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AND TECHNOLOGY  
ELECTRONICS AND ELECTRICAL  
ENGINEERING LABORATORY**

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## **Acknowledgment of Reviewers**

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Narain G. Hingorani, Los Altos Hills, California,  
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Dwight C. Streit, Northrop Grumman Space Technology.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Alton Slay, Warrenton, Virginia. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.



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## Summary

The Electronics and Electrical Engineering Laboratory (EEEL) of the National Institute of Standards and Technology (NIST) has been assessed by a panel of experts appointed by the National Research Council (NRC). The panel visited the four divisions of EEEL and reviewed their scientific and technical activities. The assessment was based on four criteria: (1) the degree to which the laboratory addressed national priorities; (2) the degree to which the programs were well motivated with respect to goals, innovation, definition of success, impact, dissemination to the end user, and cost and timeliness; (3) the technical merit of the programs; and (4) the adequacy of the facilities, the equipment, and human resources. Using these four criteria, the panel drew the following conclusions:

**Conclusion 1.** The laboratory is well focused on national priorities. Numerous examples were presented that showed the nurturing of America's science and technology enterprise, as well as the stewardship of critical research fields and their enabling infrastructure. There was evidence of research and education having been integrated through research associateships, and there were a good number of collaborations with universities. A selection of long-term, high-payoff activities was observed with applications to homeland and national security, environmental quality, economic prosperity, human health and well-being, and fundamental discovery.

**Conclusion 2.** The goals, action plans, impacts, and means of dissemination are all well articulated in divisional documentation that is publicly available. The scope and detail of the documentation on the planning of this laboratory were satisfactory, the long-term objectives were well considered, and the short-term objectives were focused and, in general, achievable. The innovation that is being developed and applied at EEEL is impressive and holds great promise. In general, EEEL is providing excellent value at a very reasonable cost. No projects examined failed to provide value for the investment.

**Conclusion 3.** The technical merit of the program is impressive. Some programs have received best-in-the-world accolades for achieving particular technical goals. Others are considered state of the art. This combination of innovation and technical achievement promises to serve well the emerging technologies of the future. Moreover, the laboratory manages to maintain a balanced portfolio of activities that support the U.S. technological infrastructure and its metrological needs.

**Conclusion 4.** In general, the resources are adequate. The staff are skilled, motivated, and creative. However, permanent staff are spread very thin over projects, and this may impact future performance. While the laboratory's resources are achieving good results at present, the panel has concerns about sustainability and adaptability to future demands.

This report also contains a chapter in which the panel comments on staffing and funding, international issues, and the planning process and suggests new directions for research within the existing laboratory organizational structure.

## Charge to the Panel and Description of the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Academies, through its National Research Council (NRC), has since 1959 annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now eight,<sup>1</sup> as well as the adequacy of the laboratories' resources. In 2007 NIST requested that four of its laboratories be assessed: the Electronics and Electrical Engineering Laboratory (EEEL), the Chemical Science and Technology Laboratory, the Information Technology Laboratory, and the NIST Center for Neutron Research. Each laboratory was assessed by a separate panel of experts, and the findings of each panel are summarized in separate reports. This report summarizes the findings of the Panel on Electronics and Electrical Engineering.

NIST requested that the panel consider the following criteria as part of its assessment:

1. The degree to which the Laboratory programs in measurement science, standards, and technology address national priorities.
2. The degree to which the Laboratory programs in measurement science, standards, and technology are well-motivated with regard to the following questions:
  - a. What is the program trying to accomplish?
  - b. What is innovative or different, as compared to efforts at other institutions, about the program's approach that will lead to success?
  - c. Is success well defined?
  - d. What will the impact of success be?
  - e. How will success be disseminated to end users?
  - f. How much will success cost, and how long will it take?
3. The technical merit of the Laboratory programs relative to the current state of the art worldwide.
4. Insofar as they affect the quality of the technical programs, the adequacy of the Laboratories' facilities, equipment, and human resources.

To accomplish the assessment, the NRC appointed a panel of 25 volunteers whose expertise matched that of the work performed by EEEL staff. The panel members were also assigned to four subsets whose expertise matched that of the work performed by staff in the four divisions in EEEL: Electromagnetics (EM), Quantum Electrical Metrology (QEM), Optoelectronics (OE), and Semiconductor Electronics (SE). These subsets of the panel separately visited EEEL facilities for 1-2 days, during which they attended presentations, tours, demonstrations, and interactive sessions with EEEL staff. Subsequently, the entire panel assembled for 1.5 days, during which they attended overview presentations by EEEL management and interactive sessions with EEEL managers; the panel also met during this period in a closed session to deliberate its findings and to define the contents of this assessment report.

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<sup>1</sup>The eight NIST laboratories are the Building and Fire Research Laboratory, the Chemical Science and Technology Laboratory, the Electronics and Electrical Engineering Laboratory, the Information Technology Laboratory, the Manufacturing Engineering Laboratory, the Materials Science and Engineering Laboratory, the NIST Center for Neutron Research, and the Physics Laboratory.

The panel's approach to the assessment relied upon the experience, technical knowledge, and expertise of its panel members, whose backgrounds were carefully matched to the technical areas within which the EEEL activities are conducted. The panel reviewed selected examples of the standards and measurements activities and the technological research presented by EEEL; it was not possible to review the EEEL programs and projects exhaustively. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the technical merit of the EEEL work, its perceived relevance to NIST's definition of its mission in support of national priorities, and apparent specific elements of EEEL's resource infrastructure that is intended to support the technical work. These highlighted examples, for each EEEL division, are intended to collectively portray an overall impression of the laboratory while preserving useful mention of suggestions specific to projects and programs that the panel considered to be of special note within the set of those examined. The assessment is currently scheduled to be repeated biennially; while the panel applied a largely qualitative rather than quantitative approach to the assessment, it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

The interested reader can find detailed descriptions of EEEL divisions and their programs at the NIST EEEL Web site: [www.eeel.nist.gov](http://www.eeel.nist.gov).

Of particular note is that the charge does not ask this assessment report to reiterate the programs; their innovation, success, impact, cost, technical merit; or their resources. Instead it does ask the panel to comment on the alignment with national priorities, the existence and adequacy of planning and assessment criteria, the technical merit of the programs, and their resource adequacy.

The first issue of alignment with national priorities raises the question of exactly what the national priorities are. This was answered by a document from the Executive Office of the President, Office of Management and Budget, whose subject is FY 2005 interagency research and development priorities. The present document outlines the national priorities of federal research and development agencies during the period of this review. The 2005 document was used as the primary definition of national priorities. A similar document addressing the FY 2008 administration research and development budget priorities<sup>2</sup> was also considered and was deemed somewhat more applicable to the next assessment of EEEL in 2009. The FY 2005 document recommends support for six general national policies:

- Sustain and nurture America's science and technology enterprise through the pursuit of specific agency missions and stewardship of critical research fields and their enabling infrastructure;
- Strengthen science, mathematics, and engineering education by enhancing access and broad availability of excellent education programs, establishing and encouraging best educational practices, and integrating research and education;
- Focus on long-term, potentially high-payoff activities that require a federal presence to attain national goals, including homeland and national security, environmental quality, economic prosperity, human health and well-being, and fundamental discovery;

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<sup>2</sup>FY 2008 Administration Research and Development Budget Priorities, June 23, 2006, Memorandum from the Executive Office of the President, Washington, D.C.

- Maximize efficiency and effectiveness of federal research and development (R&D) investments through means such as competitive, peer-reviewed processes and phase-out of programs that are neither productive nor important to an agency's mission;
- Promote collaborations among agencies, industry, academia, and states to advance common science and technology (S&T) goals; and
- Strengthen international partnerships that foster advancement of scientific frontiers and accelerate the progress of science across borders.

It also outlines five specific R&D priorities that are broad-based multi-agency goals and include R&D for combating terrorism, nanotechnology, networking and information technology R&D, molecular-level understanding of life processes, and environment and energy.

The charge to the review panel and this national priorities document include something more than simply assessing the technical merit of the activities. They touch on several aspects of strategic planning and the alignment of the activities, all in terms of addressing national priorities.

