

Nanomaterials: the Substance of Nanotechnology

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Rensselaer Polytechnic Institute*



Briefing for the President's Council of Advisors on Science and
Technology (PCAST), Washington, DC

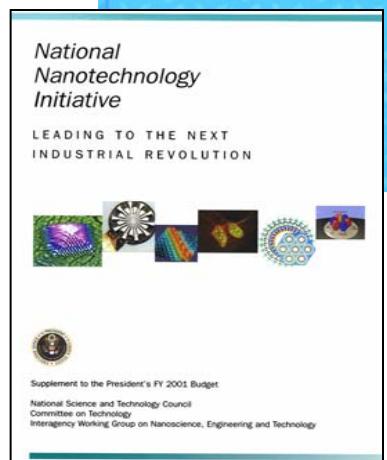
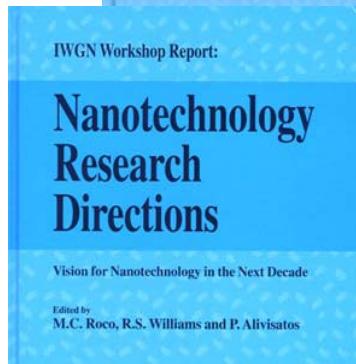
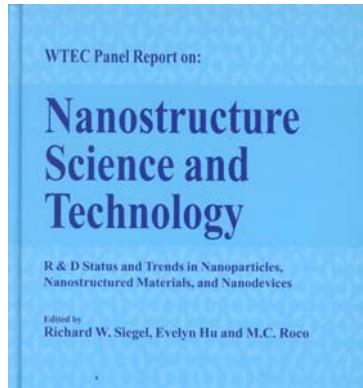
3 March 2003

*materials are needed to make
anything in technology...*

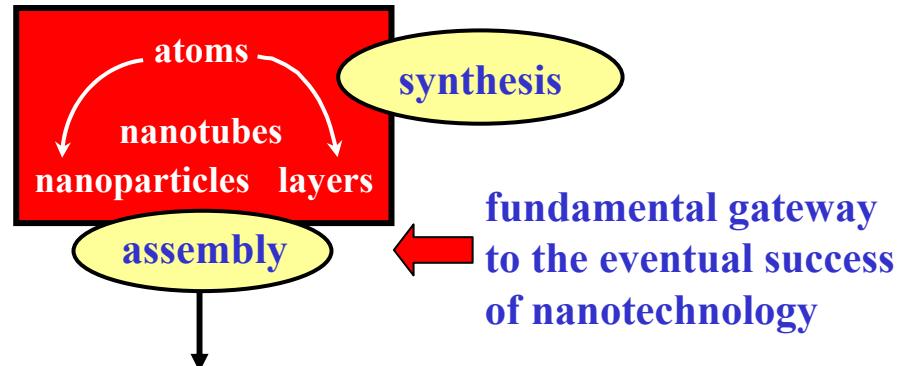
*nanomaterials are needed to make
anything in nanotechnology*



...from atoms to applications through nanoscience



nanoscale building blocks



fundamental gateway
to the eventual success
of nanotechnology

applications in our macroscopic world



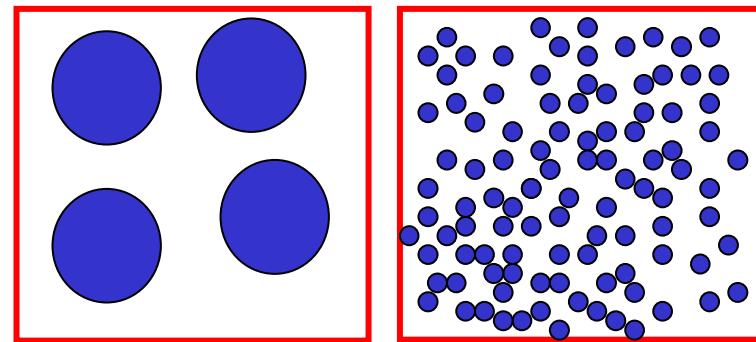
<http://www.nano.gov/>

What is special about nanoscale building blocks?

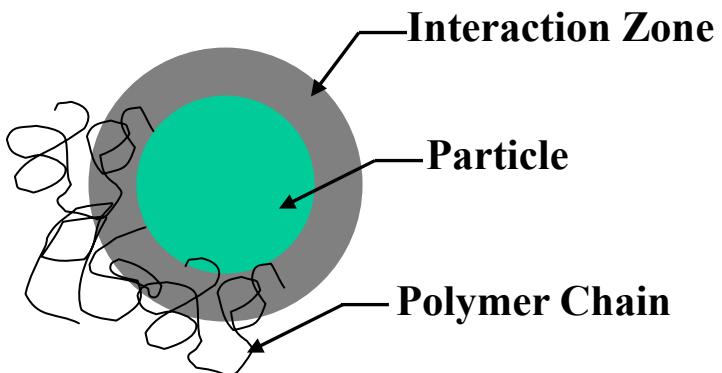
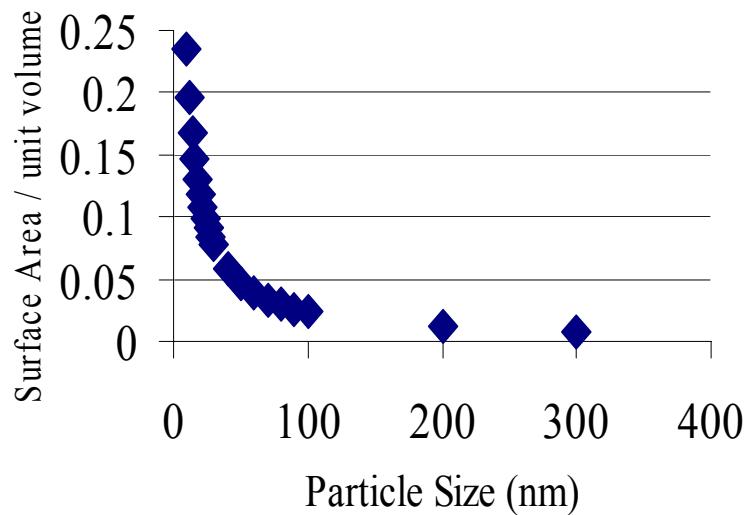
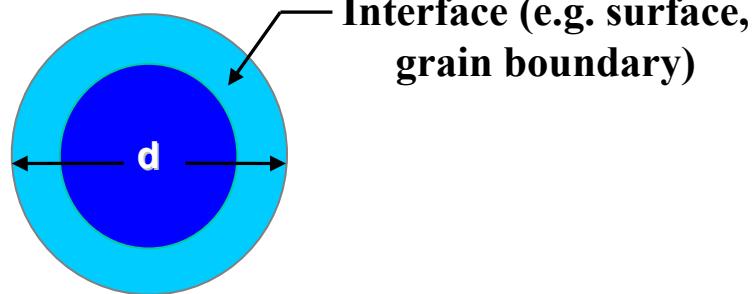
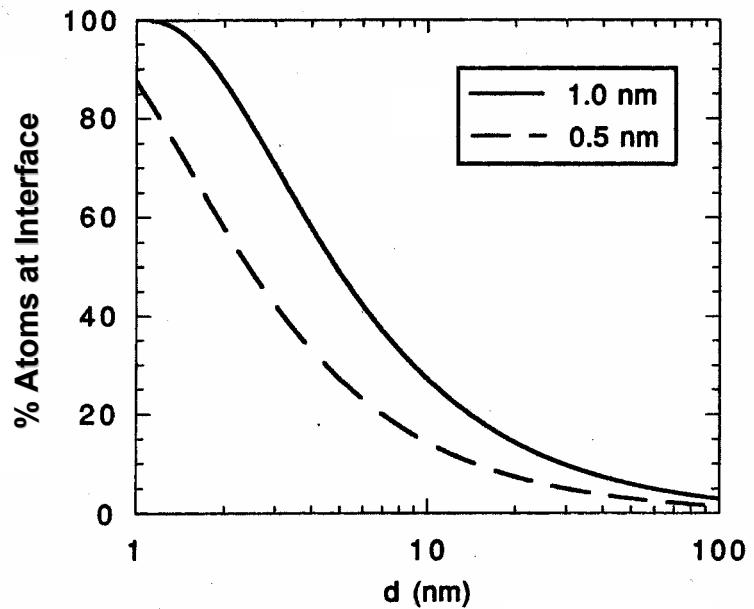
- Size confinement



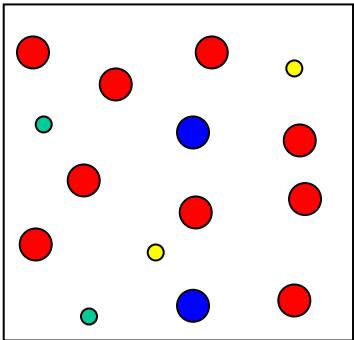
- High surface area
- Many interfaces



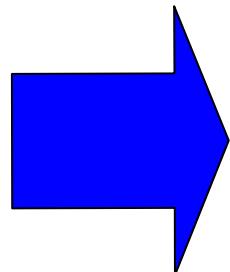
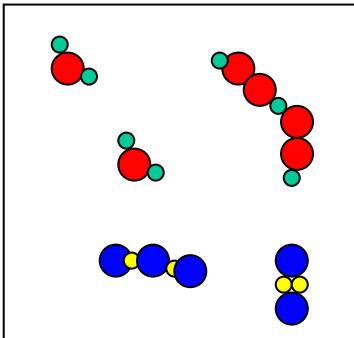
Interface effects



Atoms



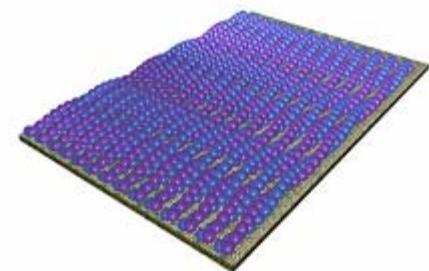
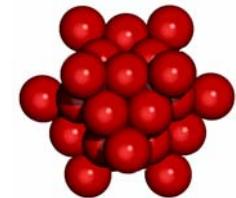
Molecules



