An Assessment of the National Institute of Standards and Technology Electronics and Electrical Engineering Laboratory: Fiscal Year 2009

Panel on Electronics and Electrical Engineering; National Research Council

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AN ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY ELECTRONICS AND ELECTRICAL ENGINEERING LABORATORY

FISCAL YEAR 2009

Panel on Electronics and Electrical Engineering

Laboratory Assessments Board

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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:

Robert W. Bower, University of California, Davis (Emeritus),
James P. Gordon, Consultant, Lucent Technologies,
Robert Hellwarth, University of Southern California,
Ivan Kaminow, University of California, Berkeley,
Linda Katehi, University of California, Davis, and
Dwight 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 D. 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 panel and the institution.

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Summary

The National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce, carries out its mission of promoting U.S. innovation and industrial competitiveness by developing and applying technology, measurements, and standards across nationally and strategically important industries. NIST is uniquely positioned to contribute to the development of U.S. industry and to technology deployment, and thereby to U.S. economic growth.

This report contains the assessment by the Panel on Electronics and Electrical Engineering of NIST's Electronics and Electrical Engineering Laboratory (EEEL), focusing on the scientific and technical work performed by the laboratory. The assessment is conducted biennially. The panel was constituted by the National Research Council (NRC) through methodical and thorough consideration of the key expertise needed to perform the assessment. The NRC is the principal operating arm of the National Academy of Sciences and the National Academy of Engineering. The panel was charged to examine the broad factors of technical merit of the laboratory's programs, the adequacy of its facilities and resources, and its achievement of its desired impacts.

The EEEL comprises four divisions—the Optoelectronics Division, the Semiconductor Electronics Division, the Quantum Electrical Metrology Division, and the Electromagnetics Division—and two operating offices: the Office of Law Enforcement Standards and the Office of Microelectronics Programs. The two offices were not subject to this formal assessment.

In this report, the panel's findings are delineated in several chapters. Included are division-by-division assessments and project-specific evaluations (Chapter 3), EEEL responses to concerns from the previous assessment (Chapter 4), general observations of the panel (Chapter 5), future thrusts or high-impact projects (Chapter 6), conclusions (Chapter 7), and recommendations (Chapter 8).

The researchers and management of the EEEL have been highly effective in addressing the laboratory's main objectives: anticipating future metrology and standards needs, enabling scientific and technology advances, and improving and refining existing measurement methods and services.

Most of projects reviewed are excellent and are exerting pervasive impact. The research on a superconducting single-photon detector in the Optoelectronics Division, which is an enabling technology for a variety of applications in leading next-generation computing, such as optical quantum computing, is the best in its field. The Electronic Kilogram project of the Quantum Electrical Metrology Division offers the most precise measurement of Planck's constant to date, integrating many of the standards developed in the EEEL. The development of phantoms and metrology for quantitative biomagnetic imaging is another standout, providing superior metrology for Magnetic Resonance Imaging machines in medical diagnostic applications.

There is an overwhelming need for improvements in physical facilities in areas ranging from heating-cooling systems to the construction of new facilities.

Certain valuable projects are severely underfunded and understaffed, jeopardizing the intended progress and the viability of the projects. The funding system warrants a thorough review. A review process for internal funding is needed that is based on technical merit rather than on economic need. For older projects that have been receiving internal funding and either have come to an end or found other funding, there should be a mechanism in place to ensure that the internal funding is reallocated. Interaction with other groups within NIST is becoming more difficult because there is less "flexible money" to incentivize collaboration.

The concept of fully documenting specialized knowledge before a staff member retires should be facilitated. Further collaboration between activities in Boulder, Colorado, and Gaithersburg, Maryland, is encouraged where overlap exists.

This report identifies high-impact and new thrust programs to augment the laboratory's base for future growth. One such area is photovoltaics. Photovoltaics stands on its intrinsic merit of direct conversion from sun power to electricity. Solar energy is one of the critical renewable energy paths and will be in the necessary mix of future energy trajectories that must respond to the need for renewable and green energy sources. However, the exploration and use of solar energy have risen and sunk with oil prices; oil constitutes only a minuscule share of the U.S. electricity generation, and oil prices should not deter renewable energy deployment. For the United States, renewable and green energy is a must. Energy is a race involving technology and deployment in the global competitive landscape. Photovoltaic electricity is the story of the power play of atoms, photons, and the free path of electrons; no country can capture another country's photons. The photovoltaics effort will also support the nation's goal of implementing the Smart Grid system.

The graphene-based quantum conductance standards, addressed in the Quantum Electrical Metrology Division, constitute another new thrust area that may provide solutions to today's challenges in resistance metrology. The Semiconductor Electronics Division has proposed bioelectronics as a possible new focus to further innovative metrology. The recent advances in biotechnology hold great potential for targeted and preventive medicine that calls for sensitive, cost-effective, high-throughput tools. Bioelectronics is an important strategic priority area. Additionally, the proposed establishment of a center for nanoelectronics reliability in the Semiconductor Electronics Division will further the collaboration with industry and other agencies by providing the much-needed know-how and services in reliability metrology.

Another strategically important program is that of addressing the Smart Grid system. Globally, countries including those in the European Union, Canada, and China have promulgated government policies to endorse smart grid initiatives. In the United States, the Energy Independence and Security Act of 2007 (Public Law 110-140) assigns to NIST a coordinating role in the development of standards for the Smart Grid capabilities. Smart Grid received further support with the passage of the American Recovery and Reinvestment Act of 2009 (Public Law 111-5), which set aside $11 billion for the creation of a smart grid. The Federal Energy Regulatory Commission is also looking at the growth in renewable, clean energy accommodated by the evolving Smart Grid system. A working system with the desired reliability, efficiency, and safety is expected to revolutionize the electricity supply, distribution, and consumption. It will also enable the embracing of green energy electricity, as well as environmentally friendly transportation—hybrid and electric vehicles—making the Smart Grid system a sustainable energy model. In the context of the intense global energy activities, the success of the integrated Smart Grid system represents an opportunity for the United States to demonstrate its technical and commercial leadership. By fully employing the wealth of collective expertise and experience in the EEEL, NIST is poised to take a leadership position among other agencies in developing and deploying the measurements to enable multi-front technologies and the standards that govern the deployment of smart grids.

The NIST mission is important to the national priority agenda that highlights energy, the environment, and manufacturing. The EEEL, equipped with diverse professional skills and comprehensive technical expertise, has demonstrated significant accomplishments in crucial areas and is ready to support further national strategic programs. The EEEL holds enormous promise, essential to NIST's mission and the national interest.

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The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the 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 nine,[1] as well as the adequacy of the laboratories' resources. In 2009, NIST requested that five of its laboratories be assessed: the NIST Center for Neutron Research, the Center for Nanoscale Science and Technology, the Information Technology Laboratory, the Chemical Science and Technology Laboratory, and the Electronics and Electrical Engineering Laboratory (EEEL). Each of these was assessed by a separate panel of experts; the findings of the respective panels are summarized in separate reports. This report summarizes the findings of the Panel on Electronics and Electrical Engineering.

For the fiscal year (FY) 2009 assessment, NIST requested that the panel consider the following criteria as part of its assessment:

1. The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide;
2. The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of laboratory's technical programs; and
3. The degree to which laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

The context of this technical assessment is the mission of NIST, which is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve the quality of life. The NIST laboratories conduct research to anticipate future metrology and standards needs, to enable new scientific and technological advances, and to improve and refine existing measurement methods and services.

In order to accomplish the assessment, the NRC assembled a panel of 22 volunteers, whose expertise matches that of the work performed by the EEEL staff.[2] The panel members were also assigned to four subgroups (division review teams), whose expertise matched that of the work performed in the four divisions in the EEEL: Electromagnetics, Optoelectronics, Quantum Electrical Metrology, and Semiconductor Electronics. These division review teams individually visited EEEL facilities in

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[1] The nine NIST laboratories are the Building and Fire Research Laboratory, the Center for Nanoscale Science and Technology, 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.

[2] See http://www.nist.gov/eeel/ for more information on EEEL programs. Accessed May 1, 2009.

Gaithersburg, Maryland, and Boulder, Colorado, for one and a half days, during which time they attended presentations, tours, demonstrations, and interactive sessions with EEEL staff. Subsequently, the entire panel assembled for 2 days at the NIST facilities in Gaithersburg, Maryland, during which they attended overview presentations by EEEL management and conducted interactive sessions with EEEL managers; the panel also met at this time in a closed session to deliberate on its findings and to define the contents of this assessment report.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas of EEEL activities. The panel reviewed selected examples of the technological research covered by the EEEL; because of time constraints, it was not possible to review the EEEL programs and projects exhaustively. The examples reviewed by the panel were selected by the EEEL. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the following: the technical merit of the EEEL work, its perceived relevance to NIST's own definition of its mission in support of national priorities, and specific elements of the EEEL's resource infrastructure that are intended to support the technical work. These examples are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs that the panel examined. The assessment is currently scheduled to be repeated biennially, which will allow, over time, exposure to the broad spectrum of EEEL activity. While the panel applied a largely qualitative rather than a 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 comments in this report are not intended to address each program within the EEEL exhaustively. Instead, this report identifies key issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular EEEL program or project should not be interpreted as a negative reflection on the omitted program or project.

