integrated antennas will often be physically large. They will also often be "electrically large". That is, they will be large relative to the wavelength (the distance from one ripple to another in a traveling microwave beam). Because of these "large" sizes, NIST will

need to develop new measurement methods for pattern. These new methods must enable present-day antenna measurement ranges to cope with antennas that are far too complex for use of traditional measurement approaches. So called quasi-far-field measurement techniques will be required.

Element interactions: Integrated antennas are composed of many elements, so the interactions among these elements will greatly affect performance and will require a variety of measurements sensitive to the relationships among them.

NIST must also develop measurements for characterizing the microwave properties of the special materials used in making integrated antennas. The quantities that must be measured are these:

Materials measurements

permittivity
permeability
uniformity
anisotropy
transmissivity
reflectivity

As with materials for integrated circuits, these quantities must be measured as a function of temperature and humidity to simulate the environment in which they will be used. They must be must be measured as a function of composition to support design and manufacturing processes. They must be measured as a function of frequency to support wideband applications.

## 3. Integrated Components for 100-1000 GHz

New measurement capability must be developed for the 100-1000 GHz region. This capability is needed to support the efforts of U.S. industry to develop equipment that will take advantage of the frequency space and special properties of the higher frequencies. Particularly attractive are the prospects for smaller antennas, higher resolution for local radar, greater versatility for local communications systems, and ultrafast speeds for signal processing.

Most of the needed work will focus on integrated components, so they are the focus of the subsections that follow. However, some measurement development for individual components will also be needed.

### 3.1 Integrated Electronic Circuits

The key parameters that must be measured are the same as those specified for the 1-100 GHz range in section 2.1, but different measurement methods will be required. The differences are caused by -

Quasi-optical behavior - The frequencies in the 100-1000 GHz range, particularly at the high end, take on the behavior of light, giving rise to new materials problems, new requirements for component designs, and higher levels interface complexity.

Smaller geometries - The characteristic sizes of circuit elements will be smaller at these frequencies.

Higher sensitivity to measurement probes - The sensitivity of integrated circuits to the presence of measurement probes will be greater at these frequencies.

Higher sensitivity to materials properties - The sensitivity of integrated circuits to materials properties will be greater at these frequencies.

In this 100-1000 GHz domain of frequency, development of non-contacting optical methods, rather than contacting electrical methods, for measuring microwave parameters within integrated circuits will be especially important to prevent disturbing the circuits being measured.

The full spectrum of materials properties cited for the range of 1-100 GHz in section 2.1 must be addressed for this new frequency range of 100-1000 GHz where the properties will differ considerably.

Measurements supportive of microwave signal processing electronics will be especially important to realize the promise that they offer for extraordinary processing speeds.

## 3.2 Integrated Antennas

Measurement development for antennas will focus initially on the domain of 100-300 GHz and later on the domain of 300-1000 GHz. As in category 3.1 above, special measurement methods will be needed to cope with quasi-optical behavior, smaller geometries, and higher sensitivity to measurement probes and to materials properties. In addition, measurements for coupling among antenna elements and other circuit elements will prove very important and challenging at these frequencies.

Development of measurement support for the range of 100-1000 GHz will assure that U.S. industry has both the measurement methods and the materials data that it needs to accelerate its research and development efforts toward the next generation of high frequency microwave products.

SUPERCONDUCTOR PROGRAM SUMMARY
FY 1988-89

Introduction

The purpose of the NIST Superconductor Program is to provide measurement methods and materials data needed by U.S. organizations for developing practical superconductor products. NIST achieves high leverage by providing measurement capability that accelerates the superconductor programs conducted by industry, universities, Government agencies, and national laboratories. In particular, the NIST program provides measurement support for: (1) relating materials characteristics to underlying physics; (2) characterizing new materials in basic form; and (3) developing and controlling processes for converting basic materials to practical materials. NIST also applies superconductor technology to advanced measurement devices. NIST addresses high and low temperature superconductors in both bulk and thin-film forms. In the future, NIST plans to develop measurement capability to support marketplace exchange for high temperature superconductor products. NIST already provides this support for low temperature superconductor products.

