The NNI at 15 – Taking Nanotechnology to New Heights

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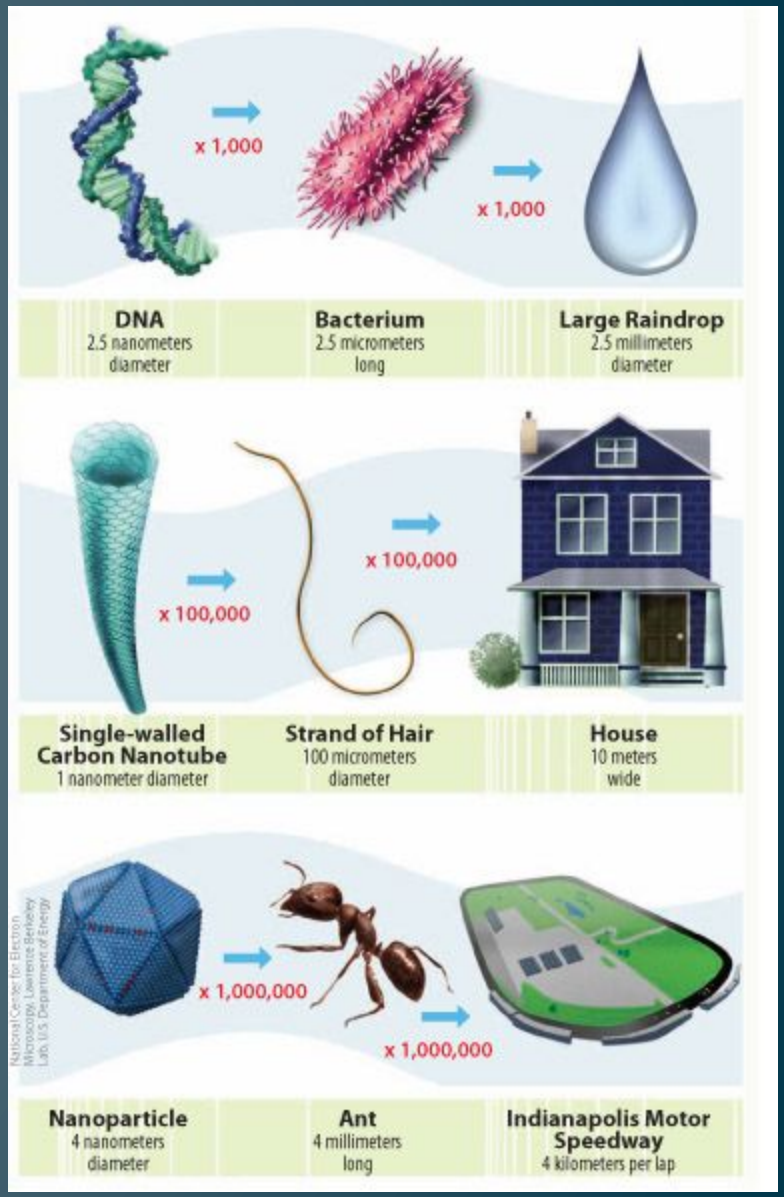
Overview

- National Nanotechnology Initiative
- President Clinton's NNI Challenges - How are we doing?
- Potential Impact of Nanotechnology on Aerospace Systems
- Use of Nanotechnology to Reduce Vehicle Weight
- Future Directions in Nanotechnology
- Summary

What is Nanotechnology?

- Control of matter and processes at the atomic and molecular level
  - Typically 100 nanometers in two dimensions
    - Nanometer is one billionth of a millimeter
      - Single sheet of paper is about 100,000 nm thick
- Conventional physics often breaks down at the nano-level
  - Affects electrical, optical, thermal and mechanical properties



Source: National Nanotechnology Initiative (www.nano.gov)

How Nanotechnology Impacts Materials Properties

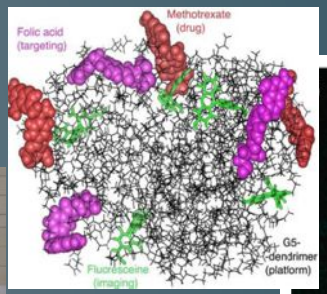
Nanotechnology enables discrete control of desired materials properties :

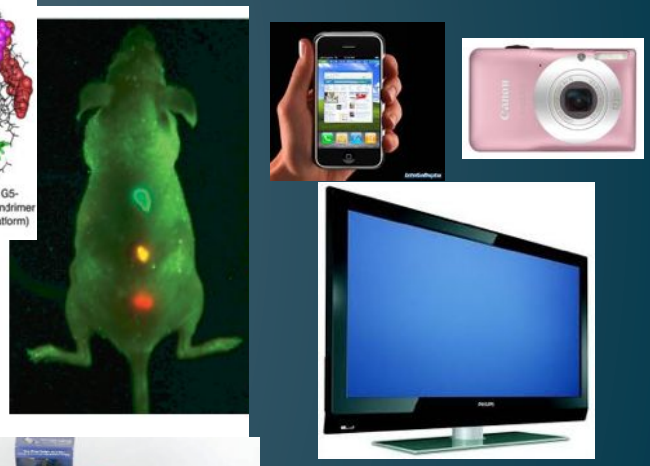
- Mechanical
  - Dictated by particle size (Griffith criteria), morphology and strength of interfaces (chemistry and roughness)
  - High aspect ratios and surface areas radically changes nanocomposite properties relative to host material
  - Molecularly perfect, highly ordered, defect free structures, e.g. carbon nanotubes, leads to maximized properties (not just mechanical)
- Thermal
  - Emissivity influenced by particle size and enhanced surface area/roughness
  - Thermal conductivity controlled by particle size (phonon coupling and quantum effects) and nanoscale voids
- Electrical
  - Nano structure and defects influence conductivity and bandgap energy (conductivity, current density, thermoelectric effects)
  - High aspect ratios enhance field emission and percolation threshold
  - Nanoscale dimensions lead to inherent radiation resistance
- Optical
  - Transparency and color dominated by size effects
  - Photonic bandgap controlled by size ($\lambda/10$) and nanostructure

NNI Vision

A future in which the ability to understand and control matter at the nanoscale leads to *a revolution in technology and industry that benefits society.*

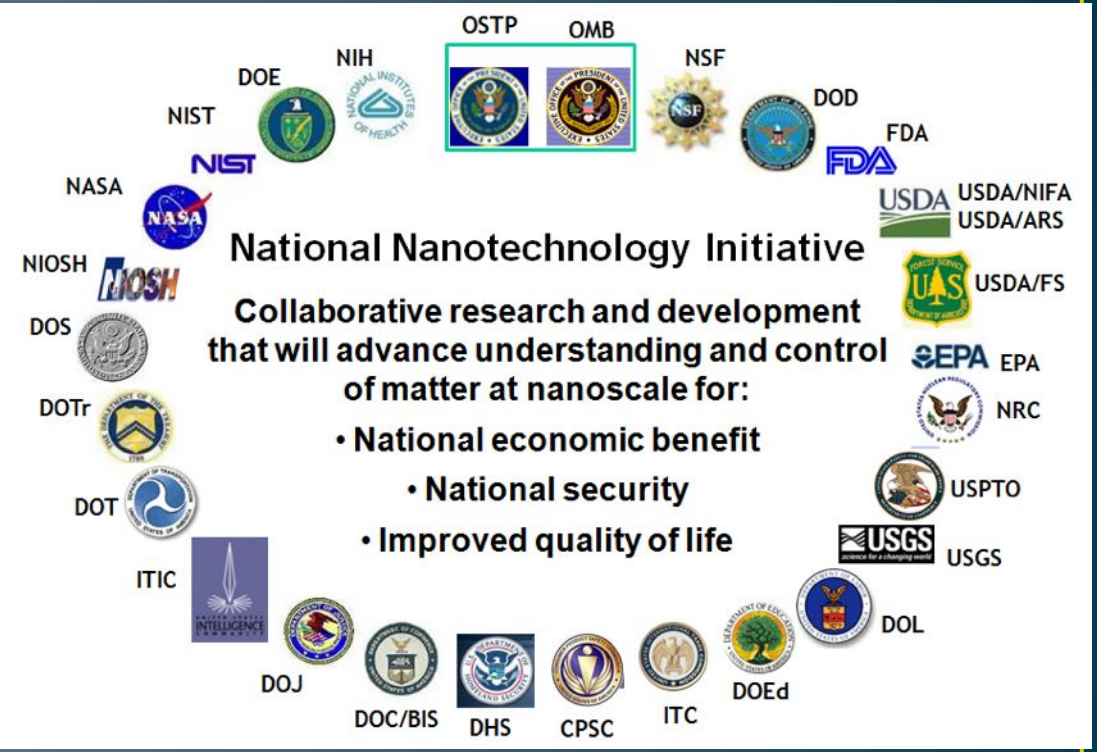






The National Nanotechnology Initiative (NNI)

- Established in 2000 under an Executive Order from President Bill Clinton
- Intent of the NNI is to provide a framework for member agencies to work together to:
  - Advance world-class nanotechnology research
  - Foster the transfer of technologies into products for commercial and public benefit
  - Develop and sustain educational resources, a skilled workforce and the supporting infrastructure and tools to advance nanotechnology
  - Support the responsible development of nanotechnology



