An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2011

Panel on Nanoscale Science and Technology; National Research Council

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Panel on Nanoscale Science and Technology

Laboratory Assessments Board

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

Milton Levenson, Bechtel International (retired),
E. Ward Plummer, Louisiana State University,
Mark A. Ratner, Northwestern University, and
Donald M. Tennant, Cornell University.

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

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Summary

The mission of the Center for Nanoscale Science and Technology (CNST) in the National Institute of Standards and Technology (NIST) 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."[1] The CNST has two components with complementary purposes—the research program, composed of three groups (Electron Physics, Nanofabrication Research, and Energy Research), and the NanoFab facility. Individuals from beyond NIST and elsewhere at NIST can interact with the CNST through collaborations with the scientific research staff in the research program and through use of the NanoFab to fabricate structures or devices.

As requested by the Director of NIST, the Panel on Nanoscale Science and Technology, a panel of experts appointed by the National Research Council (NRC), performed an assessment that employed the following criteria: (1) the degree to which Laboratory programs in measurement science, standards, and services achieve their stated objectives and fulfill the mission of the CNST; (2) the technical merits and scientific caliber of the current laboratory programs relative to comparable programs worldwide; and (3) the alignment between laboratory research and development (R&D) efforts and those services and other mission-critical deliverables for which that laboratory is responsible.

The CNST has matured significantly over the past 2 years since the previous NRC review,[2] having achieved nearly steady state in terms of staffing and projects. The center's research program consists of leading-edge nanoscale research directed toward exploring phenomena that may provide the basis for future nanoscale measurement and characterization techniques. This component of the CNST is staffed by scientific research staff with strong records of individual research accomplishment. There is an increasingly impressive record of publication by scientists at the CNST.[3] This output is supported by a significant cadre of postdoctoral appointees and support staff. The CNST should consider enhancing the professional development of postdoctoral staff by offering opportunities (possibly through partner institutions such as universities) for staff to learn skills needed for non-academic careers—for example, in entrepreneurship.

The NanoFab component of the CNST is a national shared-use facility that aspires to provide a state-of-the-art suite of nanoscale measurement and fabrication capabilities. Largely a clean-room facility, the NanoFab is attracting users from all sectors of the economy—industry, academia, and government—through its impressive capital-equipment capabilities; it appears to be operating at near capacity. The NanoFab is providing outstanding service with unparalleled capabilities to a broad range of users.

The CNST is a world leader in some of its areas of emphasis. There are many unique capabilities throughout the center, and CNST staff have extensive collaborations with scientists,

[1] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010,* NIST SP 1121, March 2011, p. 4. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

[2] National Research Council, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2009*. Washington, D.C.: The National Academies Press, 2009.

[3] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010,* NIST SP 1121, March 2011, pp. 78-81. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

engineers, and companies from the United States and around the world. The staffing is largely complete, although many laboratories, especially in the newer groups such as the Energy Research Group, are still under development. These newer efforts appear to have assembled highly talented teams that have the potential to develop a high-quality effort. These areas are likely to continue to grow and develop over the next few years.

The CNST supports researchers from industry, academia, NIST, and other government agencies. The number of users as reported to the panel is impressively high, and the increasing use by industry users appears consistent with the NIST/CNST mission. Even greater use should be possible with enhanced communication about the CNST capabilities relative to those available elsewhere.

The staff, the projects, and the facilities of many of the programs presented for review by the CNST are outstanding and in several instances unique. All of the work reviewed by the panel is scientifically very good. Much of it is original, innovative, scientifically outstanding, and among the best of its kind. Almost all of the projects are clearly focused on the stated mission of NIST as they seek to develop understanding that will lead to standards and precision measurement at the nanoscale. A fair amount of the research is directed toward developing unique instrumentation.

The substantial budget of the CNST and the self-sufficient “block funding” nature of its allocation without the concomitant expectation of supporting user-defined research in the scientific portion of the CNST organization are increasingly unusual in the U.S. scientific community. This approach enables the CNST staff to concentrate on their scientific endeavors in a way that is all too rare. Staff are able to spend a significant number of years working on extremely high risk, high payoff instrument development, which may lead to demonstration and exploitation of unique capabilities. There are very few, if any, other institutions in the United States where such endeavors are possible, making this capability at the CNST all the more valuable. In such an environment, it is manifest that the leadership of the organization has a particularly significant responsibility to evaluate projects rigorously and to curtail long-standing projects that are not paying off.

With the addition of important theoretical and chemical expertise, the balance of CNST staffing has improved significantly since the panel’s last review in 2009. The theorist in each research group has tended to become “glue” uniting the various efforts within the group.

The reviewed work of the Electron Physics Group, conducted with the use of state-of-the-art equipment, is at the level of the best in the field. The group’s laboratory facilities are state of the art and in many cases unique.

The Nanofabrication Research Group is a highly competent assemblage of scientists that has taken on the additional mission of advancing the state of the art in nanomanufacturing, an area of growing importance. The laboratory facilities available to the group could well be the best in the world. The research programs in this group are of high quality and are aligned with the group’s mission. Some of the laboratories in this group are still under development.

The Energy Research Group is now fully staffed, with a good combination of junior and more senior staff, although many of the laboratories are still under development. The work of this group is the most technologically (rather than scientifically) focused effort of the research groups. The laboratories and equipment that are in place are state of the art in all respects. It is still too early to judge in detail the quality and mission alignment of the Energy Research Group’s research programs.

The NanoFab facility has progressed significantly and is reaching capacity. The equipment and capabilities are probably as modern and complete as those of any similar facility in the United States.

It is important to recognize the tension inherent in supporting both high-quality science and measurement activities and user facilities. For the scientific groups there are scientific collaborations and interactions with industry and others; they are full scientific collaborations, not a matter of CNST scientists supporting a user-defined body of work. For the NanoFab, the focus is on user support; the users may be from the scientific part of the CNST, from elsewhere at NIST, or from outside NIST. This tension adds richness to the CNST environment, but it needs to be monitored and balanced continually. The balance seems appropriate currently, and the diversity of effort is well aligned with the CNST vision and is key to the center's ability to meet its mission, both now and in the future.

