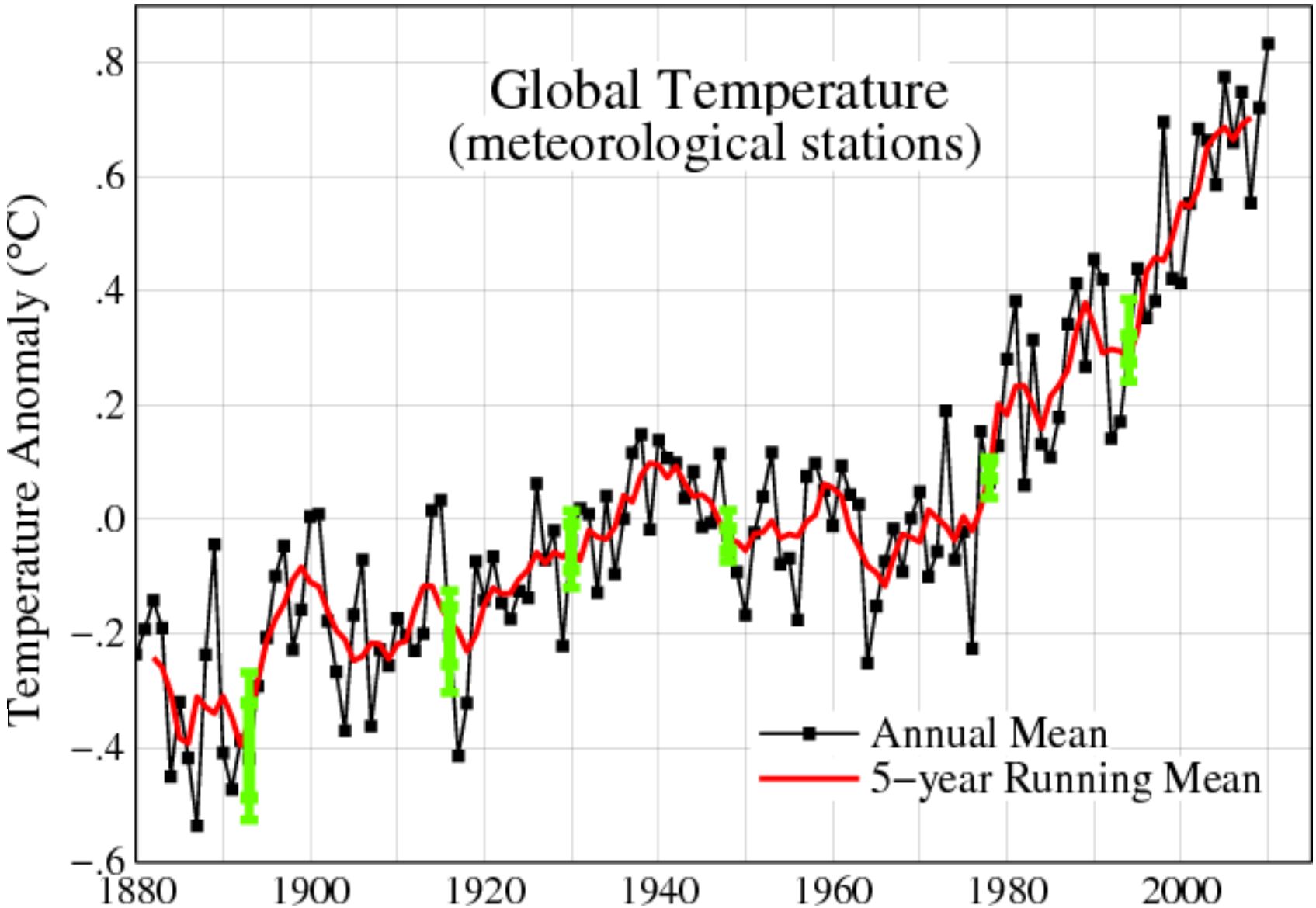
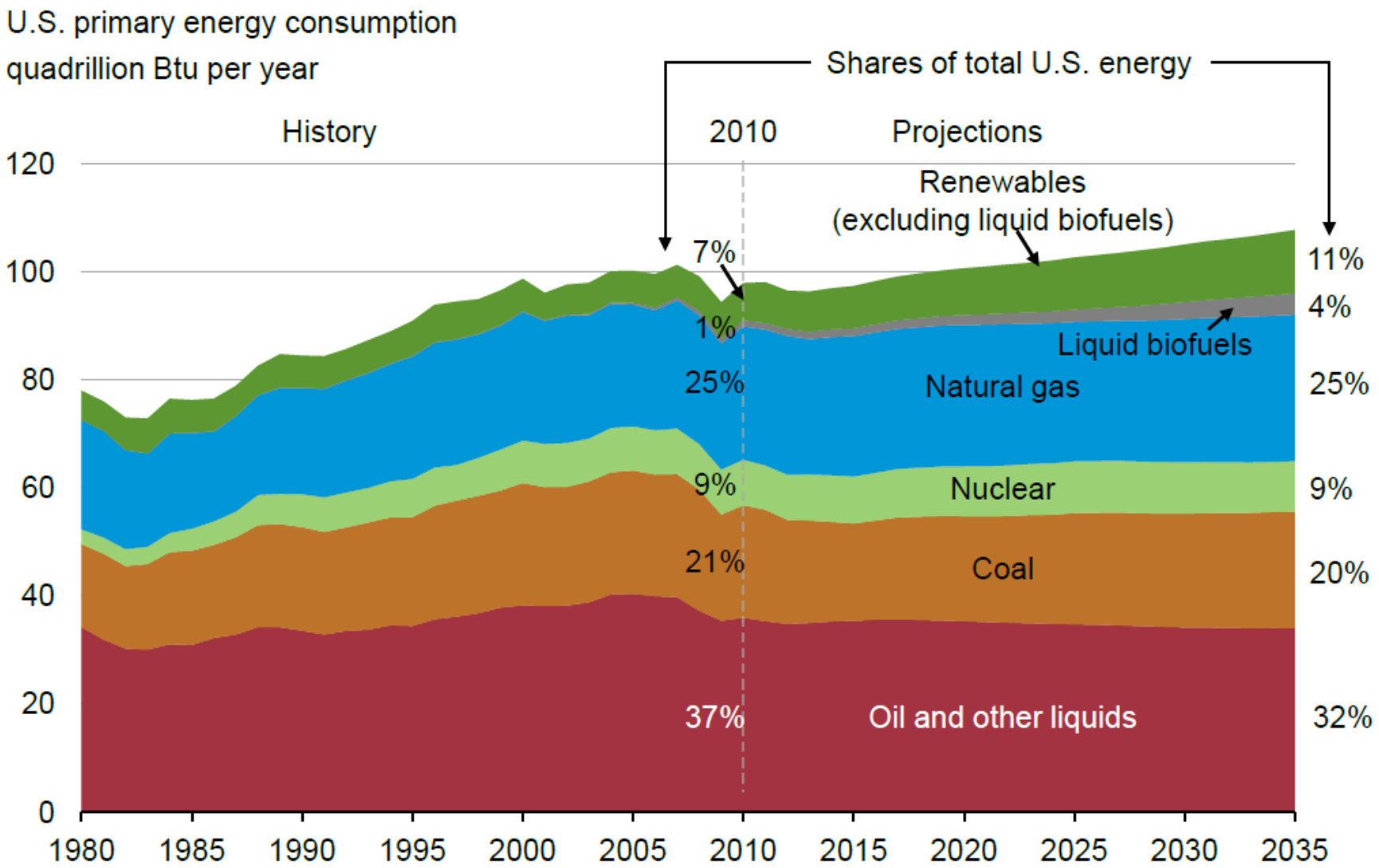
Global Average Temperature Increases with CO_2



Anomaly is deviation from 1951-1980 mean

NASA GISS, update of Hansen et al., *J. Geophys. Res.*, 106, 23947-23963, 2001

US energy consumption by source



Source: EIA, Annual Energy Outlook 2012 Early Release

Tesla – 300 miles per charge car

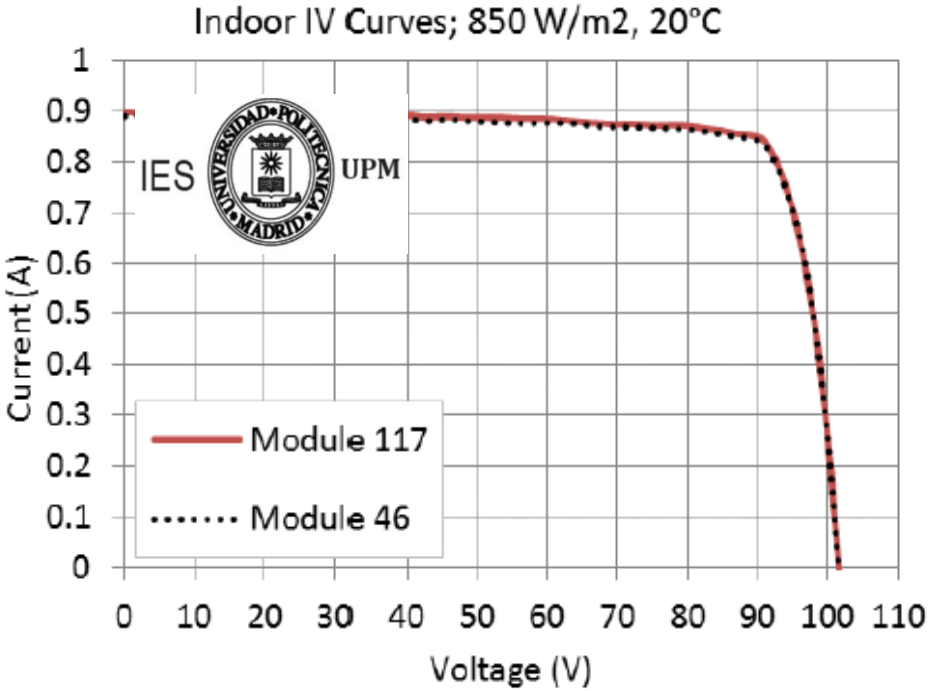
The Tesla Is One Hot Car

Four models

40 kWh	60 kWh	85kWh	85 kWh performance	
160mi	230 mi	300 mi	300 mi	
6.5 sec	5.9 sec	5.6 sec	4.4sec	zero to sixty
110 mph	120mph	125mph	130mph	

Recharges at 62 miles per hour-has a supercharger

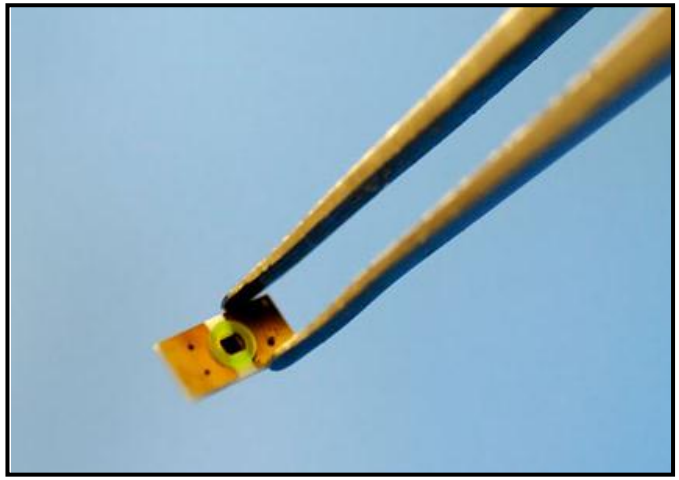
World Record Performance – Module Level



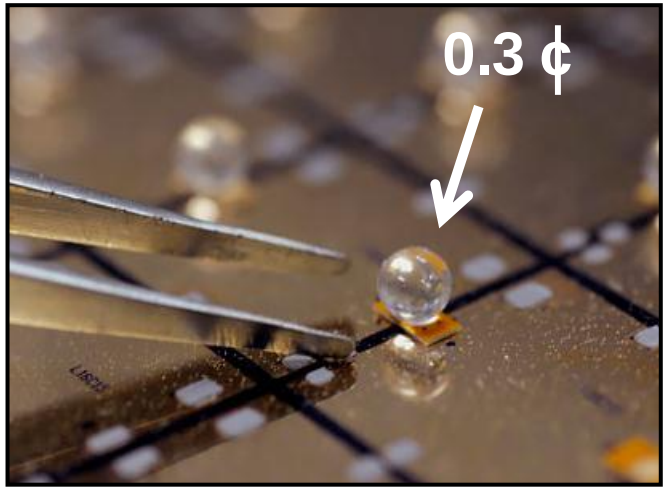
	Module 46	Module 117
Voc (V)	101.1	101.3
Isc (A)	0.890	0.898
FF	0.84	0.84
Eff (%)	33.6	33.9

These modules represent the highest-efficiency photovoltaic modules measured by the IES, and we are not aware of any published reports of a photovoltaic module with greater than 33% efficiency. To our knowledge, this Semprius technology constitutes a world record in module-level photovoltaic efficiency.