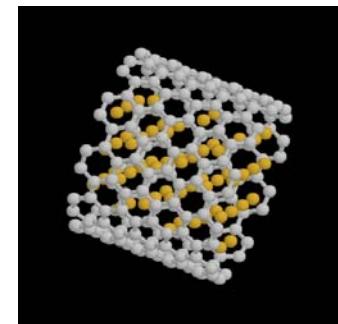
Nanoscale
building
blocks

1-100 nm

Nanoparticles

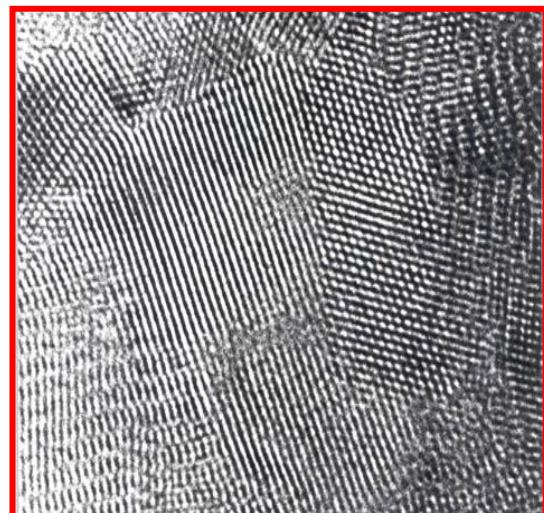
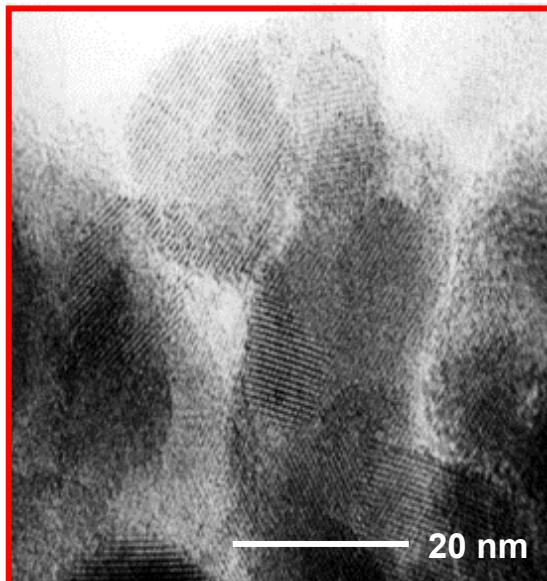
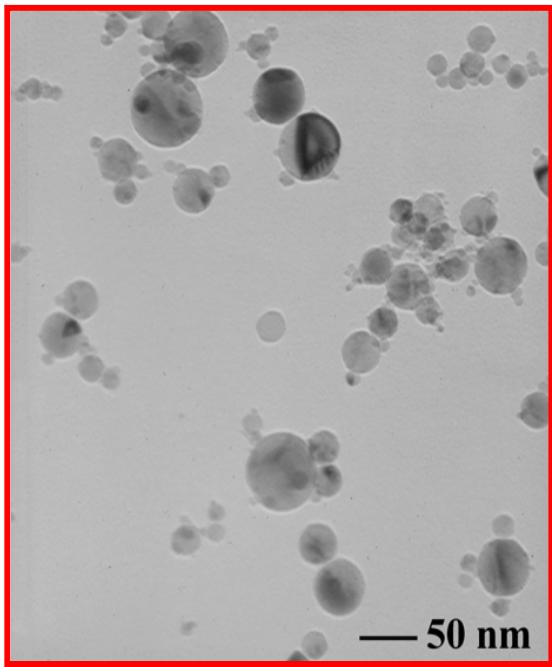
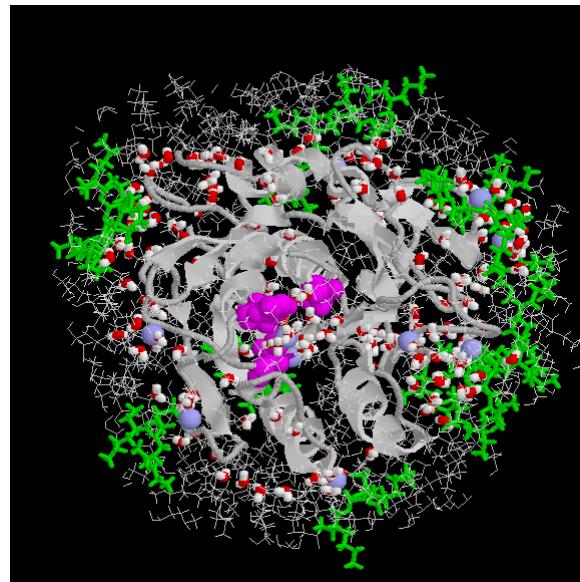
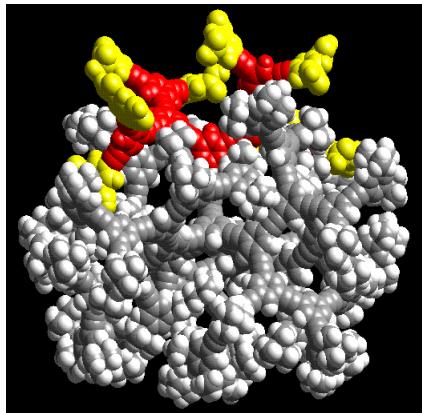
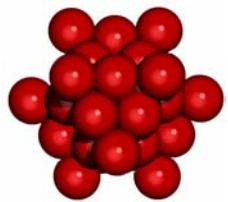


Nanolayers

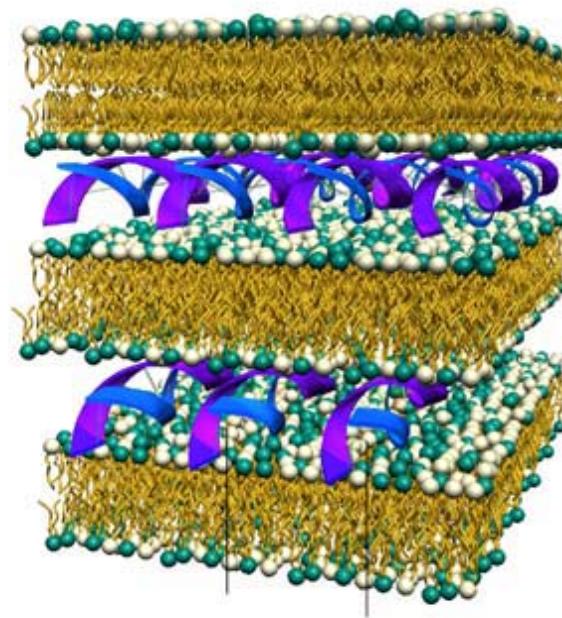
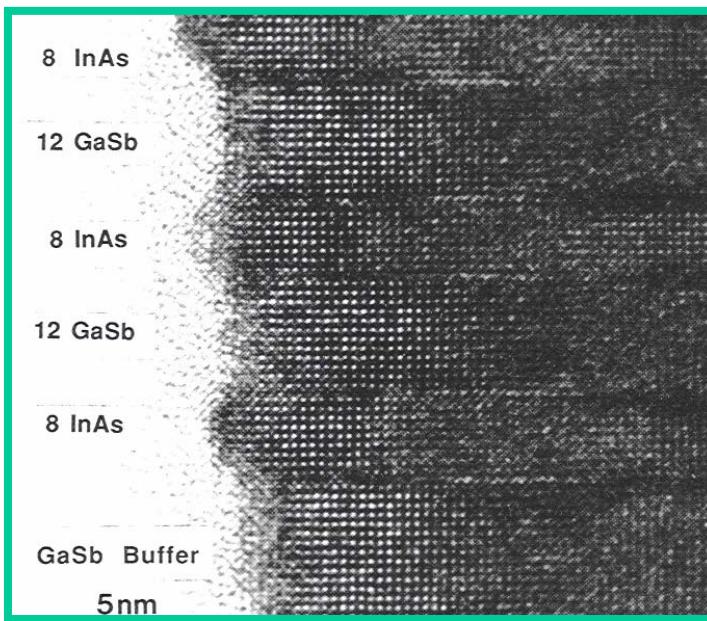
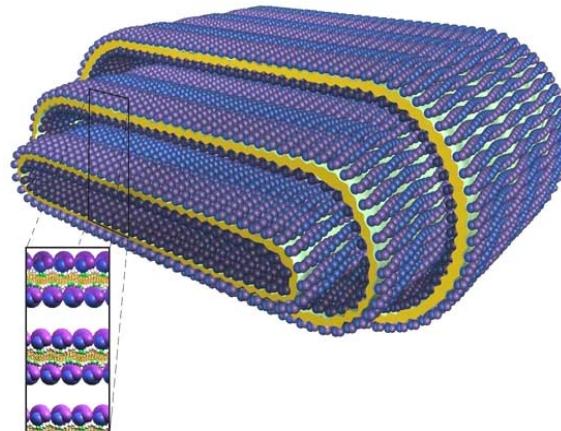
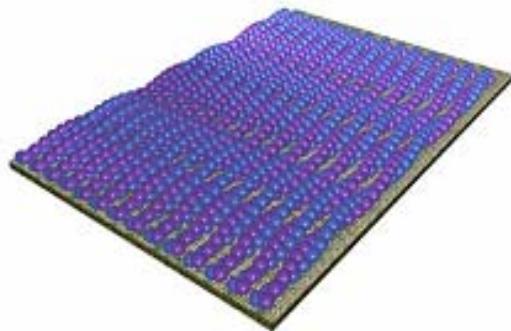


Nanotubes

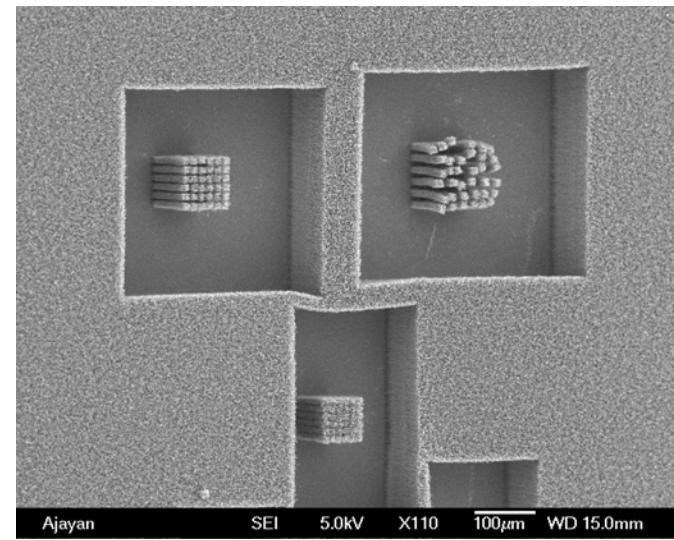
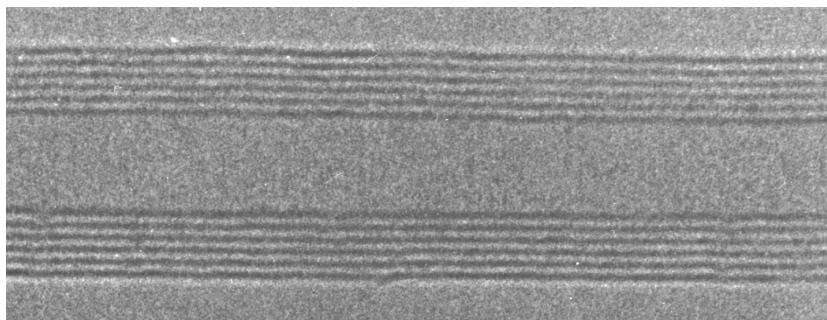
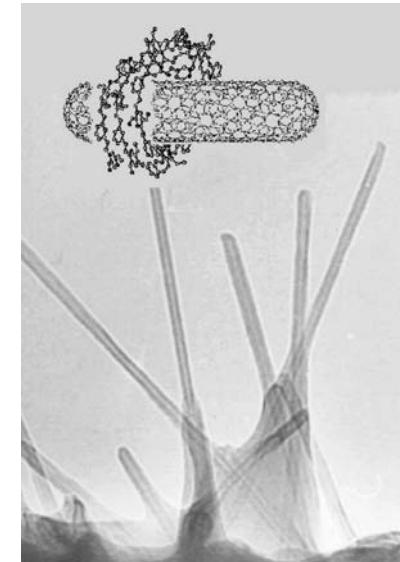
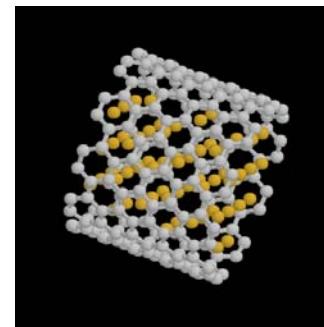
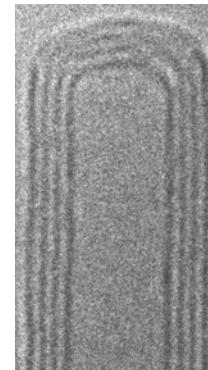
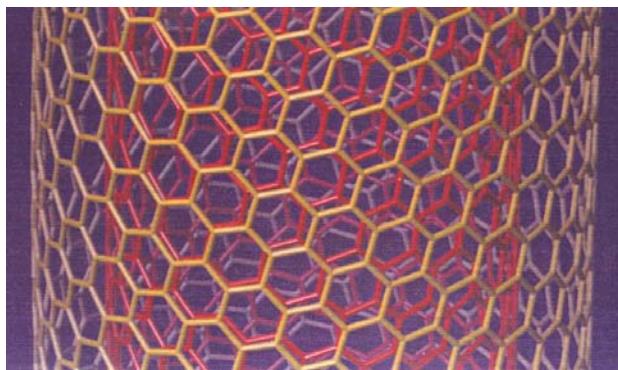
Nanoparticles