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Introduction

ORGANIZATION OF THIS REPORT AND SELECTION OF THE PANEL

This report assessing the Electronics and Electrical Engineering Laboratory of the National Institute of Standards and Technology (an agency of the U.S. Department of Commerce) represents the integration of the collective observations of the Panel on Electronics and Electrical Engineering, its on-site discussions, and off-site study of read-ahead materials. The latter include background, overview, and contextual information, as well as technical reports and program descriptions, provided by EEEL staff at the request of the panel chair and National Research Council staff. The Panel on Electronics and Electrical Engineering assesses the EEEL biennially. Its previous assessment occurred in 2007.

In this report, the panel's findings are delineated in several chapters. Included are division-by-division assessments and project-specific evaluations (Chapter 3), EEEL responses to concerns from the previous assessment (Chapter 4), general observations of the panel (Chapter 5), future thrusts or high-impact projects (Chapter 6), conclusions (Chapter 7), and recommendations (Chapter 8).

The panel membership for this assessment was carefully selected by the National Research Council to address the technical areas covered in the work pursued by the EEEL. In assembling the panel, the NRC identified areas of key expertise needed on the panel and solicited recommendations for panel candidates from a number of relevant sources, including the National Academies (National Academy of Sciences, National Academy of Engineering, and Institute of Medicine), NRC boards and committees, and databases of experts in science, engineering, and medicine.

ORGANIZATIONAL STRUCTURE OF THE LABORATORY

The Electronics and Electrical Engineering Laboratory is currently organized in four divisions—the Optoelectronics Division, the Semiconductor Electronics Division, the Quantum Electrical Metrology Division, and the Electromagnetics Division—and two additional operating offices: the Office of Law Enforcement Standards and the Office of Microelectronics Programs. The two offices were not subject to this formal assessment.

Organized as follows, each of the four divisions comprises three groups, and each group focuses on several programs/projects:

- Optoelectronics Division
  - —Sources, Detectors and Displays Group
    - o Programs/Projects:
      - Laser Radiometry
      - High-Speed Measurements

—Optoelectronics Manufacturing Group
  - Programs/Projects:
    - Semiconductor Growth and Devices
    - Optical Materials Metrology
    - Nanostructure Fabrication and Metrology
    - Quantum Information and Terahertz Technology

—Optical Fiber and Components Group
  - Programs/Projects:
    - Fiber Sources and Applications

- Semiconductor Electronics Division

—Enabling Devices and ICs Group
  - Programs/Projects:
    - Power Device and Thermal Metrology
    - MicroNano Technology
    - Nanobiotechnology

—CMOS and Novel Devices Group
  - Programs/Projects:
    - Nanoelectronic Device Metrology
    - Macro Electronics
    - CMOS Device and Reliability

—Electronic Information Group
  - Programs/Projects:
    - Infrastructure for Integrated Electronics Design and Manufacturing
    - Knowledge Facilitation

- Quantum Electrical Metrology Division

—Fundamental Electrical Measurements Group
  - Programs/Projects:
    - Metrology of the Ohm
    - AC-DC[2]
    - Electronic Kilogram
    - Quantum Conductance

—Applied Electrical Metrology Group
  - Programs/Projects:
    - Farad and Impedance Metrology
    - Electric Power Metrology
    - Smart Grid Interoperability Standards Development

—Quantum Devices Group
  - Programs/Projects:
    - Quantum Voltage
    - Quantum Sensors
    - Quantum Information and Measurements
    - Quantum Materials
    - Quantum Fabrication Facility

- Electromagnetics Division
  —Radio-Frequency Electronics Group
    - Programs/Projects:
      - Fundamental Guided Wave Metrology
      - Advanced High-Frequency Devices
      - Advanced Materials Metrology

  —Radio-Frequency Fields Group
    - Programs/Projects:
      - Field Parameters and Electromagnetic Compatibility (EMC) Applications
      - Antenna Metrology
      - Wireless Systems

  —Magnetics Group
    - Programs/Projects:
      - Nanomagnetics
      - Biomagnetics
      - Superconductivity

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Assessment of the Divisions

Focusing on the three assessment criteria that it was requested to consider (see Chapter 1), the Panel on Electronics and Electrical Engineering presents the following assessment, outlined by division, and includes a discussion of selected specific projects.

OPTOELECTRONICS DIVISION

The Optoelectronics Division's key projects are well chosen and focus on important and growing segments of the optoelectronics industry. The limited resources currently available do not allow coverage of all industry segments with sufficient critical mass. New funding is required in order to add other programs focused on areas of current national priorities. The scientific and technical work meets the highest standard of excellence. However, the conditions of some individual laboratories were found to be overcrowded and cluttered. Resources should be allocated to tidy up the laboratories and improve the environmental conditions so as to ensure the workers' safety and health.

Key segments of the optoelectronics industry include biophotonics, displays, lighting, lasers, optical communications, optical storage, photovoltaics (PV), terahertz technology, and quantum information. Owing to the limited resources available, the division's choices are to focus on four strategic program themes—radiometry, waveform metrology, quantum information and metrology, and nanophotonic metrology—which are outstanding choices given the existing resources.

Calibration services are strong and should remain at the same level.

Laser Radiometry Project

The technical merit of the Laser Radiometry project continues to be the best in its field, among other national metrology institutes (NMIs) internationally, and has been engaged in international comparisons of laser power with Germany, Great Britain, Japan, Mexico, Russia, and Switzerland. For example, the project has set the benchmark in high-power coatings, with a demonstrated damage threshold exceeding 15 kW/cm^2. A comprehensive program includes a strong theoretical effort that is modeling the optical-to-amorphous carbon/carbon nanotube interaction. This work is benchmarked with experimental results, and it has resulted in an improved understanding of the underlying photophysics of carbon nanotube (CNT) coatings, which should further broaden their application base. The researchers can do a comprehensive experimental analysis of CNT material to quantitatively determine composition—work that can be done on bulk and not just on isolated samples.

The Laser Radiometry Project team does a remarkable amount of work with modest resources. Out of NIST's $5 million per year of calibration income, this team accounts for 10 percent of total NIST income from calibration services. It performs approximately 300 tests per year (1.5 tests per day), with an on-time completion rate of

95 percent and an average turnaround time of 22 days. This is done with a modest-sized group of 5 people. The addition of new equipment, such as a state-of-the-art tunable optical parametric oscillator system, could greatly facilitate the work. Facility renovation, including updated fume hoods, is needed.

Along the same lines, a better infrastructure for handling nanotubes would facilitate the CNT work. The project team also has limited access to tools such as scanning electron microscopy (SEM), X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), transmission electron microscopy (TEM), and atomic force microscopy (AFM) for its nanotechnology work. If the EEEL were able to add one or more of these costly items, the work of this group would be further amplified, and the resource could be made available to other groups at NIST as well.

This project is well aligned with the laboratory's mission, providing the best traceable laser radiometry measurements. It has evolved into a more comprehensive program with the addition of the CNT theory component, and the extended wavelength capability (200 to 1,800 nm) and extended power range of the detector program (spanning orders of magnitude—from hundreds of kilowatts to single photons) are a critical service to the optoelectronics industry.

The availability of CNT type identification is key to developing standards for toxicity—a significant problem for which this team could play a leadership role in setting rigorous standards. This should be encouraged.

High-Speed Measurements Project

The High-Speed Measurements project has demonstrated the group's capability to achieve state-of-the-art calibration of oscilloscopes in the frequency range from 110 to 400 GHz. Its covariance-based analysis technique represents a new methodology for calibrations. The project team is developing test methods, including linear optic sampling, that are very useful for the characterization of components for advanced modulation methods. These advanced modulation methods, including phase modulation and polarization multiplexing, are being used for 40 and 100 Gb/s communications system development. Software to end users who want to perform their own calibrations is also provided.

Reasonable resources in equipment and space are provided for this project. However, there appears to be a serious problem with environmental stability. There are incidents of delayed programs owing to variations in the laboratory temperature that disrupt measurements and calibrations and cause them to be repeated in order to achieve the state-of-the-art results of which this group is capable. The root cause of the temperature variations seems to be problems in the chilled-water system.

The project meets its stated objectives of improving the calibration capabilities and measurements of high-speed waveforms. One suggestion for a new program is to look for collaborations between the optical frequency combs and the high-speed measurements projects. In order to establish some relationships with industry to apply their techniques to component manufacturers, for example, the design of lithium niobate modulators for 40 and 100 Gb/s phase-modulated systems would be beneficial.

Frequency Combs Project

The scientific work of the Frequency Combs project is one of the top five comb efforts, but at present it is not completely clear what applications the frequency comb is good for other than NIST-specific goals for timekeeping and time and frequency transfer. Specifically, the EEEL is pursuing its own program with these combs separate from the timekeeping group, and there is possibly a huge potential for the combs outside of frequency standards that needs to be pursued. The use of the combs in telecommunications-component characterization was very good, but other applications to communications, other than the long-distance time transfer, were not apparent. For example, in satellite communications there is a need for extremely accurate time synchronization. The frequency-comb time-transfer experiment between clocks in the Boulder, Colorado, area was spectacular but now seems completed. The group could explore whether these techniques can be useful over longer distances or from Earth to space platforms. Another potential application is in systems such as light detection and ranging (LIDAR) remote sensing.

The laboratory equipment seemed adequate, given that the fiber comb technology is less sensitive to environmental factors, such as temperature, than is some of the other interferometric work.

A challenge now is to find in the EEEL the nonfrequency transfer and timekeeping applications of the combs, of which there are likely many. More outreach and discussion between NIST scientists and other agencies are needed to flesh out all of the applications.

