AN ASSESSMENT OF THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY

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Panel on Assessment of the Center for Nanoscale Science and Technology at the
National Institute of Standards and Technology

Committee on NIST Technical Programs

Laboratory Assessments Board

Division on Engineering and Physical Sciences

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PANEL ON ASSESSMENT OF THE CENTER FOR NANOSCALE SCIENCE AND TECHNOLOGY AT THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. 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:

Naomi J. Halas, Rice University,
James S. Harris, Stanford University,
Catherine J. Murphy, University of Illinois, Urbana-Champaign,
Julia M. Phillips, Sandia National Laboratories, and
Henry I. Smith, Massachusetts Institute of 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 David E. Crow, University of Connecticut, who 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.

Contents

Summary

In 2016, at the request of the Director of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine[1] formed the Panel on Assessment of the Center for Nanoscale Science and Technology at the National Institute of Standards and Technology (referred to in this report as "the panel") and established the following statement of task for the panel:

> An ad hoc committee will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Center for Nanoscale Science and Technology. The panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of the NIST laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment of the quality of the technical work performed at the Center.

The Center for Nanoscale Science and Technology (CNST) is one of two user facilities established by NIST, the other being the NIST Center for Neutron Research (NCNR), which is also located at the NIST facility in Gaithersburg, Maryland. The CNST has two components with complementary purposes—the research program, composed of three groups (Electron Physics, Nanofabrication Research, and Energy Research), which makes up the NanoLab, and the Nanofabrication Facility (NanoFab). Together, the NanoLab (with its next-generation tools and access to collaborative research with its multidisciplinary research staff) and the NanoFab (with its comprehensive toolset, which includes advanced capabilities for lithography, thin film deposition, and nanostructure characterization) make up the user facility. Individuals from beyond NIST and elsewhere at NIST can interact with the CNST through collaborations with the scientific research staff in the NanoLab's research program and through use of the NanoFab to fabricate structures or devices.

The mission of the CNST is to "operate a national, shared resource for nanoscale fabrication and measurement and develop innovative nanoscale measurement and fabrication capabilities to support researchers from industry, academia, NIST, and other government agencies in advancing nanoscale technology from discovery to production."[2]

GENERAL OBSERVATIONS

The CNST is a national asset with some leading-edge, best-of-kind equipment and extremely competent research and technical staff. Most of its programs are well conceived and have demonstrated impressive accomplishments. Some projects, however, are in fields that are led by other organizations (e.g., photovoltaics and nanobiomedical research), and this introduces the question as to why these CNST

[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

[2] National Institute of Standards and Technology (NIST), *Center for Nanoscale Science and Technology 2010,* NIST SP 1121, Gaithersburg, Md., March 2011, p. 4.

projects were brought into existence. Additionally, more effort needs to be put into improved strategic planning. While several groups and activities are organized properly, some projects are not placed logically; for example, nanobiomedicine is currently housed with the Energy Research Group (ERG). Some projects do not have sufficient synergy between objectives and resources; for example, the set of tools and skills developed in the Electron Physics Group (EPG) seems to be less suited to the stated goal of neuromorphic[3] device development (which includes building test circuits in the NanoFab and developing new microspecies to measure them) than to areas such as the fundamental physics of quantum systems or quantum computing.

Despite these issues, the majority of the staff, as well as the research conducted within the CNST, are excellent. The CNST, however, is not yet optimally serving the community of potential users. CNST management does not appear to have taken a proactive approach to publicize the availability of this national resource, which includes both staff and facilities, to the scientific and engineering community at large. It is very important that this be done. This could substantially increase productivity, as judged on the basis of publications, collaborations, and growth in users. The CNST could improve its visibility through greater presence at conferences and interaction with industry, striving for more external awards, and producing a larger number of high-quality publications.

The metrics for NanoFab usage and impact need to be more logical and transparent. The NanoFab needs to maintain accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.

Furthermore, the CNST could make a greater impact, particularly in the Washington, D.C., metropolitan area, since the NanoFab is operating well below capacity. The annual federal budget of the CNST was reported as $37 million, which includes $5 million for the purchase of equipment and service contracts. Revenues generated by the external users, which includes industry, academia, and other government agencies,were approximately $1.2 million in 2015, according to the data provided to the panel. This translates to less than 3 percent of the total budget. This appears to be very low given that the CNST is primarily a user facility.

Given that the CNST is a user facility, it may be useful to have an external advisory board of stakeholders that includes users—for example, faculty and laboratory directors from academia and industry, and others as appropriate. Such an advisory board might be especially valuable should user demand ever exceed the availability of equipment, and if the CNST were to develop a strategic plan for the expansion involving new equipment responsive to changing community needs. Additionally, the recommendations of the previous (2011) National Research Council assessment panel, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*,[4] do not seem to have been addressed by the CNST. Concerned that the recommendations of the current panel may be similarly ignored, the panel concluded that it would be important to conduct the next assessment within 2 years.

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[3] Neuromorphic systems are required to develop cognitive processors as well as to understand how the brain works and how to measure brain function and dysfunction. A NIST project in the Physical Measurement Laboratory utilizes superconducting single flux quantum (SFQ) and spintronics devices to mimic neural systems. These neuromorphic systems can operate a billion times faster than biologic neural systems. NIST is developing novel metrology, analogous to functional MRI, to measure synthetic cortical function. A key goal is to be able to measure spatial and temporal correlations in high-density spiking systems to understand memory and data processing in neural systems (from NIST, "Neuromorphic Systems," https://www.nist.gov/programs-projects/neuromorphic-systems, updated August 2, 2016).

[4] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*, The National Academies Press, Washington, D.C. 2011.

KEY CONCLUSIONS AND RECOMMENDATIONS

General Conclusions and Recommendations

NanoFab usage is well below capacity. The CNST management does not appear to have taken a proactive approach to publicize the availability of this national resource, which includes both staff and facilities, to the scientific and engineering community at large. It is very important that this be done. The metrics for NanoFab usage and impact need to be more logical and transparent. The NanoFab needs to maintain accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.

Recommendation 1: CNST management should take a proactive approach to publicize the availability of CNST resources and to increase the usage of CNST resources. CNST management should support this effort by maintaining accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.

Given that the CNST is a user facility, it would be useful to have an external advisory board of stakeholders, including users. This could include faculty and laboratory directors from academia and industry, and others as appropriate.

Recommendation 2: CNST management should consider establishing an external advisory board of stakeholders, including CNST users.

The recommendations of the 2011 NRC assessment panel do not seem to have been addressed by the CNST. Concerned that the recommendations of the current panel may be similarly ignored, it would be important to conduct the next National Academies assessment within 2 years.

Recommendation 3: CNST management should arrange the next National Academies of Sciences, Engineering, and Medicine assessment within 2 years.

The Nanofabrication Facility

The detailed quantitative information needed for the evaluation of the NanoFab was difficult to obtain during the review of the facility. This is unacceptable for a user facility with this level of federal support. Detailed tracking of all users is routinely done by leading research fabrication facilities, and it is an essential tool for understanding usage trends and making rational decisions about staffing, equipment upgrades, and new equipment acquisition. The NanoFab management needs to adopt similar practices, and if already implemented, to make the results available to reviewers in a timely manner.

Recommendation 4: CNST management should initiate a process that provides, maintains, and makes publicly available detailed data on all CNST users that identifies the number of facility users per equipment, their organizational affiliations, their fields of interest, the amount of income they provide to the CNST, and the outcomes of their facility utilization. NanoFab data should not be conflated with that of the NanoLab. The former consists of commercially available equipment designed to fabricate and measure micro- and nanostructures. The latter develops and hosts unique equipment, generally designed for exquisitely detailed measurements.

The NanoFab management has not yet begun significant recruiting efforts, and additional growth is possible because the facility is far from capacity. Approaching capacity is to be viewed as a positive goal—more users decrease idle equipment time, spreading costs more broadly. New users would also increase the impact of the facility.

Recommendation 5: The NanoFab management should begin an outreach program to recruit new users.

The CNST director and the staff expressed the desire to see more users from a broader range of disciplines and external organizations, particularly from industry; however, a strategic plan with a roadmap and metrics for achieving this goal was not articulated. Developing and applying metrics to manage operations would enable the benchmarking of performance against that of similar facilities and would also be a means of goal setting for strategic planning.

Recommendation 6: CNST leadership should define a strategic plan with a roadmap and associated metrics for the NanoFab and should benchmark NanoFab operations against those of other nanofabrication facilities.

Its high level of sustained funding and collaboration with the process research team gives the NanoFab the opportunity to be a leading national resource. They need to be more engaged with the fabrication community.