## Organization of the Laboratory

The four divisions within EEEL—the Electromagnetics Division, the Quantum Electrical Metrology Division, the Optoelectronics Division, and the Semiconductor Electronics Division—undertake a broad range of activities.

The Electromagnetics Division is divided into three groups:

- The Radio-Frequency Electronics Group concentrates on guided electromagnetic transmission and includes microwave measurement services, micro/nanoelectronics, and electromagnetic properties.
- The Radio-Frequency Fields Group includes antenna theory, applications, and near-field measurements; reference fields and probes; complex fields; and time-domain fields.
- The Magnetics Group includes high-current applications, superconductor and magnetic measurements, magnetodynamics, spin electronics, magnetic devices and nanostructures, and microsystems for bioimaging.

The Quantum Electrical Metrology Division is divided into three groups:

- The Fundamental Electrical Metrology Group works on projects involving voltage, resistance, single-electron tunneling, AC-DC difference, and the electronic kilogram.
- The Applied Electrical Metrology Group concentrates on electrical power and impedance.
- The Quantum Devices Group covers quantum voltage, quantum sensors, quantum information, and advanced materials and operates a quantum fabrication facility.

The Optoelectronics Division is divided into three groups:

- The Sources and Detectors Group works on laser radiometry, display metrology, and high-speed measurements.
- The Optical Fiber and Components Group works on interferometry and polarimetry and spectral and nonlinear properties.
- The Optoelectronic Manufacturing Group includes projects on quantum information and terahertz technology, optical materials metrology, nanostructure fabrication and metrology, and semiconductor growth and devices.

The Semiconductor Electronics Division is also organized into three groups:

- The Enabling Devices and Integrated Circuits Group concentrates on power device and thermal metrology, micro/nanotechnology (MNT), and nanobiotechnology.
- The complementary metal oxide semiconductor (CMOS) and Novel Devices Group is concerned with nanoelectronic device metrology, macroelectronics, and advanced metal oxide semiconductor (MOS) device reliability and characterization.
- The Electronic Information Group includes infrastructure for integrated electronics design and manufacturing and knowledge facilitation.

There are two other organizational groups within EEEL: the Office of Law Enforcement Standards (OLES) and the Office of Microelectronics Programs (OMP). These groups were not subject to the formal assessment process.

Early in 2007 each division in EEEL prepared an internal report detailing the division's programs, activities, and accomplishments (EM-NISTIR 7371, QEM-NISTIR 7370, OE-NISTIR 7369, and SED-NISTIR 7368). These reports describe each division's mission and its organization into groups and projects. They detail each project's technical activities, manpower, goals, services, and recent accomplishments. It is clear that the new strategic planning initiatives at EEEL have been effective, since these reports have become much more useful in the review assessment process. The activities are clearly described, the plans and goals are specific, often with technical targets and target dates, and the results are concisely described and supported by publication citations. The reports have been very helpful in responding to the panel's charge.

The divisional reports are detailed, typically 80 pages long and quite comprehensive. The present assessment does not summarize these reports but comments on how they apply to assessment issues. With this in mind, this report does not attempt to describe each project's activities, goals, impacts, costs, and the like, except where such a description is needed to support a particular assessment comment. The reader is encouraged to refer to the EEEL divisional reports for further background information.

## The Assessment

The organization of this assessment report closely follows the charge given to the review panel by the NRC. For each of the four assessment criteria, the report first presents a general overview and then selects highlights or presents conclusions pertaining to each division, usually referencing specific technical projects.

### CRITERION 1. ALIGNMENT WITH NATIONAL PRIORITIES

The laboratory is very well focused on national priorities not only in its new initiatives but also in its historical role within NIST and, previously, in the National Bureau of Standards. The applied science of metrology is an enabling infrastructure for all science. It provides a coherent basis for the interpretation of all measurement and effectively links these measurements at the highest possible accuracy. Only in this way can the maximum information be gained from research and development (R&D), thereby optimizing the efficiency and effectiveness of federal R&D investments.

One of NIST's main purposes is to serve as the national metrology institute (NMI) for the United States; EEEL fulfills that function for almost all electrical and many optical measurements. This function directly enables the pursuit of specific agency missions and gives NIST stewardship of critical research fields and their infrastructure. The issue of stewardship entails a delicate balance, and it is obvious that EEEL is continually striving to maintain that balance, which was achieved by improving the nation's critical measurement and standards infrastructure, while offloading the less critical measurement work to other government agencies, commercial enterprises, or even other NMIs.

There are examples of projects (one is quantum computing) that fit well with the general policy of focusing on long-term, potentially high-payoff activities that require a federal presence to attain national goals such as homeland and national security, environmental quality, economic prosperity, human health and well-being, and fundamental discovery. Most applicable to EEEL is long-term research, but there are also numerous examples of projects that need to meet immediate national goals.

EEEL is also very involved with international partnerships that foster the advancement of scientific frontiers and accelerate the progress of science across borders. There are many examples of national and international collaborations and participation at different levels, all aimed at leveraging NIST's impact on the national and international scene and ensuring that the nation's technical and scientific interests are represented.

NIST offers postdoctoral research associateships in collaboration with the National Research Council, and each division in EEEL has attracted many candidates for these associateships. As well, a large number of guest researchers from academia, industry, and international institutes work at NIST. Finally, a number of workshops and tutorial courses have been presented to disseminate the advanced work of NIST laboratories to other governmental, educational, and industrial organizations. All of these activities strengthen science, mathematics, and engineering education by offering excellent education programs, establishing and encouraging the best educational practices, and integrating research with education.

## **Electromagnetics Division**

Most of the Electromagnetics Division's activities were well aligned with national priorities. This division develops, improves, and disseminates radio-frequency (RF) and microwave standards, and its measurements services and antennas calibration work provide traceability for the communications and RF industries. The program of this division is recognized as a leader for calibration of these types of measurements and is central to the EEEL and NIST missions. It assumes the stewardship of this measurement technology and its infrastructure on behalf of the U.S. economy.

The recently started work on magnetic resonance imaging (MRI) phantoms will allow the calibration of MRI systems in support of a key U.S. industry: human health. It is satisfying a long-standing need for the quantification of images obtained by these techniques. Similarly, the activities in superconductivity are providing critical support to the segments of the burgeoning power transmission industry that use superconductivity. The viability of this industry will rely heavily on the measurements developed at EEEL to quantify the effects of stress on superconductor critical current.

The Electromagnetics Division is also conducting significant work in support of the data storage industry, which is essential for networking and information technology R&D. It has pioneered several important measurement techniques and continues to work on areas of interest, including techniques for measuring patterned media and spin injection device dynamics.

Observing objects at terahertz frequencies of 300 GHz and beyond is a promising means of noninvasively obtaining images and spectra signatures of concealed weapons and dangerous chemicals, which would enable the safeguarding of public spaces. In the Electromagnetics Division, the new terahertz noise metrology and passive terahertz imaging demonstration is developing microwave traceability for thermal noise measurements at terahertz frequencies, which will serve bioscience, health care, and homeland security.

EEEL is also addressing national priorities relating to the security and coordination of first responders. Researchers in the Radio-Frequency Fields Group have been studying the distribution of electromagnetic fields in a host of complex environments, including falling buildings. This information could prove invaluable to first responders if communications systems are designed with it in mind. The importance of the work is increased by the participation of the researchers in professional societies and standards bodies that help to disseminate the work.

Radio identification devices are widely used for secured access, commercial inventory controls, and electronic passports. It is an important national priority to secure our electronic access controls and e-commerce by establishing a standard for their durability and security, especially when these cards are exposed to electrical discharge or to high-strength electric and magnetic fields. The Electromagnetic Division at EEEL has established an RF identification testbed at 13.56 MHz to test signal jamming, eavesdropping, and load modulation in strong fields.

Several of the biomagnetics activities within the Electromagnetics Division may have significant importance for health, particularly in medical diagnostics and treatment and exposure levels.