Signature Initiatives

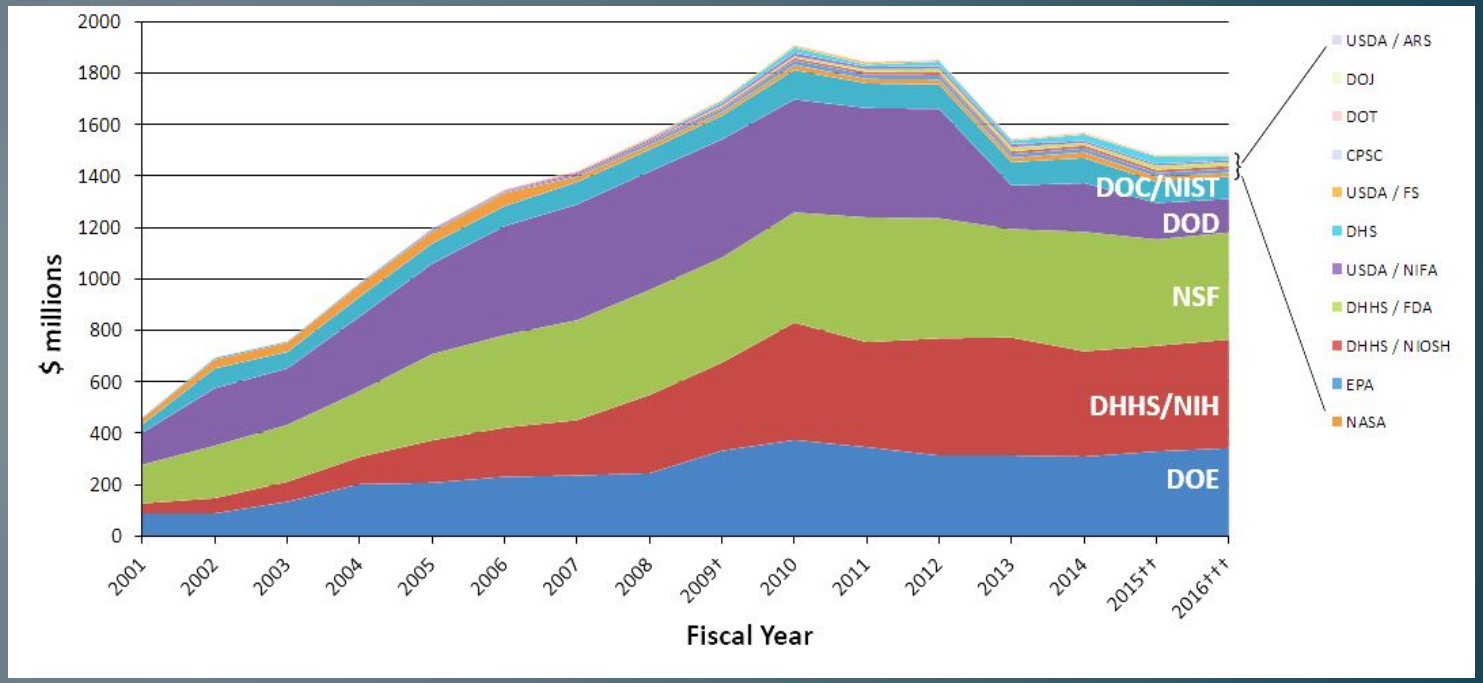
- Sustainable Nanomanufacturing
- Nanoelectronics for 2020 and Beyond
- Nanotechnology Enhanced Solar Energy Capture and Conversion
- Nanotechnology for Sensing
- Nanotechnology Knowledge Infrastructure

President Clinton's Vision

Just imagine, materials with 10 times the strength of steel and only a fraction of the weight; shrinking all the information at the Library of Congress into a device the size of a sugar cube; detecting cancerous tumors that are only a few cells in size. Some of these research goals will take 20 or more years to achieve. But that is why—precisely why there is such a critical role for the Federal Government.

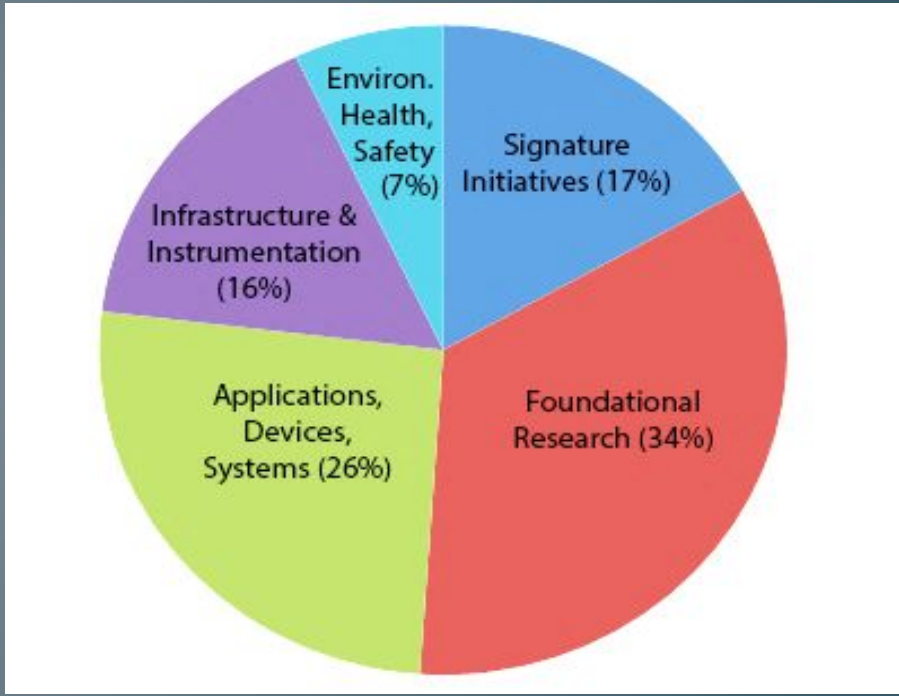
President Clinton, California Institute of Technology, January 21, 2000

NNI Funding Trends



NNI participating agencies have invested over $21B in nanotechnology R&D, unique user facilities, commercialization, education and outreach

NNI Planned Investments in FY2016



NNI Reporting

The NNI Supplement to the President's Budget:

- Funding information by agency/department and PCA for prior, current FY and requested amount for budget year
- Accomplishments from prior FY
- Plans for current FY and budget year
- Available on www.nano.gov

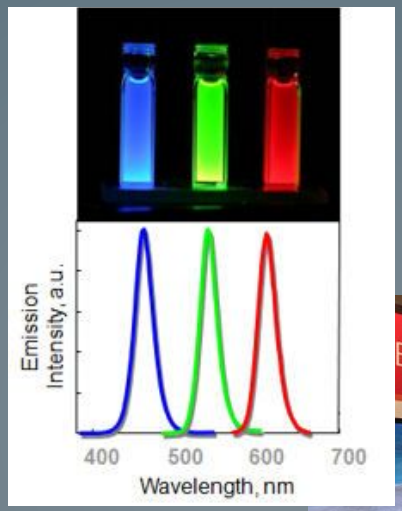
Nanotechnology Products

Nanoscale Silver Antimicrobials

Nanoscale Titanium Dioxide UV Absorbers

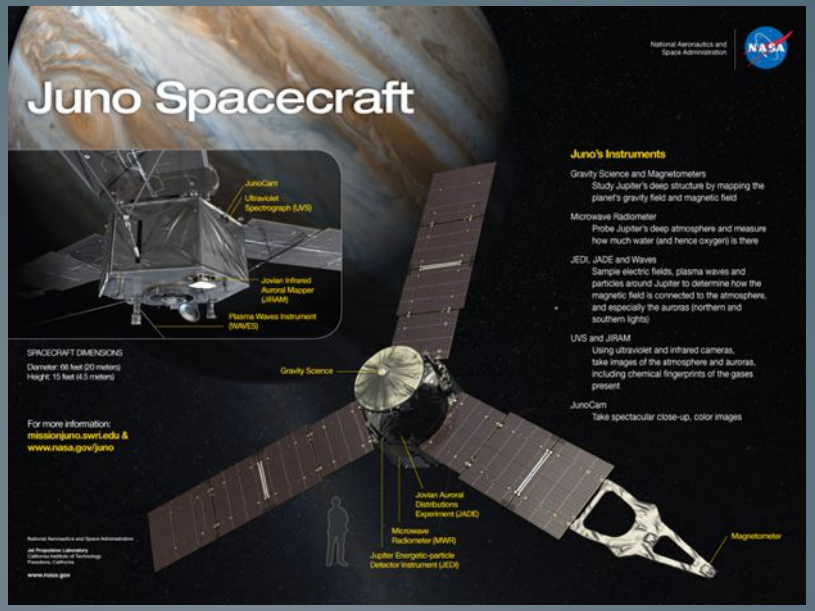
Polymer Nanocomposites

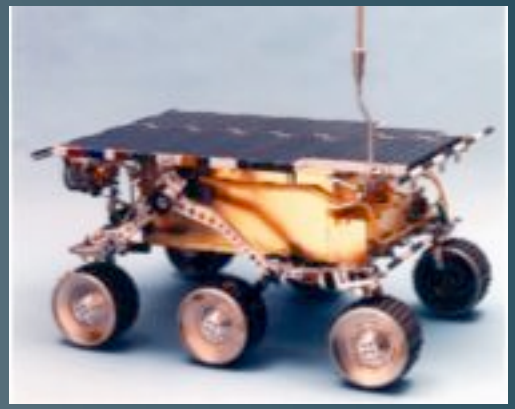
QD Vision's Color IQ Technology



- QD Vision developed CdSe quantum dots for use in solid state lighting and displays (Color IQ)
- Color IQ incorporated into Bravia LED televisions in 2013
  - "Best of 2013 CES" – *Tech Radar*
  - Reduces power consumption by 20% - less pollution
- QD Vision received EPA's Green Chemistry Challenge Award in 2014 for reducing use of hazardous materials in their manufacturing processes