Terahertz Technology Project

One goal of the Terahertz Technology project is to develop methods for calibrating optical power in the millimeter-wave to terahertz frequency range. The EEEL has served industry by acting as an unbiased tester for participants in a program of the Defense Advanced Research Projects Agency (DARPA) and has demonstrated new methods such as the blackbody calibration source for terahertz measurements. Other projects include the demonstration of a video-rate passive imaging. The results are among the best for uncooled niobium micro-bolometers used in concealed weapons detection.

Funding sources for this project include the Department of Homeland Security. It is unclear whether there is there a plan to transfer this technology to industry.

Overall, the project seems to be meeting the goal of real-time video systems. This effort represents a good example of the leadership that NIST can provide to new industries. The project is also achieving the goal of supporting industry.

Quantum Information and Terahertz Technology Project

The most striking work in the Quantum Information and Terahertz Technology project group is the development and deployment of the transition-edge superconducting (TES) photon-number-resolving detectors. This unique work is in demand worldwide, as high-efficiency detectors with number-resolving capability are viewed as a critical element in optical quantum information processing, quantum imaging, and quantum sensing. The TES detectors are currently the most efficient photon counters at any wavelength, but in particular, in the important telecommunications band. In order to be relevant for some applications (e.g., optical quantum computing), however, the time response still requires further improvements. The superconducting single-photon detector (SSPD) work is also excellent, and the high-speed response has been critical for applications, such as large-bandwidth quantum communications; however, the SSPD efficiency (approximately 0.5 percent now) needs further improvement, but there is steady work in this direction.

The generation of approximate Schrödinger cat states (by photon subtraction) is an interesting application of the photon-number-resolving characteristics of the high-efficiency TES detectors. Although it may be hard to justify this sort of fundamental project on a mission basis, it is an example of the unique fundamental research that NIST can do, because of a combination of a very good source of squeezed light combined with a TES detector that nobody else has. The correlated-photon work using four-wave mixing seems to be progressing very well, with very high coincidence to accidental rates, a necessary prerequisite to generating efficient heralded photons and high-fidelity entanglement.

The project's researchers all demonstrate commitment and dedication. However, inadequate infrastructure was clearly observed by the panel. For instance, some of the work requires stable interferometers that are extremely difficult to maintain in the current laboratories, with the radical temperature swings and a poor heating, ventilating, and air-conditioning (HVAC) system. The laboratory spaces in general are severely cramped, and the temperature control was almost completely lacking in some areas. The laboratories that require stable optical alignment associated with single-photon production, characterization, and detection probably should be relocated in the new building that is being constructed on the NIST campus in Boulder, Colorado. The planned renovations of existing space may mitigate this concern.

There is a growing need to be able to transition the TES detectors into other research laboratories around the country. The demand for the TES detectors may grow considerably in the next few years. More funding will be needed, not only to produce the detectors (and associated support systems) at a more rapid rate, but also for the training of support personnel, who can assist with the transport, installation, and maintenance of the detectors in government, university, and industrial laboratories.

The efforts of this group have helped to push the worldwide effort toward faster and more efficient detectors for quantum information applications—for example, quantum cryptography, especially in collaboration with other, external groups. These detectors have enabled some of the best results in this area. Increasing the speed of the TES detectors and increasing the efficiency of the SSPDs are obviously major goals, as is improving the system robustness to facilitate the adoption of the technology by outside entities. The detectors based on semiconductor quantum dots could eventually have a large impact (given the need to have fully integrated systems), though at present the low net efficiencies preclude this.

Linear Optical Waveform Metrology Project

In the Linear Optical Waveform Metrology project, linear optical methods for the full-vector (amplitude, phase, and polarization) characterization of repetitive optical signals have been developed. The state of the art of pulse measurement is usually nonlinear optical methods, such as frequency-resolved optical gating. Nonlinear optical methods can be limited in their utility by weak optical signals or an inability to achieve high resolution over long time periods. Competing linear optical methods include spectral interferometry, which can perform a similar analysis. However, there is a real niche for a full-vector characterization platform that employs single-element detection (performed in the time domain) as developed by NIST―especially as work continues on arbitrary waveform generation.

The laboratory space suffers from the same problems that other laboratory spaces are experiencing, specifically, lack of sufficient HVAC capacity. The staffing resources seem to be sufficient.

This calibration capability is a significant technical achievement that will be of service to the optoelectronics industry.

Nanostructure Characterization Project

The gallium nitride (GaN) nanowire growth effort in the Nanostructure Characterization project is making superb defect-free material, potentially providing breakthroughs for unique devices; the quality is particularly impressive given the comparatively limited investment in this project. The development of other novel single-photon detection techniques—for example, using semiconductor quantum dots to realize an optically gated field-effect transistor—should also be pursued as a means of realizing high-efficiency photon-number-resolving detectors; this is particularly true given the push toward fully integrated systems.

The molecular beam epitaxy (MBE) facility dedicated to gallium nitride growth is "home-built," and the facility is quite cramped. An improved facility would increase the rate of progress on this effort.

While the nanowire material is unique in terms of its perfection, the measurements characterizing the material are fairly standard. The proposed goal of creating a quantum wire ultraviolet laser as a source for quantum computing is a good fit to the goals of the Optoelectronics Division. In order to be successful, the effort needs stronger collaboration, guidance, and support from device designers.

SEMICONDUCTOR ELECTRONICS DIVISION

Overall, the quality of the technical work of the Semiconductor Electronics Division is very good, being nationally competitive and with some areas being among the best in the field. The division appears to be positioning itself well to play a significant role in the emerging priorities, such as the Smart Grid and bioelectronics, and it provides a leadership role on many of the electronics measurement and standards committees. There continues to be significant infrastructure renovation within the division. A proposed center for nanoelectronics reliability is an important focus that takes advantage of expertise residing in the division.

MicroNano Technology Project

The focus of the MicroNano Technology project is "more than Moore": that is, increasing integration of functions in combination with the size reduction of components producing the positive effect of stimulating the enhancement rates for both system miniaturization and system complexity. These effects are strongly in play at the present time, stimulated by developments in areas such as wireless systems, bioelectronics, distributed-sensor arrays, and micro-robotics, among others. NIST has a role to play in defining standards and in stimulating the U.S. efforts for this area. The continuing reduction in component sizes poses challenges in the understanding of materials, as well as in the behavior of structures and electronic devices. The listing of project-related internal proposals, press releases, reports, peer-reviewed technical papers, and the participation of project staff in professional activities was impressive, reflecting the team's diverse achievements. However, more attention should be devoted to reporting research publications.

The budget and staffing for this area both appear to be adequate.

Some of the important work of the MicroNano Technology project includes the development of three ASTM International and three SEMI (Semiconductor Equipment and Materials International) microelectromechanical systems (MEMS) standards (five for MEMS structures and one for wafer bonding); the wafer-bonding work involves extensive collaborations in the United States and European Union and collaborative associations to define values and measurement standards for the Young's modulus in materials used for MEMS structures. Micro-/nano-fluidic metrology provided three new measurement tools for nanoparticles. These include the microfluidic formation of liposomes to enable the electronic control of particle size and the composition of encapsulated species, with ongoing work to extend the capability to control charge and species. Researchers have demonstrated microwave heating in microfluidics to generate steep temperature gradients that enable temperature-gradient focusing. This appears to be a pioneering effort that can open new application avenues. The bioMEMS area to monitor cell growth using electronic monitoring is being investigated at an increasing number of laboratories around the world as more and more researchers become aware of the unfolding promise when nanotechnologies are applied to problems and opportunities in bioelectronics.

As technologies advance for the production of structures with nanometer dimensional resolution, commercial progress is strongly in need of new standards and characterization procedures. The project team is responding appropriately to meet these needs.

Macro Electronics Project

Organic electronics is a new thrust in the industry.

There were 10 publications from the Macro Electronics project between 2006 and 2008, several in journals such as *Nature Materials, Applied Physics Letters,* and *Chemistry of Materials.* The principal investigator for this project is well recognized in the area of organic/flexible electronics, having more than 40 peer-reviewed publications and more than 3,400 citations to his credit—an impressive record.

The project, undertaken by 1 full-time equivalent in staff and 1.5 associates, is barely at critical mass. With the activity expanding into organic photovoltaics and displays, the project will be severely strained without additional staffing.

The effort in understanding of device characterization and device reliability has just begun for organic electronics and flexible electronics. The team can provide a leadership role in developing the proper procedures for characterizing organic thin-film transistors and PVs. Because the degradation mechanisms are not well understood, there are no defined procedures for accelerated life testing. These methodologies need to be developed in order for organic electronics to become pervasive. Macroelectronics is as important as nanoelectronics and microelectronics. This project is severely underfunded.

Infrastructure for Integrated Electronic Design and Manufacturing Project

While the project on Infrastructure for Integrated Electronic Design and Manufacturing (IIEDM) continues to do good work, there is little interaction between the division's core technology groups and the IIEDM group. Approximately 80 percent of the funding for the group comes from NIST non-base funding. The group appears to have adequate space and infrastructure to carry out its work.

Knowledge Facilitation Project

The Knowledge Facilitation project provides computer programming expertise for NIST. The project constitutes primarily a service organization providing information technology (IT) project support to the rest of NIST. The group does a good job of developing NIST-specific IT tools and is not involved in developing measurement standards. It has developed an active radio-frequency identification (RFID) inventory tracking system for tracking capital assets within NIST. The group also developed a trip-report tracking system.

