An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2009

Panel on Nanoscale Science and Technology; National Research Council

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Panel on Nanoscale Science and Technology

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:

Ilesanmi Adesida, University of Illinois at Urbana-Champaign,
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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's (NIST's) Center for Nanoscale Science and Technology (CNST) was founded on May 1, 2007, and remains in development with respect to projects and staffing. It aspires to be recognized both as a world leader in each of its research areas and as an organization providing ready access to unexcelled nanoscale measurement and fabrication facilities. Its mission is to (1) provide measurement methods, standards, and technology to support all phases of nanotechnology development from discovery to production; (2) develop and maintain a national shared-use facility, the Nanofab, with state-of-the-art nanoscale fabrication and measurement capabilities; (3) apply a multidisciplinary approach to problem solving that involves partnering with industry, academia, and other government agencies; (4) serve as a hub to link the external nanotechnology community to the vast measurement expertise that exists within NIST, including expertise in related metrology residing in other NIST laboratories; and (5) help to educate the next generation of nanotechnologists.

The CNST has two components with complementary purposes—the research program and the Nanofab facility. The current research program consists of leading-edge nanoscale research directed toward exploring phenomena that may provide the basis for future nanoscale metrology techniques. This part of the CNST is staffed by scientific research staff with records of individual research accomplishment—although much of the output was completed before the staff joined the CNST—supported by a large number of postdoctoral appointees and various support staff. The Nanofab is a national shared-use facility that aspires to provide a state-of-the-art suite of nanoscale measurement and fabrication capabilities. It is largely a clean-room facility and is staffed accordingly. It is expected that the Nanofab will attract users from all sectors of the economy—industry, academia, and government—through its impressive capital equipment capabilities. Individuals, from elsewhere at NIST and beyond, can interact with the CNST in either or both of two ways: (1) through collaborations with the scientific research staff in the research program, and (2) through use of the Nanofab to fabricate structures or devices.

As described to the National Research Council's (NRC's) Panel on Nanoscale Science and Technology, the CNST, with a fiscal year (FY) 2008 budget of $21 million, is currently staffed by 70 full-time equivalents (FTEs), including 45 technical staff. Several staff hiring offers are pending. There are currently 9 staff members with the title of Project Leader, each of whom is allocated 2 postdoctoral researchers and one sixth each of an electrical engineer, mechanical designer/instrument specialist, computer specialist, and secretary. Two group leaders and 2 CNST Fellows also serve as project leaders; they, too, are supported by staff and laboratory resources. There are 10 administrative-support positions and 15 technical-support positions. The research program is organized in three groups—Electron Physics, Nanofabrication Research, and Energy Research. The first two groups are reasonably fully staffed, and searches are underway to staff the third group. The operation of the Nanofab is undertaken by the Nanofab Operations Group. Aggressive recruiting for all levels within the CNST is continuing, and the center is working to achieve its full complement of talent.

The panel of experts appointed by the National Research Council assessed the overall CNST accomplishments and operations for FY 2009. As requested by the Deputy

Director of NIST, the scope of the assessment included the following criteria: (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 the laboratory's technical programs; and (3) the degree to which the laboratory programs in measurement science and standards achieve their stated objectives and desired impact.

TECHNICAL MERIT OF THE CENTER'S PROGRAMS

On the basis of its assessment of the CNST, conducted in February 2009, the NRC's Panel on Nanoscale Science and Technology concluded that for the selected portion of the programs presented for review by the CNST, the staff, the projects, and the facilities are outstanding and, in many cases, unique. The various parts of the CNST are not uniformly mature. Some parts are very mature, with efforts that have evolved naturally from long-standing NIST programs, while others are extremely new, in some cases with almost no staff yet. Much of the work reviewed is scientifically outstanding; all of the work reviewed is scientifically very good. The panel was impressed by the breadth of scientific knowledge and the overall level of enthusiasm of the staff encountered throughout the CNST. The projects presented are clearly focused on the metrology mission of NIST as they seek to develop understanding that will lead to standards and metrology at the nanoscale. Much of the research presented is directed toward developing unique instrumentation. These efforts are first-rate. The quality of the science done with the instrumentation is more variable. Although much of the work reviewed is original, innovative, and among the best of its kind, some is significantly more pedestrian. The panel is particularly concerned about plans for the new Energy Research Group. Given the uniqueness of much of the CNST instrumentation, it is incumbent upon CNST staff to seek out the best collaborators from around the world to perform high-impact, game-changing experiments as programs and projects are developed. In addition, the CNST may find it useful to benchmark itself against other nanoscience/nanotechnology efforts around the world. An advisory committee composed of nanoscience/nanotechnology experts might also be helpful.

The staffing of the CNST is heavily biased toward experimental work. The relatively small theoretical effort is outstanding and has significant impact on a wide variety of programs. The CNST would benefit from having a larger theoretical component in its staffing mix. A greater presence of talent in the realm of theory could act as a catalyst to bring together efforts across the CNST and beyond.