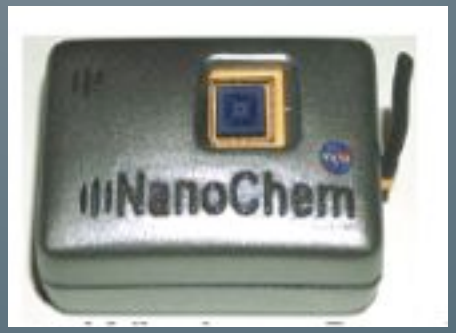
Nanotechnology Has Made it into Space



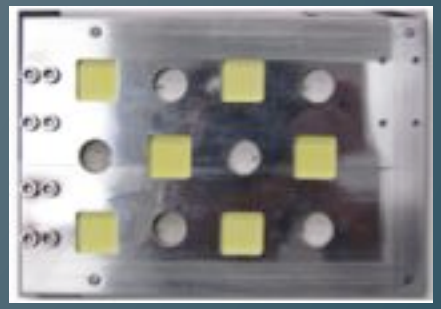


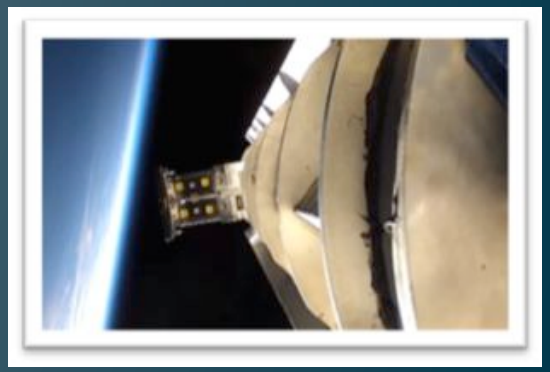
Silica Aerogels

CNT Nanocomposites for Charge Dissipation



CNT “Electronic Nose”





Polyimide Aerogels

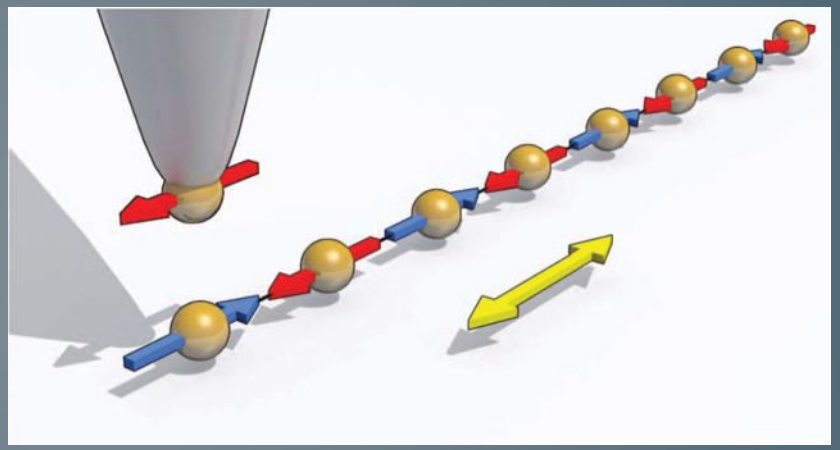
President Clinton's Vision

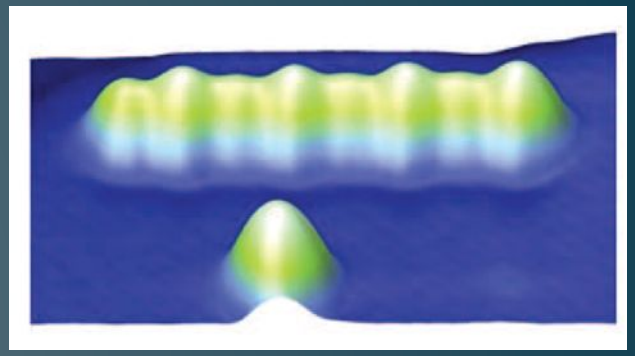
Just imagine, materials with 10 times the strength of steel and only a fraction of the weight; shrinking all the information at the Library of Congress into a device the size of a sugar cube; detecting cancerous tumors that are only a few cells in size. Some of these research goals will take 20 or more years to achieve. But that is why—precisely why there is such a critical role for the Federal Government.

President Clinton, California Institute of Technology, January 21, 2000

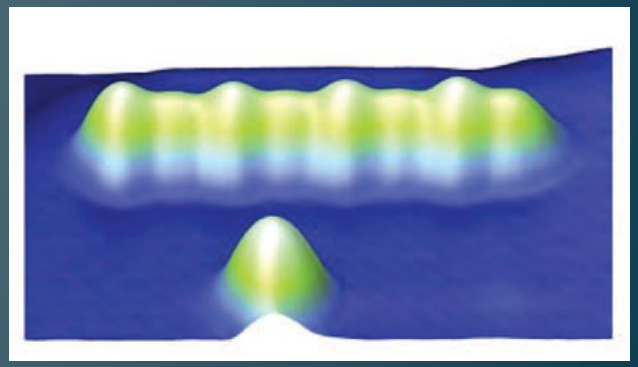
Use of a Bistable AFM Array of Fe Atoms Provides for High Density Data Storage

S. Loth, et al *Science* **2012, *335*, 196-199**





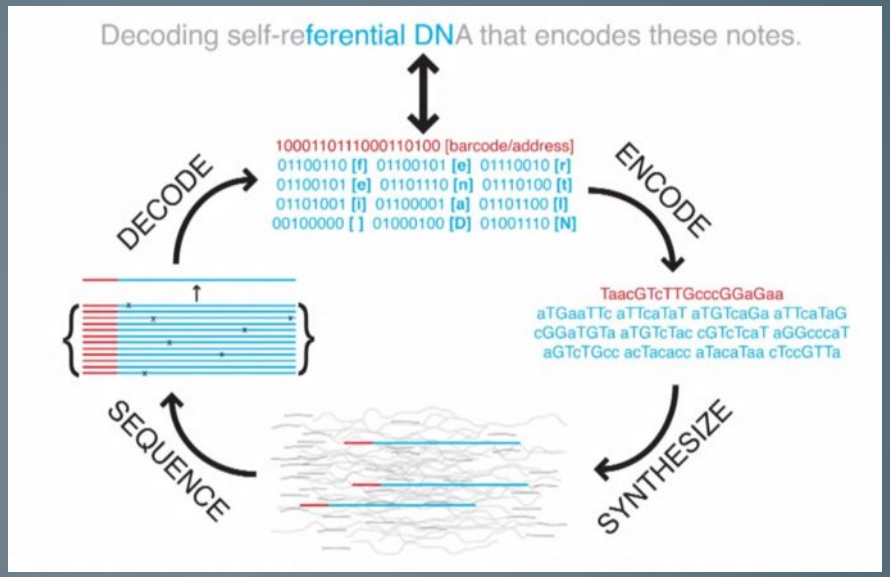
Neel State "0"

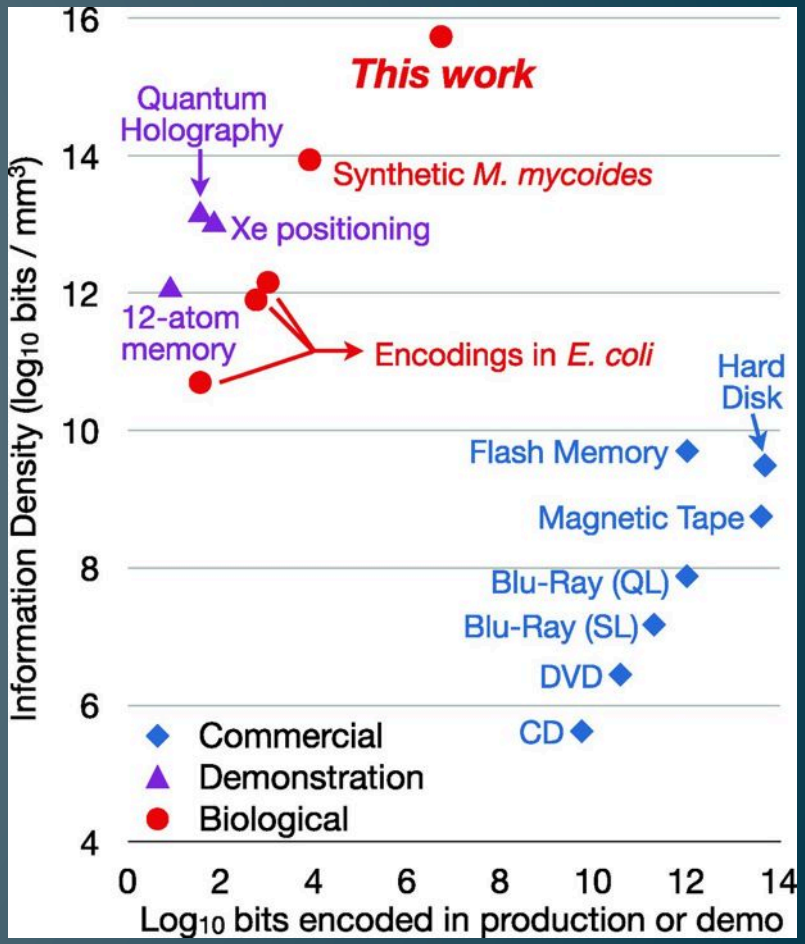


Neel State "1"

- Magnetic spins of Fe atoms aligned parallel to the easy magnetic axis due to surface-induced magneitc anisotropy fields
- Spin-polarized AFM tip reads magnetic state state of structure by magnetoresistive tunneling (magnetic field parallel to yellow arrow polarizes tip)
- Storage density is 100X greater than optical disks, 150 X greater than solid state storage devices