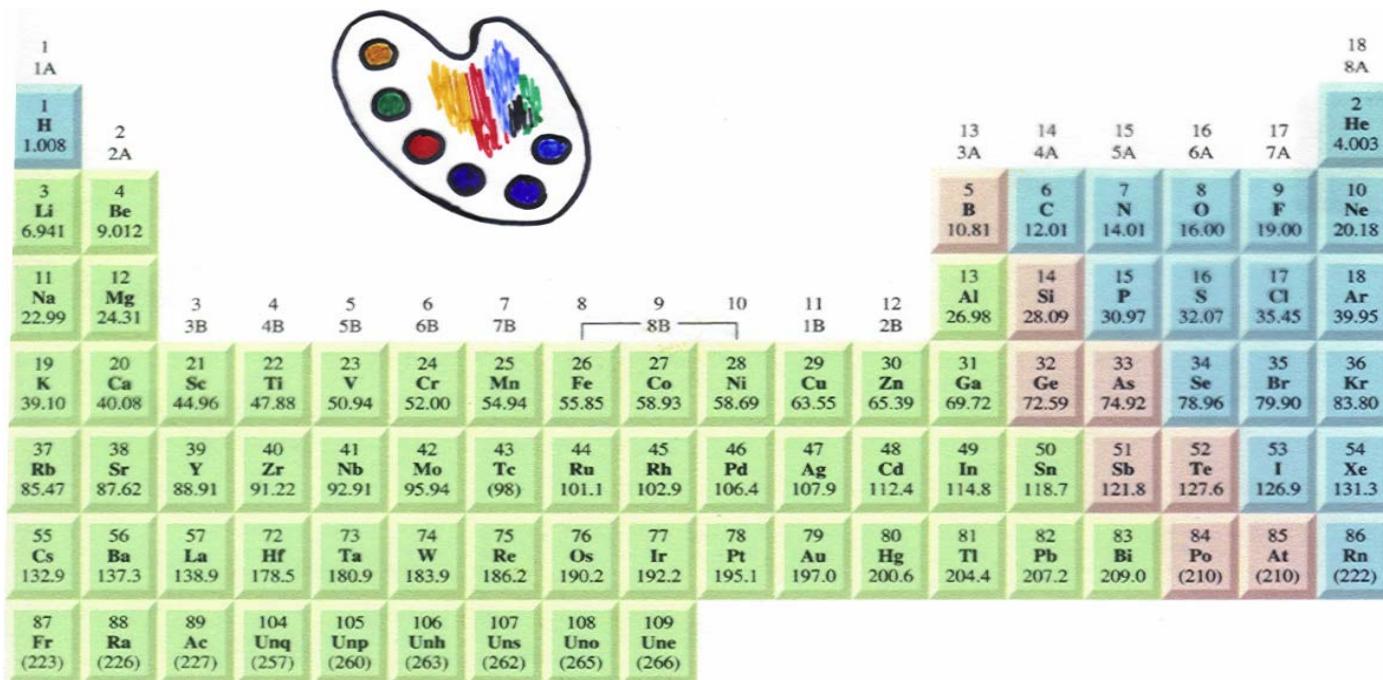
Nanolayers



Nanotubes



Palette for nanostructuring



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R. W. Siegel

Characteristics of nanostructured materials and assemblies

- Small
- Lightweight
- Novel properties
- Multifunctional
- Hierarchical
- Smart



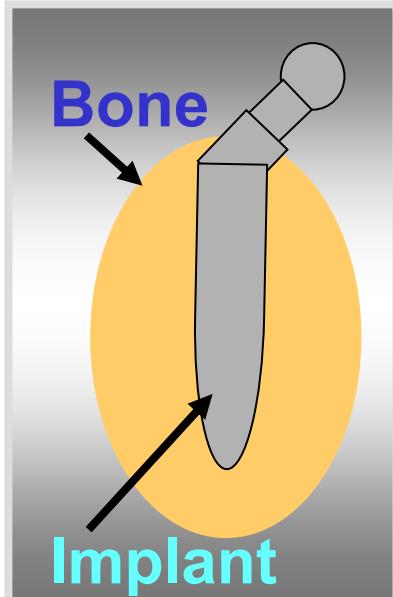
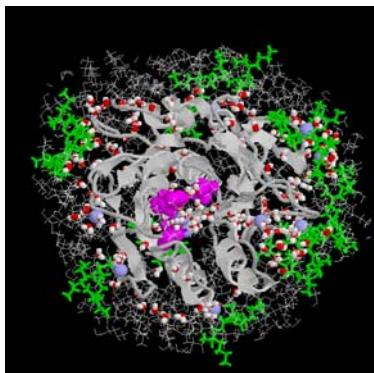
Examples of opportunities for nanomaterials

- Thermal and environmental barriers
- Wear resistant coatings and parts
- Tailored optical and chemical barriers
- Flame retardant plastics
- High capacity energy and information storage media
- Drug and food supplement delivery vehicles
- Ultrahigh-strength, tough structural materials
- Net-shape formed ceramic parts
- Magnetic/thermoelectric thermal management devices
- Smart materials with embedded sensors and actuators
- Biomaterials

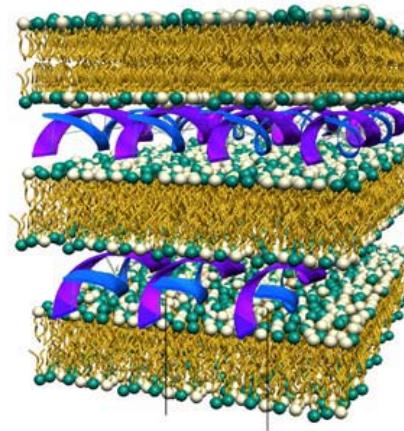


Application areas

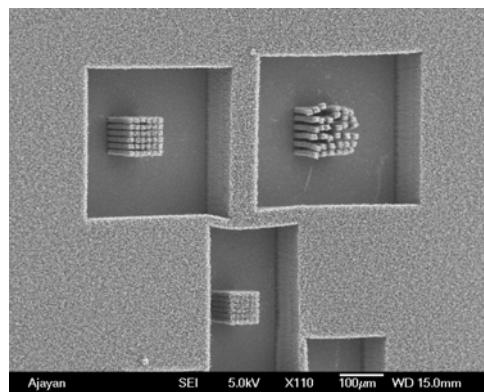
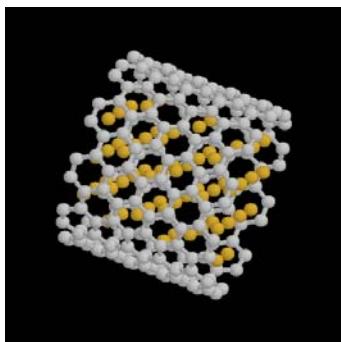
Health



Environment



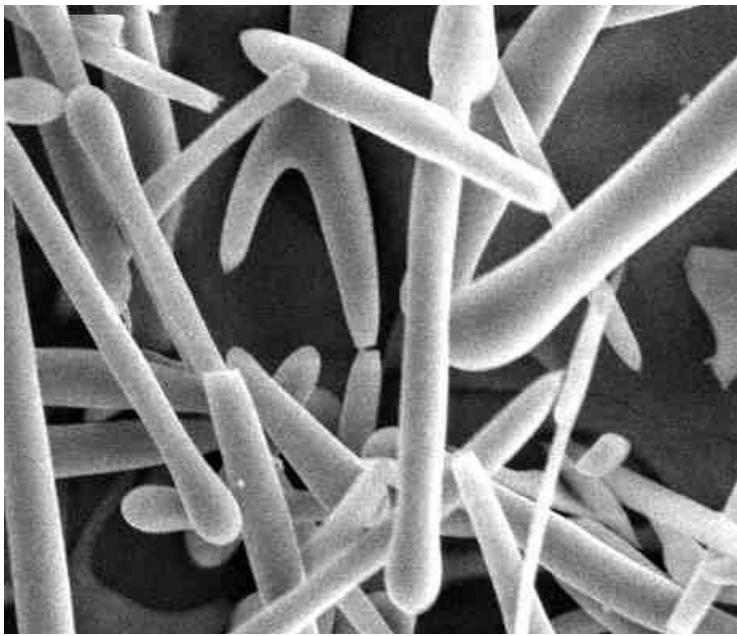
Communication



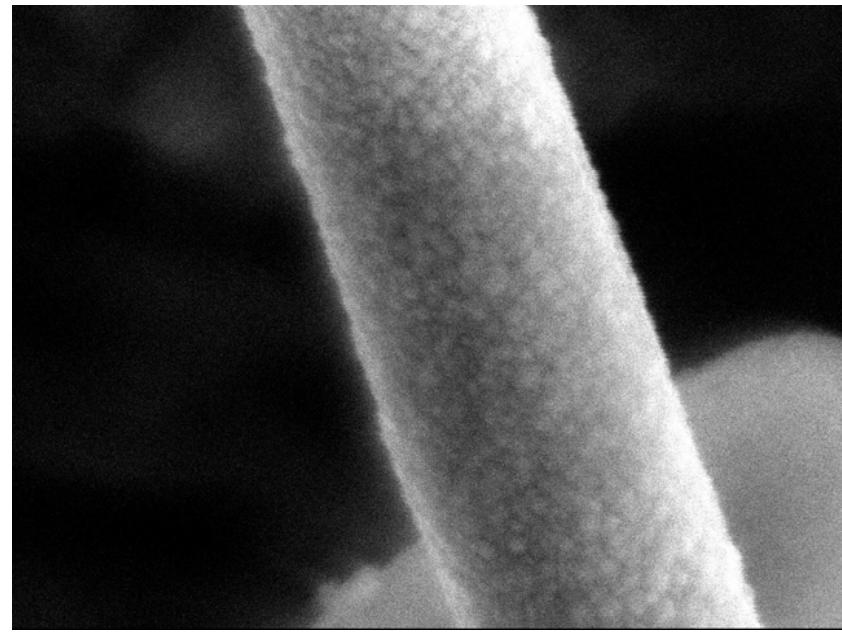
Manufacturing



Nanoparticle-assembled TiO_2 capped microtubes



6 μm



350 nm

Ma, Siegel, Schadler (2002)