The superconductivity research is providing critical measurement techniques for the international team attempting to develop a fusion reactor with superconducting containment

magnets. While definitely considered long-term research at present, this technology could one day have a significant influence on energy availability.

Short courses and workshops on microwave measurements, antenna theory and applications, magnetics and magnetic materials, noise measurement and modeling, and wireless sensor networks have been presented to disseminate the Division's advanced work to other government, educational, and industrial organizations.

### **Quantum Electrical Metrology Division**

The core activity of the Quantum Electrical Metrology (QEM) Division is focused on developing, improving, and disseminating electrical standards, particularly those based on quantum devices. This is a national priority that is at the heart of the EEEL mission and plays a major role in enabling economic prosperity and in some specific areas of homeland and national security. The division is also involved in several projects that are justifiably classed as long-term, potentially high-payoff activities and in others that are recognized as having already delivered fundamental discovery.

The Quantum Devices Group has developed projects that fit well with EEEL's overall mission and have resulted in multiple technical motivations as well as numerous deliverables to government laboratories, other agencies, and industry. These projects cover a broad spectrum of device development, including esoteric devices like superconducting qubits, which may someday have a high payoff, and sophisticated arrays of devices that are already providing scientific data for applications in space and cosmology research and homeland security (via microscopic chemical analysis and AC voltage metrology).

Both the Fundamental Electrical Metrology Group and the Applied Electrical Metrology Group have done an excellent job of choosing projects that lie within EEEL's mission domain and address important national and agency priorities. A large part of the missions of these groups is to disseminate electrical standards, which is accomplished in some cases (for example, for resistance and capacitance) by means of traditional calibration services. These services continue to support U.S. industry and have secondary benefits in supporting the scientific and technical infrastructure. Projects dealing with other phenomena—voltage is one—are beginning to disseminate their technology by transferring measurement techniques and expertise. In the case of voltage, such transfer involves developing traveling instrumentation and conducting on-site measurements. This has the benefit of strengthening science, mathematics, and engineering education, as well as disseminating the standard.

The reliable and secure operation of electric power systems, one of the most important components of the national infrastructure, is a very high priority for the nation. These systems have annual revenues of about \$290 billion, and because of their impact on the economy, human health, and national security, it is critical that they be equipped with accurate metering and monitoring systems using state-of-the-art technology. The QEM projects aimed at dynamic measurements using electrical phasors for better monitoring of grid dynamics and improved stabilization, as well as protecting the grid from accidental or intentional disruption, are indeed a national priority, because the electrical power grid is in every sense an enabling infrastructure of a modern society.

In addition to standards dissemination and development, the QEM Division emphasizes fundamental discovery in science. This includes work on the watt balance project (the electronic kilogram), which may allow redefinition of the international system of units (SI) in terms of

quantum mechanical phenomena, as well as work on closure of the quantum metrology triangle by means of single-electron counting.

The presence of over 50 associates or guest workers in the QEM Division is substantially strengthening science, mathematics, and engineering education as well as international partnerships.

### **Optoelectronics Division**

The Optoelectronics Division has a strategic focus on national priorities and carries out highly synergistic, mutually supporting efforts that have demonstrated single-photon detectors and single-photon sources and their application to quantum key distribution, as well as forward-looking quantum optical metrology. An essential part of these efforts is measurement science for photonics semiconductor nanostructures and their technology and devices.

The optical frequency comb work is clearly focused on meeting the needs of the nation, as evidenced by optical sources that will bring unprecedented metrology in length and timing references. These optical sources are compact and electrically efficient, allowing them to operate in a broad range of manufacturing and metrology environments. In addition, the optical frequency combs can be applied to optical communication, enabling a variety of secure communications capabilities.

The United States is a major consumer of electronic displays for computers, cell phones, digital cameras, automotive applications, avionics, and medical and telemedicine applications. Fundamental metrology is critical in this highly competitive commercial market, and widely accepted display standards are needed to allow users to optimize their application based on the display performance. The display metrology effort is focused on making standards and measurement techniques widely available.

The quantum optics effort has demonstrated unique capabilities that provide support for national programs in quantum computing and quantum cryptography. The effort includes both sources and detectors of single photons. The single-photon detector technology, based on transition edge sensors and superconducting single-photon detectors, provides fundamental capabilities for single-photon and number-resolving detection. These devices have been used in demonstrations of quantum key decryption systems. The portability of the detectors makes them usable at multiple sites.

The optoelectronics terahertz program on passive imaging is providing interesting results and a metrology platform for commercial systems. The program applies superconducting transition edge detectors to generate low-noise two-dimensional images. This program has strong ties with national security and homeland defense requirements.

The communications industry has resumed its inevitable push for faster systems. Forty gigabytes/second (Gb/s) for long-haul communication and even 100 Gb/s Ethernet are now being deployed. The efforts of the high-speed waveform analysis project support the measurement needs of this community and address the specific priority of networking and information technology R&D. This is being done through both measurement services and methodologies for characterizing measurements.

## Semiconductor Electronics Division

Overall, the Semiconductor Electronics Division (SED) work is clearly defined and continues to be well aligned with national priorities. The four SED research directions are all appropriate to stimulate development of the present state of the art in semiconductor electronics.

The Micro/nanotechnology project provides an example of research guided by the motivational targets listed in the SED research directions. Such projects are potential catalysts for new directions and opportunities for U.S. industry as it works to apply nanotechnology and bioelectronics. The project's four focus areas are single-molecule manipulation and measurement (SM<sup>3</sup>); bioelectronics; micro-electro-mechanical systems (MEMS) standards; and DNA separations (for forensic applications). These areas are aligned with the national priorities of nanotechnology, the molecular-level understanding of life processes, and, to a lesser extent, human health and well-being and national security. In particular the program on MEMS standards is strongly interactive with outside agencies such as Semiconductor Equipment and Materials International (SEMI) and the American Society for Testing and Materials (ASTM).

The Nanobiotechnology project is based on the in-house expertise at EEEL and international leadership in single-molecule detection using biological nanopores. This groundbreaking work relies on the convergence of biotechnology and nanotechnology and is in line with the current national and international academic and industrial trends in biotechnology and nanotechnology. The Macroelectronics project is attempting to establish metrology and technology for using organic-based thin films in lieu of silicon-based substrates in manufacturing macroelectronics. This is a medium- to long-term technological investment that could sharply reduce the costs of fabrication. With effective execution, this project promises to have a meaningful impact in the context of NIST's foundational mission, which is to promote U.S. innovation and industrial competitiveness.

The Power Device and Thermal Metrology project is focusing on the testing and characterization of high-voltage, high-power silicon carbide (SiC) devices and provides a valuable service to outside agency customers. Its work supports EEEL's core competencies in high-voltage, high-power semiconductor electronics and is in demand particularly by the electrical power utilities and the Department of Defense. This project does address national priorities, particularly insofar as it gives NIST the stewardship of critical research fields.

The Infrastructure for Integrated Electronic Design and Manufacturing (IIEDM) project, part of the Electronic Information Group, creates documentary standards that specify in a concise but sufficient fashion the necessary metrics of an electronic device. IIEDM facilitates the propagation of technology transfer within the electronics and electrical industry by virtue of its involvement in professional standards-making bodies in the United States (Institute of Electrical and Electronics Engineers [IEEE] and the American National Standards Institute [ANSI]) and abroad (International Electro-technical Commission [IEC]). The IIEDM project promotes growth in the electronics industry by providing technical expertise in an impartial forum to speed the development of standards and by providing assistance in resolving interoperability issues between similar, and often conflicting, standardization efforts. This project plays a significant role in maintaining the internal coherence of the semiconductor industry by its efforts, which range from interchangeable functionality to replacement integrated circuits.

The goal of the Nanoelectronic Device Metrology project is to develop measurement methodologies that enable new nanoelectronic technologies, including molecular electronics, while supplementing conventional complementary metal oxide semiconductor (CMOS) devices.

This is an essential bridge between emerging nanotechnology electronics and more conventional electronics.

