Defense Nanotechnology Research and Development Programs

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EXECUTIVE SUMMARY

The DoD has a long history of successfully supporting innovative nanotechnology research efforts for the future advancement of warfighter and battle systems capabilities. Since the 1980s, DoD - including the Defense Advanced Research Projects Agency (DARPA), Office of Naval Research (ONR), Army Research Office (ARO) and the Air Force Office of Scientific Research (AFOSR) - initiated numerous research programs focusing on advancing science and technology below one micron in size. By the mid-1990s, DoD identified nanoscience as one of six Strategic Research Areas (SRAs) that would require a substantial amount of basic research funding on a long-term basis. Scientific breakthroughs and advances in the last few years demonstrate the potential for nanotechnology to impact a tremendous number of key aspects for future warfighting: chemical and biological warfare defense; reduction in weight of warfighting equipment; high performance materials for platforms and weapons; high performance information technology; energy and energetic materials; and uninhabited vehicles and miniature satellites.

In support of the National Nanotechnology Initiative, DoD is a member of the Nanoscale Science and Engineering Technology (NSET) subcommittee of the National Science and Technology Council's Committee on Technology. Twenty three federal departments and agencies are members of the NSET, including the Intelligence Community. The NSET meets monthly to coordinate the federal government's nanotechnology programs through the National Nanotechnology Coordination Office (NNCO).

The DoD nanotechnology program is summarized by seven program component areas (PCAs), relating to areas of investment that are critical to accomplishing the overall goals of the National Nanotechnology Initiative (NNI): fundamental nanoscale phenomena and processes; nanomaterials; nanoscale devices and systems; instrumentation research, metrology, and standards for nanotechnology; nanomanufacturing; major research facilities and instrumentation acquisition; and societal dimensions. Significant progress has been made toward achieving the goals of these component areas, and the DoD is extremely well positioned to discover and exploit unique phenomena, which occur only at nanoscale dimensions, for the development of novel applications to enhance warfighter and battle systems capabilities.

The DoD investment in each of these seven program component areas is currently adequate in light of the investments being made by ten other government agencies including NSF, DOE, and NIH. However in future years, as we transition from basic research to a greater focus on applications, additional investment from DoD will be needed to supplement the NNI in nanomaterials, nanoscale devices and nanoscale systems research. This additional DoD investment will accelerate the ability to incorporate and design nanoscale phenomena into advanced materials with revolutionary properties for a broad spectrum of target applications. Focused investment in the Small Business Innovative Research (SBIR)/Small Business Technology Transfer (STTR) and Manufacturing Technology (MANTECH) programs will likely also be necessary to adequately facilitate transitioning of nanotechnology research results to technologies for DoD requirements.

I. Review of DoD Nanotechnology Programs

The DoD has a history of supporting research and development activities in order to meet its national security mission needs. Included in this effort is support for research in nanoscience and nanotechnology. In the early 1980s, DoD initiated the Ultra Submicron Electronics Research (USER) program that focused on electronic devices well below one micron. In the early 1990s, the Defense Advanced Research Projects Agency (DARPA) initiated a program called Ultra Electronics and Ultra Photonics (ULTRA) that focused on ultra fast and ultra dense electronic devices and chips and scaled photonic devices. At the same time, the Office of Naval Research (ONR) launched an Accelerated Research Initiative on interfacial nanostructures, and the Army Research Office (ARO) launched a nanoscience university research initiative. In the mid-1990s, ONR launched a program on nanostructured coatings, and DARPA launched the Simulation of Bio Systems (SIMBIOSYS) program to focus on bio-info-micro computing which has a major nanotechnology component. Since the mid-1990s, DoD has identified nanoscience as one of six Strategic Research Areas (SRAs) for basic research funding on a long-term basis.

The Fiscal Year 2003 National Defense Authorization Act, Section 246, requires the Director of Defense Research and Engineering (DDR&E) to submit an annual report on the nanotechnology programs within the Department of Defense (DoD) for fiscal years 2004, 2005, 2006, and 2007. These reports are to include the following: (1) A review of the long-term challenges and specific technical goals of the program, and the progress made toward meeting those challenges and achieving those goals; (2) An assessment of current and proposed funding levels, including the adequacy of such funding levels to support program activities; (3) A review of the coordination of activities within the Department of Defense, with other departments and agencies, and with the National Nanotechnology Initiative; (4) An assessment of the extent to which effective technology transition paths have been established as a result of activities under the program; and (5) Recommendations for additional program activities to meet emerging national security requirements.