There are a number of good examples of close interactions and collaborations between the CNST research groups and industry. In some cases, the instrumentation or understanding provided through the interaction helped a company develop or improve a product. In other cases, CNST staff led the development of instrumentation (through a Cooperative Research and Development Agreement, or CRADA) that significantly enhanced equipment sold by a company.

The NanoFab facility and its highly skilled staff represent a major advance in the research capabilities of the CNST. A dynamic group of researchers including students, postdoctoral researchers, and NIST staff are engaged in research utilizing this modern capability.

RECOMMENDATIONS

The CNST should:

- Further diversify the user base for the NanoFab. The capabilities are so outstanding that they would be in greater demand if more potential users knew about them.
- Given NIST's mission to increase U.S. competitiveness, continue to increase the CNST focus on industry as its key customer. Specific focus should be on the industrial segment that requires state-of-the-art nanofabrication capability and access to outstanding scientific staff.
- Actively manage the balance between high-quality science and service. The first can lead to the second, but only if time is allowed for the sufficient maturation of the research. The current balance is appropriate but needs to be monitored very closely if it is to be preserved.
- Continue the effort to mature the focus and stature of the newer research groups, especially the Energy Research Group. This effort would include more strategic planning and the identification of research issues of central importance to the energy landscape in the United States.
- Consider enhancing the professional development of postdoctoral staff by offering opportunities (possibly through partner institutions such as universities) for staff to learn skills needed for non-academic careers—for example, in entrepreneurship.

For the next review the CNST should:

- Discuss the strategic plan of the CNST and how it flows down to each group.
  —Explain how the plan is used to determine research directions, resource allocation, staff selections, and balance between research and user support.
  —Describe how projects are proposed, vetted and/or selected, evaluated, and retired.

- Discuss the intellectual property strategy of the CNST and how it aligns with CNST priorities.
- In the metrics, differentiate between users and collaborators.
- Describe the interactions with industry in more detail.
  —What are the priorities for industry interactions?
  —How are these interactions cultivated?
  —What are the criteria for accepting industry projects?
- Provide a description of the method of counting users, a complete list of projects with associated users, and a breakdown of industry versus non-NIST (non-industry) versus NIST process hours.
- Hone presentation skills.
  —Talks should adhere to the allotted time and allow adequate time for discussion.
  —Both talks and posters should provide context for the work, including a demonstration of knowledge of relevant work by others around the world and the connection of the work to the NIST and CNST mission.
  —Although many posters in the present review were very good, some of them would have benefited from being less cluttered. Posters should be uncluttered and clear, so as to be understandable to broad audiences.

1

The Charge to the Panel and the Assessment Process

At the request of the National Institute of Standards and Technology (NIST), the National Research Council (NRC) has, since 1959, annually assembled panels of experts from academia, industry, medicine, and other scientific and engineering environments to assess the quality and effectiveness of the NIST measurements and standards laboratories, of which there are now six,[4] as well as the alignment of the laboratories' activities with their missions. NIST requested that three of its laboratories be assessed in 2011: the Center for Nanoscale Science and Technology (CNST), the NIST Center for Neutron Research, and the Information Technology Laboratory. Each of these was assessed by a separate panel of experts; the findings of the respective panels are summarized in separate reports. This report summarizes the findings of the Panel on Nanoscale Science and Technology.

For the fiscal year (FY) 2011 assessment, NIST requested that the panel focus on the following criteria as part of its assessment:

1. Assess the degree to which laboratory programs in measurement science, standards, and services achieve their stated objectives and fulfill the mission of the operating unit (laboratory);
2. Assess the technical merits and scientific caliber of the current laboratory programs relative to comparable programs worldwide; and
3. Assess the alignment between laboratory research and development (R&D) efforts and those services and other mission-critical deliverables for which the laboratory is responsible.

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

In order to accomplish the assessment, the NRC assembled a panel of 11 volunteers whose expertise matches that of the work performed by the CNST staff.[5] The panel members visited the CNST facility at Gaithersburg, Maryland, for 2.5 days (March 7-9, 2011), during which time they attended presentations, tours, and interactive sessions with CNST staff; they also conducted interactive sessions with CNST managers. The panel met in closed sessions to deliberate on its findings and to define the contents of this assessment report.

The approach of the panel to the assessment relied on the experience, technical knowledge, and expertise of its members, whose backgrounds were carefully matched to the technical areas of CNST activities. The panel reviewed selected examples of the technological

[4] The six NIST laboratories are the Material Measurement Laboratory, the Physical Measurement Laboratory, the Engineering Laboratory, the Information Technology Laboratory, the Center for Nanoscale Science and Technology, and the NIST Center for Neutron Research.

[5] See http://www.nist.gov/cnst/ for more information on CNST programs. Accessed April 7, 2011.

research covered by the CNST; because of time constraints, it was not possible to review the CNST programs and projects exhaustively. The examples reviewed by the panel were selected by the CNST in consultation with the panel chair and NRC staff. The panel's goal was to identify and report salient examples of accomplishments and opportunities for further improvement with respect to the following: the degree to which the CNST programs achieve their stated objectives and fulfill the CNST mission, the technical merit and scientific caliber of the CNST work, and the alignment between CNST R&D efforts and CNST services and other mission-critical deliverables. These examples are intended collectively to portray an overall impression of the laboratory, while preserving useful suggestions specific to projects and programs that the panel examined. The panel applied a largely qualitative rather than a quantitative approach to the assessment, although it is possible that future assessments will be informed by further consideration of various analytical methods that can be applied.

For its assessment, the panel relied primarily on presentations made by NIST and CNST managers and staff and by other researchers associated with NIST projects and programs, and on informational notes prepared by NIST and CNST staff for use by the panel. Posters by various researchers involved with CNST activities were also presented to the panel during its visit to the CNST. This report does not contain extensive citations of technical articles and reports. Other documents and resources used by the panel are cited in the report, as appropriate.