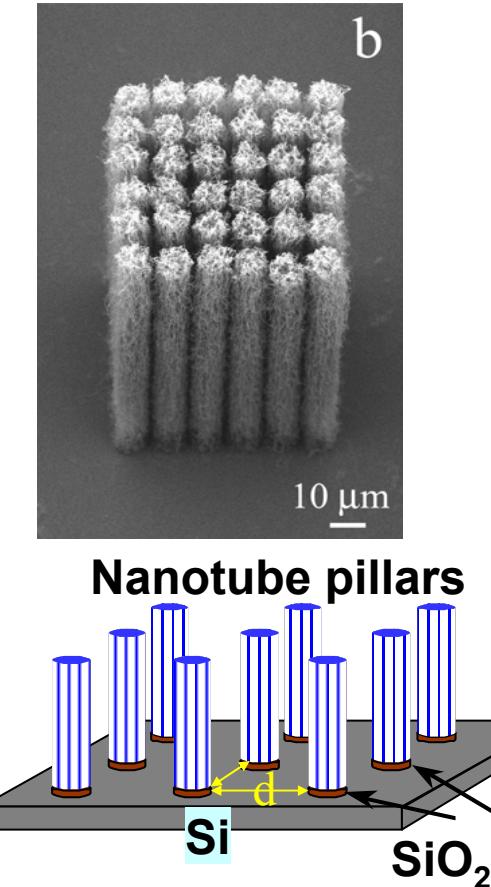
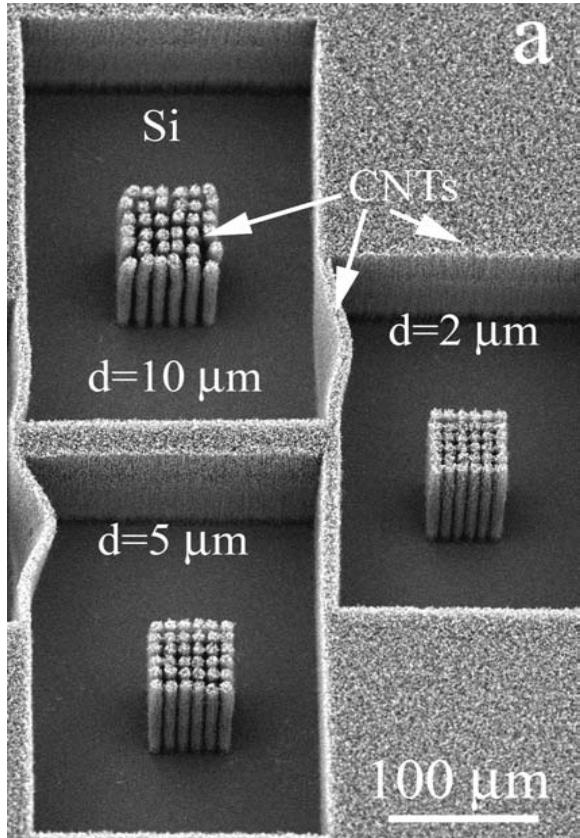
ABB



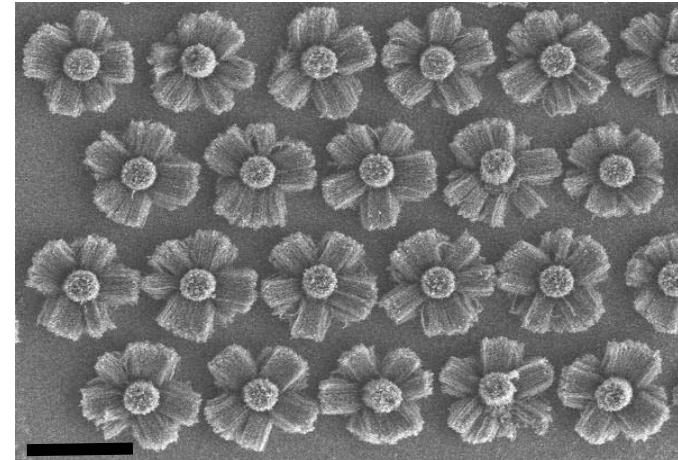
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Controlled assembly of vertical interconnects: nanotubes

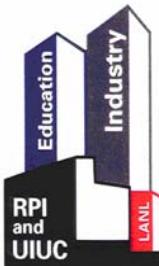


Vertical and Horizontal

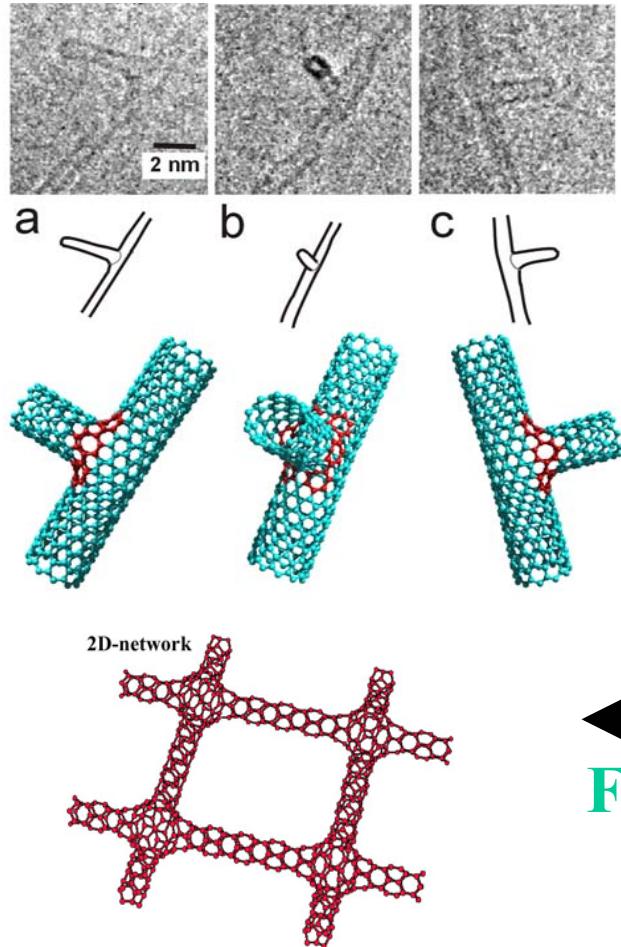


Wei, Vajtai, Jung, Ward, Zhang,
Ramanath, Ajayan (2002)

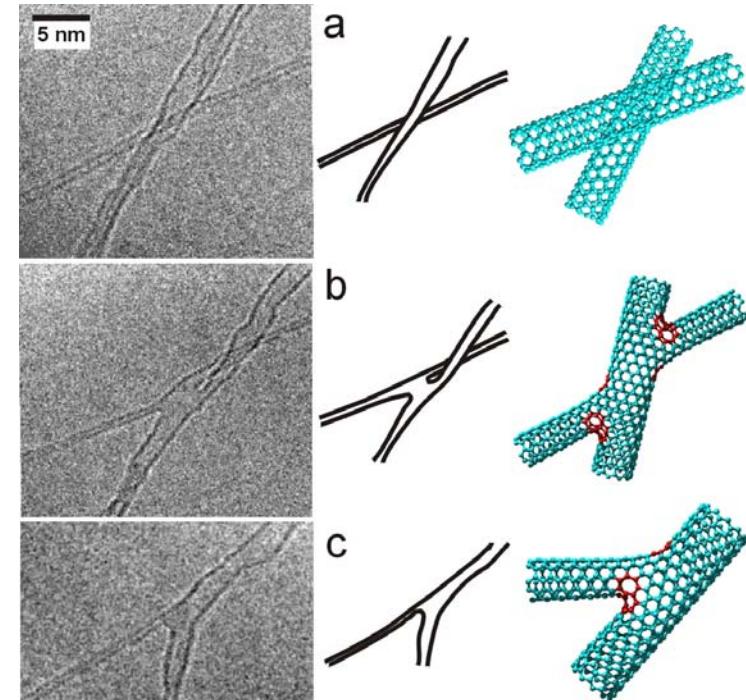
Funded by ONR and the MARCO Interconnect Focus Center (*Collaboration with Motorola*)



Creating single-walled nanotube junctions



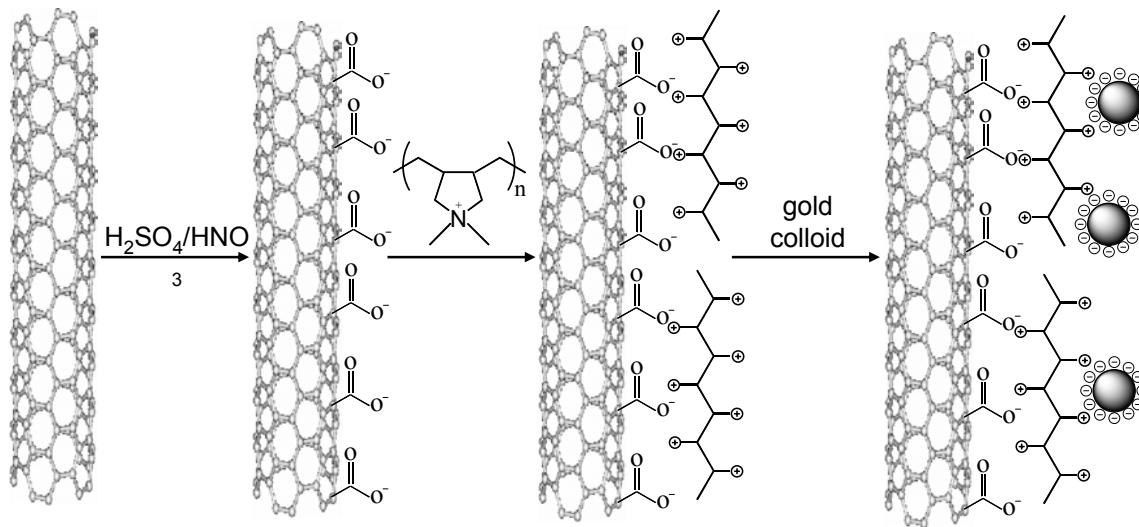
e-beam
welding



Terrones, Banhart, Ajayan et al. (2002)

Funded by the MARCO Interconnect Focus Center

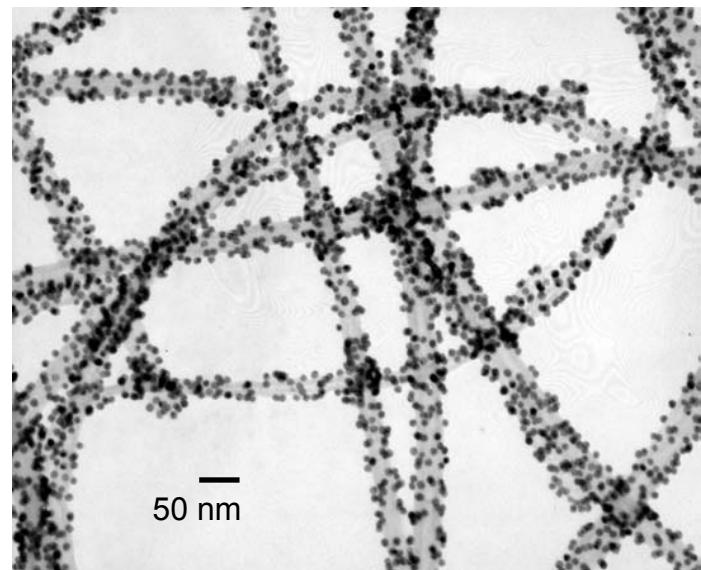
Attachment of Au nanoparticles to N-doped CNT