The NIST Superconductor Program has the levels of directly appropriated resources shown below. The $2M increase in FY 1989 for high temperature superconductors applies for that year only.

| | Thousands of Dollars | |
|---|---|---|
| | FY 1988 | FY 1989 |
| Low Temperature Superconductors | 570 | 470 |
| High Temperature Superconductors | 2800 | 4800 |

The low temperature program has been a formal activity since 1969. The high temperature program was started on a pilot level in 1987 and constitutes the work of the Superconductivity Research Center for Electronic Applications, as called for in the President's Superconductivity Initiative of July 28, 1987. Since 1987, NIST has prepared 100 publications describing the results of its work on high and low temperature superconductors. NIST works closely with collaborators in industry, universities, national laboratories, and Government agencies to assure that it is providing the measurement methods and data that their programs need. In fact, 34% of NIST's recent superconductivity publications have been co-authored with those organizations.

In its work, NIST focuses on measurement methods and data that are needed broadly and that require NIST's special measurement skills or its special facilities, such as its synchrotron, research reactor, or integrated circuit facility. NIST's reputation for impartiality and competence in measurement science is essential in achieving broad acceptance of NIST-developed measurement capability. Such acceptance strengthens the national superconductivity effort by accelerating research, by improving the quality of published data, and by enabling more meaningful comparison of findings among U.S. organizations.

Plans

The NIST program can be described in three projects that are focused on the types of measurement support that NIST is providing to U.S. organizations.

Project 1: Measurement Support for Relating Materials Characteristics to Underlying Physics

Project 2: Measurement Support for Characterizing New Materials in Basic Form

Project 3: Measurement Support for Developing and Controlling Processes for Converting Basic Materials to Practical Materials

A brief description of each project follows.

Project 1: Measurement Support for Relating Materials Characteristics to Underlying Physics

Project Focus:

NIST is providing measurement methods and data that advance the understanding of the underlying physics of superconducting materials. This information is needed to support the national effort to find new superconducting materials and to understand and optimize the performance of those already discovered. Representative of the key measurement methods that NIST is using are photoemission, x-ray fluorescence, elastic constant, electron tunneling, and neutron scattering methods. These measurement methods provide data on electron energy levels, energy gap, density of states, phase transformations, phonon behavior, electron-phonon interactions, atomic structure and substitutions, and magnetic behavior.

NIST itself is not pursuing the discovery of new superconducting materials; rather, NIST is providing the measurement methods and data that accelerate the progress of other U.S. organizations engaged in that pursuit.

Representative FY 1988 Accomplishments:

NIST has applied key measurement techniques to determine fundamental data on the copper valence states, key interatomic bonds, elastic and phonon behavior, and the energy gap in the yttrium-based high temperature superconductor. NIST has used neutron measurement techniques to develop data on the effects of non-magnetic atomic substitutions in the yttrium-based superconductor and to identify the significance of copper-oxygen planes versus copper-oxygen chains to the mechanisms of superconductivity.

Representative FY 1989 Plans:

NIST will use neutron measurement techniques to develop data on the effects of magnetic atomic substitutions in the yttrium-based high temperature superconductors. NIST will expand development of data on electronic structure and other properties of the new bismuth-based high temperature superconductor.

## Project 2: Measurement Support for Characterizing New Materials in Basic Form

Project Focus:

NIST is developing measurement methods and verified data that industry needs to characterize the basic materials from which superconducting products will be made. Key among these undertakings is the development of phase diagrams, x-ray diffraction data, atomic structural data, and measurement methods and data for compositional uniformity.