The 21st Century Nanotechnology Research and Development Act (Public Law 108-153) called for the National Science and Technology Council (NTSC) to prepare a strategic plan for the Federal nanotechnology R&D program. In response to this mandate, the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the NSTC, with significant DoD member participation, prepared an updated National Nanotechnology Initiative (NNI) Strategic Plan in December 2004, which is expected to guide the NNI for the next five to ten years. The investment strategy described in the NNI Strategic Plan identifies and defines seven major subject categories of investment, or program component areas (PCAs), relating to areas of investment that are critical to accomplishing the overall goals of the NNI. Since these seven PCAs also constitute a comprehensive taxonomy of the DoD investment, the 2005 review of defense nanotechnology research and development programs will be organized by these seven PCAs:

1. Fundamental Nanoscale Phenomena and Processes
2. Nanomaterials
3. Nanoscale Devices and Systems
4. Instrumentation Research, Metrology, and Standards for Nanotechnology
5. Nanomanufacturing
6. Major Research Facilities and Instrumentation Acquisition
7. Societal Dimensions

A. Long Term Challenges and Program Goals

Since the DoD is a mission oriented agency, its nanotechnology programs are distinguished from other federal agencies in that the program activities are simultaneously focused on scientific and technical merit and on potential relevance to DoD. The overall technical objective of these programs is to develop understanding and control of matter at dimensions of approximately 1 to 100 nanometers, where the physical, chemical, and biological properties may differ in fundamental and valuable ways from those of individual atoms, molecules, or bulk matter. The overall objective for DoD relevance is to discover and exploit unique phenomena at these dimensions to enable novel applications enhancing warfighter and battle systems capabilities. Specific long-term challenges and program goals for each of the seven nanotechnology program component areas are described below.

<u>Fundamental Nanoscale Phenomena and Processes</u>

NNI Long-Term Challenges: The discovery and development of fundamental knowledge pertaining to new phenomena in the physical, biological, and engineering sciences that occur at the nanoscale; the elucidation of scientific and engineering principles related to nanoscale structures, processes, and mechanisms.

DoD Program Goals include:

- To discover new phenomena and processes to enable breakthrough advantages for warfighter and battle systems capabilities.
- To develop robust strategies for synthesis, characterization, and assembly of individual nanostructures.
- To explore applications of nanostructures for revolutionary catalysts, scavengers, taggants and sensors.
- To elucidate fundamental aspects of phonon and electron transport in individual nanowires and two and three dimensional nanostructures as they relate to the development of high performance thermoelectric, thermionic, and photovoltaic devices for advanced solid state power generation, cooling, and thermal management.

<u>Nanomaterials</u>

NNI Long-Term Challenges: The discovery of novel nanoscale and nanostructured materials; the development of a comprehensive understanding of the properties of nanomaterials (ranging across length scales, and including interface interactions); the enabling of design and synthesis, in a controlled manner, of nanostructured materials with targeted properties.

DoD Program Goals include:

- To develop precision nanostructure synthesis techniques required to provide process control over quantum transport characteristics of devices utilizing nanostructured materials.
- To harness biological processes for low-cost synthesis and templating of designed nanostructures.
- To control and exploit interactions between synthetic and naturally-occurring (biological) materials.
- To develop nanoscale architectures to enhance local diffusion behavior, reaction kinetics, optical properties, and electrical properties.

Nanoscale Devices and Systems

NNI Long-Term Challenges: The application of principles of nanoscale science and engineering to create novel, or to improve existing, devices and systems; the incorporation of nanoscale or nanostructured materials to achieve improved performance or new functionality (note the systems and devices themselves are not restricted to this size).

DoD Program Goals include:

- To utilize breakthroughs in nanotechnology to provide revolutionary devices and systems to advance warfighter and battle systems capabilities.
- To establish a detailed understanding of nanoscale behavior related to electrochemical power source applications (batteries with enhanced discharge rate and energy density; high energy density capacitors), fuel cell catalysts, and electrode structures.
- To engage the DoD applied research and development communities to accelerate the transition of science discovery into DoD relevant technologies.
- To work with the Director, Defense Research and Engineering (DDR&E) Advisory Group on Electron Devices (AGED), US Navy groups developing technology plans for Navy Carrier Technology (CARTECH), Navy Submarine Technology (SUBTECH), and Navy Surface Technology (SURFTECH) programs, the Air Force Future Technology Branch, and the U.S. Army Research, Development and Engineering Command (RDECOM) Nanotechnology Working Group to examine future platform opportunities and requirements.

