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

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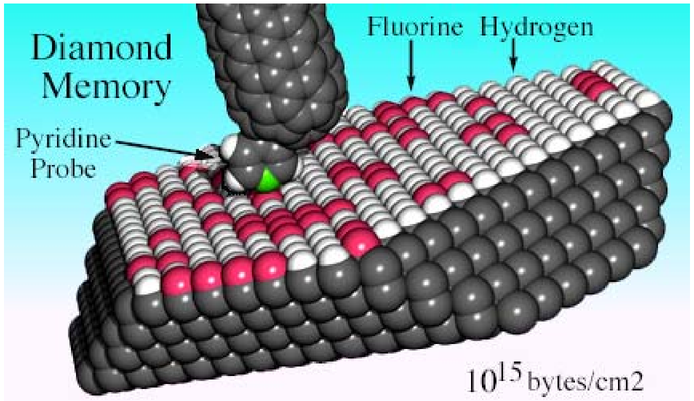
The presenter is solely responsible for the opinions expressed here.

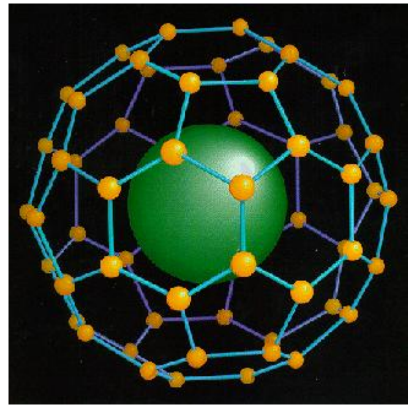
DoD's Strategic Research Areas (SRA)

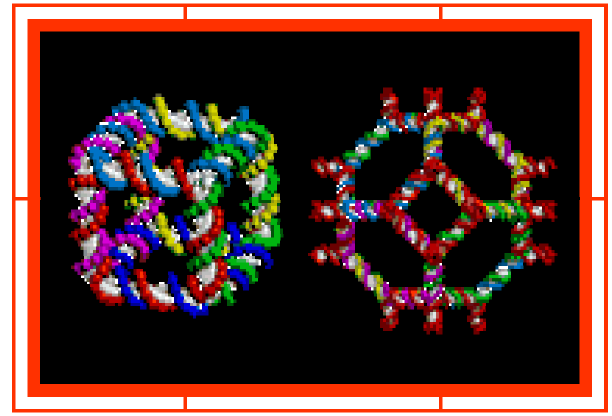
- **Bioengineering Sciences**
- **Human Performance Sciences**
- **Information Dominance**
- **Multifunction Materials**
- **Nanoscience**
- **Propulsion and Energetic Sciences**

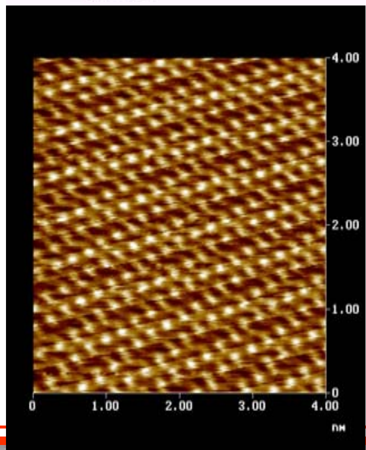
Note: Nanoscience/nanotechnology impacts all six SRAs.

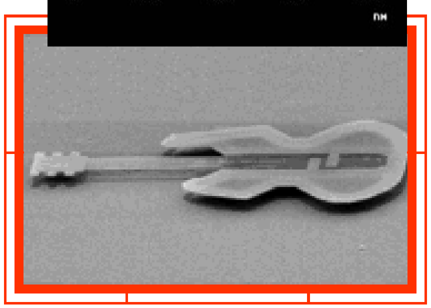
Nanoscience/Nanotechnology







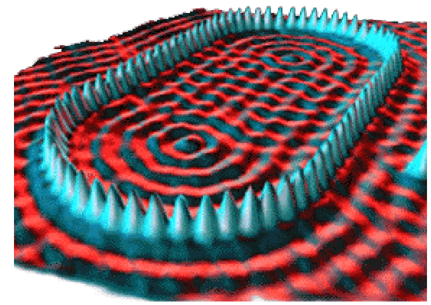


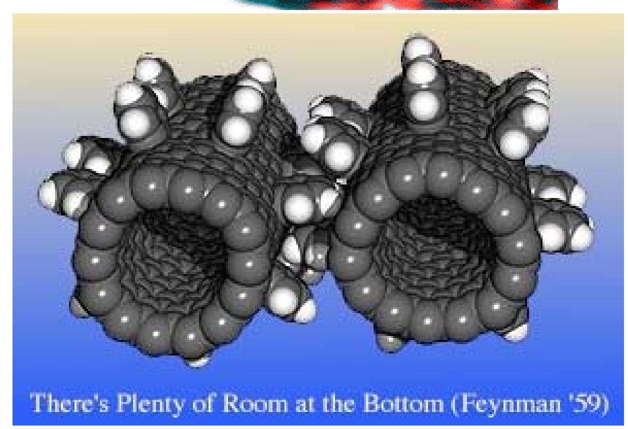


The science and technology of controlling and manipulating things at the atomic layer and nanometer (10^{-9} m) scale.

- 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





National Nanotechnology Initiative, 2001

- NNI was launched in FY2001, with the goal to double the FY00 baseline of $270M. Since then federal investment in nanotechnology has tripled.