The Advanced MOS Device Reliability and Characterization project leads in developing a basic understanding of dielectric degradation mechanisms. With the gate dielectric film thickness of silicon devices projected to scale to 0.7 nm or less by 2010, this has been identified as a critical front-end technology issue in the Semiconductor Industry Association's technology roadmap, and it is a critical research field for the entire semiconductor industry.

## **CRITERION 2. DEGREE TO WHICH EEEL PROGRAMS ARE WELL MOTIVATED**

### **What Is the Program Trying to Accomplish?**

The previously mentioned laboratory and divisional reports are quite detailed in this regard. They list broad longer-term divisional objectives, which they call "goals." Within a division, each group and project also has specific goals and milestones. The stated objectives were appropriate, and there were no instances where projects were without a clearly stated objective.

The general goals were directed toward providing state-of-the-art metrological support for the electrical, radio-frequency, optoelectronics, and semiconductor industries and developing new materials, processes, and technologies to achieve these goals. This support ranged from developing new standards or measurement techniques, to improving the understanding of device fabrication and their applications, to facilitating national and international acceptance of paper standards, and to satisfying the emerging needs of U.S. enterprises.

### **What Is Innovative or Different, as Compared to Efforts at Other Institutions, About the Program Approach That Will Lead to Success?**

The programs reviewed exhibited many specific innovations and unique research approaches; where exceptional results were demonstrated, this innovation or uniqueness was found to be a significant factor. The following are examples:

#### **Electromagnetics Division**

Novel calorimetry methods continue to be developed in support of microwave power and noise measurements. These methods extend the sensitivity of existing measurements.

For many years, high-speed oscilloscopes combined with network analyzers were used to characterize high-frequency systems. These measurement systems are good up to perhaps 70-110 GHz, the frequency range needed to measure very-high-speed optical communication systems, for example. The High-Speed Microelectronics Group within the Electromagnetics Division has been pushing this state of the art by creating new methods to enable calibration of these measurement systems and, in the process, extending their frequency range. Through the innovative approach of creating a very high speed pulse source via a high-speed photodiode that has been calibrated using an electro-optic sampling system, EEEL has been able to calibrate these very high speed oscilloscopes and network analyzers and reduce the overall uncertainty of the measurement process.

The antenna researchers have made fundamental contributions to the art of antenna pattern measurement, through refinements to a near-field measurement process. They have developed inexpensive and portable near-field probing equipment to be used at operational antenna locations to gather data at points that are precisely measured by optical instrumentation. New analysis procedures are used to transform the results into accurate antenna patterns. This permits measurements to be conducted on antenna systems that cannot be moved into test chambers, taking into account the conditions of the actual antenna installation.

The continued development of new instrumentation to allow the assessment of superconductor critical currents in applying both tensile and compressive loads is a major accomplishment and has been achieved through elegant instrument design. Innovative approaches to quantifying MRI technology through the use of calibrated phantoms were also noted.

EEEL's innovations in metrology, even in classical areas of research, are impressive. An example of this is found in the characterization of dielectric parameters of thin-material films, a problem important to the circuit industry. Researchers in the Radio-Frequency Electronics Group have created a new standard involving the measurement of such films by clamping them between two halves of a cylindrical cavity. Despite the fact that this allows the fields to leak from the cavity, the group has created a new standard for this type of measurement that allows researchers to measure the complex parameters of materials at several discrete frequencies in a band.

Besides developing precision metrology using innovative broadband techniques to accurately characterize the complex permittivities for various commercial materials such as foams, semiconductors, and liquids, the Electromagnetics Division further expanded this noninvasive material characterization technique to test a broad range of fluid types, which could help homeland security personnel to monitor shipments of commercial liquid and water supplies.

### **Quantum Electrical Metrology Division**

Some of the projects are highly innovative. For example, the Quantum Devices Group has developed pulse-driven Josephson array devices with improved chip holders for the cryogenic environment, as well as the associated biasing electronics. These systems can produce calculable AC voltages of extremely small distortion that are larger in voltage and higher in frequency than have been produced elsewhere. This technology has been transferred to the Applied Electrical Metrology Group, where it has been tested and evaluated. It is now in use for low-voltage AC-DC calibrations and has resulted in an order of magnitude reduction of calibration uncertainty. These uncertainties are the lowest offered and establish NIST as a leader in this field. This is also an excellent example of broad-scale innovation spanning multiple projects—fundamental quantum device development, coupled with system engineering and metrological testing, all of it substantially reducing calibration uncertainties, as demanded by U.S. manufacturers.

The vertical stacking of Josephson junctions is a technique that has only been demonstrated by EEEL and has resulted in the achievement of record high voltages (5.7 V) in programmable Josephson sources.

Although cross capacitors have been known for many years, there are extremely few working systems. The Farad and Impedance Metrology project has used the properties of cross capacitors in combination with other capacitor designs to substantially improve the uncertainties of the frequency response of capacitors. This work has now been applied to normal calibrations

that boast the smallest uncertainties over the 20 kHz range. It has also had a significant impact on the following project.

The Electron Counting Capacitance Standard project has achieved the lowest uncertainty of any single-electron-based current or capacitance standard. A repeatability of 1 part in  $10^7$  and a relative standard uncertainty of 1 part in  $10^6$  have been achieved, which is about 10 times better than achieved by any other entity. This project combines new developments in single-electron transistor design, as well as the development of cryogenic capacitors and the analysis of their frequency dependence.

The quantum voltage noise source system with its associated low-noise cross correlation electronics has been delivered to the Thermometry Group at NIST. This unique system can provide absolute measurement of thermodynamic temperature and is already providing independent thermodynamic data at uncertainties competitive with existing thermodynamic techniques, such as acoustic thermometry.

The Quantum Sensors Project has developed gamma-ray detectors based on transition edge sensors designed on thermally decoupled structures and sensed with multiplexed superconducting quantum interference device (SQUID) devices. These gamma-ray detectors, which have demonstrated a better than 10-fold improvement in energy resolution compared with conventional detectors, promise to resolve vexing false-positive detection problems during noninvasive monitoring of radioactive material crossing at borders and other critical entry points.

The practice of giving project leaders direct responsibility for both the scientific progress of their project and for its funding appears to have led to very dynamic teams who attract a significant fraction of their budgets from external sources. The high percentage of nonpermanent EEEL staff enables a quick reaction to changes in research directions if necessary. It also keeps the teams on average younger and more innovative. This, coupled with the common aspects of these types of technology and measurement science, enables significant synergies.

## **Optoelectronics Division**

The Optoelectronics Division has several key innovative projects that demonstrate the unique capabilities that have been developed in the division. Particularly noteworthy are the activities involving high-speed waveform measurements, the generation of ultrastable optical frequency combs, fundamental measurements of quantum dot laser linewidth, and the demonstration of gallium nitride (GaN)-based nanowire light-emitting diodes.

The high-speed measurement activity has improved its measurement capability and calibrations to 110 GHz with full time and frequency domain uncertainties. In addition, as the need for measurement capability increases for optical signals with speeds/bandwidths greater than 110 GHz, the group is developing metal-semiconductor-metal devices for the detection of ultrafast optical signals.

The optical frequency comb work has made tremendous progress in transferring the knowledge and performance capability from the  $\sim 800$  nm region, dominated by the mode-locked Ti:Al<sub>2</sub>O<sub>3</sub> laser (the gold standard), to the more relevant wavelength region of 1.55  $\mu\text{m}$  using erbium fiber as the gain. The key feature is that this group has diligently investigated the fundamental noise sources in fiber-based lasers, which has resulted in their mode-locked fiber comb source possessing a performance that directly rivals that of the Ti:Al<sub>2</sub>O<sub>3</sub>.

The Optoelectronic Division's efforts in single-photon detectors are complemented by its work on quantum-dot-based sources. The quantum-dot-based devices can provide a suitable

source for quantum-based metrology as well as quantum key distribution. Currently the NIST work is one of the few single-photon-source efforts in the United States. However, industry is working on the design and application of quantum dots for optical sources. The EEEL quantum dot metrology effort will support industry efforts through the development of characterization techniques. The measurement techniques are also helping to demonstrate short pulses and mode-locked quantum-dot-based lasers.