DNA Encoding Provides a Route to High Density Data Storage





G.M. Church, Y. Gao, S. Kosuri *Science* **2012**, *337*, 1628

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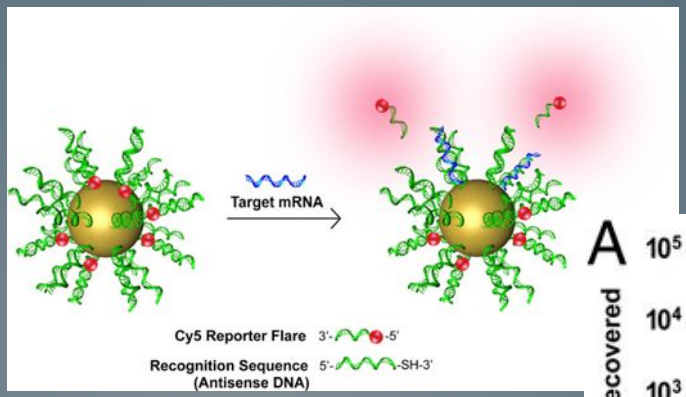
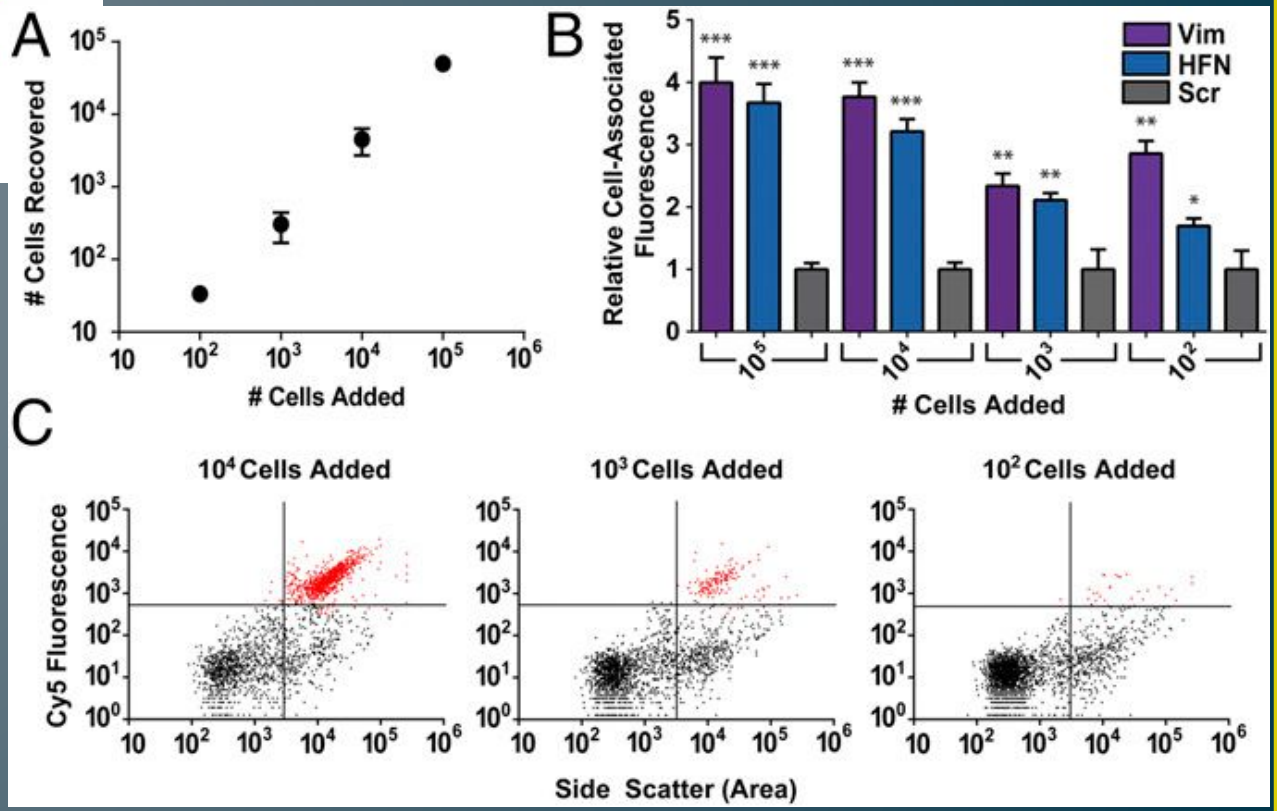
NanoFlares Can Detect as Few as 100 Cancer Cells per mL of Blood



- Gold NPs decorated with a monlayer of antisense DNA and fluorophore containing reporter flare
- Binding of target mRNA releases fluorophore



T.L. Halo et al *PNAS* **2014**, *111*, 17104-17106

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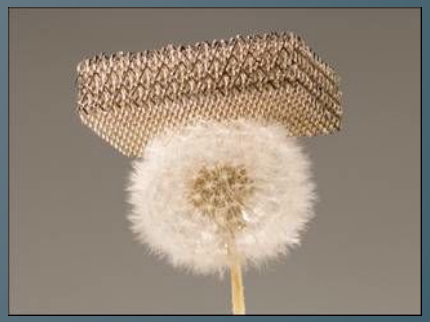
Materials 10 Times Stronger than Steel at a Fraction of the Weight

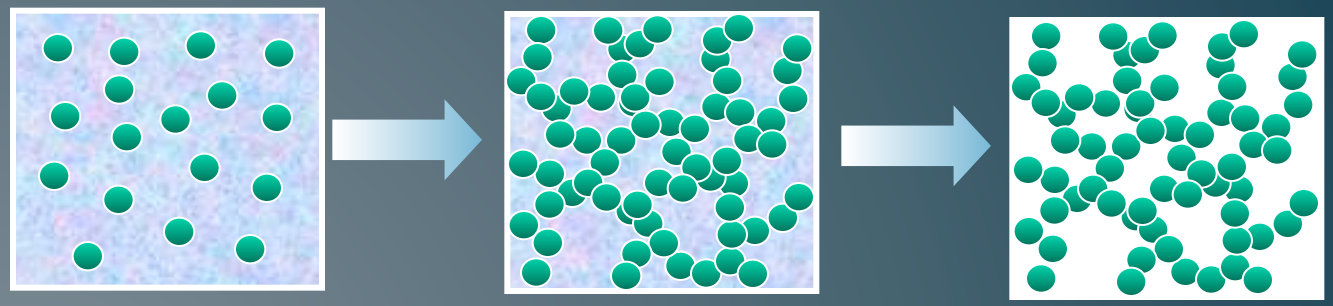
Carbon Nanotube Fibers and Composites

Polymer Aerogels



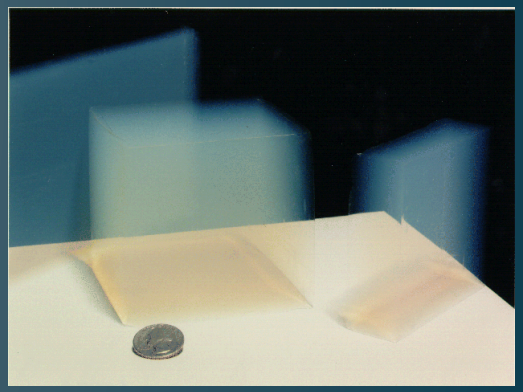
Micro/Nanolattices

What are aerogels?



Sol Gel Aerogel

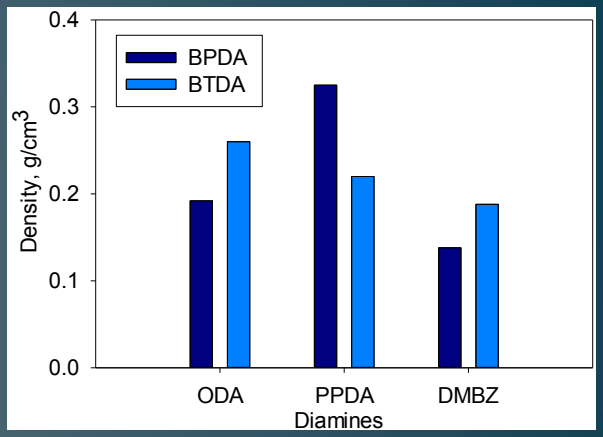
- Highly porous solids made by drying a wet gel without shrinking
- Pore sizes extremely small (typically 10-40 nm)—makes for very good insulation
- 2-4 times better insulator than fiberglass under ambient pressure, 10-15 times better in light vacuum
- Invented in 1930's by Prof. Samuel Kistler of the College of the Pacific

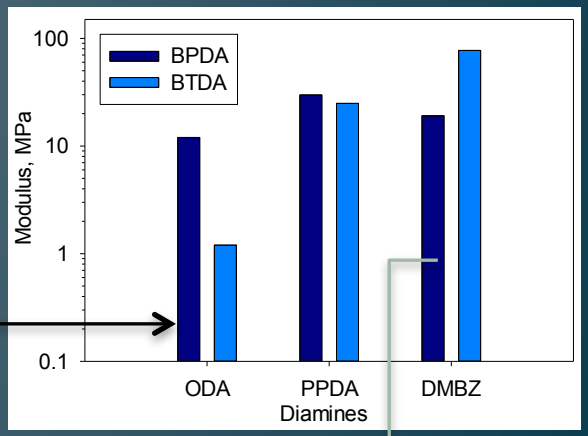


Typical monolithic silica aerogels

Polyimide Aerogels are much stronger than silica aerogels at similar density

Silica aerogel is easily broken by light finger press while PI aerogel easily supports the weight of a car

