Chapter 11

INFRASTRUCTURE NEEDS FOR R&D AND EDUCATION

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11.1 VISION

A substantial infusion of resources is needed for enhancement of fabrication, processing, and characterization equipment that must be made available to large numbers of users in the nanostructure community. It is also necessary to continue the process, already underway, of modifying the culture of universities to enable more interdisciplinary research to prosper, as well as to enable more industrial cooperation.

11.2 CURRENT INFRASTRUCTURE

Infrastructure for Research and Development

A major impediment to the growth of a viable nanostructure science and technology effort in the United States is an outcome of its strength: this is inherently a multidisciplinary activity. Many feel that the emphasis in this activity will shift in coming decades from the physical to the biological and life sciences. The fact that this is already happening is significant, but it is impeded by the lack of a suitable infrastructure supporting interactions among what have traditionally been very disparate disciplines. This chapter includes examples and describes in greater detail the unusual aspects of those programs that could be emulated by others to the benefit of the field overall. The infrastructure for nanoscience and technology is only in formation, and is undersized compared to the needs and overall promise of the nanotechnology field.

Education

Although change is occurring in universities in a relatively rapid fashion, there still exist many elements in the culture of our research universities that discourage multidisciplinary research. Examples include the administrative autonomy of academic departments and colleges, the fact that many centers and institutes "compete" with departments in terms of contract and grant proposal submission, the difficulties of determining (particularly with respect to tenure and promotion decisions) the relative creative contributions of faculty to multiauthored publications, and the unfortunate disconnect between research and teaching that is too often the case.

Worldwide Research Activity

In general, there appear to be two approaches to making nanostructures: (1) a so-called "top-down" approach where a nanostructure is "chiseled" out of a larger block of some material, and (2) a so-called "bottom-up" approach where nanostructures are built up from atoms and molecules using chemical techniques. The second class of nanotechnologies starts from particles, ultimately atoms or molecules, and assembles them into nanostructures.

Bottom-up nanotechnology is often called molecular engineering. It is clear that nature has been assembling atoms into complex “nanostructures” for millions of years, and in a remarkably efficient way. Molecular engineering self-assembles atoms into structures consistent with the laws of physics specified in atomic detail. The processes are also called “post-lithographic” because lithography doesn’t play a central role in them (Jortner and Ratner 1998).

Bottom-up nanotechnologies have a host of important potential applications. Their impact on food production, medicine, environmental protection, even on energy production might be enormous (Gleiter 1989; Whitesides et al. 1991; Aksay et al. 1992; Drexler et al. 1993; Smalley 1995; Crandall 1996; Regis and Chimsky 1996; Freitas 1999). However, it is not enough to improve and extend the techniques of assembling molecules atom by atom: we must solve the problem of artificial self-replication and integration as well. Self-assembling atoms have been proposed and demonstrated (Smalley 1995), but no experimental verification of artificial self-reproduction has succeeded as yet. It has been shown that, in principle, self-reproducing machines in special supporting environments could be realizable but not sustainable (Von Neumann and Burks 1966, Merkle 1994). In the coming decades we shall witness the evolution of nanotechnologies at an increasing pace. U.S. National Laboratories have been devoted to this development, multidisciplinary programs have been and are being launched, and industry is contributing. The selection of both top-down and bottom-up nanofabrication tools becomes richer each year.

Nanoelectronics

Many groups are working on nanofabrication (based on semiconductors, structural and composite materials, and chemistry-based methods) and on the physical phenomena observable in these nanostructures. In the case of “nanoelectronics” (the use of nanostructures for electronic applications), research funding is shifting from the study of physical phenomena to electronic devices and circuit integration, although at present, few groups are working on the latter. It is critically important that advanced circuit architectures be developed, and these may be totally different from those used today. For example, if schemes such as quantum cellular automata (QCA) are developed (Lent 1997; Porod 1997, 1998), close collaboration with architecture design experts will be essential (Csurgay 1997). Researchers in the United States, Japan, and Europe form a very highly qualified, strong community. Their fundamental nanoscience and engineering projects are mostly funded by government sources.

In the United States, the major U.S. semiconductor companies maintain small groups (about 5-10 people) to keep informed about major developments in the area of nanoelectronics. These groups either perform basic research (e.g., Hewlett-Packard’s Teramak work) or advanced development (e.g., Raytheon/Texas Instruments work on integrating resonant-tunneling devices with conventional microelectronics). The Defense Advanced Research Projects Agency (DARPA) is currently phasing out its Ultra Electronics Program, a basic research program for extremely fast and dense next-generation computing components. This was perhaps the largest U.S. Government-funded mission-oriented nanotechnology program in the United States (about $23 million/year for approximately six years). In addition, there are a few other special Department of Defense programs (e.g., MURI, URI, DURIP) that fund work in the area of nanoelectronics. The National Science Foundation also funds a few activities, including Science and Technology Centers (STCs), Engineering Research Centers (ERCs) and a recently launched project on "Partnership in Nanotechnology." All of these Government programs fund research in universities, and some (e.g., DARPA) fund programs in industry. The various university programs are listed in Section 11.7.1, and some are described in greater detail in other subsections of Section 11.7.

In Japan, most of the initiatives in the area of quantum devices and nanostructures have been funded by the Ministry of International Trade and Industry (MITI). A large part of the research work is done in industry labs (including Sony, Toshiba, Mitsubishi, NTT, Hitachi, and Motorola-Japan). Among the relatively few Japanese university groups performing advanced nanotechnology research, most notable are the University of Tokyo, Osaka University and Kyushu University. A major Japanese initiative is the R&D Association for Future Electron Devices (FED). A centralized organization manages the research, investigations, and surveys; the actual research and development work on future electron devices is subcontracted to member companies and universities; and R&D on more basic technologies is carried out by Japanese national institutes (http://www.iijnet.or.jp/fed-www/).

In Europe, ESPRIT funds two main projects as part of its Advanced Research Initiative in Microelectronics (MEL-ARI) (http://www.cordis.lu/esprit/src/melari.htm). One of these projects, OPTO, is aimed at optoelectronic interconnects for integrated circuits, and the other, NANO, at nanoscale integrated circuits. The MEL-ARI projects in general, and the NANO projects in particular, appear to mimic DARPA's Ultra Program in the United States. An ESPRIT nanoelectronics roadmap has been developed as part of the MEL-ARI initiative. The roadmap developed by the U.S. Semiconductor Industry Association (SIA) is forecasting conventional semiconductor technology, but the ESPRIT roadmap is devoted to nanoelectronics. It is known at this time that the next round of ESPRIT projects will give special attention to integration and circuit architecture of nanodevices.

11.3 GOALS FOR THE NEXT 5-10 YEARS: BARRIERS AND SOLUTIONS

There are three different levels at which the nanotechnology R&D infrastructure needs to be considered: basic research, "directed" or applied research, and development.

Basic Research

It is assumed that most of the nanoscience basic research will be done in universities and in national laboratories, because the time-line for output is too long for industry. Funding for basic research needs to be enhanced both for single investigators or small groups of faculty members, and for centers or institutes that may be located at a single campus or laboratory or involve multiple universities and national laboratories.

For individual investigators, the current size of grants is relatively small compared to the needs. It is recommended that single or principal investigator (PI) grants be increased to

$200,000-300,000 per investigator, so that a PI can support several graduate students and postdocs, can purchase moderately sophisticated equipment in-house, and has the capability of accessing national equipment facilities like the National Nanofabrication Users Network (NNUN).

It is also recommended that additional centers be created of significant magnitude (on the order of $2-4 million per year per center). These centers should develop mechanisms for increasing industrial access, with personnel moving in both directions. It was noted at the IWGN workshop that there has been a tendency for successful center proposals to involve many universities, but that many of the more successful centers have been located at a single university, involving a multiplicity of disciplines crossing college boundaries. Some centers might develop new analytical or fabrication instruments, while most would focus on creating knowledge.

A useful model for further consideration in nanoscience and engineering is the Grant Opportunities for Academic Liaison with Industry (GOALI) program (http://www.nsf.gov/goali/), which funds university-industry small-group collaborative projects for fundamental research.

