Invited Paper

Nanotechnology strategic plan for the U.S. Air Force

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ABSTRACT

I will review recent advances in DoD nanoscience and technology (NST) at the Air Force Research Laboratory (AFRL) in the areas of nano-materials, nano-electronics, and nano-energetics. NST will profoundly change all critical aspects of maintaining a technologically superior national defense capability. In this talk, I will focus on programmatic priorities for AFRL basic and applied R&D in the seven selected priority areas that comprise the AFRL Strategic Nanotech Plan. The goal of this plan is to focus, prioritize and guide future AF funding in nanotechnology. The selected topics include: tailorable dielectrics, reconfigurable optical response materials, adaptive structural materials, quantum confined optical sensors and sources, nanotechnology for RF, as well as several cross-cutting topics such as self-assembly, interfaces, and modeling and simulation.

Keywords: Strategic planning, tailorable dielectrics, optical response materials, adaptive structural materials, energetic materials, quantum confinement, self-assembly, nano interfaces

1. INTRODUCTION

In the future, nanotechnology promises revolutionary breakthroughs in many applications, from chemical & biological detectors for homeland defense, terahertz processors and terabits per square centimeter (Tbits/cm^2) storage that enable desktop computers with 10^{15} million instructions per second (MIPS) (equivalent to billions of modern Pentium 4 processors), space-lift at twice the payload-to-weight ratio, to materials many times stronger than steel but at a fraction of its weight. Such materials could be used to build better aircraft, cars, buildings, and many things that have yet to be imagined.

As with any pervasive technology, for some it is the source of much excitement, while others dismiss it as hype, and in a disturbing trend, various interest groups warn of the dangers of nanotechnology. This confusion has led to scares and fear expressed in books and movies, based in part on a lack of understanding of the reality of nanotechnology as distinguished from the futuristic ideas of molecular engineering and self-replicating nanobots.

In this article, we define nanoscience and technology (NST), and show how NST is fundamentally changing the way materials and devices will be produced in the future. We explain how the Air Force scientific and technology (S&T) community can benefit from working at the nanoscale, and describe a capabilities-based strategic NST R&D plan, to leverage the AFRL NST R&D investment, with the goal of maximizing the benefits for the Air Force and the warfighter.

The beginnings of modern nanotechnology go back to Richard Feynman's classic 1959 talk: "There is plenty of room at the bottom"[1]. It inspired many, among them Heinrich Rohrer and Gerd Binning, who in the mid-1980's invented the Scanning Tunneling Microscope (STM) – for which they received the 1986 Nobel Prize – which radically improved the imaging resolution of previous tools by over an order of magnitude. The STM and other enabling nanoengineering tools allowed the researcher for the first time to peek into and to manipulate the complicated world of solids on the atomic scale. The availability of these tools has synergistically enabled the exponential increase in knowledge of many different scientific disciplines, and has led to a convergence of biology, chemistry, physics, optics, engineering, computer sciences, and mathematics in the new field of nanoscience. The combination of nanoscience & technology (NST) has given us a better fundamental understanding and an unprecedented ability to observe, change and control matter at a length scale of 1-100nm.

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At these length scales, macroscopic and microscopic physics gives way to quantum mechanical and confinement effects, which come to dominate in at least two different ways. First, the characteristic length (grain size or device features) approaches the size of the (quantum) wave function of excitations in the material – electrons and holes, photons, magnons, phonons, etc. Second, the very large surface-to-volume ratio means that most atoms are very close to an interface (discontinuity), and that these quasi-two-dimensional structures and discontinuities start to dominate. These large surface areas and their associated unique surface interactions are driving much of the enthusiasm and research at the boundary between nano- and biotechnologies, and it is these new mechanisms at mesoscopic scales (i.e. between microscopic and the quantum limit) that enable new properties that before were unachievable.