Recommendation 7: CNST management should become more outward looking and more broadly engaged with the fabrication community beyond the traditional mechanisms of research collaborations and peer-reviewed publications. CNST management should increase service in professional organizations, sharing of fabrication protocols, and proliferating best practices (such as the NanoFab Equipment Management Operation [NEMO]). CNST management should also consider playing a leadership role in the University/Government/Industry Micro/Nanotechnology (UGIM) Symposium and the National Nanotechnology Coordinated Infrastructure (NNCI) program.

Electron Physics Group

Questions remain regarding CNST's strategic priorities with respect to the EPG. The set of tools and skills developed in the EPG seems to be less suited to the stated goal of neuromorphic device development (which includes building test circuits in the NanoFab and developing new microspecies to measure them) than to areas such as the fundamental physics of quantum systems or quantum computing. The information processing domain represents an emergent opportunity and encompasses biomimetic and hybrid transdisciplinary approaches that transcend any single team's scope.

Recommendation 8: The Electron Physics Group and the CNST should consider how best to position its work on neuromorphic versus neuronal architectures and approaches to information processing.

EPG's ultralow-temperature scanning tunneling microscope (ULT-STM) represents a unique measurement and integrated sample and tip preparation infrastructure. The fundamental research using this tool needs to continue, along with work that enables further enhancements of this multimodal measurement tool.

Recommendation 9: The CNST should continue to support the ultralow-temperature scanning tunneling microscope (ULT-STM) for continued success.

EPG collaborations outside of NIST are overwhelmingly academic. In particular, there currently appear to be few EPG collaborations and weak linkages with industrial users. For example, participation in workshops that bring together scientific leaders and identify potential options that enable future strategic measurement challenges may help to catalyze the next generation of scientific inquiry. Additionally, increasing engagement with external professional societies could increase the impact of the EPG investigators and the CNST.

Recommendation 10: The Electron Physics Group should increase its collaborative engagements with external users and its investment in external professional activities, such as conference organization, editorships, or society governance.

Energy Research Group

The ERG has very good scientific expertise, facilities, and equipment. The exclusive focus on energy may not be appropriate, given the range of related research topics and proposed future initiatives. Long-range strategic planning for the group was not clearly articulated, nor was it apparent in discussions. The ERG needs to develop a strategic plan to outline intended directions for the coming year and into the following 5 years.

Recommendation 11: The CNST should develop a strategic plan that reconsiders the mission and research focus of the Energy Research Group to more accurately reflect its breadth of research activities. As part of this effort, the CNST should consider whether there is sufficient "customer pull" for continued, significant efforts in photovoltaics.

ERG personnel are well qualified and active, with a good record of publications and involvement in the technical community. The ERG, however, is small and its staff are highly specialized. Opportunities for growing the group in more general directions need to be considered.

Recommendation 12: The CNST should evaluate the staffing of the Energy Research Group in terms of alignment with its mission and ability to carry out that mission. The CNST should strive for group staffing levels with sufficient critical mass to address important measurement challenges commensurate with its mission and strategic directions.

Research being conducted at the ERG is of high quality. The researchers need to enhance collaborations with external users. This will lead to increased visibility of ERG researchers. This will also lead to greater use of this valuable national resource.

Recommendation 13: The Energy Research Group researchers should become more engaged in the professional community via society committees and trade associations.

Nanofabrication Research Group

The diversity and quality of user-driven research projects under development in the NRG demonstrate the excellent scientific and technical expertise this group provides. It is difficult, however, to identify the alignment of the existing research activities with the group's mission. This current disconnection makes it difficult to assess the projects relative to the mission.

Recommendation 14: The Nanofabrication Research Group should redefine its mission to align it to the group's existing research or, if it does not have the flexibility to redefine its mission, it should realign the research projects to the current mission.

In line with the NRG's mission, the NRG needs to enhance engagement with the fabrication community through talks at conferences, organizing workshops and conference sessions, and society service.

Recommendation 15: The Nanofabrication Research Group (NRG) should increase engagement with the fabrication community through strategic presentation of talks at conferences, organizing of workshops and conference sessions, and society service. The NRG should consider convening or participating in existing industry/academic/government consortia. One such example is the Microphotonics Center at the Massachusetts Institute of Technology, which sponsors a road-mapping activity and has spring and fall meetings. The NRG should consider building a similarly vibrant community around its strengths in nanoelectromechanical systems, precision measurement, and/or atomic scale microscopy.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Academies of Sciences, Engineering, and Medicine[1] has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering communities to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now seven,[2] as well as the adequacy of the laboratories' resources.

At the request of the Director of NIST, in 2016 the National Academies formed the Panel on Assessment of the Center for Nanoscale Science and Technology at the National Institute of Standards and Technology and established the following statement of task for the panel:

> An ad hoc committee will assess the scientific and technical work performed by the National Institute of Standards and Technology (NIST) Center for Nanoscale Science and Technology. The panel will review technical reports and technical program descriptions prepared by NIST staff and will visit the facilities of the NIST laboratory. Visits will include technical presentations by NIST staff, demonstrations of NIST projects, tours of NIST facilities, and discussions with NIST staff. The panel will deliberate findings in a closed session panel meeting and will prepare a report summarizing its assessment of the quality of the technical work performed at the Center.

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 scientific and technological advances, and to improve and refine existing measurement methods and services.

NIST specified that the following areas of work at the Center for Nanoscale Science and Technology (CNST) would be reviewed: the NanoLab research program, which is composed of three groups (Electron Physics, Energy Research, and Nanofabrication Research) and the Nanofabrication facility. To accomplish the assessment, the National Academies assembled a panel of 12 volunteers whose expertise matched that of the work performed by the CNST staff.[3]

On May 2, 2016, the panel assembled at the NIST facility in Gaithersburg, Maryland, for a two and a half day assessment, during which it received welcoming remarks from the CNST director, heard overview presentations by CNST management and presentations by researchers at the CNST, toured portions of the CNST facility, and attended an interactive session with CNST management. The panel

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[1] Effective July 1, 2015, the institution is called the National Academies of Sciences, Engineering, and Medicine. References in this report to the National Research Council are used in an historical context identifying programs prior to July 1.

[2] The seven National Institute of Standards and Technology (NIST) laboratories are the Engineering Laboratory, the Physical Measurement Laboratory, the Information Technology Laboratory, the Material Measurement Laboratory, the Communication Technology Laboratory, the Center for Nanoscale Science and Technology (CNST), and the NIST Center for Neutron Research.

[3] See the NIST Center for Nanoscale Science and Technology website at http://www.nist.gov/cnst/ for information on CNST organization and programs (accessed May 17, 2016).

also met in a closed session to deliberate on its findings and to define the contents of this assessment report.[4]

The panel's approach to the assessment relied on the experience, technical knowledge, and expertise of its members. An exhaustive assessment of every activity at the CNST was not feasible. The panel's goal was to provide an overall assessment of accomplishments, challenges, and opportunities for improvement in the CNST. To accomplish its mission, the panel reviewed the general background material provided by the CNST and examples of technical research and other major activities. The choice of projects to be reviewed was made by the CNST. These examples were intended collectively to portray salient activities of the center while also allowing for useful suggestions specific to the projects and programs that the panel examined. The panel applied a largely qualitative, rather than quantitative, approach to the assessment.

Given the necessarily nonexhaustive nature of the review, the omission in this report of any particular CNST project should not be interpreted as a negative reflection on the omitted project.

[4] The agenda for the assessment meeting is presented on the website of the National Academies at http://www8.nationalacademies.org/cp/projectview.aspx?key=49707.

2

The Nanofabrication Facility

SCOPE AND MISSION

The role of the Nanofabrication Facility (NanoFab) in the CNST mission is to provide "economical access to and training on a commercial state-of-the-art tool set."[1] More specifically, the NanoFab is intended to perform the following functions:

1. Provides access to state-of-the-art, commercial nanoscale measurement and fabrication tools and methods, along with associated technical expertise, in a shared-access, shared-cost environment to industry, academia, NIST, and other government agencies;
2. Enables processing and characterization of a wide range of nanoscale materials, structures, and devices critical to the nation's measurement and technology needs; and
3. Fosters internal collaboration in nanotechnology across NIST's laboratories and external collaboration with NIST's partners through its shared environment.[2]

These mission statements are consistent with the statements on NIST's website that the NanoFab

> supports the development of nanotechnology from discovery to production. The Center [for Nanoscale Science and Technology—CNST] operates a national shared-use nanofabrication and measurement facility, the NanoFab, complemented by a multidisciplinary research staff are creating the next generation of tools needed to advance nanotechnology.[3]

STAFFING

The NanoFab Operations Group consists of 21 people—a manager, 2 assistant managers, 6 process engineers, 3 microscopists, 2 user coordinators, 6 technicians (which includes 4 equipment engineers), and an administrative specialist. Of the process engineers, 3 hold doctorates in science or engineering, and 3 hold masters degrees. This represents an increase of 4 positions since the 2011 National Research Council (NRC) assessment.[4] The group has, collectively, slightly more than 200 person-years of experience. In addition, the NanoFab draws on CNST support staff, who provide operational infrastructure, such as administration, information technology, facilities, and engineering. This is a reasonable level of staffing given the mission and scope of the facility.

