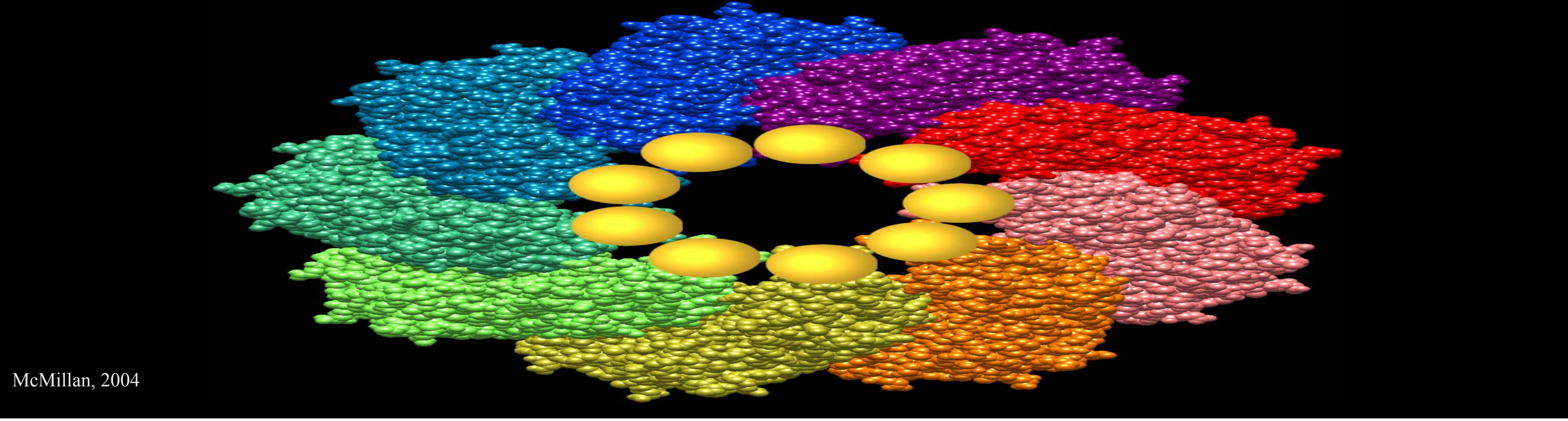


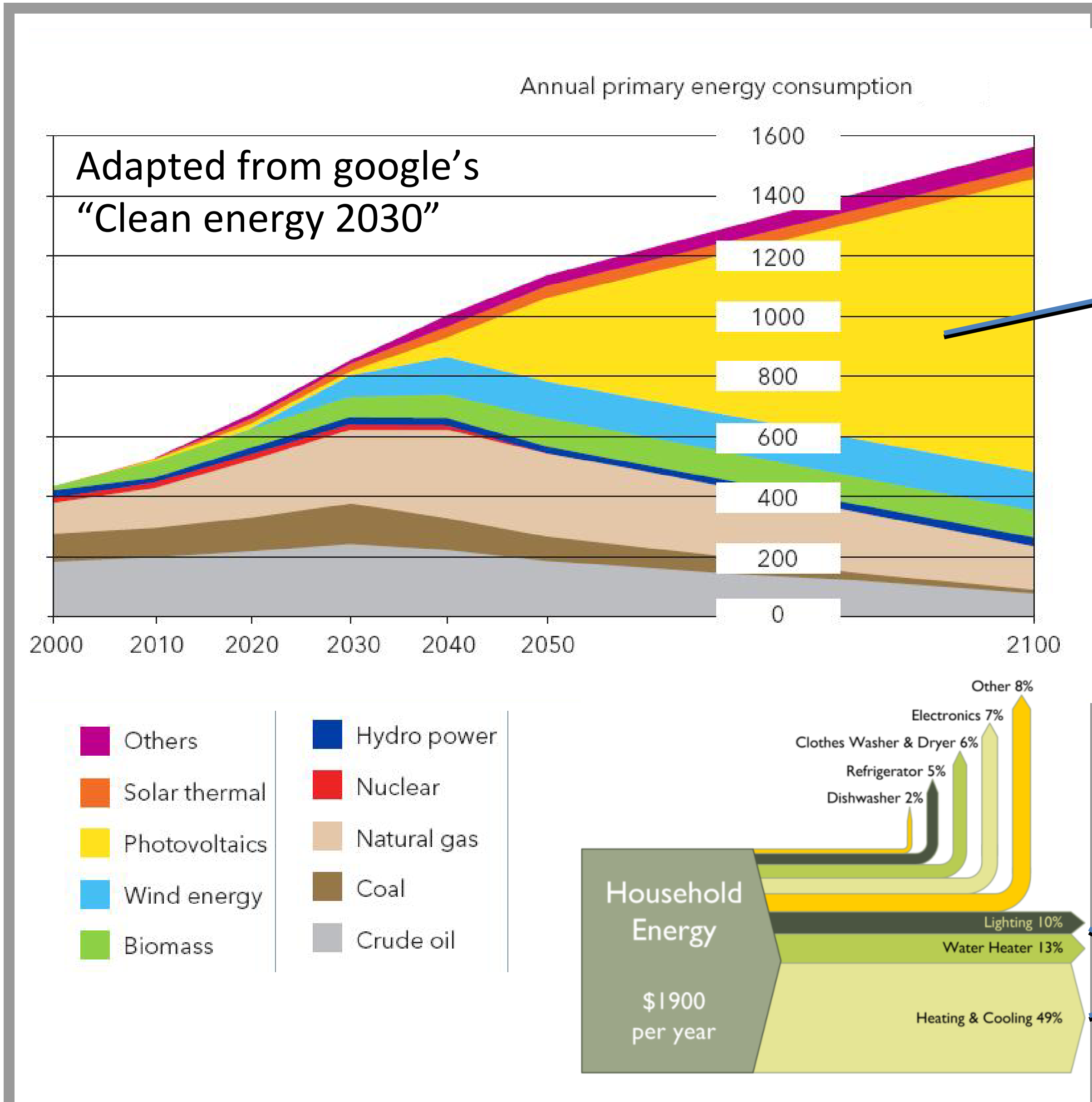
NANOTECHNOLOGY
FOR ENERGY CONVERSION, STORAGE AND INCREASED EFFICIENCY

Mihail C. Roco
National Science Foundation and
National Nanotechnology Initiative

Seoul, Korea, April 6, 2010

The impact of nanotechnology on our energy landscape | CJ Brinker David Ginger

The size of the energy challenge is enormous—we need to look for solutions that have impact on the TW scale



Energy production
Advanced Photovoltaics
Artificial photosynthesis
H_2O splitting via sunlight
Biofuels

Energy and storage
CO_2 as a feedstock
Hydrogen storage
- Carbon nanotubes
- Metal Organic Frameworks