Directed Research

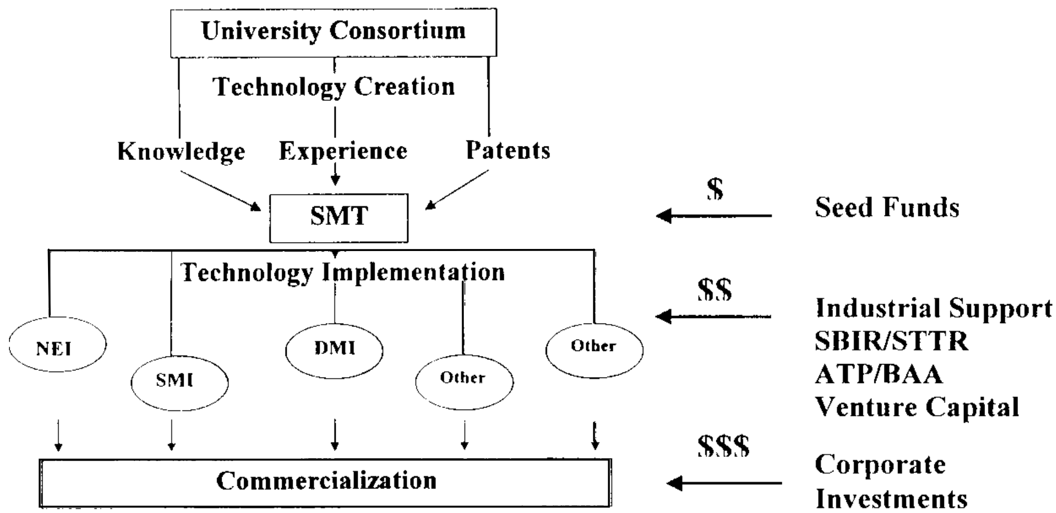
The challenges of directed or applied research in the area of nanostructures are more difficult for the single investigator model; the model of center activity is recommended as the more effective approach. Research fundamental to the integration of nanosystems is appropriate for this category. Collaboration between scientists and engineers in academe, private sector, and government laboratories needs to be integrated in the directed research programs.

Development

The development cycle for many “nanoproducts” is expected to be too long at this time for large companies and for venture capital to be able to support this research. Resources must therefore come from the Federal Government, and the work must be carried out in university and national labs and in incubators. However, to optimize the eventual commercialization of ideas generated through this research, it is essential that relationships between universities, national labs, and relevant industries be strengthened. Several recommendations are made that should encourage these relationships:

- Nanotechnology partnership programs should be formed, along the model of SBIRs, STTRs, ATP, and DARPA demonstration projects. Small high-tech companies can fill this role. Early success is apt to be in sensor and instrument areas. Grants (SBIR, etc.) can help promote the programs.
- Incubator programs should be developed at universities that support large efforts in the field of nanostructure science and technology. The university or national lab makes infrastructure available to a small company for a start-up, often with a faculty member or members taking the lead in the formation of the company. The “incubator” is a temporary intermediate stage in the formation of these start-up companies.

For example, a technology transfer approach was adopted by the Rutgers University Center for Nanomaterials Research. This center has recognized the merit of integrating focused university research in an interdisciplinary group, with process and product development in one or more spin-off companies, each of which had its own mission, application drivers, and technical leadership. In the Rutgers University model, an organization called Strategic Materials Technologies (SMT) has been established to provide a technology development bridge between university research and industrial applications. The specifics of the SMT organization are shown in Figure 11.1. It should be noted that SMT has established several nanomaterials-focused spin-off companies, and more are in the planning stage. These small businesses have remained coupled to the university research activities.



- **Each operating division is an independent company, with its own technology focus, application driver, and leadership.**

Figure 11.1. Organization and operating divisions under SMT (courtesy Nanodyne, Inc.).

One of the original groups of start-up companies, namely Nanodyne Inc., has advanced to the stage of full-scale commercialization, and hence is not shown in this diagram. The Rutgers University model should be applicable to other academic research groups and/or centers.

Finally, we note that the SMT organization is providing incentives for faculty to innovate, enabling students to gain hands-on experience in a high-tech industrial setting, and even becoming a training ground for budding entrepreneurs. In general, the level of cooperation for incubator programs should include joint submission of proposals to raise funds from state, Federal, or private sources.

A modern version of the 1870 Hatch Act that established the cooperative extension programs would be appropriate for enhancing high technology in this country. Currently, the Department of Commerce has a related program in place, the Manufacturing Extension Partnership, which should be expanded and modified to more effectively enable the development of nanotechnology.

To the extent that industry pays the cost of university research, the issue of intellectual property rights needs further discussion and investigation, because this represents a significant barrier to the development of strong industry-university relationships. It is essential that universities and industry work together to understand their mutual problems and develop solutions that encourage the transfer of technology to their mutual benefit. The Semiconductor Research Corporation has considerable experience in the area of intellectual property, which may be useful to other companies and industry consortia. Models at CalTech and Rutgers should be reviewed.

11.4 SCIENTIFIC AND TECHNOLOGICAL INFRASTRUCTURE

Infrastructure for Research and Development

National equipment user facilities such as NNUN (see Section 11.7.4) offer a partial model solution to the infrastructure problems described in Section 11.2. It is essential that a network of inexpensive and "user-friendly" user facilities be established that brings together the strategic components of activities in the physical sciences (microelectronic technologies such as CMOS and III-V semiconductor optoelectronics, organic and polymer materials, MEMS, displays, etc.) with the fundamental research activities in biology. These labs should be modular and flexible, staffed by professionals, and located where they are easily accessible to university, industry, and national lab users at a reasonable cost. Existing NNUN sites must broaden their capabilities, and the NNUN model must be extended to open many existing labs to outside users who are presently excluded. The NNUN charter already contemplates this, but funding must be provided to defray the additional costs of servicing outside users at the newly "opened" laboratories.

In addition to processing and fabrication capabilities, laboratories in research centers must make available characterization and measurement capabilities at the leading edge. For example, a central national facility having state-of-the-art scanning probe techniques of use in physics, engineering, and biology research activities should be part of this network.

In addition to the NNUN model, nanotechnology development will require a prototype fabrication facility located at a national laboratory such as Sandia National Laboratories, or at a company. This facility must be modular to accommodate MEMS, optical, chemical, and biological systems, in parallel with modern microelectronics technologies such as CMOS.

Encouragement of long-term nanotechnology and nanoscience R&D in industry is highly desirable. Infrastructure development for both start-up companies and existing companies should be stimulated by policies that facilitate a long-term focus. Furthermore, policies and funding programs should be initiated to ensure that, wherever possible and appropriate, there is sharing of nanoscience and technology R&D facilities among universities, government laboratories, and industry. In addition, as discussed in Section 11.3, there should be an emphasis on fellowships, traineeships, and internships to encourage cross-pollination of ideas among these three R&D sectors.

Education

It is not clear that the educational problems described briefly in Section 11.2 represent an area for Federal Government action, but programs could be devised that provide incentives to correct these situations and could be incorporated into solicitations for funding.

Modes of support. It must be emphasized that support of research at all levels, including single investigators, small groups, and large centers and institutes, is essential; nevertheless, multidisciplinary research centers address some of the specific issues necessary for technological education. They provide both horizontal and vertical integration of education, with students at all levels of their training interacting: undergraduate and graduate students, postdocs, and junior and senior faculty. Involvement in a research center provides a student with breadth of experience in an environment where researchers in related fields interact and work on common problems, while the student’s own research still provides the necessary depth of experience.

Outreach. To generate and maintain public support for nanostructure science and technology, significant outreach activities must be undertaken. These activities must involve students at all levels (college and pre-college), and should include a general effort to popularize this research. The NSF emphasis on educational outreach is producing significant educational benefits in current NSF centers.

Curriculum development. Curriculum development is most important to enable interdisciplinary training, particularly if a marriage between the physical and biological sciences is to become a reality. One approach might be to make some form of curriculum development a requirement for research center funding.

As an example of possible curricular changes, consider electrical engineering (EE). EE departments should be aware of the potentials, and should contribute to the development, of design-fabrication and test techniques for nanoelectronics. Choices to be made include the following:

1. Should students be allowed to major in design, fabrication, and test, or only in design and test?
2. If fabrication is not included, should cooperation with a “foundry” be recommended?
3. If fabrication is included, is top-down or bottom-up technology preferred?
4. Depending on the availability of fabrication technology, either the QMOS (quantum metal oxide semiconductor) or QCA (quantum cellular automata) approach could be chosen. It is recommended that the construction of a CAD-T (computer-aided design and test) system be established for circuit level design and testing of nanoelectronic devices and circuits.
5. The construction of CAD-T systems should involve parallel research activities in several areas: device modeling, dynamic circuit simulation, device and interconnection (layout) design, and device and circuit characterization.