For instance, consider ferroelectric performance – key to systems ranging from radars to antennas to capacitors. Ferroelectric ceramics often have large switching losses that dissipate energy as heat, compromise system efficiency, and dictate complex thermal management. These losses arise because the fundamental structure of the material (individual grains in the ceramic) are much larger than the ferroelectric domain size (each domain has a spontaneous electric dipole moment). As the grain size is reduced to below the ferroelectric domain size, domain wall movement within the grains – the main switching loss mechanism – is eliminated and losses are reduced by several orders of magnitude. Capacitors made from these nanoferroelectrics store more energy, and the reduced grain size leads to improved mechanical properties, enabling structural compound nanodielectrics that can be integrated into airfoils and multi-functional systems.

The practical formation of nanoscale structures and their integration into NST products – nanotechnologies – requires a fundamentally different approach from that at the microscale, where highly parallel ‘top-down’ fabrication technologies, such as deposition, lithography, and etching enabled the miniaturization and integration of hundreds of millions of electronic devices onto single chips. NST includes bottom-up assembly and self-assembly, both widely used by biological systems, where structures are built up from atomic and molecular units into increasingly complex structures. This enables the mass-assembly of complex functional structures with very high reliability and repeatability. As technological capabilities expand, a combination of top-down and bottom-up techniques probably will be employed for the efficient manufacturing of nanoscale systems.

In practice, one often sees very diverse approaches and different technologies competing and looking for each other. For example, the rapid growth in magnetic information storage has been driven by combined advances in a range of technologies, from new giant magnetoresistive nanoscale layered materials to read heads flying 10 nanometers over the surface of magnetic discs moving at speeds of 20 meters per second. Competing technologies include atomic point probes – using atomically sharp points to write mechanically, optically, or magnetically on surfaces – spintronics, molecular memory, or approaches using nanopillars and carbon nanotubes.

The development of NST is helped by the significant NST investments. According to Cientifica[2], worldwide government spending on NST in 2002 was about $3B per year, and corporate R&D spending was about $5-6B per year. In 2002 alone, domestic venture capital investment was over $200M. The US government investment increased from $116M in 1997 to $849M in 2004 through the National Nanotechnology Initiative (NNI) [3]. The total funding for AFRL amounts to about $71M in FY04, including ~ $15M for AFOSR.

NST is a disruptive, but gradual revolution over the coming decades, driven by the thirst for new products and capabilities, and the evolution of nanoscience and enabling technologies. This is evident from the visions that many industries and research communities have articulated for some time, such as the International Technology Roadmap for Semiconductors (ITRS[4]), the Tech Roadmap for Nanoelectronics[5], the Chemical Industry R&D Roadmap for Nanotechnology and Nanomaterials by Design (Vision 2020)[6], and the National Nanotechnology Initiative (NNI) implementation plan[7]. The ITRS projects that within 10-15 years complementary metal oxide semiconductor (CMOS) technology, used for today’s computers, will hit a barrier, where feature sizes will fall into the quantum regime, requiring a fundamental reconsideration of the current transistor physics used to establish device architecture. To overcome this barrier, and to continue improving processors according to Moore’s law, new nanotechnology breakthroughs are necessary.

2. PLANNING PROCESS

AFRL is the steward of the USAF technology portfolio. AFRL has been and continues to be a leader in selected areas of nanotechnology for military applications, including directed energy weapons, optical materials, infrared (IR) photodetectors – including Quantum Dot IR Photodetectors (QDIP), revolutionary information technologies, and high-yield energetic materials for munition and propulsion systems.

The NST-plan serves two main purposes: First, to inform and educate the Air Force S&T about the benefits of working at the nanoscale. Second, although industry is actively pushing many areas of nanotech research, active leadership by the Air Force R&D community is crucial to ensure that those critical topics with greatest impact are developed to their fullest potential. By intelligently investing our relatively small (with respect to the global NST investment) AFRL R&D effort, we can coordinate, leverage and influence extramural efforts within industry and academia, in order to maximize the benefits of NST for the Air Force and the warfighter.