Nanobiotechnology Project

The metrology involved in the Nanobiotechnology project is enabled by the use of biological nanopores, using high-input impedance electrical measurement tools to characterize the direct current (dc) and alternating current (ac) electrical and gating properties of single biological molecules. The three key activities within the project are bioelectronics for systems biology, bioelectrical optical measurements related to anthrax detection, and the structural biology of membrane proteins. These activities have garnered significant national and international recognition arising from the project members' high-impact publications and multiple national and international invited talks.

The Nanobiotechnology project team has been highly productive in applying high-performance electrical tools, leading in the demonstration of the detection and measurement of the electrical properties of single molecules and in providing insight into the mechanistic performance of biological nanopores. These efforts are addressing a critical need in the qualified metrology of single molecules and of biological nanopores. The system for single-molecule detection of spontaneously assembled and immobilized biological nanopores on solid surfaces has the potential to emerge as a high-throughput detection platform when combined with a suitable solid-state transduction modality. If realized, this activity will contribute to the development of a novel technology platform that becomes enabling for functional proteomics, and these broad capabilities at the intersection of silicon and biology could be leveraged toward analyses of other macromolecules for a variety of applications, such as drug screening and the analyses of neuromorphic systems. This project has the potential to serve as a cornerstone for a new bioelectronics thrust; it can greatly benefit from an integrated *in silico* component and from strengthened collaborations with established protein molecular modelers.

Given the available human, budgetary, and facilities resources, the output of this project is impressive. However, the small group appears to be engaged in far too many different activities, given the available resources. The group will need to add capabilities in areas such as theoretical modeling and simulation, through either collaborations or internal new hiring.

The Nanobiotechnology project is focused on developing technologies that will permit the accurate and simultaneous measurement of many macrobiomolecules. This area has major unknowns, and fundamental understanding and breakthroughs are needed across multiple disciplinary boundaries. The three key activities mentioned above are being used as models to help push forward the basic understanding in the field.

Power Devices and Thermal Metrology Project

The emphasis for the Power Devices and Thermal Metrology project is to develop electrical and thermal management methods and equipment in support of the development of advanced power semiconductor devices and integrated circuits (ICs). This project has the opportunity to make use of its expertise in device reliability and power device system integration to help improve the fundamental understanding of device aging, degradation, and failure mechanisms. The power device group will be a focal point for the Smart Grid work.

The team is an established leader in silicon carbide (SiC) power device insertion into power system switching applications and is currently the leader in high-voltage/high-power measurement techniques. Its principal investigator is recognized as one of the leaders in the field of high-voltage device characterization and the integration of high-voltage devices into power systems. The Department of Defense and Department of Energy rely heavily on this team to characterize high-power devices for many of their applications.

The current infrastructure and budget for the Power Device and Thermal Metrology group seem to be adequate.

The team has developed a unique set of capabilities for making high-voltage and high-temperature measurements and is recognized as the national leader in making these measurements. This expertise will be critical in implementing Smart Grid technologies, where high-voltage switches and solid-state power converters will be required. As it expands into Smart Grid activities, this project should be a focal point for the division.

Nanoelectronic Device Metrology Project

The Nanoelectronic Device Metrology project seeks to create test structures and associated measurement methodologies for specific target technologies: electronics based on semiconductor nanowires and confined-Si (the logical extension of silicon complementary metal-oxide-semiconductor, Si-CMOS); molecular electronics; organic spintronics; memristors; and selected carbon-based electronics. Its activities are divided into four areas of concentration: 40 percent addresses target molecular electronic structures and technologies, 50 percent is divided equally between silicon and nonsilicon nanoelectronic devices and technologies, and 10 percent is devoted to capacitance metrology at ultimate scales.

The team is providing standards for capacitance measurements in the attofarad (10^{-18} F) range and is pursuing a number of issues in the molecular electronics area. Obtaining reliable interfaces to measurement structures for molecular-electronic assemblies is particularly challenging. Another research area centers on interfaces of CMOS with molecular structures in order to enable new configurable characterization methods. An important achievement in this work has been a capability to produce ultrasmooth gold—specifically, large areas on a flexible substrate. The gold is five times smoother than any surfaces reported thus far.

Office of Microelectronics Programs support for the project has consistently been strong, ranging from 62 percent of the total budget projected in fiscal year (FY) 2009 to 71 percent in FY 2008, 63 percent in FY 2007, and 77 percent in FY 2006.

The team has demonstrated strong productivity, being responsible for 30 papers and 52 talks (15 invited) since FY 2007. Members are also active in leadership roles in professional activities.

However, two important research capabilities should be established in support of this work: a direct link to modeling and simulation studies and a closer tie to experts with a focus on the properties of materials. The significance of modeling and simulation to the success of the silicon IC technologies is unquestioned. Especially for the research involving CMOS interfaces with molecular structures, there is need either for in-house modeling and simulation or for strong bridging to places where these skills exist. Materials and their characterization are central to the full gamut of research, and it is important that researchers with a strong understanding in these areas be involved. The possible links to basic materials research areas in NIST should be explored.

Advanced Metal-Oxide-Semiconductor (MOS) Device Reliability and Characterization Project

With the CMOS technology scaled to below 50 nm dimensions at integration levels of 10^9 transistors per chip, device reliability is becoming an ever more critical issue in very large scale integration (VLSI) product assurance. A single defect developed during the use period could cause chip and system failure. The role played by the project team is vital to the microelectronics industry and national interest.

With the team's recognized leadership position in metal-oxide-semiconductor field-effect transistor (MOSFET) device reliability characterization, its recent accomplishments extend to the following: understanding of the physical mechanism of negative-temperature bias instability—one of the most serious reliability issues in advanced CMOS technology; the study of defect generation in a high-k dielectric stack under electrical stress; the development of an ultrasensitive capacitance probe for measuring a nanometer transistor directly; the application of microelectron paramagnetic resonance spectrometer for measuring a single defect; the characterization of new materials by scanning capacitance microscopy and scanning Kelvin probe microscopy; and the optical-electrical characterization of a high-k gate dielectric on III-V compound semiconductors. The team has also extended its expertise in the characterization of semiconductor-insulator interfaces to other material systems needed by the microelectronics industry or by national defense, including high-k/silicon dioxide (SiO_2) on SiC MOSFETs, high-k dielectric on III-V compound semiconductors, zinc oxide (ZnO) nanowire MOSFETs, and time-dependent dielectric breakdown of SiO_2/SiC devices. Its technical accomplishments have enabled this group to interact extensively with the microelectronics industry and other agencies, allowing it to respond to industry priorities and to meet their needs.

The impact of this team on the science and technology (S&T) of MOS reliability is evidenced by the high-quality papers that this group has published and the invited talks presented at major international workshops and conferences. A weakness of the project is the lack of extensive simulation efforts for more in-depth understanding and modeling of the characterization results.

QUANTUM ELECTRICAL METROLOGY DIVISION

The Quantum Electrical Metrology (QEM) Division, located in the Boulder, Colorado, and Gaithersburg, Maryland, NIST facilities, executes an impressive, well-coordinated, and highly synergistic effort in applied and fundamental, leading-edge research and is well matched to the mission of NIST and, in particular, to that of the EEEL.

The three groups in this division, which are the Quantum Devices group in Boulder and the Gaithersburg groups in Fundamental Electrical Measurements and Applied Electrical Metrology, provide the following technologies and services: quantum-based standards in the area of dc and ac voltage, power, and resistance; quantum sensors with ultrahigh energy resolution; quantum information devices for the realization of quantum networks, as well as quantum measurements; advanced materials research that enables the sustained improvement of these devices; a classical standard for capacitance; a realization of the electronic kilogram; and increasing activities toward smart energy grid technology and related measurement devices and protocols, such as the synchrophasor and power measurement units and cryogenic current comparators (CCC) to provide a direct link to quantized Hall resistance (QHR) over nine orders of magnitude. The efficiency and effectiveness of the division are maximized through the phaseout of programs that are not productive, that are missing synergy, or that are not important to the mission. There is collaboration with other agencies, industry, and academia, and common S&T goals are pursued; for example, high-resolution gamma-ray and alpha-particle detectors are delivered to the Los Alamos National Laboratory.

Despite continued flat funding over years, the Quantum Electrical Metrology Division has been able to acquire increasing outside funding and to excel in new areas, such as quantum information. Though the division has not received new funding for work on smart grid technologies, it is shifting resources to start this new, important program area. A key asset of the division is its unique Quantum Device Fabrication Facility, which is well managed and will be enhanced substantially by the new construction under way in Boulder. The equipment at both locations is excellent and state of the art. However, due to the continued decline of scientific and technical research services (STRS) funding and the fact that the number of permanent staff is at an all-time low, further reductions in staff may threaten core programs of the division. The cohesive and synergistic group organization has so far been able to cope with the reduced internal funding and is continuing to provide stability to the division.

The Boulder group has achieved an effective level of integration, not just in technical tools but also in the innovation of aligned and cooperative advances. One example is the Josephson voltage standard (JVS) work, which ranges from Josephson array fabrication to the development of a fully automated measurement tool for metrological evaluation and application that enables the dissemination of this standard to Gaithersburg and around the world. The complexity of this system needs a sustained engineering effort to maximize its impact.

Quantum Voltage Project

As one of the leaders in the use of Josephson voltage standards for purposes of electrical metrology, the Quantum Voltage project is now close to demonstrating a 10 V programmable standard that would significantly simplify many calibration procedures worldwide by allowing more direct comparisons. The project team is also the leader in generating state-of-the-art waveforms with amplitudes of 275 mV at up to a few hundred kilohertz. The goal is to extend these results to amplitudes up to 1 V with frequencies up to 1 MHz. Ultimately, the hope is to replace existing standards such as thermal converters. An exciting application of this arbitrary waveform synthesis is related to measurements of the Boltzmann constant by using a quantized voltage noise source to calibrate the Johnson noise of a resistor at a known temperature. The result will be the first electrical measurement of the Boltzmann constant. The expected uncertainty (on the order of 6 ppm) would be competitive with other measurements.

