Nanotechnology
Research & Development
at the U.S. Department of Defense

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The presenter is solely responsible for the opinions expressed here.
DoD’s Strategic Research Areas (SRA)

- Bioengineering Sciences
- Human Performance Sciences
- Information Dominance
- Multifunction Materials
- Nanoscience
- Propulsion and Energetic Sciences

Note: Nanoscience/nanotechnology impacts all six SRAs.
The science and technology of controlling and manipulating things at the atomic layer and nanometer (10^{-9} m) scale.

- Fabrication, synthesis, and processing of materials with predetermined properties
- Characterization, novel phenomenon, and properties for structural, electronic, and biological materials
- Nanoscale concepts and devices

**DoD Applications:** Electronics, computers, Biochem sensors

There’s Plenty of Room at the Bottom (Feynman ’59)
• NNI was launched in FY2001, with the goal to double the FY00 baseline of $270M. Since then federal investment in nanotechnology has tripled.

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### DoD Investment on Nanotechnology

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* Pending devolvement of URI to the services.
** Some uncertainty in DARPA investment on nanotechnology.
DoD Focused Areas in NNI

* **NANOELECTRONICS/NANOPHOTONICS/NANOMAGNETICS**
  - Network Centric Warfare
  - Information Dominance
  - Uninhabited Combat Vehicles
  - Automation/Robotics for Reduced Manning
  - Effective training through virtual reality
  - Digital signal processing and communications

* **NANOMATERIALS “BY DESIGN”**
  - Nano-energetic Materials
  - High Performance, Affordable Materials
  - Multifunction, Adaptive (Smart) Materials
  - Nanoengineered Functional Materials
  - Reduced Maintenance costs

* **BIONANOTECHNOLOGY - WARFIGHTER PROTECTION**
  - Chemical/Biological Agent detection/destruction
  - Soldier physical monitoring in the battlefield
DoD Programs in Nanotechnology

• Army
  Nanostructured polymers, quantum dots for IR sensing, nanoengineered clusters, nano-composites, Nanoenergetics, Institute for Soldier Nanotechnology (ISN)

• Navy
  Nanoelectronics, nanowires and carbon nanotubes, nanostructured materials, ultrafine and thermal barrier nanocoatings, nanobio-materials and processes, nanomagnetics and non-volatile memories, IR transparent nanomaterials

• Air Force
  Nanostructure devices, nanomaterials by design, nano-bio interfaces, polymer nanocomposites, hybrid inorganic/organic nanomaterials, nanosensors for aerospace applications, nano-energetic particles for propulsion

• DARPA
  Bio-molecular microsystems, metamaterials, molecular electronics, spin electronics, quantum information sciences, nanoscale mechanical arrays

• SBIR
  Nanotechnologies, quantum devices, bio-chem decontaminations

• OSD
  Multidisciplinary University Research Initiative (MURI), DEPSCoR, NDSEG
## FY01-06 DURINT Research Program

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Prime Institution</th>
<th>Research Topic</th>
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<tbody>
<tr>
<td>Josef Michl</td>
<td>Univ. of Colorado</td>
<td>Nanoscale Machines and Motors</td>
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<tr>
<td>Mehmet Sarikaya</td>
<td>Univ. of Washington</td>
<td>Molecular Control of Nanoelectronic and Nanomagnetic Structures</td>
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<td>Michael Zachariah</td>
<td>Univ. of Minnesota</td>
<td>Nano-energetic Materials</td>
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<td>Hong-Liang Cui</td>
<td>Stevens Inst. of Tech.</td>
<td>Characterization of Nanoscale Elements, Devices, Systems</td>
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<td>Richard Smalley</td>
<td>Rice Univ.</td>
<td>Synthesis, Purification, and Functionalization of Carbon Nanotubes</td>
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<td>Randall Feenstra</td>
<td>Carnegie Mellon Univ.</td>
<td>Nanoporous Semiconductors – Matrices and Substrates</td>
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<td>Deformation, Fatigue, and Fracture of Nanomaterials</td>
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<td>Paras Prasad</td>
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<td>Chad Mirkin</td>
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<td>Anupam Madhukar</td>
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<td>Synthesis and Modification of Nanostructure Surfaces</td>
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<td>George Whitesides</td>
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<td>Magnetic Nanoparticles for Application in Biotechnology</td>
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<td>Lukas Novotny</td>
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<td>Jimmy Xu</td>
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Nanoimprint Lithography
Princeton University, Professor Stephen Chou

1. Imprint
   - Press Mold
   - Imprint mold with 10nm diameter pillars

2. Remove Mold
   - 10nm diameter holes imprinted in PMMA

2. Pattern Transfer
   - RIE
   - 10nm diameter metal dots fabricated by nano-imprint lithography
Cluster Engineered Materials