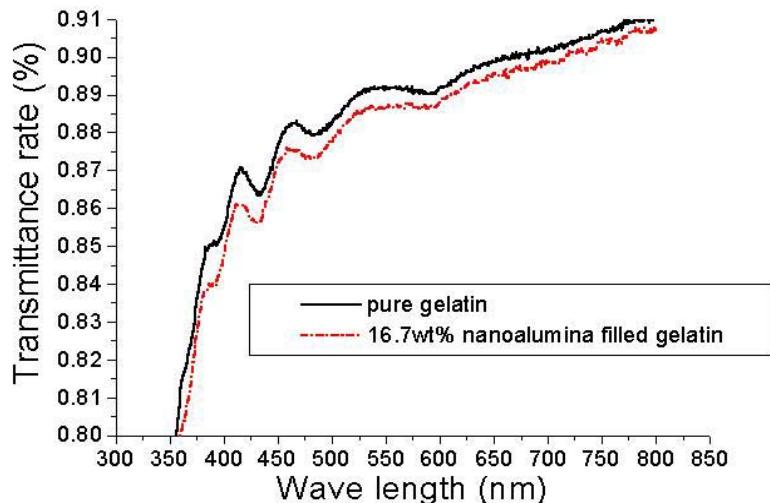
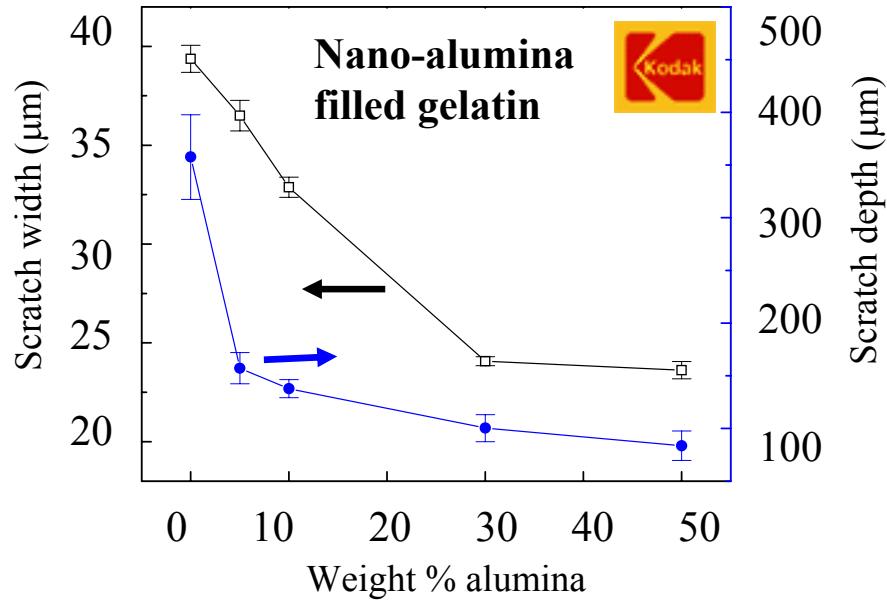
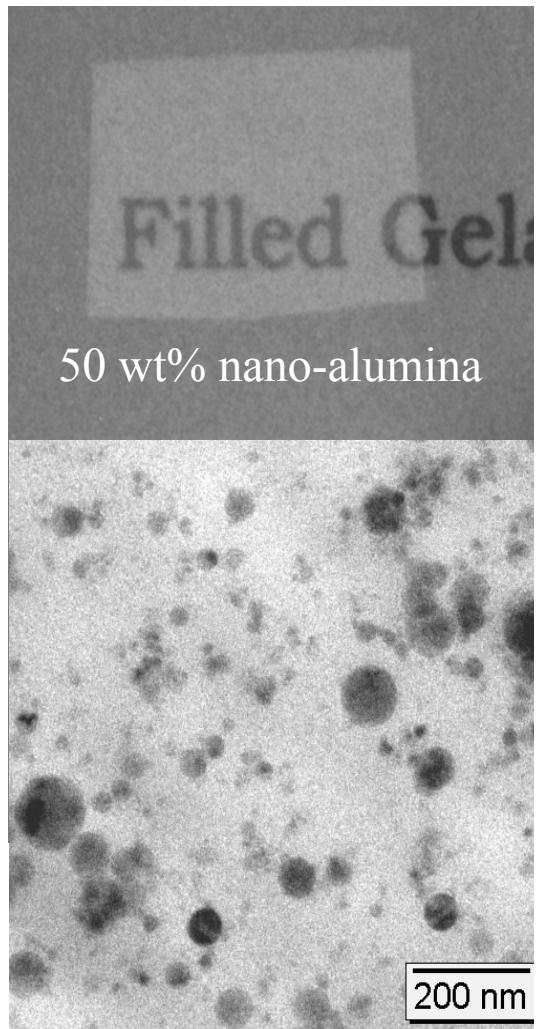
Functional groups are attached along the lengths and ends of N-doped carbon nanotubes (CNT). These become the sites for selective Au nanoparticle attachment.

Jiang, Eitan, Schadler, Ajayan, Siegel, et al. (2002)

Funded by US Army Natick Soldier Center

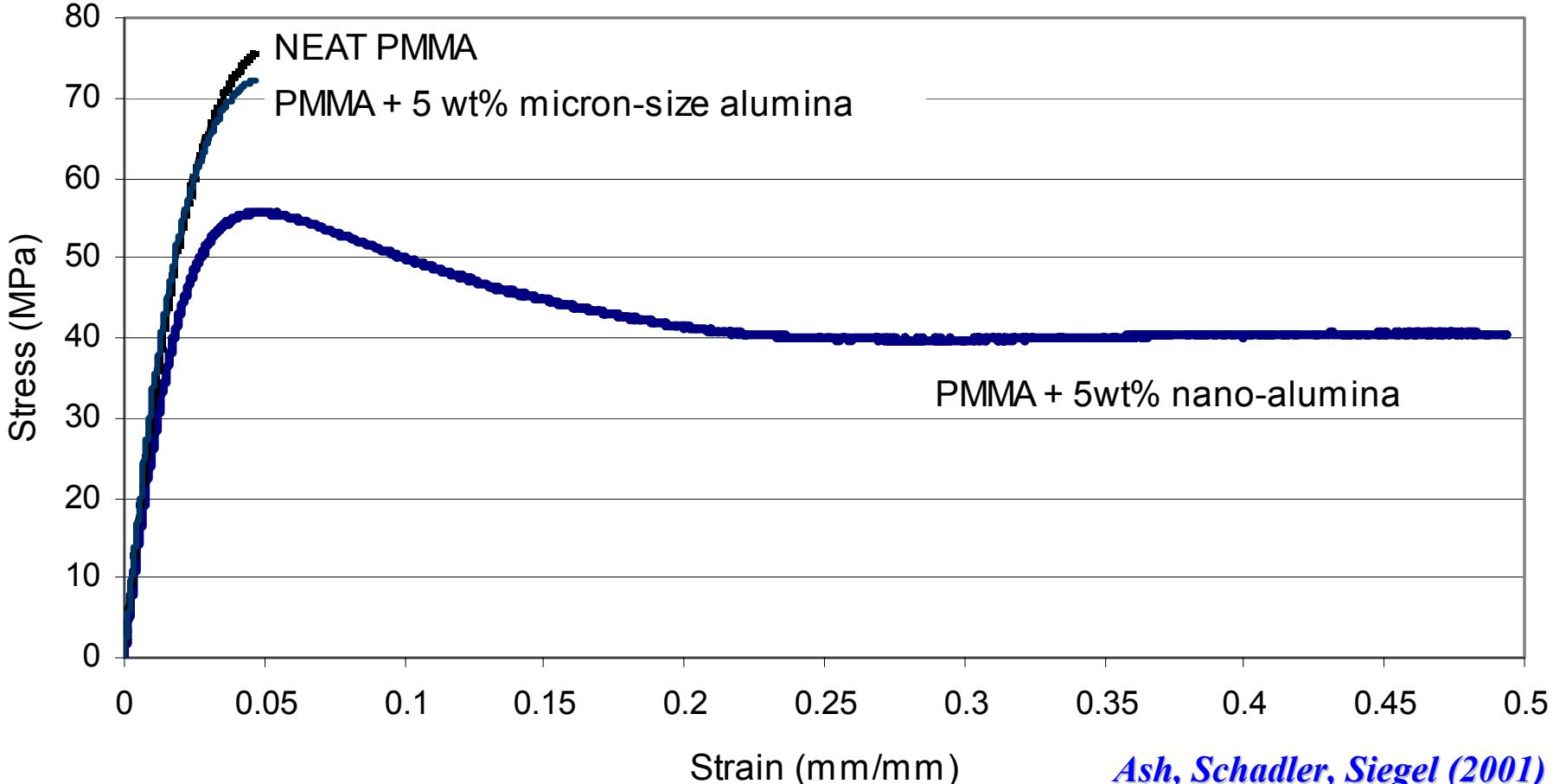


Polymer nanocomposites - assembly and properties



Chen, Schadler, Siegel, Irvin (2002)

Comparison between micron-size and nanoscale alumina fillers in PMMA



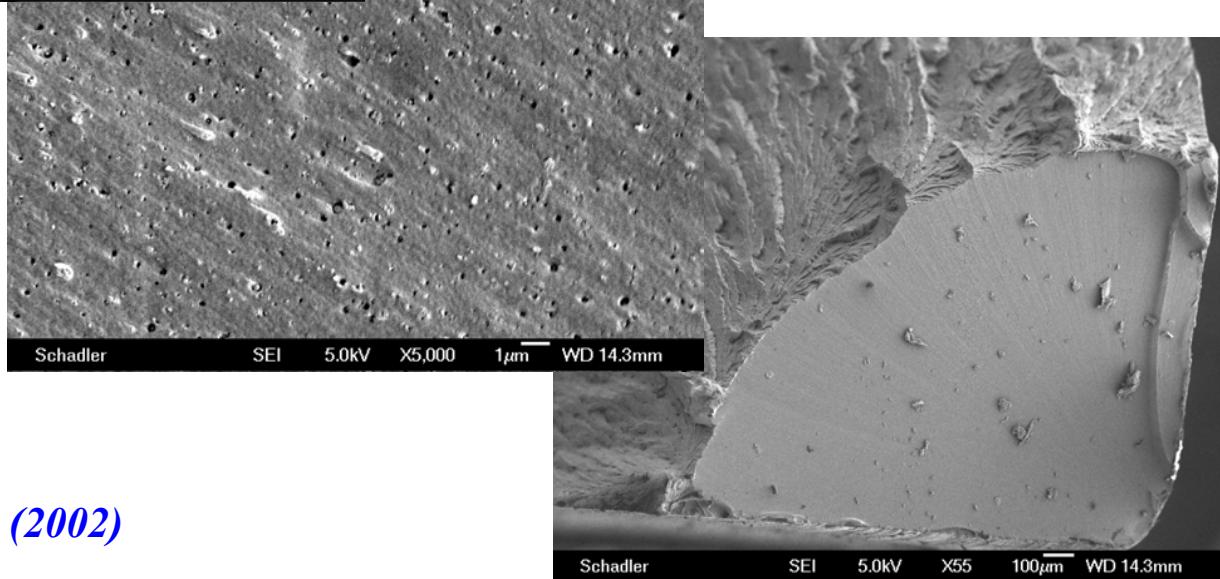
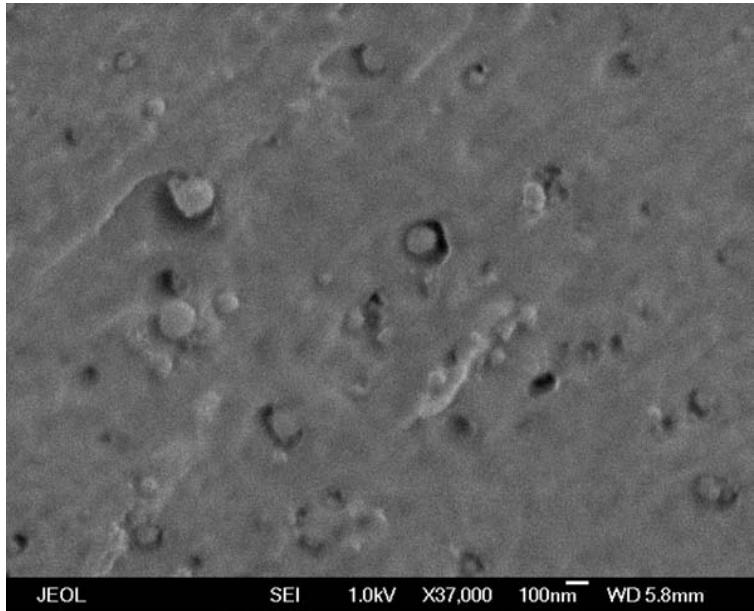
Ash, Schadler, Siegel (2001)