Ultracapacitors and CNTs
Batteries
Thermoelectrics

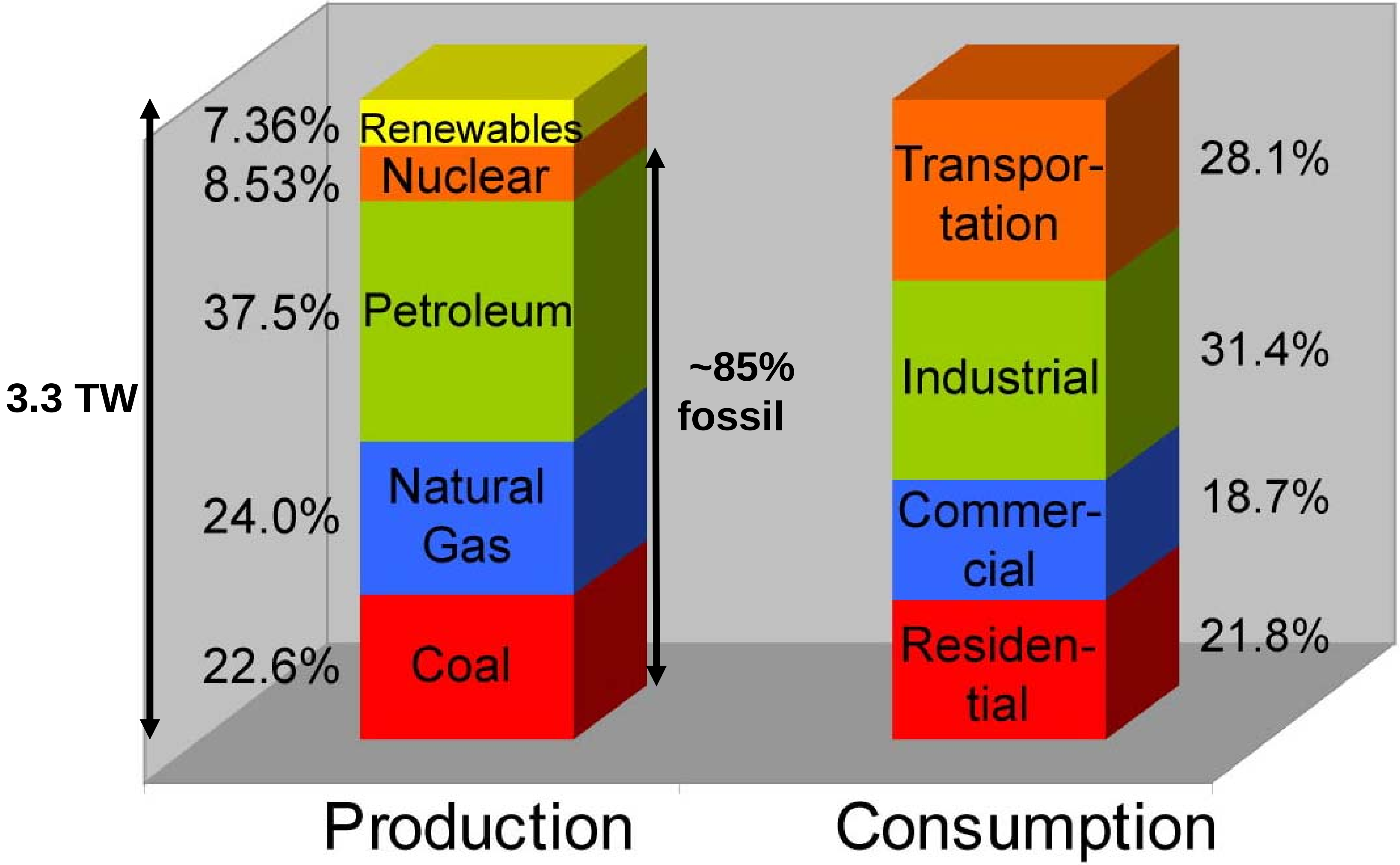
Consumption
Solid state lighting
Nano-insulation
Power transmission

MC Roco, 2010 04 06

Where does it come from? Where does it go?

We must replace several terawatts of coal, petroleum, and natural gas usage

WE DON'T HAVE THE TECHNOLOGY TO DO THIS TODAY



US population from Google report of US census data: 304059724
Energy data from DOE: http://www.eia.doe.gov/emeu/aer/contents.html