Phase diagrams identify stable phases of superconducting materials as a function of composition and temperature. Phase diagrams are fundamental sources of data needed by industry to design processes for making superconducting materials. X-ray diffraction patterns enable quick identification of the compounds formed. Atomic structural data are needed to characterize the sensitivity of the superconducting properties of the new materials to subtle changes in atomic positions and occupancy. Measurement methods for compositional uniformity are needed to improve the homogeneity of superconducting materials. To meet these needs, NIST is expanding its special capabilities for neutron diffraction and compositional mapping.

Measurement methods and data for characterizing new materials in basic form are the necessary first step toward the development of measurement support for process control, described in the next project. New data will be developed for each emerging family of high temperature superconductors with promise for practical products.

Representative FY 1988 Accomplishments:

NIST has developed the phase diagram and x-ray diffraction data for the yttrium-barium-copper-oxide superconductor, compositional mapping capability with micrometer resolution for the metallic constituents of the new superconductors, atomic structural information with emphasis on oxygen-site occupancy using neutron diffraction, and atomic building-block models with predictive capability for high temperature superconductors. NIST has also completed the conceptual design for a new neutron diffractometer with improved capability for determining atomic structure.

Representative FY 1989 Plans:

NIST will develop the phase diagram for the bismuth-calcium-strontium-copper-oxide superconductor. NIST will also develop compositional mapping measurements with submicrometer (nanometer) resolution for principal constituents. NIST will explore a broadened spectrum of measurement techniques for the elemental and chemical makeup of high temperature superconductors, with a special focus on oxygen which is very difficult to measure. NIST will implement the first of several key improvements to its neutron diffraction capability for measurements of atomic structure and other relevant materials parameters.

Project 3: Measurement Support for Developing and Controlling Processes for Converting Basic Materials to Practical Materials

Project Focus:

To develop fabrication processes, industry must have fundamental measurement methods and data for relating processing conditions to desired properties in superconducting materials suitable for products. NIST is developing this measurement capability to aid industry in developing processes and in determining the quality and performance of practical materials produced by those processes. Both bulk materials (for wires) and thin films (for integrated circuits) are being addressed.

Bulk materials

NIST is developing and applying a variety of measurement techniques for determining the variation of crystal structure and chemical composition with processing conditions. NIST is determining the relationship between processing conditions and both mechanical properties (such as structural strength) and key superconducting properties, such as critical temperature and critical current. Included will be the determination of the relationship between processing variables and flux pinning, which affects critical current and ac losses. Measurement methods are being developed and used to provide generic data on variation of critical current with magnetic field, stress, and temperature.[1] Key measurement methods are being documented for broad use as national measurement standards. This effort and others within the program are responsive to the requirement "to develop and coordinate common standards" as stated in the President's Superconductivity Initiative.

Thin films

NIST is providing special measurement capability and data to support the exploitation of the high temperature superconductors in integrated circuits for electronic applications. Using the best available fabrication technology, NIST is establishing its fabrication capability for preparing all elements of superconducting integrated circuits, including thin films, insulating cross-overs, and Josephson junctions. NIST is addressing key problems that affect the characterization of films, such as determining contact quality between normal metal films and superconducting films. NIST will aid in the transfer of data related to thin-film fabrication technology to industry to support industrial development of commercial thin-film fabrication processes. NIST is also exploiting its fabrication capability to

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[1]Outside funding (principally from DOE's Fusion Energy Program and High Energy Physics Program) contributes significantly to related work, particularly for low temperature superconductors. That funding supports development of measurement methods for critical currents above 600 amperes and complements earlier work on measurement standards for lower current levels. The outside funding also supports development of measurement methods for ac losses in multifilamentary superconductors, determination of coupling effects and stress-related critical current degradation within multifilamentary superconductors, determination of effects of low-level copper impurities on the superconducting energy gap, and other activities.

provide new superconducting devices with a special focus on national electronic measurement standards and other measurement devices. NIST earlier developed the present U.S. national standard for voltage, based on an integrated circuit array of Josephson junctions, made from the low temperature superconductors. NIST also developed the first high temperature superconducting quantum interference device (SQUID) that was fully characterized as a measurement instrument. This device measures magnetic fields with high sensitivity. Other devices that measure magnetic fields will also be developed, as called for in the President's Superconductivity Initiative.