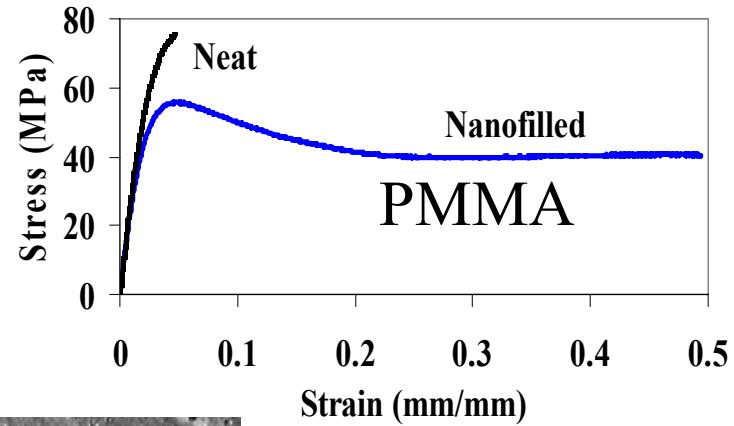
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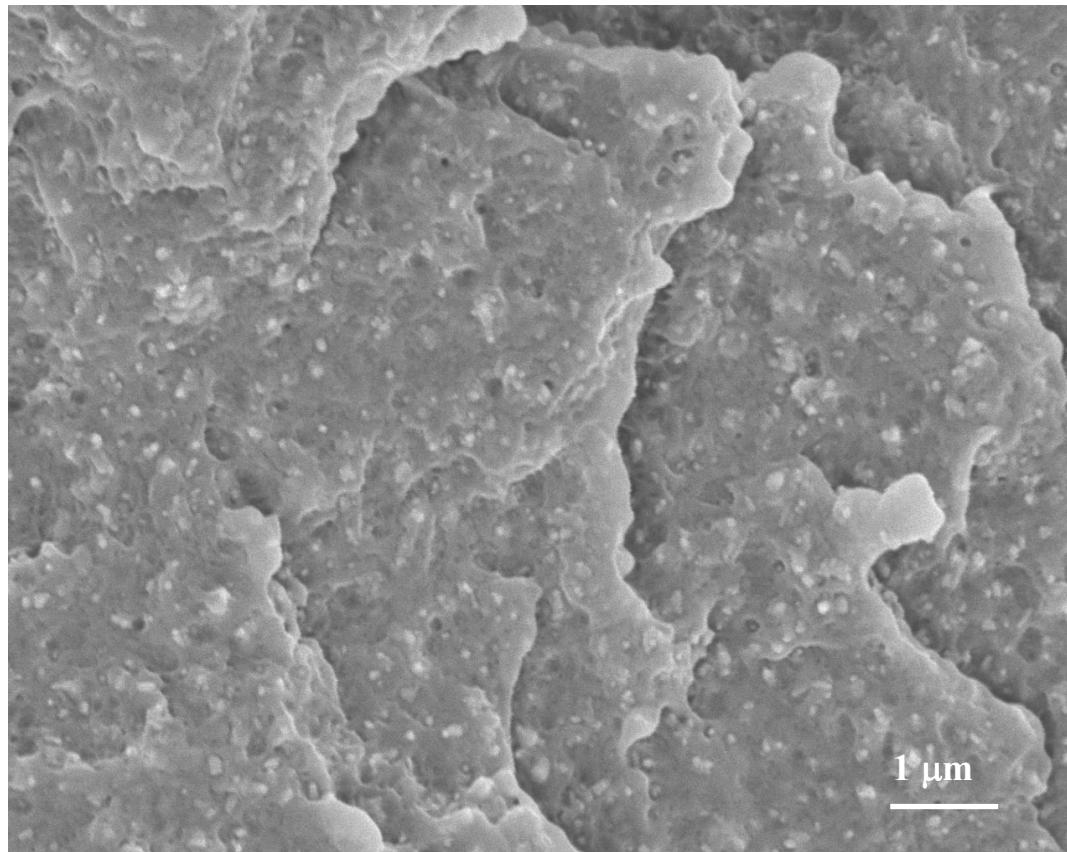
PMMA/alumina fracture surfaces by FESEM



Ash, Schadler, Siegel (2002)



ZnO/LDPE nanocomposites



SEM of 50 wt% ZnO in LDPE

Hong, Schadler, Siegel, Mårtensson (2002)

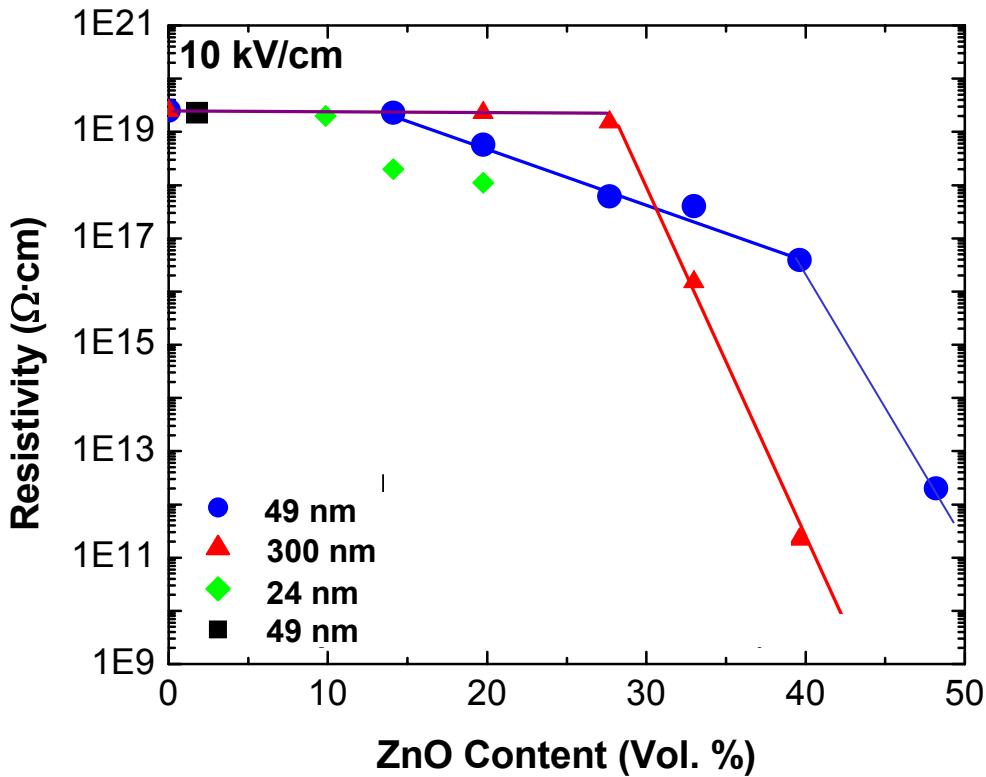
ABB



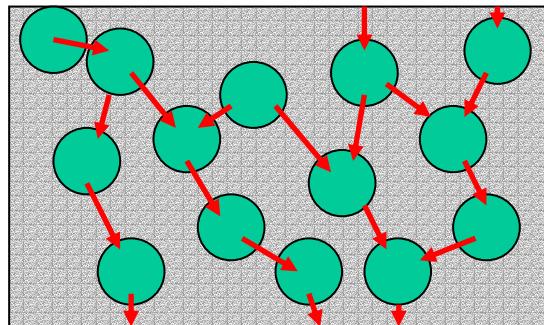
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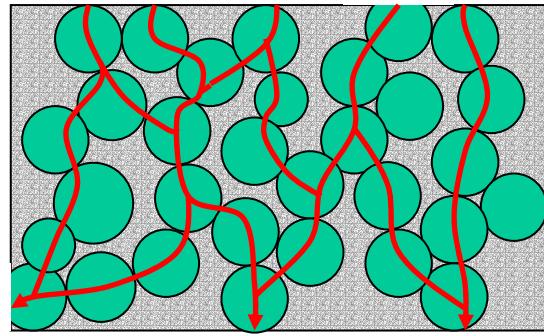
Resistivity of ZnO/LDPE nanocomposites



Conduction mechanisms:



Tunneling



Continuous paths

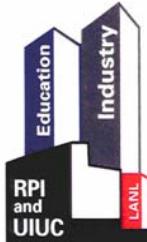
Hong, Schadler, Siegel, Mårtensson (2002)

ABB



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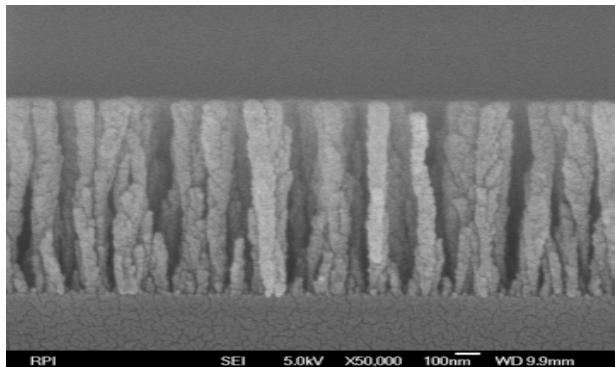
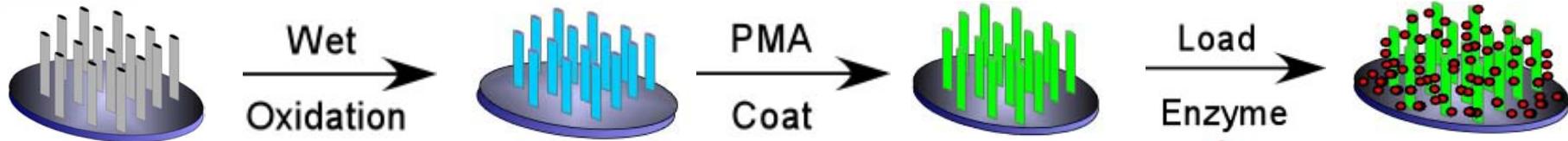
R. W. Siegel



Potential applications of biocatalytic nanocomposites

- Catalysts
- Chromatographic packings
- Biocatalytic membranes
- Non-fouling coatings and paints
 - Protein, lipid, polysaccharide resistant
 - Microbial resistant
 - Sessile invertebrate resistant
- Non-clogging drain pipes
- Implantable medical devices
- Microelectronics and microfabrication

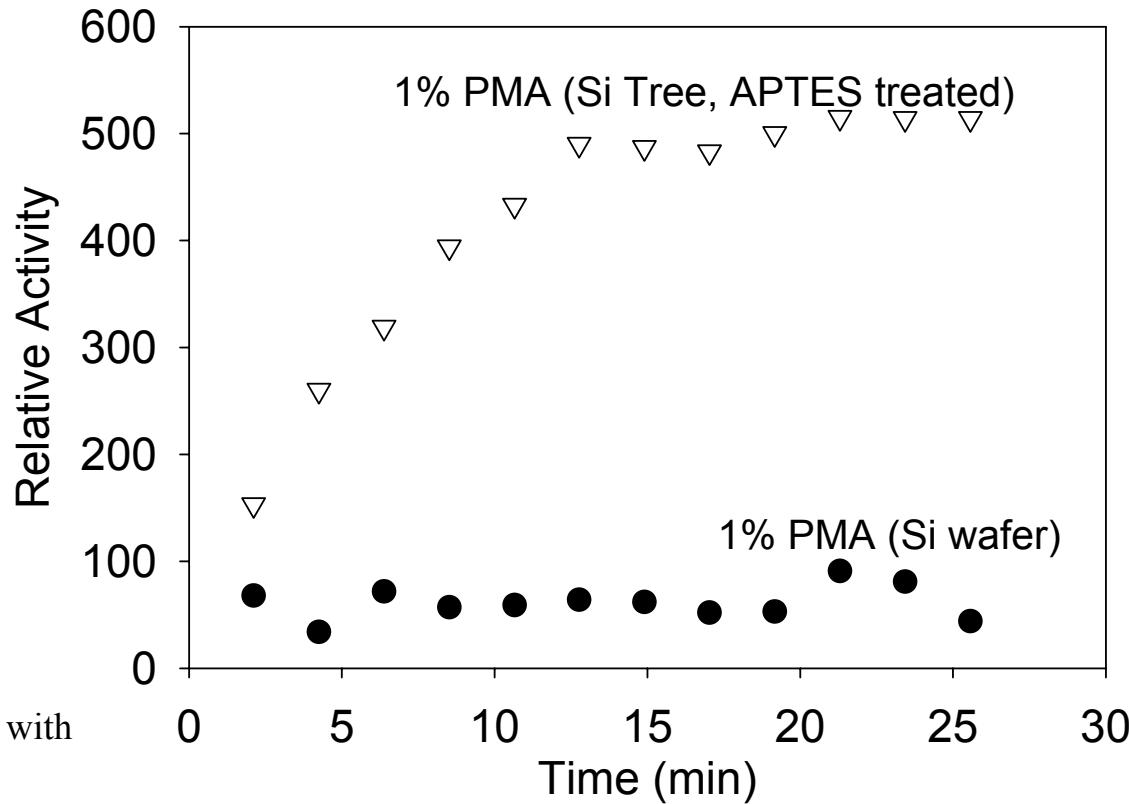
Preparation and use of peroxidase-silicon nanocomposites