The comments in this report are not intended to address each program within the CNST exhaustively. Instead, this report identifies key issues. Given the necessarily non-exhaustive nature of the review process, the omission of any particular CNST program or project should not be interpreted as a negative reflection on the omitted program or project.

The preceding Summary highlights issues that apply broadly to several or all of the groups or to the center as a whole and presents the panel's key recommendations for the CNST. Chapter 2 presents a more detailed overall assessment of the center against the three criteria established by the NIST Director. Chapters 3 and 4 present observations and suggestions specific to the groups in the CNST research program and to the NanoFab program, respectively. Chapter 5 presents the panel's overall conclusions.

2

Overall Assessment

The Center for Nanoscale Science and Technology in the National Institute of Standards and Technology was founded on May 1, 2007. The CNST mission 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."[6] The CNST has two components with complementary purposes—the research program and the NanoFab facility. The research program is organized in three groups—Electron Physics, Nanofabrication Research, and Energy Research; the NanoFab Operations Group is responsible for the operation of the NanoFab. Individuals from beyond NIST and elsewhere at NIST can interact with the CNST through collaborations with the scientific research staff in the research program and through use of the NanoFab to fabricate structures or devices.

The center has matured significantly in the 2 years since the previous review,[7] having achieved nearly steady state in terms of staffing and projects. The research program consists of leading-edge nanoscale research directed toward exploring phenomena that may provide the basis for future nanoscale measurement and characterization techniques. This component of the CNST is staffed by scientific research staff with strong records of individual research accomplishment. There is an increasingly impressive record of publication by scientists at the CNST.[8] This output is supported by a significant cadre of postdoctoral appointees and support staff. The CNST should consider enhancing the professional development of postdoctoral staff by offering opportunities (possibly through partner institutions such as universities) for staff to learn skills needed for non-academic careers—for example, in entrepreneurship.

The NanoFab component of the CNST is a national shared-use facility that aspires to provide a state-of-the-art suite of nanoscale measurement and fabrication capabilities. It is largely a clean-room facility and is staffed accordingly. The NanoFab is attracting users from all sectors of the economy—industry, academia, and government—through its impressive capital-equipment capabilities; it appears to be operating at near capacity.

As described to the panel, the CNST, with an FY 2010 budget of $23 million, is currently staffed by 97 full-time-equivalent (FTE) employees, including 60 technical staff. There are currently 19 staff members with the title of "project leader," 9 of whom are new to the CNST since the previous review. Each project leader is allocated 2 postdoctoral researchers and one-sixth each of an electrical engineer, a mechanical designer/instrument specialist, a computer specialist, and an administrative assistant. There are 11 administrative support positions, 8 technical support positions, and 12 NanoFab staff positions.

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[6] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010,* NIST SP 1121, March 2011, p. 4. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

[7] National Research Council, *An Assessment of the National Institute of Standards and Technology Center for Nanoscale Science and Technology: Fiscal Year 2009*. Washington, D.C.: The National Academies Press, 2009.

[8] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010,* NIST SP 1121, March 2011, pp. 78-81. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

ACHIEVEMENT OF OBJECTIVES AND FULFILLMENT OF MISSION

The vision of the CNST is "to be recognized for providing ready access to unexcelled nanoscale measurement and fabrication facilities and as a world leader in each of our measurement science research areas."[9] The CNST has, overall, made dramatic strides toward achieving this vision since the previous review, as exemplified by specific details provided in Chapters 3 and 4.

The NanoFab has progressed impressively and is providing outstanding service with unparalleled capabilities to a broad range of users. Anecdotal inputs from users indicate that users are highly satisfied with their experience.

The CNST is a world leader in some of its areas of emphasis, as discussed in the more detailed reviews of the four groups in Chapters 3 and 4. The focus areas that are well established, especially those whose genesis predates the formation of the CNST, are among the best in the world. There are many unique capabilities throughout the CNST, and CNST staff have extensive collaborations with scientists, engineers, and companies from the United States and around the world. Although the center's staffing is largely complete, many laboratories, especially in the newer groups such as the Energy Research Group, are still under development. These newer efforts appear to have assembled highly talented teams that have the potential to develop a high-quality effort. These areas are likely to continue to grow and develop over the next few years.

The CNST supports researchers from industry, academia, NIST, and other government agencies. As reported to the panel, the number of users is impressively high. Although the center's method of counting users is different from that used by other laboratories, the approach seems to take into consideration measurement against outcomes that are important to the key stakeholders (for example, NIST leadership and the Department of Commerce). There has been growth in the user base in all sectors since the previous review; industrial users accounted for the largest percentage growth, consistent with the NIST/CNST mission. Given NIST's mission to increase U.S. competitiveness, the CNST should continue to increase its focus on industry as its key customer. Specific focus should be on the industrial segment that requires state-of-the-art nanofabrication capability and access to outstanding scientific staff. The users represent a broad geographic distribution. Even greater demand from across the country should be possible with enhanced communication about the CNST capabilities relative to those available elsewhere.

TECHNICAL MERIT OF THE CENTER'S PROGRAMS

For many of the programs presented by the CNST to the panel for review, the staff, the projects, and the facilities are outstanding and in several instances unique. The various parts of the CNST are not uniformly mature, although the gap between mature programs and the newer ones has closed significantly since the previous review.

All of the work reviewed by the panel is scientifically very good. Much of it is original, innovative, scientifically outstanding, and among the best of its kind. The breadth of scientific knowledge and the overall level of enthusiasm of the staff throughout the CNST are impressive. Almost all of the projects are clearly focused on the stated mission of NIST as they seek to develop understanding that will lead to standards and precision measurement at the nanoscale. A fair amount of the research is directed toward developing unique instrumentation.

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[9] Robert J. Celotta, CNST, "Overview of the Center for Nanoscale Science and Technology," presentation to the panel, Gaithersburg, Maryland, March 7, 2011.