	FY2000	**FY2001**	**FY2002**	**FY2003 (plan)**	**FY2004 (request)**
NSF	$97M	$150M	$204M	$221M	$249M
DoD	$70M	$123M	$224M	$243M	$222M
DoE	$58M	$88M	$89M	$133M	$197M
NASA	$4M	$22M	$35M	$33M	$31M
NIH/HHS	$32M	$40M	$59M	$65M	$70M
NIST/DoC	$8M	$33M	$77M	$69M	$62M
EPA		$5M	$6M	$6M	$5M
DHS(TSA)		$2M	$2M	$2M	$2M
USDA				$1M	$10M
DOJ			$1M	$1M	$1M
Total	**$270M**	**$464M**	**$697.1M**	**$773.7M**	**$849.5M**

DoD Investment on Nanotechnology

	FY2000	FY2001	FY2002	FY2003	FY2004 Request
DoD	**$70M**	**$123M**	**$180M**	**$243M**	**$222M**

FY2003:

OSD	$ 28M
DARPA	$142M
Army	$ 29M
Navy	$ 31M
Air Force	$ 13M

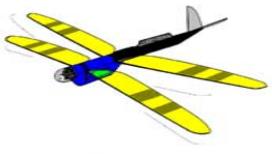
FY2004 Request:

OSD*	$ 28M
DARPA**	$117M
Army	$ 30M
Navy	$ 29M
Air Force	$ 18M

* 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

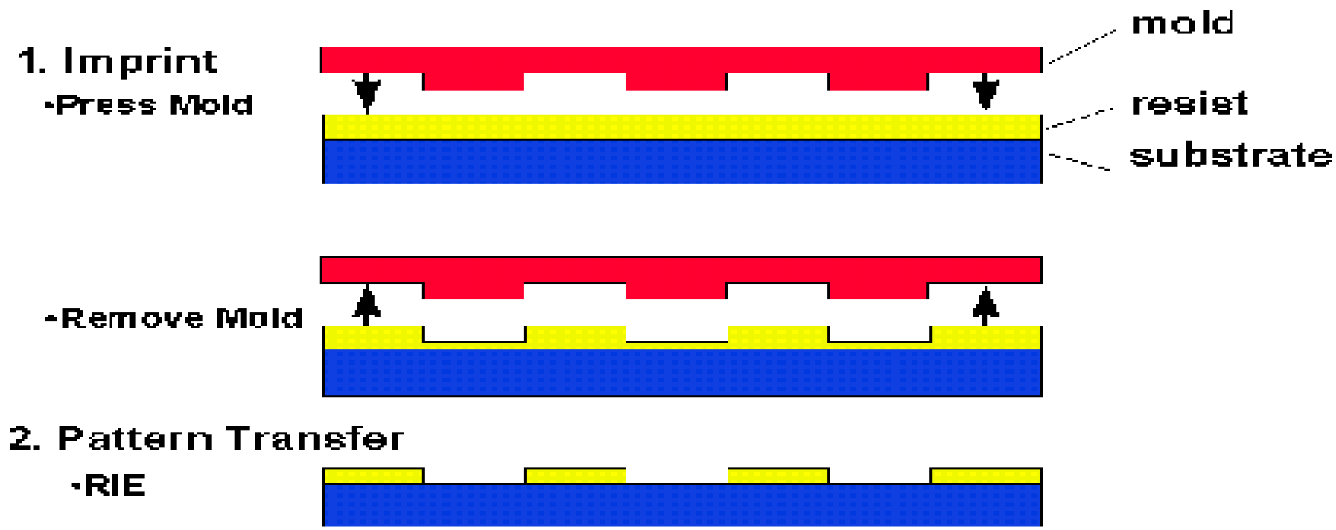
Investigator	Prime Institution	Research Topic
Josef Michl	Univ. of Colorado	Nanoscale Machines and Motors
Mehmet Sarikaya	Univ. of Washington	Molecular Control of Nanoelectronic and Nanomagnetic Structures
Michael Zachariah	Univ. of Minnesota	Nano-energetic Materials
Hong-Liang Cui	Stevens Inst. of Tech.	Characterization of Nanoscale Elements, Devices, Systems
Richard Smalley	Rice Univ.	Synthesis, Purification, and Functionalization of Carbon Nanotubes
Randall Feenstra	Carnegie Mellon Univ.	Nanoporous Semiconductors – Matrices and Substrates
Subra Suresh	MIT	Deformation, Fatigue, and Fracture of Nanomaterials
Horia Metiu	UC Santa Barbara	Nanostructure for Catalysis
Mary C. Boyce	MIT	Polymeric Nanocomposites
Paras Prasad	SUNY at Buffalo	Polymeric Nanophotonics and Nanoelectronics
Terry Orlando	MIT	Quantum Computing and Quantum Devices
James Lukens	SUNY, Stony Brook	Quantum Computing and Quantum Devices
Chad Mirkin	Northwestern Univ.	Molecular Recognition and Signal Transduction
Anupam Madhukar	USC	Synthesis and Modification of Nanostructure Surfaces
George Whitesides	Harvard Univ.	Magnetic Nanoparticles for Application in Biotechnology

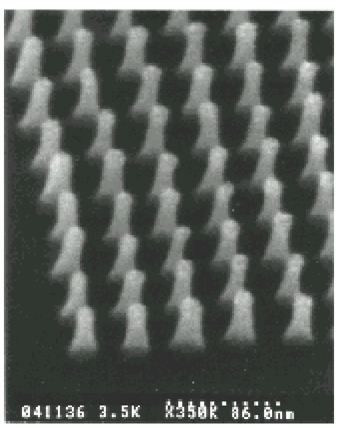
Multidisciplinary University Research Initiative (MURI)