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[1] NIST, "Center for Nanoscale Science and Technology" http://www.nist.gov/cnst/, accessed June 10, 2016.

[2] Vincent Luciani, NanoFab Operations Manager, CNST, NIST, "Overview of the NanoFab Operations Group," presentation to the panel, Gaithersburg, Md., May 2, 2016.

[3] NIST, "User Facilities" http://www.nist.gov/user-facilities.cfm, accessed June 10, 2016.

[4] National Research Council (NRC), *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*, The National Academies Press, Washington, D.C., 2011.

Process engineers are responsible for approximately 11 tools each. On those tools, they provide training, develop processes, and provide process services for remote users. In addition, they consult with users to help them develop processes or integrate processes to fabricate a desired structure. One of the process technicians works in the evening to provide onsite user support and to perform remote user support. A second process technician performs tool maintenance in the evenings. The facility relies heavily on external maintenance support through contracts on 10 of the 100 tools. In addition, the facility uses outside consultants to support annual safety audits. The NanoFab manager justifiably puts considerable emphasis on laboratory safety.

Staffing and equipment have increased since the 2011 NRC assessment in a way that seems commensurate with the expanded scope of work. Based on the growing numbers of research participants over the past few years, it would be expected that the staffing and equipment set would continue to grow accordingly, to fill what appears to be available space in the cleanroom and adjacent laboratories.

ALIGNMENT WITH MISSION

Consistent with the observation in the 2011 NRC assessment, the NanoFab operation, with its excellent facility and staff, is well aligned with the mission to serve as a national user facility. The presentations provided during the review showcased how these facilities were leveraged to support NIST research projects and industry and, through collaborations, academia. Performance against mission objectives was difficult to assess because a detailed strategic plan with a roadmap and performance metrics was not presented to the panel. Only limited user information was provided, as discussed below.

QUALITY OF RESEARCH AND FACILITIES

The CNST facility is equipped to support a broad range of research activities, including many materials and substrates. This requires a highly flexible tool set that can handle anything from 1 cm samples to full 200 mm wafers. In that respect, it is reasonable to compare the facility to those found in leading research universities. One would see similar equipment at Cornell University or Stanford University. The CNST facility has somewhat more equipment and gives users access to a few higher-end capabilities, but the difference is not dramatic.

Overall, the NanoFab tool set is robust. The lithography capabilities are strong, with standard contact printing, an i-line ASML stepper, direct write optical, and two JEOL 6300 electron-beam lithography systems. An array of resist-processing equipment exists, including an unusual resist-dispense system that supports highly nonplanar substrates. The NanoFab has multiple dual-beam, focused-ion beam systems that are used for fabrication and transmission electron microscope (TEM) sample preparation. The NanoFab hosts multiple field emission scanning electron microscopes (FE-SEMs) and an FEI Titan S/TEM for extreme (<0.2 nm) resolution microscopy. Other tools include several thin film deposition systems, including an impressive physical vapor deposition (PVD) system capable of ultra-flat interfaces of metals and oxides. A soft lithography bay is currently being set up.

The current capability of the facility is somewhat above the leading university fabrication facilities, and tool acquisition is continuing at a strong pace. The NanoFab is on a path to become one of the best fabrication laboratories in the country that are open to outside researchers. A key distinguishing feature of the CNST facility is the pervasive use of statistical process monitoring. All of the major tools had charts showing the history of some standard process results. This helps to provide more consistent process results, although it requires routine running of standard processes, and so adds cost.

Examples of several user projects were given during the review. These included several that required considerable process development and/or unusual capabilities.

One issue facing university and other small fabrication facilities is the dearth of laboratory management platforms that can support a large, shared-use facility in a way that is compliant with respect to cost and to network security and versatile enough to accommodate the multitude and variety of user transactions. The commercial options are vulnerable, one-person operations. Many fabrication facilities have resorted to in-house software development, which is challenging and beyond the financial wherewithal of most. With in-house software development resources, the NanoFab staff have developed the most advanced, elegantly designed in-house laboratory management system that the panel has seen. The system is compliant with even the stringent security constraints of NIST. Moreover, in contrast to the monolithic design of most available laboratory management systems, the NanoFab Equipment Management Operation (NEMO) was built using current software development methods. It is module-based, making it easy to modify, upgrade, and maintain. The CNST would do the country well by making NEMO available to the fabrication research community.

URGENT NEED FOR EVALUATION OF THE NANOFAB AS A USER FACILITY

As noted in the 2011 NRC assessment, the NanoFab and its highly skilled staff are responsible for a major advance in the research capabilities of the CNST. The NanoFab and its staff address the core mission of operating a shared-use facility. Facility usage was difficult to assess, because the information provided by the CNST director was insufficient. When pressed on this point, he provided some additional information, but detailed analysis was difficult because the information was partial and provided only at the last minute, and there was insufficient opportunity to ask follow-up questions.

Considering the limited information that was provided, the following represents an attempt to benchmark the CNST NanoFab against the National Nanotechnology Infrastructure Network (NNIN) facilities, which are reasonably comparable in mission, size, staffing, and number of tools. The former NNIN consortium of 14 national user facilities collected user statistics over its 12 years of operation. Over the course of the NNIN, seven of the sites built new facilities or joined with new facilities. They aggressively marketed themselves following the open, shared-use model that has been demonstrated to be an effective way to cultivate a critical mass of users. For each of the new NNIN facilities, the user base was largely established in 5 years, with growth slowing thereafter. The CNST NanoFab has been in operation for about 9 years, and the expectation is that this would have provided sufficient opportunity to establish the bulk of its user base.

Without the needed data, it was difficult to determine how much capacity is available; however, during a nearly hour-long in-laboratory tour in the middle of the day, only one non-staff person was observed. Furthermore, in comparison to similarly sized NNIN facilities, the user base numbers are much lower, by at least 25 percent and perhaps up to 300 percent. This leads to the conclusion that despite its enviable location and advanced capabilities, the CNST NanoFab is not aggressively recruiting new users, particularly external ones. This conclusion was confirmed by comments made by the CNST management during the review.

A more reliable source of data is user fee income, which captures both user number and use intensity for both local and remote users. With a current operating budget of about $7 million, about half is provided by user fees. This is a reasonable balance, judging by the experience of NNIN facilities. External NanoFab income has increased significantly since 2011 and is now approximately $1.2 million per year. Income from NIST sources outside of the CNST has declined somewhat over the same period. The fiscal year (FY) 2015 users fees came from the following sources: $1.5 million from users employed by CNST, $0.9 million from users employed by NIST (outside of the CNST), and approximately $1.2 million from users external to NIST. Overall, the user fee income is increasing by about 10 percent per year; however, this was heavily influenced by a large spike in CNST usage in FY2015. Ignoring that spike, total user fee income has been nearly flat since the NRC assessment in 2011.[5]

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[5] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*, The National Academies Press, Washington, D.C., 2011.

The NanoFab is a key asset for the CNST and the Washington, D.C., area. Proximity to a large number of universities, major agencies such as the National Institutes of Health (NIH), and a significant number of companies, all of which have little or no capabilities in nanoscale fabrication and characterization, makes the CNST NanoFab a tremendous potential asset for economic development and training of nanoscale researchers in the region. Furthermore, given its level of support and access to the process research team, it could become a national resource for research fabrication facilities. Considerations pertaining to the NanoFab and its management are summarized below.

The detailed quantitative information needed for evaluation of the NanoFab was difficult to obtain. This is completely unacceptable for a user facility with this level of federal support. The lack of evidence of external users during the review tour, combined with the opacity of the data given, creates an impression that the picture being provided was overly optimistic. The NanoFab needs to maintain and freely provide accurate year-to-year data on the number of users, the sources of these users, and the amount of user income. The latter provides the most unambiguous measure of facility usage. Furthermore, to provide an accurate assessment of the NanoFab, this data cannot be conflated with that of the NanoLab. The former consists of commercially available equipment designed to fabricate micro- and nanostructures. The latter develops and hosts unique equipment, generally designed for exquisitely detailed measurements.