The substantial budget of the CNST and the "block funding" nature of its allocation are increasingly unusual in the U.S. scientific community. This approach enables the CNST staff to concentrate on their scientific endeavors in a way that is all too rare. Staff are able to spend a significant number of years working on extremely high risk, high payoff instrument development, which may ultimately lead to the demonstration and exploitation of unique capabilities. There are very few, if any, other institutions in the United States where such endeavors are possible, making this capability at the CNST all the more valuable. The staff expressed recognition of its enviable position and great appreciation of the NIST and CNST leadership for their roles in making this funding model possible. In such an environment, it is manifest that the leadership of the organization has particularly significant responsibility to evaluate projects rigorously and to curtail long-standing projects that are not paying off.

With the addition of important theoretical and chemical expertise, the balance of CNST staffing has improved significantly since the previous review. Since that review, the theorist in each research group has tended to become "glue" uniting the various efforts within the group, and each group has made significant progress:

- The technical merit of the reviewed work of the Electron Physics Group relative to the state of the art is at the level of the best in the field. The group's laboratory facilities are state of the art and in many cases unique. The outstanding accomplishments of the group and the external recognition of group members indicate the achievement of the group's stated objectives and impact.[10]
- The Nanofabrication Research Group is a highly competent assemblage of scientists that has taken on the additional mission of advancing the state of the art in nanomanufacturing, an area of growing importance. The laboratory facilities available to the group could well be the best in the world. The group's research programs are of high quality and are aligned with its mission. Some of the laboratories in this group are still under development.
- The Energy Research Group is now fully staffed, with a good combination of junior and more senior staff, although many of the laboratories are still under development. The work of this group is the most technologically (rather than scientifically) focused of the research groups. The addition of a theorist provides needed intellectual coherence within the group. The laboratories and equipment that are in place are state of the art in all respects. It is still too early to judge in detail the quality and mission alignment of the research programs.
- The NanoFab facility has progressed significantly and is reaching capacity. The equipment and capabilities are probably as modern and complete as those in any similar facility in the United States. The facility is well managed and has dramatically increased its capabilities and support of users since the previous review.

The productivity of staff while affiliated with the CNST has grown nicely since the previous review. The number of publications with CNST affiliation was 24 for FY 2008, rising to 33 for FY 2009, 41 in FY 2010, and 19 as of March FY 2011. An additional 18 publications

[10] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010*, NIST SP 1121, March 2011, pp. 76-77. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

are currently in press, with 26 more submitted for publication. CNST staff and leadership have also garnered an impressive array of external professional awards since the previous review.[11]

ALIGNMENT BETWEEN RESEARCH AND DEVELOPMENT AND THE CENTER'S SERVICES

The work carried out at the CNST covers a wide range, varying from nanofabrication and other services, through relatively near term collaborations with industry, to extremely fundamental science that may lead to future measurement capabilities. It is important to recognize the tension inherent in supporting both high-quality science and measurement capabilities and user facilities. This tension adds richness to the CNST environment, but it needs to be monitored and balanced continually. The diversity of effort is well aligned with the CNST vision and is key to the center's ability to meet its mission, both now and in the future.

A number of good examples of close interactions and collaborations between industry and the research groups were discussed during the review. In some cases, the instrumentation or understanding provided through the interaction helped a company develop or improve a product. In other cases, CNST staff led the development of instrumentation (in a Cooperative Research and Development Agreement, or CRADA) that significantly enhanced equipment sold by a company. These interactions appear to be rather common throughout the CNST, but a quantification of the number and scale of such collaborations was not provided to the panel.

The NanoFab facility and its highly skilled staff can be credited with a major advance in the research capabilities of the CNST. A dynamic group of researchers including students, postdoctoral researchers, and NIST staff are engaged in research utilizing this modern capability. A very high percentage of presentations (both oral and poster) during the review indicated that the research described in the presentations depended in some way on the NanoFab.

[11] National Institute of Standards and Technology, *Center for Nanoscale Science and Technology 2010*, NIST SP 1121, March 2011, pp. 76-77. See http://www.nist.gov/cnst/upload/cnst_2010_report.pdf. Accessed June 29, 2011.

3

The Research Program

The Center for Nanoscale Science and Technology continues to address the challenge of actively managing the balance between high-quality science and service. The first can lead to the second, but only if time is allowed for the sufficient maturation of the research. The current balance is appropriate but needs to be monitored very closely if it is to be preserved.

ELECTRON PHYSICS GROUP

Scope and Mission

The Electron Physics Group (EPG) conducts a wide range of cross-disciplinary research that focuses on developing innovative measurement capabilities for nanotechnology, with an emphasis on applications for future electronics. The EPG is the most established group within the CNST, having been a part of NIST since 1954. A number of the project leaders are among the founding members of the center. EPG research encompasses scanning-probe microscopy; nanomagnetic imaging and dynamics; theory, modeling, and simulation; and laser manipulation of atoms. The research conducted by the group is uniformly of a very high standard, and the capabilities in terms of the measurement tools and methods that the EPG is developing are impressive.

Staffing

The EPG consists of 20 scientific staff (5 project leaders, 11 postdoctoral researchers, and 4 visitors) in addition to 7 support staff (2 in electronics, 2 in instrumentation, and 3 in information technology). Although the support staff are attached to the EPG, they provide support for all of the CNST research groups. The EPG is well established, with senior staff having been in place for some time. 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 adequate and is uniform across areas.

Quality of Research and Facilities

The scanning-probe microscopy is extremely strong and clearly a world-leading area. The instrumentation is unique in its capability, with the newest instrument combining a scanning tunneling microscope (STM) with high-energy resolution, cryogenic temperatures (10 mK), and high magnetic fields (15 T), and a range of ultrahigh vacuum (UHV) sample-preparation chambers. The quality of the research and the degree of collaboration with both internal and external researchers are excellent. The work on graphene addresses scientific issues that probably could not be addressed anywhere else. The emphasis on understanding changes to graphene that occur on its incorporation into device structures is critical. The EPG is very widely recognized and is a highlight of the CNST. The extension of scanning-probe microscope (SPM) spin-electronics measurements to topological insulators promises to be very fruitful as well. The integration of experiments with theory is also noteworthy.