The technical merit of the reviewed work of the Electron Physics Group relative to the state of the art is at the level of the best in the field. The group's laboratory facilities are state of the art and in many cases unique. The outstanding accomplishments of the group indicate achievement of stated objectives and impact.

Many members of the CNST staff have been at NIST for a very short time. These new hires have shown impressive results in their previous positions but have not been at NIST long enough to have established new research directions or reputations. The panel looks forward to evaluating their progress in future reviews. Likewise, the Nanofab facility has not been operating for very long. The current Nanofab leadership arrived at the CNST only recently, and the operating mode for the facility is still developing. Some of the efforts of the Nanofabrication Research Group are producing outstanding results and have shown excellent success in achieving stated objectives. This rather new group has articulated an outstanding vision and direction. The combination of creative personnel with excellent facilities that enable them to push in new, unexpected directions makes for an exceptional infrastructure. The panel recommends that the Nanofab be reviewed again in about a year, when it has been operating long enough for its performance to be judged.

The Energy Research Group is even more embryonic, with almost no staff in place. The description of the group's dual role in improving measurements in the energy area and particularly in addressing nanometer-dimensional problems in energy is insufficiently focused. The plan to focus on nanometer aspects of energy research does not suggest disciplinary activities characteristic of a well-considered program driven by the investigation of physical principles through good measurements. The vision for this group requires further development if it is to occupy a unique, NIST-appropriate position in the very crowded field at the intersection of nanoscience and energy. This vision should be developed before the group is staffed. The next year will be critical in defining the role of the Energy Research Group. Review of the group within the next year will be important to ensure that it is on the right track.

The productivity of CNST staff since 2007 has been impressive, although much of the output was completed before the staff joined the CNST. The number of publications with CNST affiliation totals 43 for 2007-2008. In the same time period, current CNST staff members have been authors of more than 150 publications representing work done before they joined the CNST. So far in 2009, a total of 20 publications by CNST staff are in press, half of which have the CNST affiliation. This high level of productivity is likely to continue, with a substantially higher proportion of the total number of publications having a CNST affiliation as the center matures. CNST staff and leadership have also garnered an impressive array of awards over the same time period.

Many of the capabilities in the CNST are unique, having been developed by NIST personnel with both the talent and the resources to develop novel instrumentation and techniques. These unique capabilities will have their maximal impact when they are applied to forefront scientific and technical challenges that can only be addressed through such cutting-edge techniques. It is imperative that the CNST seek out and work with the best collaborators from around the world in order to have the game-changing impact of which it is capable.

The generous budget of the CNST and the "block funding" nature of its allocation are increasingly unusual in the U.S. scientific community. This approach enables the CNST staff to concentrate on their scientific endeavors in a way that is all too rare. The staff recognize their enviable position and greatly appreciate the NIST and CNST leadership for their roles in making this funding model possible. The rather "comfortable" nature of this funding arrangement means that it is incumbent on CNST leadership to ensure that the CNST is pursuing the best possible science consistent with its mission. Also, the leadership must develop quality assessment tools and mechanisms to end any less productive projects and to change scientific directions where appropriate.

ADEQUACY OF INFRASTRUCTURE

The CNST facilities are clearly among the best in the world and in many cases are unique. Such facilities are appropriate for the elements of the CNST mission that involve developing the understanding and techniques for nanoscale standards and metrology. Likewise, the staff is outstanding. The inability to hire foreign nationals as NIST employees is, however, a significant impediment, because the United States certainly does not have a monopoly on the best and brightest talent in nanoscience and nanotechnology. The restrictions on access by and employment of foreign nationals are likely to be detrimental to the CNST's efforts to remain at the forefront of nanoscience and nanotechnology for the long term. Although an innovative arrangement with the University of Maryland is in place to enable foreign nationals to work at the CNST, these individuals do not enjoy the same unfettered access to the facilities and information that is taken for granted by staff who are U.S. citizens.

The leadership of all of the measurements and standards laboratories at NIST, including the CNST, has impressive incentives at its disposal for recruiting top talent; these include offering generous starting bonuses and paying off student loans. The recruiting challenges that the CNST is experiencing at the moment are far from unique to NIST.

There is a striking lack of diversity of the staff, from management, to project leaders, to postdocs, to technical support. Few women or underrepresented minorities were part of any of the groups with which the panel met, although the panel understands that a few women have recently departed and that a female staff member will be starting soon. The CNST must continue to work hard to attract and retain a diverse workforce that more closely represents the available pool of talent. There is apparently more diversity in the makeup of the recently recruited staff; the panel expects to see noticeably different demographics during the next review.