11.5 R&D INVESTMENT AND IMPLEMENTATION STRATEGIES

Nanotechnology R&D requires a balanced, predictable, strong, but flexible infrastructure to stimulate the further rapid growth of the field. Ideas, concepts, and techniques are moving at such an exceedingly rapid pace that the field needs coordination and focus from a national perspective. Demands are high, and the potential is great for universities and government to continue to evolve and transition this science and technology to bring forth the technological changes that will enable U.S. industry to commercialize many new products in all sectors of the economy. Even greater demands are on industry to attract new ideas, protect intellectual property, and develop appropriate products.

Tools must be provided to investigators in nanotechnology for them to carry out state-of-the-art research to achieve this potential and remain competitive. Centers with multiple grantees or laboratories where these tools would be available for this support should be established at a funding level of several million dollars annually. In addition to university- and government-led centers and networks, co-funding should be made available to industry-led consortia that will provide a degree of technology focus and different areas of relevance that are not always present in academic-led consortia. These centers should also have diverse research teams that will be effective in different scientific disciplines. Funding is needed for supporting staff to service outside users at existing and new centers. We should also investigate means to achieve the remote use of these facilities. Funding mechanisms that encourage centers and university-national laboratory-industrial collaboration should be emphasized, as well as single investigators who are tied into these networks.

Support to single investigators should provide a corresponding level of personnel and equipment support. University grants should encourage work among research groups to make maximum use of concepts and ideas being developed in other disciplines. The infrastructure must include building links between researchers, developers, and users of nanotechnology innovations. The focus must be on developing critical enabling technologies that will have significant value added in many industries.

It will also be necessary to fund training of students and support of postdocs under fellowships that will attract some of the best students available. Students should receive multidisciplinary training in various nanotechnology fields. Both organizational attention and funding should also be devoted to ensuring the open exchange of information in multidisciplinary meetings and rapid publication of results through, for example, workshops and widely disseminated summaries of research.

11.6 PRIORITIES AND CONCLUSIONS

Because of the fundamental and highly interdisciplinary nature of research and development of nanostructures, a broad and balanced approach to research funding and user facilities should be established in this country. It is recommended that nanostructure research be given the highest priority for a Federal high technology funding initiative.

Fostering collaboration between scientists and engineers in academe, private sector, and government laboratories is a priority. Multidisciplinary R&D partnerships through programs such as SBIR, STTR, ATP, and DARPA, as well as incubators at universities, should be encouraged. Industry and universities should be encouraged to participate in a review of intellectual property rights issues.

Funding of fellowships, traineeships, and internships not tied to one discipline at all levels—from high school and college students through senior investigators—is necessary to ensure free flow of ideas among disciplines, areas of relevance, and R&D sectors.

11.7 PRESENT U.S. NANOTECHNOLOGY EFFORTS

Included below are a number of examples of ongoing programs in the U.S. Government and university laboratories and in private industry. Some are merely noted; others are described in greater detail. The opinions expressed to the IWGN were diverse, as is illustrated by the statements presented below. Despite the successes highlighted here, a number of weaknesses in the U.S infrastructure, such as insufficient measuring and fabrication equipment for R&D and smaller efforts in areas such as nanodevices and ultraprecision engineering, may put the United States behind in the international effort to harness the discoveries. The centers and facilities outlined below exemplify some successful models for further development of the field. Section 11.7.2 lists a number of published accounts of cutting-edge nanoscience research selected by the authors of this chapter.

11.7.1 Federal, Industry, and University Research Programs on Nanoscience, Engineering, and Technology in the United States (selected by the chapter authors)

Contact persons: J.L. Merz, Notre Dame University, and A. Ellis, University of Wisconsin (for additional references see Siegel et al. 1999, NSTC Report)

Federal and Industry Research Programs

California Molecular Electronics Corporation (CALMEC): Molecular Electronics

Defense Advanced Research Projects Agency (DARPA): The Ultra Electronics Program (http://www.darpa.mil/mto/ultra/index.html)

Foresight Institute: Nanotechnology (http://www.foresight.org); (http://www.nanothinc.com/)

Hewlett Packard Lab: Teramak Program

IBM: Nanotech program (http://www.almaden.ibm.com/vis/vis_lab.html), with its corresponding laboratory abroad, Zurich Research Laboratory, where research is underway on microscopy at the atomic level

MITRE Corporation: Nanoelectronics and nanocomputing (http://www.mitre.org/technology/nanotech)

Molecular Manufacturing Enterprises, Inc. (MMEI)

Molecular Nanotechnology NanoLogic, Inc.: Integration of nanotechnology into computers

Nanophase Technologies Corporation

NanoPowders Industries (NPI)

Nanotechnology Development Corporation

NASA: Nanotechnology, nanoelectronics (http://www.ipt.arc.nasa.gov)

National Institute of Standards and Technology (NIST): Nanostructure fabrication

Naval Research Laboratory (NRL): Nanoelectronics processing facility

National Science Foundation (NSF): Partnership in Nanotechnology; Nanoscale processes in biological systems (updated programs on the Web site: http://www.nsf.gov/nano)

Office of Naval Research (ONR): Nanotechnology, nanoelectronics

Raytheon Co.: Nanoelectronics

Texas Instruments: projects on QMOS program and TSRAM (tunneling-based static RAM)

Xerox Palo Alto Research Center (PARC): Nanotechnology, molecular nanotechnology (http://nano.xerox.com/nano)

Zyvex Co.: Molecular manufacturing

Universities

Arizona State University: Nanostructure Research Group

CalTech: Materials and Process Simulation Center (http://www.theory.caltech.edu/~quic/index.html)

Cornell University: Cornell Nanofabrication Facility (http://www.nnf.cornell.edu); NSF Science and Technology Center for Nanobiotechnology (http://www.research.cornell.edu/nanobiotech/)

Georgia Institute of Technology: Nanocrystal Research Laboratory; nanostructure optoelectronics

Johns Hopkins University: Center for Nanostructured Materials (http://www.pha.jhu.edu/groups/mrsec/main.html)

Massachusetts Institute of Technology: NanoStructures Laboratory (http://www-mtl.mit.edu/MTL/NSL.html)

National User Facilities (NSF sponsored) in x-ray synchrotron radiation, neutron scattering, and high magnetic fields provide access to major facilities for the benefit of researchers in a wide range of science and engineering fields including nanoscience and engineering (http://www.nsf.gov/mps/dmr/natfacil.htm)

New Jersey Institute of Technology: Nonlinear Nanostructures Laboratory (NNL)

NNUN, a partnership involving NSF and five universities (Cornell University, Stanford University, UC Santa Barbara, Penn State University and Howard University) (see Section 11.7.4 below and http://www.nnun.org/)

Oxford Nanotechnology (MA): Molecular nanotechnology, nanolithography

Pennsylvania State University: Nanotechnology

Princeton University: Nanostructure Laboratory

Rensselaer Polytechnic Institute: Nanolab

Rice University: Center for Nanoscale Science and Technology (fullerenes)

Stanford University: Stanford National Nanofabrication Users Network (NNUN) (http://snf.stanford.edu/NNUN); (http://feynman.stanford.edu/qcomp)

University of California, Santa Barbara: NSF Science and Technology Center for Quantized Electronic Structures (QUEST) (http://www.quest.ucsb.edu)

University of Illinois at Urbana-Champaign: Beckman Institute (http://130.126.116.205/research/menhome.html); Molecular and Electronic Nanustructures Group

University of Notre Dame: Center for Nanoscience and Technology

University of Washington: Center for Nanotechnology

University of Wisconsin at Madison: Center for Nanostructured Materials and Interfaces (http://mrsec.wisc.edu)

Washington State University: Nanotechnology Think Tank

Yale University: Optoelectronic structures/nanotechnology

11.7.2 Sources of Information on Nanostructures (selected by the chapter authors)

Contact person: J.L. Merz, Notre Dame University

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11.7.3 Samples of Courses on Nanoscale Science and Engineering Offered in U.S. Universities

Contact persons: A. Ellis, University of Wisconsin, Madison, and M.C. Roco, National Science Foundation

Advanced quantum devices, University of Notre Dame, EE 666

Nano-course, Cornell Nanofabrication Facility (A. Clark, M. Isaacson)

New technologies, University of Wisconsin, Madison (R. Hamers)

Nanostructured materials, Rensselaer Polytechnic Institute (R.W. Siegel, P.M. Ajayan)

Colloid chemical approach to construction of nanoparticles and nanostructured materials, Clarkson University (J.N. Fendler)

Nanoparticles processes, Yale University (D. Rosner)

Nanorobotics, University of Southern California (A. Requicha)

Nanotechnology, Virginia Commonwealth University (M. El-Shall)

Chemistry and physics of nanomaterials, University of Washington (Y. Xia)

Scanning probes and nanostructure characterization, Clemson University (D. Correll)

Nano-scale physics, Clemson University (D. Correll)

11.7.4 NNUN Network

Contact person: J. Plummer, Stanford University

Figures 11.2-11.5 outline the basic facts about the National Nanofabrication User's Network (NNUN), established in 1994 by NSF at Cornell University, Stanford University, Penn State University, University of California in Santa Barbara, and Howard University.

