Status Report on the (various) National Nanotechnology Initiative(s)

Industrial College of the Armed Forces

March 6, 2003

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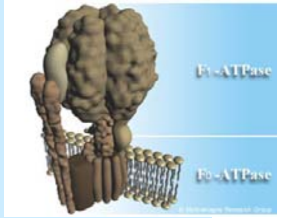
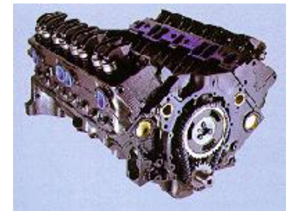
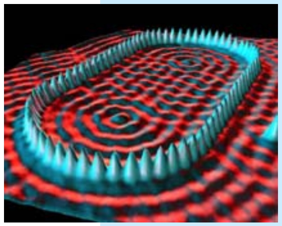
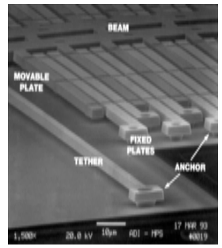
Head, Chemistry Division, Naval Research Laboratory
Director, National Nanotechnology Coordination Office

NANOMETER (nm) SCIENCE AND TECHNOLOGY

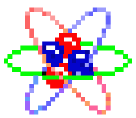


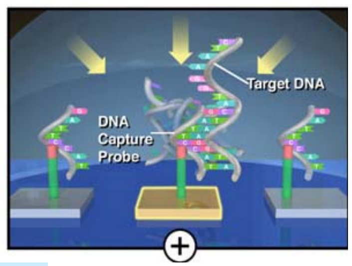



MAT - TECH

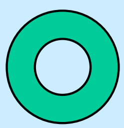
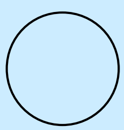
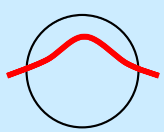
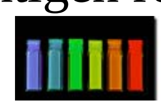



INFO - TECH

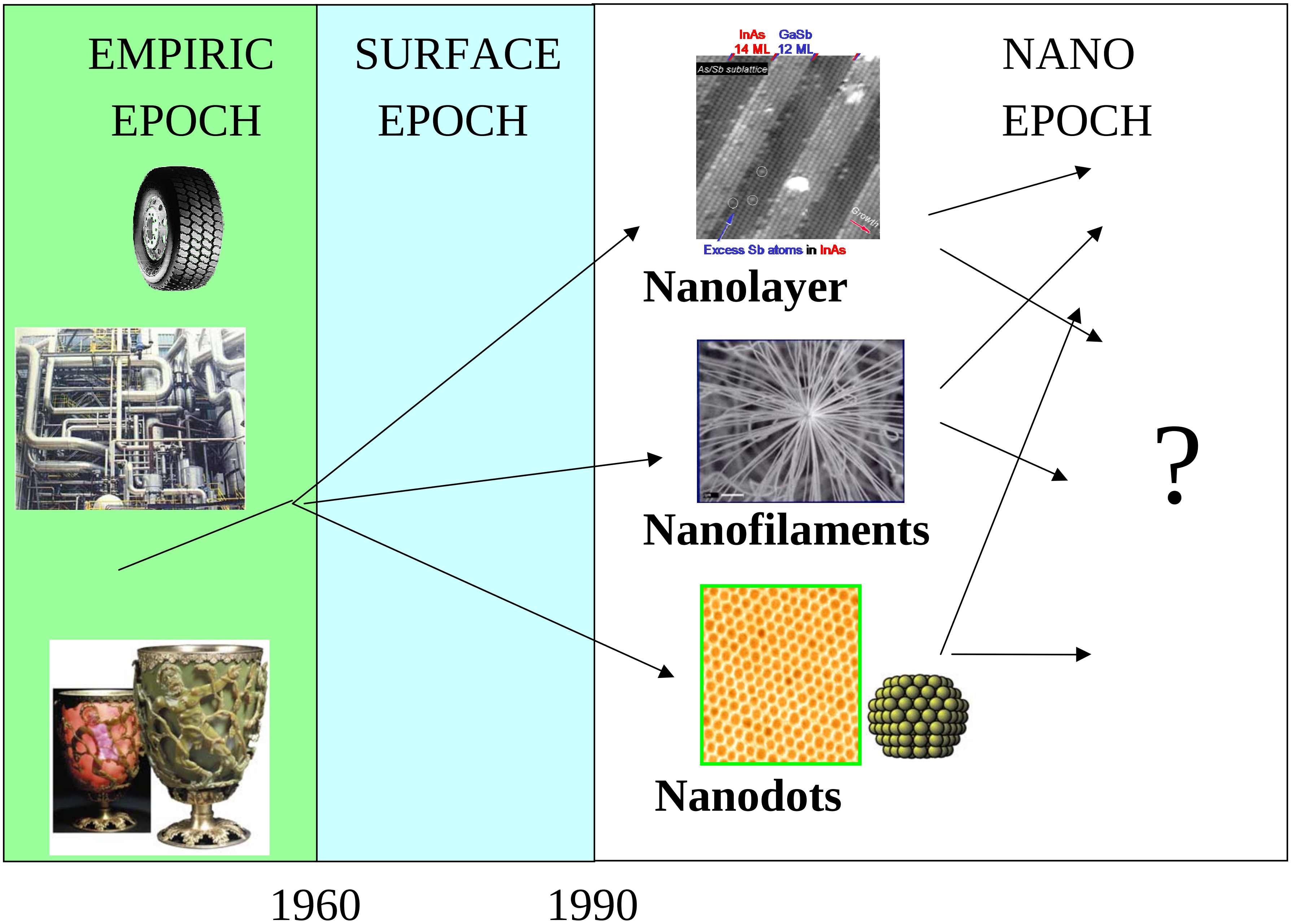
pm  nm µm mm meter km


BIO - TECH

	PHENOMENA	EXAMPLE
	Interface/Interphase	oxide layer
		cell membrane
	Size effects	paramagnetic limit
		antibody/antigen recognition
	Quantum confinement	QD color 
		Single electron device

Paleontology of Nanostructures



NANOTECHNOLOGY

Potential Economic Impact in 15-20 years: "NANO INSIDE"

Estimates by various Industry Representatives

$340B	Materials	materials, processing
$300B	Electronics	"nanoelectronics"
$180B	Pharmaceuticals	½ of production
$100B	Chemical Manufacture	catalysts
$70B	Aerospace	
$20B	Tools	automation, life cycle cost
$30B	Improved Healthcare	tools for healthcare
$45B	Sustainability	agriculture, water, energy
~$1T	Total	

NanoBusiness Alliance www.nanobusiness.org/
CMP Cientifica www.cmp-cientifica.com/cientifica/frameworks/generic/public_users/NOR/NOR.htm