ACHIEVEMENT OF OBJECTIVES AND IMPACT

The vision presented to the panel in the overview presentation on the CNST is clear, compelling, and consistent with the mission of NIST. During discussion, the panel heard clearly that others generally work on future nanotechnologies (e.g., devices), whereas NIST focuses mostly on the instruments to measure properties within the new technologies and on current needs of industry. The efforts of individual projects are generally aligned with the CNST vision.

Given the youth of the CNST as an organization and the recent arrival of many of its staff, the center has made outstanding progress toward achieving its goals. It has not, as its leadership well recognizes, fully achieved its objectives, and it continues to grow very rapidly. The CNST should be reviewed annually for progress until the rate of change has slowed significantly from its current rate.

RECOMMENDATIONS

The panel offers the following recommendations:

- The CNST should continue aggressively to seek out and work with the best collaborators from around the world in order to have the game-changing impact that is its promise. The CNST should consider benchmarking itself against other nanoscience/nanotechnology efforts around the world. The center should also consider forming an advisory committee composed of nanoscience/nanotechnology experts. Such a committee would provide the CNST with more access to current industrial technology trends, for example in information technology.
- The inability to hire foreign nationals as NIST employees is a significant impediment that is likely to be detrimental to the CNST's efforts to remain at the forefront of nanoscience and nanotechnology for the long term. CNST leadership needs to convince NIST leadership of the importance of this issue.
- The CNST should work harder to attract and retain a diverse workforce that more closely represents the available pool of talent.
- The CNST should consider increasing the relative proportion of theorists and chemists in its overall staffing.
- The CNST should be reviewed annually for progress until the rate of change has slowed significantly from its current rate. Annual reviews of the Nanofab and the Energy Research Group are especially critical.

1

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 (CNST), the Information Technology Laboratory, the Chemical Science and Technology Laboratory, and the Electronics and Electrical Engineering Laboratory. 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 Nanoscale Science and Technology.

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 the laboratory's technical programs; and
3. The degree to which the 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.

To accomplish the assessment, the NRC assembled a panel of 8 volunteers whose expertise matches that of the work performed by the CNST staff.[2] The Panel on Nanoscale Science and Technology held a 2.5-day meeting on February 23-25, 2009, at the Center for Nanoscale Science and Technology facility in Gaithersburg, Maryland. The agenda consisted of presentations, tours, demonstrations, and interactive sessions

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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://cnst.nist.gov/ for more information on CNST programs. Accessed May 1, 2009.

with the CNST leadership and staff. The panel also met in a closed session to deliberate on its findings and to define the contents of this assessment report.

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas within which the CNST activities are conducted. The panel reviewed selected projects across the breadth of CNST activities presented by the CNST management and staff. It was not possible to review the CNST programs and projects exhaustively. The examples reviewed by the panel were selected by the CNST. 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 CNST work, the impact of the work with respect to achieving the CNST's own definition of its objectives, and specific elements of the CNST's resource infrastructure that are intended to support the technical work. The highlighted examples for each CNST group are intended collectively to portray an overall impression of the center, while communicating useful suggestions specific to projects and programs that the panel considered to be of special note within the set of those examined. The assessment is currently scheduled to be repeated biennially, although the review panel recommends more frequent annual reviews of the center during this critical start-up period. 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 CNST exhaustively. Instead, this report identifies key issues and focuses on representative programs and projects relevant to those issues. Given the necessarily nonexhaustive nature of the review process, the omission of any particular CNST program or project should not be interpreted as a negative reflection on the omitted program or project.

The preceding Summary highlights issues that apply broadly to several or all of the groups or to the center as a whole. The following individual chapters present observations specific to the various center groups. Finally, the report presents the overall conclusions of the review. Appendix A contains information about CNST process activities described during the review. Appendix B presents impressions expressed by CNST staff during informal discussions with panel members.

2

The Research Program

The research program of the Center for Nanoscale Science and Technology is carried out by three groups: Electron Physics, Nanofabrication Research, and Energy Research. The Electron Physics Group has been in existence for more than 50 years (and led by the CNST director for over half that time); it was transferred intact to the CNST when the center was established. The Nanofabrication Research Group is a new effort that has been in existence only since the CNST was founded. While significant staffing has already taken place, hiring for this group continues at a brisk pace. The Energy Research Group is very new, currently populated only by the acting group leader, supported by a small number of postdoctoral researchers. Searches for group members are underway. The panel's observations and recommendations for each group are discussed separately below.

ELECTRON PHYSICS GROUP

With its history of more than 50 years, the Electron Physics Group is well established at NIST, having an impressive track record of accomplishments in electron optics, spin-polarized magnetic imaging (scanning electron microscope with polarization analysis, or SEMPA), laser manipulation of atoms, and nanoscale characterization. This group was incorporated as a whole into the CNST at the inception of the center. The science done in this group is of very high quality, currently focusing on nanomagnetics, theory and modeling of nanostructures, nanotechnology with laser-controlled atoms, and atomic-scale characterization and fabrication. Twenty-three technical staff members (project leaders, postdocs, visitors, and support staff) constitute the group.