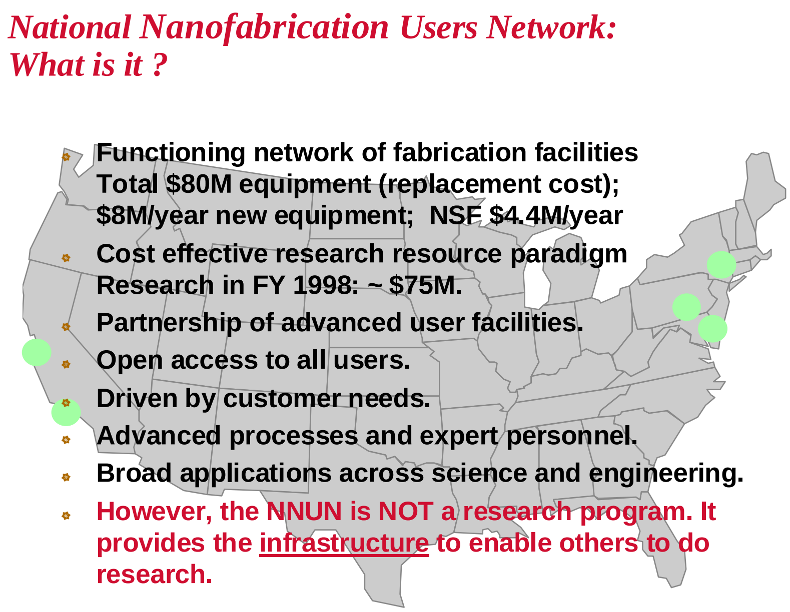

Figure 11.2. National Nanofabrication Users Network.

NNUN:
Network Vision

- **Productive "sand box" for**
  - **new approaches to nanofabrication**
  - **new applications of nanofabrication**
- **Education:**
  - **training**
  - **disseminate results**
  - **technology transfer**
- **Responsive to user needs.**
- **Sensitive to new and developing areas.**
- **Maintain leading edge nanotechnology.**
- **Catalyze new developments in nanotechnology.**

Figure 11.3. NUNN: Network Vision.

NNUN: What Does it Provide?

- Lithography-based μm & nm-scale science and technology.
- State-of-the-art facilities, equipment, & processes.
- Enables state-of-the-art research in broad areas.
- Efficient use of expensive resources.
- Critical mass:
  - equipment, personnel, facilities, fabrication expertise
- Outreach to new users and new disciplines.

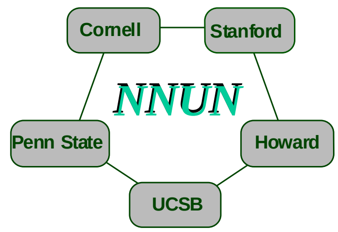

Figure 11.4. NNUN: What does it provide?

NNUN Nodes

- Currently 5 nodes which provide basic micro & nanofabrication capability + particular expertise due to equipment and local users.

CNF	• General micro & nanofabrication • Electron beam lithography
SNF	• General micro & nanofabrication • Si devices and technology
Howard	• Wide band gap semiconductors
PSU	• General micro & nanofabrication • Nanofabrication in novel materials
UCSB	• Dry etching and III-V semiconductor structures

Figure 11.5. NNUN nodes.

11.7.5 The Center for Quantized Electronics Structures (QUEST)

Contact person: E. Hu, University of California, Santa Barbara

QUEST, the Center for Quantized Electronic Structures (http://www.quest.ucsb.edu), is a National Science Foundation Science and Technology Center (www.nsf.gov/od/oia/stc), established in 1989 at the University of California at Santa Barbara (UCSB). QUEST's focus is a frontier field in nanostructure science and technology: the formation and study of "quantum structures." These are structures that generally have sizes sufficiently small that novel electronic, optical, and magnetic behavior emerges, which in turn can provide the basis for entirely new device technologies. QUEST integrates the research efforts of a multidisciplinary faculty from the departments of chemistry, chemical engineering, electrical and computer engineering, physics, and materials (see Figure 11.6). The work of QUEST spans the full range of growth and synthesis of quantum structures, characterization of their basic properties, and utilization of quantum structures in novel device schemes.

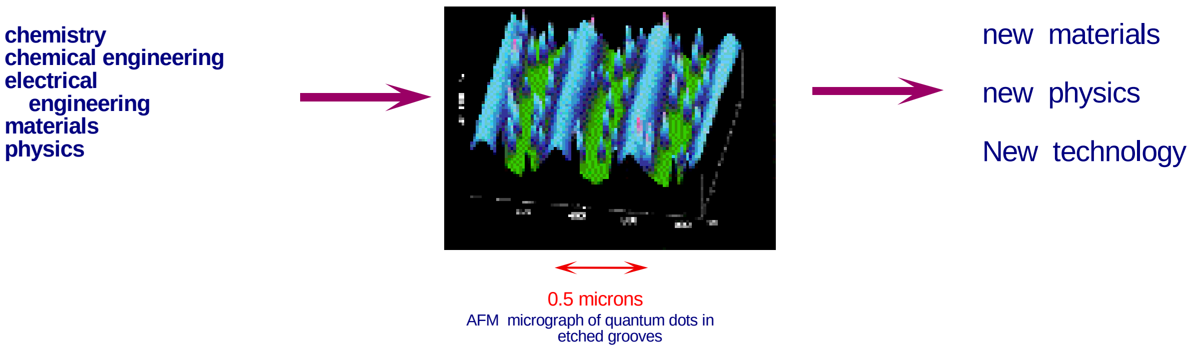

Figure 11.6. Science and technology at the atomic level.

QUEST Research

QUEST's focus has been the exploration of the novel physical and chemical properties of low-dimensional structures: where one or more of the structure's critical dimensions is below about 100 nanometers. It is at those lengths that the quantum mechanical nature of the material becomes more evident, and where the structure dimensions become equal to or less than important physical parameters such as the elastic mean free path for electrons. By controlling the critical dimensions of a structure, QUEST researchers hope to alter limitations to electronic transport and optical efficiency, in essence providing new materials that will sustain new device technologies. Although the majority of QUEST research has focused on quantum structures fabricated using compound semiconductors, the scope of the research is broadening to encompass a variety of other materials including oxides, superconductors and magnetic materials.

QUEST research strives to address the full range of issues necessary in spanning the science and technology of quantum structures. These include the following:

- The problems involved in the growth and fabrication of quantum structures
- The underlying physics and chemistry of these structures—what can be learned about their electronic, magnetic and optical properties
- The possible technological applications of quantum structures that may result once their behavior is well understood and controlled

The philosophy underlying QUEST's research strategy is illustrated in Figure 11.7, which represents the continuous, closely coupled interactions between fabrication, characterization, and simulation of quantum structures that takes place. The boxed text describes the critical challenges to be met in each area of research.