Instrumentation Research, Metrology, and Standards for Nanotechnology

NNI Long-Term Challenges: The development of tools needed to advance nanotechnology research and commercialization, including next-generation instrumentation for characterization, measurement, synthesis, and design of materials, structures, devices, and systems; the development of standards, including standards for nomenclature, materials, characterization and testing, and manufacture.

DoD Program Goals include:

- To develop breakthrough next-generation instrumentation for developing advanced nanotechnology-based materials and devices.
- To extend magnetic force microscopy and enable robust single spin measurement devices.
- To extend new measurement capabilities into innovative sensors for use in defense missions.

Nanomanufacturing

NNI Long-Term Challenges: The enabling of scaled-up, reliable, cost effective manufacturing of nanoscale materials, structures, devices, and systems; the development and integration of ultra-miniaturized top-down processes and increasingly complex bottom-up or self-assembly processes.

DoD Program Goals include:

- To guide and monitor the introduction of nanotechnology into military hardware.
- To identify appropriate opportunities to introduce nanomanufacturing into the DoD Small Business Innovative Research (SBIR)/Small Business Technology Transfer (STTR) and Manufacturing Technology (MANTECH) programs.
- To enable the synthesis, generation, and assembly of individual nanostructures using lessons drawn from biology, including use of viruses and related structures as templates for nanowires and for arrays of inorganic materials of particular interest.
- To develop affordable manufacturing approaches to nanostructured bulk materials.

Major Research Facilities and Instrumentation Acquisition

NNI Long-Term Challenges: The establishment of research facilities, acquisition of major instrumentation, and other activities that develop, support, or enhance the nation's scientific infrastructure for the conduct of nanoscale science, engineering, and technology research and development; the ongoing operation of major facilities and networks.

DoD Program Goals include:

- To provide advanced nanoscience instrumentation via the Defense University Research Instrumentation Program (DURIP).
- To provide DoD facilities and instrumentation capable of contributing to nanoscience research.

Societal Dimensions

NNI Long-Term Challenges: The identification and mitigation of potential risks to health and to the environment posed by nanotechnology (including those resulting from human, animal, or environmental exposure to engineered nanoscale materials, nanostructured materials, or nanotechnology-based devices and their byproducts); the development of relevant nanotechnology materials for schools, undergraduate programs, technical training, and public outreach.

DoD Program Goals include:

- To assure health and safety of war fighters utilizing future nanotechnology-based applications.
- To enable physicochemical characterization and toxicology for water, air and space environments.
- To sustain an investment strategy to enable a multidisciplinary education system capable of sustaining the skilled workforce needed to meet future defense needs.
- To assess, avoid and abate any adverse environmental or health impact from defense utilization of nanotechnology.

B. Progress in Meeting the Challenges and Goals

Significant progress has been made in meeting the long-term challenges and goals described for each of these seven nanotechnology program component areas. Specific accomplishments in each of these areas across the DoD nanotechnology programs are listed below.

Fundamental Nanoscale Phenomena and Processes

DoD research in this program component area (PCA) includes only those 6.1 research projects specifically addressing the synthesis, characterization, properties, or assembly of individual nanostructures.

Program Accomplishments include:

- Functional molecular “paddlewheels” have been fabricated, mounted on a gold surface, and forced to rotate by the application of an electric field. This prototype structure will be further explored for applications such as stopping intense laser pulses.
- The world’s fastest simulation tools for studying tunneling processes in nanoscale heterostructures have been developed and applied to the study of oscillations in resonant tunneling diodes and superlattices.
- A new computational method for predicting the transport properties of nanowires in the presence of disorder and foreign chemical species has been developed that allows the explicit inclusion of

helical symmetry in the underlying wire and hence opens up a new class of problems for treatment. Already these methods have been used to arrive at new criteria for designing semiconducting nanowires which can sustain ballistic transport over micron distances for potential uses in ballistic transistors.
- Novel algorithms to predict the selective phonon scattering by embedded metallic nanodot - semiconductor superlattices identified a reduction of thermal conductivity below the alloy limit, providing an opportunity for the development of higher efficiency thermoelectric materials and devices for power generation and cooling applications.

Nanomaterials

DoD research in this program component area (PCA) includes mostly 6.1 nanotechnology research projects.