Three project leaders perform research that addresses nanomagnetism, including the following areas: (1) imaging using scanning electron microscopy with polarization analysis (SEMPA), (2) techniques to measure and quantify spin-wave modes, (3) the development of novel electron beams that carry orbital angular momentum (OAM), (4) the development of magnetic resonance force microscopy (MRFM), and (5) theory and modeling. The EPG has a strong presence within the nanomagnetics community, and its research, both experimental and theoretical, is highly regarded. The project leaders are continuing to develop new measurement tools that enhance their existing capabilities—for example, extension of SEMPA to analyze ultrathin magnetic multilayers by means of profiling using very-low-energy ion beams. The initiation of a program on transmission electron microscopy (TEM) beams with OAM opens up possible new applications and is to be encouraged.

The experimental effort in the area of laser manipulation of atoms is superb. It is leading to an entirely new method of producing focused-ion beams through laser trapping of metallic atoms using a magneto-optical trap ion source (MOTIS). This method may enable focused-ion-beam (FIB) systems with a broader range of choices of source ion than is available in commercial systems. The ability to choose the source ion enables the optimization of the ion for the appropriate application: for example, for imaging, etching, pattern definition, beam chemistry, or materials analysis. The MOTIS also improves the energy resolution of the FIB instrument. The EPG interacts with industrial partners such as the FEI Company, a leading manufacturer of commercial FIB systems, through CRADAs and has patented aspects of the method.

Alignment with Mission

Research and development work in the EPG ranges from very fundamental work to applications with foreseeable technological or commercial applications. The EPG is involved in a wide range of interactions with collaborators from industry, academia, and national laboratories. Most of its collaborators are U.S.-based, although it is engaged in some international academic collaborations. NIST is a contributing member of the Nanoelectronics Research Initiative (NRI) funded by the Semiconductor Research Corporation (SRC). This involvement has led to 12 academic collaborations. Collaborators are helping the EPG to develop new measurement tools and also are acting as "users" of existing tools. The group's industrial collaborators are somewhat fewer, although a strong interaction exists between the ion-beam development project and FEI Company. The new technique developed for measuring spin polarization by means of analysis of Doppler-shifted spin waves involves collaboration with Hitachi Global Storage Technology. Project leaders in the nanomagnetics area commented to the panel that collaborations with the magnetic-storage industry are becoming harder to set up. The difficulty is in part a result of the decline of that industry in general. The theory and modeling part of the program has strong interactions with academic collaborators and with other members of the EPG. These interactions are very appropriate and critical to the success of the EPG. In summary, all efforts of the EPG seem highly aligned with the overall mission of NIST in terms of measurement and the development of new methods.

Future Plans

The EPG has historically done very well in progressing from one exciting project to another. Well-positioned near-term ideas are apparent in a number of areas. Given the overall service mission of the CNST and the expectation of a continually changing base of collaborators, it may be difficult to develop plans beyond the short term. It will be helpful nevertheless for the research staff to have a plan and to update it continually in order to prioritize the wide range of high-impact activities and collaborations with which the group is becoming involved.

Evaluative Comments and Suggestions

Overall, the EPG is carrying out research that is cutting edge and of extremely high quality. The project leaders and postdoctoral researchers display a high degree of enthusiasm and commitment to their research, and there is clearly a positive work ethic. The presentations of the group were generally well organized and clear, and the posters were well presented by enthusiastic and knowledgeable postdoctoral researchers. Extensive written materials were provided to the panel. As noted above, the research being carried out in the group ranges from very fundamental to more applied, which is appropriate. A case in point is the research on focused ion beams, initially a basic research program that has now evolved into a CRADA and may result in a commercial product and a start-up company.

The CNST takes seriously its role in preparing postdoctoral associates for their next position, and in general it does this very well. There may, however, be an opportunity for some enhancements that would enable postdoctoral associates to acquire skills that would be needed for non-academic careers. For example, training in entrepreneurship would be invaluable for postdoctoral associates contemplating starting a company or joining a start-up. If it is not possible to provide such training in-house, it may be possible to partner with neighboring institutions or to provide release time and resources. It is, of course, imperative to continue to make sure that postdoctoral associates, especially those who are more involved in service work than in research, have the opportunity to attend meetings and produce publications.

The leader of the EPG identified the emerging requirement that measurements address novel electronics beyond complementary metal oxide semiconductor (CMOS) electronics, and provided a detailed list of potential devices for both memory and logic applications. The group should consider addressing the measurement needs of a wider range of these systems beyond magnetic materials and graphene. For example, technologies based on resistance change (both phase-change materials and resistive-switching oxide materials) have been identified as likely candidates for future applications, but they are attended by fundamental issues that would benefit from exploration by the techniques available in the EPG.

NANOFABRICATION RESEARCH GROUP

Scope and Mission

The Nanofabrication Research Group (NRG) was formed in 2007. Its mission is to advance the state of the art in nanofabrication and nanomanufacturing. The research programs within the group cover a broad range, with a healthy mix of theory, modeling, and experiment. Several research projects that definitely do advance the state of the art of nanofabrication are outside the group—for example, the work on electron beams with angular momentum and that on focused-ion-beam extraction from optical traps, which are within the Electron Physics Group.

This statement is not intended as a criticism but rather as an observation that technology advancements can come from many quarters, and this should be encouraged. Nano-manufacturing, an area of growing importance, has been added to the mission of the Nanofabrication Research Group since the previous review.

Staffing

The Nanofabrication Research Group has added new staff members since the previous review. It appears now to be appropriately staffed at the level of 8 project leaders, 14 postdoctoral associates, and 4 visiting fellows. The competence of the researchers was evident from their presentations and from their discussions with panel members during the laboratory visits.