FY	Investigator	Institution	Research Topic
98-03	J. Sturm	Princeton Univ.	Engineering of Nanostructures and Devices
98-03	A. Epstein	MIT	Microthermal Engines for Compact Powers
98-03	B. Zinn	Georgia Tech	Microthermal Engines for Compact Powers
98-03	S. Goodnick	Arizona State U.	Low-power, High Performance Nanoelectronic Circuits
98-03	James	Univ. Minnesota	Computational Tools for Design of Nanodevices
99-04	Brueck	U. New Mexico	Nanolithograph
99-04	Datta	Purdue Univ.	Spin Semiconductors and Electronics
00-05	Mabuchi	Caltech	Quantum Computing and Quantum Memory
00-05	Shapiro	MIT	Quantum Computing and Quantum Memory
01-06	Bruce Dunn	UCLA	3-D Nanoarchitectures for Electrochemical Power Source
01-06	Ken Poppelmeier	Northwestern	3-D Nanoarchitectures for Electrochemical Power Source
01-06	Shelton Taylor	Univ Virginia	Multifunctional Nano-engineered Coatings
01-06	Ed Cussler	Univ. Minnesota	Multifunctional Nano-engineered Coatings
02-07	I. Schuller	UC San Diego	Integrated Nanosensors
02-07	D. Lambeth	CMU	Integrated Nanosensors
03-08	Dan van der Weide	Wisconsin	Nanoprobes for Laboratory Design Instrum. Research
03-08	Lukas Novotny	U. Rochester	Nanoprobes for Laboratory Design Instrum. Research
03-08	William Doolittle	Georgia Tech	Next Generation Epitaxy for Laboratory Instru. Design
03-08	Jimmy Xu	Brown Univ.	Direct Nanoscale Conversion of Biomolecular Signals

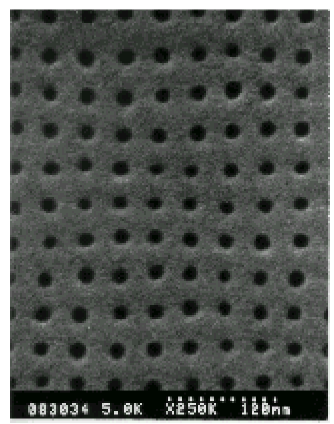
Nanoimprint Lithography

Princeton University, Professor Stephen Chou

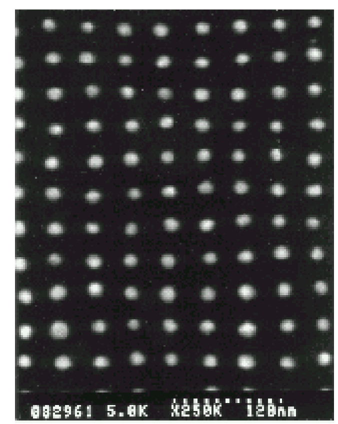




Imprint mold with 10nm diameter pillars



10nm diameter holes imprinted in PMMA



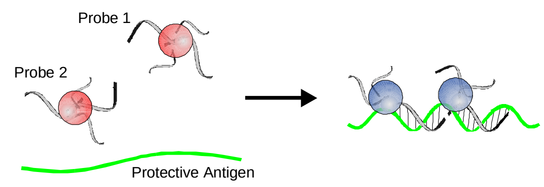
10nm diameter metal dots fabricated by nano-imprint lithography

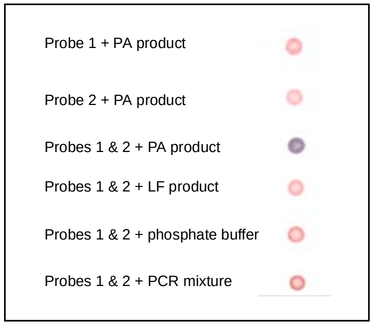
Cluster Engineered Materials

Chad Mirkin, NWU

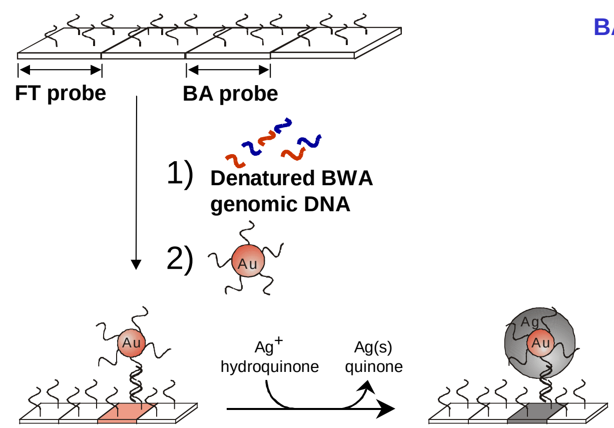
- Biological agent detection
  - PCR-free bioagent recognition
  - DNA/Nanosphere-based
    - Anthrax detection in solution
      - 30 nucleotide region of a 141-mer PCR product (*blue dot*)
      - Sensitivity: <10 femtomole
      - Detect single BP mismatch
    - Anthrax detection on substrate
      - 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

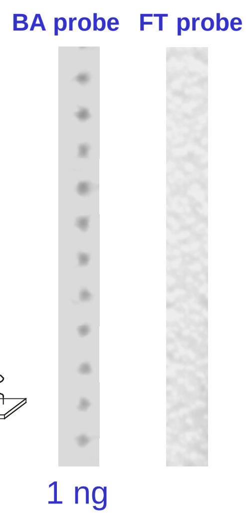
Colorimetric Detection of Anthrax in Solution