Support for this project, unlike many at the Boulder site, is currently based entirely on internal NIST funding. For many years this was not the case, but changes in the funding climate caused a shift away from outside-agency funding. This change has created pressure on the Quantum Voltage project leader to consider a greater focus on more applied programs that could bring in external support.

The Quantum Voltage project has an enormous impact. Its efforts often drive the direction followed elsewhere. For example, recently the team convinced others in the field that the usual dc Josephson voltages standards, while appropriate for dc and 60 Hz applications, will not work as a standard for higher frequencies. The result has been significant work worldwide over the past 2 years in ac quantum standards.

International partnerships are formed to foster the advancement of scientific frontiers and accelerate the progress of science across borders through the exchange for standards, for example the JVS, and formal collaborations with other national metrology institutes (NMIs; in China and Mexico).

Quantum Sensors Project

The Quantum Sensors project team continues to produce leading sensors, primarily based on superconducting quantum interference devices (SQUIDs), including spectrometers for x-ray, gamma/alpha, and microwave background polarimetry. Many of these have spectral resolution several times better than that of the closest classical technology. Recent work has included the development of multiplexed SQUID arrays for the International X-ray Observatory. Continued work on transition-edge sensors has allowed a new understanding of excess noise issues, which should allow continued device optimization. The project is also leading an effort in nuclear forensics. The use of high-resolution gamma-ray spectroscopy, driven by a leading gamma energy resolution of 22 eV at 100 keV, may allow the nondestructive assay of spent reactor fuel.

This project has recently enjoyed a very high level of outside-agency support. Sensors produced by this project have been delivered to multiple users in government and academia, including the Los Alamos National Laboratory and multiple telescopes around the world. The project has very high impact.

Quantum Information and Measurements Project

Efforts in the Quantum Information and Measurements project are competitive with other major groups worldwide, as evidenced by recent publications in leading journals such as *Nature*. The team is involved with the development of air-gap capacitors for improved qubit performance. The elimination of an oxide dielectric has given some improvement in coherence times. Efforts are ongoing to couple multiple qubits together through a superconducting bus in an attempt to create prototype quantum processors.

A large portion of the support for this project is derived from competitive internal NIST funding.

The work, particularly with regard to the coupling of qubits through a superconducting bus, is having significant impact on its field, as indicated by high-profile publications.

Quantum Materials Project

Developing epitaxial dielectrics for use in Josephson-junction-based qubits is the main task of the Quantum Materials project. The project members were the first to use such techniques to produce and characterize qubits based on epitaxial Josephson junctions, and they demonstrated that such growth techniques can significantly increase decoherence times. Support for the project is good; it includes some outside-agency funding. There is potential for extremely high impact in the quantum information science community once the results associated with epitaxial growth are more widely disseminated.

Quantum Fabrication Facility Project

The Quantum Fabrication Facility project maintains the Boulder clean room and its extraordinary capability for the fabrication of integrated Josephson-junction circuits. The pressure on the Boulder fabrication facility will be reduced by the new fabrication facility under construction and enabled by stimulus funds from the American Recovery and Reinvestment Act of 2009. However, the existing clean-room management model (i.e., the facility is run by the QEM group in Boulder but used by many other Boulder groups) cannot be extended to the new enlarged facility. A new approach toward fabrication facility management is being developed to maintain this unique fabrication facility while expanding its throughput.

Particular support for this project includes the new clean room and associated fabrication equipment that will be created in the new building on the Boulder campus. This project enables many of the other activities at the Boulder campus. Its impact is, therefore, best measured through that of the other projects, which, as discussed above, is extremely high.

Metrology of the Ohm Project

The Metrology of the Ohm effort provides an excellent calibration service that is a significant and stable source of income and serves a broad array of industrial and government customers. The project team has made efforts to expand its work into new areas. These include the development of a new, easier-to-operate cryogenic current comparator that will, it is hoped, be commercialized and made generally available. New efforts also include collaboration with the new Quantum Conductance project, which involves the development of graphene-based quantum Hall devices, as well as the development of expertise in bioelectronics.

The Metrology of the OHM project is supported in part by a stable, well-regarded calibration service that is highly valued by industry. The project has led comparisons of resistance measurements at multiple scales and has delivered the new CCCs to three other national metrology institutes, in Argentina, Australia, and Mexico.

AC-DC^2 Project

The AC-DC^2 project combines the earlier AC/DC and DC projects for simplified management. A significant amount of effort is given to very high quality calibration services for both ac and dc measurements. Research is focusing on the development of new thermal voltage converters, based on multijunction technology that should allow operation at frequencies up to 100 MHz and voltages of 2 V. This will cover a range of frequencies, voltages, and currents that cannot be reached by the ac Josephson voltage source (ACJVS). Project staff is also working with the Quantum Voltage project team in Boulder in the development of a 10 V programmable Josephson voltage standard (PJVS).

Calibration services, while excellent, are currently at risk, especially dc voltage calibrations. The service provided for standard calibration is not properly charged, leading to low revenue for NIST. The project has begun the dissemination of ac voltage standards based on ACJVSs, allowing state-of-the-art accuracy in comparison of ac and dc voltages to become more widely available.

Electronic Kilogram Project

The artifact mass standard for the kilogram unit is suffering from 120 years of wear and contamination, so its value over time is becoming uncertain at several parts in 10^8. As a potential replacement, the Electronic Kilogram project compares the energy in power generated by mechanical and electrical means. Einstein's famous equation $E = mc^2$ can relate this energy measurement to mass. Except for the kilogram, the standard units involved are all quantum-based: the second (atomic clocks), meter (laser wavelength), volt (Josephson effect), and ohm (quantum Hall effect). These are all unchanging in time. The result is a measured value for the Planck constant, h, relative to the mass artifact standard, or vice versa, if the international community redefines mass in terms of a value for h. Stable results have been produced by the Electronic Kilogram project for the past 4 years, and the project is aiming to produce improved results by the end of 2010 in considering the redefinition of the kilogram. The project has attained the best relative uncertainty, and work is in progress to improve the uncertainty to 20 ppb. Efforts to design a new electronic kilogram calibration system for use after a potential redefinition are also underway. Support for this project, despite its fundamental significance, has been minimal over the past few years, with staffing dropping from four or five people to only one at present.

To the present time, this project has produced the most accurate measurement of Planck's constant. The project also plays a leading role in the upcoming redefinition of the International System (SI) of units.

Quantum Conductance Project

The goal of the Quantum Conductance project is to develop graphene-based quantum Hall effect devices that will do for resistance metrology what the development of the Josephson voltage source did for voltage metrology. These graphene-based devices should be able to operate at higher temperatures than gallium arsenide (GaAs)-based quantum Hall devices, and they could possibly be easier to produce. An informal graphene group, involving NIST staff at both Gaithersburg and Boulder, has been formed, and collaboration with the Resistance Metrology project is also underway.

The support for the Quantum Conductance project is reasonable, although at the moment the project has only one staff member. The project is new, and its impact has yet to be determined. The potential impact could be very high if an easily disseminated quantum resistance standard can be developed.

Farad and Impedance Metrology Project

A significant new effort—the Farad and Impedance Metrology project—is underway, focusing on the development of a new capacitance metrology project. This project would make use of frequency combs for length measurement and will, it is hoped, result in a 10-fold improvement in calibration accuracy. It may allow calibration to be extended to the femtofarad regime, which is important for efforts in nanoscale science. It is hoped that the new standard will be more portable and automated than the existing calculable capacitor; the new standard has a target accuracy of 5 ppb.

This project is the leader in the field of uncertainties for capacitance measurements. The project staff recently organized and led a multination capacitance comparison for several countries in the Americas. Capacitance calibrations, driven by customer needs, have generated income of $200,000 in FY 2008, which is commendable.

Electric Power Metrology Project

The Electric Power Metrology project has now moved to a quantum standard, based on stepwise sine wave approximation using a Josephson voltage source. As a result, uncertainties have been reduced by a factor of five. The other major effort of this project has been focused on the synchro-phasor effort, and on the development of techniques for the measurement of dynamical waveforms. Synchro-phasors have become increasingly important to power system operators, and the synchro-phasor test laboratory developed at NIST provides a state-of-the-art testing tool for phasor measurement units (PMUs), to verify that they meet the current industry standard and to provide an assurance of the interoperability of PMUs of different manufacture. Support for this project seems reasonable. The work of this project has significant impact on industry, and the project staff is also closely involved with the new Smart Grid effort.

Smart Grid Interoperability Standards Development Project

Unlike the other projects of the Quantum Electrical Metrology Division, the Smart Grid Interoperability Standards Development project is not technical in nature, but instead leverages NIST's position as a neutral and objective source of technical information to play a role in developing a new set of standards and performance testing. This fast-moving project represents both a significant opportunity and a risk for the division. The effort has greatly raised NIST's visibility in this area and is expected eventually to lead to new research programs. Although this project is too new for its impact to be accurately judged, it is nonetheless the focus of intense interest and has the potential for extremely high impact.