The work on laser control of atoms is among the best in its field. In particular, the Magneto-Optical Trap Ion Source (MOTIS) is very exciting and unique, potentially moving forward focused ion beam (FIB) technology, which has stagnated for more than a decade. Such leading-edge, high-risk research is exactly the type of work that an organization like NIST should be doing. The current Cooperative Research and Development Agreement with FEI Company will provide a mechanism for coupling with the manufacturing of a tool at the appropriate time. In this role, it would be appropriate for the CNST to bring the best talent to work together on this and, if successful, to use the tool to study high-impact questions to which it is ideally suited.

The ultrahigh vacuum (UHV) cryogenic scanning tunneling microscopy (STM) work is of high quality. The instrument itself is a magnificent tour de force that exhibits seldom-matched expertise in instrument design. In particular, the application of the cryogenic STM to understand the electronic states of graphene is a good example of the use of such an instrument to address the science behind these possibly technologically important materials. A spin-off from this work, well aligned with the NIST mission, is the realization that graphene, because of its large Landau level spacing at room temperature, might be used as a resistance standard, providing an excellent tie to the NIST mission.

The nanomagnetics effort, including imaging SEMPA and ferromagnetic resonance (FMR) imaging of domain motion, is being applied to studies in magnetic storage such as Magnetoresistive Random Access Memory. This group should collaborate more closely with a storage technology company in order to couple with technologically relevant problems in magnetic storage. The group is adequately staffed and of very high quality, and it appears to be well leveraged through collaborations with other NIST groups. The theoretical component of the effort is among the best in its field. The interplay between experiment and theory is extremely powerful, enabling the group to attack complex, important problems successfully. Efforts on interference lithography for magnetic-dynamics studies and on spin-transfer torques for magnetoelectronic devices are also impressive.

The facilities of the Electron Physics Group are extremely impressive. The Atomic Scale Quantum Nanoelectronics Laboratory is in the final stage of construction. It centers on a new ultralow-temperature scanning probe microscope (SPM) that has been designed to address the challenge of measuring and understanding electronic structure–property relationships as device sizes continue to decrease. Measurements with very high spatial and energy resolution are required in order to understand such systems for future electronics. The scanning tunneling microscope that is being built is very impressive and, to the knowledge of the panel, one of a kind. Maximizing the impact of such a unique capability will demand judicious choice of the science problems to be addressed, as the CNST leadership is well aware.

The current evaluation yields the following conclusions. The technical merit relative to the state of the art is at the level of the best in the field. The laboratory facilities are state of the art and in many cases unique. Outstanding accomplishments indicate achievement of stated objectives and impact.

NANOFABRICATION RESEARCH GROUP

The Nanofabrication Research Group was formed in 2007 and has grown to include expertise in nanofabrication, directed self-assembly, nanoplasmonics and metamaterials, nanophotonics, nanoelectromechanical systems and microelectromechanical systems (MEMS), and nanoscale electronic measurements. Recruiting efforts are underway for staff with expertise in theory and in situ/dynamic electromagnetics, with further planned hires in novel lithographic processing and/or molecularly controlled assembly. The new group leader brings a broad perspective and a set of new ideas to the CNST that, coupled with the talents of the impressive recent hires, promise great opportunity for this group.

Projects reviewed by the panel covered several of the focus areas of the group. The effort on nanoplasmonics, which has demonstrated a MEMS structure formed with nano-processing capable of measuring photon pressure in a “left-handed” metamaterial system, is particularly clever. This MEMS structure was an exemplary demonstration of the processing capability of the NIST Nanofab facility. Even more impressive output from this group is anticipated as the new staff ramp up their research programs at the CNST.

The facilities of the Nanofabrication Research Group are excellent, and the results are stunning. For example, in-house sputter disposition, FIB, and reactive-ion etching (RIE) were used to make left-handed metamaterials (multilayered Ag/a-Si) cantilever structures, which were combined with the predicted radiation response in a left-handed metamaterial to perform the first-ever measurement of the negative radiation pressure response by observing the cantilever deflection (microns) in a scanning electron microscope (SEM).

The panel's evaluation yields the following conclusions:

- Some of the efforts are producing outstanding results. This rather new group has articulated an outstanding vision and direction. Many staff members are very new, so the quantity of results is expected to increase dramatically over the next few years.
- The laboratories are excellent. The combination of creative personnel with excellent facilities that enable them to push in new, unexpected directions makes for an exceptional infrastructure.
- Excellent success in achieving stated objectives has been shown to date.

ENERGY RESEARCH GROUP

The Energy Research Group is the newest organization within the CNST. The group leader is serving in an acting capacity, supported by a small number of postdoctoral researchers. Four hires are planned in 2009. The Energy Research Group aims to combine measurement research in areas that overlap energy and nanometer science. The stated goals of the group are these: energy storage, transport, and conversion, including light–matter interaction, charge transfer, and energy transfer; catalytic activity; and interfacial structure in energy-related devices.