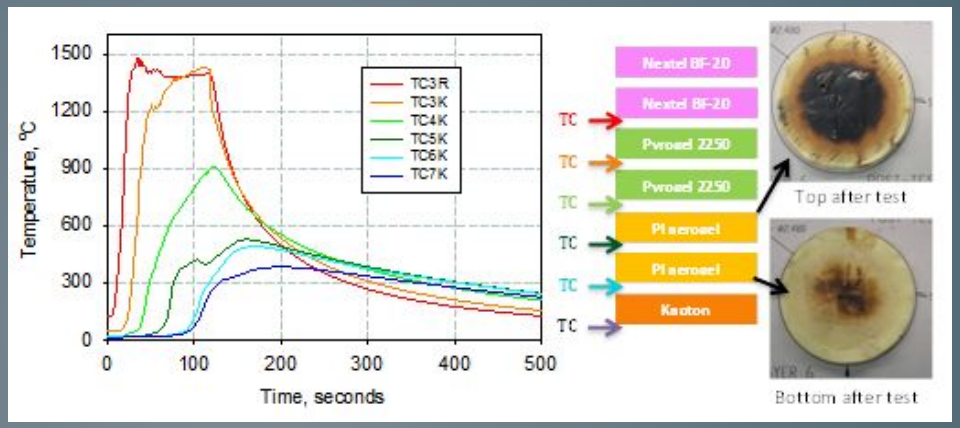


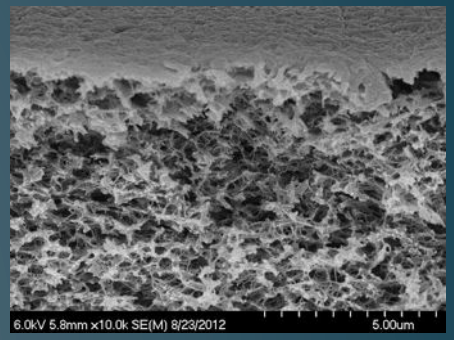


This formulation is actually *stronger* and *lighter* than one shown in picture

High Performance Polyimide Aerogels

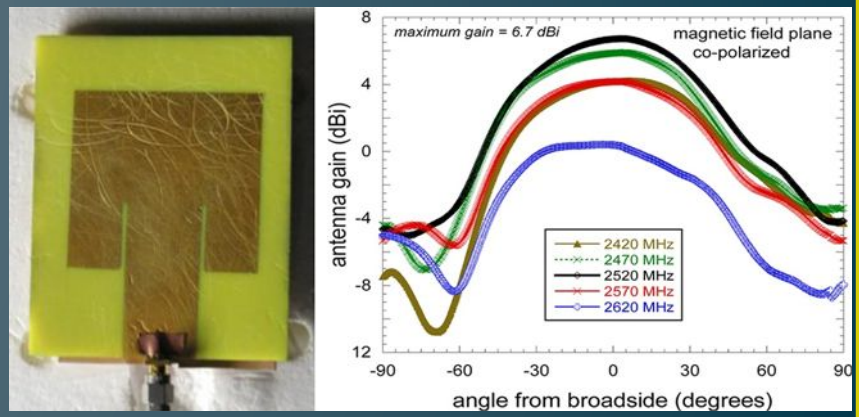
High heat flux test results indicate potential for flexible thermal protection





Nanoporous structure

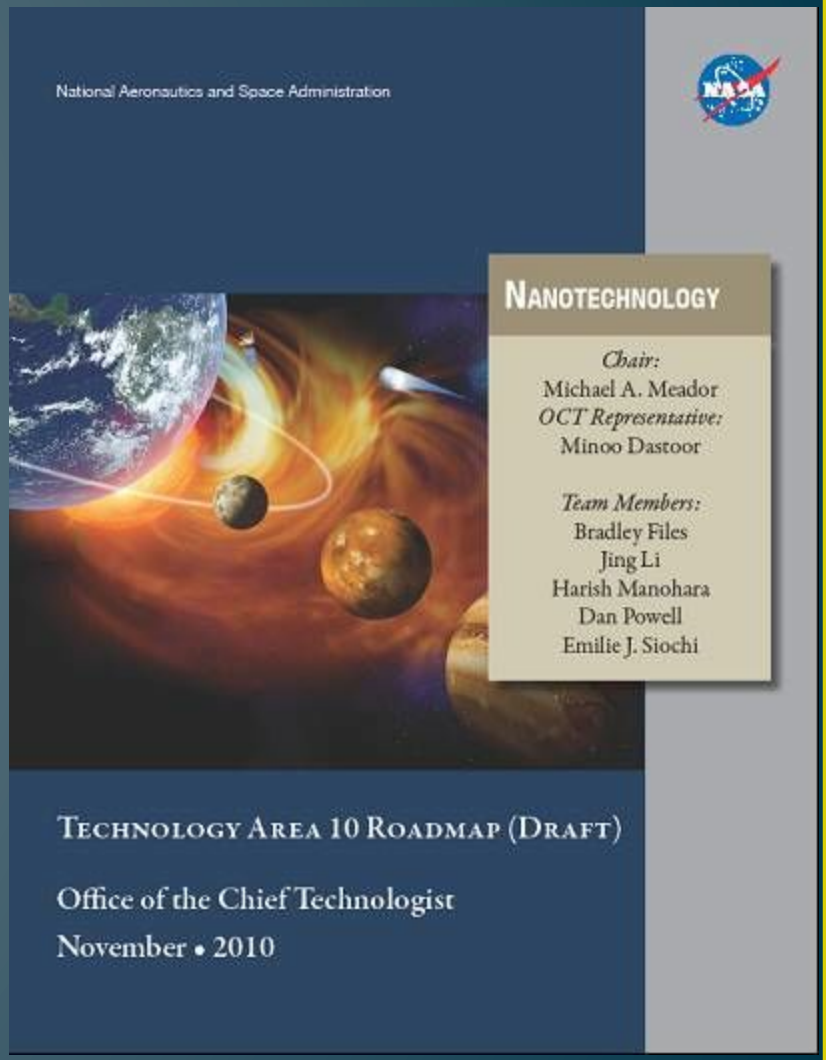
Good compressive properties and durability



Aerogel substrate enables antennas with 67% higher bandwidth, higher maximum gain than PTFE at 1/10th the weight

NASA Nanotechnology Roadmap

- Drafted 20+ year technology roadmap for development of nanotechnology (TRL 6) and its insertion into NASA missions
  - Includes both mission “pull” and technology "push”
  - Covers four theme areas
    - Engineered Materials and Structures
    - Energy Generation, Storage and Distribution
    - Propulsion
    - Sensors, Electronics and Devices
  - Used to guide future funding decisions
- Identified 18 Key Capabilities enabled by nanotechnology that could impact current and future NASA missions
- Identified 5 Grand Challenges with potential for broad Agency impact
- Plans to update the roadmaps in FY14



Grand Challenge: Ultralightweight Structural Nanomaterials

Objective: Reduce density of state-of-the-art structural composites by 50% and equivalent or better properties.

Approach: Use nanomaterials with combination of high performance characteristics

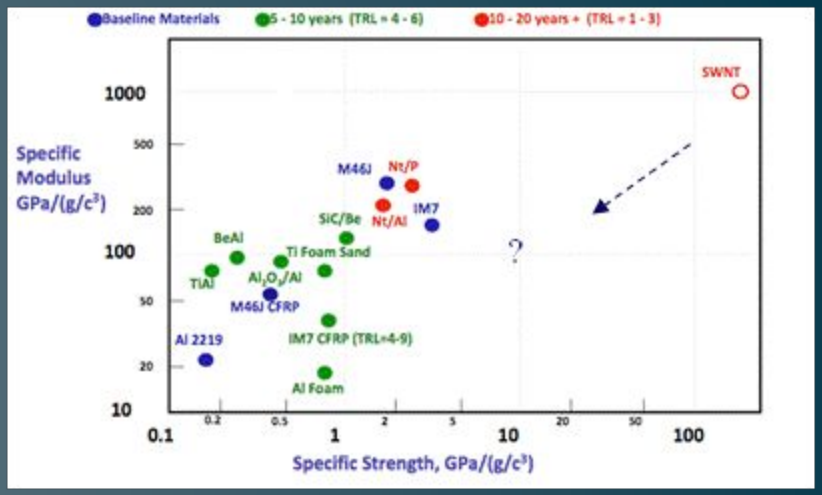
- Utilize nanostructured additives to produce low density carbon nanotube fibers with properties equivalent to aerospace grade intermediate modulus fibers but at half the density
- Durable nanoporous materials (polymers, metals or hybrids) less than half the density of monolithics
- Addition of nanoscale fillers to improve strength and toughness

State-of-the-Art:

- Aluminum and Titanium alloys, carbon fiber reinforced polymeric composites, ceramic matrix composites, metal matrix composites

NASA Benefits/Applications:

- Potential vehicle dry mass savings of up to 30%
- Enhanced damage tolerance for improved safety
- Enable design concepts with tailored performance
- Enabling technology for environmentally friendly vehicles
- Enabling technology for extreme environment operations



Technical Challenges to TRL 6:

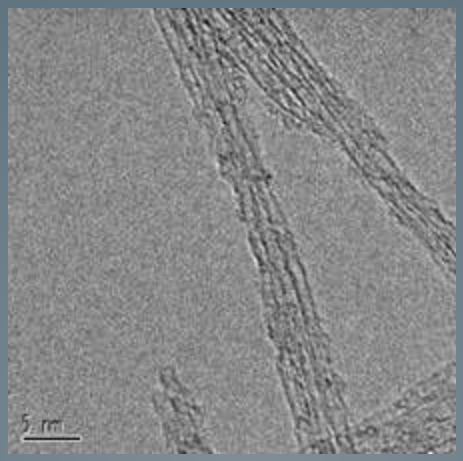
- Development of reliable, reproducible, and controlled nanomaterials synthesis process on a large scale
- Development of tailored geometries at nano and macro scale for structural components
- Fabrication methods that can be practically implemented at bulk or macro scale
- Early assessment of systems payoffs in cost, operational safety and reliability.