If it has not already done so, the NanoFab needs to start a process that provides a detailed tracking of all users to determine their origin and their fields of interest (microelectromechanical systems [MEMS], materials, electronics, etc.). Laboratory operating software can then be used to determine laboratory usage by group. This is routinely done by leading research fabrication facilities, and it is an essential tool for understanding usage trends to make rational decisions about staffing, equipment upgrades, and new equipment acquisition. Furthermore, polling of users is essential and needs to be done regularly. The difficulty experienced by the panel in getting this data is a glaring deficiency.

The NanoFab management needs to begin an outreach program to recruit new users. Since they have not yet begun significant recruiting efforts, additional growth is possible. More users decrease idle equipment time, spreading costs more broadly. They also increase the impact of the facility. Contrary to the evaluation provided to the panel, the panel assesses that the laboratory is nowhere near capacity. Approaching capacity is to be viewed as a positive goal and would yield an increased impact. Furthermore, the NanoFab can increase staffing levels and/or add equipment or start to attract more external users by the quality of the projects.

The demonstration of support for industry users that distinguishes the NanoFab from university facilities is encouraging. More rigorous process control provides more reproducible processes that enable commercial success for companies. This comes with an increase in user rates relative to university laboratories. For example, the NanoFab electron-beam lithography rates, even subsidized, are 2 to 3 times those of comparable machines at universities. Concerns were raised about the application of the NIST subsidy to private companies. In the Department of Energy (DOE) model, companies are given access free of charge, but applications go through a reasonably rigorous external review process. The current CNST review process appears to be cursory. This can be an issue, especially if the facility begins to approach capacity and starts to become more selective.

The leadership needs to define a strategic roadmap for the NanoFab. The CNST director and the staff expressed the desire to see more users from a broader range of disciplines and external organizations, particularly from industry, given the association with the Department of Commerce (DOC); yet the action plan and metrics for success were not articulated. Developing and incorporating metrics to manage operations would enable the benchmarking of performance against that of similar facilities and would also be a means of goal setting for strategic planning.

The laboratory needs to continue drawing down resources devoted to complementary metal-oxide semiconductor (CMOS) technology because research in this area has declined sharply. Support for the new nanobiomedical area will be required, but details of the nature of this support are difficult to predict at this time due to the embryonic nature of the current effort. The investment of CNST resources to recruit a leading researcher to break new ground in the nanobiomedical area for the NanoLab is acknowledged;

however, the NanoFab only needs to look to similar facilities in universities where nanobiomedical research is taking hold, or to engage with NIH, to learn which equipment and processes are most needed to support research efforts in this area.

Its high level of sustained funding and collaboration with the process research team gives the CNST NanoFab the opportunity to be a leading resource in the country. As such, they need to be more outward looking and more broadly engaged with the fabrication community beyond the traditional mechanisms of research collaborations and peer-reviewed publications, through service in professional organizations, sharing fabrication protocols, and proliferating best practices (such as NEMO). Playing a highly visible role in University/Government/Industry Micro/Nanotechnology (UGIM) Symposium and the National Nanotechnology Coordinated Infrastructure (NNCI) are two possible avenues. An effort to make the CNST process detail readily available for publication in the NIST research journal is an excellent idea, as is the lithography toolbox developed by a project leader in the NRG. Still, distribution mechanisms need to be developed if the work is to have any impact. NIST could do the nanofabrication world a great service by playing a leading role in developing and propagating fabrication research processes and practices.

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The Research Program

The CNST's research program is composed of three groups that make up the NanoLab: the EPG, the ERG, and the NRG.

ELECTRON PHYSICS GROUP

Introduction

The research effort in the EPG is largely unchanged since the 2011 NRC assessment.[1] The group performs five well-defined projects: scanning probe microscopy; nanomagnetic imaging; nanomagnet dynamics; theory, modeling, and simulation; and novel ion sources. These activities are supported by a team comprising eight researchers with expertise in electronics, equipment design, and information technology. The EPG focuses on the development of enabling metrological tools and fundamental research in the field of nanoscale electronics.

Assessment of Technical Programs

Accomplishments

The research effort in scanning probe microscopy involves unique instrument design and is among the best in its field. Driven by the necessity to understand the low-temperature physics of quantum, strongly correlated, and low-dimensional materials, comparable tools to those at NIST have been developed worldwide. The set of tools developed at NIST, however, offers noise performance that is orders of magnitude above these competing efforts. This performance is enabled by the unique instrument design and low-noise facility developed by NIST. This tool set also allows a broad spectrum of physical studies, enabled by independent control of the (vector) magnetic field, gate bias, and probe bias.

The seamless integration between the imaging facility and the in situ sample preparation enables the study of a broad range of functional materials beyond the classical cleavable samples, such as graphene, high-temperature superconductors, or layered correlated oxides. The scientific output made possible by these unique instruments is extremely impressive. It has enabled multiple collaborative works published in top scientific journals, and several notable results are, potentially, of textbook quality. The EPG has a measured and consistent plan for future instrument development that incorporates force-based detection. This may facilitate collaborations in unexplored areas of fundamental physics research.

The research in nanomagnetic imaging and nanomagnet dynamics is equally impressive. One project leader is a pioneer in scanning electron microscopy with polarization analysis (SEMPA), and another leads a commendable program in diamond nitrogen-vacancy center (N-V center) magnetometry and magneto-optical measurements. This combination of techniques is unique to NIST and provides the

[1] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011,* The National Academies Press, Washington, D.C.

NIST community with a special set of tools for probing static and dynamic domain structures. The team focused on theory provides the necessary theoretical support to enable a smooth transition from measurement results to domain-specific knowledge.

The effort that is focused on the development of novel ion sources for ion-beam-based fabrication and imaging requires a long-term dedicated effort. The effort contributes to the development of the next generation of imaging and fabrication capabilities for fundamental and applied science. There has been a successful transition of some developed technologies to commercial settings.

Research efforts in the EPG have focused on quantum and low dimensional systems, nanomagnetic phenomena, and ion beam science. These efforts match with the NIST strengths in nanoscale measurement device fabrication; characterization and metrology; broad magnetic device-based metrology; and the emerging area of functional ionic devices, including energy research and neuromorphic computing.

Opportunities and Challenges

Questions remain regarding CNST's strategic priorities with respect to the EPG. The set of tools and skills developed in the EPG seems to be less suited to the stated goal of neuromorphic device development (which includes building test circuits in the NanoFab and developing new microspecies to measure them) than to areas such as the fundamental physics of quantum systems or quantum computing. The EPG and CNST need to consider how best to position its work on neuromorphic versus neuronal architectures and approaches to information processing. The information-processing domain represents an emergent opportunity and encompasses more biomimetic and hybrid transdisciplinary approaches that transcend any single team's scope.

The research efforts in the EPG provide significant unexploited opportunities for growth. The output of the group has been fairly constant over the past decade, owing to the numerous opportunities forged by the need for high-resolution and high-veracity imaging, metrology, and atomic manipulation. Opportunities have also been driven by the fact that semiconductor technology crossed below the 10 nm threshold. There is potential for rapid growth in the emergence of quantum computing and other single-atom devices as well as magnetoelectronic and spintronic devices.

Portfolio of Scientific Expertise

The staffing and composition of the EPG is largely unchanged since the NRC 2011 assessment.[2] EPG research encompasses scanning-probe microscopy; nanomagnetic imaging and dynamics; theory, modeling, and simulation; and laser manipulation of atoms. The EPG conducts a wide range of cross-disciplinary research that focuses on developing innovative measurement capabilities for nanotechnology, with an emphasis on future electronics applications. The research conducted by this group is uniformly of a very high standard. The EPG is developing impressive measurement tools and methods.

Adequacy of Facilities, Equipment, and Human Resources

Accomplishments

The EPG consists of 17 scientific staff (5 project leaders, 9 postdoctoral researchers, 1 staff scientist, and 2 students). It also has 8 support staff (2 in electronics, 2 in instrumentation, and 4 in information technology). Although the support staff is attached to the EPG, they provide support for all of

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[2] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology,* 2011, p. 11.

the CNST research groups. Senior staff of the EPG have been in place for several years. The integration of postdoctoral researchers into projects is smooth, and there appears to be collaboration and communication across research areas and across groups. The input of the support staff is very important to these efforts, given the fact that much of the equipment is home-built. Staffing is uniformly adequate across areas.