The description of the group's dual role in improving measurements in the energy area and particularly in nanometer-dimensional problems in energy is insufficiently focused. The plan to focus on nanometer aspects of energy research does not suggest disciplinary activities characteristic of a well-considered program driven by the investigation of physical principles through good measurements.

The talents desired in each of the four prospective hires are, as described to the panel, almost impossible to imagine being embodied in single individuals. Anyone who might appear to bring such a wide distribution of talents as are desired will probably not be deeply trained in any. For example, it is difficult to imagine someone who would have advanced understanding of industrial energy, thermoelectrics, and field emission.

The main accomplishments in this new group to date center on the behavior of organic photovoltaic devices. Activities such as the use of a conductive atomic force microscope (AFM) to measure the spatial distribution of electron emission from a working organic photovoltaic device are interesting, but they do not probe the physical reasons for the observed nonuniform spatial distribution of photocurrent or of surface potential under illumination conditions.

The proposed plans for coupling electrode characterization techniques to actual working electrodes in order to learn what factors affect electrochemical-cell behavior are crude compared to successful UHV research in this area completed more than 20 years ago in laboratories at Case Western Reserve University; the University of California, Santa Barbara; and the University of California, Berkeley. Most of the measurement techniques proposed for the study will not probe the essential key issues at work in electrochemistry.

Although not specifically mentioned, it would appear that planned work in catalysis has not been considered with sufficient care—with understanding of the scientific status of the field and with knowledge of key problems remaining to be solved. Much is well understood in this field after more than 20 years of atomic-level experimental research on single-crystal model catalysts coupled with modern theory involving, for example, density functional methods that have reached chemical accuracy. Work of the following should be considered: Gerhard Ertl, recipient of the 2007 Nobel Prize in chemistry, at the Fritz Haber Institut, Berlin, Germany; Jens Norskov, of the Danish Technical University-Lyngby, Denmark; D.W. Goodman, of Texas A&M University, College Station, Texas; and H.J. Freund, of the Fritz Haber Institut, Berlin, Germany.

The work presented in the laboratory visited by the panel is embryonic, including nanoscale photoresponse in photovoltaic (PV) materials using the electrostatic force mode of AFM and the development of functional tips suitable for photoresponse measurement in liquid environments. Future plans include measurement of the time-resolved transient photoresponse of energy materials using ultrafast optical physics by a scientist to be hired.

In summary, the CNST should undertake a careful reexamination of the goals and approaches of the Energy Research Group before continued investment.

To date, the technical merit relative to the state of the art appears low. The CNST should undertake a serious reexamination of the focus and direction of the group before significant hiring takes place. The laboratory facilities are excellent. There has been no discernible impact of the work to date, however, owing at least partially to lack of staff.

3

The Nanofab Program

OVERVIEW

The NIST Nanofab is an integral part of the mission of the Center for Nanoscale Science and Technology—to develop and maintain a national shared-use facility, the Nanofab, with state-of-the-art, nanoscale fabrication and measurement capabilities—and it is an integral part of the CNST vision to be recognized as a world leader in each of its research areas and for providing ready access to unexcelled nanoscale measurement and fabrication facilities. The group leader has been at NIST for only a short period of time.

The Nanofab facility contains a modern set of commercially available fabrication and metrology tools that exceed or match capabilities at university nanofabrication facilities. A small subset of this tooling is on a par with equipment at industrial nano-facilities. The Nanofab is supported by seven process engineers and three process technicians. This high level of staffing in the Nanofab differs from that in university facilities, where such support is minimal. For reference, typical industrial processing support operates with a 1:1 ratio of process engineers and technicians.

The Nanofab model for meeting the needs of the fabrication projects required by its users provides two options: hands-on processing by the user or processing by Nanofab staff. With either strategy, the Nanofab staff provides consultation services to define both process development requirements and a process flow for the project.

PHYSICAL PLANT AND TOOLS

The Nanofab is housed in a newly constructed, 19,000 ft^2 clean-room facility incorporating the necessary requisites for safe, contamination-free operation in Class 100 and Class 1000 environments—that is, temperature control, humidity control, deionized (DI) water, air volume handling, and laminar airflow. At present, 25 percent of the clean-room space is unused and available for future tooling and wafer processing needs. The Nanofab tooling is a mixture of inherited equipment from the NIST complementary metal oxide semiconductor facility (deposition, RIE, film thickness measurement, diffusion, contact print lithography, and SEM applications), new RIE and characterization tooling and FIB tooling, and new nanofabrication-specific tooling (electron-beam [or e-beam], nanoimprint, and mask-making applications). The Nanofab tool set can nominally accommodate 150 mm diameter wafers and has the flexibility to process small-dimension (20 mm) substrates. In the second quarter of 2009, significant new tooling (a second e-beam lithography system, an atomic layer deposition [ALD] unit, and two additional RIE units) will be added to the Nanofab. Reports from the CNST director, the Nanofab manager, and process staff indicate that the facility has reached limits in air-handling capacity, and yet at least five new tools are planned for delivery. Other utility deficiencies (DI water and heating, ventilating, and air conditioning [HVAC]) were also described.