Time to Mature to TRL 6: 5-10 years

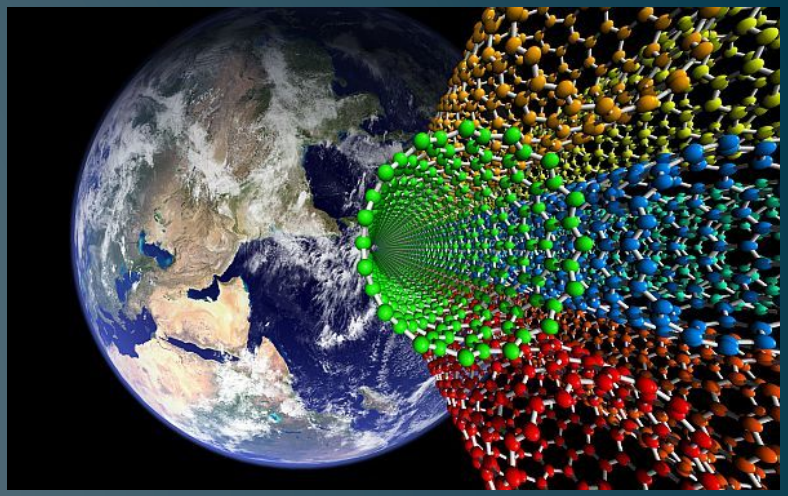
Potential for Partnering with Other Agencies:

- Partnerships under NNI Nanomanufacturing SI

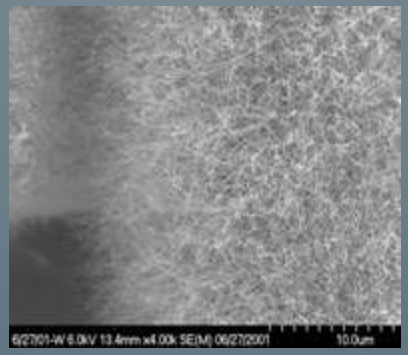
Carbon Nanotube Based Materials



Purified Single Wall Carbon Nanotubes



Carbon Nanotube Space Elevator



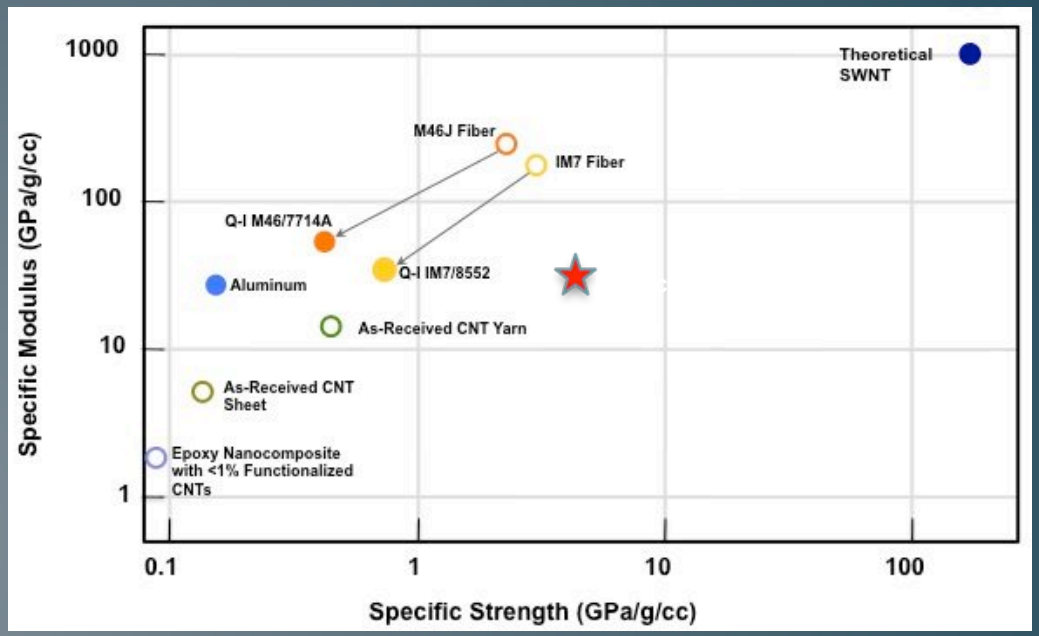
Nanotube Modified Substrates

Nanotubes have remarkable properties-

- Specific strength 150X that of conventional carbon fibers, 100X aluminum
- Elongation 10X that of conventional carbon fibers
- Electrical and thermal conductivities ~10X that of high conductivity carbon fibers

Because of these properties, carbon nanotubes have been proposed for disruptive applications such as a space elevator cable

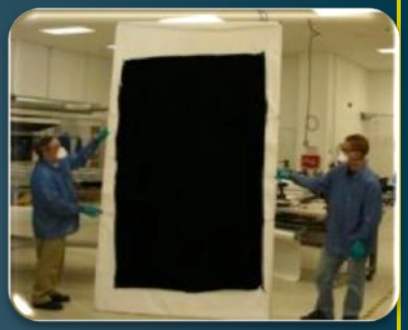
State of the Art for Nanocomposites

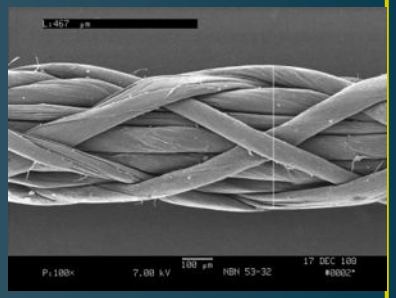


- Remarkable properties of CNTs have not been realized in composites
- Bulk of the studies have focused on dispersion of CNTs in a matrix or composite
  - → Improvements in mechanical, thermal and/or electrical properties reported
  - → Amount of nanotubes that can be used and resulting properties limited to a few wt %
    - CNTs agglomerate due to van der Waals forces – inhomogeneous materials, defects
    - Viscosity of polymer increases with increasing CNT content making processing difficult
- Better approach is to incorporate the CNT into the reinforcement
  - → Achieve higher loading levels, control placement within the composite
  - → "Drop-in" replacement for carbon or other fiber reinforcements

Nanotechnology Enabled Ultralightweight Structures

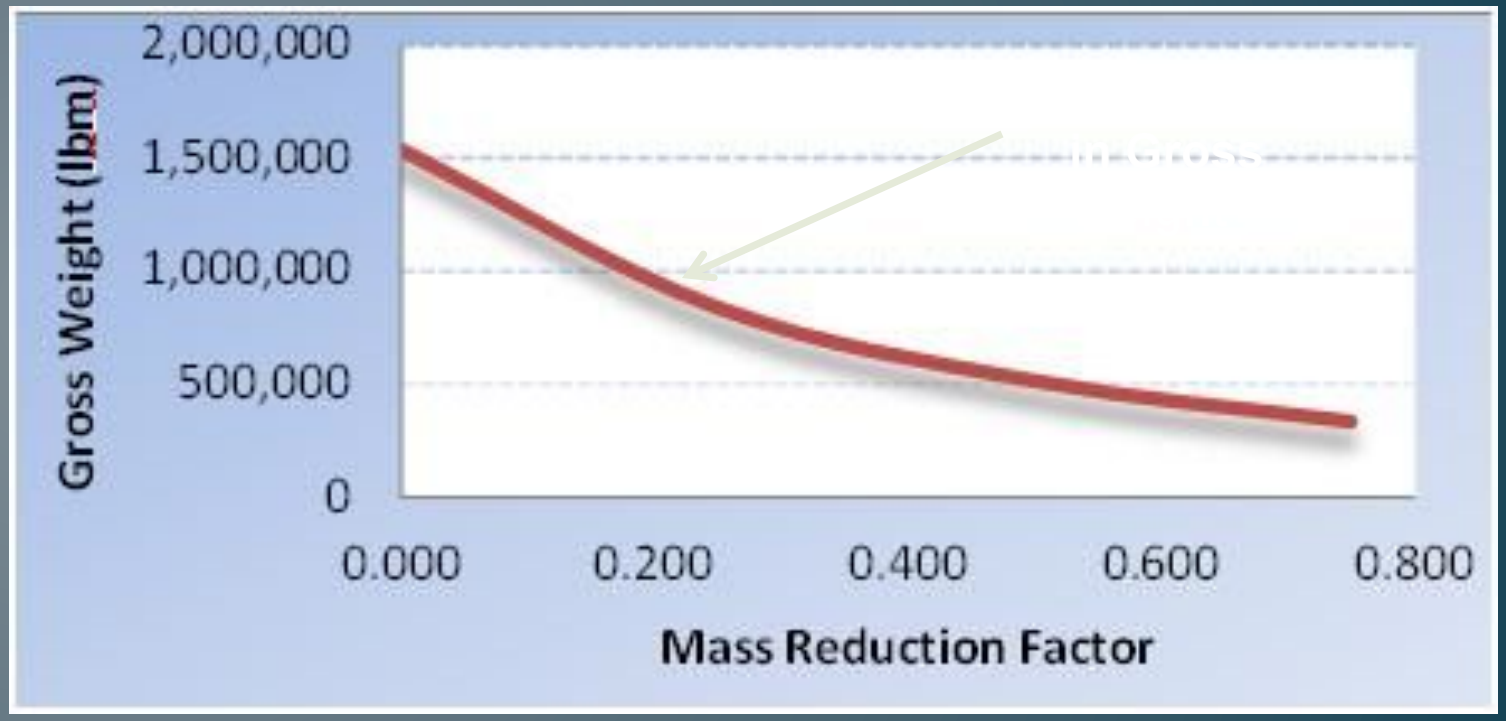
- What are we trying to do?
  - Develop carbon nanotube (CNT) reinforced composites with 1.5 to 2 times the strength of conventional carbon fiber composites, such as those used in the Boeing 787
- Why is it important?
  - Use of these ultra-lightweight materials in place of conventional composites in aerospace vehicles will enable a 30% reduction in vehicle weight
  - Ultra lightweight materials were identified as one of 16 top technologies by the NRC in their reviews of the Space Technology Roadmaps
- How are we doing this?
  - Improve the strength of available CNT sheets, tapes and yarns through a combination of processing improvements and post-processing treatments
  - Measure the improvements in mechanical properties by testing CNT reinforcements and composites
  - Develop/identify manufacturing approaches for CNT reinforced composites
  - Validate these materials by design, fabrication, ground and flight testing of a CNT reinforced composite overwrap pressure vessel





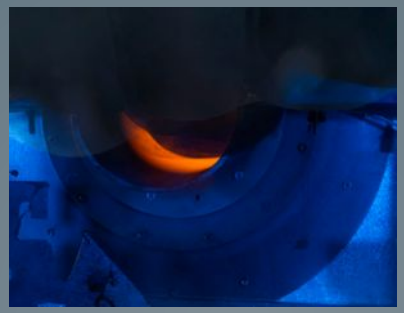
Reducing Composite Aerial Density Has Huge Impact on Vehicle Weight