Representative FY 1988 Accomplishments:

For bulk materials, NIST has developed new standard measurement methods for critical current at zero applied magnetic field in high temperature superconductors; to accomplish this, NIST reduced contact resistance by eight orders of magnitude to enable more accurate and reproducible measurements, especially at high current levels. NIST has shown that the superconducting properties of the high temperature superconductors are highly sensitive to processing conditions and impurities. In particular, NIST has established the relationship between transition temperature and oxygen annealing, has demonstrated that critical current can be increased with impurity reduction and with chemical preparation techniques for starting powders, and has determined the trade off between mass density and critical current in sintered materials.

For thin films, NIST has implemented its first fabrication capability for high temperature superconductors and has produced films with good superconducting properties. NIST has created single-layer patterns in those films with structures representative of those required for interconnections and ultimately for active devices. These are the first steps toward application of the high temperature superconductors to measurement problems. For low temperature superconductors, NIST has implemented a new version of the one-volt national standard using all-niobium technology. This technology provides high stability in the integrated-circuit array of Josephson junctions used in the standard. NIST has also implemented the first version of a ten-volt national standard with lead/niobium technology.[2]

Representative FY 1989 Plans:

For bulk materials, NIST will develop standard measurement methods for critical current versus applied magnetic field and for critical magnetic field in high temperature superconductors. These measurement methods will provide greater accuracy and reproducibility in evaluating materials produced by promising fabrication processes. NIST will develop and apply measurement methods for determining the correlation of processing variables and microstructure with mechanical, electrical, magnetic, and structural properties. Special emphasis will be given to structural defects and to grain

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[2]Outside funding (principally from DOD) contributes significantly to the application of low temperature superconductors to new measurement devices for voltage, millimeter-wave power, millimeter-wave signals for radio astronomy, and high speed waveforms via superconducting analog-to-digital converters.

alignment to overcome anisotropy problems. NIST will also continue to examine promising chemical preparation routes. Much of this work will focus on the yttrium-based superconductor, but the bismuth-based superconductor will be increasingly addressed.

For thin films, NIST will implement more powerful fabrication processes that provide greater control. This effort is the next step toward development of NIST's capability for making high temperature superconducting integrated circuits with active elements, with an emphasis on measurement applications. NIST will focus on low-loss circuit interconnections, on compatibility of multi-layers with each other and with substrates, and on measurements and data required to realize working Josephson junctions. For low temperature superconductors, NIST will take further steps toward implementation of all-niobium technology and will move from an initial to an advanced form of the new 10-volt national standard. NIST will also explore the potential of new superconducting effects for national standards.

ADVANCED MAGNETICS METROLOGY
Future Initiative
Project Plan

The science and practice of magnetics has stagnated in the United States in spite of the existence of major industrial segments such as magnetic recording (U.S. market for magnetic recording devices of $40 billion in 1987, estimated to be growing at some 20% per year). "Magnetic materials are an integral part of our modern industrial society, often rivaling semiconductors for breakthroughs in high-technology capabilities. They play a key role in power distribution, they permit the interconversion of electrical and mechanical energy, they underlie microwave communication, and they provide both the transducers and the active storage material for data storage in computer-based information systems." These sentences, taken from Directions in Engineering Research -- An Assessment of Opportunities and Needs, Report of the Engineering Research Board of the National Research Council, document the importance of magnetic technology, impacting a large fraction of the U.S. electronic market (U.S. firms shipped $223 billion in 1987) and individual industrial sectors ranging from motors and generators (U.S. firms shipped $7 billion in 1986) to industrial controls (U.S. firms shipped about $5 billion in 1986). [1-2]

Yet this prestigious Board found that "Despite the many practical uses for the materials, and despite their critical importance to the nation's industry and defense, it has become increasingly clear in recent years that the role of the United States in the science of magnetic phenomena, in magnetic materials, and in magnetic technology has been declining....Since the mid 1970s, American manufacturers have looked increasingly to foreign sources for newer, better, and cheaper magnetic materials and devices. Nations such as Japan have invested far more than the United States has in the R&D needed to advance the performance of magnetic materials."