Roco, NSF

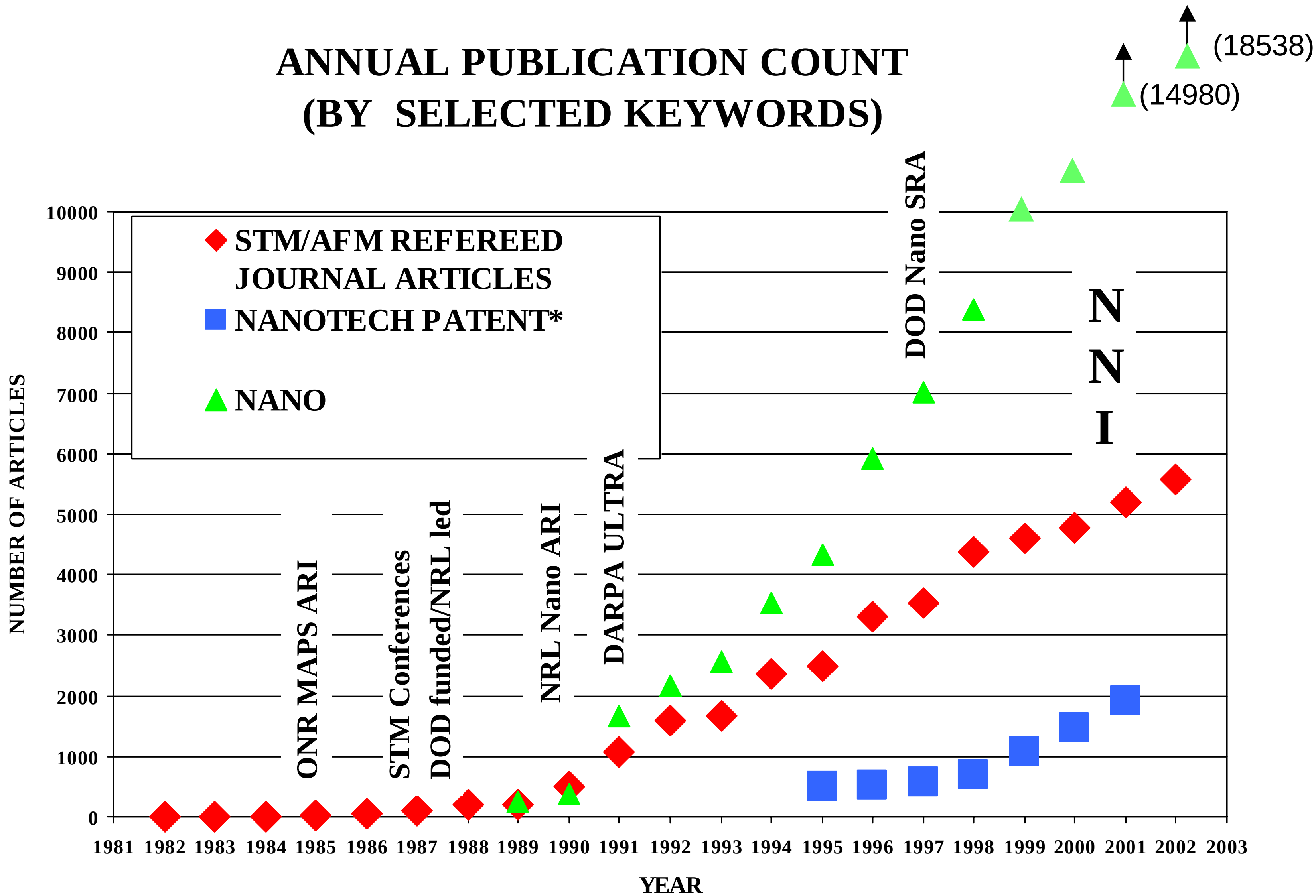
“NANOTECHNOLOGY” RESEARCH PROGRAMS IN THE WORLD
Main government sponsored research programs

	~1997 (WTEC)	2001	2002 (est)
USA	$115M	$420M	~$700M
JAPAN	$120M	$500M	~$800M
WESTERN EUROPE	$125M	$250M	~$300M
OTHER COUNTRIES (FSU, China, Canada, Australia, others)	$ 70M	$200M	~$400M
TOTAL	$430M	~$1400M	>$2000M

Fiscal year start/stop varies from country to country

Return on Basic Research Investment:

Nurturing Nanoscience into DoD Nanotechnology



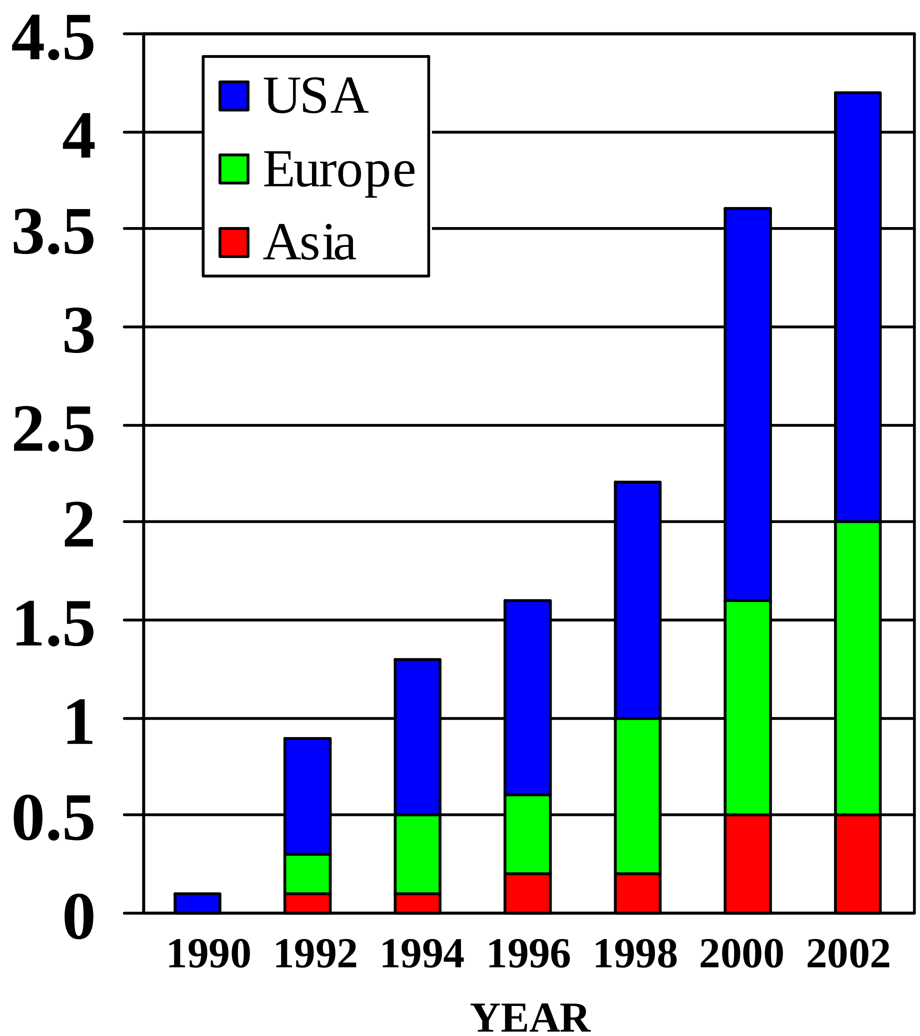
* “Nanotechnology – Size Matters”, white paper, 10 July 2002, Institute of Nanotechnology

Journal ISI Impact Factors (2001)