Program Accomplishments include:
- Structure-based computational design techniques have directed the construction of catalytically active sites in proteins of known structure, enabling the functionality of a binding protein with no catalytic activity to be converted into an enzyme.
- The splitting of a Bose-Einstein Condensate (BEC) has been demonstrated, including the first coherent splitting of a BEC confined in a magnetic waveguide potential.
- New thermoelectric materials with record efficiencies in the temperature ranges required for power generation applications were synthesized in thin film and bulk form.
- Nanostructured graft copolymer electrolytes have been fabricated and demonstrated to function at 0 °C, proving the ability to overcome typical ion transport limitations at low temperature when the lithium ion motion is decoupled from the polymer.
- Amphiphilic block copolymer additives have been developed that, during membrane formation, self-assemble a low-fouling hydrophilic surface on all membrane surfaces (both macroscopic and pore surfaces).
- A new method for processing of ceramic nanocomposites has been demonstrated, in which a homogeneous, metastable powder is produced that decomposes to form a nanocomposite during sintering. Superior strength and optical transparency have been demonstrated with this process.
- Single-walled carbon nanotubes (SWNTs) have been "cloned," enabling very specific types of SWNTs to be replicated.
- The spin Hall effect has been discovered, demonstrating a relativistic interaction between electron spin and electron motion in a transverse electric field: spin up and spin down electrons flow separately to opposite sides of a semiconducting film without any magnetic field or magnetic materials being present.
- A novel fluorinated p-phenylene vinylene (PPV) homopolymer has been developed with unprecedented photostability, representing an extremely promising photovoltaic material.
- The synthesis of nanometer-scale materials with an optical response tunable from visible to infrared wavelengths has enabled (via joint support from DoD and NIH) non-invasive destruction of tumors in mice with 100% success.

Nanoscale Devices and Systems

DoD research in this program component area (PCA) includes most 6.2 and 6.3 nanotechnology research projects, in addition to 6.1 nanotechnology research projects germane to specific devices.

Program Accomplishments include:

- Complex single-chip opto-electronic systems have been fabricated with sub-micron photonic elements in conjunction with mixed-signal electronic circuits in standard complementary metal oxide semiconductors (CMOS).
- Chip scale all-optical components have been developed for optical communications and networking utilizing photonic crystals and demonstrating a variety of functions including guiding, switching, splitting, modulating, coupling and filtering.
- Single ion implantation into silicon has been demonstrated and registered under gates used to control cyclical electron tunneling from dopant to dopant, representing a major step toward solid state quantum computing.
- The first nonvolatile and programmable nanodevice with gain has been fabricated.
- The first ever light emitting transistor has been developed, which emits light from the base layer of a novel heterojunction biopolar transistor and is controlled by the base current, forming the basis for future high-speed signal processing integrating electrical and optical signals.
- The first known photovoltaic (PV) fiber has been developed and demonstrated. This technology, based on dye-sensitized nanoparticle thin films on ultra thin plastic substrates, would allow the fabrication of PV devices that can be dyed to match specific patterns and woven into uniforms.
- An electrospun fiberized adhesive has been developed for fabric laminates that provides greatly improved fabric breathability characteristics.
- 4.5 Kbit memory has been demonstrated using ultra high density nanowire circuits (150 by 30 crossbars).
- High moment, magnetic nano-tags have been fabricated that allow DNA fingerprinting without DNA amplification (i.e., the polymerase chain reaction is not required, greatly enhancing portability).
- The first ever experimental demonstration of Induced-Charge Electro-Osmotic (ICEO) flow, enabled by nanoscale fluorescent tracer particles has been achieved in a microfluidic device, offering superb potential for automated biomedical monitoring.
- Synthetic nanochannel glass (in the form of 3200 five micron wires) has been demonstrated to replicate the performance of the human retina.
- Integrated bio-molecular microsystems have been synthesized and have demonstrated a detection limit of 500 zM (~10 target DNA strands) in the presence of interfering non-complementary DNA.
- Single ion channels using polycarbonate membrane over field effect transistors have been fabricated that successfully reproduced stochastic signals with stability of weeks.

Instrumentation Research, Metrology, and Standards for Nanotechnology

DoD research in this program component area (PCA) includes Multidisciplinary Research Program of the University Research Initiative (MURI) research projects (6.1) and other significant work on these specific topics.

Program Accomplishments include:

- The capability to detect the presence of a single isolated electron spin on a silica surface has been demonstrated using magnetic resonance force microscopy (MRFM), a cantilever-based technique much like that used in scanning tunneling microscopy.

- Thermal dip pen nanolithography has been demonstrated, in which local temperature controls materials transfer from a force microscopy tip to a substrate.