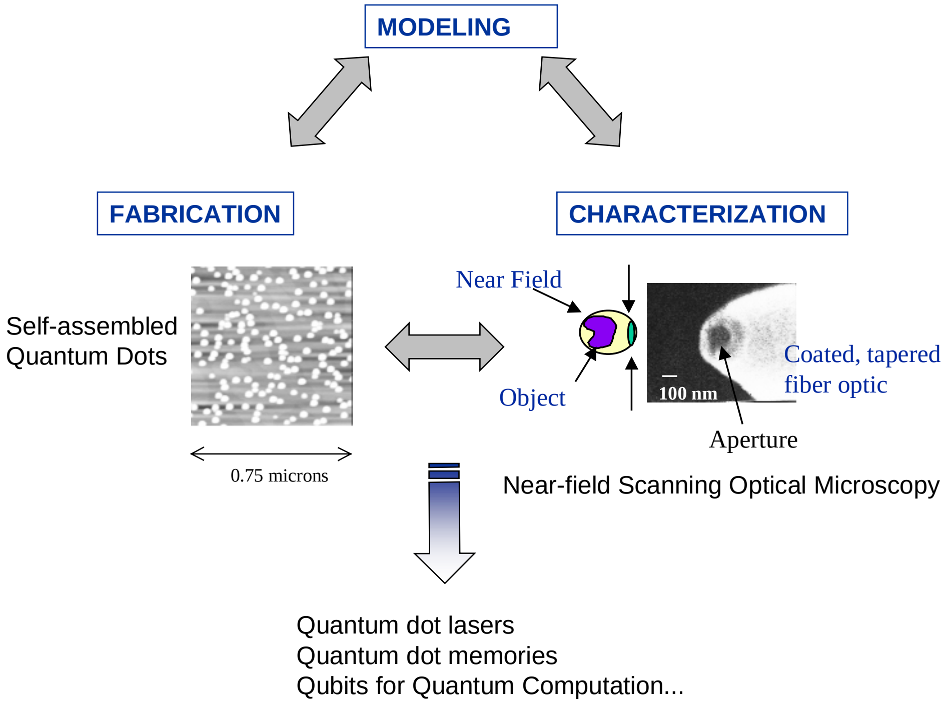

Figure 11.7. A continuous cycle of interactions.

QUEST research is supported by world-class laboratories that include unique crystal growth and materials synthesis capabilities, a 3,500 sq. foot clean room with a Class-100 lithographic capability, and state-of-the-art fabrication processes. These latter include e-beam lithography and various dry etch and deposition processes. In addition, QUEST researchers utilize laboratories for low-temperature, optical, high-speed, and magnetic measurements, and they also have access to sophisticated surface science labs and make use of the Free Electron Laser at UCSB.

QUEST currently receives ~$3 million/year from NSF, along with additional industry and University funds for related work.

11.7.6 Distributed Center for Advanced Electronics Simulations (DesCArtES)

Contact person: K. Hess, University of Illinois

The NSF-supported Distributed Center for Advanced Electronics Simulations (DesCArtES) consists of teams at Arizona State University, Purdue University, Stanford University, and the University of Illinois at Urbana-Champaign. Its mission is to attack key research and educational challenges for electronic devices and materials by complementing theory and experiment with large-scale computation. The focus, engineering-oriented but long-term, is on collaborative theme projects addressing (1) atomic scale effects in electronics, (2) silicon technology beyond the roadmap, and (3) optoelectronics. In addition to its core research efforts, DesCArtES provides outreach and leadership to the electronics research community through intellectual networking, network-based simulation and collaboration, and educational programs with input from industrial and Federal laboratories.

DesCArtES is co-directed by Karl Hess of the University of Illinois and Robert Dutton of Stanford. Umberto Ravaioli (Illinois) oversees research liaison and outreach activities, and Mark Lundstrom (Purdue) oversees educational outreach. To complement its core activities, partnerships have been formed with industrial researchers at a number of companies, including Lucent Bell Laboratories, Hewlett-Packard, Motorola, and Raytheon. An industrial advisory board has been formed to guide the center. DesCArtES has strong ties to several centers and organizations, including the National Computational Science Alliance (NCSA) for high-performance computing and the National Nanofabrication User's Network (NNUN) to connect with academic experimentalists. Collaborative projects are also underway with the Jet Propulsion Laboratory and the NASA Ames Research Center. A computational electronics "hub" that makes advanced simulation tools available to experimentalists and students has been deployed. The network already serves a worldwide user base. Figure 11.8 summarizes the core partnerships within DesCArtES.

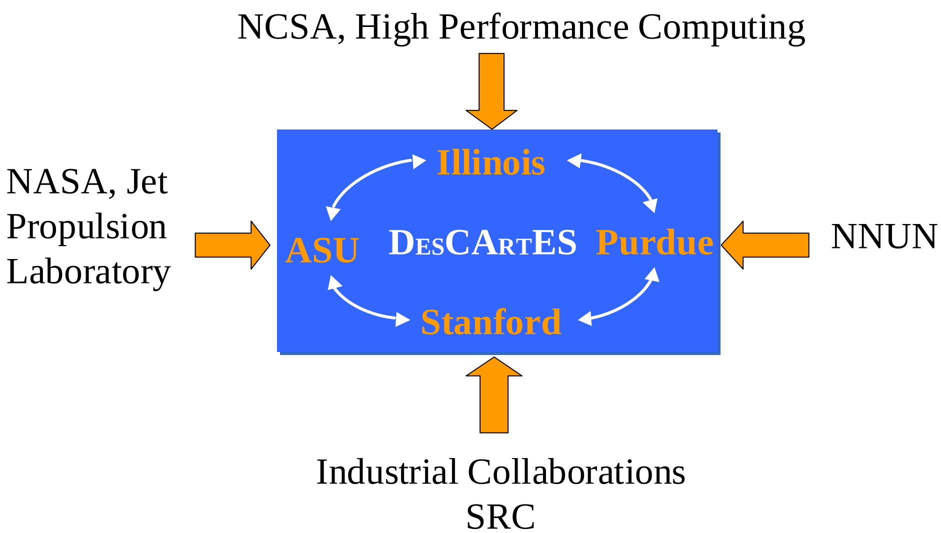

Figure 11.8. Distributed Center for Advanced Electronics Simulations (DesCArtES).

11.7.7 Nanoscience and Engineering at Materials Research Science and Engineering Centers (MRSEC Network)

Contact person: T. Weber, National Science Foundation

In 1999, nanoscale science and engineering is an area of focus in all 28 NSF Materials Research Science and Engineering Centers (MRSECs) funded by NSF. The centers are highly interdisciplinary, with the over 600 faculty participants coming from over a dozen academic departments. Approximately 75% of the annual budget of $45.5 million is targeted toward nanoscience and nanotechnology-related areas. The study of biomaterials, including biomimetic materials, which are synthesized based on examples provided by nature, is a very rapidly growing area of nanoscience and MRSEC research. Currently, extensive research in this area is carried out at eight centers, two of which are described below.

The work on abalone shell at the MRSEC at the University of California Santa Barbara draws faculty from materials chemistry, chemical engineering, physics, mechanical engineering, and molecular genetics fields. This group has been investigating the reasons that the abalone seashell is 3,000 times more fracture resistant than the basic calcium carbonate material that is the dominant shell ingredient. The group discovered that the secret lies in the polymer "glue" holding the layers of the shell together. Using atomic force microscopy techniques of pulling on single molecules of the polymer it has been shown that the polymer is made up of "knots" that unravel, one at a time, as an increasing force is applied. The stress is therefore relieved internally in the polymer molecule before the entire shell breaks apart. This discovery has allowed the UCSB researchers to propose the basic ingredient for making a "molecular" adhesive, with properties that mimic those of the natural product. This discovery is likely to have far-reaching impact in the technology of adhesives.

The University of Wisconsin, Madison, MRSEC is focused on nanoscale properties of semiconductors and high temperature superconductors. Through these efforts, which involve extensive materials growth and characterization capabilities, the center has also instituted an aggressive new program, funded out of MRSEC "seed" funds for innovative projects, on the fabrication of nanostructured surfaces as templates to study the growth of biological cells, in particular corneal epithelial cells. The focus and hypotheses for this "seed" project are noted in Figure 11.9. Although the project is still in its early stages, its researchers have been able to create synthetic templates that can serve as substitutes for the equivalent in a living organism. They have observed changes in the growth of cells based on the nanoscale substrate structure that are of fundamental importance in biodiversity and bioengineering.

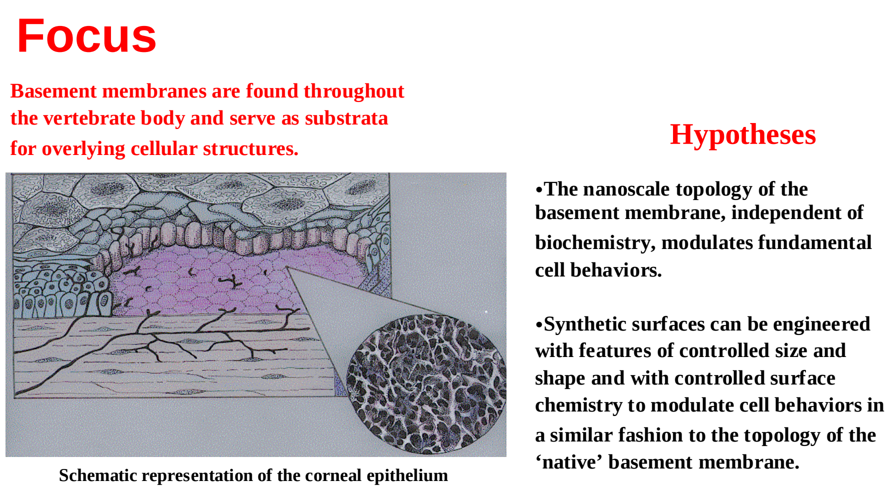

Figure 11.9. The influence of substrate topography on cell growth (©courtesy C.J. Murphy, Univ. Wisc.).