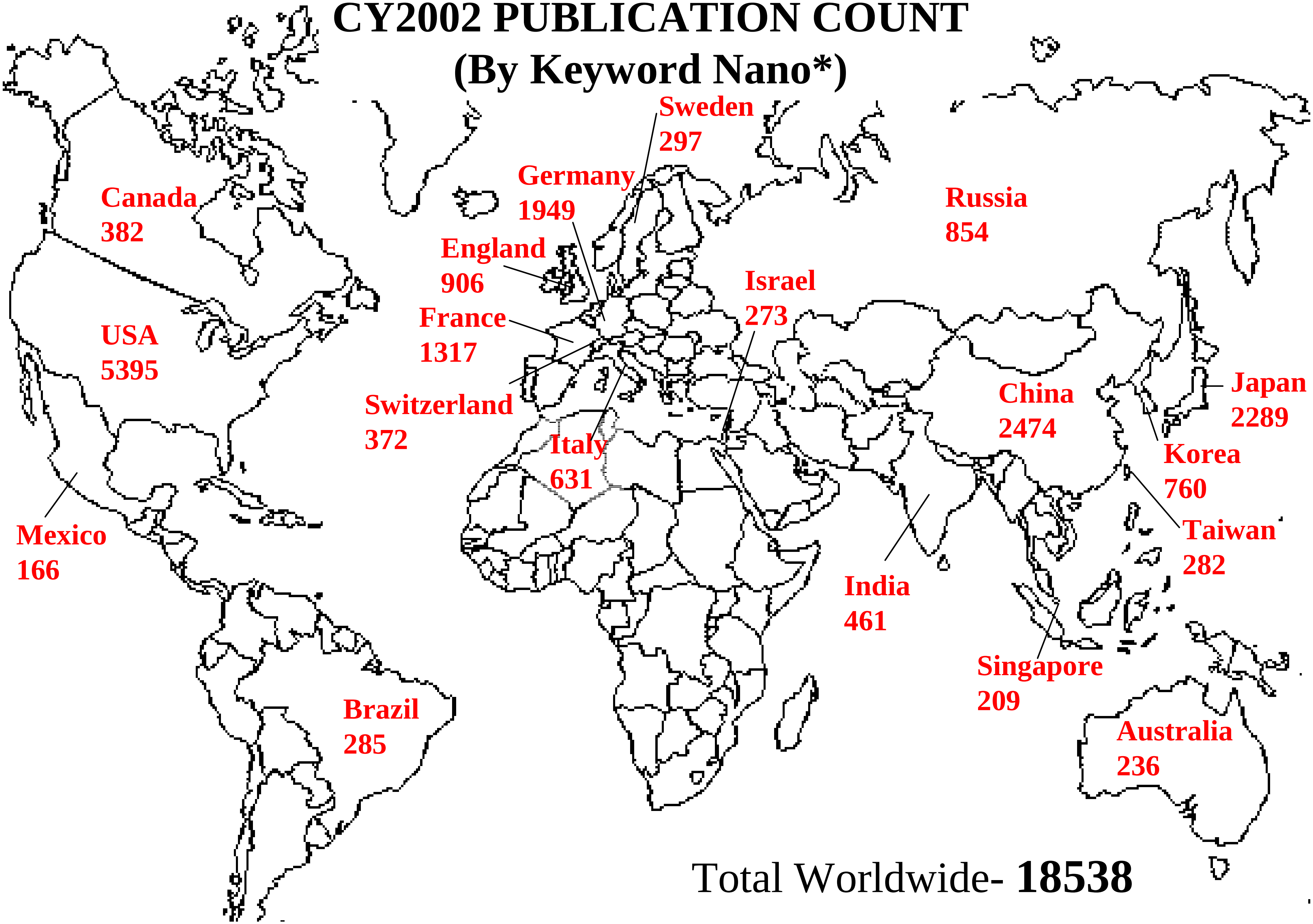
Nature	27.9
Science	23.3
Phys Rev Lett	6.6
Appl Phys Lett	3.8
Prog Polym Sci	3.7
Macromolecules	3.7
Chem Matl	3.6
J Phys Chem B	3.3
J Chem Phys	3.1
Phys Rev B	3.0
Phys Rev A	2.8
J Matl Chem	2.7
Chem Phys Lett	2.3

Percentage of “Nano*” Articles in

Nature/Science/PRL



CY2002 PUBLICATION COUNT
(By Keyword Nano*)



Total Worldwide- **18538**

Science Citation Index of 5300 Journals

Murday, NRL #227 02/03

US: NATIONAL NANOTECHNOLOGY INITIATIVE (NNI) PROGRAM ($M)

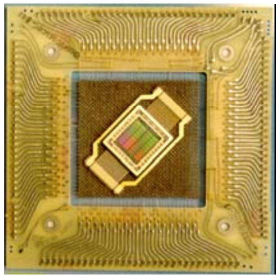
		FY01	FY02	FY03	FY04
KNOWLEDGE GENERATION		**152**	**212**		
GRAND CHALLENGES		**151**	**235**		
NANOSTRUCTURED MATERIALS BY DESIGN	**NSF**		~55		
NANOELEC, PHOTONIC, MAGNETIC	**DOD**		~90		
ADVANCED HEALTHCARE/THERAPEUTICS	**NIH**		~20		
ENVIRONMENTAL IMPROVEMENT	**EPA**		~10		
ENERGY CONVERSION/STORAGE	**DOE**		~10		
MICROCRAFT & ROBOTICS	**NASA**		~5		
CBRE PROTECTION/DETECTION	**DOD**		~20		
INSTRUMENTATION & METROLOGY	**NIST**		~15		
MANUFACTURING SCIENCE	**NSF**		~10		
CENTERS/NETWORKS		**71**	**89**		
INFRASTRUCTURE		**77**	**52**		
ETHICAL/SOCIAL IMPLICATIONS		**13**	**16**		
TOTALS		**464**	**604**	**~775**	**~850**

DoD Nanoscience Funding Summary
($M – "mainstream")

	FY00	FY01	FY02		FY03 (est)		FY04 (rec)	
			6.1	6.2/6.3	6.1	6.2/6.3	6.1	6.2/6.3
Air Force	7	10	10	8	9	4	9	10
Army	6	6	18	4	22	7	20	10
Navy	21	31	37	3	30	1	28	1
DARPA	40	40	49	69	42	100	36	80
DDRE	15	36	26		28		28	
Total	89	123	224		243		223	

Enhanced warfighting capabilities

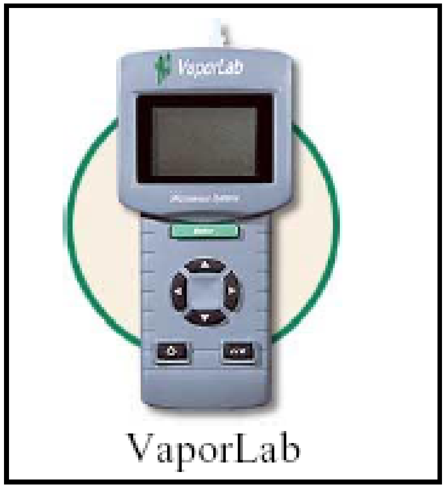
* Chem-bio warfare defense
  Sensors with improved detection sensitivity and selectivity, decontamination
* Protective armors for the warrior
  Strong, light-weight bullet-stopping armors
* Reduction in weight of warfighting equipment
  Miniaturization of sensors, computers, comm devices, and power supplies
* 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