Colorimetric Detection of Anthrax on Substrate

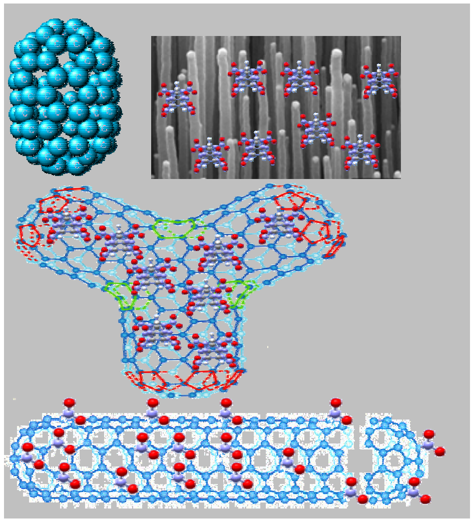




BA = Bacillus Anthracis
FT = Francisella Tularensis

Nano-Systems Energetics (DURINT)

P.I.: Michael Zachariah, U. Minnesota, mrz@me.umn.edu
http://www.me.umn.edu/~mrz/CNER.htm



Nanoscale Energetic Materials

CNER: Center for Nano-Energetics Research

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.

Research Accomplishments

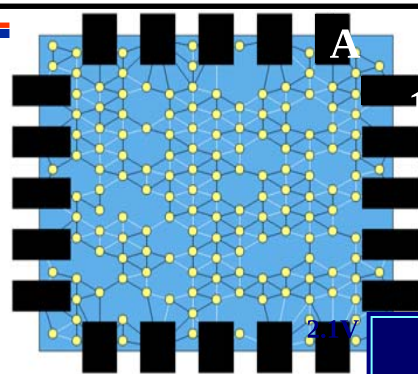
- **Developed continuous flow reactor for nanoparticle production and passivation (copy at ARL-WMRD)**
- **Formulated model for nanoparticle formation and growth**
- **Designed experiments for characterization of size, composition and reactivity of nanoparticles**
- **Computed oxidative reactions of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

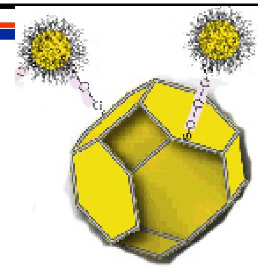
Nanocell Approach to a Molecular Computer

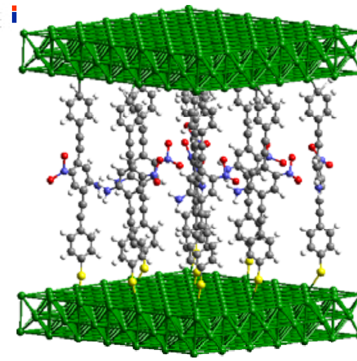
J. Tour (PI, Rice U.), D. Allara and P. Weiss (Penn State), P. Franzon (NC State), P. Lincoln (SRI), M. Reed (Yale), J. Seminario (S. Carolina), R. Tsui, H. Goronkin, I. Amlani (Motorola).

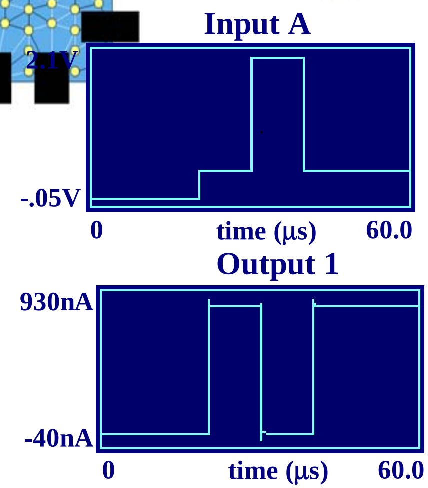
Technology Issues: Nanocell assembly, programming, and packaging

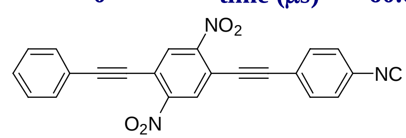
Objectives: Construct logic devices using programmable Nanocells

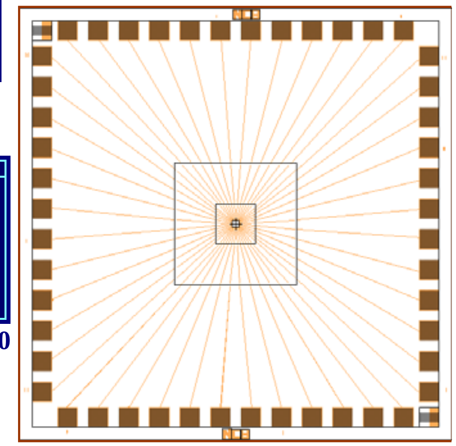










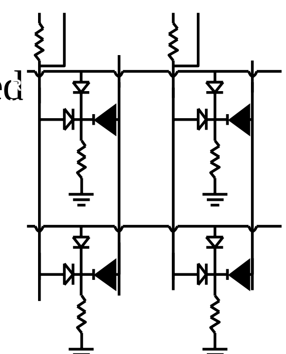


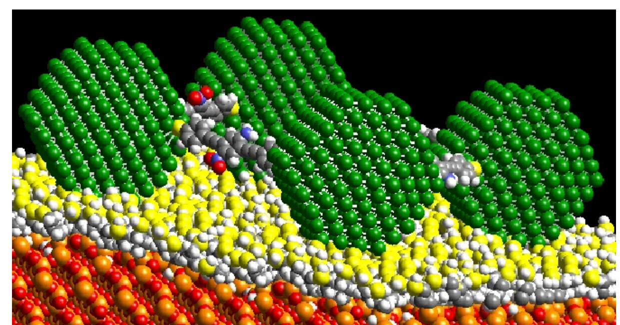
Approach

- •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

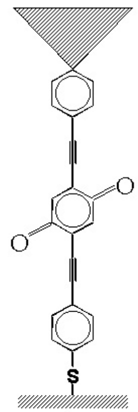




Impact & Transition: Molecular Electronics Corp., Motorola

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).