ELECTROMAGNETICS DIVISION

The Electromagnetics Division consists of top-quality researchers who serve in several journal editorial positions and on standards bodies. Much progress in the projects of this division was noted by the panel. However, project prioritization and budgets remain sketchy. Strategic projects were not well defined, in part due to the uncertainty associated with the leadership and budgets. There might be too many projects for the number of full-time staff in the division.

While some calibration/standards functions are curtailed and mothballed at end of life, there needs to be a means of capturing the years of learning associated with these efforts. One way is to put together handbooks on the standards calibration and methodology that would otherwise be lost. One example of this is the book *Experimental Techniques for Low Temperature Measurements,* published by Oxford University Press in 2006 (ISBN-13: 9780198570547; see the subsection below).

Superconductivity Program

The Superconductivity program team has a reputation for being the best for its sustained work in characterizing the behavior of superconductors. This team has been uniquely influential in setting worldwide standards for making such measurements and in improving the basic understanding of the impact of mechanical strain on behavior. Team collaborations with other U.S. government agencies, U.S. industry, and institutions and projects throughout the world are commendable. It is noted that the continuity in the specialized skills is maintained by overlap between the long-term members and the young members of the team.

The volume *Experimental Techniques for Low Temperature Measurements* referenced above, written by a recently retired staff member, presents a model for outreach and transfer of information. The concept of fully documenting specialized knowledge before retirement should be facilitated. The concept of writing teams can be useful in this regard.

Biomagnetics Program

New metrology work being done by the Biomagnetics program to support magnetic resonance imaging (MRI) devices has high technical merit. The necessary close collaboration with the medical community is evident. The initiative by the team to develop a smart contrast medium for use with MRI devices also has widespread potential.

The decision by the EEEL to purchase a nuclear magnetic resonance (NMR) system, needed for biomagnetics as a dedicated MRI machine, free from clinical scheduling, is strongly supported. However, it will be a requirement that such a facility also have a close collaboration with one or more medical radiologists. The development of spectroscopic detection at terahertz frequency for molecule identification (for purposes of biology and homeland security) and of microsystems for quantitative metrology of scanning probe microscopes (magnetic nanoparticle manipulation) are two new activities considered incubator initiatives.

Nanomagnetics Program

Initiatives of the Nanomagnetics program in spintronics and in dense-pack recording medium and switching are in sync with rapid and widespread growing interest in the broader community. The underlying goal of the work is to develop the metrology for studying these nanodevices, but in pursuing that goal it is necessary to be intimately familiar with the development and improvement of those devices. The necessary depth of understanding for device development is evident in the work presented. Nevertheless, the staff must be vigilant to undertake work that is generic and focused on widely useful metrology and not on device development for its own sake.

Field Parameters and Electromagnetic Compatibility (EMC) Applications Project

The Field Parameters and Electromagnetic Compatibility (EMC) Applications project is advancing the state of the art in measurements for transverse electromagnetic (EM) cells, reverberation chambers, calibration field probes, and open-air test sites. It also provides measurements in an anechoic chamber. The resources for the project are adequate. This project is important for the metrology mission of the division.

Wireless Systems Project

The wireless industry has welcomed the development, standardization, and popularization of reverberation chambers for EMC use, as the chambers enable easy, compact, and inexpensive measurements. The reverberation chamber provides a repeatable multipath simulation environment for wireless device testing. However, NIST has the responsibility to inform its wireless customers that conventional measurements of pattern and polarization are critical in the design and development of new systems and hardware. Reverberation chambers alone are insufficient. The project completed an interesting study of the electromagnetic environment in buildings that are being destroyed. The facilities for this project are adequate. The project is in keeping with the metrology and standards missions of NIST and has been specifically sought by wireless providers.

Antenna Metrology Project

The work in the Antenna Metrology project on the development of near-field scanning metrology for antennas is outstanding. NIST led the development of near-field scanning many years ago and has, in the intervening years, significantly refined the technique for gain and pattern measurements, especially for very short wavelengths. The resources for the project are adequate.

Fundamental Guided Wave Metrology Project

The enhanced effort of the Fundamental Guided Wave Metrology project on the waveform for over 200 GHz is timely, as the operating frequencies have continued to rise. The measurement of noise other than thermal noise should also be looked at, and the swift development of four and multiport s parameters and Automatic Network Analyzer (ANA) measurement calibration is essential because more and more differential circuits are penetrating into radio-frequency (RF) front ends.

There is need for updating of equipment to handle new connector types and higher frequencies and for extending metrology to waveforms of greater complexity and bandwidth.

The Electromagnetics Division's stated objective for measurement services is to evolve services for greater efficiency and better support for customers. This objective is being met. With respect to the objective of developing better on-wafer noise and s-parameter techniques, the work is in early stages, with appropriate direction. For the objective of redeveloping primary power standards (to find substitutes for nonreplaceable primary transfer standards), the work is in early stages, with appropriate direction. With respect to the objective of developing fast pulse sources for waveform measurements up to 400 GHz, at present up to 200 GHz has been worked out, and work is in progress for 200 to 400 GHz.

Advanced High-Frequency Devices Project

For the Advanced High-Frequency Devices project's objective of developing techniques for determining EM device characteristics of nanoscale devices (spin currents, resistivity, etc.), an understanding of electrical characteristics and nanoscale devices, such as nanowires and nanotubes, is critically important and encouraged for the beyond-CMOS era. The results eventually contribute to industrial device development. For the project's objective of expanding network analysis to beyond the 50 ohm world, at present most high-frequency measurement is carried out in the 50 ohm environment; however, non-50 ohm characterization is increasingly relevant for such environments as nanowire electronics. The establishment of more streamlined procedures is encouraged.

The scope of the work of this project appears to be aligned with its resources. No significant lack of instrumentation appears to exist.

Advanced Materials Metrology Project

Five tasks of the Advanced Materials Metrology project were briefed to the panel during the review. The basic thrust of these tasks is to support the electronics industry through classical measurements of substrates and printed-circuit-board materials and to apply this knowledge to such areas as homeland security and bioscience.

An understanding of the basic interaction between EM waves and molecular structure is essential. The challenge is to extend this understanding to terahertz frequencies and nanometer scale. What the EEEL brings to this effort, in contrast to university and commercial laboratories, is the ability to identify and describe best practices and a respect for uncertainties in measurement. The project has been characterizing the permittivity and permeability of various materials. It has developed on-wafer probing for substrate and thin films, in particular, low-k materials for microelectronics applications. The method based on a split-cylinder resonator for material characterization has been developed within NIST, together with some international collaboration. This technique has been transitioned to industry successfully. In many measurement schemes, there is a difference between measurement uncertainty and device physics uncertainty. Such information is desirable. Recent work on the evanescent probe method provides a new dimension of noninvasive and nondestructive measurement capabilities. The biochemistry project is in line with national priorities.

Because of the limited resources, it is necessary to concentrate on the unique mission of supporting basic physics with metrology, analysis of uncertainties, and reduction of errors through an understanding of instrumental and basic physical limitations. The stated objectives of the project are broad and generally amount to maintaining and expanding NIST's ability to support industry and other government agencies. The project team appears to be making adequate progress toward these goals.

4

EEEL Responses to Concerns from the 2007 Assessment

The following items of concern were noted in the 2007 report of the Panel on Electronics and Electrical Engineering.[1] The sections below present the responses of the Electronics and Electrical Engineering Laboratory to these concerns.

OPTOELECTRONICS DIVISION

Concerns About Funding

The Optoelectronics Division noted that its current level of non-NIST external funding (approximately 20 percent) seems to work well to maintain the scientific excellence of its work. The division suggested that although the burden of obtaining external funding is non-negligible, the external funds provide a very useful, ongoing "reality check" on programs and provide one measure of a project's importance.

Biophotonics Initiative

NIST agrees with the panel's conclusion that biophotonics is a very important and rapidly growing industry with strong potential impact on medical applications and the national priority of health care. In 2007, three NIST operating units summarized their assessment of biophotonics for the panel, but the specific current plans for action in this field by the Optoelectronics Division remain unclear to the panel. It appears that NIST needs an exploratory program to understand the field and to see where it can be of the most help. Two important areas where NIST can help immediately are the toxicity of carbon nanotubes and power standards for laser surgery instruments.

SEMICONDUCTOR ELECTRONICS DIVISION

System-on-a-Chip Project

Responding to the panel's suggestion, in 2007 the EEEL phased out the System-on-a-Chip project. Staff and funding were moved to other projects.

Spintronic Devices

In 2007 the panel suggested that the EEEL look at how the Semiconductor Electronics Division and the Electromagnetics Division might be able to interact on spintronic devices. The Semiconductor Division and the Electromagnetics Division

[1] National Research Council, *An Assessment of the National Institute of Standards and Technology Electronics and Electrical Engineering Laboratory: Fiscal Year 2007.* Washington, D.C.: The National Academies Press, 2007.

combined on an Innovations in Measurement Science proposal in 2007 to work on spintronics, which was funded in 2008. The groups are putting the equipment in place to start making measurements.

Center for Nanoscale Science and Technology

There remains a concern about how the Semiconductor Electronics Division can best make use of the Center for Nanoscale Science and Technology (CNST), a recently established center at NIST whose mission focuses on providing nanofabrication and nanotechnology resources to NIST and to the outside community, as well as performing targeted research in nanoscience and nanotechnology (research in these areas is also performed in other NIST laboratories). The extent to which the Semiconductor Electronics Division has adequate access to the CNST resources remains unclear to the panel.