PROCESSING ACTIVITIES

The Nanofab tour, the presentations by group leaders and project leaders, the posters, and the presentation by the Nanofab manager did not provide sufficient information for the panel to be able to gauge the process activity level and the process capabilities of the Nanofab facility. Process integration capabilities, workloads, and tool utilizations for the facility were not adequately described. A general impression of the panel is that the facility is large, almost lavish. The Nanofab is underused at this stage. It is currently completing its initial tool-up, and the tools being turned on this year will result in greater overall utilization of the facility. Staffing and utilities are being stressed by the addition of new tools, even with the modest level of use in the facility. The process activities described during the review are summarized in Appendix A.

The process examples explicitly described during the review imply that the Nanofab program has as its major focus the fabrication of MEMS structures and as its secondary focus, the fabrication of a single layer of nano features using one photolithography step—that is, a combination of an e-beam exposure, a metal deposition, and a subtractive or additive removal of material. The CNST is a relatively new entity, so such a focus is not unexpected. Two of the five examples presented highlighted individual process steps in multilevel nanostructures. As the center’s projects mature, it can be assumed that Nanofab activities will transition to creating more nanoscale structures.

TOOLING ISSUES

The Nanofab facility is tool-rich and yet is expanding in the next 6 months by increasing its capabilities in deposition (ALD), RIE, and e-beam lithography. These tool additions are significant in terms of capitalization, complexity, and engineering support requirements. The justifications for these tool additions, in view of the fact that the present tool set is underused, were not described. Future Nanofab tooling additions would benefit from a long-term planning strategy for tools, staffing, and process needs to ensure efficiencies in tool utilizations.

The centerpiece tool for the Nanofab is the Vistec 300 E-beam writer. Commentary on tool utilization and e-beam-specific projects was lacking, even though a second e-beam tool has been acquired.

Tooling inconsistencies were observed during the panel’s visit, including the following:

- Justification for six RIE-specific tools (two arriving in the second quarter of 2009),
- Justification for a second state-of-the-art e-beam tool and justification for locating this sophisticated tooling outside the clean-room area,
- Lack of state-of-the-art metal lift-off tooling (spray heated solvent) and CO_2 snow cleaning,
- Lack of sputter deposition tooling, and
- No ion milling capability.

OPERATIONAL STRATEGY

The goal of the Nanofab program is to serve researchers from NIST, other government laboratories, academic institutions, and commercial enterprises. Operational strategies to reach the broader commercial user base are not well defined. Much of the operation and the suite of equipment seem to have been modeled after academic nanofabrication facilities. While this emulation of existing facilities increases the chances of quickly creating a functional entity, for the development of this new facility the significant and rarely possible investment in new capability should be done in a way that would not duplicate but rather create entirely new capability for the U.S. research and development (R&D) community. Coupling and exploiting the unique strengths of the CNST and NIST, in metrology, for example, and making these available to the R&D community would be a significant contribution to the U.S. research base and a tremendous asset in the United States. Also useful to guide direction and operation would be an analysis of the user community and identification of currently unmet needs.

CONCLUSIONS AND RECOMMENDATIONS

The Nanofab facility contains a remarkable set of the most modern commercially available fabrication and metrology tools. This major investment in capital equipment and staff resources should be a tremendous asset for the CNST researchers and could be extremely valuable for commercial enterprises.

The Nanofab facility is a new entity. It requires time to mature and to demonstrate its full potential as an asset to NIST and to academic and industrial users. The CNST and the Nanofab program must analyze the unmet needs in the growing nanoscale research community and determine how strengths of the CNST and NIST can address these needs, taking care not simply to duplicate existing capabilities.

The Nanofab facility requires oversight in several areas:

- Chart e-beam activity in the laboratory, thereby justifying a two e-beam facility;
- Document tool utilization;
- Chart processing experiments in the facility to create a process history and an activity history for the facility;
- Develop a tool plan and a complementary staffing plan to support the tooling plan;
- Develop for the outside user a set of charging and access methods that is based on clear criteria for allocating resources;
- Develop a plan to remedy HVAC, air handling, and DI water deficiencies in the laboratory; and
- Develop a set of process capabilities complemented with process modules for the facility.

The Nanofab program should be reviewed again during the 2010 calendar year to gauge progress in meeting the Nanofab goal of state-of-the-art nanoscale processing.