Chad Mirkin, NWU

- Biological agent detection
  - PCR-free bioagent recognition
  - DNA/Nanosphere-based
    - Anthrax detection in solution
      - 30 nucleotide region of a 141-mer PCR product (blue dot)
      - Sensitivity: <10 femtomole
      - Detect single BP mismatch
    - Anthrax detection on substrate
      - Agent binds Au cluster
      - Ag: 10^5 amplification
      - Amount: grey scale
  - Tested
    - Dugway PG, 2001
      - 32 parallel tests in 1.5 hrs!
  - Active technology transfer
    - Nanosphere (spin off company)
    - Medical & industrial interest

Colorimetric Detection of Anthrax in Solution

Colorimetric Detection of Anthrax on Substrate

BA = Bacillus Anthracis
FT = Francisella Tularensis
Nano-Systems Energetics (DURINT)
P.I.: Michael Zachariah, U. Minnesota, mrz@me.umn.edu
http://www.me.umn.edu/~mrz/CNER.htm

Research Accomplishments

- Developed continuous flow reactor for nanoparticle production and passivation (copy at ARL-WMRD)
- Formulated model for nanoparticle formation and growth
- Designed experiments for characterization of size, composition and reactivity of nanoparticles
- Computed oxidative reactions of energetic materials (Nitromethane, HMX and FOX-7) on aluminum surfaces

Objective

Develop new methods for and understanding of nano-scale energetic materials
- Synthesis,
- Characterization,
- Reactivity

Research Areas

- Methods for nanoparticle growth and surface passivation
- Sol-Gel methods for generation of nanostructures
- Modeling of particle formation from thermal plasmas
- Methods for nanoparticle characterization
- Thermochemistry of nanoparticles and nanostructures
- Nanoparticle oxidation kinetics
- Characterize rates of energy release for nanostructures
- Measurement of solid-solid exothermic reactions
- Computational chemistry/physics of nanostructures
Nanocell Approach to a Molecular Computer

J. Tour (PI, Rice U.), D. Allara and P. Weiss (Penn State), P. Franzon (NC State), P. Lincoln (SRI), M. Reed (Yale), J. Seminario (S. Carolina), R. Tsui, H. Goronkin, I. Amlani (Motorola).

Technology Issues: Nanocell assembly, programming, and packaging

Objectives: Construct logic devices using programmable Nanocells

Approach
• prove molecular circuit programming through simulation
• predict properties of new molecules
• synthesize new molecules
• self-assemble in nanocells
• program and package nanocells

April-June 01 Accomplishments:
• Half-adder, inverter and NAND simulated
• 25 new molecules synthesized
• Nanocell wafers (e-beam) designed and in fab
• Dry box ready for assembly
• Test bed nanocells (optical) in fab
• 60 nm Au particle deposition developed
• Molecule-based circuits designed
• New Molecules proposed for memory

Impact & Transition: Molecular Electronics Corp., Motorola
Theoretical Analysis, Design, and Simulation of the Nanocell

- Calculated electrical characteristics for two new molecules proposed during the kick-off meeting: the dioxo with three rings (1), and the dinitro with four rings (2).
- First realistic molecular simulation of a fragment of the nanocell (below).
- New candidates for one-year room temperature memory proposed (lower right).
Objective:
Relieve the strain which occurs when films are grown on substrates with mismatched lattice constant.

Results:
GaN films have been grown by MBE on porous SiC substrates with a range of surface pore densities. Strain in the films is characterized by stylus profilometry. Significant strain relaxation is found, with the residual strain being about 3 times smaller than for films grown on nonporous substrates.

Interpretation:
For MBE growth, pores from the SiC continue into the GaN. These pores are “stress concentrators”, acting as nucleation sites for half loop dislocation as seen by TEM. These half loops then propagate and relieve the strain in the film.
Carbon Nanotube Based Materials and Devices
University of North Carolina at Chapel Hill
URL: http://www.physics.unc.edu/~zhou/muri

Objectives

- To understand and control the materials chemistry and physics of nanotubes and nanotube-based materials;
- To develop new nano-composites with enhanced mechanical, thermal and electrical properties;
- To fabricate nanotube-based electron field emission devices and evaluate their properties for technological applications;
- To investigate energy-storage capability of carbon nanotubes;
- To fabricate nanotube NanoElectroMechanical Systems (NEMS).

DOD Relevance

New materials and technology for structural reinforcement, energy storage, electron emission, and nano-device applications.

Multidisciplinary Approach

- Materials synthesis, assembly, functionalization;
- Nanometer-scale manipulation and measurements of transport, electronic and mechanical properties;
- Spectroscopic characterization and studies;
- Large-scale ab initio and empirical molecular dynamics simulation and theoretical calculations.

MURI Team

UNC: Physics, Chemistry, Materials Science and Computer Science
NCSU: Physics and Materials Science
Duke: Chemistry
Industrial Partners: Lucent Technologies, Raychem Co. and Ise Electronics

Major Accomplishments

- Established materials synthesis and processing capability
- First observation of rolling at nanometer scale, including manipulation and simulation of NEMS friction
- Measured and simulated the electro-mechanical properties of carbon nanotubes
- Synthesized nanotube-based polymer composites
- Fabricated nanotube field emission devices and demonstrated high current capability (4A/cm²)
- Performed the first 13C NMR measurement of the electronic properties of the carbon nanotubes.
- Demonstrated high Li storage capacity in processed SWNTs.