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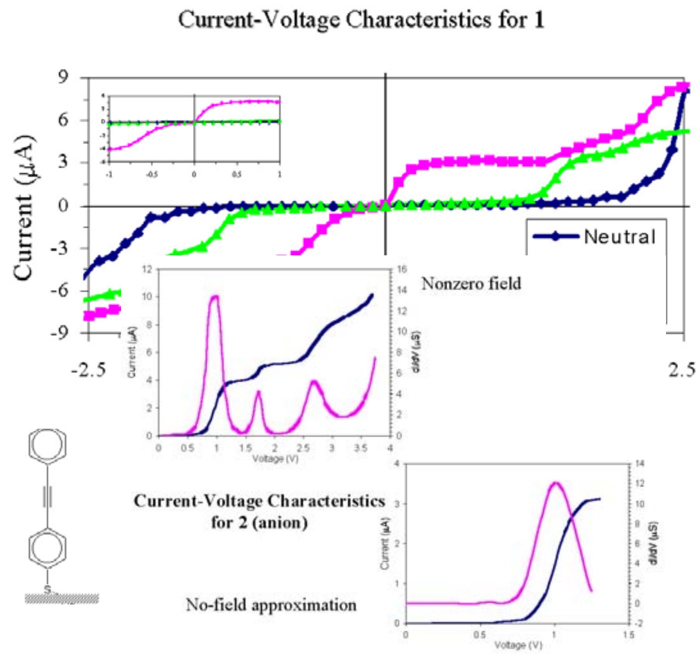
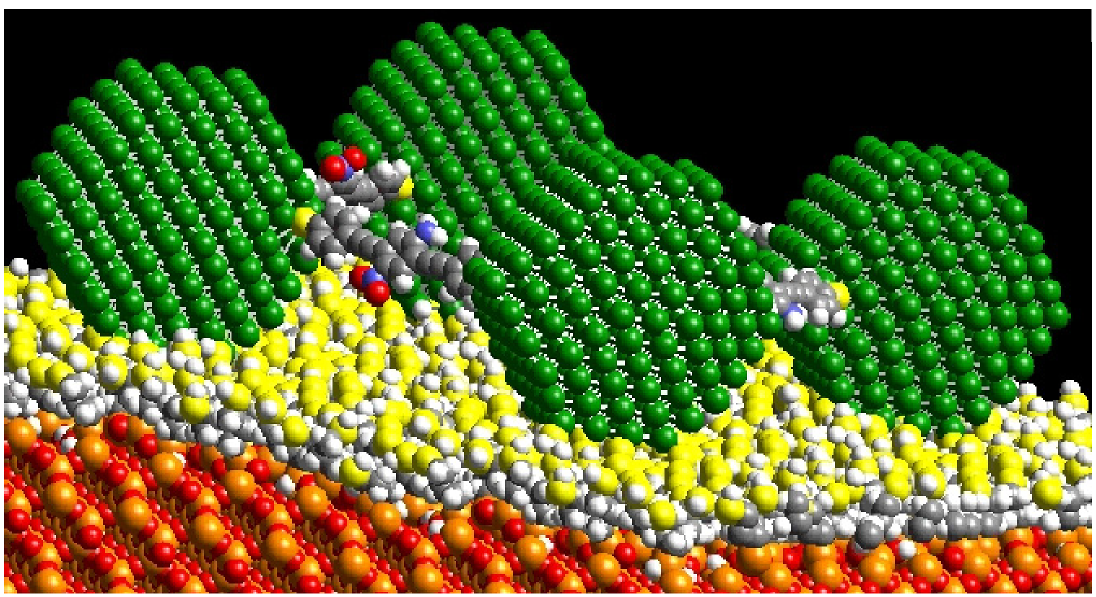
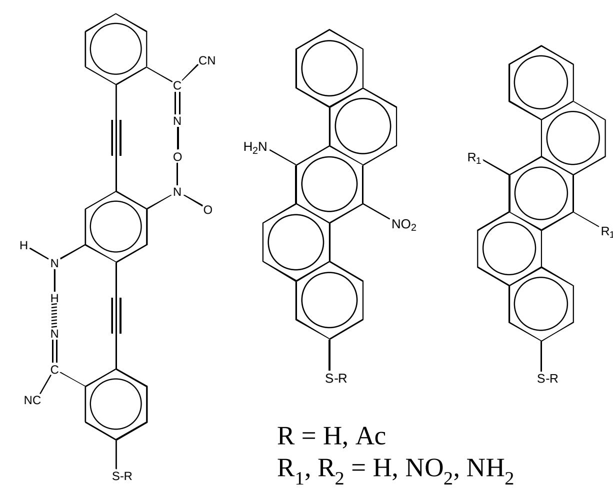






R = H, Ac
R_1, R_2 = H, NO_2, NH_2

DURINT - Nanoporous SiC and GaN

Strain Relief During Epitaxy of GaN on porous SiC

Prof. Randall Feenstra, CMU

Objective:

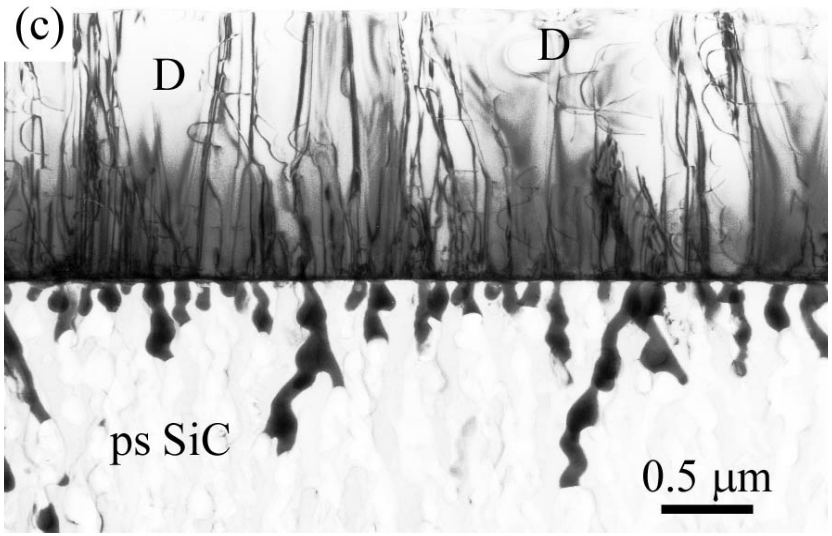
Relieve the strain which occurs when films are grown on substrates with mismatched lattice constant.

Results:

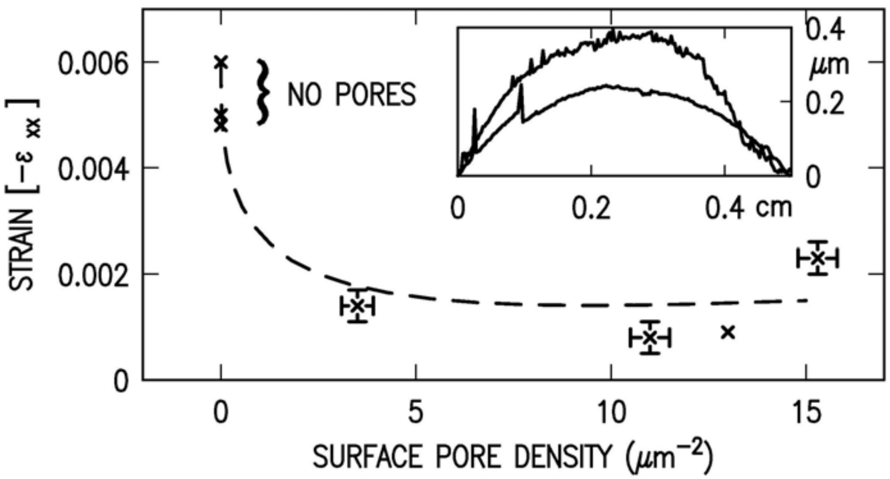
GaN films have been grown by MBE on porous SiC substrates with a range of surface pore densities. Strain in the films is characterized by stylus profilometry. Significant strain relaxation is found, with the residual strain being about 3 times smaller than for films grown on nonporous substrates.

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.



TEM image of MBE-grown GaN on porous SiC



Strain in GaN film vs. surface pore density

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.

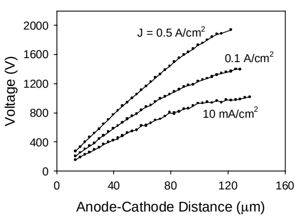
Multidisciplinary Approach

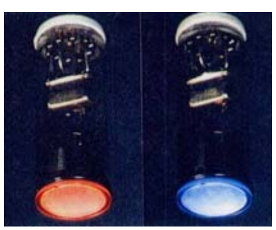
•Materials synthesis, assembly, functionalization;
•Nanometer-scale manipulation and measurements of transport, electronic and mechanical properties;
•Spectroscopic characterization and studies;
•Large-scale *ab inito* and empirical molecular dynamics simulation and theoretical calculations.

MURI Team

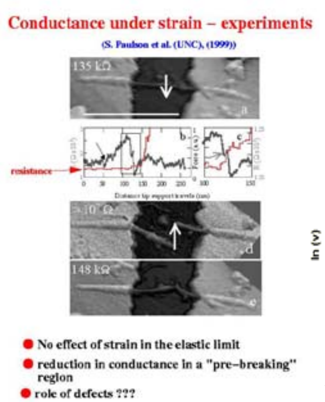
UNC: Physics, Chemistry, Materials Science and Computer Science
NCSU: Physics and Materials Science
Duke: Chemistry
Industrial Partners: Lucent Technologies, Raychem Co. and Ise Electronics

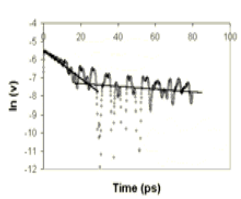
Research Highlights





Carbon nanotube field emitters provide high current density and stability

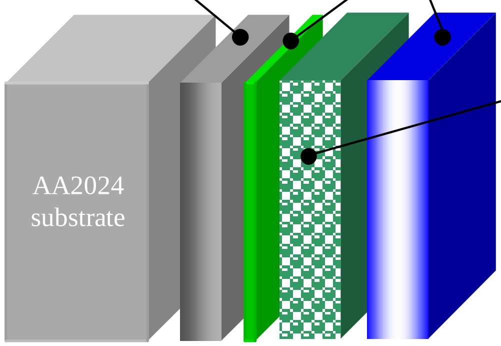




Rolling and Friction at the atomic scale

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/cm^2)
•Performed the first ^{13}C NMR measurement of the electronic properties of the carbon nanotubes.
•Demonstrated high Li storage capacity in processed SWNTs.