## **Semiconductor Electronics Division**

SED is working on standards for microelectromechanical systems (MEMS), which is particularly important for fabless MEMS companies. SED is taking a leadership role in developing these standards. It understands the requirements for the standards, develops and fabricates MEMS devices, and understands the need for standards. At this point SED is focusing on material-property measurements, metrology needs for microfluidics applications, and bioelectronics.

SED has international leadership in single-molecule detection using biological nanopores. Nanopore technology has many potential applications in a broad range of molecular and biological areas. Single-molecule electronic detection has been demonstrated. Mass spectroscopy has been demonstrated in a liquid. Various practical uses for such pores have been proposed, including arrays of different pores with varying molecular transmission properties, pores at the tips of cellular probes for studying molecular activities within living cells, and DNA detection for forensic analysis and identification.

The transition from silicon-based electronics to organic-based compounds would revolutionize the field of macroelectronics. SED has a critical activity in metrology, reliability, and new technology development for organic electronics. Little work is under way at universities or industry on metrology for or reliability of organic electronics. The success of the project would create a new platform for SED, as well as for NIST.

The Power Device and Thermal Metrology project is focusing on the testing and characterization of high-voltage, high-power SiC devices. SED's core competencies in high-voltage, high-power semiconductor electronics are a valuable resource for the electronics industry, the power industry, and the Department of Defense. The SED measurement infrastructure in this area is unmatched. The group is already established as a leader in SiC power device insertion into power system switching applications.

The Infrastructure for Integrated Electronic Design and Manufacturing (IIEDM) project contributes to the development of information exchange standards and conformance. It promotes collaborations among agencies, industry, academia, and governments to advance common S&T goals. Industrial standards consortia (such as Accellera) and standards bodies (such as IEEE and IEC) hold IIEDM in high regard for its neutrality in helping to define and resolve issues in industry. EEEL is seen as providing a unique contribution to the electronic and electrical industry.

The SED Advanced MOS Device Reliability and Characterization Group has extended its expertise in characterization of semiconductor-insulator interfaces to other material systems needed by industry and by national defense. These new systems include high-k/SiO<sub>2</sub> on SiC metal-oxide-semiconductor field-effect transistors (MOSFETs), high-k dielectrics on III-V compound semiconductors, ZnO nanowire MOSFETs, and time-dependent dielectric breakdown

of SiO<sub>2</sub>/SiC devices. SED provides unique expertise in understanding the fundamental science of device reliability.

### **Is Success Well Defined?**

EEEL's recent strategic planning efforts have answered this question in a much more quantitative manner than before. Success has been more clearly identified by having the general goals of the laboratory and its divisions and groups more carefully articulated and with more attention to consistency across their mutual objectives. The setting of specific milestones for most projects has exposed planning detail that was not previously revealed. In three of the divisional reports the plans or milestones are contained in each project's "Plans" section. This practice should be followed by the other division as well. Similar planning details were presented during the site visits.

The milestones have been made applicable to general ongoing activities, as well as to research-oriented activities, where the ultimate technical results simply cannot be known. For example, some projects provide calibrations or other measurement services, and the plans associated with these projects include such things as timelines for equipment improvements, for completion of international comparisons, extension of calibration ranges, lowering of achievable uncertainties, and, in some cases, the phasing out of less-critical services. The milestones for research-oriented projects are just as comprehensive, including planned studies of particular devices or measurement techniques, publication of reports on specified topics, achieving various numerical benchmarks in critical measurements, or the pursuit of definitive answers to questions that will set the direction of future research.

### **Electromagnetics Division**

In the Electromagnetics Division, short-range goals define success for each of the projects. For example, in the project on magnetic resonance imaging (MRI) phantoms, an ability to quantitatively compare images in different MRI instruments constitutes success. The work on superconductors clearly targets the mapping of the allowed operating region within the current density, stress, and temperature degrees of freedom. In radio-frequency circuits, success has been defined as the evolution of the measurements services to support an evolving set of waveguides and connectors, as dictated by customer needs.

In the more mature programs success is often defined on a longer time scale. For example, the antenna group has identified eight specific areas in which advancing customer technologies require long-term programs of improvement in, say, accuracy, extension to higher frequencies, measurement of lower sidelobe levels, measurements on new types of complex phased-array antennas, in situ and remote measurements, production-line evaluation, reliability of radio-frequency identification, and evaluation of anechoic chambers and compact ranges. Meeting evolving requirements in these areas is a worthy goal that forces the group to think far into the future in planning its activities and programs.

### **Quantum Electrical Metrology Division**

The following is a sampling of the specific project plans that define success in QEM projects:

- Achieve better values of the Planck constant at about 0.02 mW/W uncertainty, to meet the conditions specified in an October 2005 recommendation by the International Committee for Weights and Measures.
- Fabricate NbN thin films with high  $T_c$  ( $>9$  K) and investigate their efficacy in single-photon transition-threshold detectors.
- Complete the SIM<sup>3</sup> energy comparison and publish the results.
- Begin calibration service for AC current shunts at 100 kHz up to 100 A.
- Increase the output voltage and measurement bandwidth of the AC Josephson voltage standard (JVS) to 1 V and 1 MHz.

### **Optoelectronics Division**

The following is a sampling of the specific plans that define success in Optoelectronics Division projects:

- Demonstrate the next generation of coatings for laser power and energy measurement standards based on carbon nanotubes. The coatings will allow the expansion of existing measurement services to include ultraviolet laser measurements and high-power laser diode measurements.
- Demonstrate thermal detectors suitable for the range of laser wavelengths served by division calibration services (0.157  $\mu\text{m}$  to 10.6  $\mu\text{m}$ ).
- Continue to offer in-house courses on display metrology providing hands-on laboratory measurements. Plan to teach the in-house course on display metrology at least once per year and as frequently as four times per year.
- Evaluate division phase-dispersion contrast measurements of cell and tissue samples in order to verify the measurements, validate the scatterer size, demonstrate contrast, and estimate the measurement uncertainty.
- Demonstrate the applicability of fiber frequency comb sources to remote sensing, including precise range-Doppler measurements.
- Investigate the application of photonic crystals to emission control in single-photon sources and other devices. Demonstrate dispersion compensation with chirped gratings to shorten pulse widths in monolithic mode-locked diode lasers.
- Extend the single-pixel imaging to a full-scale millimeter-wave, terahertz imager that operates in real time. Deliver copy of scanned imager to the Transportation Security Administration laboratory.

### **Semiconductor Electronics Division**

The following is a sampling of the specific plans that define success in SED projects:

- Report results of modeling the distributed resistance and capacitance values of interconnect conductors that can be simulated by both analytical solutions and a commercial Maxwell solver.

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<sup>3</sup>SIM is the regional organization of NMIs for North and South America.

- Devise and demonstrate a hybrid optical-e-beam, direct-write lithography process to pattern a selection of 100-mm or 200-mm bulk-silicon (110) wafers with single crystal critical dimension reference materials (SCCDRM) test structures with critical dimensions at or below 20 nm.
- Synthesize and fabricate a microcontroller Internet Protocol core with an IEEE 1451-compatible interface in a standard 0.25  $\mu\text{m}$  CMOS process virtual component (VC).
- Develop methodology and standards to allow embedded sensor VCs to be synthesized by standard multi-technology (MT)-synthesis tools and demonstrate their viability via SED's micro-hotplate gas-sensor VC.
- Apply EEEL high-voltage, high-frequency power device test systems to evaluate the performance of the 10-kV, 100-A, 50-ns half-bridge power modules produced by the Defense Advanced Research Projects Agency (DARPA) wide-band-gap semiconductor technology high power electronics (WBST-HPE) program and assess the potential for enabling advanced commercial and military power distribution systems.
- Complete development of a prototype microfluidic forensic DNA separation system for demonstration to forensic scientists.
- Develop an integrated microwave transmission line with a microfluidic network and investigate the feasibility of using microwave power to heat fluid in specific points in the channel.