2.1 AFRL Nanotechnology Working Group

The AFRL NST Working Group formulated a concise and focused AFRL Strategic NST Plan using *capabilities-based planning*. We used key strategic documents like CONOPS, "AF Vision 2020", and Long Term Challenges to refine future warfighter needs and the changing paradigm of future engagements. *We focused on those capabilities that are most critical for the Air Force, lack major commercial drivers, and thus demand AF leadership.*

The AFRL Nanoscience & Technology (NST) Working Group (NST-WG) was formed in 2001 to coordinate the growing nanotechnology efforts within all of AFRL. It was formally chartered in February 2003 by the AFRL Technical Directors and the commander of AFRL, MajGen Paul Nielsen, and serves as a model for other AFRL working groups. Each of the ten AFRL Technical Directorates (TDs) is represented in the NST-WG, and all ten members of the NST-WG are technical bench-level scientists and engineers with their own intra- and extra-mural NST R&D activities. The NST-WG meets on a monthly basis via VTC under the general ground rules for IPTs (Integrated Product Teams), and the meetings are open to all members of the AFRL S&T community. Because of the background of its members, most discussions within the NST-WG are focused on technical issues, and the development of the NST Strategic Plan is based in large part on that extraordinary broad technical expertise.

The NST-WG has several purposes. First, it is an information clearinghouse for relevant domestic and worldwide NST activities. The information database includes meeting and workshop reports, important papers, intramural and extramural collaboration reports, information and dissemination of international activities (like the AFOSR Taiwan and Korean initiatives), as well as monthly reports from each TD on their intra- and extra-mural R&D activities. Second, due to the far-reaching and pervasive nature of nanotechnology, and the technical expertise of its members, the NST-WG is also the advocate for NST for the Air Force, and represents AFRL's NST interests at the DoD and national level. Finally, the NST-WG coordinates and defines plans and policies for nanotechnology in a bottom-up approach.

In August 2003, we organized a workshop to define the basis for the current AFRL Strategic Plan and POM initiative, which was subsequently formulated and refined in less than two months, before being presented at the AFRL Corporate Board in its October 2003 meeting, where it was approved an incorporated as the AFRL Strategic NST plan.From a pool of over forty, we chose seven NST topics that could be broadly categorized into materials, sensing, and cross-cutting. The topic selection addressed about 95% of the shortcomings found by the National Research Council Study on Micro and Nanotechnologies[8], as well as an AFOSR gap analysis of our NST basic research portfolio. The planning process defined the seven topics contained in the AFRL Strategic NST Plan, a living document allowing for refinement of future investments.

3. TOPICS

The seven topics include (1) Tailorable Dielectrics, (2) Optical Response Materials, (3) Adaptive Structural Materials, (4) Energetic Materials at the Nanoscale, (5) Quantum Confined Optical Sensors and Sources, (6) Nanotechnology for RF, and (7) Crosscutting technologies for Manufacturing and Integration, including Assembly and Self-Assembly, Nano-Micro-Macro Interfaces, and Modeling & Simulation.

3.1 Tailorable Dielectric Susceptibility

Dielectrics materials are non-metallic substances as varied as glass, ferroelectrics, and plastics. Low-loss dielectrics are primarily used for capacitors, RF substrates, as well as materials for electromagnetic radiation management (RF and IR). Dielectric materials greatly benefit from a reduction of the grain size to the nanoscale. Recent improvements include an increase in the electric breakdown voltage from 100kV/cm to over 1MV/cm in nano-ferroelectrics and polymers, allowing high-voltage breakdown strength materials.

Nano-dielectrics are often multifunctional, and can be used in load-bearing structures, for instance as an integrated capacitive skin for High-Power Microwave (HPM) systems, tactical laser weapons, unmanned combat air vehicles (UCAVs), and satellites. This enables a system weight reduction by a factor of two-to-three. Other applications of nano-dielectrics include load-bearing and tailorable RF antenna for airplanes, UCAVs, and satellites with reduced weight and enhanced thermal durability.

3.2 Reconfigurable Optical Response Materials

Reconfigurable optical response materials alter their refractive index profile in response to thermal, electrical, or optical stimuli. They allow for the manipulation and processing of light at sub-wavelengths, show strong photon localization, and non-linear optical effects. They are used extensively in modern optics, and for laser eye and sensor protection. Within the next decade, these nanomaterials will allow enhanced tailorability, and enhanced parameters, such as ultra-fast (nanoseconds) and broad spectral response (10-100nm bandwidth), and tailorable optical attenuations exceeding 99%.