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

GOALS/OBJECTIVES

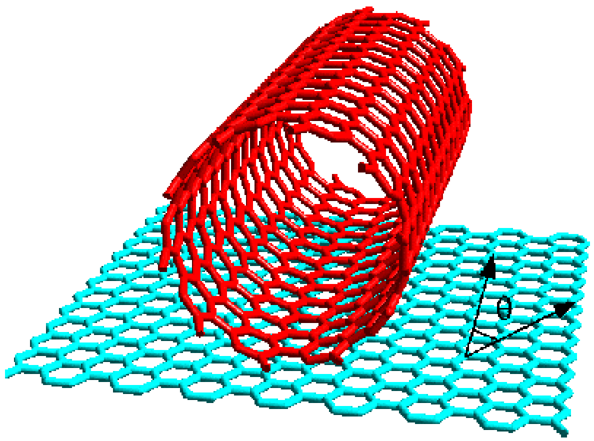
- To develop a new multi-functional coating system for military aircraft
- Coating will sense corrosion and mechanical damage
- Initiate mitigation response to mechanical and chemical damage
- Provide corrosion protection and adhesion using environmentally compliant materials

DOD TECH PAYOFF

- Will provide significant advancement in corrosion protection, life cycle costs, and mission safety

Synthesis, Purification, and Assembly of SWNT Carbon Fibers

Prof. Richard Smalley, Rice University



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

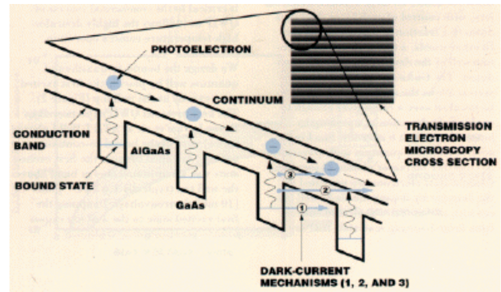
Structures with controlled dielectric properties

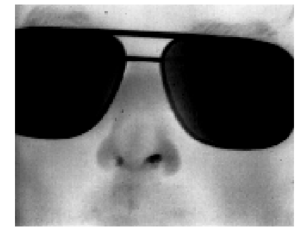
Potentials in hydrogen storage and electrode technology

Quantum Well IR Sensors

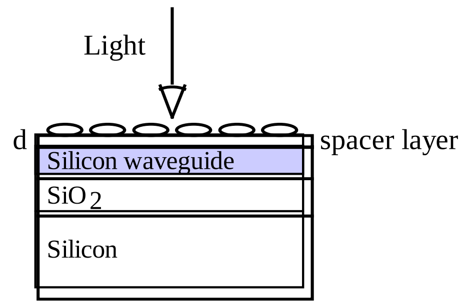
- Advanced Photodetectors
  - Quantum Well Infrared Photodetectors
    - Use electronic band engineering and nanofabrication techniques
    - Multispectral IR imaging
  - Uncooled Infrared Detectors
    - Uses nanofabrication and advanced materials
  - Nanoparticle-Enhanced Detection
    - Increase light 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

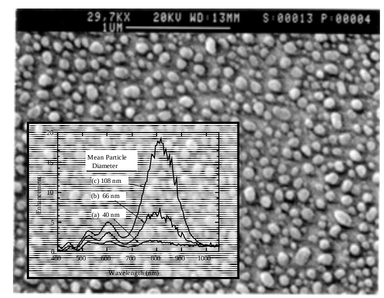
Quantum Well Infrared Photodetectors





Nanoparticle Enhanced Detection



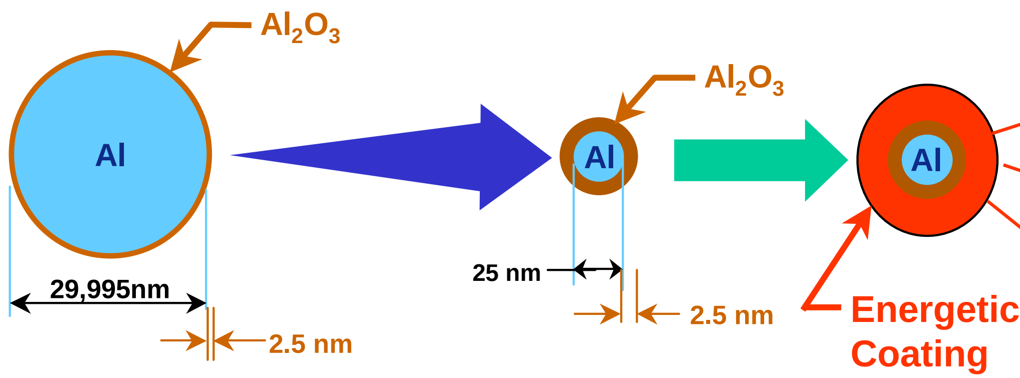


AH-64 Apache

Hellfire

Nanometric Energetic Materials Research at AFRL Munitions Directorate

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.