Quality of Research and Facilities

The research programs within the Nanofabrication Research Group are of high quality. Group competencies include the following: nanofabrication, nanoscale stochastics, single-particle tracking, nanophotonics, nanoplasmonics, nanomechanics, nanotribology, in situ transmission electron microscopy, and nanosystems control. The laboratory facilities available to the group are among the best in the world. It is gratifying to see that such superb facilities are so widely available for service, collaboration, and the dissemination of information.

Alignment with Mission

The alignment of the research programs of the NRG with its mission of advancing the state of the art in nanofabrication is not uniformly obvious, although alignment with the overall mission of NIST is, in general, good. The research on nano-optics is focused on sensing and measurement. Although this effort is fully compatible with the NIST mission of measurement, it is only indirectly related to advancing the state of the art of nanofabrication. The research on nanomechanics covers both sensing and tribology. The former is fully compatible with the NIST mission of measurement; the latter is more basic in nature but with the potential to impact nanometrology significantly well into the future. The research on automated dual-beam nanomanufacturing addresses a serious problem with FIB systems and is definitely in line with the group’s stated mission of advancing nanofabrication. While awaiting the arrival of a new TEM, research on environmental transmission electron microscopy (ETEM) is employing instruments at the NanoFab, the NIST Materials Measurement Laboratory, and extramural organizations. Questions were raised about the validity of measurements made in an ETEM, as electron beams are well known to produce damage and could interfere with the phenomena being observed. That said, ETEM provides a unique means of monitoring events such as catalysis in real time, and the issue of intrinsic disturbance will be sorted out with further research. The in situ Raman thermometry extends Raman analysis into the ultraviolet (UV) to evaluate more materials and observe subtle phonon effects.

The work on nanomanufacturing is welcome and is fully compatible with NIST’s mission of aiding U.S. industry. Much of the work in this area, especially the work on deconvolving substrate-particle interactions and on the high-throughput near-field scanning optical microscope (NSOM), is directly related to advancing the state of the art in nanomanufacturing. The convergence of these nondestructive methods shows promise for enabling a more fundamental understanding and control of buried nanoscopic structures, which is required for many nanomanufacturing processes. Focus on this issue will ensure that U.S. industry has ample opportunity to exploit innovations in nanoscale science and engineering. The plots of resolution versus throughput and complexity versus cost/area identify key problems. It would be beneficial if these plots could be further enhanced, clarified, and promulgated. The new emphasis on nanomanufacturing in the NRG is well integrated with initiatives at other agencies, including the National Science Foundation.

Future Plans

The NRG did not discuss future plans. The energy and youth of the staff and the intrinsic quality of the research, however, predict future success. Overall, the research, collaboration, and service of the Nanofabrication Research Group are exemplary. Now that the group is at full staffing, the connection with and synergistic emphasis on nanofabrication technology are likely to evolve significantly during the next review cycle.

Evaluative Comments and Suggestions

Research in the Nanofabrication Research Group is of high quality and well coupled to the NIST and CNST missions. The project leaders, postdoctoral researchers, and visitors are competent and enthusiastic. The presentations of the group were well organized and clear, but the posters were not. Some of the poster presentations were difficult to understand and lacked context or clarity of purpose or method. In the future, the review should have well-prepared posters or should eliminate them altogether.

Given the critical importance of nanofabrication technology, a greater emphasis on research directed toward improving the efficacy and flexibility of nanofabrication methods is encouraged. This will require going beyond commercially available techniques, including those developed for the semiconductor industry.

The Nanofabrication Research Group has hosted a number of workshops, which should be continued as a means of getting the NIST message out to the academic and industrial communities.

ENERGY RESEARCH GROUP

Scope and Mission

The scope and mission of the Energy Research Group (ERG) are characterized as “developing measurement and fabrication methods relating nano-/atomic scale morphology and structure to functional properties in energy-related materials and devices.”[12]

Staffing

The ERG is staffed appropriately with senior, junior, postdoctoral, and technical staff. There are currently 6 project leaders and 7 postdoctoral researchers. The hiring of a theorist with broad capabilities follows the recommendation made by the NRC review panel 2 years ago. The theorist’s work provides a needed intellectual coherence within the group. The prospects for

[12] Nikolai Zhitenev, CNST/ERG, “The Energy Research Group,” presentation to the panel, Gaithersburg, Maryland, March 7, 2011.

achievements resulting from the hiring of a physical electrochemist (consistent with another recommendation of the previous panel) with interests and a research style that fit well into the physics-oriented effort in the group are promising. The addition of a senior staff member to work on thermoelectric materials is a bold move designed to couple to industrial interests in this area. The group has also added a very strong senior researcher in nanotechnology and applications in energy. At this point, the Energy Research Group is relatively new, still growing, and coalescing as a unit.

Quality of Research and Facilities

The scope of ERG research is meant for the development of new measurements relating nano- and atomic-scale morphology and structure to functional properties addressing three areas: energy generation, energy conversion and storage, and energy efficiency. Five project areas are active: photovoltaics (PV), solar thermal energy, solar fuels, thermoelectrics, and batteries.

The three core areas of measurement expertise are the following: (1) the theory and modeling of nanomaterials for renewable energy (calculations of electric, thermal, and ionic transport for materials and nanostructures used in energy-relevant applications, such as photovoltaics and thermoelectrics); (2) vibrational spectroscopy and microscopy (development and application of new spectroscopic methods, including infrared imaging with nanoscale spatial resolution, for characterizing nanomaterials with infrared and Raman spectroscopy); and (3) nanomaterials for solar fuels and artificial photosynthesis (methods to correlate structure and performance of nanocatalysts for solar fuels, and biotemplated approaches to artificial photosynthesis and nanofabrication).

Examples of current research topics include the following: developing an understanding of structure/function correlations of photoanodes for water splitting, the in situ characterization of lithium-ion batteries, electrochemical measurements using surface plasmons, the fabrication and characterization of field emission sources based on arrays of 1D structures for x-ray sources, photothermal infrared absorption spectroscopy of condensed materials using atomic force microscope (AFM) detection, the development and characterization of nanostructured thermoelectronic materials, and nanoscale studies of charge transport in organic photovoltaic devices.