MC Roco, 2010 04 06

Benchmark with experts in over 20 countries in 1997-1999

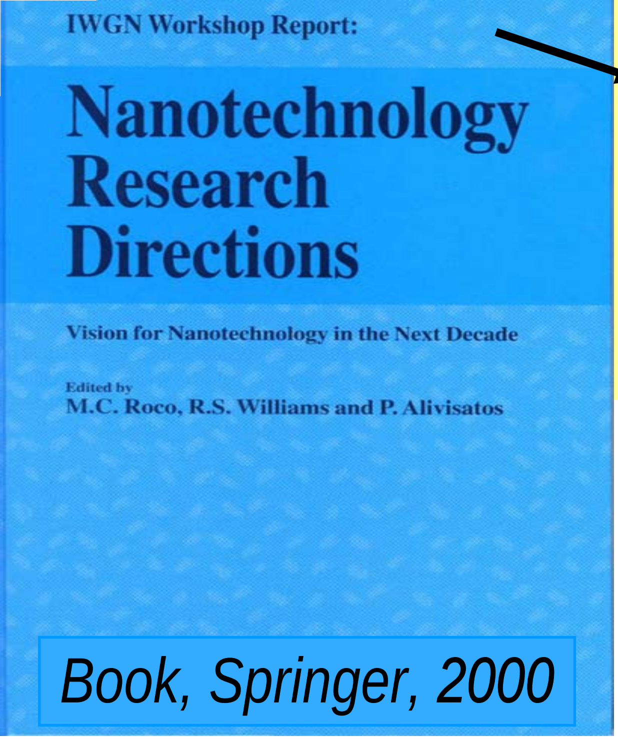
"Nanostructure Science and Technology"

NNI preparatory Report, Springer, 1999

Nanotechnology Definition for the R&D program

Working at the atomic, molecular and supramolecular levels, in the length scale of ~ 1 nm (a small molecule) to ~ 100 nm range, in order to understand, create and use materials, devices and systems with fundamentally new properties and functions because of their small structure

- NNI definition encourages new R&D that were not possible before:
  - *the ability to control and restructure matter at nanoscale*
  - *novel phenomena, properties and functions at nanoscale*,
  - *integration along length scales, systems and applications*



Book, Springer, 2000

"Vision for nanotechnology in the next decade" (2001-2010)

Systematic control of matter on the nanoscale will lead to a revolution in technology and industry

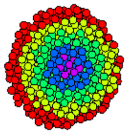
- *Change the foundations from micro to nano in knowledge, industry, medicine, sustainability, ..*
- *Create a general purpose technology (similar IT)*

More important than miniaturization itself:

- Novel properties/ phenomena/ processes/ natural threshold
- Unity and generality of principles
- Most efficient length scale for manufacturing, biomedicine
- Show transition from basic phenomena and components to system applications in 10 areas and 10 scientific targets

Introduction of New Generations of Products and Productive Processes (2000-2020)

Timeline for beginning of industrial prototyping and nanotechnology commercialization

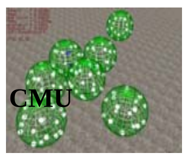


2000

1st: Passive nanostructures (1st generation products)
Ex: coatings, nanoparticles, nanostructured metals, polymers, ceramics

~ 2005

2nd: Active nanostructures Ex: 3D transistors, amplifiers, targeted drugs, actuators, adaptive structures

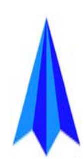


~ 2010

3rd: Nanosystems
Ex: guided assembling; 3D networking and new hierarchical architectures, robotics, evolutionary

15-2020

4th: Molecular nanosystems
Ex: molecular devices 'by design', atomic design, emerging functions