Effect of Reducing Material Mass on Launch Vehicle Gross Weight

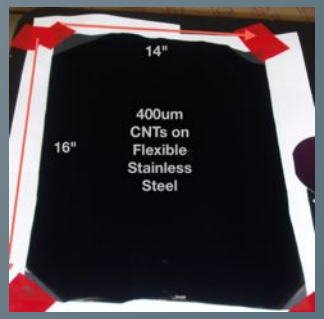


Carbon Nanotube Reinforcements

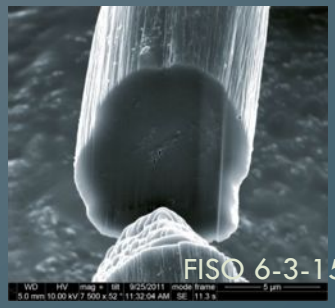
Floating Catalyst Method – Nanocomp Technologies

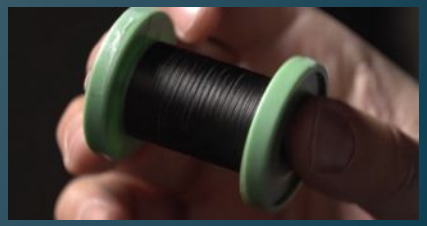


Spinning from VANTA – Baughmann, General Nano



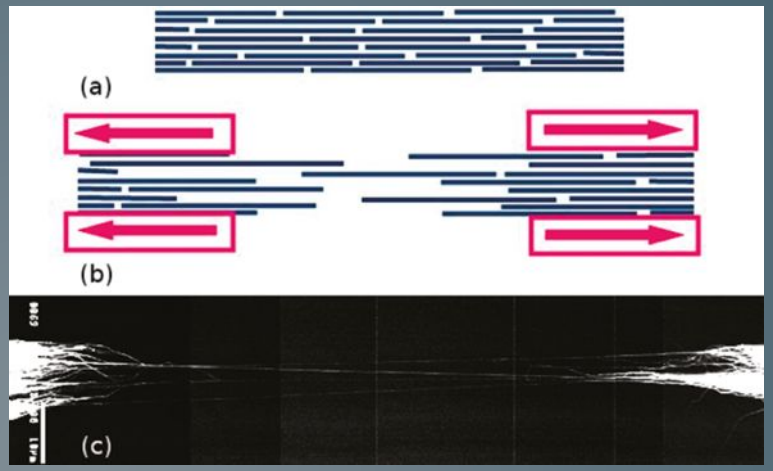
Spinning from Lyotropic CNT Solutions – Pasquali, Teijin Industries





Transitioning Nanobased Technology To High Performance, Volume Production…Spun Yarns

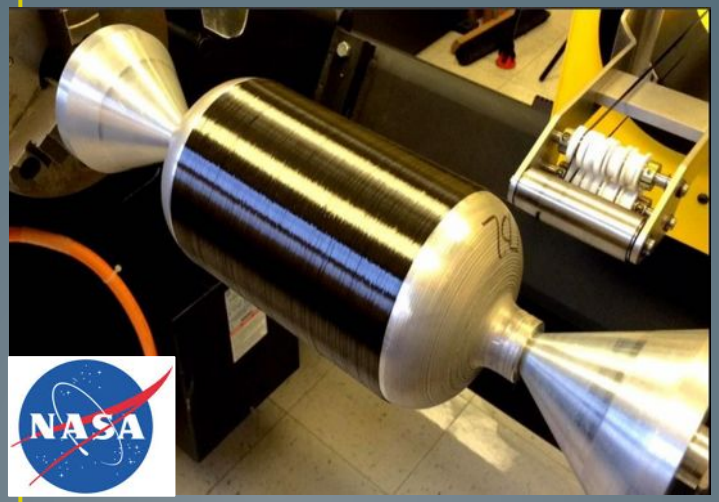
Issues with Carbon Nanotube Fibers



Source: Vilatela, Elliott and Windle *ACS Nano* **2011,** *3*, 1921-27

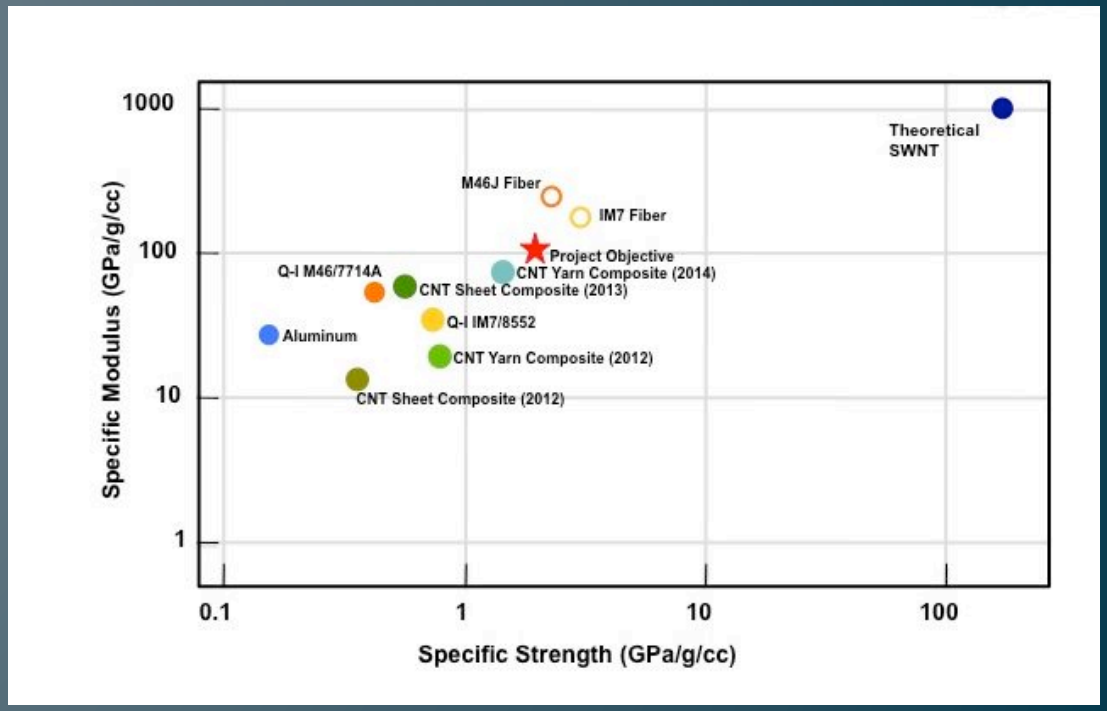
- Tensile strength of carbon nanotube fibers influenced by nanotube alignment, packing, waviness, and frictional forces
  - Current fiber production methods give nanotubes with ~ 40-50% alignment
  - Nanotubes have low friction coefficients – nanotubes shear under tensile load
  - Longer nanotubes are desired for use in fibers, waviness can be a problem
- Focus in this project is on development of processing and post-processing methods to improve tensile strength
  - Processing modifications to better align nanotubes in the fiber
  - Synthesis/processing modifications to produce nanotubes with lengths >1cm, increase contact length – reduces CNT-CNT slippage
  - Post –processing methods to increase CNT-CNT interactions, e.g., cross-linking

Nanocomp's Hi-Strength Yarns To Show Promise For Stronger, Lightweight Composite Cryogenic Tanks



Our current installed capacity is able to supply hundreds of kilometers…sufficient for flight test programs

Additional capacity needed for full scale program usage



Carbon Nanotube Based Data Cables are Up to 70% Lighter than Conventional Cables

Cables Provided By:

MINNESOTA WIRE
Life Saving Connections

MICRO-COAX
Leading the way in transmission line solutions.

TE connectivity

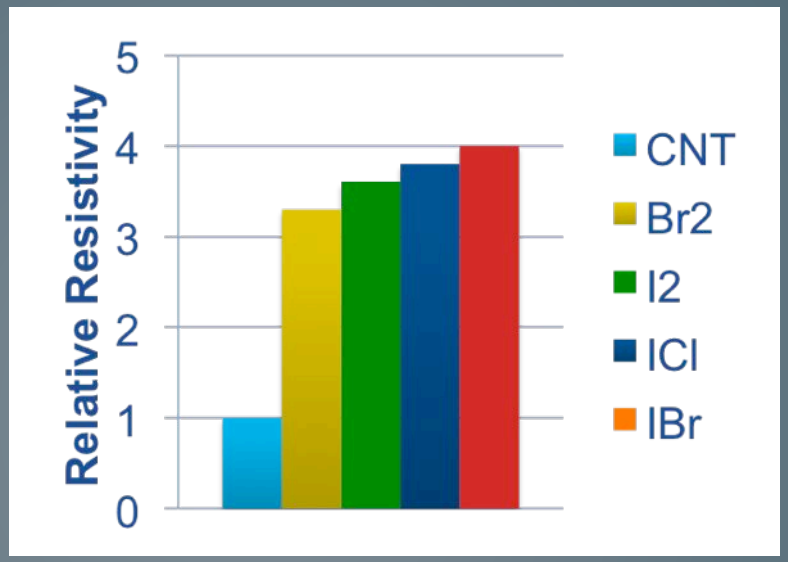
NORTHROP GRUMMAN

LOCKHEED MARTIN

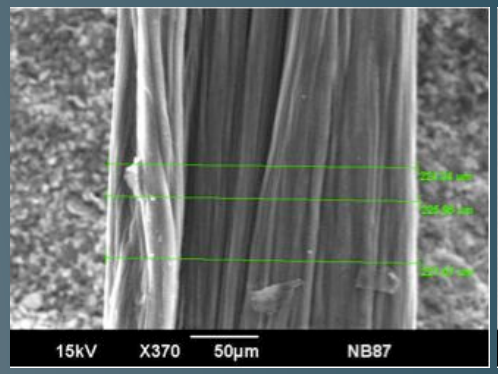
BOEING

nanocomp TECHNOLOGIES, INC.