The panel's evaluation yielded the following conclusions:

- The technical merit relative to the state of the art is low in terms of impact to date; the potential, with appropriate continued development, is high.
- The capital infrastructure is outstanding in many cases, although some highly useful tools seem to be missing. Some essential facility capabilities such as air handling are reported to be inadequate. Staffing levels seem low.
- The achievement of desired objectives and impact will be examined when more information is available in future reviews.

4

Conclusions

The Center for Nanoscale Science and Technology has, at this early stage of its life, made significant progress toward meeting its stated objectives of (1) providing measurement methods, standards, and technology to support nanotechnology development; (2) developing and maintaining a national shared-use facility (the Nanofab) with state-of-the-art nanoscale fabrication and measurement capabilities; (3) applying a multidisciplinary approach involving diverse partners; (4) serving as a hub to link the external nanotechnology community to relevant NIST expertise; and (5) helping to educate the next generation of nanotechnologists. The more mature parts of the CNST are outstanding, especially in terms of the quality and productivity of the staff, the uniqueness of the capabilities, and the alignment with the overall NIST mission. The vector of the newer parts of the CNST is positive, with excellent new staff and outstanding laboratories, but there is still significant work to be done to achieve the same level of impact currently enjoyed by the more established efforts.

The CNST will maximize its potentially great impact on U.S. and global nanoscience and nanotechnology by (1) continuing its development of unique, powerful instrumentation and maintaining consistently high quality of the research conducted with the instrumentation; (2) breaking down barriers to full participation as equal partners of foreign nationals in the science program; (3) attracting and retaining a diverse world-class workforce; and (4) appropriately balancing its workforce to cover the multitude of disciplines required for nanoscience.

The Center for Nanoscale Science and Technology is off to an impressive start, but it is still at a formative stage. It is important that its progress be reviewed annually until its development stabilizes. It will be informative to include as part of the reviews a description of the ways in which the CNST interacts with programs and projects in nanoscience and nanotechnology across the NIST laboratories.

Appendixes

Appendix A

Process Activities of the Nanofab Program

Table A.1 presents information on process activities in the Center for Nanoscale Science and Technology's Nanofab program, described during the FY 2009 review by the Panel on Nanoscale Science and Technology.

Exclusive of the Nanofab presentation to the panel, eight processing activities were described: MEMS devices (#6, #12, #17); MEMS structure (#9); large linewidth structures >1 μm (#1, #16); e-beam patterned 25 nm lines (#8); and large linewidth (~5 μm) e-beam patterned electrodes (#4). The Nanofab presentation described an additional seven processing examples: five of the process examples were shown as SEMs with no technical details: MEMS device (#25) and patterned features <100 nm using e-beam lithography (#28, #29, #30, #31); two of these process examples were described in detail: FIB patterning of probe tips (#32) and e-beam patterned 100 nm gold islands (#33).

TABLE A.1 Nanofab Process Activities

Type of Project or Activity		NIST Process Item	Use of Nanofab
Electron Physics Group			
	Project:		
1	Nanomagnetics	Magnetic lines with edges, fabrication of magnetic nanodots	Yes
2	Modeling of Magnetics	None	No
3	Laser Controlled Atoms	None	No
4	Atomic Fabrication	Graphene structures with leads	Yes
Nanofabrication Group			
	Project:		
5	Electronic Nanodevices	Nanoscale shadow masks, graphene device fabrication, functional tip fabrication, polymer brush synthesis	Yes
6	Nanoplasmonics	Photo pressure cantilever	Yes
7	Nanophotonics	None	No
8	Directed Self-Assembly	25 nm lines	Yes
9	Directed Self-Assembly	Si_3N_4 membranes	Yes
10	Sublithographic Patterns	50 nm lines	No
11	Patterned Arrays	40 nm pitch dots	No
12	MEMS/NEMS	MEMS torque device	Yes
13	Nanofluidics NEMS	None	No
Energy Research Group			
	Project:		
14	Response in PV Materials	None to date	No
15	Thermionic Devices	None to date	No
16	CdTe PV Cells	Electrodeposited features	Yes
17	Precision Measurements	SOI cantilever device	Yes
Posters			
	Activity:		
18	Spin Torque Modeling	None	No
19	Graphene Measurements	None	No
20	Scanning Probe Microscopy	Scanning probes	Yes
21	Photoresponse in PV Materials	None	No
22	Particle Tracking	Etched silicon trenches	Yes
23	Plasmon Metrology	Photolithography	Yes
24	Tapered Optical Fibers	None	No
25	Fabrication for Graphene Measurements	Photo, e-beam lithography	Yes
26	Interference Lithography for Nanomagnetics	Photolithography, etching	Yes
Nanofab (Process Examples)			
	Activity:		
27	Gas Sensor	MEMS microscale	Yes
28	Nano Imprinting	Imprint feature	Yes
29	Molecular Transport	Nanopore devices	Yes
30	Nanostructures	Magnetic islands	Yes
31	AFM Standards	Patterned HSQ resist	Yes
32	AFM Tip Structures	Patterned AFM tip using FIB	Yes
33	SERS Array	Gold dot pattern	Yes

NOTE: MEMs, microelectromechanical systems; NEMs, nanoelectromechanical systems; PV, photovoltaic; SOI, silicon on insulator; AFM, atomic force microscope; HSQ, hydrogen silsesquioxane; FIB, focused ion beam; SERS, Surface Enhanced Raman Spectroscopy; SEM, scanning electron microscope.