Nanomanufacturing

DoD research in this program component area (PCA) includes MURI research projects (6.1) focused on nanomanufacturing, Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) projects with a specific nanotechnology focus, Manufacturing Technology (MANTECH) efforts focused on nanotechnology, and other significant work on this specific topic.

Program Accomplishments include:

- An aerosol-based sol-gel method (Aero-sol-gel) for preparing nanoporous iron-oxide nanoparticles with high internal surface area has been developed; a nano-sized oxidizer and fuel material offer the potential (high surface area) for applications that involve rapid energy release.
- A new experimental facility was developed for studying plasma synthesis and processing of aluminum nanoparticles for nanoenergetics applications via ARO-funded research at the University of Minnesota. Aluminum nanoparticles were synthesized using a plasma torch over a range of operating conditions. Particle size distributions, elemental composition and particle morphology were characterized.
- Recombinant virus protein-directed synthesis of semiconductor nanowires has been utilized to fabricate functional electronic circuits.

Major Research Facilities and Instrumentation Acquisition

DoD research in this program component area (PCA) includes Defense University Research Instrumentation Program (DURIP) grants (6.1) for nanotechnology instruments at Universities, Military Construction (MILCON) for dedicated nanotechnology research buildings, and other significant efforts addressing these specific topics.

Program Accomplishments include:

- The Naval Research Laboratory Nanoscience User Fabrication Facility was formally opened for NRL users, including 5000 sq. ft. of class 100 cleanroom space, optical lithography mask aligners, deep ultraviolet lithography, electron-beam lithography, and a focused ion beam work station.

Societal Dimensions

DoD research in this program component area (PCA) includes MURI research projects (6.1) focused on toxicology, National Defense Science and Engineering Graduate (NDSEG) Fellowships with nanotechnology intent, Historically Black Colleges and Universities/Minority Institutions (HBCU/MI) with nanotechnology intent, and other significant efforts addressing these topics.

Program Accomplishments include:

- NDSEG nanotechnology-focused fellowships were awarded.
- The Physicochemical Characterization and Toxicology for Air and Space MURI was initiated at the University of Rochester.

II. Assessment of Current and Proposed Funding Levels

The principal DoD investments in nanotechnology are made by DARPA, the Air Force, the Army and the Navy. In addition, the Defense Threat Reduction Agency (DTRA) and the US Army Medical Research and Material Command (MRMC) are assessing the opportunities for future year investment in nanotechnology.

DoD nanotechnology research programs are carried out both within the DoD laboratories and in extramural research institutions. In both contexts, nanotechnology research is directed by single investigators, multidisciplinary teams, and research centers. Single investigator research represents a critical component of the DoD nanotechnology research effort and is critical to the continued inception and maturation of high risk innovative scientific concepts that will lead to breakthroughs in nanotechnology. Multidisciplinary teams at the intersections of traditional disciplines provide an optimal means of developing the necessary understanding of nanoscale phenomena and identifying promising applications. Research centers provide sustained support and a broad range of expertise focused on key opportunities emerging from nanotechnology research. Table 1 shows the amount of DoD funding in nanotechnology from FY2004-FY2006 for each of the seven program component areas (PCAs) previously described.

Table 1
Historic DoD Investment in Nanotechnology by PCA ($ in Millions)*

	2004 Appropriated	2005 Appropriated	2006 Requested
PCA #1	51	34	35
PCA #2	98	98	83
PCA #3	120	113	99
PCA #4	8	3	3
PCA #5	2	1	2
PCA #6	10	6	6
PCA #7	2	2	2
Total	**291**	**257**	**230**

* does not include Congressional adds

PCA #1: Fundamental Nanoscale Phenomena and Processes
PCA #2: Nanomaterials
PCA #3: Nanoscale Devices and Systems
PCA #4: Instrumentation Research, Metrology, and Standards for Nanotechnology
PCA #5: Nanomanufacturing
PCA #6: Major Research Facilities and Instrumentation Acquisition
PCA #7: Societal Dimensions

DoD nanotechnology programs are a collection of many programs that focus on nanotechnology and are not summarized by a small number of program elements. The overall budget requests for each of the services and DARPA in nanotechnology are stable and are maintaining level funding. The reported budgets for FY05 and FY06 reflect some uncertainty due to the completion of several nanotechnology programs (particularly DARPA) and new programs yet to be obligated. Out-year funding is expected to stabilize around the $275M level.