### **What Will Be the Impact of Success?**

The impact of success may be considered from different standpoints. To the end user, whether this be the U.S. public as a whole, the U.S. economy, U.S. industry, or the international scientific community, success will be measured and quantified by some metric that is a measure of the change that is caused in that sector. Quantifying this change is beyond the scope of this report, but it is typically approached in a comprehensive strategic plan through cost-benefit analysis. Perhaps EEEL management in its continuing exercise of strategic planning will provide its own quantification of these impacts. Instead, the current report provides a selection of projects that have been highlighted and describes the importance of the work to a particular sector.

In the short term, and within NIST and EEEL, the impact of success may be viewed as the successful completion of a project, the delivery of a service or product (the delivery of services such as calibrations is fully detailed in the EEEL divisional reports), the increase in total knowledge about a particular subject, the maintenance of a particular facility for future use, or the development and training of qualified staff for future projects. In some cases the successful completion of one project leads to the discovery of a new and possibly more interesting field of investigation.

In the longer term, and within NIST and EEEL, the impact of success may be viewed in at least two other ways. Particularly in the mature areas of measurement services, the impact of success is that vital services are being delivered expertly and without interruption and will continue to be delivered and improved. This directly promotes the national priority, to sustain and maintain stewardship of critical research areas and maintain the enabling infrastructure. Success also has implications for education, training, and succession planning within EEEL.

As in most other fields of research, success means that new techniques will be developed and new metrology methods will be invented. For example, hybrid time/frequency metrology

methods are being developed using an electro-optic sampler, which itself evolved out of earlier optical and radio-frequency metrology work.

### **How Will Success Be Disseminated to End Users?**

The dissemination of success is in general well documented in the EEEL divisional reports. The delivery of services and calibrations is detailed by project in terms of both total volume and numbers. The availability of services and critical specifications are listed on the NIST Web site and in other publications. Publications of recent research in peer-reviewed journals and conferences are also listed by project and during this review were examined by the panel.

The participation of EEEL staff as members of editorial boards and scientific and professional committees, as well as their involvement in conference organization, shows EEEL's strong leadership in the national and international communities.

Training of guest workers, presentation of workshops, and publication of textbooks and normative standards all attest to the involvement of EEEL staff in furthering the general education of scientists and engineers.

Several awards or prestigious appointments illustrate individual achievement that has been recognized inside or outside NIST. For example, an EEEL staff member has been appointed editor of the journal *IEEE Transactions on Magnetics*.

A number of devices, instruments, or measurement systems have been developed, constructed, tested, and delivered to other groups within NIST or organizations outside NIST. These include such things as the Josephson Noise Thermometry system and the improved detector array for the Submillimeter Common-user Bolometer Array (SCUBA) submillimeter telescope.

While EEEL has been attempting to publicize its success and achievements by various means, including tours, presentations to the general public, announcements in various trade magazines, and features on television, radio, and the Web, it is clear that these efforts are not adequate. Many projects remain unknown to the public and even to the metrology community. The task of making people aware of the excellent work going on at EEEL is indeed difficult, but it does need to be performed more effectively.

### **How Much Will Success Cost and How Long Will It Take?**

Summaries of laboratory and divisional budgets, including internal base funding from NIST, funding received through internal competitive processes, and external funding, were made available for review. Staffing numbers associated with individual projects were also presented. The overhead costs of such things as building facilities and support staff were divulged only in generalities or not at all. This report does not attempt to verify or justify these costs but instead considers whether the overall costs seem to offer good value to the American public.

In general EEEL is providing excellent work at a very reasonable cost. All projects examined were providing value for the investment. The long-term objectives appeared to be well considered, and the short-term objectives were focused and in general achievable.

If success is measured in terms of achieving the immediate plans of the projects, then the completion times are generally 1 year and in a few cases 2 years. If success is measured in terms of achieving the long-term objectives of the groups or divisions, then the timescales are much

longer. In many cases the long-term objectives will be viable for as long as their associated technological subject areas are critical for the American infrastructure. Reasonably, this may be as short as 5 years, especially for projects examining the suitability of particular research directions that encounter technical impediments or may be supplanted by other technologies. On the other hand, the broader objectives of the divisions are applicable to large sectors of the economy, and these can be expected to be important for decades into the future. The electronic, semiconductor, and optoelectronics sectors of the American economy are extremely large and will be essential to society for many decades.

### **CRITERION 3. TECHNICAL MERIT RELATIVE TO THE CURRENT STATE OF THE ART**

In general the technical merit of the projects examined was impressive. Many projects demonstrated unique capabilities. Some projects were considered “best in the world” by at least one metric (e.g., smallest uncertainty, a particular level of operation, or some other combination of operational parameters). There were also other projects among the top few in the world when technical merit was considered. The following are examples of noteworthy activities.

#### **Electromagnetics Division**

The services of the RF Electronics Group are considered the gold standard in radio-frequency (RF) fields and guided RF waves. All measurements of RF power, power efficiency, and RF field strength made by the RF Electronics Group are traceable to the painstaking calorimetry measurements that are used as the primary standard for microwave power.

The EMC Group at EEEL has long recognized the importance of reverberation chambers as a key tool for EMC testing. In application of the reverberation chamber for wireless communications, this group has been working on multiple input–multiple output system testing. Its work on the simultaneous calibration of several probes in a reverberation chamber is an appropriate step toward establishing measurement standards for reverberation chambers.

The RF Fields Group is currently involved in a one-of-a-kind effort in on-site antenna metrology. The method involves the construction of a portable near-field scanner that can accurately measure the position of its own sensing elements and then use the near-field data to characterize the near- and far-field behavior of the antenna. This work builds on the group’s previous work in near-field scanning that relied on the accurate placement (as opposed to measurement) of the antenna sensors and has become something of a standard in its own right. Especially impressive is the constant focus in this work on the quantization of error in the measurement, despite the complexity of the governing equations and the measurement setup.

The superconductivity metrology activities are unique and innovative. The systematic and detailed analysis of the dependence of critical current on wire stress levels is an important topic that has not been addressed elsewhere. It is particularly relevant in large superconducting magnet design, where forces from the magnetic field can alter the current-carrying capability of the windings.

The spin-current-driven oscillation studies in the Magnetics Group are noteworthy. Of particular interest is the examination of mode locking, which is likely to be a central feature of any realistic implementation of this technology, owing to the need to use a number of oscillators in parallel to get adequate power.

## **Quantum Electrical Metrology Division**

The Quantum Device Group has established itself as a leader in the development of improved dielectrics for quantum computing purposes. In addition, it was the first to demonstrate coupling of two phase qubits via a transmission line resonator and to demonstrate a simple quantum memory with coherent state transfer between these three quantum devices. The Josephson volt effort has produced world-record results in development of an AC Josephson voltage standard, has demonstrated a 5-V programmable DC voltage standard, and is well on its way to producing a 10-V turnkey standard that could revolutionize voltage standards technology. The Josephson noise thermometry application is unique but is being actively pursued by other entities.

The activities of the Fundamental Electrical Measurement Group and the Applied Electrical Metrology Group demonstrate impressive technical expertise. Examples include the metrology of the ohm, which is currently based on the quantum Hall effect and scaled at NIST over roughly 20 orders of magnitude in dynamic range using cryogenic current comparators; metrology of the farad by means of the calculable capacitor, which currently enjoys the lowest uncertainty for capacitance; and the electronic kilogram, which has measured Planck's constant with a degree of uncertainty that is not expected to be matched within the next few years.

## **Optoelectronics Division**

The research team working on the optoelectronics frequency comb has evolved the frequency comb work in fibers to rival work of the original optical frequency comb source that won the Nobel prize. As noted above, the ability to transition the performance of the erbium-based laser evinces a keen understanding of the fundamental issues and the technical ability of staff members.

The project in optomanufacturing of quantum optics has demonstrated unique capabilities that provide support for national programs in quantum computing and quantum cryptography. These include unique demonstration of single-photon sources and detectors. Currently the EEEL work is one of the few single-photon-source efforts in the United States. There is considerable excitement over the use of superimposed coherent states of light, called "cat" states, to demonstrate a loophole-free measurement of Bell's inequality.