11.7.8 Nanotechnology at Sandia National Laboratories

Contact person: S.T. Picraux, Sandia National Laboratories

Sandia National Laboratories is a multiprogram Department of Energy (DOE) laboratory with 7,500 employees. Its principal mission is nuclear weapons stewardship. Sandia science and technology research supports a wide range of activities, including national security, nonproliferation, energy, and environmental programs. In accomplishing these tasks, the staff members interact extensively with industrial, academic, and government partners. Advances in nanoscience and technology are benefiting DOE research and development activities. The manipulation of the nanostructure of materials enables unique properties to be achieved for applications ranging from microlocks for weapons to high-efficiency photovoltaics, and from microchemical sensor systems to radiation-hardened microelectronics.

Integrated microsystems provide a striking example of the growing importance of nanotechnology. Microsystems are collections of small, smart devices that not only think (i.e., process information) but may also sense, act, and communicate. They combine microelectronic, photonic, micromechanical, and microchemical devices to create new generations of low cost miniature and highly reliable systems. Although they are built at the micron to centimeter dimensional scales, their performance depends on the control of materials properties at the nanoscale. Sandia's leadership in this emerging field is built on the ability to integrate this broad range of technologies. Across the wide range of activities from research to application, about 500 people are working in this area. Microsystems provide an excellent opportunity to combine nanotechnology advances with Sandia's inherent strengths in microfabrication.

To accomplish these tasks, special facilities and scientific expertise are maintained in the areas of nanoscience, microfabrication, and integration, including materials synthesis and processing; micro- to nanoscale probes; microelectronics; photonics; microsensors; microelectromechanical devices (MEMS); and computer, information, and systems science.

Examples of incorporating nanoscience into new technical capabilities for defense and energy applications at Sandia are wide ranging. For example, self-aligned monolayers provide dramatic improvements in surface tribology to reduce sticking and wear for MEMS devices. Vertical cavity surface emitting lasers (VCSELs) developed at Sandia use layered quantum well structures to produce highly efficient light sources for low power applications. Nanoclusters such as 3 nm diameter crystals of MoS_2 are being explored for their ability to photocatalyze the oxidation (destruction) of organic pollutants using only visible room light. Organically functionalized mesoporous structures are being integrated into micromachined devices on a centimeter-sized chip to provide thousand-fold chemical preconcentrators for on-chip analysis of chemical warfare agents.

The strength of such integrated capabilities is illustrated by the µChemLab™ project. In this exploratory project, a hand-held chemical sensing microsystem is being developed for detection of chemical and biological materials such as explosives and biological warfare agents. This system-on-a-chip approach involves preconcentration using nanostructured materials, separations with approximately one meter of spiral separating column embedded into a chip only 1 cm on a side, and then detection based on integrated optical fluorescence and/or piezoelectric acoustic wave detectors. The µChemLab™ depends upon integrating chemical, electronic, micromechanical, and photonic devices into microsystems. To achieve this broad integration goal, approximately 40 technical staff members from across the laboratory and an overall budget of $20 million (over 3 years) are currently focused on this project.

Increasingly we see that technical success depends on the ability of multidisciplinary teams to combine both the science and technology that cut across conventional disciplinary lines. Future technological advances in microsystems will depend upon discoveries in nanoscience and technology, combined with the ability to integrate technologies through low-cost, high-volume microfabrication methodologies (Figure 11.10), as can be done readily at a multipurpose national laboratory such as Sandia. Sandia's capabilities include, for example, 0.5 micron radiation-resistant Si IC design and fabrication, Sandia-developed five-layer MEMS device fabrication, growth and processing of photonic devices such as VCSELs, processing of novel new microchemical sensing devices, and a wide range of materials diagnostics, ranging from Sandia-developed new scanning probe techniques at the nanoscale to coupling first principles atomic scale modeling with microscale materials performance.

Nanotechnologies integration

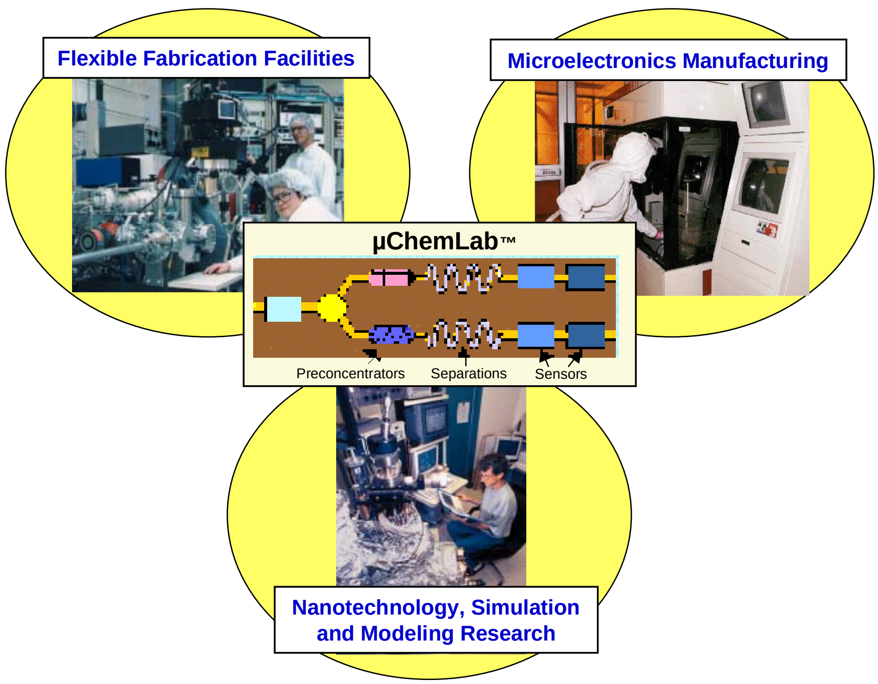

Figure 11.10. Nanotechnologies draw upon extensive multidisciplinary capabilities and a broad facilities base. The figure illustrates three key capabilities that are integrated together at Sandia: microelectronics manufacturing, flexible fabrication facilities, and nanoscale materials, simulation, and modeling research.

11.7.9 University of Notre Dame Center for Nanoscience and Technology

Contact person: J.L. Merz, University of Notre Dame

The Center for Nanoscience and Technology at the University of Notre Dame actively explores multidisciplinary fundamental concepts in nanoscience and engineering, with strategic emphasis on applications to unique functional capabilities. The center, established in 1998, integrates six research thrusts in molecular-based nanostructures: semiconductor-based nanostructures, device concepts and modeling, nanofabrication characterization, image and information processing, and function systems design. This effort cuts across four departments at Notre Dame: electrical engineering, computer science and engineering, chemistry and biochemistry, and physics, and it teams 24 senior faculty members along with their graduate students and postdoctoral researchers.

A major emphasis of the center is the concept of computing with quantum dots—quantum-dot cellular automata (QCA)—which is based on encoding binary information through the charge configuration of quantum-dot cells. The QCA notion has spurred further studies into nano-based cellular architectures for information processing that includes hierarchical functional design. The center also supports other initiatives in nanoscience and electronics, such as resonant-tunneling devices and circuits; photonic integrated circuits; quantum transport and hot carrier effects in nanodevices; and optical and high-speed nano-based materials, devices, and circuits.

The center has excellent on-site research facilities and capabilities including nanolithography and scanning tunneling microscopy; nanodevice and circuit fabrication; nanooptical characterization, including femtosecond optics and near-field scanning optical microscopy; electrical characterization at helium temperatures and in ten tesla magnetic fields; fifty gigahertz high-speed circuit analysis; and device and circuit simulation and modeling. In recent years, Federal grants received to support research in nanoscience and technology have totaled approximately ten million dollars, including two major grants from DARPA for Ultra molecular electronics ("Moletronics") programs, and several other awards from NSF, ONR, and the Army Research Office (ARO).