The unique modifications being developed to support CNST's world-leading scanning-probe microscopy research will combine a scanning tunneling microscope (STM) with an atomic force microscope (AFM) at cryogenic temperatures (10 mK) and a range of ultrahigh vacuum (UHV) sample-preparation chambers.

The EPG has also developed superb tools that support research on nanomagnetism, including imaging using SEMPA, measurements of magnetic dynamics, and new work on magneto-optical ferromagnetic resonance. The group continues to work on the development of new ion sources for focused ion beams to improve imaging, nanoscale milling, circuit editing, and nanoscale implantation.

Opportunities and Challenges

EPG's ultralow-temperature scanning tunneling microscope (ULT-STM) represents a unique measurement and integrated sample and tip preparation infrastructure that needs to be funded for continued success. The fundamental research in this area needs to continue, along with work that enables further enhancements of this multimodal measurement tool.

Dissemination of Outputs

Accomplishments

Based on information provided by NIST along with *Web of Science* searches, the EPG's five project leaders published more than 50 papers between 2012 and 2015. Many of these papers involved more than one project leader along with postdoctoral researchers. These papers—approximately one-fifth of the total CNST publications for that period—were often published in excellent journals such as *Physical Review Letters* and *Applied Physics Letters*. These papers are also highly cited by their peers.

Opportunities and Challenges

While the papers published by the EPG are excellent, it is expected that a group of this size, with the remarkable experimental capability available to them, would have many opportunities to exploit this capability and publish much more. While maintaining quality is of central importance, there is room for a more aggressive approach to publishing. In particular, EPG collaborations outside of NIST are overwhelmingly academic, and there is opportunity to reach into the commercial community for collaborations as well.

Furthermore, given its collective creativity, infrastructure, and resources, the EPG could increase its output of foundational publications that further enhance the basic understanding of innovative single and multimodal nanoscale measurement methods and tools beyond current capabilities.

The EPG could also beneficially increase its emphasis on collaborative engagements with external users; there currently appear to be few collaborations and weak linkages with industrial users. Workshops that bring together scientific leaders and identify potential options that enable future strategic measurement challenges may help to catalyze the next generation of scientific inquiry. The EPG also does not appear to be particularly active in external professional society activities in a significant way. This includes conference organization, editorships, or society governance. While EPG staff members have received significant DOC recognition, it appears that the group has not received society awards and other peer recognition for their work to the extent that they could. Greatly increasing the investment in external professional activities would enhance the recognition and impact of the investigators and of the CNST.

ENERGY RESEARCH GROUP

Introduction

The mission of the ERG was stated as follows:

> Working with facility users, develop new measurement methods in the areas of energy generation, conversion and storage, focusing on correlation of atomic and nanoscale structural and morphological properties of materials and devices with functional performance.[3]

The ERG aims to accomplish this mission through addressing the

> unmet needs of users focusing on cross-cutting measurement challenges brought forward by energy materials and devices and leveraging broader CNST and NIST expertise. Use novel fabrication methods to enable new measurements.[4]

The evaluative comments and suggestions from the 2011 NRC assessment are presented below. It is particularly noteworthy that the comments made 5 years ago remain very relevant today, and little or no progress in the suggested directions was apparent from the documents, presentations, and discussions associated with the current assessment.

> The ERG is still very young. It is too early to judge the quality of the staff with accuracy, and it is even somewhat difficult to gauge the alignment of the work with the mission of the group and the mission of the CNST, as many laboratories are still under development. Over the next 2 years, the group needs to establish greater coherence, accompanied by the development of a stronger connection between nanoscale measurements and important problems in energy. The ERG is still in the process of growth and stabilization. The following are suggestions for the ERG as it moves forward:
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> - Over the next 2 years, it should establish greater coherence, accompanied by the development of a stronger connection between nanoscale measurements and important problems in energy.
> - Although the new laboratories are outstanding, most of the equipment is commercial or modified-commercial. As the group continues to mature, it should aspire to the design and fabrication of some noncommercial equipment to address the frontier of nanoscale measurements connected to energy.
> - Long-range strategic planning for the group was not apparent and needs to be discussed more explicitly during the next assessment.
> - The CNST should continue the effort to mature the focus and stature of the newer research groups, especially the ERG. This effort would include more strategic planning and the identification of research issues of central importance to the energy landscape in the United States.[5]

[3] N. Zhitenev, CNST, NIST, “Energy Research Group Overview,” presentation to the panel, Gaithersburg, Md., May 2, 2016.

[4] Ibid.

[5] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology,* 2011, p. 17.

Assessment of Technical Programs

Accomplishments

The ERG has been actively working on a few research topics. The group has been collaborating with researchers from academia, and these collaborations have been very fruitful because the expertise and facilities at the CNST are unique and most universities do not have such facilities. Two examples are their collaborative papers on fuel cell materials and lithium-ion batteries. High-resolution transmission electron microscopy (HRTEM) contributions by the ERG researchers have been important to the effort to explain the fundamental properties of oxygen ion conductors (solid oxide fuel cells) and the intercalation properties of certain oxides (lithium ion batteries). Noteworthy accomplishments include the three-dimensional re-construction of a fuel cell cathode using focused ion beams and tomographic microscopy and work on optical probing of cadmium telluride (CdTe), published in *ACS Nano*.[6] By probing the structure of solar cells at relatively large depths, the latter provides important insights that are not possible by typical surface characterization methods.

Opportunities and Challenges

There are several other current energy topics that can utilize the ERG expertise. For example, virtually all electrochemical devices with solid-state materials are based on nanostructured materials (polymer electrolyte membrane [PEM] fuel cells, super-capacitors, etc.). ERG researchers need to be proactive in communicating their expertise and the availability of their facilities to researchers from other organizations, especially academia. Examples include the design and synthesis of core-shell catalysts for PEM fuel cells and nanostructured composite electrodes for solid-oxide fuel cells.

There is some question about the title and charge of the ERG. The intent of the CNST to establish a group with a specific focus on the important aspects of energy technology associated with the NIST charge is commendable. The charge and scope of the ERG, however, is not entirely clear in the context of the total field of science and technology associated with energy in the United States and the context of the other agencies and organizations charged with various responsibilities in that technical area. The scope defined by the *Workshop on Nanoscale Measurement Challenges for Energy Applications*,[7] the *Grand Challenges for Advanced Photovoltaic Technologies and Measurement,*[8] and by the "input/requests from industry,"[9] listing "General Electric, Applied Materials, Northrop Grumman, Dow Chemical, QD Vision, Amprius, Clevious, Nantero, CuPont, Intel, etc."[10] was not specifically defined by the background material provided during the review.

Additionally, as a group focused on photovoltaics, ion transport, and solid-liquid interfaces, the ERG needs to be able to clearly differentiate itself from other very significant energy research efforts at many universities, national laboratories, and industry. For instance, how does the current effort in photovoltaics compare to the many photovoltaics efforts across the globe? What is the compelling reason for NIST to be a player in this already crowded field? The ERG has insufficient critical mass to make real and substantial impact in the range of energy topics covered.

The ERG has very good scientific expertise, facilities, and equipment. As currently constituted, the ERG efforts are focused and motivated by energy needs, including energy generation, conversion, and storage, to elucidate the role of atomic and nanoscale structure and morphology in the performance of

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[6] M.S. LeiteM. Abashin, H.J. Lezec, A. Gianfrancesco, A.A. Talin, and N.B. Zhitenev, "Nanoscale imaging of photocurrent and efficiency in CdTe solar cells," *ACS Nano* 8(11):11883-11890, 2014.

[7] Zhitenev, "Energy Research Group Overview," 2016.

[8] Ibid.

[9] Ibid.

[10] Ibid.

devices and materials. The ERG has successfully developed several techniques for imaging and measurements and have effectively used both in situ and ex situ measurements. In essence, it is characterizing nanomaterials and structures using multimodal techniques. The ERG is, however, below critical mass to make a significant impact on a sustained basis. The techniques that are currently being developed by the ERG are motivated by energy, yet they are relevant to a wide range of technologies. As such, the group may be missing significant opportunities to address issues associated with other economic sectors.

The exclusive focus on energy may not be appropriate given the range of related research topics and proposed future initiatives.

Long-range strategic planning for the group was not clearly articulated, nor was it apparent in discussions. The ERG needs to develop a strategic plan to outline intended directions for the coming year and into the following 5 years.