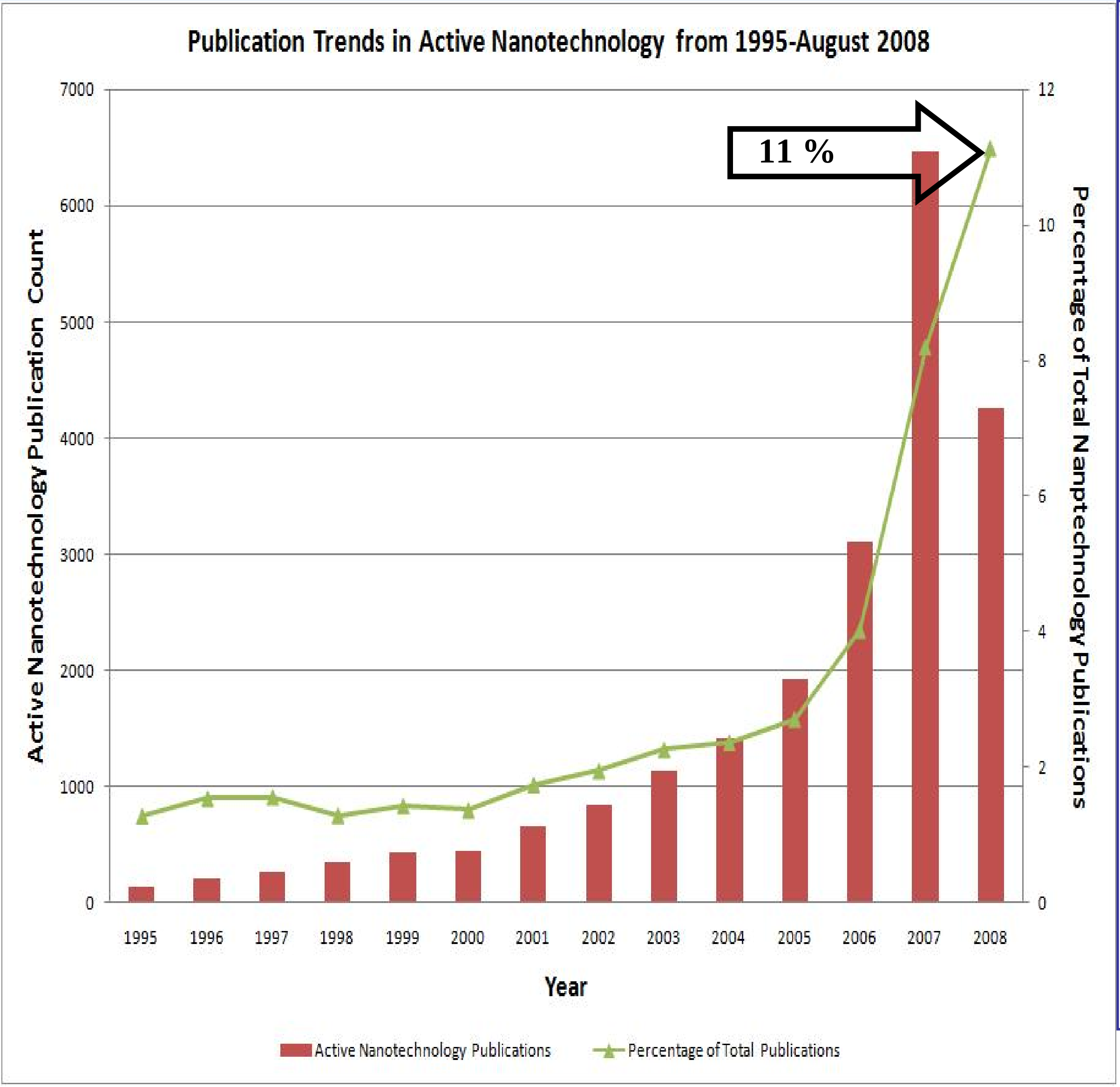
Converging technologies
Ex: nano-bio-info from nanoscale, cognitive technologies; large complex systems from nanoscale

Increased Complexity, Dynamics, Transdisciplinarity

	R&D →		*Broad Use*
IT	1960	-	2000
BIO	1980	-	2010
NANO	2000	-	2020
NBIC	2010	-	2030

Reference: AIChE Journal, Vol. 50 (5), 2004

A shift to “active nanostructures” after 2006



On active nanostructures

21,000+ articles from WOS/SCI from 1995 to 2008

Exemples:

- Transforming (e.g., self-healing materials)
- Remote actuated (e.g., magnetic, electrical, light and wireless tagged nanotechnologies)
- Environmentally responsive (e.g., actuators, drug delivery)
- Miniaturized device (e.g., molecular electronics)
- Hybrid (e.g., uncommon material combinations, biotic-abiotic, organic-inorganic in chips)
- Drug delivery

Source: V. Subramanian, J. Youtie, A. Porter, and P. Shapira (2009). Is there a shift to "active nanostructures?" *Journal of Nanoparticle Research*, 2010, Vol. 12(30

Ten highly promising products incorporating nanotechnology in 2010

- Catalysts
- Transistors and memory devices
- Structural applications (coatings, hard materials,.)
- Biomedical applications (detection, implants,.)
- Treating cancer and chronic diseases
- Energy storage (batteries), conversion and utilization
- Water filtration
- Video displays
- Optical lithography
- Environmental applications