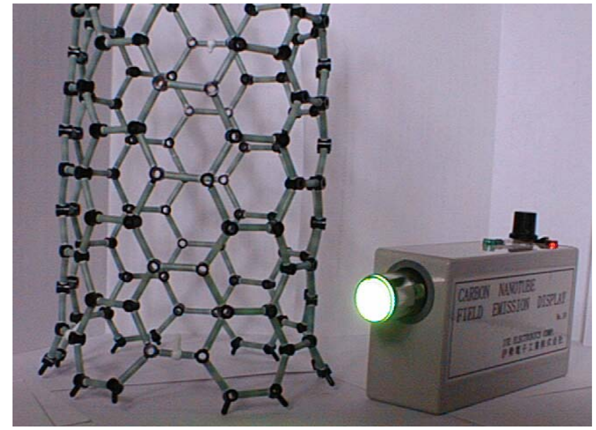
INFORMATION NANOTECHNOLOGY

AU Nanocluster Vapor Sensor;
Snow NRL, MSI/SAWTEK

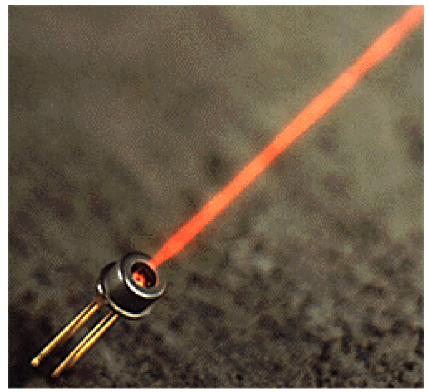


SENSE

DISPLAY



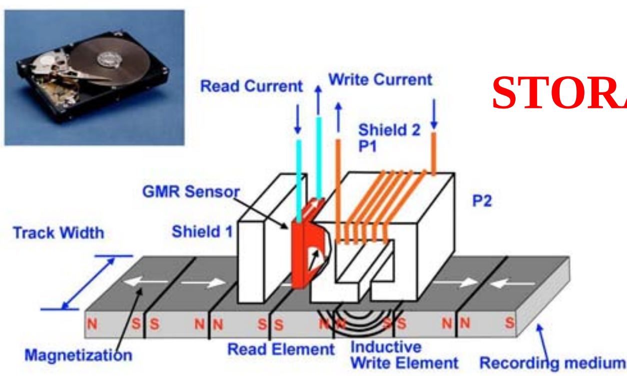
CNT FED Display; Zhou, UNC



TRANSMISSION

Superlattice VCSEL; Honeywell

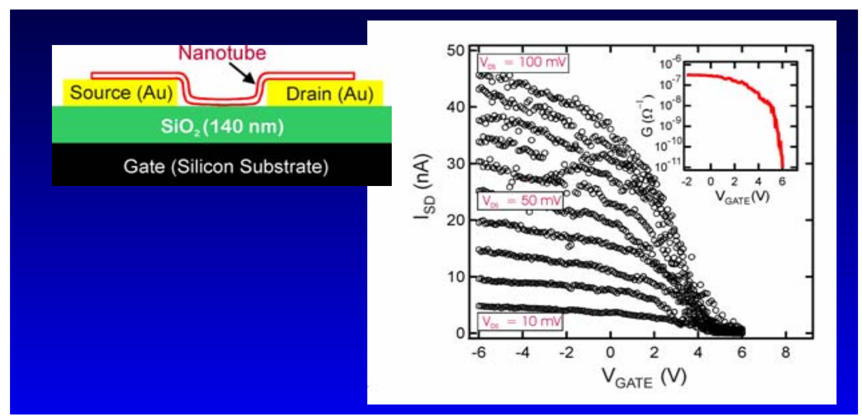
GMR Reading Head; IBM



Magnetic recording process.

STORAGE

LOGIC

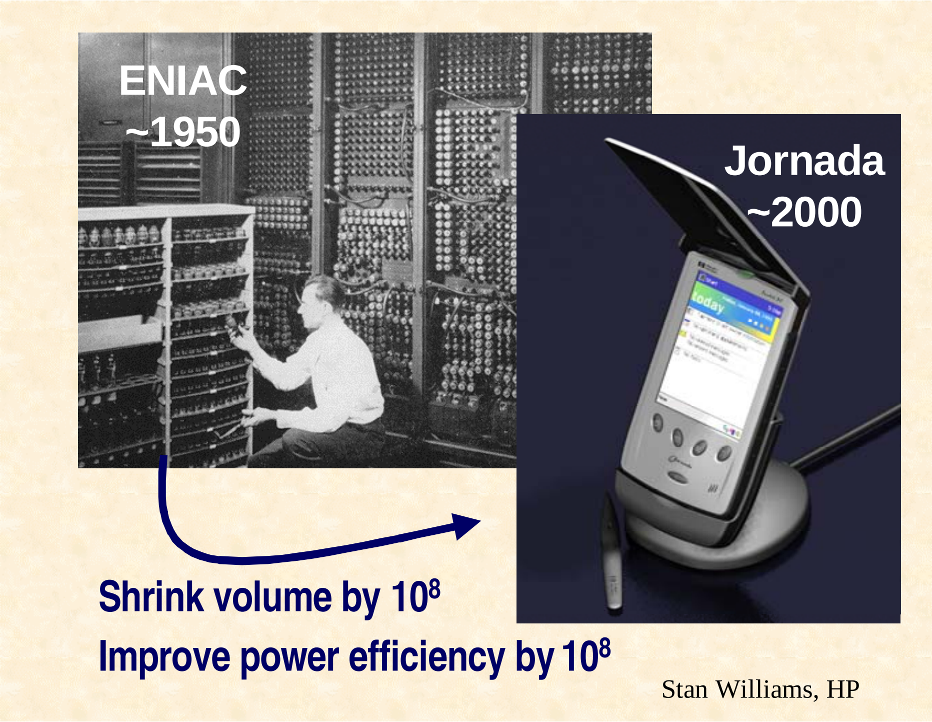


CNT FET; Avouris, IBM

Why Nanoelectronics?

The evolution of computer technology over the last few decades has revolutionized computational capability

Faster electronics
Lower power consumption
Larger data handling capabilities
More complex information processing



The era of Nanoelectronics (<100 nm) is forecast (ITRS) to begin within 3 years (2005)

Information Technology NanoDevice Options

Fabricate
Communicate
Display
Logic
Store
Sensing

2005 **2010** **2015** **2020** **Time**

Terabit/in^2 (optical memory)

Terabit/in^2 – INSIC goal (magnetic memory)

Innovative NanoDevice Concepts

Magnetic rods	Chou	Princeton
Magnetic nanocrystal	Sun	IBM Almaden
NanoCrystal memory	Tiwari	Cornell
Plastic deformation	Vettiger	IBM Zurich
Molecular switch	Heath	CIT
CNT switch	Lieber	Harvard
Ag_2S switch	Aono	RIKEN
GMR	Prinz	NRL
QD charge storage	Quate	Stanford
Back storage	Tiwari	Cornell
Ballistic magnetoresistance	Chopra	SUNY Buffalo
Molecular (64 bit)	Williams	HP
Heat assisted magnetic recording	Schlesinger	CMU
Near-field “apertures”	Schlesinger	CMU
Nanophotonics	Ohtsu	Tokyo Inst Technology

Information Technology NanoDevice Options

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2005 **2010** **2015** **2020** **Time**

↑ 90 nm gate length transistor

↑ 65 nm ITRS node ↑ 22 nm ITRS node

Innovative NanoDevice Concepts

Ferromagnetic hairpin	**Cowburn**	**U of Durham**
CNT	**Avouris**	**IBM Yorktown**
	Dekker	**TU Delft**
	Lieber	**Harvard**
	Dai	**Stanford**
Molecular cascade	**Eigler**	**IBM Almaden**
Molecule gated nanowire	**Lieber**	**Harvard**
Molecular transistor	**McEuen**	**Cornell**
12 nm gate CMOS		**Intel**
Back-plane configurable	**Tiwari**	**Cornell**
Three-dimensional vertical	**Plummer**	**Stanford**
Quantum cellular automata	**Lent**	**Notre Dame**
Self assembled networks	**Bandyopadhyay**	**VA Commonwealth**

Information Technology NanoDevice Options

Fabricate

Communicate

Display

Logic

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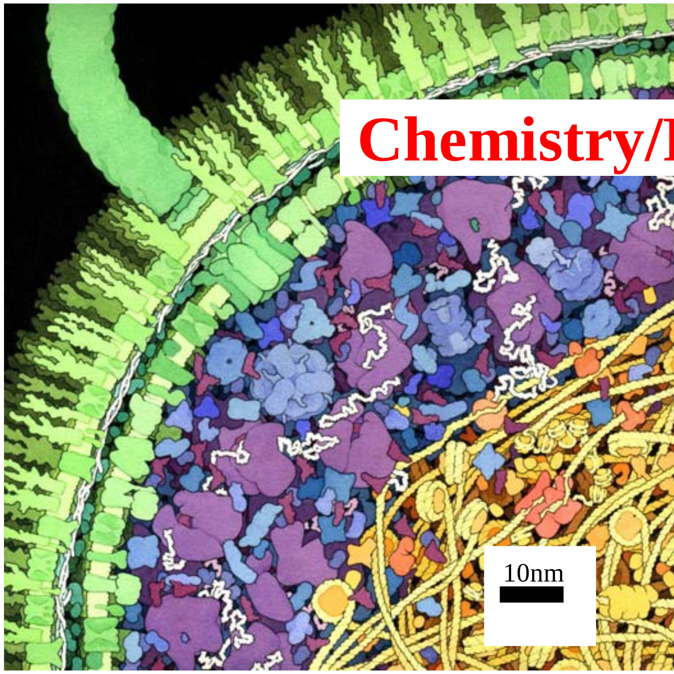
Sensing