Portfolio of Scientific Expertise

Accomplishments

ERG researchers have been active in publishing in good-quality topical journals such as *Solid State Ionics* and some high-impact journals such as *Nanoscale, Nano Letters* and *ACS Nano*. They have facilities and expertise for probing at the nanoscale as well as, simultaneously, at the microscale in a chemically reacting system (e.g., growth of carbon nanotubes). This allows them to obtain information about structure at the nano level—without causing variances due to the probing itself—while, at the same time, obtaining relevant information about reaction mechanisms and kinetics. Many ERG researchers have been publishing in high-quality journals, and their work is well cited. Several ERG researchers have cumulative citations exceeding 5,000, and a few have in excess of 10,000 citations. This is a good indicator of scientific expertise as recognized by their peers.

Opportunities and Challenges

The CNST microscopy facilities are unique, and the high-temperature capability with variable atmosphere capability is also distinctive. ERG personnel are well qualified and active, with a good record of publications and involvement in the technical community. They are highly qualified to take advantage of the resources available; however, the group is small (six total) and highly specialized on an individual basis. Opportunities for growing the group in more general directions need to be considered.

The new nanobiomedical area that is being incubated within the ERG includes the recent recruitment of a project leader whose expertise is in nanofabrication and biological science.[11] While the nanobiomedical area is a growth area in research, it is unclear if it should become a part of the ERG. The connection to this area seems tenuous.

[11] Some of the areas of nanobiomedical research that this project leader and the ERG are focusing on include: developing new measurements that bridge nano/micro length scales; incorporating sensors and actuators; and detecting and quantifying the integration and disintegration of materials at biotic and abiotic interfaces (V. Szalai, CNST, NIST, "Nanobiomed: A New Strategic Direction for the CNST," presentation to the panel, Gaithersburg, Md., May 2, 2016).

Adequacy of Facilities, Equipment, and Human Resources

Accomplishments

The facilities appear to be appropriate for the small group with a focused scope of activity and, overall, appear to be excellent. In operando measurements are very difficult to make, and enabling equipment is not readily available to the public user. The CNST can play an important role in making equipment available. Morphology-specific measurement, especially for nonequilibrium processes, is also greatly needed by the user community, and the ERG seems to be supporting developments in that area.

Opportunities and Challenges

The CNST and the ERG have recently invested in a suite of soft materials tools that provide an exciting range of new opportunities related to soft materials fabrication. With the introduction of a soft lithography polydimethylsiloxane (PDMS) bench, a microfluidic inspection station, dynamic light scattering (DLS) instrumentation, and cryoTEM capability, the ERG has an opportunity to expand its role. The Washington, D.C., area is home to many small companies, government laboratories, and universities that may provide a host of new and exciting opportunities and challenges.

In particular, nanobiomedicine is one growth area that has been developed by CNST researchers and led by the ERG. The group will be challenged to provide a critical mass of expertise to attract a new user base and grow this potentially significant high-impact area. To be successful, the proposed new initiative in nanobiomedicine needs sufficient critical mass to make an impact.

The nanobiomedical area can gain from the development of measurement tools to view nanoscale events in real time and in three dimensions, without loss of macroscale information. A new hire in August 2016, and a new activity related to a “body-on-a-chip” platform with integrated nanosensors to measure physiological responses of tissues will be initiated. This represents an exciting opportunity that may lead to significant national and global impact.

As a user facility open to soft materials efforts, the ERG could be in a position to develop new measurements that bridge nano- and micro-length scales; incorporate sensors and actuators for optical, mechanical, and electrical interrogation; detect and quantify the integration and disintegration of materials at the biotic and abiotic interface; print or pattern in or on flexible, stretchable substrates other than PDMS; create nanosensors in a specific shape or position in or on a larger probe; and produce curved surfaces, curved patterns, or smooth gradients of materials.

The ERG needs to move far beyond the energy sector to contribute real and significant science and technology and to make economic impact in other sectors.

Dissemination of Outputs

Accomplishments

The ERG, which consists of 6 project leaders and 14 postdoctoral researchers, has been active in scholarly work; however, a list of the papers published since the 2011 NRC assessment[12] was not provided during the review. Also, since the CNST is a user facility, the accomplishments of the ERG, as well as the CNST as a whole, need to include publications generated by external users. Since such a list was missing in the materials provided during the review, it was difficult to assess productivity. According to the material provided, the number of researchers in all areas, including energy research, participating in

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[12] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology*, 2011.

activities that use the CNST facilities has increased from 192 in FY 2007 to 1,885 in FY2013. It would be important to know the corresponding increase in total publications, including those using CNST facilities, over the same period. The ERG has been actively engaged in the National Nanotechnology Initiative (NNI) and NIST initiatives, including the NNI Signature Initiative on Nanotechnology for Solar Energy Collection and Conversion and several of NIST's Innovation In Measurement Science programs. CNST staff are interacting with several industrial organizations, including General Electric, Applied Materials, Northrop Grumman, Dow Chemical, QD Vision, DuPont, and Intel, among others. This is a good user base foundation.

Opportunities and Challenges

Research being conducted at the ERG is of high quality. The researchers are encouraged to enhance collaborations with external users. Opportunities exist for increasing the use of the CNST by external users. Since it was stated during the assessment that, to date, only one user proposal has, on the basis of poor technical merit, been turned down, it would appear that there is scope for increasing the user base. Increased collaborations should result in increased numbers of publications by CNST scientists and increased visability of ERG researchers, which would raise the reputation and profile of the CNST as a whole and the ERG in particular. Enhanced collaborations will also lead to greater use of this outstanding national resource.

CNST staff publications since 2012 were identified during the review; however, the ERG did not provide a summary list of its specific output. This is a regrettable missed opportunity, because several of the publications from ERG members are of excellent quality and published in excellent journals.

Especially notable work includes the in situ analysis of battery materials with a specific focus on solid-liquid interface chemistry incorporating six-dimensional super-resolution microscopy. More specific annotation of the output to the community of that and other work would have been welcome during the review. The research in chemical imaging is good but not superb. The ERG does not have sufficient critical mass to make significant advances in a sustainable way. There are many opportunities to tie imaging with theory, which would have major impact, but those efforts need to be well integrated.

NANOFABRICATION RESEARCH GROUP

Introduction

The NRG has a stated mission of "working with facility users, develop new measurement methods to enable the development and effective industrial-scale use of nanomanufacturing and nanofabrication processes."[13] The group has grown slightly since the 2011 NRC assessment;[14] it currently consists of 8 project leaders, 3 staff scientists, a process engineer, and 17 postdoctoral researchers, with expertise that includes electron microscopy and nano-electromechanical systems.

The NRG has demonstrated scientific productivity, expressed eagerness to work with users, and uses the resources available in an effective manner. However, the scientific activities under way seem uncorrelated, making it difficult to identify the essence of the group. The NRG, and the CNST, can do a better job in formulating and articulating its core mission.

[13] NIST, CNST, *2015 Strategic Plan*, v.1.5, Gaithersburg, Md., August 31, 2015.

[14] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology*, 2011.

Assessment of Technical Programs

The NRG is involved in a wide array of projects. The independent researchers are very strong in their areas. *Google Scholar* profiles reveal that the five senior project leaders each have an h-index above 35 and more than 4,000 citations, which is one measure of visibility. From the project descriptions that were presented during the review, it was clear that they make effective use of the state-of-the-art nanofabrication facilities.

The project on super-resolution fluorescence microscopy for materials science exhibits exceptional real space resolution that is ideal for soft materials. The study focus is on the emission lifetime of molecules, which are sensitive to the local environment providing a sixth dimension of imaging. The project uses in situ/operando microscopy at the atomic scale. Although specific applications were not provided, possible applications for this research include studies of polymers, composites, and catalysis.

Another project, which is supported by theory, is the one-of-a-kind environmental TEM for dynamic and spectroscopic analysis of nanomaterials at the atomic scale. Work on this project is in an early stage of development.

The project on nanoplasmonic optomechanics is an exciting and unique approach to the use of plasmons. The project exhibits capability for both actuation and sensing of motion at unprecedented levels. It also has a capability for both electronic direct current (DC) and optical alternating current (AC) operation and has the potential to demonstrate faster and denser spatial light modulators.

The work on motion detection and calibration for MEMS and nanoelectromechanical systems (NEMS) is an impressive demonstration of capability. Going forward, a comparison to existing technologies commercially available (PolyTec) would be useful.

The project on advancing nanoparticle manufacturing exhibits a good understanding of the challenges currently limiting the manufacturing of nanoparticles. The project staff is working with experts from industrial, governmental, and academic sectors to address technical challenges. While not explicitly mentioned, the expectation is that pharmaceutical companies would be particularly interested in this capability.

The Nanolithography Toolbox represents the development of an extremely valuable tool for computer-aided designing (CAD-ing) and layout of complex lithography patterns used in the micro- and nanofabrication of a wide variety of devices (in particular photonic devices, where smooth curves are key for low loss). The toolbox is filling an important need of the nanofabrication community, and it is enhancing the CNST user experience.