Research Highlights

- Conduction under strain – experiments
- Rolling and Friction at the atomic scale
- Carbon nanotube field emitters provide high current density and stability

Carbon Nanotube Based Materials and Devices
University of North Carolina at Chapel Hill
URL: http://www.physics.unc.edu/~zhou/muri
An Environmentally Compliant, Multi-Functional Coating for Aerospace Using Molecular and Nano-Engineering Methods
University of Virginia, Prof. Shelton Taylor

**GOALS/OBJECTIVES**

- To develop a new multi-functional coating system for military aircraft
- Coating will sense corrosion and mechanical damage
- Initiate mitigation response to mechanical and chemical damage
- Provide corrosion protection and adhesion using environmentally compliant materials

**APPROACH**

- Multi-coat system built upon thermally spayed amorphous Al-alloy cladding
- Combinatorial chemistry and nano-encapsulation to identify/deliver non-chromate inhibitors
- Colloidal crystalline arrays, and other molecular probes to provide sensing

**DOD TECH PAYOFF**

- Will provide significant advancement in corrosion protection, life cycle costs, and mission safety
Program Goal:
Transforming a new type of carbon, single wall nanotubes (SWNTs) into highly organized bulk materials

Activities Underway:
- Understand chemistry & kinetics of the HiPCO process for SWNT synthesis
- Development of purification methods for SWNT
- Mobilization of SWNTs in solutions and/or suspensions
- Mechanical and molecular modeling of sidewall chemistry and tube/polymer interactions
- Spinning of composites with nanotube fibers

DoD Impact:
High strength, light weight fibers
Structures with controlled dielectric properties
Potentials in hydrogen storage and electrode technology
• Advanced Photodetectors
  – Quantum Well Infrared Photodetectors
    • Use electronic band engineering and nanofabrication techniques
    • Multispectral IR imaging
  – Uncooled Infrared Detectors
    • Uses nanofabrication and advanced materials
  – Nanoparticle-Enhanced Detection
    • Increase light detection by 20X

• Target Designation and CCM
  – IR Lasers for Target Designation
    • Need: Compact, 300K IR lasers
    • Solution: Quantum cascade lasers

• Impact on Future Army
  – Smart, multispectral sensors coupled with ATR for target ID
  – Shorter logistics tail
New approach for energetic materials: nano-thick energetic material coating-layer on nanoscale aluminum fuel particles gives improved, intimate mixing in energetic formulations, and very high specific surface area. These effects support very high burn rates.

• **Scale Differences**...
  - Very High Specific Surface Area
    • 4-6 Orders of Magnitude Increase
  - Short Diffusion Path-Length in Burning

• **... Can Lead to Important Performance Enhancements**
  - Complete Burning of Fuel Particles
  - Accelerated Burn Rates
  - Ideal Detonation in Fueled Explosives

• **Coating Benefits**...
  - Intimate Contact Between Fuel, Energetic Material
  - Fewer Problems with Processing, Handling
  - Material Coating Thickness on Nano-fuel Particles Is Nano-scale
    • Fewer Defects, Better Crystals
    • Improved Insensitivity Properties
University Affiliated Research Center
• Investment in Soldier Protection
• Industry partnership/participation
• Accelerate transition of Research Products

Goals
• Enhance Objective Force Warrior survivability
• Leverage breakthroughs in nanoscience & nanomanufacturing

Investment Areas
• Nanofibres for Lighter Materials
• Active/reactive Ballistic Protection (solve energy dissipation problem)
• Environmental Protection
• Directed Energy Protection
• Micro-Climate Conditioning
• Signature Management
• Chem/Bio Detection and Protection
• Biomonitoring/Triage
• Exoskeleton Components
• Forward Counter Mine

Accomplishments
• Ribbons made of electroactive polymers
• Artificial muscle and molecular muscle
• Organic/inorganic multilayers for optical Communications
• Tunable optical fibers
• Dendrimers for protective armors
• Conducting polymer for bio-status monitors

September 2003
Impact

Enhanced National Security capabilities

* Chem-bio warfare defense
  Sensors with improved detection sensitivity and selectivity, decontamination

* Protective armors for the warrior
  Strong, light-weight bullet-stopping armors

* Reduction in weight of warfighting equipment
  Miniaturization of sensors, computers, comm devices, and power supplies

* High performance platforms and weapons
  Greater stealth, higher strength light-weight materials and structures

* High performance information technology
  Nanoelectronics for computers, memory, and information systems

* Energy and energetic materials
  Energetic nano-particles for fast release explosives and slow release propellants

* Uninhabited vehicles, miniature satellites
  Miniaturization to reduce payload, increased endurance and range