11.7.10 Nanophase Technologies Corporation: A Small Business Focused on Nanotechnology

Contact person: R.W. Siegel, Rensselaer Polytechnic Institute

Nanophase Technologies Corporation (NTC) was founded in late November 1989 by a scientist (R.W. Siegel) at Argonne National Laboratory (ANL) and ARCH Development Corporation (the technology transfer arm of ANL), and the University of Chicago, the DOE contractor for ANL. The company was a spin-off from a pioneering fundamental nanophase materials research effort in the Materials Science Division at ANL funded by the Department of Energy Basic Energy Sciences program.

Initial funding for NTC was supplied by ARCH, through its associated venture capital fund, and by the State of Illinois, through grants for new job creation. Subsequent funding was raised from a consortium of venture capital funds, and later also from high net worth private individuals and groups. The company went public with a successful IPO in late November 1997. An additional source of funding that was very important to NTC's development was an ATP grant from the Department of Commerce, which enabled the company to develop its patented physical vapor synthesis (PVS) process for manufacturing nanocrystalline materials in commercial quantities. This process was based on the laboratory-scale technology used at ANL from 1985 onward. NTC has also developed complementary nanoparticle coating and dispersion technologies, including its proprietary discrete particle encapsulation (DPE) process, as well as capabilities for superplastic forming of ceramic parts. Together, these technologies have enabled NTC over the past decade to enter a number of viable commercial markets. The company presently employs about 40 full-time workers (about 15 of whom hold advanced degrees) in its suburban Chicago facility.

NTC currently targets several markets: electronics (including advanced electronics, electromagnetic radiation protection, and advanced abrasives for chemical mechanical polishing); ceramic parts; specialty coatings and catalysts; and other technologically similar applications. In each of these market areas, NTC establishes collaborative relations with major corporate customers to develop and jointly implement nanoscale solutions for the customer's needs. In many cases, products developed to satisfy a particular vertical market need also have significant applicability across similar or horizontal markets. For instance, materials used in conductive coatings also have applicability for antistatic coatings and conductive strip carriers for color toners.

The applications for materials developed by NTC technology range from transparent protective coatings for CRT displays to highly engineered materials for chemical process catalysts. The NTC Web site provides current updates: http://www.nanophase.com. NTC is now focusing on, and will continue to emphasize, those applications where its nanoscale materials represent a technology breakthrough. As a nanomaterials company, NTC's continuing interest is to gather core technologies that provide the capability to service multiple major markets ranging from electronics to chemical processing.

11.7.11 Nanotechnology Infrastructure Capabilities and Needs in the Electronics Industry

Contact person: R.K. Cavin, Semiconductor Research Corporation

The electronics industry has a substantial interest in and history of exploring and exploiting nanotechnology in the development and fabrication of microelectronics. Metal lines as narrow as 10 nm can be printed in research, dielectrics as thin as 1 nm are being fabricated, and a variety of electron beam and atomic force metrologies are being used to characterize materials and structures at the atomic scale.

Future microelectronics opportunities for nanotechnology include engineering new materials integrated into conventional silicon chips (e.g., high permittivity, high-frequency permeability, high thermal conductivity, and high electrical resistivity). Other nanomaterials opportunities include self-assembly techniques related to new materials and nanometer-scale line printing. Opportunities also exist for nanotechnology to overcome scaling limits of current CMOS gate structures through the invention and development of radically new information processing technologies (e.g., FET replacement, ultra-high density memories, millimeter-wave devices). Applications that extend the capabilities of electronic systems can benefit from the innovative use of nanotechnology as well. These include mixed-function integration of new detectors, sensors, and optical and mechanical switches. Furthermore, hybrid integration of these devices (including digital and analog functions) also can be enabled by nanotechnology.

The electronics industry has an impressive array of capabilities and facilities related to nanotechnology. These include facilities for fabricating and characterizing complex nanostructures in electronic materials. Fabrication processes include epitaxial growth techniques (e.g., MBE, MOMBE, CBE, OMVPE, ALE), lithographic fabrication techniques (e.g., e-beam, EUV, X-ray) and characterization techniques (SEM, TEM, STEM, AFM, XPS, UPS, AES, EELS, etc.). The industry is also developing a new array of modeling tools to comprehend the quantum phenomena made possible by nanotechnology. An example of nanotechnology fabrication, the operation of quantum dot flash memory, is shown in Figure 11.11.

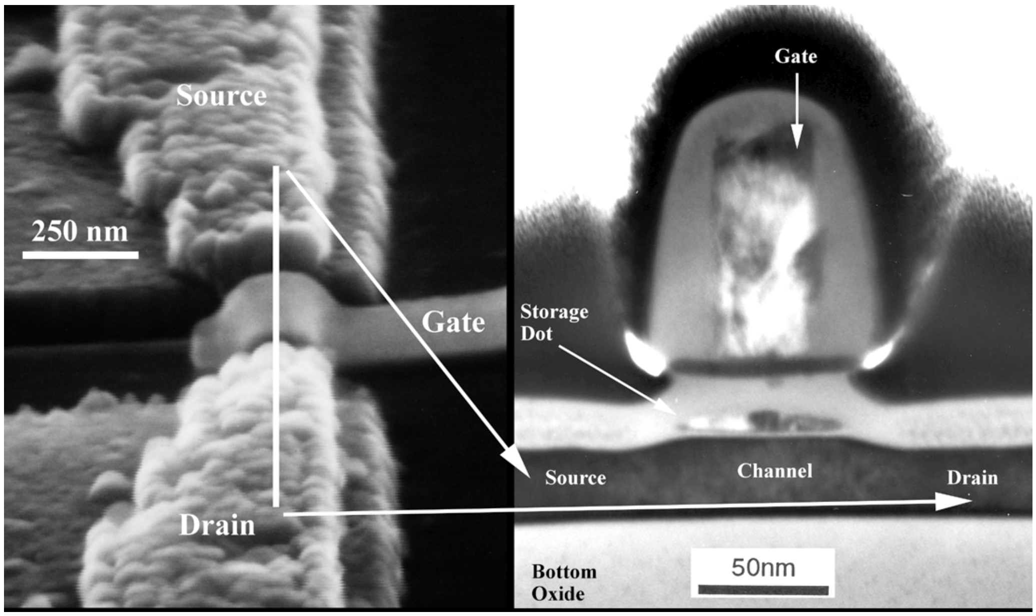

Figure 11.11. Room-temperature operation of a quantum-dot flash memory (reprinted with permission from Welser et al. 1997, ©1997 IEEE, courtesy of IBM).

11.7.12 Nanoscience and Nanotechnology at Lawrence Berkeley National Laboratory (LBNL)

Contact persons: M. Holm and M. Alper, Lawrence Berkeley National Laboratory

Lawrence Berkeley National Laboratory (LBNL) is a multiprogram DOE laboratory that conducts research addressing national needs in fields including the materials, chemical, earth, life, and environmental sciences and also energy efficiency, high energy, and nuclear physics. It is located adjacent to the University of California, Berkeley campus; 250 members of the Berkeley faculty lead Berkeley Lab research groups, 360 of their graduate students are trained and do their thesis research at LBNL, and 320 undergraduates are introduced to research in its laboratories. Each year, more than 2,000 guests come to work with Berkeley Lab staff and its unique research facilities. These include a wide variety of state-of-the art instruments developed at the laboratory and also five national user facilities, two of which have been designed, constructed, and operated by the DOE Office of Basic Energy Sciences: the Advanced Light Source, the world's brightest source of soft X-rays, and the National Center for Electron Microscopy, home to the country's highest-resolution transmission electron microscope.

Berkeley Lab was one of the first to develop strong nanoscience programs and has a number of ongoing activities (Figure 11.12). The lab has been notably successful in linking chemists, physicists, biologists, and materials scientists in its efforts. In 1991, a program was begun to develop techniques for synthesizing nanocrystals of semiconductors and metals of controlled size. A theory component studies electronic and optical properties of nanocrystals and nanometer-size conducting polymers.