The work on nanotechnology includes innovative development of defect-free GaN nanowires on silicon. This ability to grow material has also led to single nanowire isolation and the development and demonstration of nanowire bridge structures. The group doing this work is a leader in material growth and in the measurement of the properties of GaN, specifically in the polarization anisotropy from  $\sim 77$  K to room temperature. The success of this group's work was recognized by *R&D Magazine*, which awarded it the 2006 Micro/Nano 25 Award.

The display standards and measurement methods of the division's display work are extremely robust and reproducible. The key attributes that are measured are clearly observable to the end user. A major contribution of the display group is its sponsorship of the Display Metrology Workshop, which is a good source of funding and has been recognized as having great value to entities required to perform display measurements by the president of the Society for Information Displays, the leading professional society for display technologies.

The quantum dots and characterization projects of the division are very successful and highly visible. As an example, the division has demonstrated that the use of molecular beam epitaxy for growth produces quantum dot ensembles with greater uniformity of height and density than conventional quantum dots grown by metal organic chemical vapor deposition. The group has also performed linewidth measurements on the quantum dot ensembles and has observed the narrowest linewidths for self-assembled quantum dots. These new materials are being incorporated into device structures for realizing single-photon detectors, demonstrating a record 70 percent internal quantum efficiency.

### **Semiconductor Electronics Division**

As tools for semiconductor fabrication have attained the capacity to pattern structures with dimensions in the 100-nm range, manipulative and metrological tools that can work with single molecules will make possible new paradigms for experimentation and processing. EEEL is carrying out research on the cutting edge of this important development, and its progress to date is very encouraging.

EEEL plays an international leadership role in single-molecule detection using biological nanopores. This is important and groundbreaking technical work that addresses the convergence of biotechnology and nanotechnology. The nanobiotechnology activity on nanopores is important work with significant applications and has achieved a number of milestones. Blockage of pores has been demonstrated for the purpose of studying anthrax infection. Single-molecule optical detection is about to be demonstrated. DNA sequence detection is close to being demonstrated by studying residence times within the pore and time-varying current amplitudes during transition through the pore.

High-voltage, high-power semiconductor devices are becoming more important with the development of electric vehicles and the deregulation of the power industry. EEEL has the core competencies in high-voltage, high-power semiconductor electronics, which is a valuable resource for the nation. The Enabling Devices and Integrated Circuits Group is a leader in SiC power device insertion into power system switching applications.

The Nanoelectronics Device Metrology and the Advanced MOS Device Reliability and Characterization research projects are among the best in the country for advanced electronic devices. The former is one of the best teams in the country in molecular electronics metrology. The latter activity is a good example of how EEEL can impact U.S. industry.

### **CRITERION 4. TECHNICAL PROGRAM QUALITY WITH RESPECT TO ADEQUACY OF EEEL FACILITIES, EQUIPMENT, AND HUMAN RESOURCES**

The panel was impressed with the quality and expertise of the staff, who seemed to be well motivated, technically flexible, and inclined to take on multiple projects. There were numerous examples of excellent synergy among projects. However, there were also concerns about the demographics of the staff, particularly in the many areas that were considered essential and need to be continued even though technical staff is approaching or past retirement age. While the recent increase in and apparent high quality of associates holds promise for ultimately alleviating this problem, succession planning for the near future remains problematic.

Staff morale appeared good. This may be due to promised increases in general government R&D funding over the next few years, to the increased numbers of younger staff at

the associate level, or to the improvements in laboratory space offered by the Advanced Measurement Laboratory (AML) facilities and the proposed increase in new laboratory space at the Boulder facilities.

The new AML facilities are impressive. While laboratories in older buildings still have specific problems, these problems now seem to be the exception rather than the rule. In general, the quality of laboratory space ranges from acceptable to excellent. While the Boulder clean room and fabrication facilities are extremely cramped and suffer from poor control of air conditioning and humidity, most facilities are now considered acceptable by the staff, since the promised Boulder expansion will reduce dependence on the older facilities.

The facilities are reasonably well instrumented. There are specific cases, however, where expensive instruments are needed to support particular projects; these needs are described below.

There was substantial concern about a recent investment at the NIST Gaithersburg nanofabrication facility (not part of EEEL)—namely, the \$5 million purchase of an e-beam tool that seems inappropriate for the level of use it is likely to enjoy and the level of maintenance support that will be needed (estimated at \$200,000 to \$500,000 per year). Solutions that could have been purchased for \$1 million to \$2 million would have been wiser. There should be a better mechanism for EEEL researchers to influence the nanofabrication facility's capital allocations, so as to maximize the utility of purchased equipment.

Many of the EEEL projects are currently supported to a large extent by external funding. For example, 47 percent of the Optoelectronics Division's overall funding is now from external, or nonbase, sources. In past reviews the panel recommended increasing that fraction, and EEEL did so very successfully. In the Optoelectronics Division, the ratio had once been only 17 percent but grew to about 50 percent, and in the other divisions the improvement was similar. Nonetheless, the lesson learned from obtaining external support is that as researchers spend more time securing external funds to support the EEEL mission, they have less time to perform their critical work, and this decreases long-term sustainability.

There seems to be some concern within EEEL about the gradual degradation of facilities and infrastructure at NIST Boulder in general. There were even some staff concerns about the overall future of the Boulder campus. The staff should be commended for maintaining the excellence in their programs despite the atmosphere of uncertainty. The labs there are very overcrowded, but relief may be in sight in the form of a new building. If the Optoelectronics Division can acquire an appropriate share of the new facilities, its ability to maintain and continue to grow its programs would improve.

Although worthwhile and well-performed, some projects performed by the Electromagnetics Division, such as the work on RF identification devices, could have been performed by qualified organizations outside NIST. Many other projects were understaffed and required the unique skills of the EEEL staff. Innovation around EEEL's areas of core expertise should receive first priority, and EEEL resources should be focused on projects requiring its staff's unique capabilities.

In spite of the obvious success of the Optoelectronics Division's photonics, semiconductor, and nanostructures activities, EEEL does not seem to be giving it sufficient resources.

In the Electromagnetics Division, the cost and burden of providing calibration services appears to be onerous for some groups, while in other groups this does not seem to be a problem. EEEL should to try to recoup as much of the equipment amortization and maintenance costs as

possible when it charges for these services. Additional cost increases could help to regulate demand and help EEEL to stay out of the retail calibration business as much as possible.

Funding for the Advanced MOS Device Reliability and Characterization project in the Semiconductor Electronics Division (SED) may not be stable. While it has been identified as one of the mandated programs in EEEL, the project is supported mostly by the Office of Microelectronic Programs. A shift toward more core support would be desirable.

Facilities control in Boulder is still a major issue. There are too few federal personnel on site to maintain the infrastructure, so contractors are used to fix and repair everything within the buildings. This means there is no continuity—that is, the legacy of construction of any given laboratory is lost when contractors are changed. In one example, a clean room was flooded, and there were only two people (one of them was retired) who knew where the shutoff valve was located. Clearly, this puts laboratory facilities and personnel in a precarious situation. Outsourcing facility maintenance may be a failed experiment and needs to be addressed.

The Office of Microelectronics Programs (OMP) continues to be successful in starting and managing a broad portfolio of NIST programs to support the semiconductor industry. OMP programs have effectively coordinated several EEEL activities in SED by fostering collaboration with industry. Many core SED programs are too dependent on OMP funding. The use of OMP money to fund outside Nanotechnology Research Initiative (NRI)-friendly programs will help get SED programs involved with university-based NRI programs, but it might be worthwhile to look at the potential benefit of spending American Competitiveness Initiative money within EEEL for NRI-related activities.

## **Additional Concerns of the Panel**

### **STAFFING AND FUNDING**

Many of the panel's comments can be classified as one of the three closely related concerns that were applicable to projects in all four divisions:

- The thinness of staffing, especially in critical projects;
- The preponderance of temporary staff over permanent staff; and
- The low fraction of internal funding for many projects.

Project staff resources seem to be spread very thinly, and many important projects are just one person deep. Sustaining a core competence in critical areas is essential to the EEEL and NIST missions. Some projects, especially in emerging areas, require more resources if they are to have more impact. Both considerations will require more staff to achieve continuity of expertise in essential areas and critical mass in emerging areas.