2005 **2010** **2015** **2020** **Time**

Innovative Nanofabrication Concepts

Dip Pen	Mirkin	Northwestern
Imprint	Whitesides	Harvard
	Wilson	UT-Austin
Emboss	Chou	Princeton
Laser assisted impact	Chou	Princeton
Flexible stamp patterning	McClelland	IBM Almaden
Millipede	Vettiger	IMB Zurich
Assembled nanowires	Lieber	Harvard
	Mallour	Penn State
Aligned growth	Dai	Stanford
Nanowire	Lieber	Harvard
CVD with optical nearfield	Ohtsu	Tokyo Inst Technology
Nanoparticle arrays	Willner	Hebrew Univ
Assembly with DNA	Mirkin	Northwestern
	Seeman	NewYork Univ

NANOBIOTECHNOLOGY

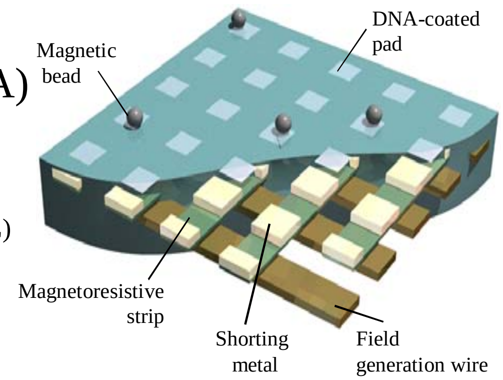


Small portion of an Escherichia coli cell
(Goodsell, Scripps; Sigma Xi 1999)

Chemistry/Physics of Biological Nanostructure

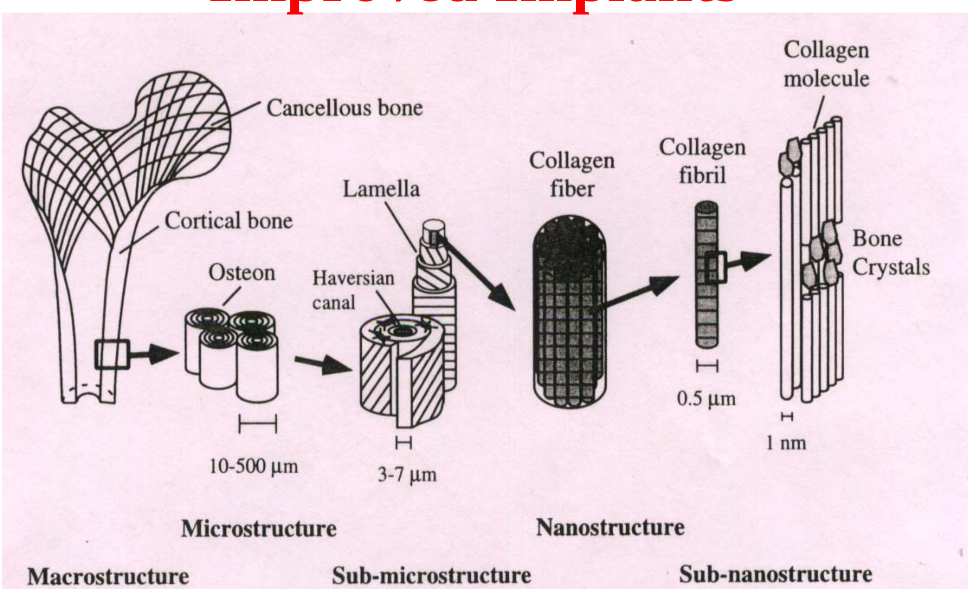
Earlier Detection and Treatment of Disease

Contrast Agents for Imaging
Sensors
Susceptibility Testing (DNA/RNA)



BARC Sensor (Colton, NRL)

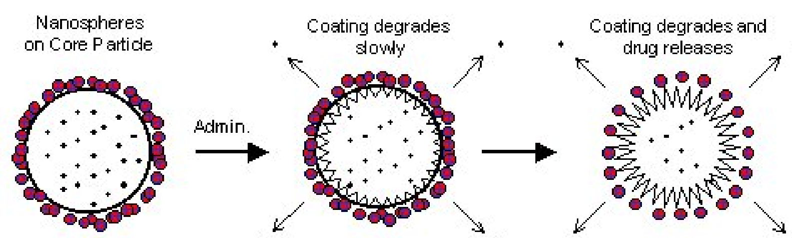
Improved Implants



Bone Structure (Siegel, RPI)

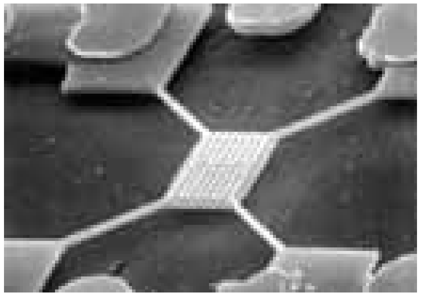
Therapeutic Delivery

Enhanced Solubility
Targeted, Local Delivery

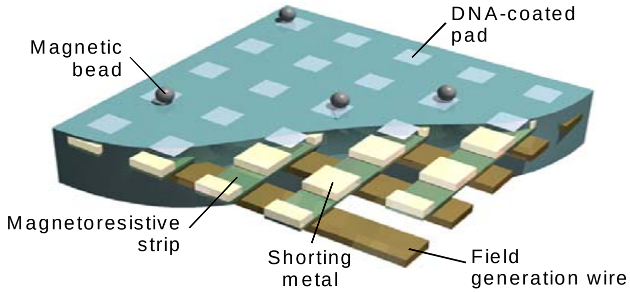


Nanosphere enhanced drug solubility
(Nanosphere)

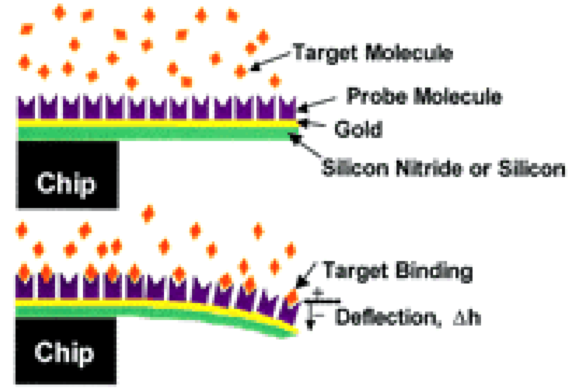
Why Nanostructures for Sensing



Nanocalorimeter; Roukes CIT



GMR Biosensor; Whitman/Prinz, NRL



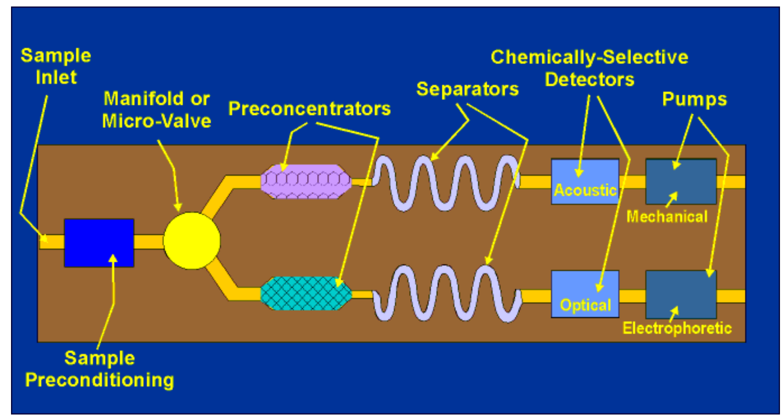
Cantilever Sensor; Thundat ORNL

- Signal to noise improvements:

  yocto(10^{-24})joule,

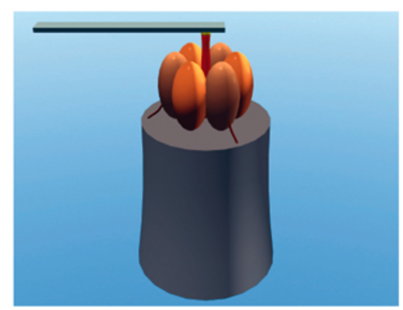
  atto(10^{-18})newton,

  single molecule, ….