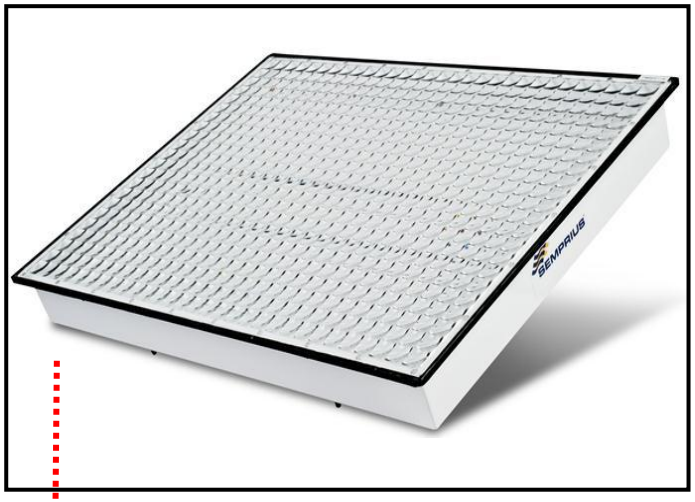
GaAs Microconcentrator Photovoltaics



World's Smallest Cell



'Ball Bearing' Micro-Optics



Compact Sub-module

- High efficiency, ~42%
- Efficient electrical mgmt
- Efficient thermal mgmt

- Uniform illumination
- High shading tolerance
- Low cost, ball lenses

- Efficient optics
- Low profile layouts
- Lightweight forms

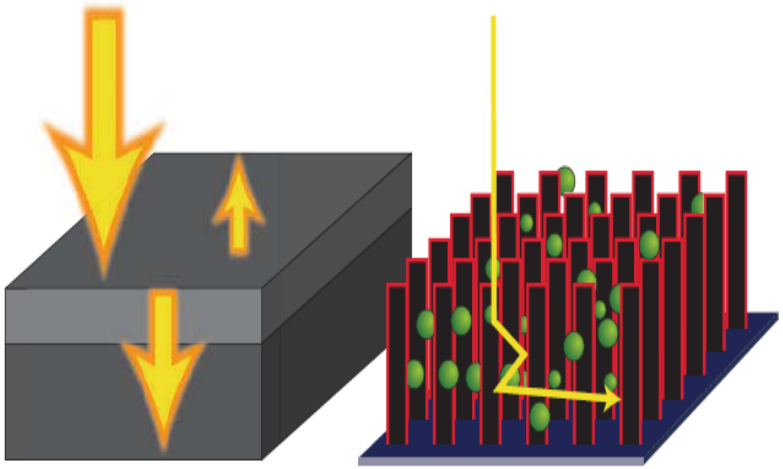
completed module

Nanoscience will help solve the serious problems facing mankind

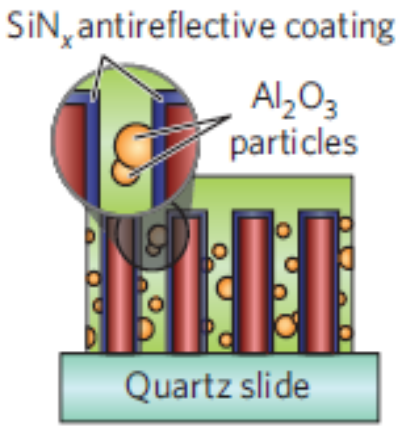
It will not only address the issues at the nano scale level but we will progressively apply the capabilities developed to do nanoscale to larger and larger systems

AND THIS IS WHAT WE ARE DOING TODAY

Nano Science Example: Materials by Design – Light absorption in nanowire arrays



Al_2O_3 nanoparticles reflect light towards Si wire arrays

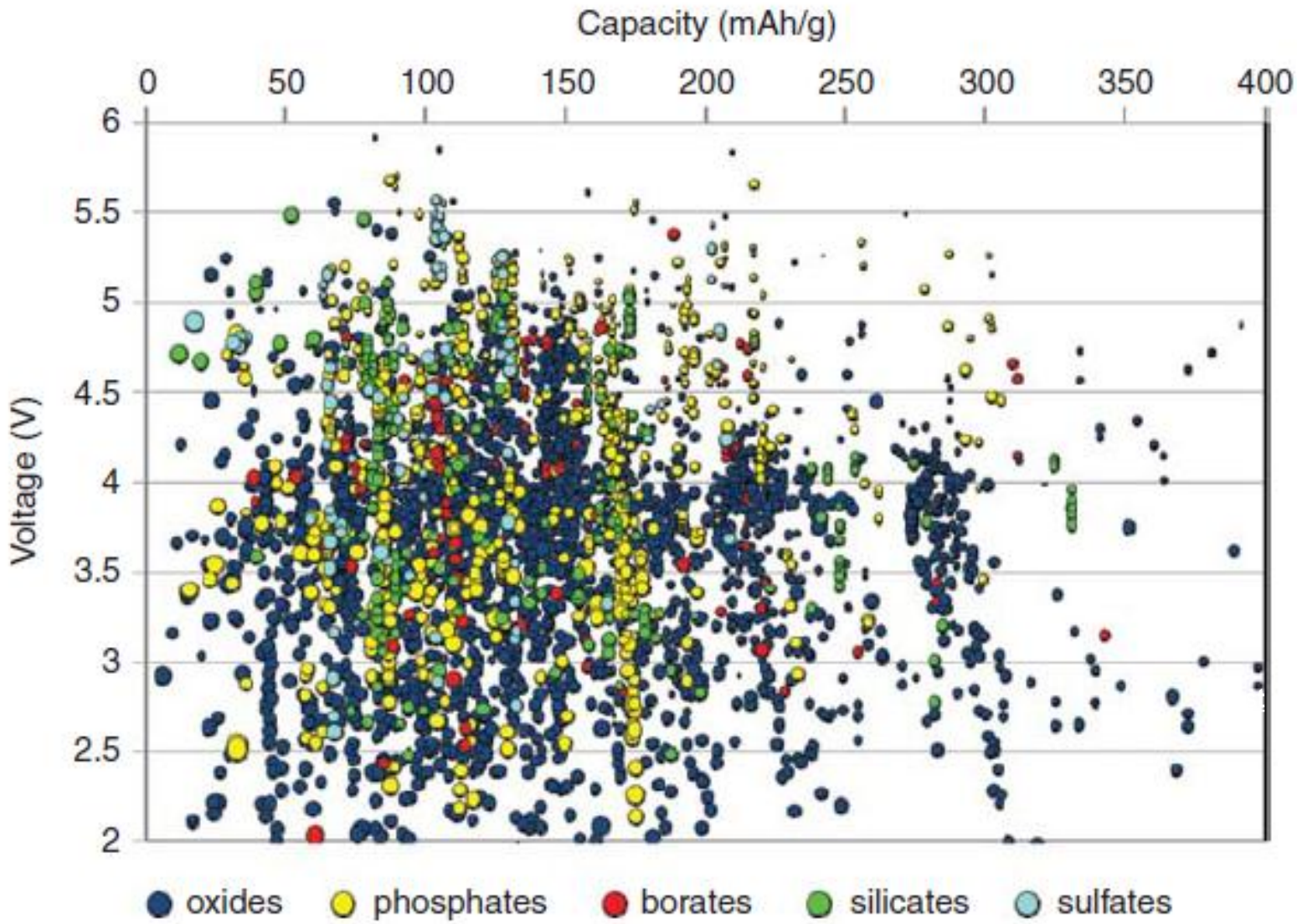


- **Assembly on a reflective backing**
  - Light absorbing nanowires surrounded by polymer that contains Al_2O_3 scattering particles
- **Wire arrays can absorb just as much sunlight as a conventional PV cell, but with only 2% of the Si**
  - Silicon wires fill as little as 2% of the cell's volume and absorb up to 85% of the sunlight
- **More than 90% of the absorbed light generates electricity rather than heat**
- **Flexible arrays are inexpensive to make**

Nature Materials, 9, 239 (2010).

Materials and Chemistry by Design

Accelerating Discovery for Global Competitiveness

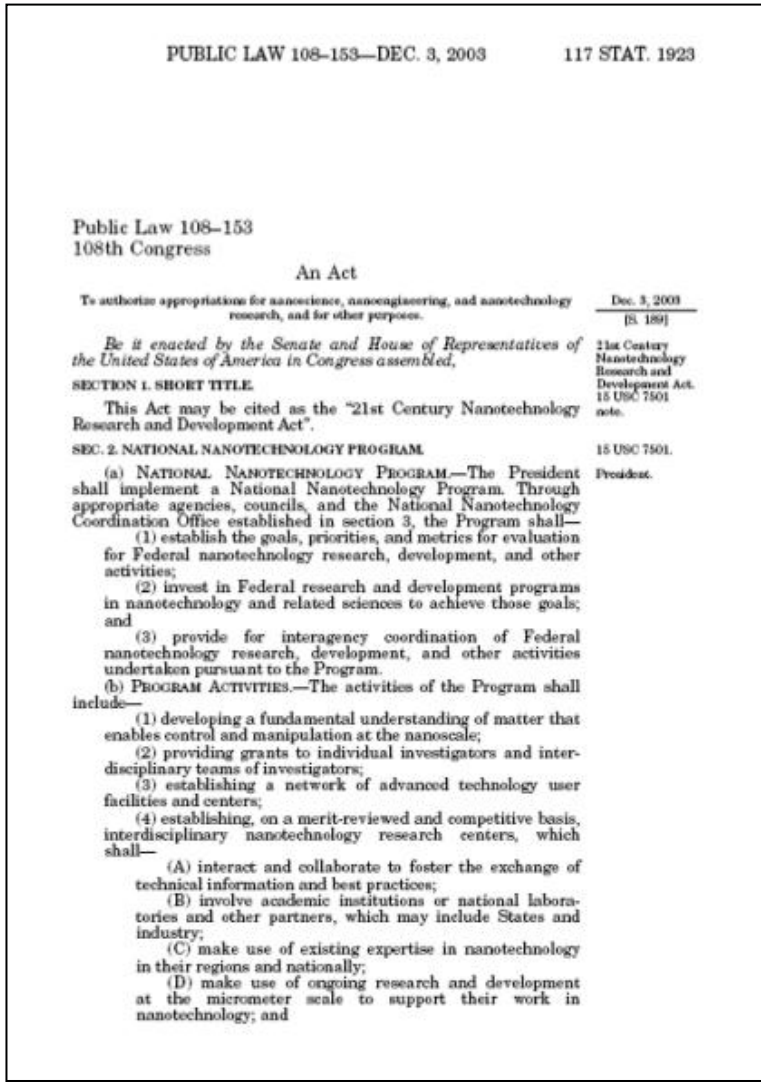


History of Nanoscience has origins at Cornell

- Started in the 1976 when the NSF requested proposals for Nano scale research
- Throughout the 1980's and 1990's this facility grew and prospered
- Bell Labs scientists came up here to use the e-beam machines - our's were not as good
- By 2001 this field had become popular and NNI was formed.

What is the National Nanotechnology Initiative?

- **The NNI is an interagency program that coordinates Federal nanoscale research and development activities (currently 25 agencies)**
- **The NNI began in 2001**
- **Federal NNI funding was over $1.8 billion for FY 2011**



PUBLIC LAW 108–153—DEC. 3, 2003 117 STAT. 1923

Public Law 108–153
108th Congress

An Act

To authorize appropriations for nanoscience, nanoengineering, and nanotechnology research, and for other purposes.

Dec. 3, 2003
[S. 189]

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

21st Century Nanotechnology Research and Development Act. 15 USC 7501 note.

SECTION 1. SHORT TITLE.

This Act may be cited as the "21st Century Nanotechnology Research and Development Act".

SEC. 2. NATIONAL NANOTECHNOLOGY PROGRAM.

15 USC 7501.

President.

(a) NATIONAL NANOTECHNOLOGY PROGRAM.—The President shall implement a National Nanotechnology Program. Through appropriate agencies, councils, and the National Nanotechnology Coordination Office established in section 3, the Program shall—

(1) establish the goals, priorities, and metrics for evaluation for Federal nanotechnology research, development, and other activities;

(2) invest in Federal research and development programs in nanotechnology and related sciences to achieve those goals; and

(3) provide for interagency coordination of Federal nanotechnology research, development, and other activities undertaken pursuant to the Program.