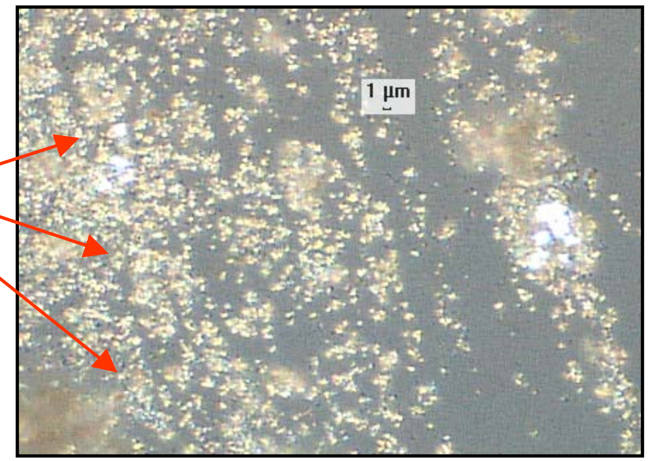


Surface Area = 0.1m²/g

30 Micron Particle

Surface Area = 74 m²/g

30 nm Particle



30 nm Aluminum Particles Each Coated with Energetic Material Layer

- *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

Institute for Soldier Nanotechnologies

Prof. Ed Thomas, MIT

University Affiliated Research Center

- Investment in Soldier Protection
- Industry partnership/participation
- Accelerate transition of Research Products

Goals

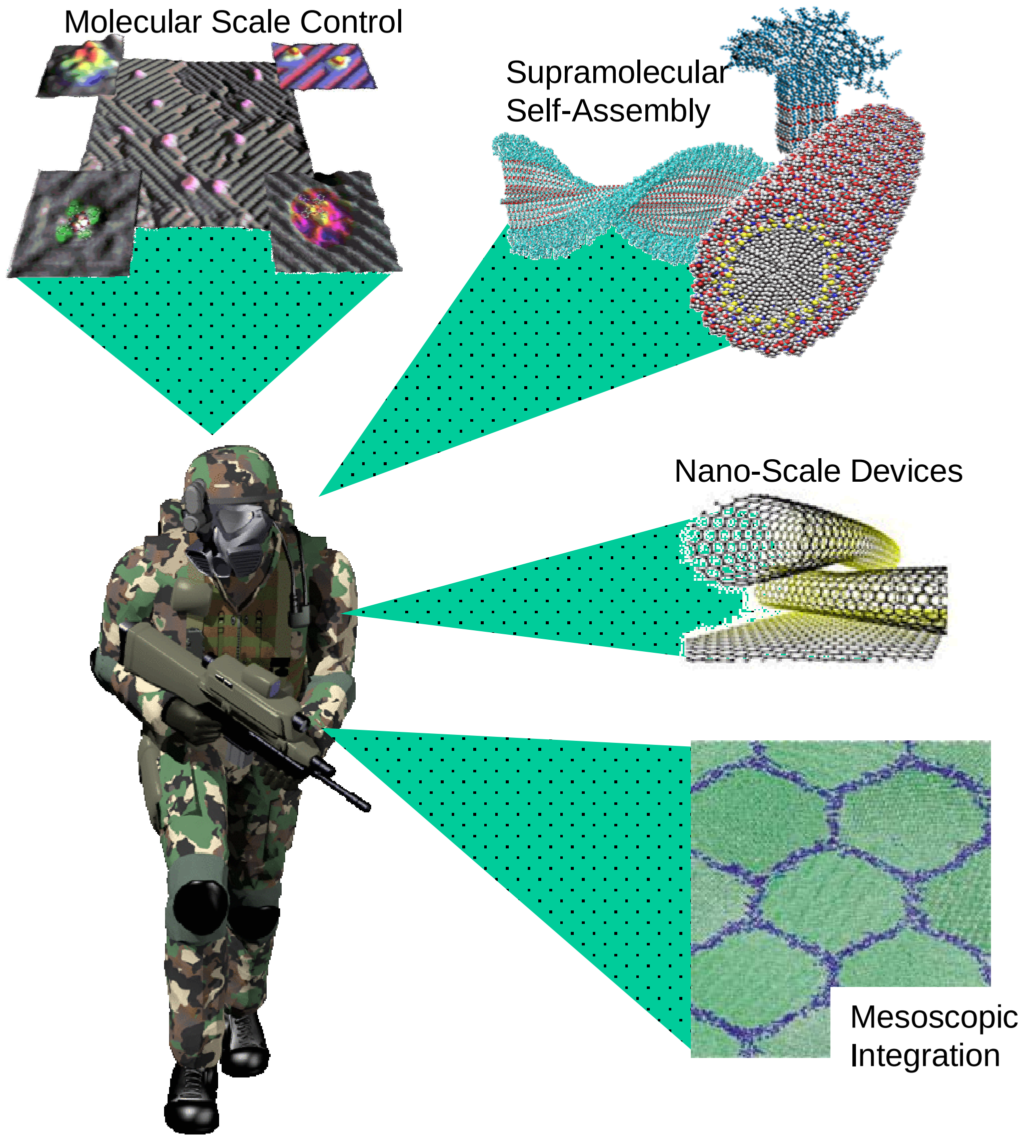
- Enhance Objective Force Warrior survivability
- Leverage breakthroughs in nanoscience & nanomanufacturing

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

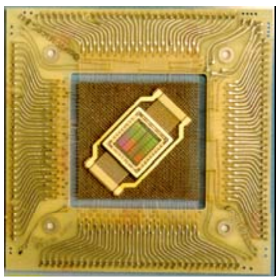
- Ribbons made of electroactive polymers
- Artificial muscle and molecular muscle
- Organic/inorganic multilayers for optical Communications
- Tunable optical fibers
- Dendrimers for protective armors
- Conducting polymer for bio-status monitors



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