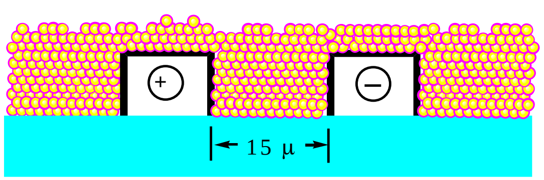


Lab-on-a-chip; Sandia

- Miniaturization – size/weight - arrays
- Lower power, potentially scavenged
- Locally process data into information

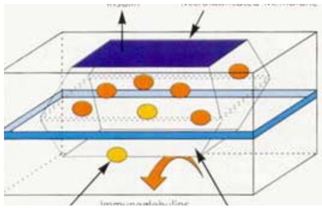


Molecular Motor; Montemagno Cornell



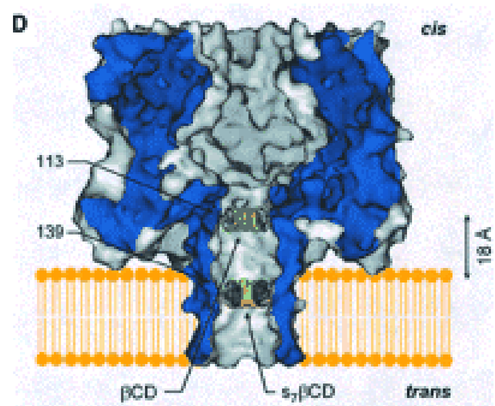
NanoAu Chemiresistor; Snow NRL

Why Nanostructures for Protection/Neutralization



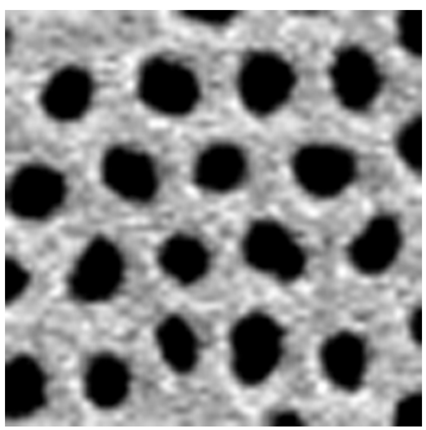
MEMS capsule, Desai

- High surface to volume ratio
- Porosity for separation

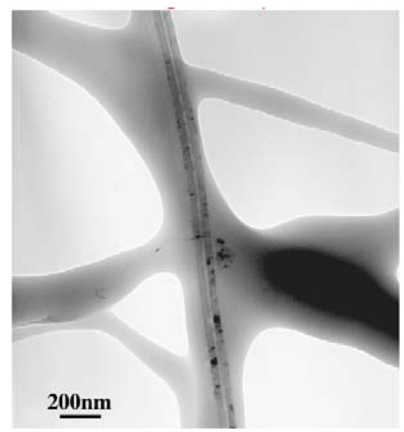


Cell membrane transport, Bayley

- Nanofibers for membranes, clothing
- Multiple reactive sites for catalysis/adsorption
- Disrupt physiological function
- Hierarchical assembly for multifunction



Nanopore Al, Martin



CNT in Electrospun Polyurethane, **Schreuder- Gibson**

Homeland Defense
Expected Impact of Nanotechnology

Lighter, smaller, and highly functional sensing systems that
provide rapid, accurate, low cost detection
distributed surveillance “platforms” for buildings, transportation hubs,…
uninhabited vehicles for response teams to reduce the risk to human lives.
personnel monitors for CBRE threats, physiological fatigue, medical applications

Protective clothing that
incorporates decontamination activity rather than simple adsorption, and
permits water vapor migration for cooling.

Masks/filters with adsorbents
having greater selectivity and capacity for harmful agent,
incorporating miniaturized sensing to detect breakthroughs, and
potentially neutralizing the agent.

Decontamination more benign to humans and environment

Innovative approaches to the **deactivation of biological agents**, especially spores

Manufacturing and processing industries **free of hazardous materials and wastes**

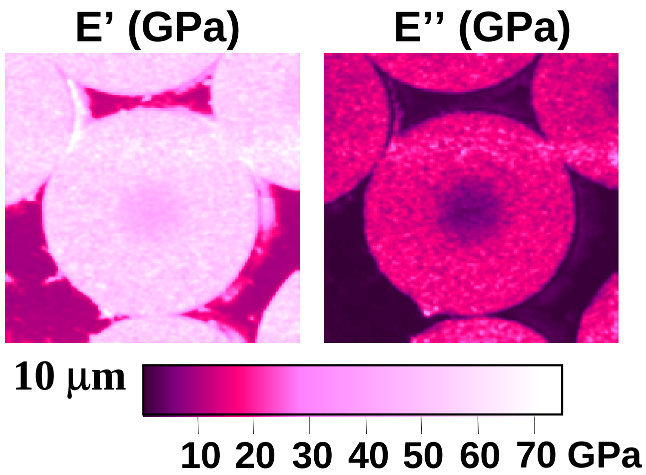
NANOMATERIALS

Q-Dot Contrast Enhancers; Frankel, MIT

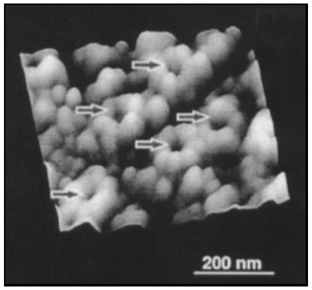
NANOSTRUCTURES

Netshape Formed Nanoceramics; Siegel, RPI

CONSOLIDATED NANOSTRUCTURED MATERIALS

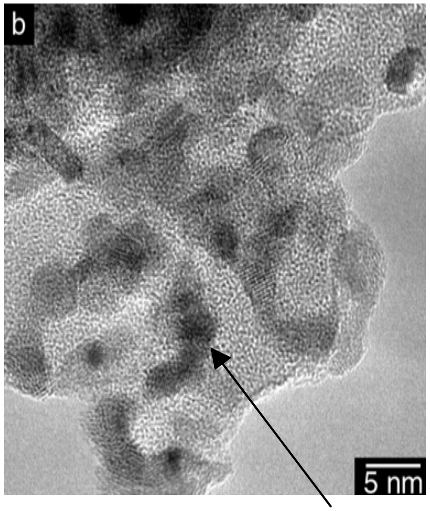


Composite Moduli Measurement; Wahl, NRL



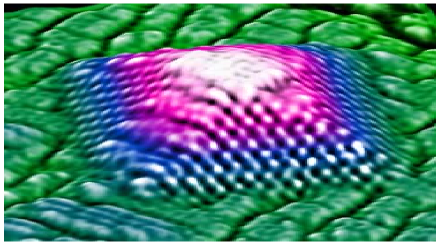
Cell Membrane; Oberleithner, Münster

NANOCOMPOSITES



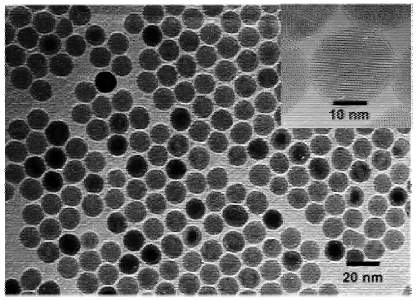
Nanocrystalline RuO_2 wire in Silica Aerogel; Rolison, NRL