These tuneable material properties enable many new applications with increased robustness, reduced size, weight and power (SWaP), resulting in reduced system costs. They include: (a) Enhanced system hardening for agile response for future developing threats; (b) Antireflective coatings (> 98% from the visible to the near-IR), and low-cost large-area optical appliqué; (c) Very efficient radiating antenna (visible to IR), threshold-less lasers, and high quality factor (high-Q) resonators ($Q>10^4$) that can be enabling elements for agile sources and receivers for secure communication and optical information processing; and (d) Ultra-sensitive cavity resonators able to detect single (or a few) molecules for chemical-bio-explosives detection (CBED).

3.3 Adaptive Structural Materials & Coatings

Adaptive structural materials and coatings have tunable mechanical properties and durability. They are designed for deployable lattice fins, space deployment, coatings, digital projectors, and amorphous metal housing for high-tech consumer electronics.

Improved performance and multifunctionality will require Significant R&D in coatings that are designed to reduce the number of wear cycles, and to work in various environments – Early success stories include coatings for bearings in Navy propeller drive shafts, integrated structures with various nano-sensors (for strain, pressure, and temperature), and research into intelligent structures with integrated processing and drive actuation systems.

3.4 Energetics on the Nanoscale

Energetics are paramount to the military enterprise, and our ability of rapid delivery to target, and controlled effect on target. The modern warfighter requires weapon systems with increased weapon's loadout, high thrust-to-weight-ratio systems, and smaller, lighter, cheaper, more effective and lethal munitions.

Nano-enabled energetic materials lead to very high surface to volume ratio using for example nano-aluminum, and thereby significantly enhancing reaction efficiency and tuneability. Furthermore, multifunctional nano-energetic materials may potentially be used as missile bodies or other structural elements, resulting in an increase in the lethality of nano-munitions by three to five times.

Nano-propellants use new chemistry (like nano-aluminum) to allow for higher specific impulse and higher energy density, resulting in 3-5 times higher thrust-to-weight-ratio. This in turn benefits rapid response, and precision &

standoff weapons. They can also be used as stabilizers for jet fuels, increasing heat retention and flame point, resulting in a substantial projected cost reduction by ~$2B/year for the Air Force in the existing fleet, and longer fuel lifetimes.

3.5 Quantum Confined Optical Sensors and Sources

Information dominance is key in today's military, and thus one of the major Air Force missions is the knowledge and predictability of all forces (friend, enemy, and neutrals) for Persistent Battlespace Awareness, Persistent Global Intelligence, Surveillance & Reconnaissance (ISR), communications, and the Sensor Web. The Sensor Web is enabled by a set of ubiquitous ground, air, and space-based sensors, that generally fall into two categories: electro-optical (EO) sensors (UV, visible, IR, and terahertz (THz) bands), and RF sensors (RF, microwave and millimeter wave), and they communicate with one another and the warfighter using massive local processing power and very fast and high-volume data streams.

Electro-optic (EO) detectors based on quantum wells, quantum wires, quantum dots and superlattices provide desirable revolutionary new capabilities and enhanced sensing capabilities for the Air Force. They can be designed to selectively cover a large portion of the electromagnetic spectrum, from UV (10 – 400 nm) to the very long IR (15 – 30 _m), with tailorable performance parameters such as sensitivity, noise, and wavelength bandwidth. This enables detectors with high sensitivity in a narrow wavelength band, higher operating temperatures in the very long wavelength IR range, and multiple wavelength bands in the same detector pixel. These capabilities reduce system costs and offer reduced SWaP, radically improve performance, and allow for better tracking, targeting, and identification (ID) of threats. In addition, terahertz (THz) technology is an emerging field, with potential as an effective means for detecting chemical/biological/explosive materials, as well as imaging through container walls.