(b) PROGRAM ACTIVITIES.—The activities of the Program shall include—

(1) developing a fundamental understanding of matter that enables control and manipulation at the nanoscale;

(2) providing grants to individual investigators and interdisciplinary teams of investigators;

(3) establishing a network of advanced technology user facilities and centers;

(4) establishing, on a merit-reviewed and competitive basis, interdisciplinary nanotechnology research centers, which shall—

(A) interact and collaborate to foster the exchange of technical information and best practices;

(B) involve academic institutions or national laboratories and other partners, which may include States and industry;

(C) make use of existing expertise in nanotechnology in their regions and nationally;

(D) make use of ongoing research and development at the micrometer scale to support their work in nanotechnology; and

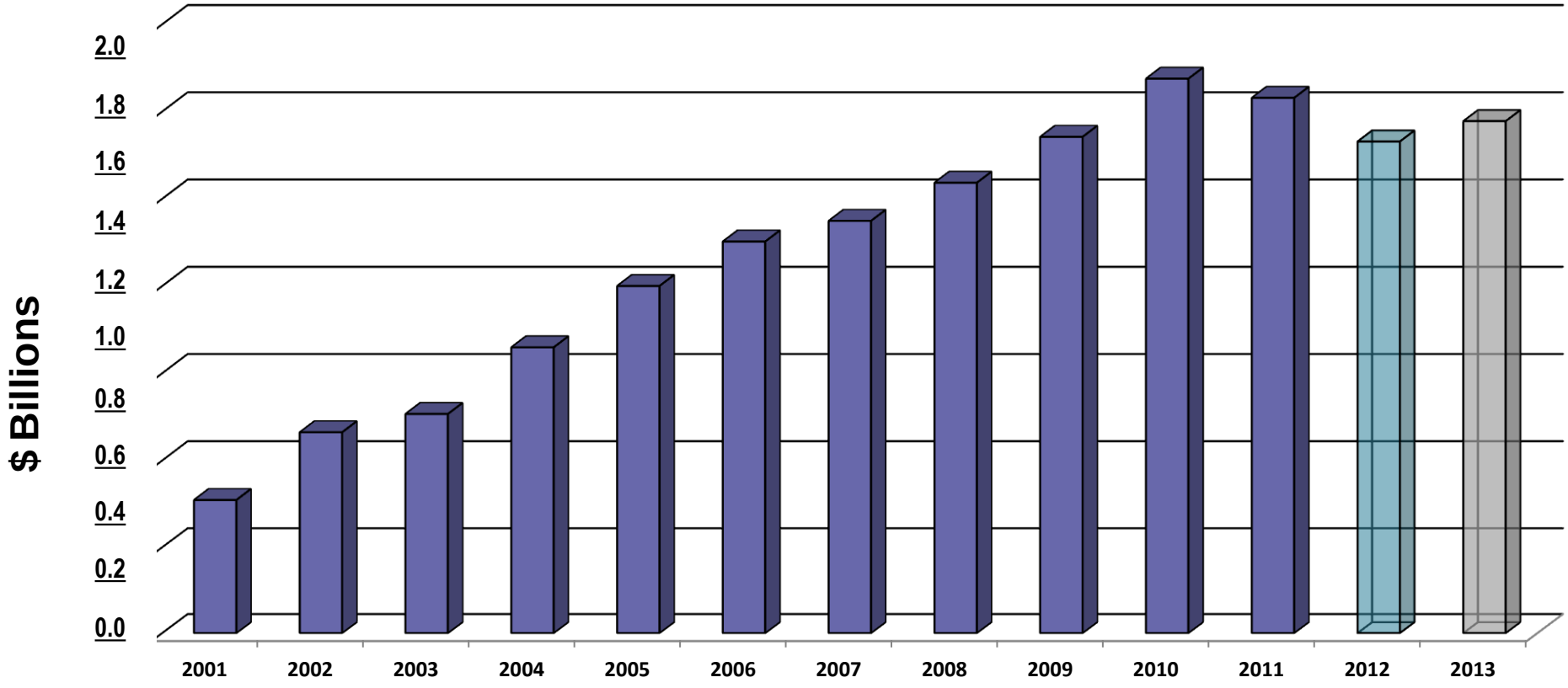
The National Nanotechnology Initiative: Vision and Goals

<u>The vision of the NNI</u>:

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

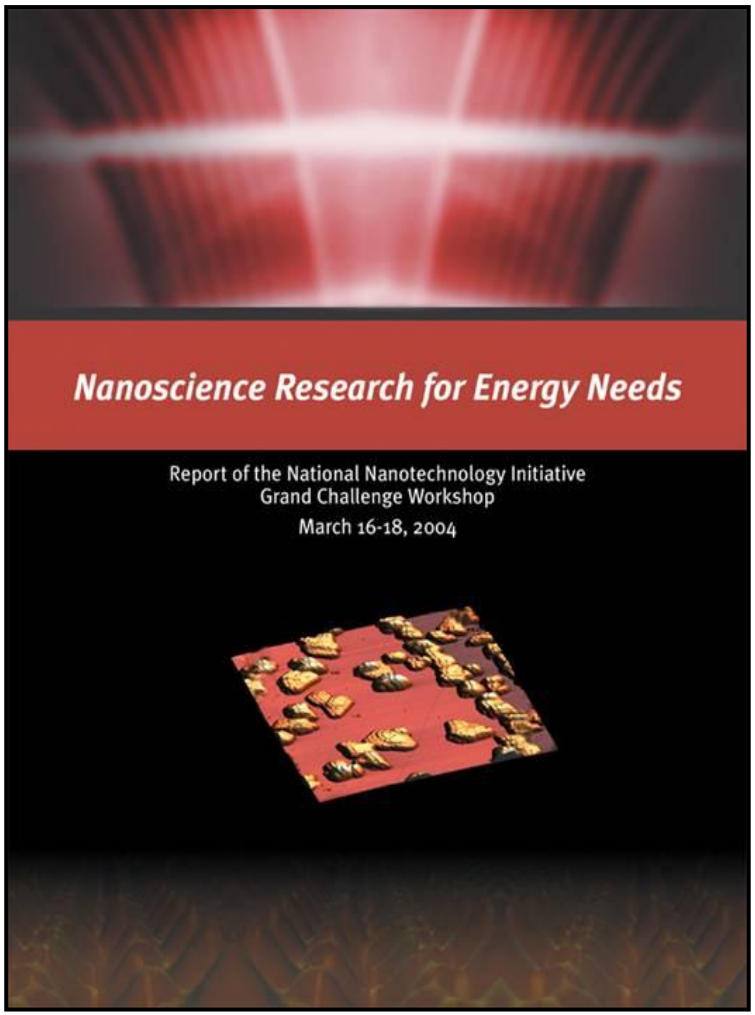
National Nanotechnology Initiative Investments by Year

$464 million (FY '01) to over $1.76 billion (FY '13, proposed)



- All numbers shown above are actual spending, except 2012, which is estimated spending and 2013, which is requested amount for next year.
- FY '09 figure shown here does not include ~$500 million in ARRA funding.
- 2012 estimate and 2013 request do not include DOD earmarks as in previous years.

The National Nanotechnology Initiative and DOE



"At the root of the opportunities provided by nanoscience to enhance our energy security is the fact that all of the elementary steps of energy conversion (e.g., charge transfer, molecular rearrangement, chemical reactions, etc.) take place on the nanoscale."

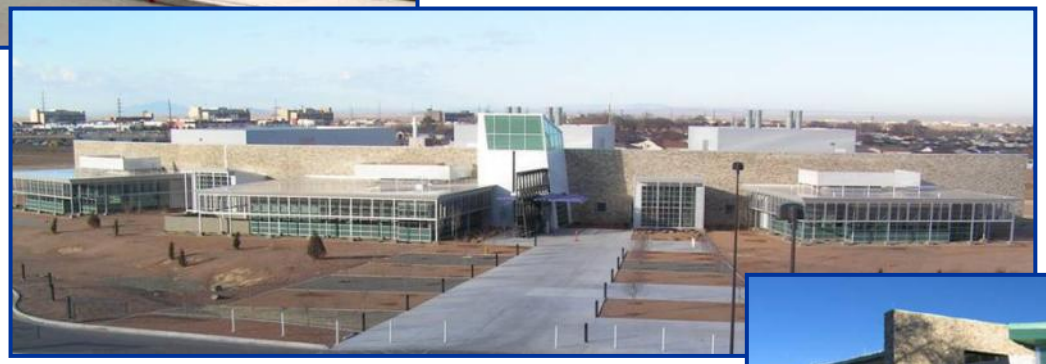
Completed in 2006-2008, the NSRCs have nearly 1800 users per year

Center for Functional Nanomaterials (Brookhaven National Lab)

Molecular Foundry (Lawrence Berkeley National Lab)

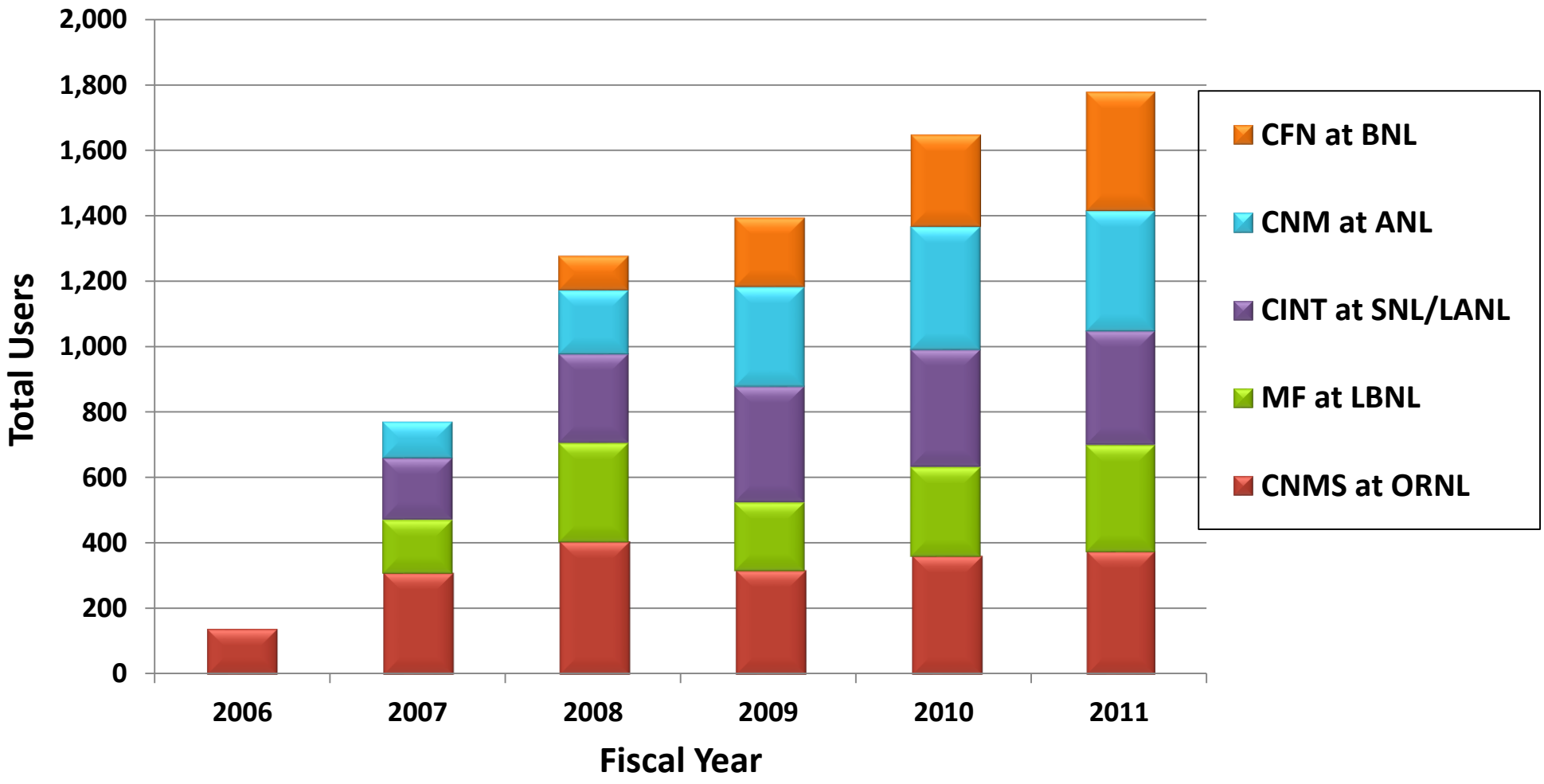
Center for Nanoscale Materials (Argonne National Lab)

Center for Nanophase Materials Sciences (Oak Ridge National Lab)



Center for Integrated Nanotechnologies (Sandia & Los Alamos National Labs)

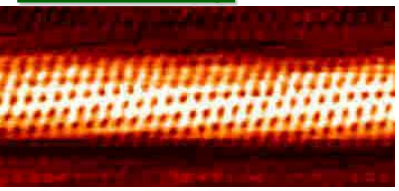
User Numbers at the NSRCs Continue to Increase



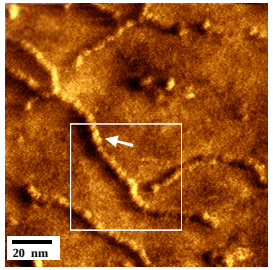
Numbers of unique users, including badged users, remote users, and, starting FY 2007, off-site users. One NSRC was in full-year operation in FY 2006, four in FY 2007, and all five in FY 2008. Over 80% of users in each year have been badged (on-site) users.