The connection of this work to fundamental problems in physics, chemistry, and materials science is less clear than the connection to technological issues. For example, the selection of field emission arrays for investigation hardly addresses fundamental issues or recognizes the basic contributions to this field made at NIST in previous decades by the Electron Physics Group. The study of charge transport at nanoscale in organic photoelectric devices hardly recognizes the fundamentals of charge transport along molecules as currently achieved theoretically in fields such as molecular electronics and protein conduction.

Despite being a relatively new group, the ERG has established projects to address a number of issues in the energy area. The quality of the research varies widely throughout the group. It was not clear to the panel whether many of the selected areas of energy-related research address the most critical problems of measurement in energy science. Certainly the investigation of field emission arrays, for example, cannot be connected to a major need in the energy field. The group should seriously consider the most important opportunities on the energy landscape in problem selection.

The new laboratories, many of which are still under development, and new equipment are first rate in all respects. Most of the new 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.

Alignment with Mission

The alignment of the Energy Research Group's research program with the stated scope and mission of the ERG is appropriate.

Future Plans

The Energy Research Group has some good ideas and views with respect to its future research. However, long-range strategic planning for the group was not apparent and needs to be discussed more explicitly during the next review.

Evaluative Comments and Suggestions

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 Energy Research Group is still in the process of growth and stabilization. Following are suggestions for the ERG as it moves forward:

- 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 review.

The CNST should continue the effort to mature the focus and stature of the newer research groups, especially the Energy Research Group. This effort would include more strategic planning and the identification of research issues of central importance to the energy landscape in the United States.

4

The NanoFab Program

SCOPE AND MISSION

The functional statement of the NanoFab was described to the panel as being threefold:

1. Provide 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. Enable the processing and characterization of a wide range of nanoscale materials, structures, and devices critical to the nation's measurement and technology needs; and
3. Foster internal collaborations in nanotechnology across NIST's laboratories and foster external collaborations with NIST's partners through its shared environment.[13]

This NanoFab mission statement is consistent with the CNST mission statement goals of operating a national, shared-use facility for nanoscale fabrication and for developing innovative nanoscale fabrication capabilities supporting researchers from industry, academia, NIST, and other government agencies. Based on the reported increases in both research participation and hours of clean-room usage, it appears that the processing activities in the NanoFab have increased twofold over the previous 2 years, with participation from both internal NIST users and external industry users. However, because no breakdown of the industry versus NIST process hours was detailed, the panel was not able to evaluate the degree of industry impact in the NanoFab shared-use facility.

STAFFING

The facility's processing activities are supported by a NanoFab manager and 12 experienced staff members, an increase of 2 staff members over 2009 levels. Process staffing consists of 6 process engineers, 3 microscopists, and 3 equipment engineers. There are 3 staff members with PhD degrees and 4 staff members with MS degrees. In addition, 3 administration personnel support NanoFab user interactions and usage coordination. The large number of staff and high level of staff education enhance the productivity of the NanoFab and distinguish it from comparable nanofabrication facilities in universities with less-experienced and fewer staff members.

The NanoFab staffing model for meeting the process needs for its fabrication projects takes two forms: (1) hands-on processing by the users with initial process training by the staff, or (2) processing by the staff only. In both cases, the NanoFab staff provides consultation services to define both process development requirements and a process integration flow for the process project.

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[13] Vincent Luciani, CNST NanoFab, "The NanoFab," presentation to the panel, Gaithersburg, Maryland, March 7, 2011.

Because staff members maintain tools and provide process oversight, laboratory process capability will become limited by the number of staff in the NanoFab. Six major new tools are coming online in 2011: a chemical mechanical polishing tool (CMP), an ion mill, an aligner from ASML (a provider of lithography systems for the semiconductor industry), two FIB systems, and a TEM. The project count has increased 40 percent per year for the past 2 years. The present staffing level will likely be required to increase to sustain future additional tooling or future increases in laboratory processing initiatives.

QUALITY OF RESEARCH AND FACILITIES

The NanoFab clean-room facility has an impressive array of the most modern commercially available tools for micro- and nanofabrication. The physical facility is excellent, with a clean room and other laboratory space configured for easy access to a wide suite of modern fabrication tools. The equipment capabilities are as modern and complete as in any similar facility in the United States with which the panel is familiar.

Over the past 2 years, several new pieces of equipment have been brought online and added to the laboratory capabilities. It appears that most of the tools are characterized and available for general use, with the exception of one of the electron-beam systems. Focused-ion-beam and electron-beam lithography represent the core nanoscale fabrication tools, with sets of deposition, etching, and metrology tools for use in a modest level of process integration for research-scale devices. Although photolithography capability above 1 micrometer is available with several contact printing systems, a needed capability for higher-resolution photolithography is planned with the upcoming acquisition of an i-line stepper. Projects seem primarily to be directed toward a range of inorganic materials, including various semiconductors, metals, graphene, and a limited number of organic materials.

The nanofabrication laboratory facilitates a wide range of projects for NIST researchers and, to a lesser extent, activity for academic institutions and industry. Neither a complete summary of projects and users nor a list of projects with users was provided for evaluation by the panel. The quality of the research examples that were presented as being facilitated by the laboratory ranged from highly innovative work to somewhat limited use of less sophisticated processes such as thin-film deposition. Limitations in activity and research facilitated by this laboratory are not due to equipment limitations, but rather to staff availability and the need to prioritize the projects to be supported.

ALIGNMENT WITH MISSION

As noted, the process activities of the NanoFab program are aligned with the mission of the CNST and NIST. The NanoFab staff is well managed, operates a nanofabrication user facility, and supports the research mission of serving NIST, academia, and industry in measurement activities. The reported increase in both the number of users and of processing hours over the past 2 years in the NanoFab clean room further serves to verify the alignment of the NanoFab with both its mission and the CNST mission.