AFRL is a world leader in the development of high performance ultraviolet and IR materials, devices and focal plane arrays (FPA) technology. AFRL funded some of the earliest quantum engineered detector materials like quantum wall IR photodetectors (QWIPs) in the early 1980s. In recent years, much of the research focused on QWIPs and superlattice materials and detectors. QWIPs have been used for multi-spectral imaging in the key long wavelength band of 8 to 12 _m. Superlattice detectors cover broad spectral bands, and they are a high performance alternative to mercury cadmium telluride (MCT). Recently, superlattice photodiodes reaching wavelengths as long as 30 _m were first demonstrated under AFRL in-house and external programs, and they thus offer significant performance advantages over MCT in the wavelength ranges beyond 15 _m.

3.6 Nanotechnology for RF

RF is the second leg of Air Force sensing technologies, and it continues to be the technology of choice for long-range sensing and communication. Power requirements in RF systems will increase 10 – 100-fold, creating a need for "thermal superconductors" – stable, low cost, and low weight nano-materials with unparalleled thermal conductivities (K > 2000 W/mK), tailored electrical conductivities, tuneable emissivity and reflectivity for radiative cooling, and low absorptance. These materials (and possibly metamaterials – materials engineered to have negative permittivity and permeability that have exotic behaviors) will also be crucial for HPM, and propulsion systems.

NST will be crucial for various electronic and information technology applications. Recent R&D include a plethora of emerging technologies such as photonic bandgap materials, nano-electronics using nanotubes, nanowires, and massively parallel approaches using quantum confined or molecular materials (i.e. moletronics). Many of these technologies have inherently low switching losses, often orders of magnitude lower than CMOS.

3.7 Manufacturing and Integration of Nanostructures

System implementation of nanostructured devices and components requires cross-cutting and multidisciplinary approaches to manufacturing and integration. Many future Air Force systems, like UCAVs and RF-systems, will require "smart materials" – integrated multifunctional elements that sense and respond to external stimuli. This enables futuristic concepts, such as surface-directed flight control, that use adaptive structural materials with integrated nano-sensors for smooth flight surfaces, nano-integrated multifunctional structures with embedded electronics, antennas, metrology, data processing, energy management, etc. – all with lower weight and cost, reduced fatigue, and reduced maintenance and operational costs. Nano-materials and devices require controlled composition and positioning in three dimensions controllably – possibly at a fraction of an atom diameter – in a very reliable and repeatable way. These methods will include bottom-up approaches, such as bio-inspired or bio-directed methods, self-assembly, use of templates, or massively parallel approaches to build those systems and to radically reduce the costs. We also need to address nano-, micro- and macro- interface & interconnection issues and problems, including mechanical, nano-signal (optical, electrical, thermal, etc.), environmental, and encapsulation issues.

Today, we understand very well the nature of conventional semiconductors (at scales large compared to the quantum limit), and we understand quantum physics. The goal is to bridge the mesoscopic gap between those two worlds, and to provide to the device engineers the rational modeling and simulation tools that incorporate the nature of quantum confined materials and nano-devices.

4. CONCLUSIONS

Nanotechnology is pervasive, and will substantially affect our lives in the long term. It will generate new knowledge, products, production mechanisms, new commercial and military capabilities, and new markets. Nanotechnology not only improves old technologies, but also often generates new capabilities (many of which are unknown), by extending material and device properties to their quantum limit.

There are two significant challenges for AFRL: first, pushing R&D in military relevant nanotechnologies, and secondly, transitioning domestic and worldwide scientific and technological developments in NST into operational systems as these nanotechnologies mature. AFRL has world-class capabilities and expertise as integrators for military technologies. Building on these historic strengths, we need to be national leaders in our in-house capabilities to manufacture & integrate nanotechnology products – using assembly, interface, and modeling & simulation tools – and influencing the community to ensure that those necessary tools are available to address Air Force needs. The purpose of the strategic AFRL NST plan is to guide future AFRL NST investment to address those core issues most relevant to the warfighter, in order to secure continued technological superiority for the United States Air Force in a technologically rapidly evolving world.

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