Nanoscale Characterization Tools

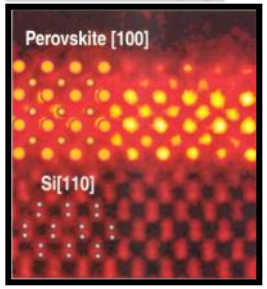
Scanning Tunneling Microscopy



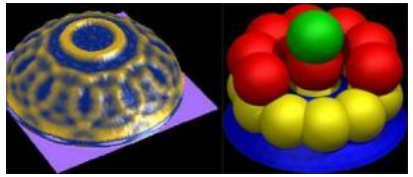
Atomic Force Microscopy



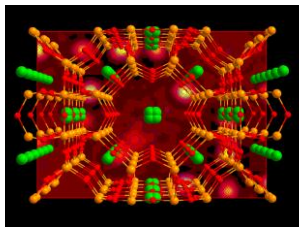
Electron Microscopy



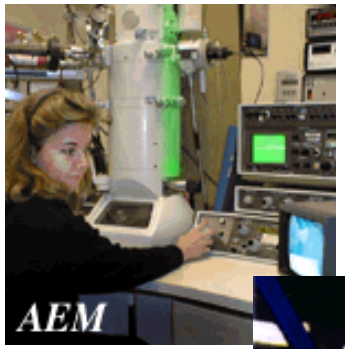
X-ray scattering



Neutron scattering

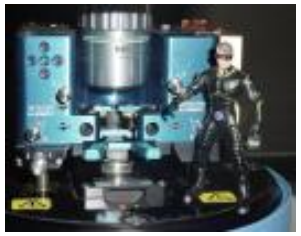


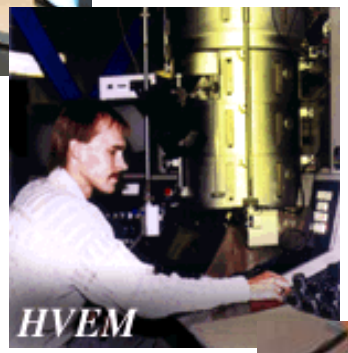
STM



ALS

AFM

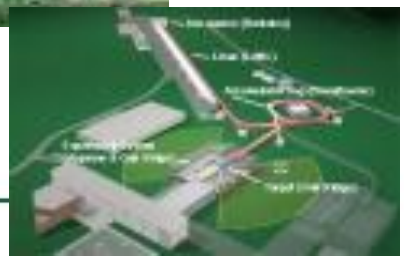




APS

NSLS

XRD



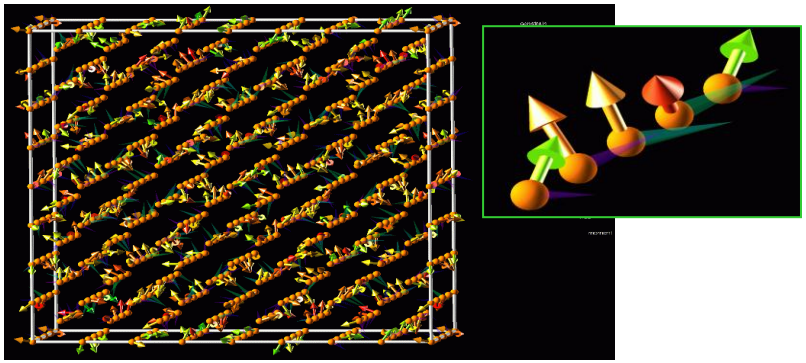
SNS

XPS

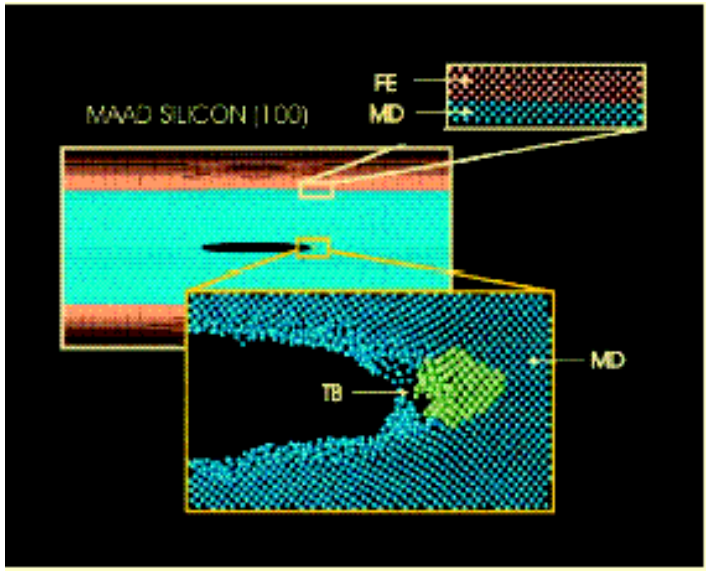
Nanoscale Theory, Modeling, and Simulation

Significant Recent Progress in Theory and Modeling:

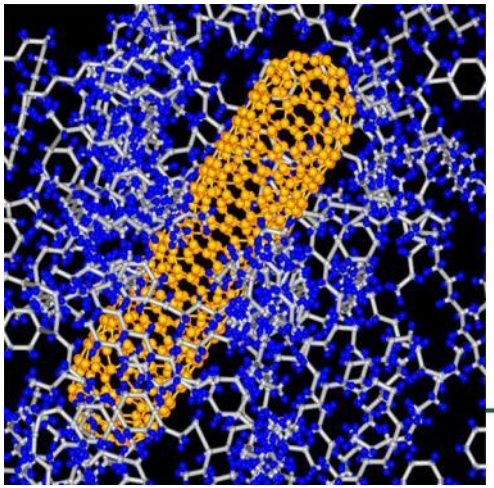
- Density Functional Theory, ab initio Molecular dynamics, Quantum Monte Carlo, Dynamic Mean Field Theory
- New leadership-class scientific computing facilities



A first-principles method describing the dynamics of magnetic moments in materials

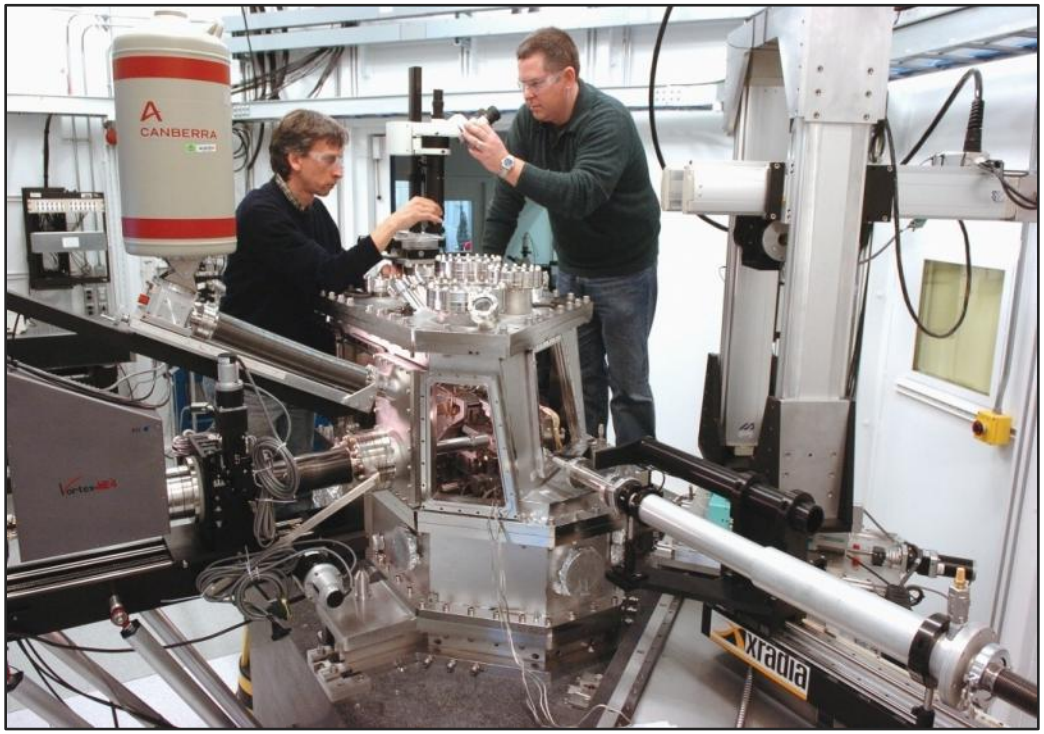


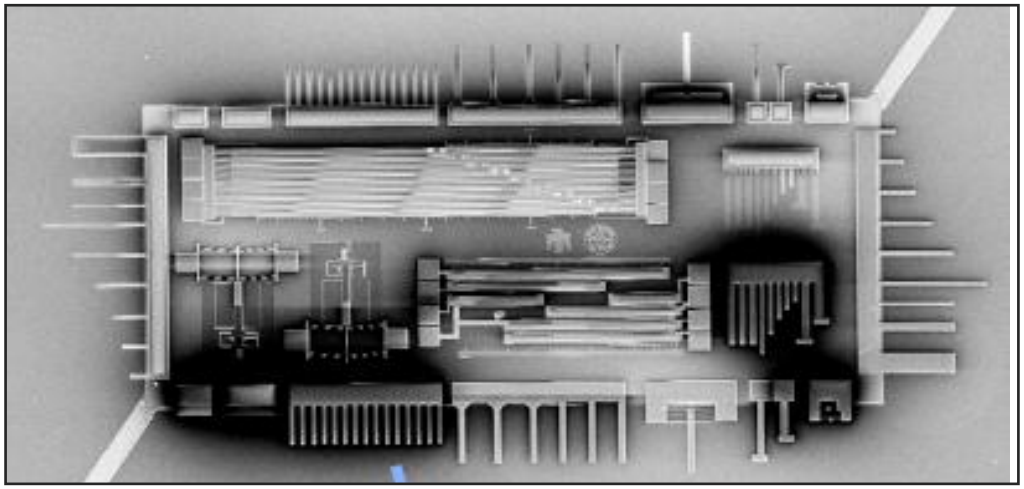
Multiple length scale simulations of crack propagation in silicon



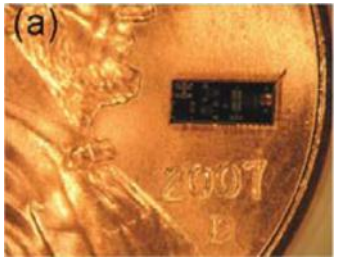
MD simulation of interactions of carbon nanotubes with organic molecules

NSRCs Create New Tools and Capabilities – Big and Small





Cantilever Array Discovery Platform: The size of an AFM chip, the CADP has multiple cantilevers projecteng from all edges for nanomechanics, novel scanning probe technologies, chem and bio sensing, magnetization studies, and studies of the physics of coupled systems.