QUANTUM ELECTRICAL METROLOGY DIVISION

Boulder and Gaithersburg Facilities and Synergy

The EEEL reported that the work has been reduced to fewer, strongly focused and highly synergistic efforts in Boulder; work on single-electron transistors and on magnetic materials was put on hold. There is strong collaboration between the Boulder and Gaithersburg groups in the area of dc-ac JVS. Other projects (graphene and calculable capacitor) have found NIST collaborators outside of the division.

Sustainability

The EEEL reported to the present panel that the ratio of permanent to associate staff is further declining. The new focus on Smart Grid offers opportunities for Gaithersburg to establish a new core effort of national interest and, therefore, also for more outside or new funding.

Management and Use of Fabrication Facilities

The position of a clean-room manager for the current fabrication facility has been implemented but is currently vacant. The relationship with the CNST is still evolving. A unified approach toward using the various clean-room facilities at NIST needs to be established in order to use resources efficiently.

ELECTROMAGNETICS DIVISION

Gradual Degradation of Facilities and Infrastructure at NIST Boulder

In order for the Electromagnetics Division to perform its stated missions, some areas require updating. For example, electronic communications, heating and cooling, lighting, and space utilization all need to be improved to accommodate the staff, experiments, and calibration services. The new buildings being constructed are expected to improve the conditions noted in both 2007 and 2009. The Building 1 Extension (B1E) is an example of this construction.

Cost and Burden of Providing Calibration Services

The Fundamental Guided Wave Metrology group is to be commended for easing out the repetitive tasks of calibrating industrial-type equipment and limiting its services to upper-level standards laboratories. The group should continue the transfer of repetitive tasks to other standards laboratories to make limited EEEL resources available for unique NIST responsibilities already identified or still below the horizon.

Planning Process

At the start of a political transition year in the U.S. government, despite the best efforts of the (acting) leadership of the Electromagnetics Division, project prioritization and budgeting remain a bit sketchy.

5

General Observations and Concerns

- The funding system of the Electronics and Electrical Engineering Laboratory warrants a thorough review. A review process for internal funding is needed that is based on technical merit rather than on economic need. For older projects that have been receiving internal funding and either have come to an end or have found other funding, there should be a mechanism in place to ensure that the internal funding is reallocated.
- The physical structure and the temperature control in some of the existing laboratories of the EEEL need work. It seems that any maintenance takes a very long time. This situation should be corrected.
- The number of permanent staff is barely adequate to maintain existing programs, albeit all are of high quality; the possible loss of expertise is a concern.
- The concept of fully documenting specialized knowledge before a staff member retires should be facilitated.
- Interaction of EEEL groups with other groups in NIST is becoming more difficult because there is less “flexible money” to incentivize collaboration. Internal collaborations seem to be particularly difficult in the biotechnology area.
- While the work related to the Knowledge Facilitation project is good, it seems to be more of a NIST-wide infrastructure function rather than a divisional function.
- As projects are developed, the EEEL should remain attuned to opportunities for further collaboration between the Boulder and Gaithersburg groups.
- There were two examples of issues where the organizational processes may be getting in the way of the efforts. One example involves the external calibration services in the Optoelectronics Division. The Boulder group has an internal goal of decreasing the calibration time. There were several complaints from this group suggesting that the routing of external funds or work through Gaithersburg may lead to increased cost and delays, with no added value resulting from adding Gaithersburg into the loop. EEEL management should examine this complaint and, if appropriate and feasible, improve the process in a way that would lead to lower costs and better customer service in terms of turnaround for service work. The other issue pertains to the work in display technology. This effort is being phased out, but there is still interest in the measurement course in the external community. EEEL management should consider whether it would be a good thing to sell any equipment that is no longer needed by NIST to a commercial enterprise; if so, the process needs to be facilitated.
- The required payback for capital equipment limits the acquisition of new equipment, and the purchase of large new equipment now requires greater

coordination across organizational entities. At the present time, the lack of people seems to be a bigger limitation than the lack of new capital equipment in the Semiconductor Electronics Division (SED).

- There is a general lack of modeling and simulation expertise and work in the Semiconductor Electronics Division. The laboratory understands the need for more modeling and simulation work, but there is not enough funding to support it. The SED tries to augment the modeling and simulation work by collaborating with universities. This area could benefit from additional resources.
- The Semiconductor Electronics Division depends heavily on money from the Office of Microelectronics Programs; reliance on such focused funding could limit the ability of the SED to start much-needed new research initiatives.
- A flat or declining budget is also a concern within the Quantum Electrical Metrology (QEM) Division. A long-term evaluation of the overall funding model for the division to support core metrology functions and services is encouraged.
- In the management and use of the fabrication facilities, the financial burden of clean-room operation in the new Building 1 Extension (B1E) needs to be spread beyond the QEM Division.
- The change in management structure, in which the EEEL director and the QEM Division leader are now both stationed in Boulder, has created challenges and uncertainty in Gaithersburg. This has led to significant stress and morale problems, particularly among the staff most closely involved with the calibration effort.
- One of the items of interest in the Electromagnetics Division is measurement related to metamaterials. Although metamaterial measurement was mentioned, no details were provided during this year's review.

6

New Thrusts or New High-Impact Projects

PHOTOVOLTAICS

The exploration and use of solar energy have risen and sunk with oil prices. Energy sources used in generating electricity in the United States roughly comprise 49 percent coal, 21 percent natural gas and other gases, 19 percent nuclear energy, less than 2 percent petroleum, 7 percent hydroelectric power, and less than 3 percent other renewable sources. Oil constitutes a minuscule share of the U.S. electricity generation, and its price should not deter renewable energy deployment.

As part of the future electrical energy portfolio, photovoltaics stands on its intrinsic merit of providing direct conversion from sun power to electricity. Photovoltaic electricity is the story of the power play of atoms, photons, and the free path of electrons. As to solar energy, no country can capture another country's photons. When the technology can offer cost parity with the grid, or closer to it, photovoltaic solar energy will become an essential part of mainstream electricity in everyone's life. The winning technology is the one that can deliver the desired economics.

Going forward, as manufacturing capacity continues to increase and production techniques continue to improve, the expanded scale and enhanced manufacturability will drive the cost of photovoltaics down. Technologically, the global efforts on increasing the cell efficiency are ever more rigorous and vigorous. The scale effect, coupled with the anticipated technological advancements, will move solar-cell-generated electricity toward grid parity.

Tying the NIST effort with the National Renewable Energy Laboratory (NREL) needs that will support the goals of the Smart Grid Initiative is another important effort. Photovoltaics is a growing industry and highly relevant to the national priorities of alternate energy sources and green energy technology. A photovoltaics project is warranted.

BIOELECTRONICS

The Semiconductor Electronics Division has proposed bioelectronics as a possible new focus area for furthering its innovation and metrology within the EEEL. The recent advances in biotechnology have generated much exciting potential for targeted and preventive medicine. However, understanding of the underlying mechanisms in human health and complex diseases has barely begun. There is a lack of predictive and diagnostic biomarkers for complex diseases. This prompts the need for ultrasensitive, cost-effective, high-throughput tools, which can derive from the sophisticated metrology established in the semiconductor industry. The convergence of biology and electronics is at an early but critical juncture, with a great deal of isolated work going on within academia, small entrepreneurial companies, and federal laboratories. It is appropriate that the Semiconductor Electronics Division take a leadership role, not only within NIST, but in concert with academic and industrial partners to propel the field forward.

With the highly multidisciplinary nature of research and development in bioelectronics, the EEEL should approach this initiative with project-minded leadership, drawing on human and materiel resources across divisional lines in a matrix-like structure. Bioelectronics is an important new thrust area deserving support.

GRAPHENE-BASED QUANTUM CONDUCTANCE STANDARDS

The project involving graphene-based quantum conductance standards is viewed as a potential new thrust in the Quantum Electrical Metrology Division. At present, the resistance standard is based in the integer quantum Hall effect in devices fabricated from gallium arsenide/aluminum gallium arsenide (GaAs/AlGaAs) heterostructures. It is quite difficult to produce GaAs-based devices that are suitable for resistance metrology, and today there are no reliable sources of the material needed to produce them. (Very high mobility GaAs is routinely available, but for technical reasons it is unsuitable for resistance metrology.) In addition, the integer quantum Hall effect in GaAs devices reaches metrological accuracy only at sub-kelvin temperatures (typically 0.3 K), making measurements of such devices quite demanding.

Quantum Hall devices based on graphene instead of GaAs may provide a solution to both of these issues if their mechanical and electrical stability prove acceptable. Energy-level spacings in graphene are roughly 100 times or more than in GaAs, potentially allowing operation at up to room temperature. In addition, graphene-based devices are potentially much simpler to fabricate and optimize than are GaAs-based devices. The development of a simple-to-produce quantum Hall standard capable of room-temperature operation could revolutionize resistance metrology as the development of the Josephson voltage standard revolutionized voltage metrology.

SMART GRID SYSTEM INITIATIVE

The Smart Grid program is being implemented in NIST, and the effort of deliberating and structuring an integrated, collaborative process across the divisions based on the respective expertise is essential to the program’s timely progress.

Countries around the globe are launching concerted activities in addressing energy independence and climate and environmental issues. As the world’s energy needs continue to increase, the energy generation, distribution, and consumption must resort to a more sustainable model by embracing all energy sources and delivering higher efficiency and lower cost.

The Smart Grid system holds high promise of revolutionizing how electricity is generated, distributed, consumed, and conserved by automatically monitoring and controlling two-way energy flow. It also can enable the use of renewable and alternative energy more effectively, efficiently, and intelligently, thus potentially transforming today’s economy.