The project on nanophotonic device development for metrology represents state-of-the-art nanophotonic devices applied to the development of chip-scale atomic clocks and optical frequency combs. This project is an excellent example of how CNST capabilities and scientists can enable NIST-wide projects.

The project on metamaterials represents promising early work on plasmonics and metamaterials. The NRG was a clear leader early in this area, although this leadership role has waned over the past few years. It would be useful for this project to identify new research directions or new collaborative opportunities inside and out of NIST.

For the project on high-speed manufacturing measurements, there was a lack of clarity about the relationship of this research to nanoscience and nanotechnology. Additionally, the impact of this work was not clearly explained. While there appears to be an attempt to be customer-focused, the choice of this project does not seem to be a good match with the staff’s strengths.

Portfolio of Scientific Expertise

Opportunities and Challenges

The diversity and quality of user-driven research projects under development in the NRG demonstrates the excellent scientific and technical expertise this group provides. The NRG has a challenge, however, because it is difficult to align the existing research activities with the mission. It is not known how much flexibility the NRG has to define its mission, but the current disconnection makes it difficult to assess the programs relative to the mission. If the flexibility exists, given its research strengths, a mission such as the following might provide the necessary alignment: developing tools for characterization of nanomaterials *and* using nanofabrication to develop new measurement and metrology tools. If it does not have the flexibility to redefine its mission, then the harder job of aligning the research projects to the mission needs to be addressed in the next strategic plan.

The SWOT (strengths, weaknesses, opportunities, and threats) analysis within the CNST *2015 Strategic Plan* was generally insightful, but had a couple of gaps. First, there is an issue with the definition of "research participants" that makes it challenging to get a clear view of the true NanoFab user base. While the information that was provided in response to questions regarding facility usage was illuminating, those data did not support the statement in the CNST *2015 Strategic Plan* that "by any measure the Nanofabrication facility is a success; its utilization continues to grow with each year."[15] Furthermore, it was learned during the review that the NanoFab is well below capacity; however, the *2015 Strategic Plan* identifies a different weakness that seems to be contradictory: "technical support services have not kept up with the general growth in CNST and may need a new management model."[16] Understanding the costs, technical staffing needs, and user capacity needs to be a top priority. In particular, the NRG could be more aggressively looking for opportunities for growth in its users aligned with the research activities that are identified in its strategic plan. In addition to the financial benefits, an increased user base from industry will both enhance the impact of the NRG and serve as a source of new and challenging problems.

The strategic plan could be strengthened by identifying meaningful metrics and plans to track those metrics. The tracking of those metrics will be invaluable information for the next assessment panel.

Adequacy of Facilities, Equipment, and Human Resources

Accomplishments

The NRG is making great use of the NanoFab for the fabrication of its MEMS, NEMS, and nanophotonics devices. It is constantly evaluating the tool set, balancing the need for exploratory research and the need for process consistency to test designs. It has done a good job of keeping the tools up to date, sometimes by developing relationships with its tool vendors. For example, it has teamed up to develop the next-generation focused ion beam with FEI. Two capabilities that stand out are the environmental TEM and the Nanolithography Toolbox, a very useful design tool that could have impact beyond the CNST and its users. Additionally, the NRG is doing an excellent job of hiring nanofabrication experts to aid both facility users and CNST staff.

[15] NIST CNST, *2015 Strategic Plan*, 2015.
[16] Ibid.

Dissemination of Outputs

Accomplishments

As already noted, many of the individual researchers in the NRG have good outside recognition of the quality of their work, as evidenced by their citations and name recognition. The group members mentioned that they are looking for a way to disseminate the processing recipes for their technical advances, including, for instance, processing recipes for the gap-plasmon resonator. This activity is a very useful service.

Opportunities and Challenges

In line with the its mission, the NRG needs to spend more time "taking the pulse" of the community through strategically placing talks at conferences, organizing workshops and conference sessions, and society service. It will take focus and energy to engage industry. Industry, academic, and government consortia are one means. A very successful consortium in the photonics space is the Microphotonics Center at the Massachusetts Institute of Technology, which sponsors a road-mapping activity and has spring and fall meetings. The NRG could create a similarly vibrant community building on its strengths in NEMS, precision measurements, and/or atomic scale microscopy.

A list was provided of conference presentations given by NRG members over their careers. Although this list is quite long, the conference attendance seems to be somewhat random, and there was no mention of this in the CNST *2015 Strategic Plan*.[17] One way that the NRG (and the CNST) could increase its visibility is by being strategic with respect to conference attendance by identifying a few of the key conferences and having a large presence at these as opposed to small (and possibly) overlooked attendance at a much larger number of conferences. This strategy might also result in increased user interest.

[17] Ibid.

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Key Conclusions and Recommendations

The CNST is a national asset with some leading-edge, best-of-kind equipment and extremely competent research and technical staff. Most of its programs are well conceived and have demonstrated impressive accomplishments. Some projects, however, are in fields that are led by other organizations (e.g., photovoltaics and nanobiomedical research), and this introduces the question as to why these CNST projects were brought into existence. Additionally, more effort needs to be put into improved strategic planning. While several groups and activities are organized properly, some projects are not placed logically; for example, nanobiomedicine is currently housed with the Energy Research Group (ERG). Some projects do not have sufficient synergy between objectives and resources; for example, the set of tools and skills developed in the Electron Physics Group (EPG) seems to be less suited to the stated goal of neuromorphic[1] device development (which includes building test circuits in the NanoFab and developing new microspecies to measure them) than to areas such as the fundamental physics of quantum systems or quantum computing.

Despite these issues, the majority of the staff, as well as the research conducted within the CNST, are excellent. The CNST, however, is not yet optimally serving the community of potential users. CNST management does not appear to have taken a proactive approach to publicize the availability of this national resource, which includes both staff and facilities, to the scientific and engineering community at large. It is very important that this be done. This could substantially increase productivity, as judged on the basis of publications, collaborations, and growth in users. The CNST could improve its visibility through greater presence at conferences and interaction with industry, striving for more external awards, and producing a larger number of high-quality publications.

The metrics for NanoFab usage and impact need to be more logical and transparent. The NanoFab needs to maintain accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.

Furthermore, the CNST could make a greater impact, particularly in the Washington, D.C., metropolitan area, since the NanoFab is operating well below capacity. The annual federal budget of the CNST was reported as $37 million, which includes $5 million for the purchase of equipment and service contracts. Revenues generated by the external users, which includes industry, academia, and other government agencies,were approximately $1.2 million in 2015, according to the data provided to the panel. This translates to less than 3 percent of the total budget. This appears to be very low given that the CNST is primarily a user facility.

Given that the CNST is a user facility, it may be useful to have an external advisory board of stakeholders that includes users—for example, faculty and laboratory directors from academia and

[1] Neuromorphic systems are required to develop cognitive processors as well as to understand how the brain works and how to measure brain function and dysfunction. A NIST project in the Physical Measurement Laboratory utilizes superconducting single flux quantum (SFQ) and spintronics devices to mimic neural systems. These neuromorphic systems can operate a billion times faster than biologic neural systems. NIST is developing novel metrology, analogous to functional MRI, to measure synthetic cortical function. A key goal is to be able to measure spatial and temporal correlations in high-density spiking systems to understand memory and data processing in neural systems (from NIST, "Neuromorphic Systems," https://www.nist.gov/programs-projects/neuromorphic-systems, updated August 2, 2016).

industry, and others as appropriate. Such an advisory board might be especially valuable should user demand ever exceed the availability of equipment, and if the CNST were to develop a strategic plan for the expansion involving new equipment responsive to changing community needs. Additionally, the recommendations of the previous (2011) National Research Council assessment panel, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*,[2] do not seem to have been addressed by the CNST. Concerned that the recommendations of the current panel may be similarly ignored, the panel concluded that it would be important to conduct the next assessment within 2 years.

KEY CONCLUSIONS AND RECOMMENDATIONS

General Conclusions and Recommendations

NanoFab usage is well below capacity. The CNST management does not appear to have taken a proactive approach to publicize the availability of this national resource, which includes both staff and facilities, to the scientific and engineering community at large. It is very important that this be done. The metrics for NanoFab usage and impact need to be more logical and transparent. The NanoFab needs to maintain accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.