X-Ray Beamline with Nanoscale Resolution at the Advanced Photon Source

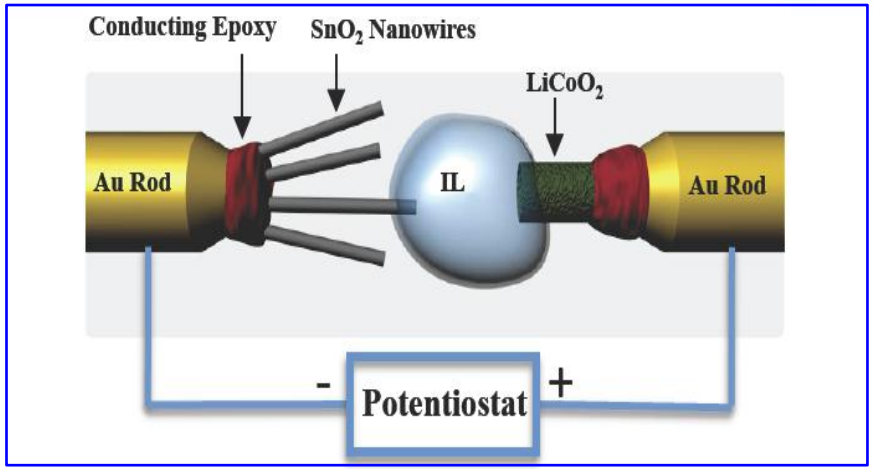
- Unique instruments to study individual nanostructures
- Quantitative structure, strain, orientation imaging
- Sensitive trace element and chemical state analysis

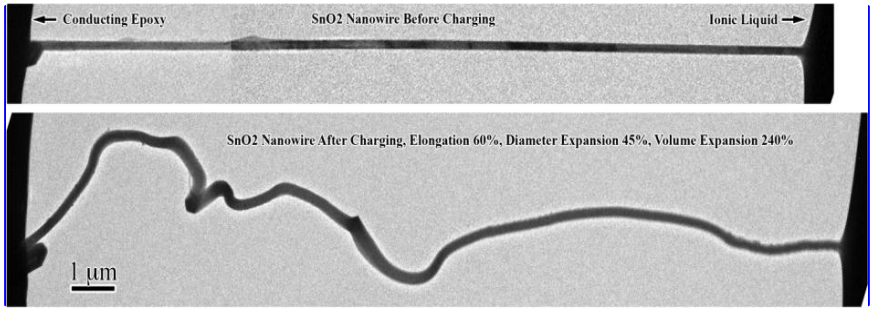
"Discovery Platforms": modular micro-labs for nanoscience

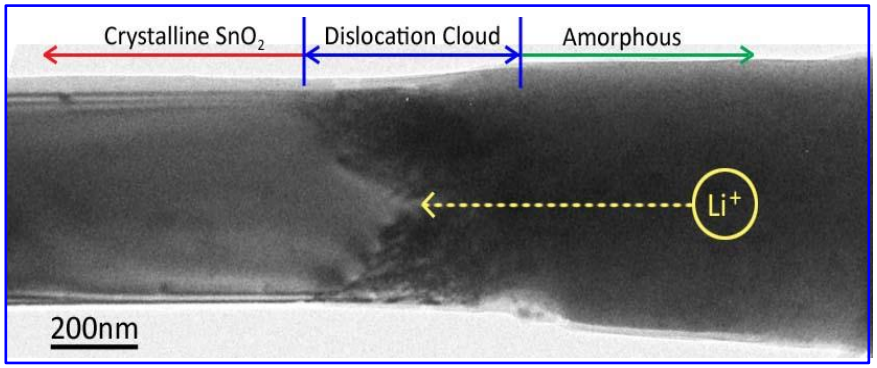
- Standardized and batch fabricated
- Access to a range of diagnostic and characterization tools

EFRC Research Reveals Unusual Nanowire Behavior in Battery

- World's smallest battery placed inside an electron microscope yields images of electrochemistry at atomic scales
- New insight into electrochemical processes at the nanoscale:
  - Nanowires can sustain large stresses (>10 GPa) caused by Li^+ transport without breaking—good candidate for battery
  - Elongation and twisting of nanowires during charging may lead to a short circuit and failure of the battery, a key factor to consider during design







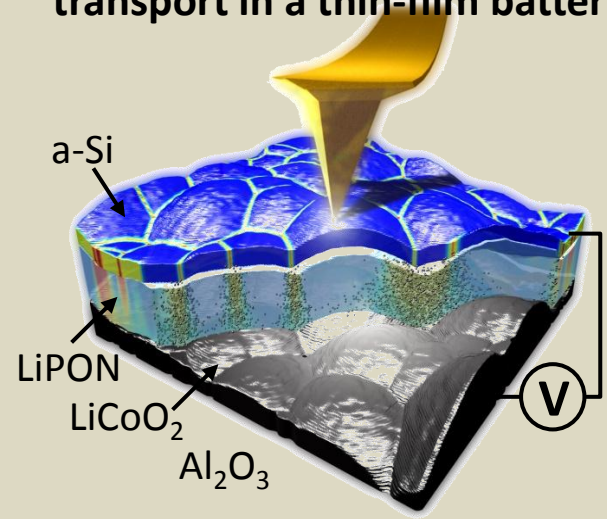
Jian Yu Huang, et al., **Science 330, 1515 (2010)**

Research at SNL supported by the *Center for Science of Precision Multifunctional Nanostructures for Electrical Energy Storage* (an EFRC led by University of Maryland) and in collaboration with PNNL and university contributors

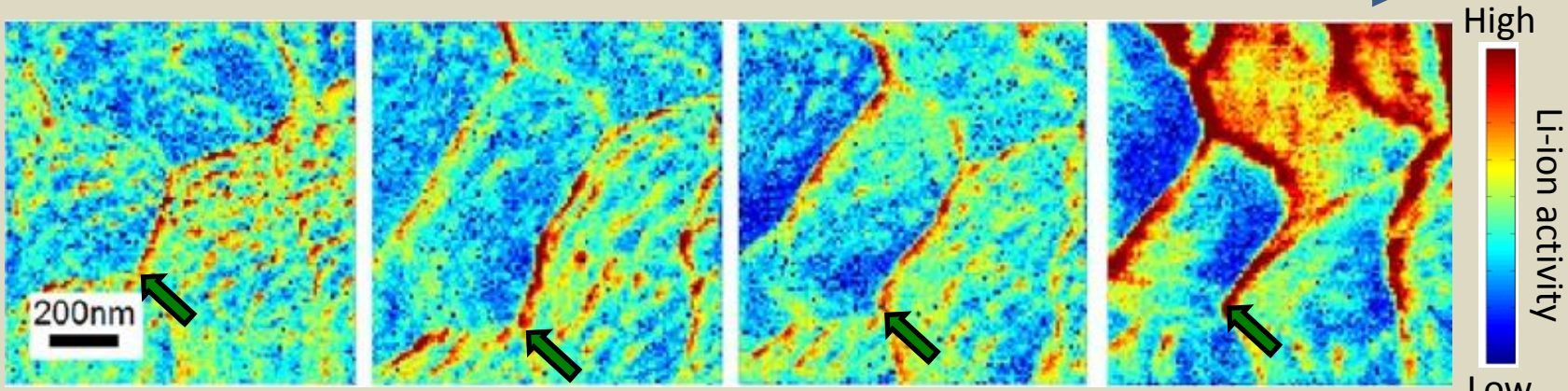
EFRC Research Demonstrates Real Space Mapping of Lithium-Ion Transport in Anodes with Nanometer Resolution

- Understanding ionic flow on a local scale is key to improving battery technologies
- Atomic force microscopy detects local volume changes in heterostructures due to ionic flow induced by tip biasing
  - Probes lithium-ion transport by high frequency biasing
- Lithium-ion flow is correlated with the structure of electrodes and interfaces
- Performed by Fluid Interface Reactions, Structures and Transport (FIRST) EFRC led by Oak Ridge National Laboratory

Atomic Force Microscopy characterizes the local lithium-ion transport in a thin-film battery



Change in Li-ion kinetics in the Si anode with increasing charging state



N. Balke et al, ***Nano Letters*** *10, 3420-3425 (2010).*

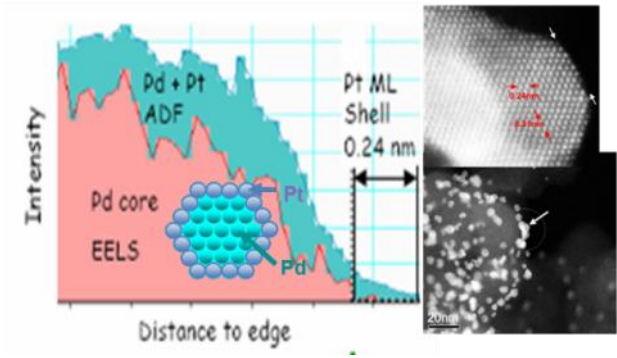
The a-Si anode surface roughness induces localized Li-ion transport which is enhanced with increasing battery charging.

Fortune 500 Users of BES Scientific Facilities

BOEING
United Technologies
GE
MONSANTO
NORTHROP GRUMMAN
HALLIBURTON
SAIC
P&G
DOW
Honeywell
Chevron
ExxonMobil
DUPONT
3M
Sun Data Center Efficiency Resource Kit SOFTWARE. HARDWARE. COMPLETE.
Ford
GM
JOHN DEERE
CAT
Rockwell Collins
Building trust every day
WD Western Digital
Kodak
MOTOROLA
intel
Boston Scientific
Defining tomorrow, today.
MERCK
ITT
TEXAS INSTRUMENTS
Abbott
A Promise for Life
Medtronic
Pfizer
IBM
hp
Bristol-Myers Squibb
Johnson & Johnson
AMGEN
Lilly

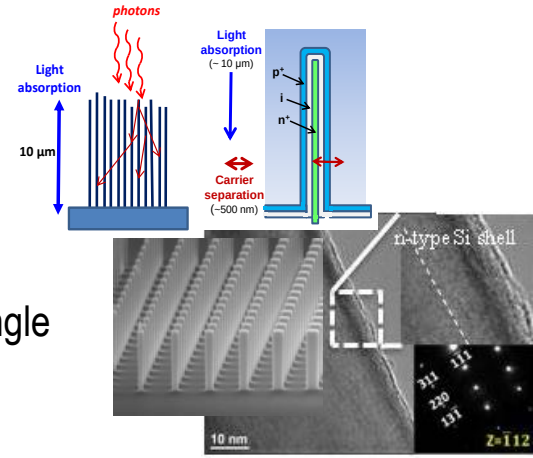
Highlights of NSRC Industry User Projects

Core-shell Pd/Pt Nanocatalysts for Fuel-Cells (BNL, CFN,U. Delaware, Toyota Motor Corp., ORNL, Hitachi CRADA funded by GM, Toyota, UTC and Battelle)



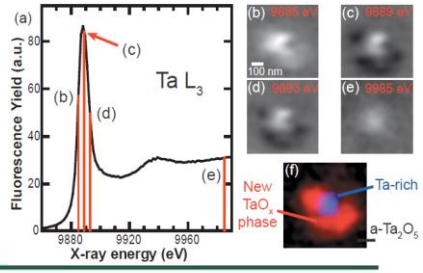
- Significantly better performance than conventional Pt catalysts with practical scaleable synthesis
- High-resolution aberration-corrected transmission electron microscopy at CFN revealed atom-scale nanocatalyst structure and chemical composition

Si Solar Cells with Single Crystal Efficiency at Thin Film Cost (Sharp Labs of America, CINT DOE Energy Efficiency & Renewable Energy Project)



- Radial p-i-n nanowires decouple absorption and carrier collection for solar energy harvesting
- Nanoscale epitaxy and fabrication at CINT provided insights into low temperature radial epitaxial single crystal growth and fabrication of large area arrays

X-ray Nanoprobe Observing the Nanoscale Origins of Memory Resistive Switching (HP, CNM)



- High resolution x-ray fluorescence microscopy identified nanoscale metallic channel regions formed during memristive switching in a TaO metal/oxide/metal device structure

Varying the approaches to funding scientific Research

- Individual research group grants of conventional type
- Energy Frontier Research Centers typically focused on specific application
- Hubs- focused on major issue in energy

Energy Frontier Research Centers
Grand Challenge and Use-Inspired Research

46 EFRCs in 35 states were launched in Fall 2009

- Science crosscuts energy-use-inspired and grand challenge research
- **~850** senior investigators and **~2,000** students, postdoctoral fellows, and technical staff at **~115** institutions
- **>250** scientific advisory board members from **13** countries and **>40** companies