Much of the cutting-edge research is being performed by temporary staff, while permanent staff are increasingly involved in managing the projects and applying for outside agency (OA) funding. While this mode of staffing can be cost effective, the work being done by these researchers, both permanent and temporary, will make them attractive candidates for jobs outside EEEL, aggravating the problem of long-term planning, vision, and sustainability.

EEEL has been quite successful in pursuing OA funding. Many projects now obtain 50 percent or more of their total funding from OA. However, this success could also result in an increase in the fraction of temporary staff, an increased workload for the permanent staff to maintain the OA funding, a shift away from EEEL's mission to satisfy the OA objectives, a diminishment of NIST's independent authoritative position, and a further strain on EEEL's ability to maintain its core competency.

These issues are well known to EEEL management but remain an ongoing challenge. The recent strategic planning efforts should result in a long-term plan detailing how and in which disciplinary areas these issues can be addressed.

### **INTERNATIONAL ISSUES**

A serious concern for some of the panel members is the extent to which international relationships could damage rather than reinforce U.S. competitiveness. They noted that the 2008 national priorities<sup>4</sup> document supports this finding. As one example, the measurements services and antenna calibration work at EEEL are recognized as the gold standard for calibration of these types of measurements and are central to the NIST mission. The EEEL personnel performing this activity have been hosting their counterparts from Korea to assist them in duplicating this critical capability in their national measurement facility. Other examples of activities that would strengthen the capabilities of some of our most serious competitors included the recruitment of guest researchers from China, which served to train the staff of China's national counterpart to

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<sup>4</sup>FY 2008 Administration Research and Development Budget Priorities, June 23, 2006, Memorandum from the Executive Office of the President, Washington, D.C.

NIST. Other panel members had less restrictive interpretations of the above-mentioned national priority documents. During the next review the panel will seek clearer and more specific policy guidance on this point.

## **THE PLANNING PROCESS**

The two new research areas, macroelectronics and nanobiotechnology, are very strong and have allowed for the recruitment of outstanding young investigators. The linewidth standard activity has been phased out ever since suitable standard reference materials were developed and made available through NIST. This example of starting new research areas and phasing out mature programs is evidence that the formal strategic planning process is ongoing and being implemented across SED.

Strategic planning is being conducted throughout EEEL, but the detail and implementation are least developed in the Electromagnetics Division. This may be due to recent changes in division management, but all staff should become fully engaged in this process.

In many cases, activities are being initiated that lie at the boundary between EEEL's mandate and the mandates of other laboratories within NIST. Representatives of EEEL did not describe clearly the process by which these boundaries are set. Is it strictly based on the entrepreneurial efforts of the individual scientists, or is some coordination at the lab level attempted? One such issue is the decision about which activities fall within the sphere of the Center for Nanoscale Science and Technology (CNST) and which fall within that of EEEL. Another is how the spintronics activity within the magnetics efforts might interact with the efforts related to time and frequency or integrated circuits.

There is still some question as to how new projects are initiated and old ones stopped in response to the EEEL strategic planning. In other words, there is some question about how the strategic plan is translated into action.

A plan for how EEEL will interact with and utilize the CNST should be established. CNST is a large investment for NIST, and EEEL should be a large customer. There is an opportunity for an interaction between CNST and the EEEL work on localized materials properties measurements (permittivity and permeability). CNST may be able to provide submicron test structure fabrication, while EEEL can provide test structure design and measurement.

## Recommended New Directions

One potential research component of the Optoelectronic Division's biophotonics effort could provide a substantial contribution to national needs. EEEL should give the division some exploratory funding to understand the issues and needs in biophotonics.

Single-photon detectors could also serve as a link to metrology at the quantum level. Detection at the scale of single photons should be particularly useful for radiometric measurements. Additional efforts looking at the use of single-photon detection should be undertaken.

There is an emerging interest in the wireless and antenna research to make use of reverberation chamber techniques. Some quantification of parameters and recommended measurement processes should be agreed on by the researchers on this subject.

The commendable and continuous focus on uncertainty and error characterization should be encouraged. NIST needs to be seen as the leader by example for this activity, especially in those technical areas in which uncertainty characterization is less well developed.

EEEL should increase awareness of metrological needs in emerging technologies. Emerging wireless systems such as WiFi, WiMax, and cellular systems are one such opportunity.

The quantum dot single-photon detector is a good example of the strength of the various quantum programs at NIST. This device integrates the design and fabrication capabilities for quantum dots with the need for single-photon detection. The device structure looks promising for a semiconductor-based device. The current device, however, is not based on an indium phosphide (InP) platform, which would be suitable for use at 1550 nm.

A symposium on optical fiber measurements is no longer organized by EEEL. Perhaps EEEL personnel, working with the Optical Fiber Communications Conference, could help to present a symposium on this topic at the conference.

The research staff routinely develops unique, patentable works. Given its responsibility for disseminating the research work, EEEL should reexamine its intellectual property and licensing practices. In particular, linkage should be strengthened between the optoelectronics terahertz program and commercial concerns. The blackbody calibration source is another possible candidate for licensing.

New investments need to be made in areas of core competencies, even if those investments are not high-profile. Every effort should be made to invest in core areas as well as new areas when the opportunities arise.

The Electromagnetics Division may have overlooked an opportunity—namely, that metrology for the complex modulated signals used by cell phones and the communications industry is absent or nascent. This seems to be an important direction for EEEL to move into.

SED should take a critical look at how its system-on-a-chip project is differentiated from similar activities at universities or in the private sector. It might be time to transfer this technology to a company that can make a product.

The Optoelectronics Division should consider adding projects on promising new photonic technologies such as organic photonics, including organic light-emitting diodes (OLEDs). Perhaps this effort could be coupled with the ongoing effort in the display group.

There are some specific opportunities for further leveraging existing projects. One example is the coupling between the Semiconductor Electronics Division and the work in the Electromagnetic Division on spintronics (specifically, microwave oscillators). Some attempt should be made to understand the relevant performance parameters of the device and the circuits

such devices might eventually be applied to. This would happen much more readily if there were an ongoing discussion between these two groups. Additional opportunities might arise by involving the Time and Frequency Division as well. Perhaps CNST and/or OMP can offer some leadership in this collaboration.

Emerging wireless systems such as WiFi, WiMax, and cellular systems utilize multiple antennas to transmit and receive signals for better channel capacity and user coverage. However, there are very few metrology techniques in this field to help the design and performance evaluation of this class of antennas. EEEL should increase its participation in evolving wireless antenna technology and the exploration of new metrology techniques and testing facilities (such as reverberation chambers). EEEL personnel should also proactively engage in the roadmapping activities of these emerging wireless standard bodies to forecast and develop critical metrology techniques for future industry needs.

EEEL is currently leading the calibration of scattering parameters with vector network analyzers extending to millimeter-wave frequencies. As the frequency of operation approaches the terahertz regime, many components and systems will be based on quasi-optical concepts. EEEL could build on its expertise at lower RF frequencies and in the optical regime to lead in this emerging measurement area.

## Conclusions

The assessment panel has reviewed the Electronics and Electrical Engineering Laboratory of NIST with respect to the charge presented by the National Research Council. The panel found that the laboratory was well aligned with national priorities and is continuing to provide support for critical research fields within its mandate. The projects are well planned and backed by documentation on the short- and long-term goals, accomplishments, and expected impacts. In general, EEEL is providing excellent value at a reasonable cost. All the projects reviewed were providing value for the investment.

The technical merit of the programs is generally excellent. Many of the projects are state of the art and offer valuable support to the U.S. technological infrastructure and metrological needs. As well, there is promise of significant advancement in emerging technologies. The resources of the laboratory are generally adequate. The quality of the laboratory facilities varied widely, from excellent to barely acceptable. The quality of the staff is generally excellent, but the manpower expended on almost all projects was no more than minimal. This report also details a number of concerns about sustainability of activities, staffing, and the planning process and suggests new directions in research within the existing EEEL organization.