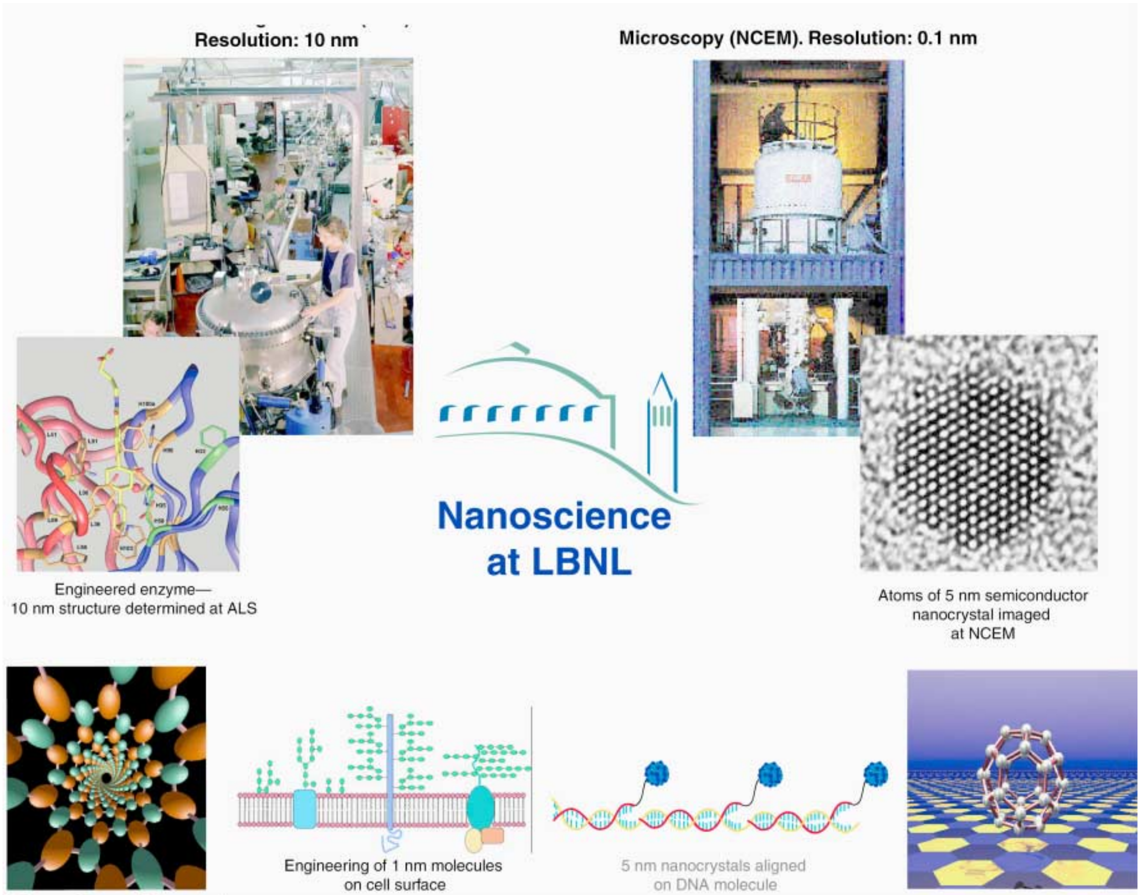

Figure 11.12. Nanoscience at Lawrence Berkeley National Laboratory.

Arrays of nanocrystals of defined spatial geometry have been fabricated at Berkeley Lab by attaching the crystals to strands of DNA of defined base sequence. A variety of techniques are employed to fabricate and study nanometer-size artificial magnetic structures. A team of experimentalists and theorists has predicted and synthesized nanostructures of carbon. They discovered the small C36 "buckyball" and nanotubes of rolled graphite that, depending on their structure, have either semiconducting or metallic properties. When linked, these tubes are postulated to behave as "nanodiodes." Lithographic techniques are used to build nanometer-size devices into which nanocrystals or nanotubes can be inserted. These are used to study the electronic and transport properties of these materials.

Investigators at Berkeley Lab have, for almost two decades, used optical methods to explore the dimensionality dependence of fundamental physical processes. Other groups are studying approaches for solving the difficult problem of introducing dopants into nanocrystals. A group is exploring the use of nanometer-size magnetic particles in high-sensitivity sensors.

Berkeley Lab was one of the first to develop a focused biomolecular materials program, recognizing that biological structures are nature's nanostructures. Enzymes are engineered through the introduction of specific alterations at the atomic level. Carbohydrates and related biomolecules are designed to control surface properties. Biologically inspired, nanometer-size polymers of specific structure and function, (dendrimers) are made “shape-persistent” with defined shape, chemical reactivity, and flexibility. They are being explored for their unique catalytic activity, light harvesting, energy transfer activity and other functions.

Tools are at the heart of cutting-edge research and the Berkeley program has a wide repertoire of advanced instrumentation. The Advanced Light Source, a unique third generation source of UV and soft X-ray photons, is utilized to give detailed structural and electronic information on, for example, polymers, semiconductors, layered materials, and proteins. The National Center for Electron Microscopy, with some of the most powerful microscopes in the world, provides images, for example, showing the uniform atomic distribution, faceting, and coatings of core structures of nanocrystals. In addition, LBNL’s vast experience in developing and using scanning probe technologies (e.g., STM, AFM) and spectroscopies is of great value to the research groups. Instruments have been developed to operate at low temperature, at high pressure, with femtosecond time resolution, and with single molecule resolution.

11.7.12 The Social Impact of Nanotechnology: A Vision to the Future

Contact person: J. Canton, Institute For Global Futures

To state that nanotechnology will have a profound impact on society would be a gross understatement. If we had tried to explain to an eighteenth century person how a television or a computer worked, let alone the Internet, we would have been considered mad. These innovations, though they seem routine today, offer only a hint of what is to come. We lose track of the fact that there have been more innovations that have changed society in the past fifty years than in the previous five thousand years. New tools such as computers and networks have empowered fantastic innovation. But all that has been accomplished in the past will seem small in the face of the changes brought by nanotechnology in the future.

Nanotechnology is a comprehensive design science that will give us powerful new tools that may change every aspect of society. This technology will place in our hands the ability to design matter at the molecular and atomic level. We will be able to eventually fabricate existing products on-demand and more inexpensively. More interestingly, using natural principles and processes, we will design products that have never existed in nature.

Two critical factors will emerge in society: how fast people adapt and how smart they become about the application of nanotechnology solutions. These factors will determine the competitiveness of individuals, organizations, and nations. Nanotechnology knowledge, how to develop it, and how to use it, will become a strategic asset. Those societies that support nanotechnology education, research, and development the fastest will thrive in the new millennium. Just as today’s digital technology drives personal and business success, nanotechnology will dominate the twenty-first century.

The general societal impact of nanotechnology will be felt in some of the following ways:

- Consumer and industrial products will be smaller, more durable, smarter, faster and less expensive due to the super-efficiency of nanoengineered materials and manufacturing.
- Healthcare will become less expensive, more accessible, and more effective at preventing disease, replacing human parts, and enhancing life. New drugs and diagnostic devices will be available. Nanobiology will empower people to live longer and healthier lives. Synthetic tissue and organs, genetic and biomolecular engineering, and "directed evolution" will emerge.
- Embedded intelligence will be everywhere: from chips in paper, to clothing that talks, to cars that self-generate their own energy, to Internet-ready devices that combine the functions of a TV, telephone, and computer. Everyone, anyplace, anytime, will be interconnected.
- Business will need to retrain workers with the skills necessary to survive in a new economic reality based on nano-products and nanotechnology knowledge. This is a paradigm shift that will demand knowledge of nano-engineering. Just as the Internet is forcing every business to become an e-business, every business in the twenty-first century will become a nano-business.
- Education will need to change entirely to address the fast development of nano-industries. The coming generations will need to be trained in nanoscience. Every educational discipline from engineering to chemistry to physics will require new learning.
- Nano-energy will make for both a cleaner and more fuel-efficient world. New engines for vehicles, fuel cells, and transportation will be possible.
- Food production will become nano-engineered, providing a bounty of inexpensive, nutritious, and appealing culinary choices that are less dependent on nature than on nanoscience.
- Work and careers will be deeply affected as people retool for a nanotechnology-enhanced economy that is less product-driven and more service and knowledge driven. Lifestyle choices will become more varied as nanotechnology changes the global economics of supply and demand.
- New choices will be developed for the augmentation of cognitive processes, and increase of physical and sensory performance.
- The virtual asset-based economics of living in a society that is dominated by nanotechnology will quickly reward those individuals and organizations that hold the intellectual properties to this new technology.

Nanotechnology's impact on society will be comprehensive, touching all aspects of lifestyle, quality of life, and community. Inevitably, nanotechnology will give people more time, more value for less cost, and provide for a higher quality of existence. The convergence of nanotechnology with the other three power tools of the twenty-first century—computers, networks, and biotechnology—will provide powerful new choices never experienced in any society at any time in the history of humankind.

The social impact of nanotechnology will need to be a managed-change process. Never has such a comprehensive technology promised to change so much so fast. A national policy on nanotechnology should include responsible oversight. Those organizations and citizens who are unaware of this impeding power shift must be informed and enabled so that they may adequately adapt.

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