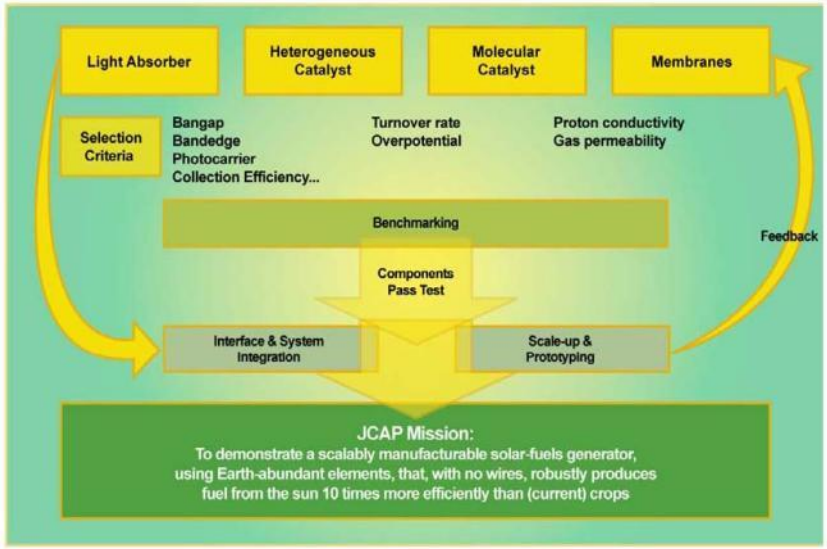
Impact to date (~2.5 years):

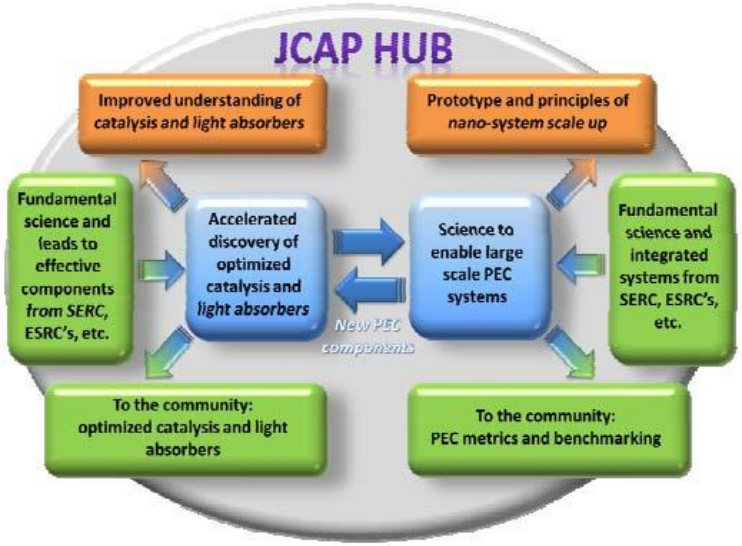
- **>2,400** peer-reviewed papers including more than **60** publications in *Science* and *Nature*.
- **> 125** patents applications, nearly **55** additional patent/invention disclosures, and **22** licenses
- **>30** companies have benefitted from EFRC research results

- Solar Energy
- Combustion
- Bio-Fuels
- Catalysis
- Energy Storage
- Solid State Lighting
- Geosciences for Energy Applications
- Superconductivity
- Advanced Nuclear Energy Systems
- Materials Under Extreme Environment
- Hydrogen

Nanoscience is a central theme in many of the EFRCs.

Fuels from Sunlight Hub:
Joint Center for Artificial Photosynthesis (JCAP)





JCAP Mission: To demonstrate a scalable, manufacturable solar-fuels generator using Earth-abundant elements, that, with no wires, robustly produces fuel from the sun ten times more efficiently than (current) crops.

JCAP R&D will focus on:

- Robustness of components
- Accelerating the rate of catalyst discovery for solar fuel reactions
- Discovering earth-abundant, robust, inorganic light absorbers with optimal band gap
- System integration, benchmarking, and scale-up

JCAP's role as a solar fuels Hub:

- Incorporating the latest discoveries from the community (EFRCs, single-PI or small-group research)
- Providing metrics and benchmarking to the community

JCAP JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS

Nanoscience is a major theme in JCAP.

Other hubs or hub like structures

Existing:

- **Biofuel Centers – (Science)**
  - Joint BioEnergy Institute
  - BioEnergy Science Center
  - Great Lakes Bioenergy Research Center
- **Energy Efficient Buildings Hub (EERE)**
- **Consortium for Advanced Simulation of Light Water Reactors (Nuclear Energy)**

Coming soon:

- **Battery Hub (Science, EERE and ARPA-E)**
- **Critical Materials Hub (EERE, Science ARPA-E)**

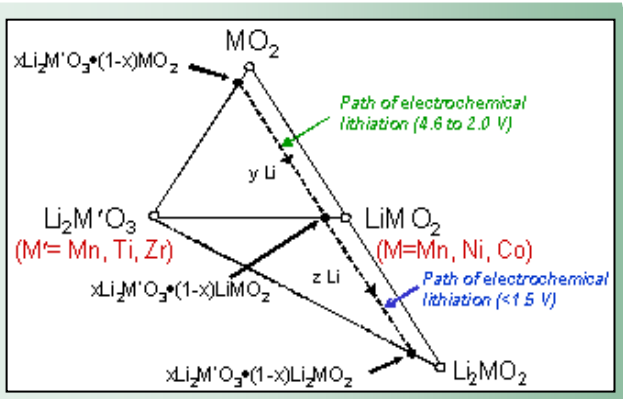
U.S. DEPARTMENT OF ENERGY

Congratulations on 35 years of great success

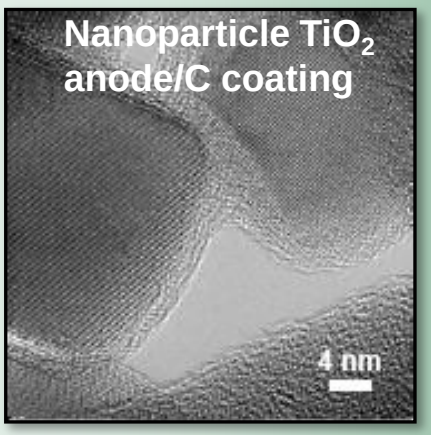
From the Director of the Office of Science and
all my colleagues

From Nano Science to Commercialization: High-Energy Lithium Batteries

Basic Science



Discovered new composite structures for stable, high-capacity cathodes

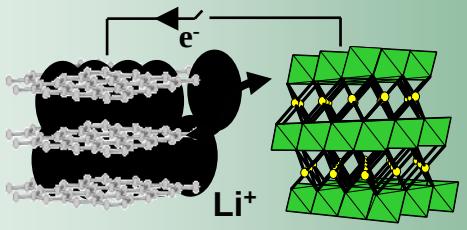


EFRC research

Tailored electrode-electrolyte interface using nanotechnology

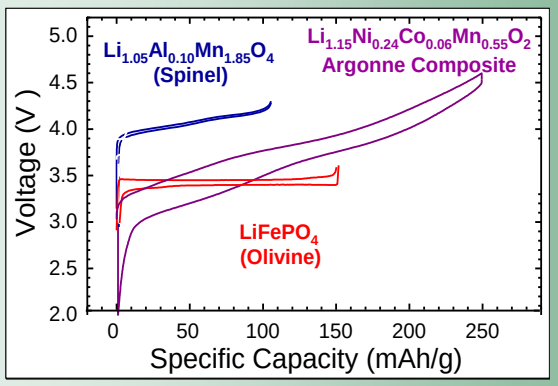
Applied R&D

Li_xC_6 (Anode) $xLi_2MnO_3•(1-x)LiMO_2$ (Cathode)



Created high energy Li-ion cells…

…with double cathode capacity, enhanced stability



Manufacturing/ Commercialization

ENVIA SYSTEMS

BASF The Chemical Company

TODA KOGYO CORP.

LG Chem

GM

VOLT

Licenses to materials and cell manufacturers and automobile companies

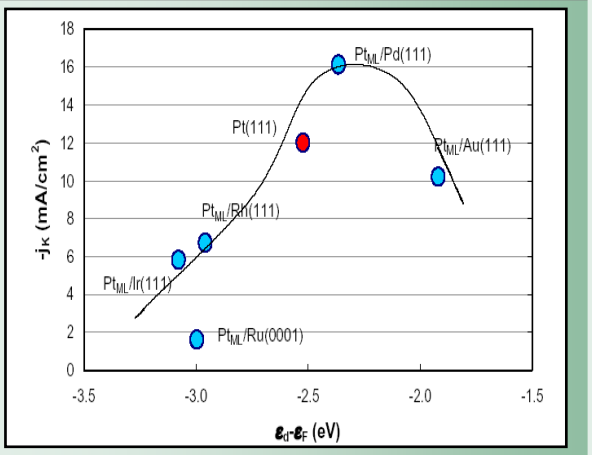
Platinum Monolayer Electro-Catalysts:
Stationary and Automotive Fuel Cells

Basic Science

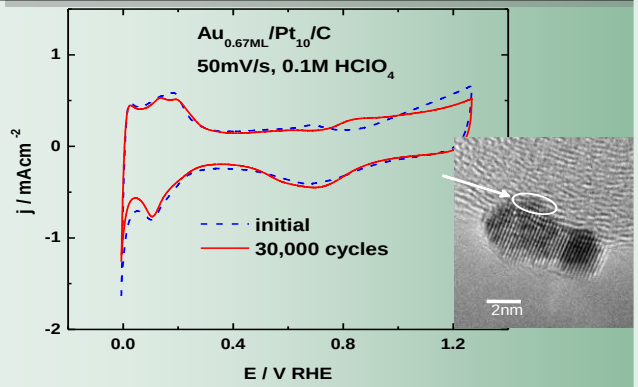
BES

Two research advances

Pt core-shell nano-catalysts: high activity with ultralow Pt mass



Pt stabilized against corrosion in voltage cycling by Au clusters



Science **315**, 220 (2007)

Applied R&D

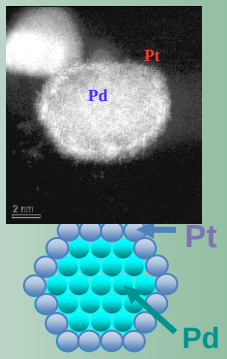
BES → EERE

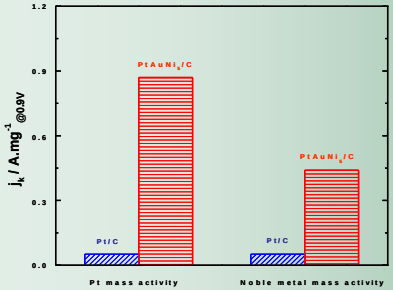
Core-Shell Nanocatalysts

Active Pt ML shell – Metal/alloy core

Core tunes activity & durability of shell

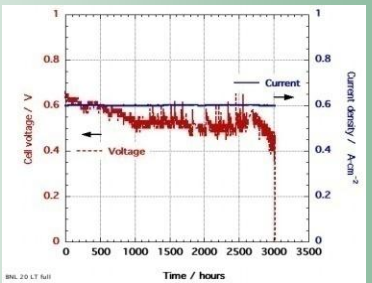
Model and actual image of a Pt Monolayer on Pd nanoparticle





Pt-mass weighted activity enhanced 20x

3000 hr Fuel Cell Durability Performance

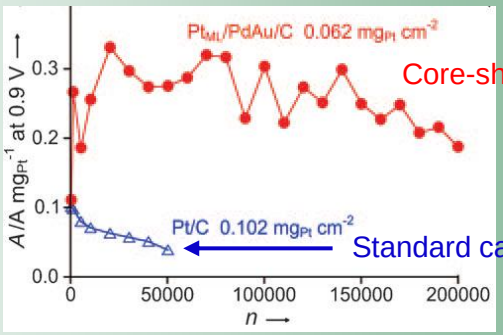


Manufacturing/ Commercialization

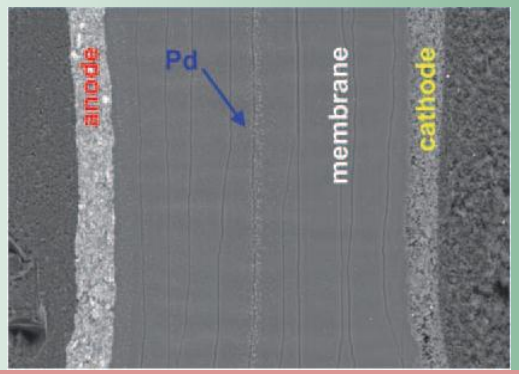
CRADA with Industry

Scale-up synthesis: **Pt-ML/Pd_9Au_1/C**

Excellent fuel Cell durability 200,000 cycles



Membrane Electrode Assembly >200K cycles
Very small Pt diffusion & small Pd diffusion

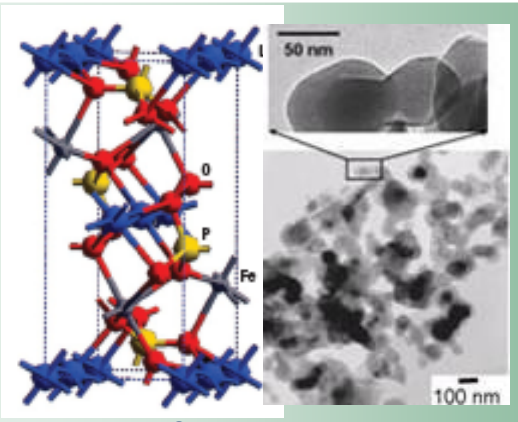


Angewandte Chemie ***49***, *8602 (2010)*

Fuel Cell Catalyst readied for automotive application

High Impact Basic Research: Nanotechnology Approach Leads to Commercial Batteries