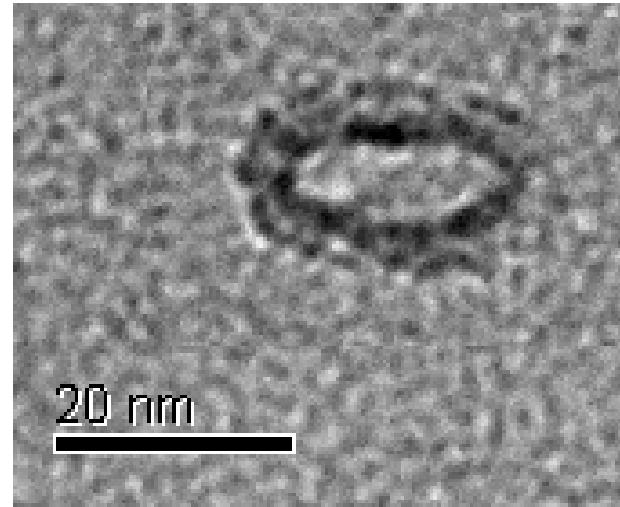
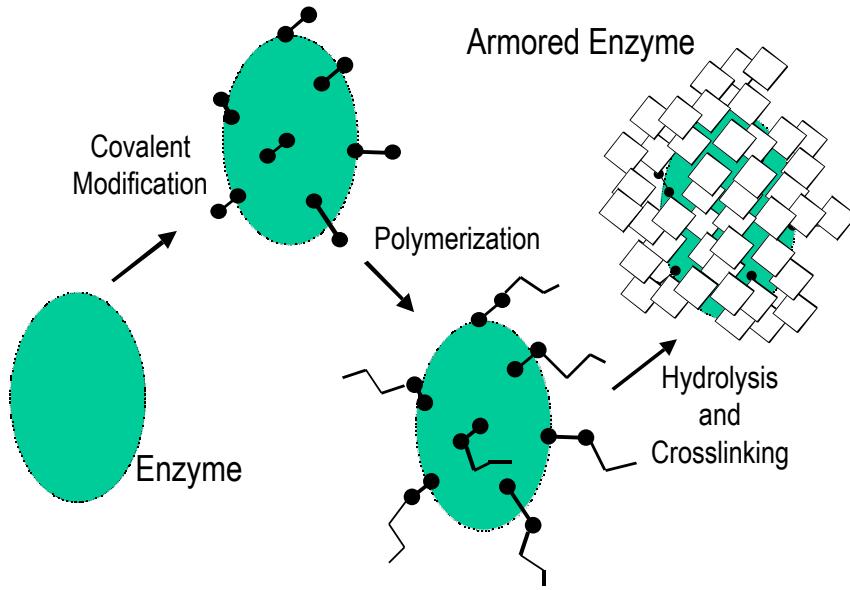
Dordick et al. (2002)

Enzyme: Soybean Peroxidase (SBP)

Assay: *p*-cresol [40 mM] in phosphate buffer with 20% DMF, H₂O₂ [0.13 mM]

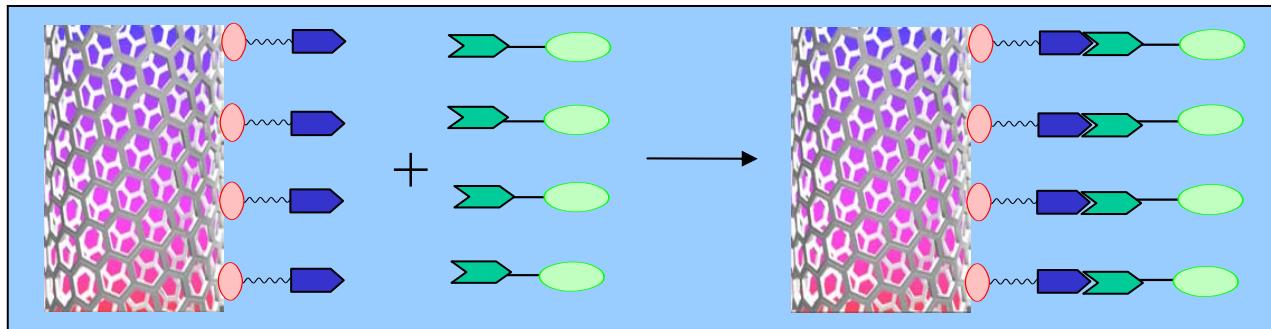


Silicate-based “armored” enzyme nanocomposites

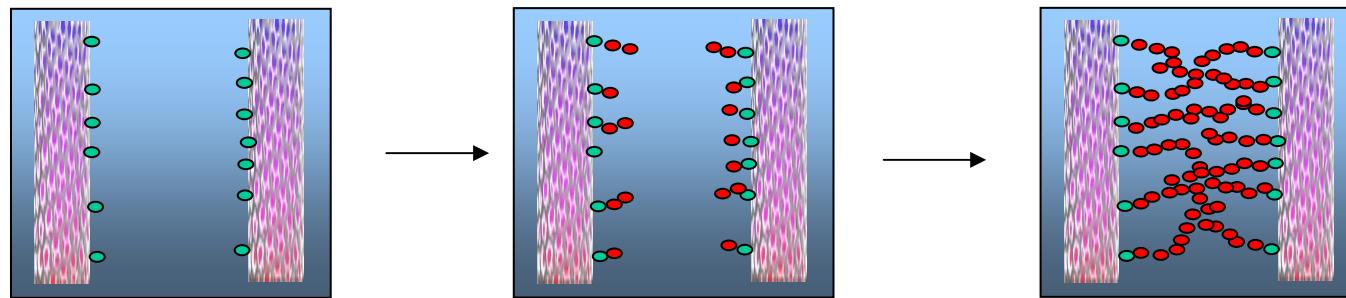


| Preparation | $\tau_{1/2}$ (days) |
|--|------------------------|
| Free α -chymotrypsin | 0.01 |
| Sol-Gel entrapped α -chymotrypsin | 0.29 |
| Armored α -chymotrypsin composite | 358 |

Exploiting enzymes for structured polymer growth and membrane applications on nanotubes



Polyhydroxyalkanoate synthesis with different monomers



Immobilized PHA pathway

Growing polymer network

Controlled membrane properties within NT network

- ◆ Create controlled environments from templated nanotubes
- ◆ Assemble nanotube architectures from biopolymer linkers

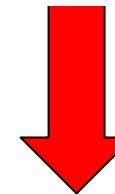
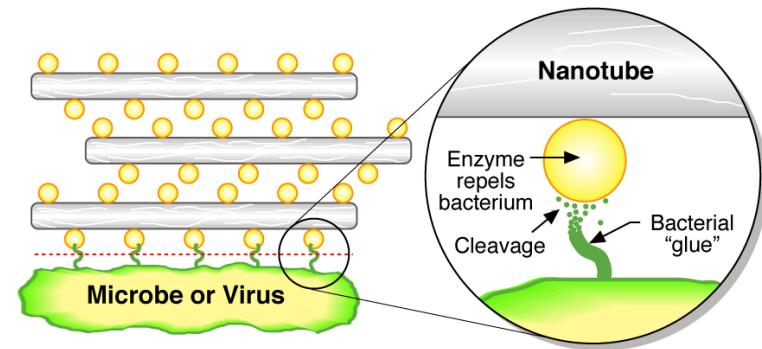
Adaptable nanostructures that self clean and detoxify

Long-term opportunities:

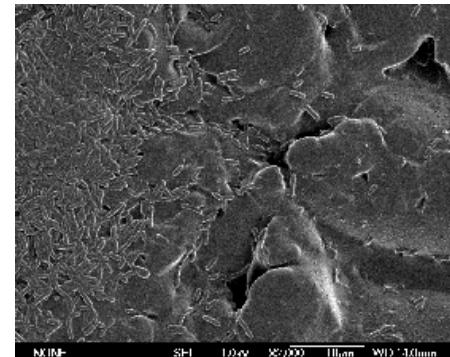
- ◆ Anti-microbial surfaces →
- ◆ Anti-fouling surfaces
- ◆ Nerve gas detoxification



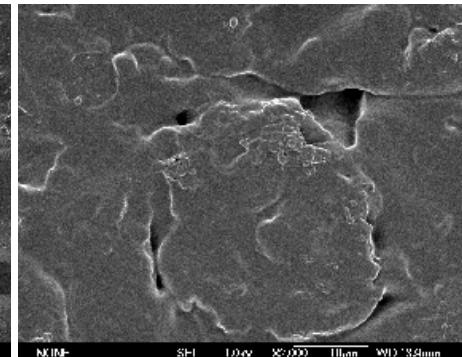
- ◆ Proteases → Proteins
- ◆ Lipases → Lipids (fats and oils)
- ◆ Amylases, glycosidases → Biofilms
- ◆ Lysozyme, Peroxidases → Microbes
- ◆ Organophosphohydrolase → Nerve gas
- ◆ Mixture → Dirt



Control



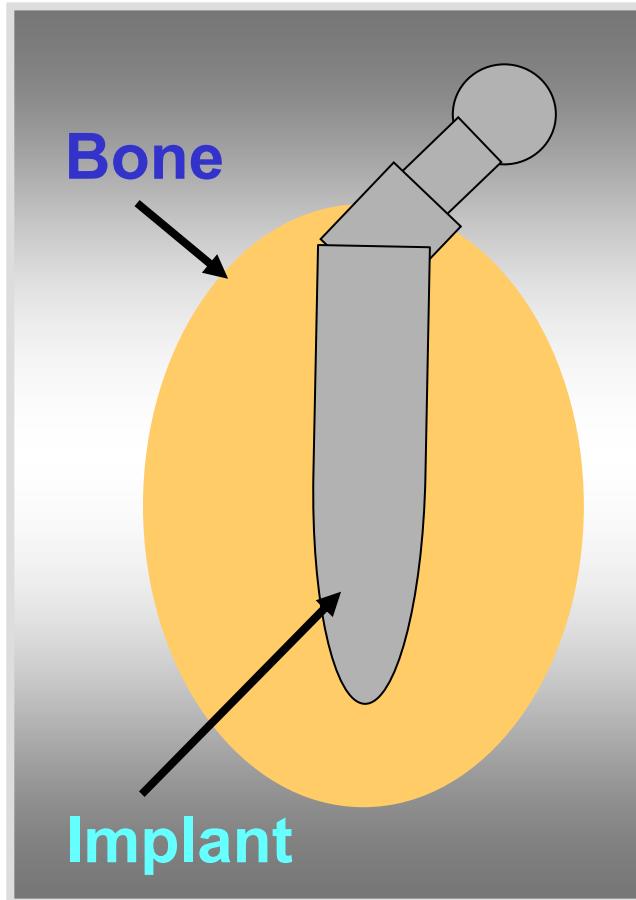
Enzyme



Dordick et al. (2002)