III. Coordination within DoD and with Agencies in NNI

In support of the National Nanotechnology Initiative, DoD regularly participates in meetings of the Nanoscale Science and Engineering Technology (NSET) subcommittee of the National Science and Technology Council (NSTC) Committee on Technology. The NSET subcommittee membership consists of representatives from the Office of Science and Technology Policy (OSTP), Office of Management and Budget (OMB), National Science Foundation (NSF), DoD, National Institute of Standards and Technology (NIST), Department of Commerce (DoC), Department of Energy (DoE), Department of Homeland Security (DHS), Department of Transportation (DoT), Department of Justice (DoJ), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), National Institutes of Health (NIH), Department of Agriculture (USDA), Department of State (DoS), Food and Drug Administration (FDA), National Institute of Occupational Safety and Health (NIOSH), Patent and Trademark Office (PTO), National Regulatory Commission (NRC), International Trade Commission (ITC), Department of the Treasury (DoTr), Consumer Product Safety Commission (CPSC), as well as a representative from the Intelligence Community. The NSET subcommittee meets every month at the National Science Foundation to coordinate all federal government programs in the NNI through the National Nanotechnology Coordination Office (NNCO). Additionally, appropriate coordination of the overall DoD investment in nanotechnology is assured through DoD reliance panels, the DDR&E Nanoscience Strategic Research Area joint committee, the Naval Working Group on Nanoscience, the Air Force Nano S&T Working Group, and the U.S. Army RDECOM Nanotechnology Working Group.

The NSET has created working groups with various industrial sectors named Consultative Boards to Advance Nanotechnology (CBAN). Along with other appropriate NSET agencies, the DoD is participating in CBAN addressing information technology and chemicals. New CBAN activities, with anticipated DoD participation, are under discussion for the automotive, aerospace and biotechnology sectors.

The following are examples of the many ongoing collaborative efforts directly between individual agencies participating in the National Nanotechnology Initiative:

DoD – NSF, DoE	Nanostructured materials
DoD – DoE, NASA, NIST, NSF	Quantum computing
DoD – NASA, DOE	Directed energy conversion
DoD – NSF, DOE	Nanostructure-based advanced energy technologies (fuel cells, capacitors, thermoelectrics, and thermionics)
DHS – DoD, NASA	Nanostructures for explosives and chemical detection – An initiative with NASA Ames Research Center and the Naval Research Laboratory for single molecule detection of trace levels of explosives
DHS – DoD, DoE	Explosive Vapor Detection – DHS is funding an evaluation at DoE's ORNL of a system using nanoexplosions on microcantilever surfaces related to research done at NRL
DHS – DoD, DoE	Collecting and Measuring Explosive Materials – A study involving an interagency collaboration among DoT, DoE's ORNL, and DoD's NRL.
DHS – DoD , DoE	Miniaturized System for Detecting Chemicals and Explosive Materials – DHS is co-funding and supporting with DoD and DoE's

	Sandia National Laboratory the development of a miniaturized, handheld system for detecting explosive particles or vapors, hazardous chemicals, and chemical agents.
DHS – DoD	Mass Spectrograph on a Chip – DHS is co-funding with DoD's DARPA, and Army Research Laboratory (ARL) a system to detect both chemical agents and explosives.
NSF – DoD	Joint funding of Materials Research Science and Engineering Centers (MRSECs), and co-funding of two Nanoscale Science and Engineering Centers (NSECs).
NSF – DoD	Co-funding the Nanoscale Science and Engineering Centers at Northwestern University and Rice University (each with a NSF center and DoD MURI on complementary topics from basics to applications)
NSF – DoD	Joint effort with SRC (Semiconductor Research Corporation) to explore future nanoelectronics directions and platforms.
NSF – DoD – NIST	Nanomanufacturing
DoD – NSF	Joint program to fund an educational opportunity for undergraduate and graduate students in nanotechnology teaming with Navy R&D centers and NSF university grantees. Students would transition to Navy R&D centers upon graduation.
DoD – NASA Ames	Quantum well structures for terahertz emitters.

Table 2 shows the amount of DoD funding in nanotechnology for each of the seven program component areas (PCAs) relative to the other major participating agencies in the National Nanotechnology Initiative.