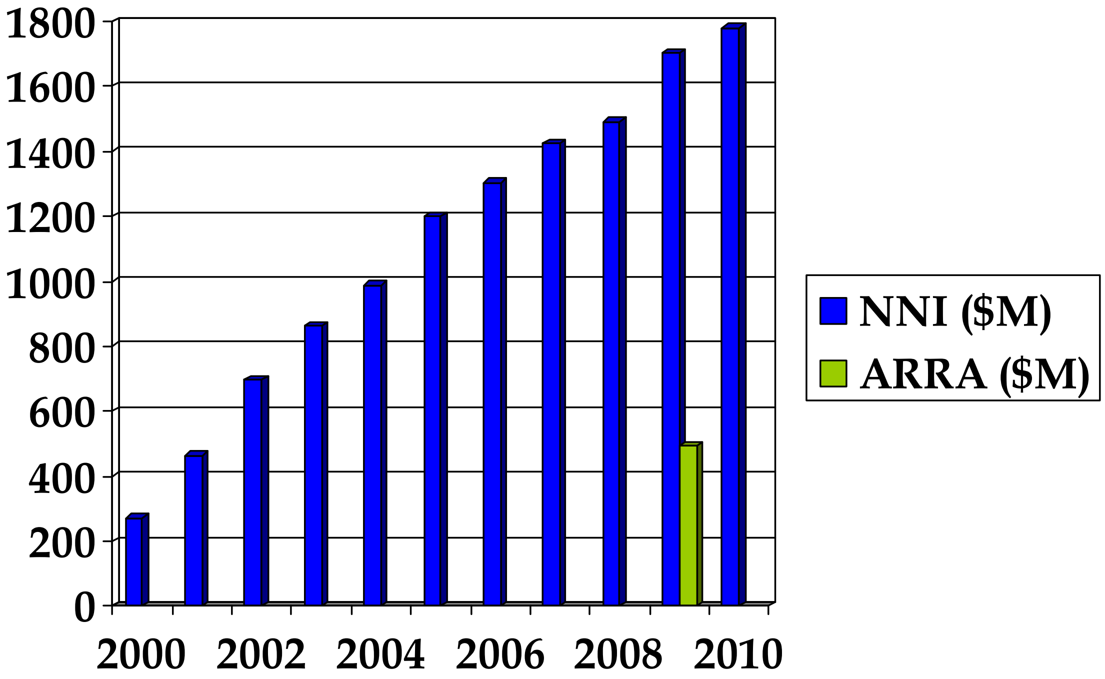
With safety concerns: cosmetics, food, disinfectants,..

2001-
2010

Changing national investment

FY 2011 NNI Budget Request $1,781 million

Fiscal Year	NNI
2000	$270M
2001	$464M
2002	$697M
2003	$862M
2004	$989M
2005	$1,200M
2006	$1,303M
2007	$1,425M
2008	$1,491M
2009	$1,703M + $494M ARRA = $2,197M
2010	$1,781M