Robert M. White, Chief Technical Officer and Vice President of Research and Engineering of Control Data, echoes this view in a 1987 commentary in Physics Today: "In fact, the whole field of magnetics has largely been ignored by the U.S. science community." "In 1985 the National Academy of Sciences sponsored a study of magnetic materials in the United States through the National Materials Advisory Board. The results of the study showed that although magnetic technology is critical to our economic and strategic well-being, we are rapidly losing our ability to compete."[3]

White goes on to report that "Recent workshops at Purdue University (sponsored by the Office of Naval Research) and in San Diego (sponsored by DARPA) reached

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[1] Directions in Engineering Research -- An Assessment of Opportunities and Needs, Report of the Engineering Research Board, Commission on Engineering and Technical Systems, National Research Council, p. 250; National Academy Press (1987).

[2] 1989 U.S. Industrial Outlook, Chapter 25 Electrical Equipment, pp. 25-1 through 25-4; U.S. Department of Commerce (January 1989).

[3] Physics Today, Vol. 40, No. 11, p. 89 (November 1987).

the same conclusion." And the head of a magnetics group in the U.S. Naval Research Laboratory notes, "The precarious status of the magnetic recording industry here in the United States vs. Japan is now widely recognized and the amount of time still available to ensure our technological competitiveness is extremely short."[4]

The evidence is in: the state of U.S. magnetic technology is parlous, and the U.S. magnetics industry is under serious market threat from abroad. Various programs are being proposed to address the situation. Inevitably, comparisons are made with the semiconductor industry, and at least one proposal is modeled on the creation of SEMATECH.[5]

For these proposals to succeed, they (like SEMATECH) will need to consider carefully the measurements needed. NIST is already being called upon to provide infrastructure support for magnetics as it has for semiconductors and many other areas -- providing reference data and materials, developing and disseminating test methods needed by industry for marketplace measurements, contributing to voluntary standards development, providing calibration services for parameters required by industry, and serving as the measurement court of high appeal.[6] It should be noted that, with industry support and collaboration, centers to develop basic magnetic technology have been established at Carnegie Mellon University (Magnetics Technology Center); at the University of California at San Diego (Center for Magnetic Recording Research); and at the University of Minnesota (Center for Magnetics and Information Technologies). These centers primarily are concerned with research leading to commercial implementation and as a consequence do not conduct substantive metrology development. They also are not in position to provide the national reference measurements and services needed by industry and for commerce.

This draft Advanced Magnetics Metrology budget initiative describes that component of the NIST response falling within the technical competence of the Center for Electronics and Electrical Engineering.[7] It addresses current industry needs, reflecting priorities identified by industry in the Survey, through numerous contacts at meetings, in visits by NIST staff to industry, and in visits by industry to NIST.

High-Density Information Storage

The U.S. magnetic recording industry has serious measurement needs with respect to present technology and products and will depend on measurements

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[4]Private communication.

[5]Institute of Electrical and Electronics Engineers Magnetics Society Newsletter, Vol 24, No. 5, p. 3, 5 (May 1988).

[6]NBSIR 84-3018, F.R. Fickett, Magnetic Measurements, Calibrations, and Standards: Report on a Survey (October 1984).