NANOPOROUS MATERIALS



DIRECTED SELF ASSEMBLY

NANOTECHNOLOGY HAS THE REAL DOT.COM



y-Fe_20_3 Nanocrystallites
(J.Am. Chem. Soc., 123, 12798 (2001))

Mechanical – ceramic, powder metallurgy

Pfund Condensation – metals, ceramics

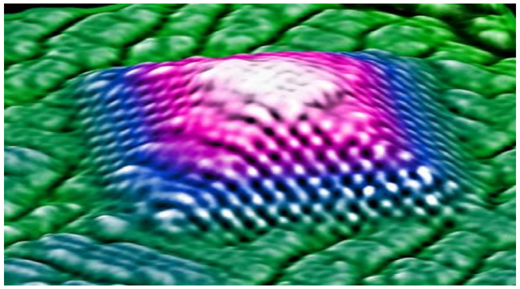
Colloid Chemistry

- Chemical Precipitation – metals, intermetallics, ceramics
- Surfactants – stabilize, size control

Sol-Gel – ceramics (oxides), porosity

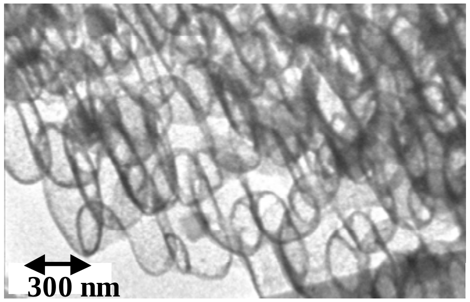
Strained Layer Growth

Molding



GE Self Assembled Pyramid on Si. 10nm at Base
(S. Williams, HP)

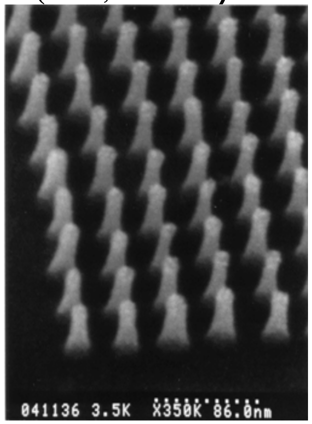
Nanomolded polymer
(Colvin, Rice)

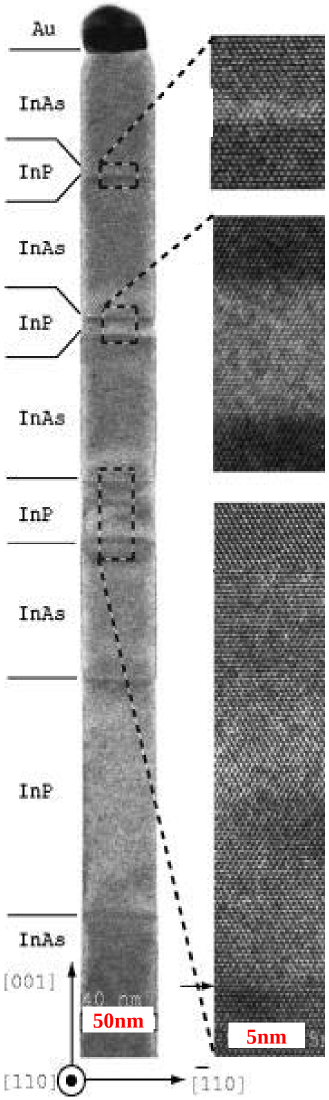


NANOTECHNOLOGY IS WIRED FOR SUCCESS

Catalytic Growth		
	Laser assisted:	III-V, II-VI, IV-IV - GaAs, GaP, InP, InAs, CdS, $Si_{1-x}Ge_{x}$,...
	Gas transport:	CNT, MoS_2, WS_2,BN, $NiCl_2$, SiO_2,
	Laser ablation:	Si
Self Assembly		
	Surfactant assisted:	Cu, Zn, Cd - sulfides, selenides
	Amphiphilic	lipids
Template		
	Pore filling:	metals, polymers, semiconductors, carbons
	Edge decoration:	Mo
Stressed Thin Films		SiGe

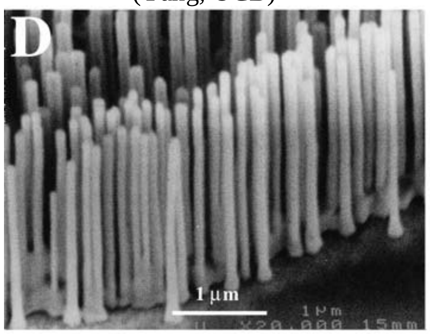
10 nm dia. SiO2 Mold
(Chou, Princeton**)**

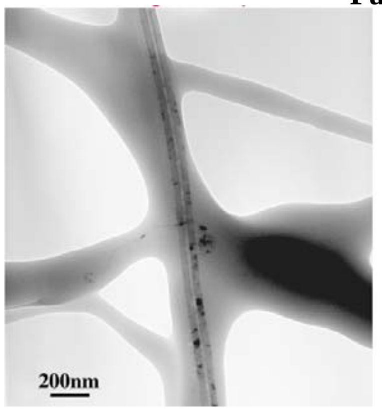




Nanowire Superlattice
(Samuelson, Lund**)**

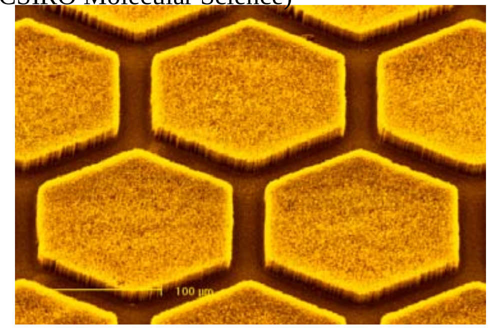
ZnO nanorod
(Yang, UCB)





10% CNT in Electrospun Polyurethane
(Schroeder-Gibson, Natick Soldier Center)

Patterned carpets of aligned carbon nanotubes
(CSIRO Molecular Science)



Nanotechnology: When it Reigns, it Pores

Ion track etch

Anodized films

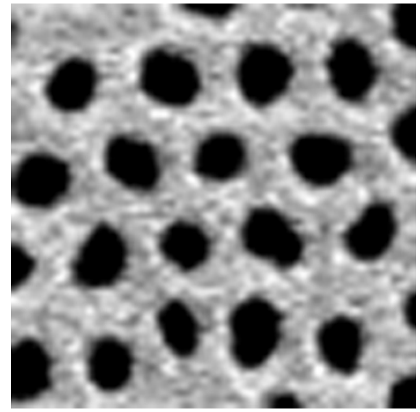
Surfactant aided “self-assembly”

Drawn glass-fiber nanochannels

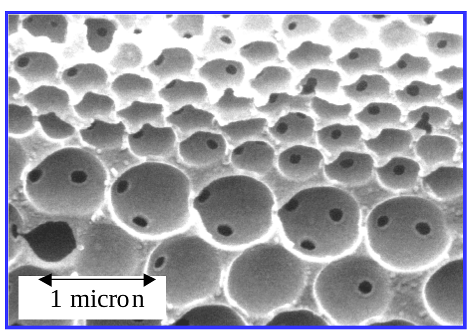
NEMS/MEMS

Crystallization with small pores – zeolites,…

Sol/Gel – aerogel, xerogel, ambigel



Nanopore Alumina
(Martin, Univ of FL)