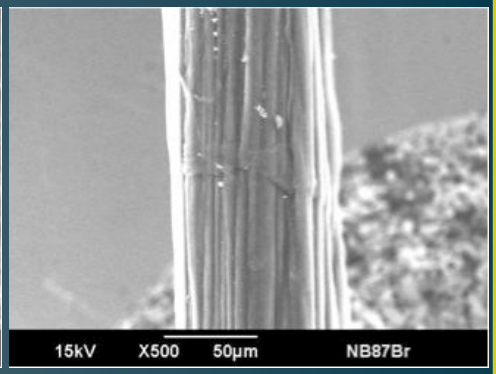
Halogen Intercalation Reduces CNT Yarn Resistivity



No Change in Fiber Gross Structure

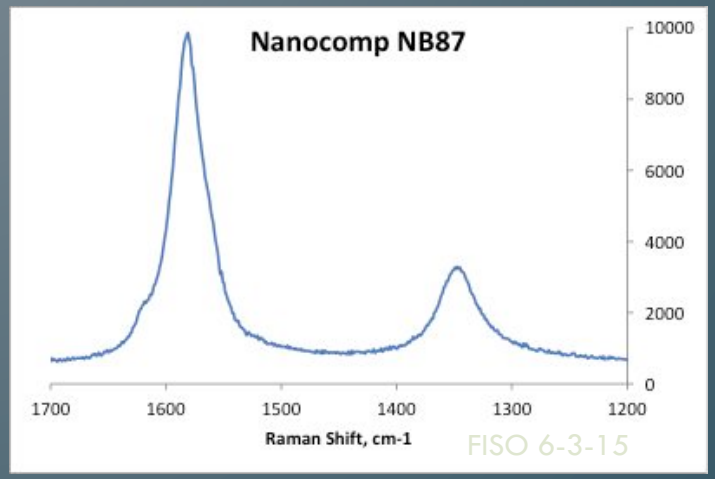


Before



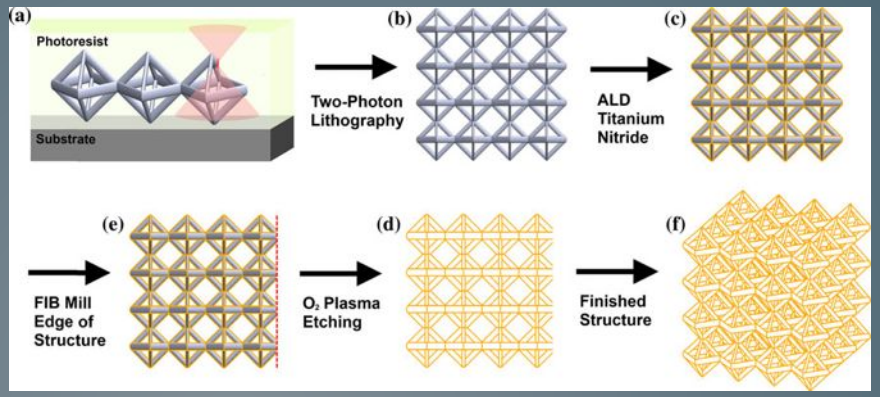
After

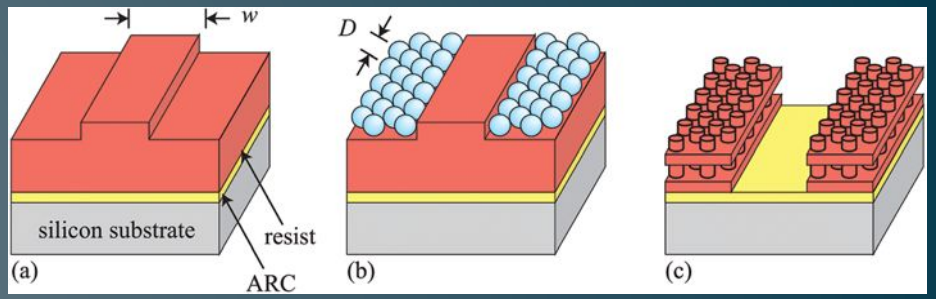
Minor Changes in Raman

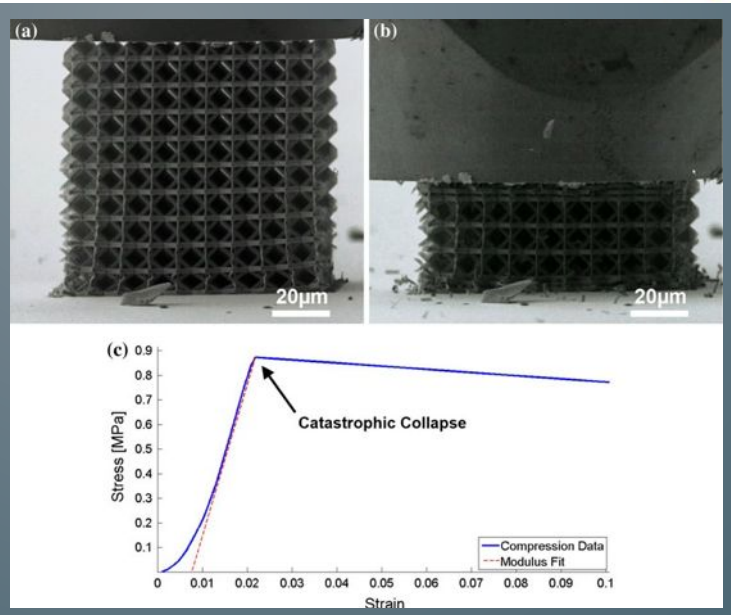


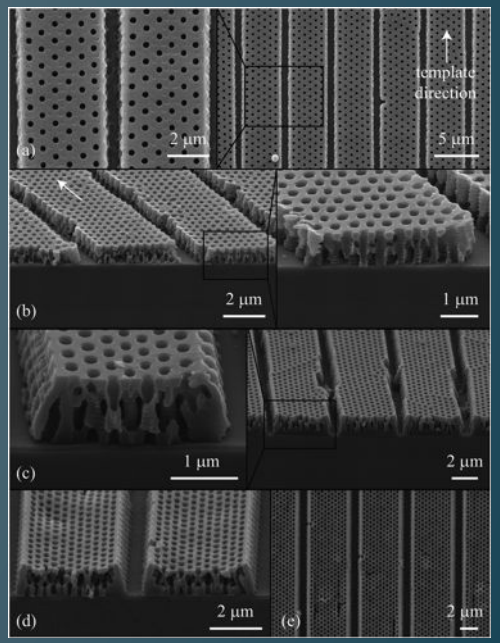
Fiber	1360/1580	σ
NB87	0.26	0.05
NB87-Br_2	0.34	0.05
NB87-I_2	0.30	0.08
NB87-ICl	0.24	0.11
NB87-IBr	0.25	0.04

Nanomanufacturing Provides Routes to Hierarchical Structures





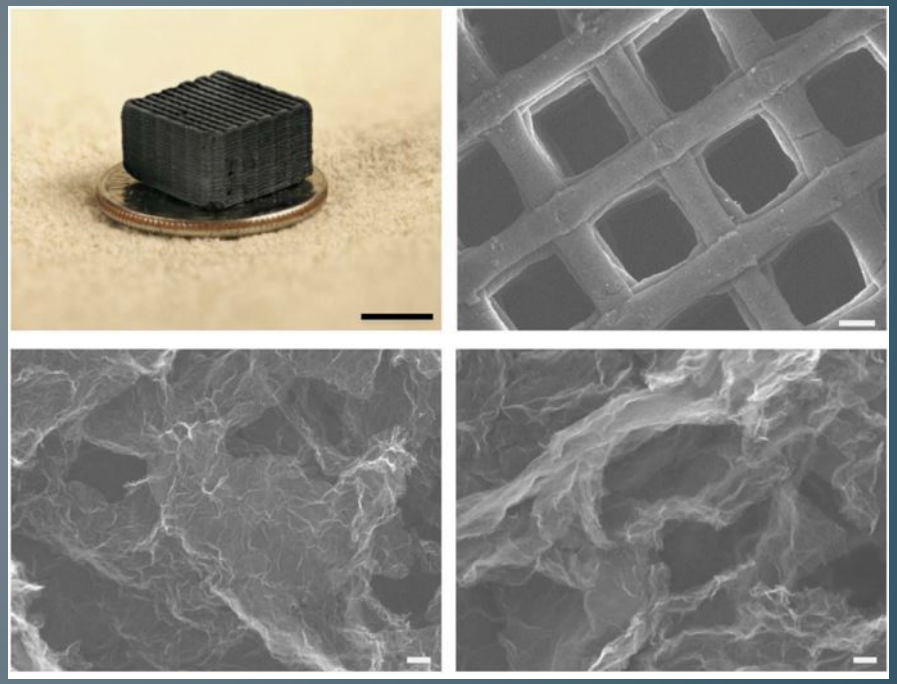




L.R. Meza and J.R. Greer *J. Mater. Sci* **2014,** *49*, 2496-2508

J.E. Elek, et al *Nanoscale* **2015,** *7, 4406-10*

3-D Printed Graphene Aerogels



Zhu et al *Nature Comm.* **2015,** 6:692

Grand Challenges

- Recommended by PCAST in their 2014 review of the NNI
- Definition derived from Administration's Innovation Policy
- Attributes of Grand Challenges are:
  - ✓ Require advances in fundamental scientific knowledge, tools, and infrastructure for successful completion.
  - ✓ Drive the need for collaboration between multiple disciplines, some of which do not normally interact, to come together, collaborate and share resources and information to solve the challenge.
  - ✓ Span efforts from discovery and fundamental science to engineering demonstration and commercialization, i.e., catalyze the transition of technologies from lab to market.
  - ✓ Be too big to be undertaken by one or even a few organizations.
  - ✓ Be exciting enough to motivate decision makers to provide funding and resources and multiple organizations to collaborate, share resources, and information to solve the challenge.
  - Have a measurable end-point andclear intermediate milestones that are measurable and valuable in their own right
- Major topic of NSET retreat, stay tuned for RFI to solicit ideas and input

Summary

- The Federal government has invested over $22B in nanotechnology R&D, user facilities, commercialization, and responsible development of nanotechnology
- Significant technical progress has been made in:
  - Lightweight, high strength materials
  - Nanoelectronics
  - Nanodiagnostics and therapeutics
- Greater emphasis on commercialization over the coming years
- New Federal initiatives present opportunities for collaboration and new applications for nanotechnology