Table 2
2006 NNI Investment in Nanotechnology by PCA ($ in Millions)

	DoD	DHS	DOC/NIST	DOE	DOJ	EPA	NIH	NIOSH	NASA	NSF	USDA
PCA #1	**35**	0	5	48	0	<1	48	0	4	95	1
PCA #2	**83**	0	1	33	0	0	17	0	17	75	2
PCA #3	**99**	0	2	5	0	<1	72	0	9	54	3
PCA #4	**3**	0	39	11	0	0	7	0	0	12	0
PCA #5	**2**	0	19	0	0	0	0	0	1	24	1
PCA #6	**6**	0	8	109	0	0	1	0	0	24	0
PCA #7	**2**	0	1	1	2	4	0	3	0	60	1
Total	**230**	**0**	**75**	**207**	**2**	**5**	**144**	**3**	**32**	**344**	**8**

PCA #1: Fundamental Nanoscale Phenomena and Processes
PCA #2: Nanomaterials
PCA #3: Nanoscale Devices and Systems
PCA #4: Instrumentation Research, Metrology, and Standards for Nanotechnology
PCA #5: Nanomanufacturing
PCA #6: Major Research Facilities and Instrumentation Acquisition
PCA #7: Societal Dimensions

IV. Effective Technology Transition Paths

Nanotechnology is still very much emerging and at the early stages of development; for this reason, the majority of the effort is currently focused on basic research and exploration. Nonetheless, significant research results have been transferred to technology development, both within DoD laboratories and in industry. For example: nanometer sized carbon (carbon black) has been used to improve the mechanical properties of tires; nanometer size silver particles have led to the development of photographic film; and DoD supported research on high electron mobility transistors, vertical surface emitting lasers, and giant magneto resistance read heads has led to the development and enhancement of advanced digital storage media. DoD agencies are exploring nanotechnology successes as sources of potentially disruptive innovations in order to accelerate transition of these discoveries into future platforms, and increasing emphasis is being given to transitioning research discoveries in nanoscale materials into development through 6.2, 6.3, SBIR/STTR, and MURI programs. Specific recent examples of technology transitions resulting from Defense support include:

- Resonant tunneling simulation programs, developed with DURINT support at Stevens Institute of Technology, have been distributed to government and industry organizations, research laboratories, and production facilities, resulting in active use by researchers at the Naval Research Laboratory (NRL), Air Force Research Laboratory (AFRL), and US Army Communications and Electronics Command (CECOM).
- Simulation software developed at the University of Illinois with DURINT support has been successfully transferred to: Sandia and the University of California at Santa Barbara to define terahertz photoconductivity experimental on nanoscale detectors; Motorola to characterize 3-D charge interface effects on mobility in metal oxide semiconductor (MOS) dielectric stack gate structure; and Intel to perform 3-D optimizations of multi-channel tri-gate MOS devices.
- Experimental characterization studies conducted at Yale University with DURINT support have been employed by: the Army Research Laboratory (ARL) to provide insight into molecular conformational models and biodetector devices; NIST to optimize nanopore device fabrication; and Motorola to define new molecular devices.
- Thermodynamic simulations and experimental validation of new percussion primer candidates for nanoenergetic composites, developed with DURINT support, have resulted in a joint patent disclosure between South Dakota School of Mines and Technology and the Naval Surface Warfare Center (NSWC). Currently, a startup company, Innovative Materials and Processes, L.L.C., is conducting further R&D of percussion primers based on this system.
- The first U.S. demonstration of a commercial prototype Terahertz Quantum Cascade Laser has been achieved with SBIR support.
- Thermal spray ceramic nanocomposite alumina-titania has been commercialized for wear resistant coatings of propeller shafts of MCMs (Mine Countermeasure Ships) with SBIR support, with plans underway to evaluate coating shafts on the rest of the fleet as well as through-hull ball valves for submarines.
- Carbon nanotube-filled epoxy resins are being designed as gap sealants to seal seams on naval aircraft, under SBIR support, with the potential to significantly reduce the weight over traditional gap sealants that contain metal fillers. In addition, the nanotube fillers impart electromagnetic absorbing and shielding properties that make the resultant organic based conductive resins attractive for use in a corrosive salt-fog environment.
- The flammable organic components in vinyl ester resin were replaced with a novel composite developed under SBIR support and derived containing nonvolatile, nonflammable, and nontoxic nanoscale silsesquioxane groups. The composite directly passed Mil. Spec. 2031, saving the expense of coating or wrapping the final structure with an additional coating or fire blankets.