[7]For indication of scope of accomplishments, see NBSIR 88-3097, Metrology for Electromagnetic Technology: A Bibliography of NBS Publications, section on "Superconductor and Magnetic Measurement," pp. 36 through 55 (August 1988).

even more in the future with increasing emphasis on quality control and advanced recording systems. For example, analysis of a coercivity round-robin exercise conducted by NIST with volunteers from industry and university research laboratories shows such a broad spread in the results that systematic differences are masked between the two principal instruments used (vibrating-sample magnetometer and B-H looper). NIST measurements show that the tape specimens used in this study are not the source of these large variations. Since coercivity is the single most important characteristic for specifying the performance of magnetic recording media, the situation is serious. One small company has already failed in part at least because of an inability to agree on coercivity measurements with its customers.

The development of new recording technologies (vertical, ceramic, and thin film media; magneto-optical recording) and the increase in bit density of the conventional technologies require either an improvement in existing measurements or new methods that are more accurate and dependable. Not only is the recording medium itself involved, but also the read/write heads and other auxiliary equipment.

Coercivity

In response, NIST will investigate measurement problems in magnetic recording, beginning with a study to identify the physical causes of the wide variation evidenced in coercivity measurements. This study will provide an understanding of the interaction of a given instrument type with the system under measurement and identify those measurement conditions that need to be controlled. Nist will also develop the artifact standards (Standard Reference Materials), calibration services, or both required to support industrial use of the vibrating-sample magnetometer (VSM) and the B-H looper. NIST also will carry out round-robin evaluations of test methods for media having high coercivities, such as new videotapes.

Magnetization and Demagnetization Parameters

An understanding of time-dependence effects in the magnetization cycle of magnetic media is another area that has been identified as being of great importance to industry. NIST will develop methods for determining and characterizing these effects, working with industry to institutionalize these methods in voluntary standards developed under the aegis of the American Society for Testing and Materials, the American National Standards Institute, the Institute of Electrical and Electronics Engineers, and other appropriate professional and technical societies. More specifically, NIST will study these effects using a new method based on toroidal specimens; NIST will also investigate Barkhausen noise in thin-film heads used for recording on high-coercivity media.

With respect to thin-film media, NIST will develop methods for accurate measurement of magnetization (moment per unit volume) which will account for the uncertain demagnetization factor and the regional demagnetization fields as well as the problems resulting from the multilayer nature of the specimens. To support future technologies, NIST will expand this work to cover magneto-optic systems and other high-density media.

### Hard Disk Measurements

Hard disks pose special measurement problems to industry, as they involve the intimate contact of magnetic media with aluminum alloys. NIST will identify and study the measurement requirements; for example, NIST will modify its scanning tunneling microscope (STM) into an atomic-force microscope configuration to aid in these investigations.

### Measurements on Advanced Media

New magnetic storage media are being developed and introduced, at least some of which will have market implications in the 1990s. NIST will conduct measurement research to support the introduction of advanced media types such as perpendicular recording, permanent magnet particulate, and magneto-optical. NIST will also study measurement problems relating to head systems, track densities, etc.

## High-Performance Electronics

Major advances have been made in a wide range of magnetic materials over the last decade. The resulting new capabilities impact the design and production of advanced electronic systems and instrumentation. Very low temperatures, high frequencies, regions of very high and variable magnetic field are examples of new environments that now need to be considered for magnetic materials and devices. Measurement technology has not kept up with either the advances or the applications. As a result, a wide range of producers and users of electronic systems need NIST help in marketplace measurements supporting for example: magnetic ferrites for microwave applications and other electronic instrumentation; conventional ferrous alloys and specialty alloys such as metallic glasses and the nickel-based superalloys; permanent magnets, ranging from conventional Alnico through the newer samarium cobalt to the revolutionary rare-earth-based materials such as NdFeB; and superconductor applications in which the hysteretic behavior of the material is the controlling feature for applications in medical diagnosis or particle physics (i.e., Superconducting Super Collider).

Examples of the NIST response include the following. NIST will study the characteristics of powder materials that lead to measurement problems, such as the effect of powder formulations on coercivity, anisotropy, energy product, and magnetization stability at both low and high temperatures.