Appendix B

Impressions Expressed by CNST Staff

During its review of the Center for Nanoscale Science and Technology, members of the Panel on Nanoscale Science and Technology had the opportunity to discuss the CNST with three groups separately: project leaders, postdoctoral researchers, and support staff. The following summary of impressions expressed by CNST staff members during those discussions are presented for consideration by the CNST management. These impressions are not presented here as conclusions or recommendations of the panel.

Project leaders noted that CNST staff are generally happy and the technical credentials of the CNST management are excellent. The project leaders praised CNST leadership for its conservative hiring policy, which preserves sufficient funding for equipment, supplies, and travel. Project leaders think that about 20 percent of the staff should be theorists. The CNST taps into expert knowledge outside the National Institute of Standards and Technology (NIST) through sabbatical appointments and other types of visits. Bringing in external experts by this method is encouraged. The current ratio of projects to senior staff is about 2:1 and is seen as appropriate.

Not all projects are active at the same time, and they are in varying levels of maturity. There are many interconnections among projects. The CNST has grown extremely quickly. The bureaucracy is minimal. The required project plans force principal investigators to think critically and to compare against worldwide effort. There is some difficulty in keeping up with the wide range of activities in the CNST. Informal discussions seem best for this, and more of these would be good. The institution of a coffee hour or other informal mechanisms would encourage networking.

The relationship between scientists and technical staff is fostered by a teamwork philosophy. Technical support staff are excellent and are involved in the work up to the level approaching actually doing science. Support staff are stretched very thin as the CNST has grown. There are very few “job shop” projects; when they exist, they naturally connect to industrial interests as they evolve. Project leaders are satisfied with the level of professional staff development in the CNST and believe that management puts a lot of effort into professional development and recognition. Staff are free to attend appropriate technical meetings. Senior staff are typically the ones who attend foreign meetings; attendance at domestic meetings is broader. There is an excellent seminar program. Continuity of postdoctoral researchers is a problem. They are extremely good and can disappear quickly. It is hard to keep the really good postdocs.

Fifteen CNST postdoctoral researchers participated in a separate discussion with panel members. Their tenure at NIST ranged from 1 week to about 2 years. While chemistry is frequently the centerpiece of nanoscience centers, at the CNST 14 of the 15 postdocs held a PhD in physics; the other held a PhD in chemistry (polymer chemistry). Gender diversity was nonexistent within the discussion group; all 15 were male.

The discussants uniformly expressed that they were happy overall. They were engaged in their research work; they felt intellectually challenged, respected by their supervisors, and supported by the CNST administration; they voiced only institutional gripes, not CNST-specific ones. Their concerns revolved around the procurement processes, problems of after-hours and weekend site access for noncitizens (approximately 30 to 40 percent of the total number of postdocs), and issues with barriers to migrating data home in order to do analysis work there.

These postdocs believed that they could make a case for pursuing new research directions and that there was a process in place for doing so. They felt more connected within the CNST research team than when they had belonged to larger university research groups in graduate school. They also commented on the rigor of the internal peer-review system for publications at NIST, and how it takes extra time but leads to a final document that is of the high standard for which NIST is recognized. Approximately 20 percent of the postdocs expressed a desire to be academics. Some wanted and liked the guidance, while others seemed content with the freedom that they had. In general, their environment seems to them to be more structured than in academia. They noted that there is no research ethics training, although the internal publications vetting program attempts to make sure that data handling is sound.

About 12 support staff members attended a separate luncheon discussion meeting with panel members. They expressed dedication to meeting and exceeding the expectations of their customers—both researchers and users. Some expressed a great need to hire more supporting staff in two areas—clean room and research laboratories—due to the rapid expansion of staff, facilities, and equipment. They noted that hiring in the areas of mechanics, process engineers, and technical administrators is particularly urgent and mentioned that the CNST director is aware of these specific needs.

The staff used to support fewer than 20 scientists and engineers, but they are now supporting more than double that number. In addition to providing technical support, the staff also have responsibilities related to property management and safety issues.

Continuing education, such as seminars and workshops, is available in-house for those who are interested. Support staff indicated that they do not meet formally, but they interact informally. They noted that NIST encourages staff to pursue advanced degrees. A couple of staff among the attendees have received MS degrees while working at NIST. Two staff cultures have merged in the CNST—the Nanofab and the Electron Physics Group. The Nanofab staff meet routinely. The Electron Physics Group staff do not meet routinely and would welcome more group meetings.