- A 44 cm^3 atomic clock has been developed with DARPA support that includes not only the MEMS-based physics package, but also all the electronics at the (small) board level. The electronics include both feedback for the physics package and microwave oscillator electronics, and consumes a total of 189mW of power, generating significant interest and future transition potential from the Office of the Assistant Secretary of Defense for Networks and Information Integration OASD/NII due to the potential to revolutionize network architecture.
- A new class of compact, short wavelength (280 nm to 340 nm) optical sources has been developed with DARPA support for integration into compact biological warning sensors. The program has demonstrated prototype two-wavelength sensors that outperform the fielded Biological Aerosol Warning Systems (BAWS-III), and has also leveraged Defense Threat Reduction Agency (DTRA) development support.
- A conjugated polymer-based sensor developed under UARC support has been fabricated into commercially viable platforms by Agilent Technologies for its detection platforms with Army Edgewood Chemical Biological Center (ECBC) support and collaborations.
- A molecular-wire based sensor developed at MIT and Nomadics, Inc. under SBIR and UARC support has been demonstrated to detect ultra trace amounts of explosives, and recently received excellent preliminary feedback from field tests conducted by the Marine Corps at Yuma Proving Grounds and in Iraq.

V. Recommendation for Program Activities

Nanotechnology research covers many science and technology areas that are of primary interest to DoD. Nonetheless, because basic research in nanotechnology involves high-risk efforts with the potential for extremely high payoffs, major advances in the application of nanotechnology to the military are often unpredictable. For this reason, it is critical to maintain a balanced and stable research investment portfolio in order to identify and capture the critical technological breakthroughs needed to provide revolutionary advantages for warfighter and battle systems capabilities. The current DoD nanotechnology programs represent a balanced investment portfolio addressing both near-term national security needs and long-term challenges. As a part of the reliance process, DoD will continue to coordinate its nanotechnology programs amongst the Services, DARPA and other federal agencies to avoid duplication and redundancy.

As basic research in nanotechnology continues to mature, it is anticipated that the results will be transitioned to applied research and advanced technology development and to industry. Increasing emphasis is being put on effective transitioning of research to technology development for the services, which will require more effective coupling between the different funding categories, and between the basic research programs and SBIR/STTR and MANTECH programs. The DoD will work with the NSTC Interagency Working Group in its joint efforts with the NNI to augment the Federal program in nanomanufacturing. DOD sponsored conferences, such as “Nanomaterials for Defense Applications,” are also providing an opportunity to develop linkages between the DoD funded research and industry.

Nanotechnology research remains a major national initiative, with DoD playing a major role since its inception. Considerable scientific knowledge is yet to be learned, and DoD guidance is critical to assure both the optimum direction of ongoing research efforts and the optimum leveraging of this knowledge to advance warfighter and battle systems capabilities. Furthermore, DoD’s sustained investment in nanotechnology basic research funding over the long term will ensure that we can meet the challenges and goals set out in this report.

Recommendations for program activities

- The area of fundamental nanoscale phenomena and processes, which constitutes one of the three primary DoD investment areas, should maintain level funding to ensure the discovery of new phenomena and processes necessary for breakthrough advantages in DoD systems.
- The investment in nanomaterials, the second primary DoD investment area, is adequate.
- The area of nanoscale devices and systems, which represents the third primary DoD investment area, is presently adequate, but is expected to grow in future years to ensure the continual development of unprecedented devices and systems for DoD mission areas. DoD is currently working with the information technology industry through the NNI Consultative Board to Advance Nanotechnology in order to identify technology opportunities with specific DoD impact and value to commercial products. Also, DTRA and US Army Medical Research and Materiel Command are evaluating the opportunities for investment toward impact on their missions.
- The area of instrumentation research, metrology, and standards for nanotechnology should maintain level funding to ensure appropriate involvement and guidance by DoD in this area.
- The investment in nanomanufacturing is currently adequate, but in the future greater focused investment in the SBIR/STTR and MANTECH programs will likely be necessary to facilitate transitioning of research results to defense technologies.
- The area of major research facilities and instrumentation acquisition should maintain level funding to ensure continual development of advanced instrumentation and appropriate guidance by DoD of these efforts.

- The area of societal dimensions should presently maintain level funding to assure the health and safety of warfighters utilizing future nanotechnology-based applications, a sustained emphasis on creating a pipeline of skilled workers for defense applications of nanotechnology, and an awareness of environmental and health impact from the anticipated growth in defense applications of nanotechnology.

VI. References

1. Basic Research Plan, Director of Defense Research and Engineering, February 2003.
2. Joint Warfighting Science and Technology Plan, Office of the Deputy Under Secretary of Defense (Science and Technology), February 2003.
3. Defense Technology Area Plan, Office of the Deputy Under Secretary of Defense (Science and Technology), February 2003.
4. National Nanotechnology Initiative, Research and Development Supporting the Next Industrial Revolution, 2004.
5. The National Nanotechnology Initiative Strategic Plan, December 2004.