> **Recommendation 1: CNST management should take a proactive approach to publicize the availability of CNST resources and to increase the usage of CNST resources. CNST management should support this effort by maintaining accurate year-to-year data on the number of users, the sources of these users, and the amount of income derived from users.**

Given that the CNST is a user facility, it would be useful to have an external advisory board of stakeholders, including users. This could include faculty and laboratory directors from academia and industry, and others as appropriate.

> **Recommendation 2: CNST management should consider establishing an external advisory board of stakeholders, including CNST users.**

The recommendations of the 2011 NRC assessment panel do not seem to have been addressed by the CNST. Concerned that the recommendations of the current panel may be similarly ignored, it would be important to conduct the next National Academies assessment within 2 years.

> **Recommendation 3: CNST management should arrange the next National Academies of Sciences, Engineering, and Medicine assessment within 2 years.**

The Nanofabrication Facility

The detailed quantitative information needed for the evaluation of the NanoFab was difficult to obtain during the review of the facility. This is unacceptable for a user facility with this level of federal support. Detailed tracking of all users is routinely done by leading research fabrication facilities, and it is an essential tool for understanding usage trends and making rational decisions about staffing, equipment

[2] NRC, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011*, The National Academies Press, Washington, D.C. 2011.

upgrades, and new equipment acquisition. The NanoFab management needs to adopt similar practices, and if already implemented, to make the results available to reviewers in a timely manner.

Recommendation 4: CNST management should initiate a process that provides, maintains, and makes publicly available detailed data on all CNST users that identifies the number of facility users per equipment, their organizational affiliations, their fields of interest, the amount of income they provide to the CNST, and the outcomes of their facility utilization. NanoFab data should not be conflated with that of the NanoLab. The former consists of commercially available equipment designed to fabricate and measure micro- and nanostructures. The latter develops and hosts unique equipment, generally designed for exquisitely detailed measurements.

The NanoFab management has not yet begun significant recruiting efforts, and additional growth is possible because the facility is far from capacity. Approaching capacity is to be viewed as a positive goal—more users decrease idle equipment time, spreading costs more broadly. New users would also increase the impact of the facility.

Recommendation 5: The NanoFab management should begin an outreach program to recruit new users.

The CNST director and the staff expressed the desire to see more users from a broader range of disciplines and external organizations, particularly from industry; however, a strategic plan with a roadmap and metrics for achieving this goal was not articulated. Developing and applying metrics to manage operations would enable the benchmarking of performance against that of similar facilities and would also be a means of goal setting for strategic planning.

Recommendation 6: CNST leadership should define a strategic plan with a roadmap and associated metrics for the NanoFab and should benchmark NanoFab operations against those of other nanofabrication facilities.

Its high level of sustained funding and collaboration with the process research team gives the NanoFab the opportunity to be a leading national resource. They need to be more engaged with the fabrication community.

Recommendation 7: CNST management should become more outward looking and more broadly engaged with the fabrication community beyond the traditional mechanisms of research collaborations and peer-reviewed publications. CNST management should increase service in professional organizations, sharing of fabrication protocols, and proliferating best practices (such as the NanoFab Equipment Management Operation [NEMO]). CNST management should also consider playing a leadership role in the University/Government/Industry Micro/Nanotechnology (UGIM) Symposium and the National Nanotechnology Coordinated Infrastructure (NNCI) program.

Electron Physics Group

Questions remain regarding CNST's strategic priorities with respect to the EPG. The set of tools and skills developed in the EPG seems to be less suited to the stated goal of neuromorphic device development (which includes building test circuits in the NanoFab and developing new microspecies to measure them) than to areas such as the fundamental physics of quantum systems or quantum computing.

The information processing domain represents an emergent opportunity and encompasses biomimetic and hybrid transdisciplinary approaches that transcend any single team's scope.

Recommendation 8: The Electron Physics Group and the CNST should consider how best to position its work on neuromorphic versus neuronal architectures and approaches to information processing.

EPG's ultralow temperature scanning tunneling microscope (ULT-STM) represents a unique measurement and integrated sample and tip preparation infrastructure. The fundamental research using this tool needs to continue, along with work that enables further enhancements of this multimodal measurement tool.

Recommendation 9: The CNST should continue to support the ultralow-temperature scanning tunneling microscope (ULT-STM) for continued success.

EPG collaborations outside of NIST are overwhelmingly academic. In particular, there currently appear to be few EPG collaborations and weak linkages with industrial users. For example, participation in workshops that bring together scientific leaders and identify potential options that enable future strategic measurement challenges may help to catalyze the next generation of scientific inquiry. Additionally, increasing engagement with external professional societies could increase the impact of the EPG investigators and the CNST.

Recommendation 10: The Electron Physics Group should increase its collaborative engagements with external users and its investment in external professional activities, such as conference organization, editorships, or society governance.

Energy Research Group

The ERG has very good scientific expertise, facilities, and equipment. The exclusive focus on energy may not be appropriate, given the range of related research topics and proposed future initiatives. Long-range strategic planning for the group was not clearly articulated, nor was it apparent in discussions. The ERG needs to develop a strategic plan to outline intended directions for the coming year and into the following 5 years.

Recommendation 11: The CNST should develop a strategic plan that reconsiders the mission and research focus of the Energy Research Group to more accurately reflect its breadth of research activities. As part of this effort, the CNST should consider whether there is sufficient "customer pull" for continued, significant efforts in photovoltaics.

ERG personnel are well qualified and active, with a good record of publications and involvement in the technical community. The ERG, however, is small and its staff are highly specialized. Opportunities for growing the group in more general directions need to be considered.

Recommendation 12: The CNST should evaluate the staffing of the Energy Research Group in terms of alignment with its mission and ability to carry out that mission. The CNST should strive for group staffing levels with sufficient critical mass to address important measurement challenges commensurate with its mission and strategic directions.

Research being conducted at the ERG is of high quality. The researchers need to enhance collaborations with external users. This will lead to increased visibility of ERG researchers. This will also lead to greater use of this valuable national resource.

Recommendation 13: The Energy Research Group researchers should become more engaged in the professional community via society committees and trade associations.

Nanofabrication Research Group

The diversity and quality of user-driven research projects under development in the NRG demonstrate the excellent scientific and technical expertise this group provides. It is difficult, however, to identify the alignment of the existing research activities with the group's mission. This current disconnection makes it difficult to assess the projects relative to the mission.

Recommendation 14: The Nanofabrication Research Group should redefine its mission to align it to the group's existing research or, if it does not have the flexibility to redefine its mission, it should realign the research projects to the current mission.

In line with the NRG's mission, the NRG needs to enhance engagement with the fabrication community through talks at conferences, organizing workshops and conference sessions, and society service.

Recommendation 15: The Nanofabrication Research Group (NRG) should increase engagement with the fabrication community through strategic presentation of talks at conferences, organizing of workshops and conference sessions, and society service. The NRG should consider convening or participating in existing industry/academic/government consortia. One such example is the Microphotonics Center at the Massachusetts Institute of Technology, which sponsors a road mapping activity and has spring and fall meetings. The NRG should consider building a similarly vibrant community around its strengths in nanoelectromechanical systems, precision measurement, and/or atomic scale microscopy.

Acronyms

AC	alternating current
ACS Nano	American Chemical Society Nano
AFM	atomic force microscope
CAD	computer-aided design
CdTe	cadmium telluride
CMOS	complementary metal-oxide semiconductor
CNST	Center for Nanoscale Science and Technology
DC	direct current
DOC	Department of Commerce
DOE	Department of Energy
DLS	dynamic light scattering
EPG	Electron Physics Group
ERG	Energy Research Group
FE-SEM	field emission scanning electron microscope
FY	fiscal year
HRTEM	high-resolution transmission electron microscopy
IT	information technology
MEMS	microelectromechanical systems
MIT	Massachusetts Institute of Technology
NanoFab	Nanofabrication Facility
NCNR	NIST Center for Neutron Research
NEMO	NanoFab Equipment Management Operation
NEMS	nanoelectromechanical systems
NIH	National Institutes of Health
NNCI	National Nanotechnology Coordinated Infrastructure
NNI	network-to-network interface
NNIN	National Nanotechnology Infrastructure Network
NIST	National Institute of Standards and Technology
NRC	National Research Council
NRG	Nanofabrication Research Group
NV	nitrogen vacancy
PDMS	polydimethylsiloxane
PEM	polymer electrolyte membrane

PVD	physical vapor deposition
SEMPA	scanning electron microscopy with polarization analysis
STM	scanning tunneling microscope
SWOT	strengths, weaknesses, opportunities, and threats
TEM	transmission electron microscope
UGIM	University/Government/Industry Micro/Nanotechnology
UHV	ultrahigh vacuum
ULT-STM	ultralow-temperature scanning tunneling microscope