FUTURE PLANS

The NanoFab does not appear to have independent research programs, in contrast to the three other research groups comprising the CNST. Rather, the NanoFab staff's understanding of its role, and consequently the NanoFab mode of operation, has been to maintain the nanofabrication clean-room laboratory as a user and/or service facility. This effort involves maintaining the facility in excellent working condition, ensuring the operation of complex processing equipment, establishing and maintaining process-control metrics for critical process tools, and developing processing integration methods to assist internal (NIST) and external users of the facility. It is apparent that the NanoFab staff has worked efficiently over the past 2 years with postdoctoral research scientists from NIST and research engineers from industry in satisfying the facility's processing mission as documented by CNST internal reports and CNST external publications.

Future planning goals for the NanoFab program include the installation of three new tools critical for lithography, patterning, and planarization improvements in the clean room during 2011; new tooling justifications in the area of liftoff processing for 2012; improvement in tool uptime, especially for the Vistec e-beam writer; and continued outreach activities to attract more industry users. Future planning discussed during the review did not address staffing needs, which may ultimately limit productivity and new user participation in the NanoFab clean room. Future planning also does not appear to include process-development strategies that would be necessary for the NanoFab staff to stay at the forefront of nanofabrication technologies.

EVALUATIVE COMMENTS AND SUGGESTIONS

The nanofabrication laboratory and its highly skilled staff are responsible for a major advance in the research capabilities of the CNST. A dynamic group of researchers including students, postdoctoral researchers, and NIST researchers are engaged in research utilizing this modern capability. The nanofabrication laboratory and its staff clearly address the core mission of operating a shared-use facility, although the facility's national reach could be broader than it is currently. The NanoFab staff and clean room appear to support, first, NIST researchers; secondly, local academic institutions; and thirdly, industrial users. Although it is not an issue at present, as the laboratory matures and becomes fully functional it will become increasingly important to develop methods for prioritizing access to critical staff time and to the most heavily used capabilities.

The following are suggestions for the NanoFab program:

- In the next review the NanoFab staff should provide to the panel more detailed data on the NanoFab projects and the key enabling processing features for these projects in order to enable a more complete evaluation of the NanoFab. Relatively few data were presented for the current review, and it was difficult for the panel to gain a full understanding of the breadth, the impact, and the overall quality of the work supported by the nanofabrication laboratory. For example, it was stated in presentations that capabilities were available to commercial entities, with no connection to NIST/CNST required, but few examples of such interactions were provided.
- In the next review the NanoFab staff should present to the panel a plan for evaluating the evolving fabrication needs of the growing nanoscience and nanoengineering community, particularly those of the commercial sector. The current approach seems to be to emulate the existing capabilities of the National Nanotechnology Infrastructure Network and to try to obtain the latest commercially available models of the same tools. There is the opportunity, not yet fully realized, to use the knowledge, technical capabilities, and resources of NIST to develop entirely new nationally available fabrication capabilities. It would be valuable for the CNST to

develop a strategic plan for this facility to address the nanofabrication-related metrology needs and fabrication capabilities of greatest impact on nanomanufacturing in key areas of national economic importance. The CNST should also consider expanding the NanoFab mission to include process-specific developments in nanofabrication and to encourage NanoFab staff members to publish papers related to processing topics.
- The CNST should further diversify the user base for the NanoFab. The capabilities are so outstanding that they would be in greater demand if more potential users knew about them.
- Intellectual property (IP) protection of CNST developments was not emphasized in the CNST technical presentations overall. The CNST should pursue IP protection where appropriate. Specifically, some processing accomplishments in the NanoFab facility are of sufficient merit to warrant IP discussions—for example, (1) deep reactive-ion etch wall process control and (2) uniformity of reactive-ion etch processing with differential pattern loading on a wafer.

5

Overall Conclusions

The Center for Nanoscale Science and Technology continues to make significant progress toward meeting its stated objectives of (1) safely and reliably operating a national, shared-use facility for nanoscale fabrication and measurement; (2) developing innovative nanoscale measurement and fabrication capabilities; (3) supporting researchers from industry, academia, NIST, and other government agencies in nanoscale technology from discovery to production; (4) disseminating new nanoscale measurement methods by incorporating them into facility operations, collaborating and partnering with others, and providing international leadership in nanotechnology; and (5) serving as a hub linking the international nanotechnology community to the comprehensive measurement expertise within the NIST laboratories and centers.

There has been significant maturation and development of the CNST since the previous review in 2009. The capabilities that were judged to be mature in 2009 continue to be outstanding, especially in terms of the quality and productivity of the staff, the uniqueness of the capabilities, and the alignment with the CNST and NIST mission. Capabilities that were judged to be significantly less mature in 2009 have made significant progress. All of the CNST facilities are among the best in the world, and in many cases they are unique. Staff are of high quality, and their productivity within the CNST is growing impressively. The center is now more or less fully staffed. The NanoFab facility is now an impressive and smoothly running facility that is attracting a wide range of users. Given its state-of-the-art capabilities, it has the potential to draw an even larger user base from across the country. The Nanofabrication Research Group has made significant strides, with research of uniformly high quality. Alignment of the group's research with its mission continues to evolve. The Energy Research Group is the least mature of the units within the CNST. The group is now staffed with high-quality personnel, although many of the laboratories are still under development. It is expected that this group will continue to coalesce as a unit and increase its focus on the most important problems within its mission space in the coming review period.

The CNST will further maximize its impact on U.S. and global nanoscience and nanotechnology by (1) further diversifying the user base for the NanoFab; (2) continuing to increase the CNST focus on industry as its key customer; (3) continuing to manage actively the balance between high-quality science and measurement; (4) continuing to mature the focus and stature of the newer research groups, especially the Energy Research Group; (5) considering the further enhancement of the already-strong professional development of postdoctoral staff by offering opportunities (possibly through partner institutions such as universities) for the staff to learn skills needed for non-academic careers—for example, in entrepreneurship.

The Center for Nanoscale Science and Technology is maturing impressively as a state-of-the-art nanoscience and nanotechnology center of excellence aligned with the overall mission of NIST. The program is already impressive in its national and international reach. Given the quality of the facilities and staff in addition to the youth of the organization, the impact of the CNST is expected to continue to grow.