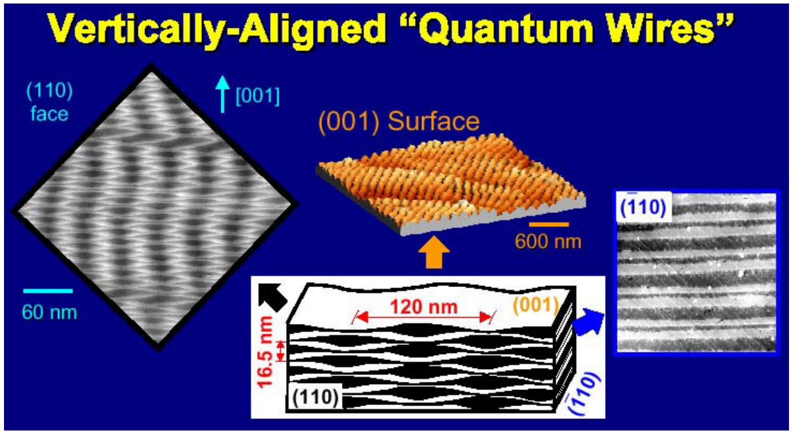


Macroporous polymer
(Colvin, Rice)

450-nm channels

Nanochannel glass
(Tonucci, NRL)

Directed, Hierarchical "Self"-Assembly of Nanostructured Systems



Whitman, NRL

Directed

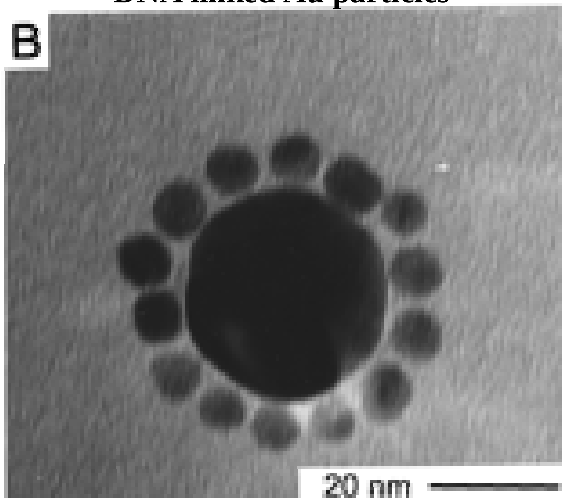
Surface/Interface	strained layer overgrowth
	graphoepitaxy
Patterning	embossing
	printing
	dip-pen
Recognition	hydrophobic/hydrophilic
	biological – DNA, Antibody/Antigen

"Self"-Assembly

- direct growth
- flow oriented structures
- field oriented structures

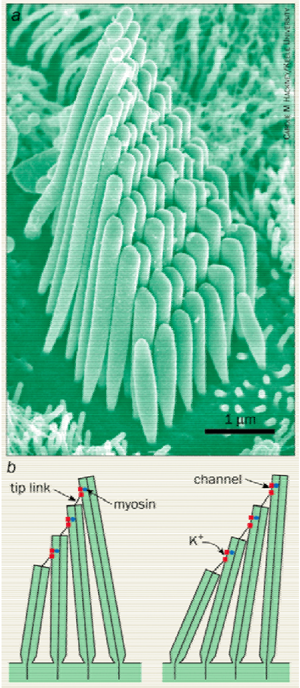
Hierarchical

DNA linked Au particles



Mirkin, Northwestern

Nanorod bundles in ear



Physics World, May 2002

NANOTECHNOLOGY – EARLY RETURN TO NAVY

EVOLVING SUCCESS STORY:
NANOSTRUCTURED COATINGS

1981: Gleiter initiates nanocrystalline metal science

1990: Science Base for nanophase materials begins to expand rapidly

1996: First nanostructured coating (WC-Co) produced by thermal spray processing

1997: Nanostructured ceramic coatings successfully fabricated using plasma spray

1998: Nanostructured ceramic coatings produced directly from liquid precursors, greatly lowering cost

1999: Begin full scale testing of nanostructured coatings on shipboard components.

2001: R&D 100 Award

2002: Nano coating on U.S. Navy ship air intake/exhaust valve with estimates savings of $20M over 10 years.

Dr. Lawrence Kabacoff and Dr. Asuri Vasudevan, ONR, co-winners of the Dual Use Science & Technology Achievement Award

Nanostructured thermal sprayed coatings offer greatly enhanced adhesion, toughness, wear resistance and machinability and thickness (compared to conventional coatings)

Properties of Inframat Nano-Alumina/Titania Coating
(www.inframat.com)

Properties	Conventional Alumina/titania	Nanostructured Aluminia/titania	Improvement
Toughness	Poor	Excellent	Dramatic
Hardness (VHN)	1,000 VHN	1,000	--
Wear resistance ($N*m/mm^3$)	7.5×10^3	40×10^3	~5X
Corrosion resistance	Good	Exceptional	Significant
Grindability	Poor	Excellent	Dramatic
Fatigue life	Failure @ < 1 million cycles	No failure up to 10 million cycle	>10X
Flex tolerance	Will result in coating spallation	Can be bent to over 180 without any spallation	Dramatic
Bond strength (psi)	1,900	~ 8,000	$\geq$ 4X

References.

1. Y. Wang, S. Jiang, M.Wang, S. Wang, T.D. Xiao, P.R. Strutt, "Abrasive Wear Characteristics of Plasma Sprayed Nanostructured Alumina/Titania Coatings," *Wear* **237** (2000) 176-185
2. R.W. Rigney, Presentation at ONR DUST Nanostructured Coating Program (ONR contract No. N00014-98-3-0005), Cape Code, May 17-19, 2000.
3. M. Gell, "Advanced Coating Technology Development for Enhanced Durability and Reduced Cost in Naval Application," ONR Contract No. N00014-98-C-0010, June 1997-Dec 2001.
4. T.D.Ciao, Y.Wang, S. Jiang, S. Wang, D.M. Wang, & P.R.Strutt, "Thermal Spray of nanostructured Alumina/Titania Coatings with Improved Mechanical Properties,"Procs. 2nd Intnl. Conf. Surface Eng., Wuhan, China, Oct 17-22, 1999, pp12-146

DOD VISIONS POTENTIALLY ENABLED BY NANOTECHNOLOGY

Warfighter System

- Personal Information System - oral com, heads-up display, "map", decision aids
- Access to network, scavenged power
- Monitor/actuation system for CBRN, fatigue
- "Smart uniform" – camouflage, CB/ballistic protection

Virtual/Augmented Reality Training/Education/(Entertainment)

- Full oral, visual, tactile interaction – tailored learning modes
- Interactive group involvement
- Electronic "paper" with conformal thin film power source

Uninhabited Combat Vehicle

- Full image storage/processing in RF, mm, IR, visual, UV,…
- Rapid (ms) decisions with "strategic' human intervention
- High g maneuverability, low observable

CBRE Detection/Protection

- Sensor suites with sensitivity and selectivity
- Protective clothing/masks with decon capacity
- Automated therapeutic responses

NNI Major Opportunities/Challenges

Marriage of biology and the nanoscale

"Second Industrial Revolution" vs Evolution hinges on:

- Control and availability of affordable building blocks
- Directed, hierarchical self-assembly

Environmental/human impact as quantities of nanostructures increase

Integration of world-wide activity

Nanotechnology becomes "mainstream" rather than "buzzword"

Determine appropriate NNI metrics