Pseudomonas aeruginosa – a common opportunistic pathogen

Bioengineered nanocomposites for tissue engineering



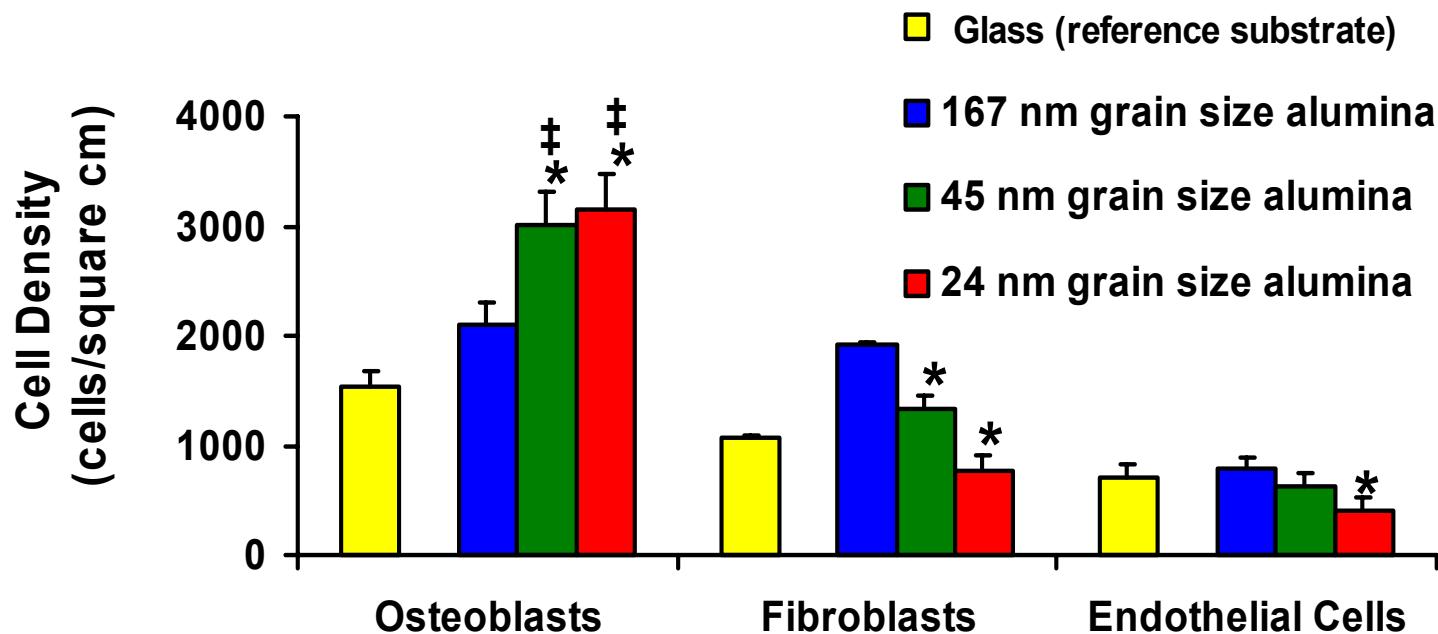
Implant requirements:

- mechanical behavior close to that of bone
- cellular compatibility
- osseointegration

Webster, Siegel, Bizios (2000)

Cellular compatibility

Data for alumina nanoceramic; similar behavior found for other nanoceramics and ceramic/polymer nanocomposites



Webster, Siegel, Bizios (2001)

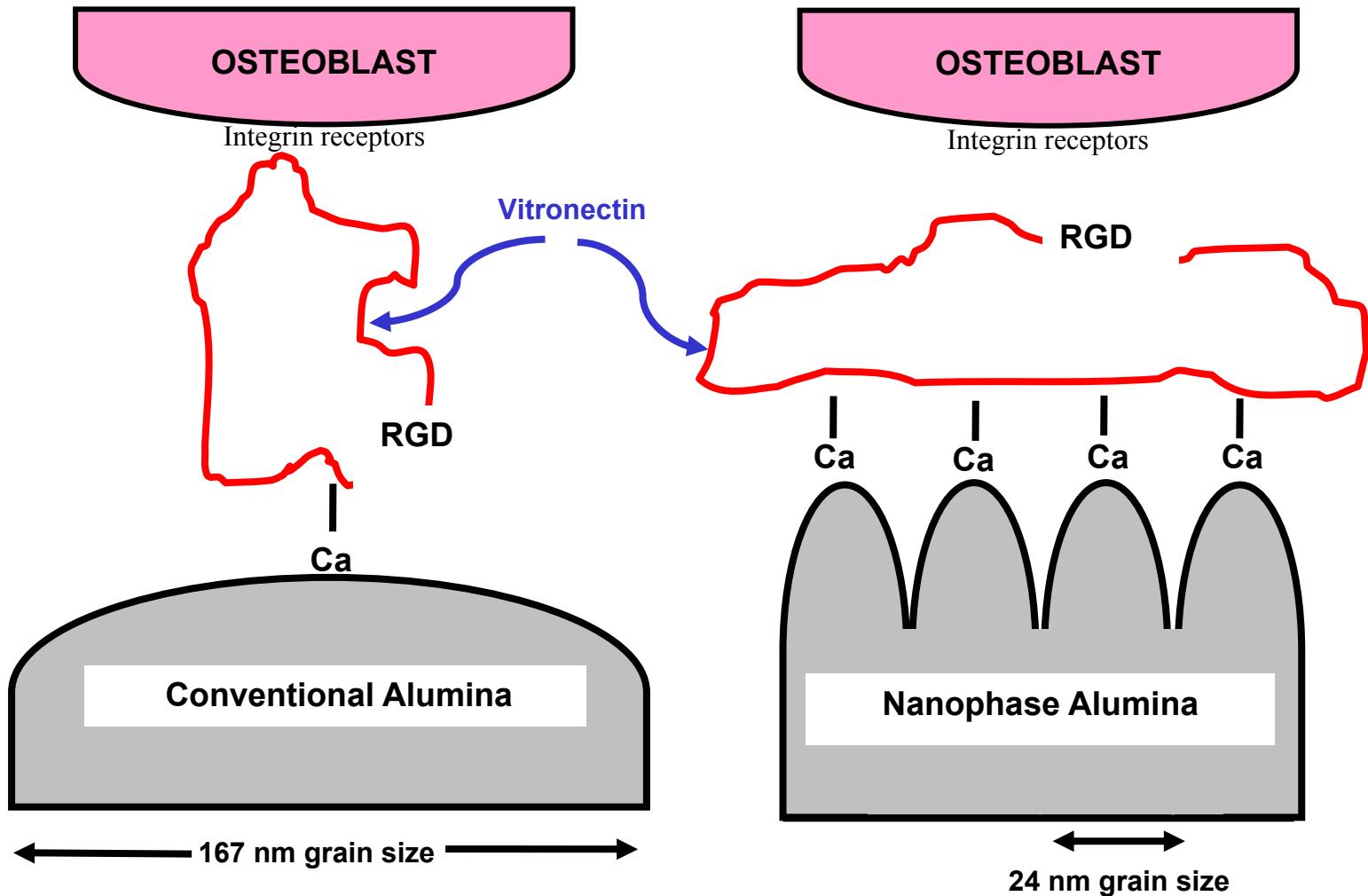


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Osteoblast adhesion

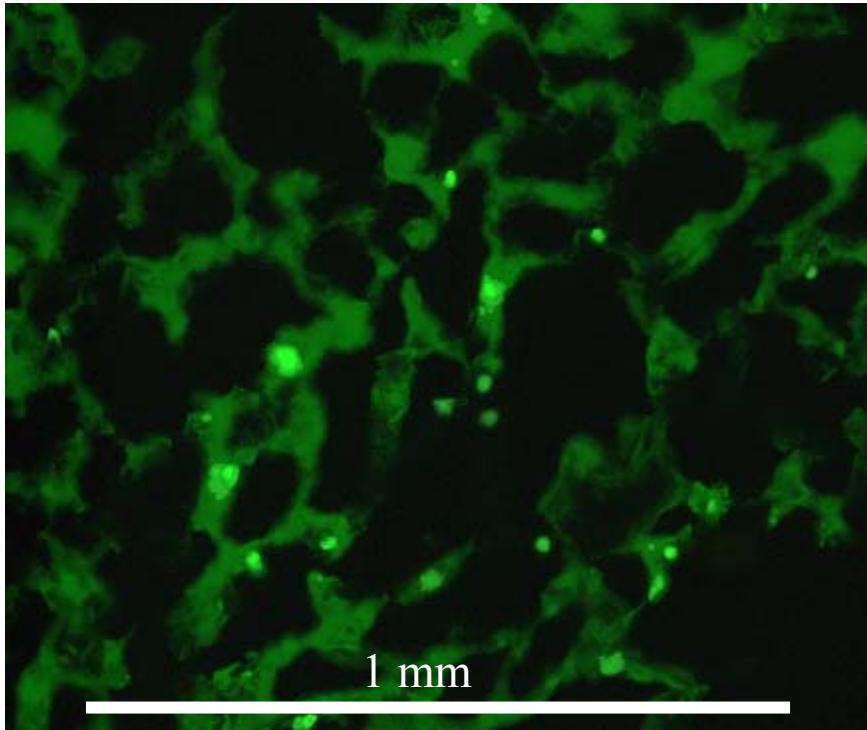
driven by surface topography



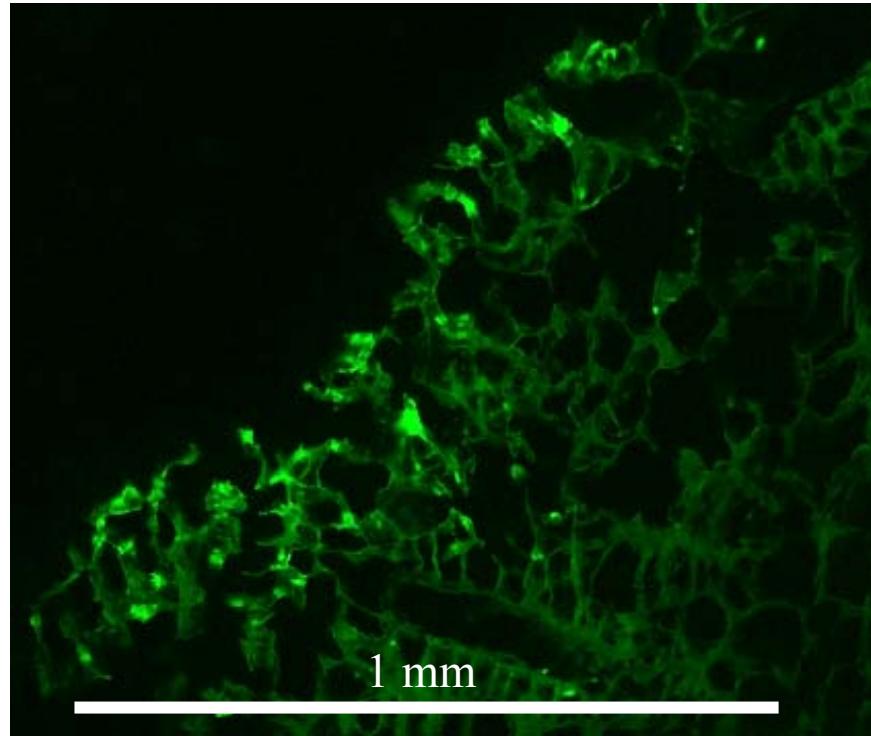
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Osteoblast distribution in $\text{Al}_2\text{O}_3/\text{PLA}$ nanocomposite



Scaffold Center



Scaffold Surface

Representative fluorescent micrographs illustrating
osteoblast distribution 24 hours after cell seeding.

Dulgar, Bizios, Siegel (2002)

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Conclusions:

- We are now able to create a wide variety of nanoscale building blocks
- We are learning how to assemble them into useful nanostructured materials and devices
- Society is beginning to benefit from nanoscience and its applications
- There is much more to come....!