NIST will also investigate ferrite materials with its new variable-frequency radiofrequency permeameter to discover the source of the observed wide variation in the measured high-frequency magnetization. Magnetostrictive effects in amorphous alloys are also important and NIST will study the measurement implications of these effects at a later stage in the effort.

Instruments for determining magnetic properties require calibration over new ranges to support applications of magnetic materials and devices already identified and advanced applications just now emerging. For example, the advent of amorphous ferrous alloys and high-temperature superconductors has resulted in an increased demand for calibration standards for ranges of field, temperature, and magnetic susceptibility not previously felt to be of importance. In response, NIST will develop artifact standards for the calibration of temperature-variable magnetometers and susceptometers. NIST will also undertake a program of theoretical evaluation of magnetometry to better understand the problems introduced by the measurement system and the sample geometry due to demagnetization and field images. Both SRMs and standard methods for measurement would be outcomes.

Because industry needs guidance for applying the many new measurement methods now available to new materials, as well as to old, NIST will review definitions of fundamental parameters and prepare and publish a comprehensive handbook on magnetic measurements.

Data on, and measurement methods for, very-low-level magnetic effects in materials not commonly regarded as magnetic, such as fiberglass epoxy, are needed by organizations developing sensitive magnetic detection systems for medical, NDE, and military applications. NIST will study these effects, identify marketplace measurement implications, and develop responsive test methods.

<u>High-Efficiency Motors, Generators, and Transformers</u>

Concerns for efficiency have lead to applications of new magnetic materials in products ranging from fractional-horsepower motors to multi-kilovolt-ampere power system distribution transformers. In vehicular and aircraft transportation systems, for example, there is need for electric motors and generators that produce maximum output for minimum weight. In power transformers, the concern is loss; it is estimated that the average annual capitalized cost of losses in transformers in the United States is about $2 billion. "The economic impact of power transformer losses is at a state where the cost of evaluated losses over the lifetime of a power transformer often rivals the initial price of the transformer."[8] The corresponding measurement needs include support for parameters discussed in earlier sections, together with the nature of the NIST response (measurement services, test method development, reference artifacts, as appropriate). NIST will also identify special needs and implement responsive solutions, For example, NIST will develop new methods for determining magnetic properties of the magnetic steels and new amorphous materials, such as core loss. NIST will develop a temperature-variable yoke magnetometer for small samples as a key development for these investigations. Existing techniques require very large samples, but the yoke configuration is essential to eliminate the very large demagnetization corrections required by other methods in high-permeability materials. NIST will also develop methods for evaluating the effects of very high stresses (as encountered in large magnets) on magnetic properties.

<u>Nondestructive Evaluation</u>

Nondestructive methods for evaluating structures and artifacts are becoming increasingly important to the nation's economy, for example to increase

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[8]NBS Technical Note 1204, Oskars Petersons and S.P Mehta, <u>Calibration of Test Systems for Measuring Power Losses of Transformers</u> (August 1985).

efficiency in manufacturing by identifying flawed starting materials and to promote safety in air travel and other transport modes by detecting incipient failure sites without requiring disassembly. Many of these methods depend on eddy-current techniques and hence on magnetic measurements. In response to needs of the nondestructive evaluation (NDE) community, NIST will develop methods for standardizing and calibrating eddy-current NDE probes and methods for characterizing advanced ferrites for these probes.

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This NIST Internal Report has been prepared by the Center for Electronics and Electrical Engineering (CEEE) within NIST. The report identifies emerging technologies in electronics that CEEE believes will require increased measurement support from CEEE in coming years. The emerging technologies described here are new to the marketplace or are experiencing major technological advances.

This report is an internal planning document. The document is designed to stimulate feedback that CEEE needs to refine its plans for developing measurement capability to support emerging electronic technologies that are important to the national interest.

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