Basic Science



$LiFePO_4$ structural model and nanostructure

- Research at MIT over a decade ago led to the discovery that drastically refining the structure of ceramics enhanced their conductivity (DOE Office of Science)
- Minor chemical additions to the fine-grained $LiFePO_4$ further increased the conductivity by eight orders of magnitude

Applied R&D

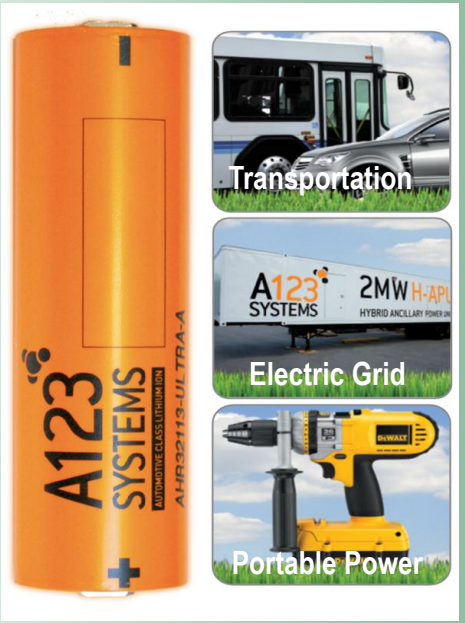
Formation of A123 Start-up

DOE Small Business Innovation Research (SBIR)

Enabled development of an A123 lithium-ion battery that

- Improved battery life by up to 10 times compared to other Li batteries
- Has more than twice the power density of high power NiCd and NiMH batteries
- Operates over a wide temperature range, from -30 to >60°C
- Charges to more than 90% capacity within 5 minutes

Manufacturing/ Commercialization

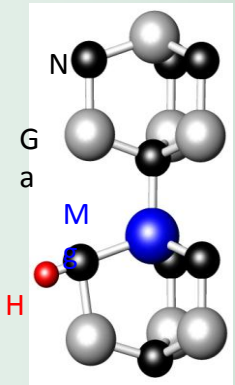


Today - A123Systems' batteries have reached the commercial marketplace in power tools, hybrid and plug-in hybrid electric vehicles, and grid applications. A recent DOE-Vehicle Technologies grant paved the way for what is now the largest lithium ion automotive battery plant in North America.

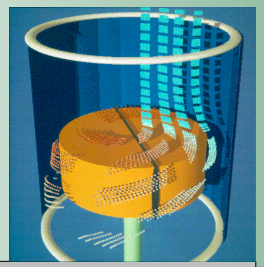
Solid-State Lighting Goal: reduce 22% of nation's total electrical energy usage in half

Basic Science

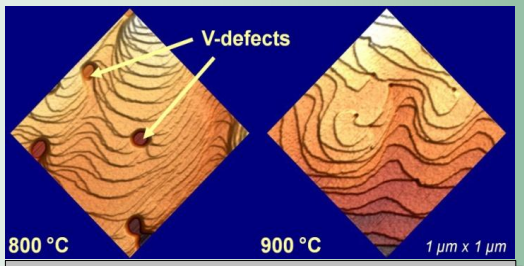
Wide Bandgap Semiconductors Heteroepitaxial systems



Theory and modeling of defect energies



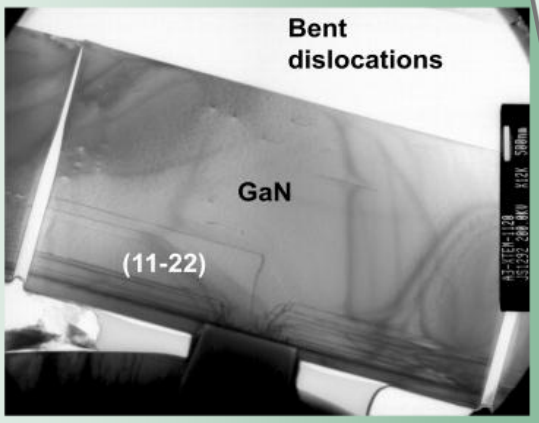
Synthesis : Chemical Vapor Deposition Modeling



Fundamental understanding helps eliminate Defects

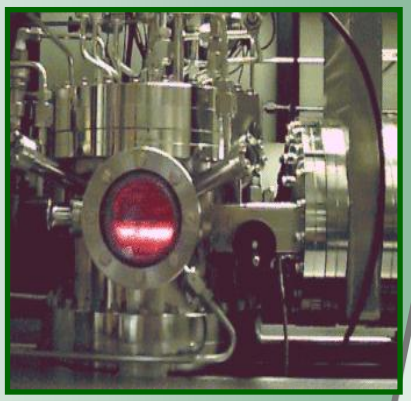
Applied R&D

Sandia Labs & Lumiled Collaboration: Cantilever Epitaxy reduces dislocation densities 100X (R&D 100 Award)



Sapphire post

Essential Tool Development

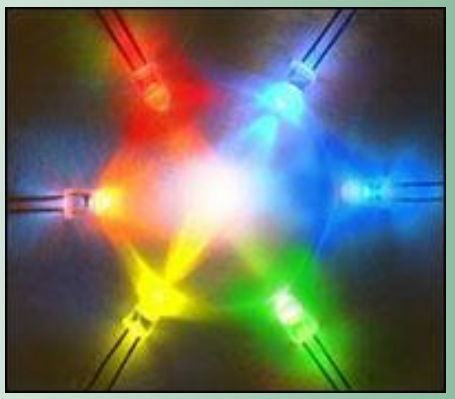


Emcore Discovery 125 system

Manufacturing/ Commercialization

Key Enabler for Manufacturing

- **Lumileds (originally with HP)**
- **General Electric**
- **Cabot Superior Micropowders**
- **Dow Corning**
- **Veeco**
- **Emcore**
- **Cree**
- **Bridgelux (under discussion)**



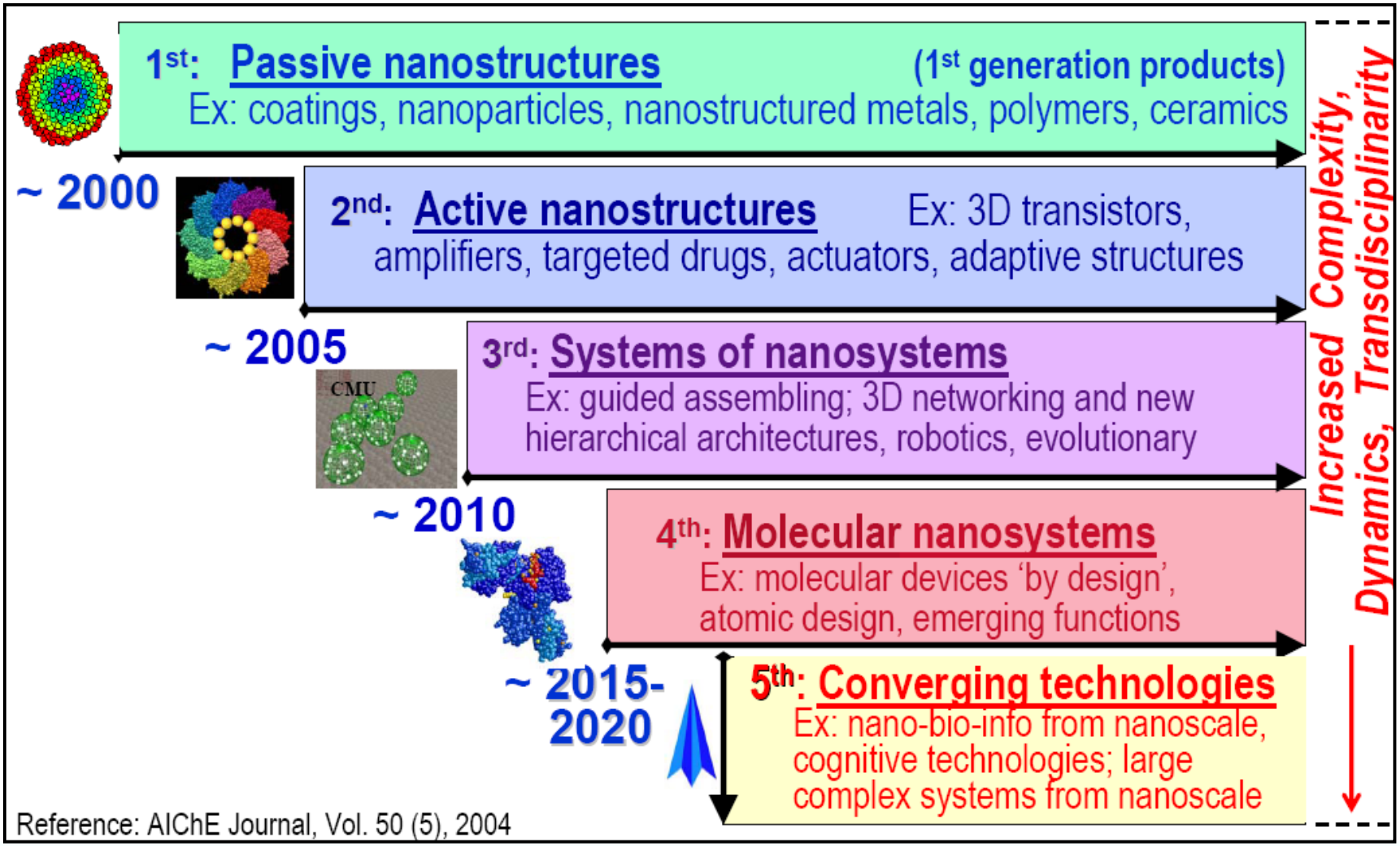
Sandia Labs & RPI demonstrates an 18% increase in light output efficiency by modifying heteroepitaxial interface

Future directions in nanoscale science and technology?

- Areas of increasing activity and emphasis:
  - ESH, Public engagement, Standards
  - International cooperation
  - Technology transfer, commercialization, and economic impact
- Evolving techniques for 3-D and 4-D characterization of nanostructures
  - Assessment of functionality and dynamic behavior
- Increasing emphasis on nanoscale systems
  - Control and designed behavior
  - 3-D synthesis and fabrication of systems
  - Predictive design

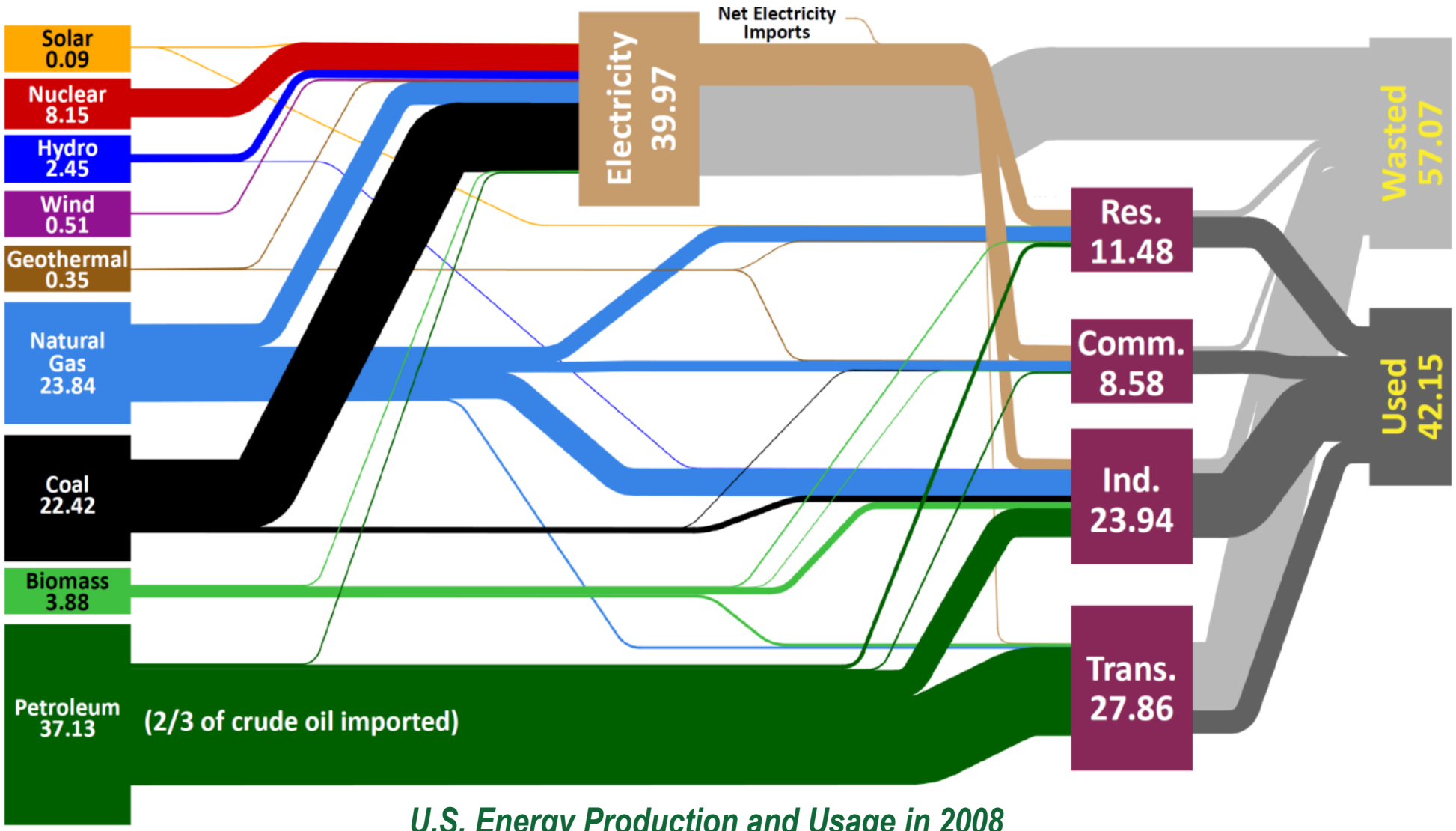
Where are we going?
Greater complexity and sophistication