The ultimate goals of smart grids are to enhance the power grid’s reliability, efficiency, and safety through real-time communication; to provide flexibility of power consumption; to enable decentralized power generation; and to increase the nation's economic growth by integrating renewable energy sources and creating green jobs.

By using real-time information from embedded sensors and automated controls, power outages, power-quality problems, and service disruptions can be mitigated. The ability to anticipate, detect, and respond to system problems and to isolate affected areas and redirect power flows around damaged facilities makes a self-healing loop. The optimized power flow reduces waste and maximizes the use of lowest-cost generation resources. Through seamlessly interconnecting renewable energy sources and other distributed generation technologies at local and regional levels, the energy efficiency is maximized. The decentralized power generation provided by smart grids also can increase fault tolerance.

Technologies in communications, sensing, measurement metering, and digital infrastructures are key elements of smart grids. Also, innovations in superconductivity, fault tolerance, storage, power electronics, and diagnostics components constitute its foundation.

On top of many other facets of the Smart Grid system, the system's security is of the ultimate importance. To secure the nation's critical electrical power infrastructure, smart encryption is a necessity. This should be taken into consideration at the outset of the program.

In the Smart Grid arena, NIST can play a leading role in developing and deploying the multi-front technologies and national standards.

7

Conclusions

Overall the deliverables and the accomplishments of the EEEL are commendable, considering the broad criteria for assessment listed below:

- The technical merit of the current laboratory programs relative to current state-of-the-art programs worldwide;
- The adequacy of the laboratory budget, facilities, equipment, and human resources, as they affect the quality of laboratory's technical programs; and
- The degree to which laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

The EEEL staff in management and research alike have earned high regard for their professionalism and dedication. However, a balance between the permanent staff and on-assignment researchers is needed. The number of permanent staff is declining, threatening the operation's continuity and stability.

Some projects (as outlined in Chapter 3) are under strain due to budget constraints. For example, the Macro Electronics project is severely underfunded. Macroelectronics, parallel to nanoelectronics and microelectronics, is equally important to the fulfillment of the EEEL's overall objectives.

Further roadmapping of each project should be done, and possible synergy among the projects is encouraged.

Certain facilities are in need of updating, renovation, and augmentation.

An incremental progress continues, yet new thrusts are also desired, conducive to the future of the institution. The new thrusts and strategic projects recommended in Chapter 6 will further propel the EEEL to a growth mode and impart increasingly high impact to the NIST mission.

The success of an integrated Smart Grid system will epitomize the country's commercial leadership and technological prowess. A working Smart Grid system, with the desired reliability, efficiency, and safety, is expected to revolutionize electricity supply, distribution, and consumption. It also will demonstrate the capability of embracing green energy electricity, as well as environmentally friendly transportation (hybrid and electric vehicles), making it a sustainable energy model. By fully employing the wealth of collective expertise and experience in the EEEL, NIST is poised to take the leadership position among other agencies in developing and deploying the multi-front technologies and the standards that govern the deployment of smart grids.

The Electronics and Electrical Engineering Laboratory, equipped with diverse professional skills and comprehensive technical expertise, has demonstrated significant accomplishments in crucial programs and is ready to take on challenging national strategic programs.

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Recommendations

The panel recommends that the concerns detailed in Chapter 5, "General Observations and Concerns," be addressed. Additional recommendations in general areas across divisions, as well as those that are division-specific, are listed below.

GENERAL

- Calibration services in all divisions call for a transparent process, guideline criteria, and a monitoring procedure. Considerations include funding sources, fees generated, initiating new services, terminating old services, and increasing or decreasing services in relation to industry needs and strategic rationale.
- The current panel assessment criteria used for this report are adequate and comprehensive, yet additional considerations should include the following:
  —Synchronization in the strategic plans of NIST, the EEEL, and EEEL's divisions;
  —Project priority setting, using clearly defined factors;
  —Workability of the administrative boundary between NIST and the EEEL; and
  —Projects' alignment with the national priorities.
- The Smart Grid program, in need of an integrated and collaborative effort, calls for the deliberation of a technical management structure that sets the program's roadmap, selects expertise, monitors the process, and manages the operation, being responsible for the program's progress.
- Initial planning of the Smart Grid program should include the security of data links with more than one encryption scheme. Multiple, redundant data links including fiber, microwave, and radio frequency are essential.
- Photovoltaics is a growing industry and highly relevant to the national priorities of alternate energy sources and green energy technology. A photovoltaics project is warranted.

OPTOELECTRONICS DIVISION

- In the strategic program theme area of Quantum Information and Metrology, which includes very fine work, the underlying connecting theme requires clarification. There are projects in detectors, sources, the quantum candela, the Schrödinger cat, the entangled photon, and other areas. These form the components of a potentially exciting program with great impact, but the details of what the program is, where it is going, and how staff are interconnected require clarification. There is a need for better explication of how the single- and entangled-photon source work fits into the overall vision of the EEEL and how the sources play into the detector. It is clear, for example, that to develop high-efficiency detectors and also ways to characterize (e.g., quantum entanglement), one must also be able to produce clean sources of single photons, photon pairs, and entanglement. This overall mission and the relation of each project to it need to be stated more clearly. A clearer roadmap is needed, or at least a more coherent picture of how the detector work complements the source work and how this all comes together into a coherent program that encompasses all of the interesting research. There should be a specific roadmap for the quantum candela project, stating the problem, the specific goal of the single-photon source to replace the current blackbody source, and a proposed plan on how to get from here to there. Perhaps the roadmap will change as more is learned, and that is fine, but the importance of such a roadmap is to concentrate thought into a concrete plan.

- There is a need to tie the materials analysis of the carbon nanotubes to toxicity studies. This is a great opportunity to provide some interorganizational efforts and also points out the need for providing a safe environment for NIST researchers.
- Stating the goal of the project and a brief description of the roadmap to the goal would be helpful for all projects during future reviews.

SEMICONDUCTOR ELECTRONICS DIVISION

- Until now, most of the power-device testing has been at the device level. With the emphasis on smart grid technology, it will be more important for the power-device group to look at reliability, not only at the device level, but also at the system level. The smart grid work should provide an opportunity for other-agency funding, since the DARPA SiC project is winding down. The division is planning the establishment of a center for nanoelectronics reliability. The idea is to leverage the resources at NIST and to coordinate research efforts of universities, industry, and other agencies to meet the future reliability challenge. It has already gained the support of the Semiconductor Research Corporation, SEMATECH, and the National Science Foundation. The goal of the center will be to develop new measurement techniques to push the frontier, to provide measurement facilities too costly for universities to acquire, and to enable universities to access samples from the industry while protecting sensitive information. One of the visions of the group is to develop a microelectron paramagnetic resonance spectrometer for nondestructive detection of a single defect by full wafer probing. The plan and the effort merit support.
- The Semiconductor Electronics Division should play a leadership role in the development of metrologies in the emerging area of bioelectronics. This would require adding new personnel.
- There is a resurgence in analog and mixed-signal electronics because of the large growth in sensor networks, sensor arrays, and wireless interconnectivity. Analog will be a critical component of bioelectronics because of the need to

interface bioelectronic sensors with digital processors. The SED currently has a very small effort in analog and mixed-signal electronics. Since the U.S. semiconductor industry is expanding its activities in analog technology, it would be important for the SED to have an activity to support analog development. The focus could be analog reliability, which would fit in the planned center for nanoelectronics reliability, but it could also be a bridge between bioelectronics and device reliability. There is need for an intersection with mixed-signal electronics to support projects in bioelectronics. Among the projects that could benefit from mixed-signal electronics would be the impedimetric cell physiometer. This should align well with work in the Office of Microelectronics Programs.

QUANTUM ELECTRICAL METROLOGY DIVISION

- The business model for calibration services at the facilities of the Quantum Electrical Metrology Division in Gaithersburg, Maryland, should be clarified.
- The excellent fabrication facilities at Boulder, Colorado, and the Center for Nanoscale Science and Technology are particularly valuable. The pressure on the Boulder fabrication facility will be reduced by the new fabrication facility under construction, which was supported by the stimulus money. However, the existing clean-room management model (i.e., the facility is run by the QEM group in Boulder but used by all other Boulder groups) should not be extended to the new, enlarged facility. A new approach toward fabrication facility management must be developed to maintain the internationally leading fabrication while expanding the throughput.

ELECTROMAGNETICS DIVISION

- A focus on the application of superconductivity to the future smart electrical grid initiatives should be pursued to continue the Superconductivity program team's national leadership role in superconducting measurements and to participate in an important cross-divisional laboratory project.
- Widespread collaboration is essential; the extent of these collaborations should be more formally explained during future reviews.
- The division should consider open sourcing the work to avoid potentially inhibiting intellectual property concerns in the new fields.
- The area of metamaterials warrants investigation, particularly from the point of view of metrology, in developing the capability for rigorous metamaterial measurements. Metamaterial slab properties should be measured with sufficient bandwidth to elucidate the effects of dispersion. Metamaterial performance versus sample size should be studied; negative-index materials (NIMs) that are large in wavelengths may have certain useful properties—a critical question is how the NIM properties degrade as the sample size is decreased. The behavior of metamaterials in near fields (as opposed to plane waves) should be studied, because most proposed antenna applications are in

the near field. Methods for measuring the phase, loss, and reflection coefficient of artificial magnetic conductors should be developed and calibrated. This work should be carried out with both experiments and numerical simulations in which the microscopic structure of the metamaterial is faithfully represented.