One has to be careful not to oversimplify, and activities across this spectrum have been part of the initiative from the beginning and will continue to be, but as fundamentals become better understood there is a natural shift in the type of work that is undertaken and supported:



Credit: Mike Roco, NSF

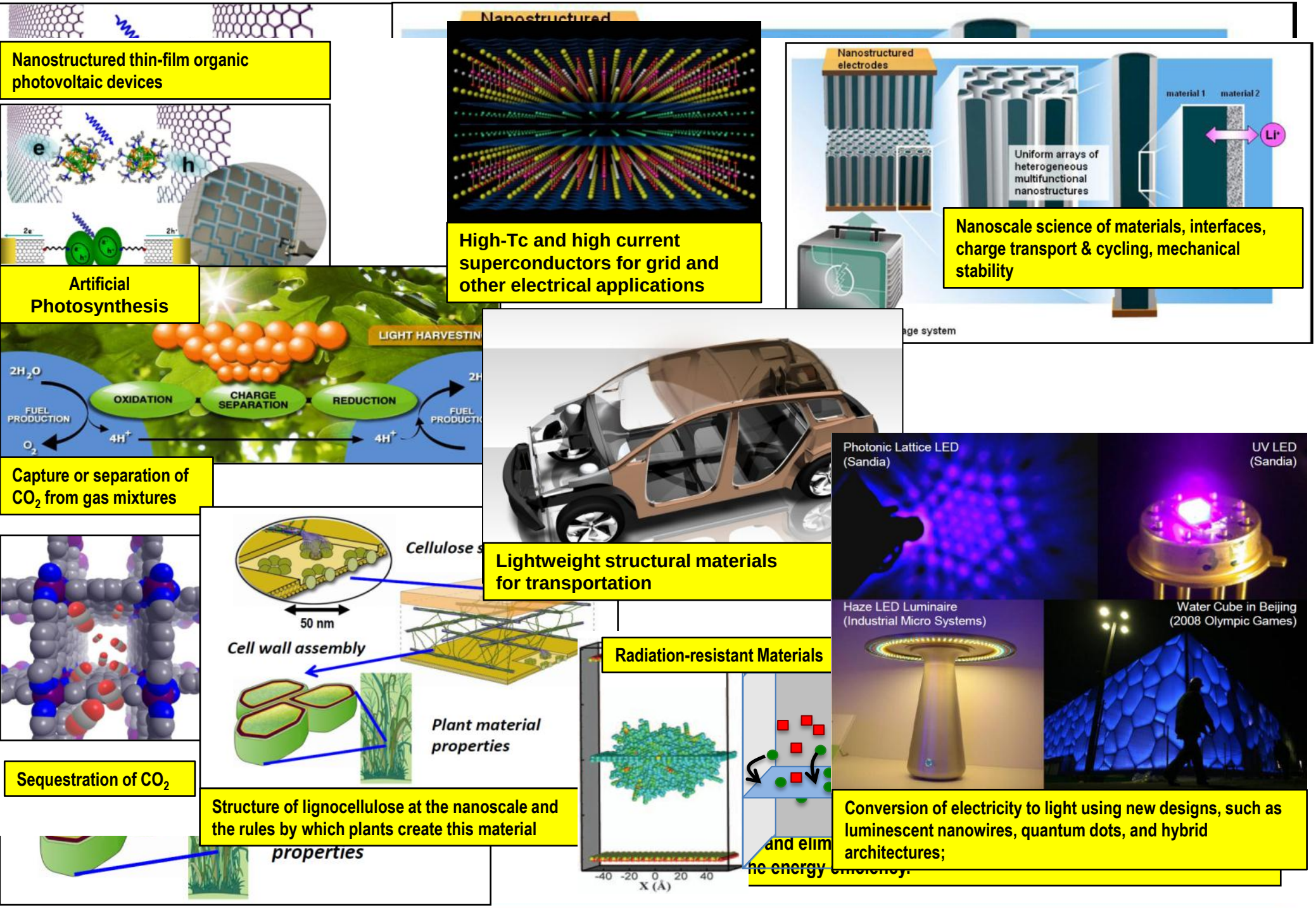
Path Forward:
A Nano Research Agenda for a New Energy Economy



U.S. Energy Production and Usage in 2008

Units in Quadrillion BTUs (Quads)

Source: Lawrence Livermore National Laboratory and the Department of Energy, Energy Information Administration, 2009 (based on data from DOE/EIA-0384(2008), June 2009).

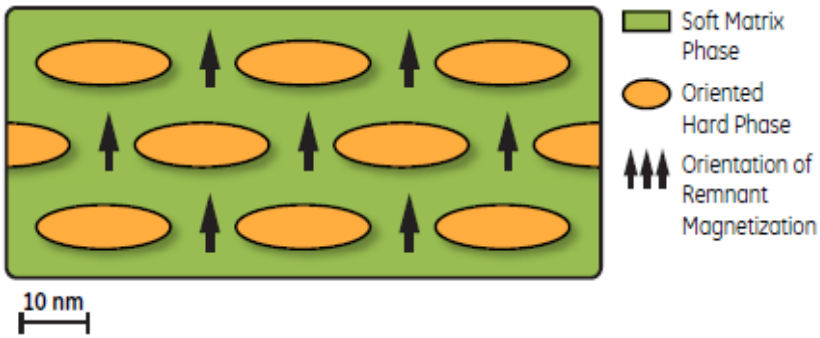

Nanostructured thin-film organic photovoltaic devices
e
h
Artificial Photosynthesis
LIGHT HARVESTIN
2H2O
OXIDATION
CHARGE SEPARATION
REDUCTION
FUEL PRODUCTION
O2
4H+
Capture or separation of CO2 from gas mixtures
Sequestration of CO2
Cellulose s
50 nm
Cell wall assembly
Plant material properties
Structure of lignocellulose at the nanoscale and the rules by which plants create this material
High-Tc and high current superconductors for grid and other electrical applications
Nanostructured electrodes
material 1
material 2
Li+
Uniform arrays of heterogeneous multifunctional nanostructures
Nanoscale science of materials, interfaces, charge transport & cycling, mechanical stability
Lightweight structural materials for transportation
Radiation-resistant Materials
-40 -20 0 20 40
X (Å)
Photonic Lattice LED (Sandia)
UV LED (Sandia)
Haze LED Luminaire (Industrial Micro Systems)
Water Cube in Beijing (2008 Olympic Games)
Conversion of electricity to light using new designs, such as luminescent nanowires, quantum dots, and hybrid architectures;

EERE: Nanoparticle Silicon Inks (Innovalight)

- Developed a printing process that reduces manufacturing costs & complexity to produce high-efficiency solar cells
- Recognized by *R&D Magazine* as one of the top 100 innovations for 2011
- Demonstrated a 1% absolute increase in cell efficiency to 18.5% on monocrystalline
- Company bought by DuPont

ARPA-E: Transformational Nanostructured Permanent Magnets (General Electric)

imagination at work



Core/Shell Hard/Soft Exchange Coupled Nanocomposite Magnets with:

- 80 MGOe (vs 59 MGOe NdFeB)
- 59 MGOe with 80% less rare earth

Nanocomposite phases:

NdFeB: (Hard)

H_c = 10,000 - 12,000 Oe

B_r = 11-15 kG

Fe: (Soft)

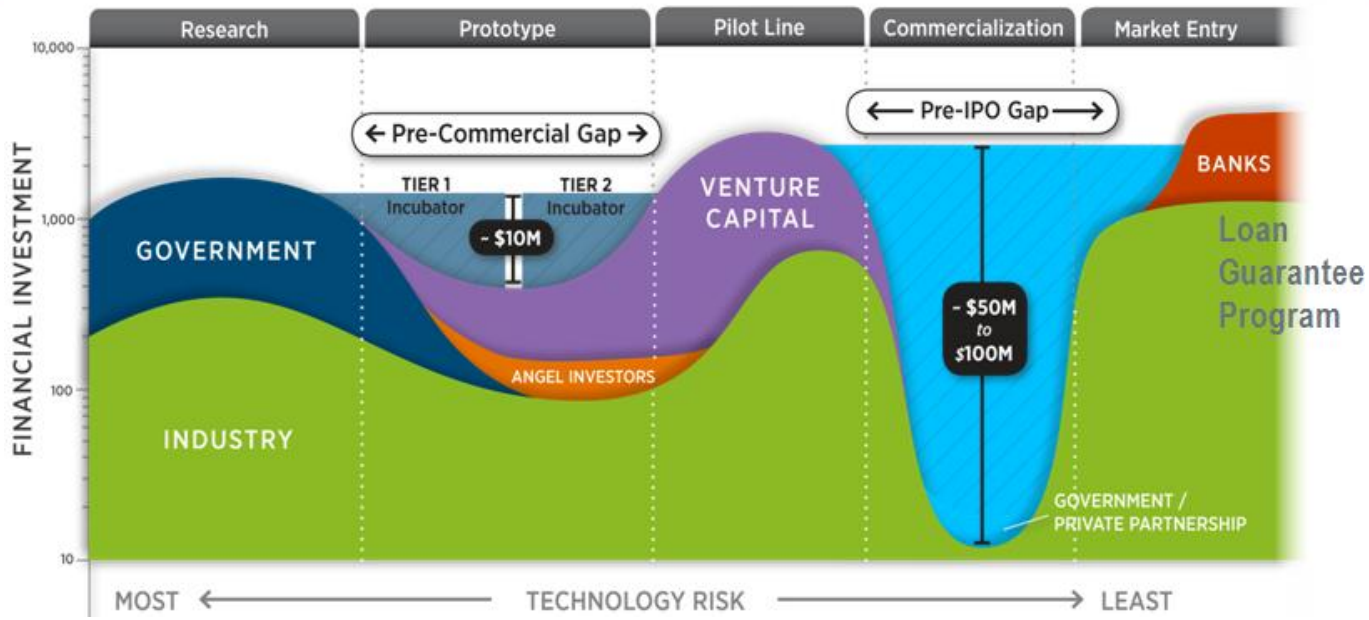
H_c = 0.05 Oe

B_r = ~22 kG

Nanocomposite exchange coupled permanent magnets with high energy product and less rare earths

EERE SunShot Incubator –

Example of technology commercialization



- **Typical metrics of success such as # Publications, # Patents not sufficient**
  - **Instead: Dollars of federal investment leveraged, # of jobs created, economic value of output**
- **SunShot Incubator Program run out of DOE's Solar Program**
  - **Foster innovation and growth in the domestic solar industry**
- **Help domestic start-up companies transition to early pilot production**
  - **Leverage National Lab device expertise and R&D resources**
- **History of success**
  - **~$60M in Federal funds since 2007 into 29 startups**
  - **Incubator funding helped leverage $1.3B in private sector funds**
  - **Awardees have created over1300 jobs in aggregate**