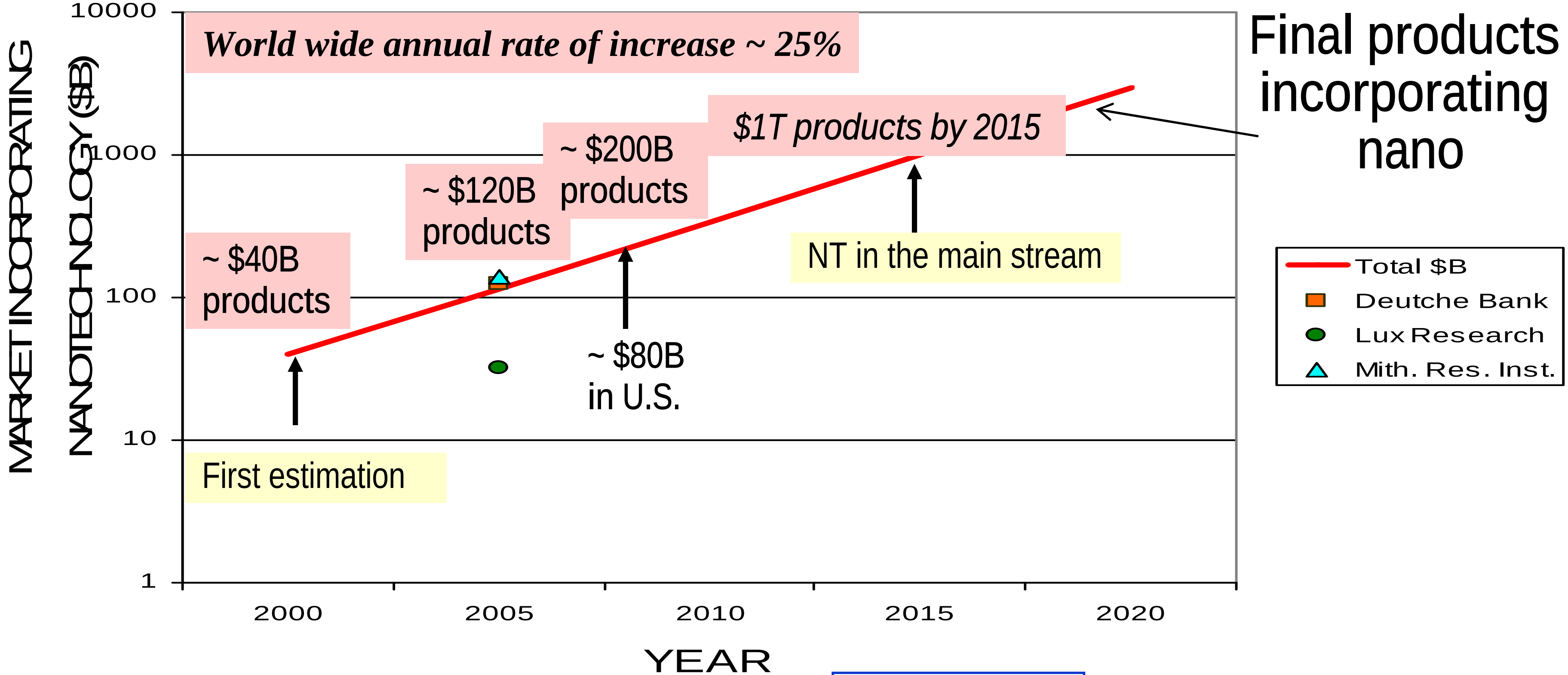
Request in FY 2011 $1,776M; where nano EHS is $117M

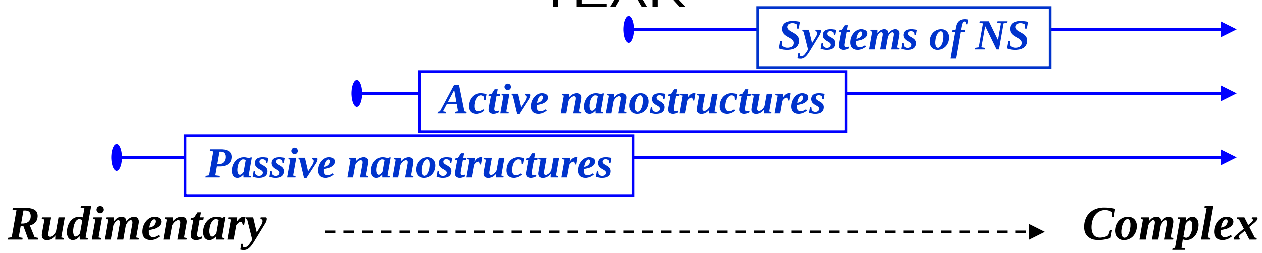
US NNI R&D ~ 1/4 of the world R&D

MC Roco, 2010 04 06

WORLDWIDE MARKET INCORPORATING NANOTECNOLOGY

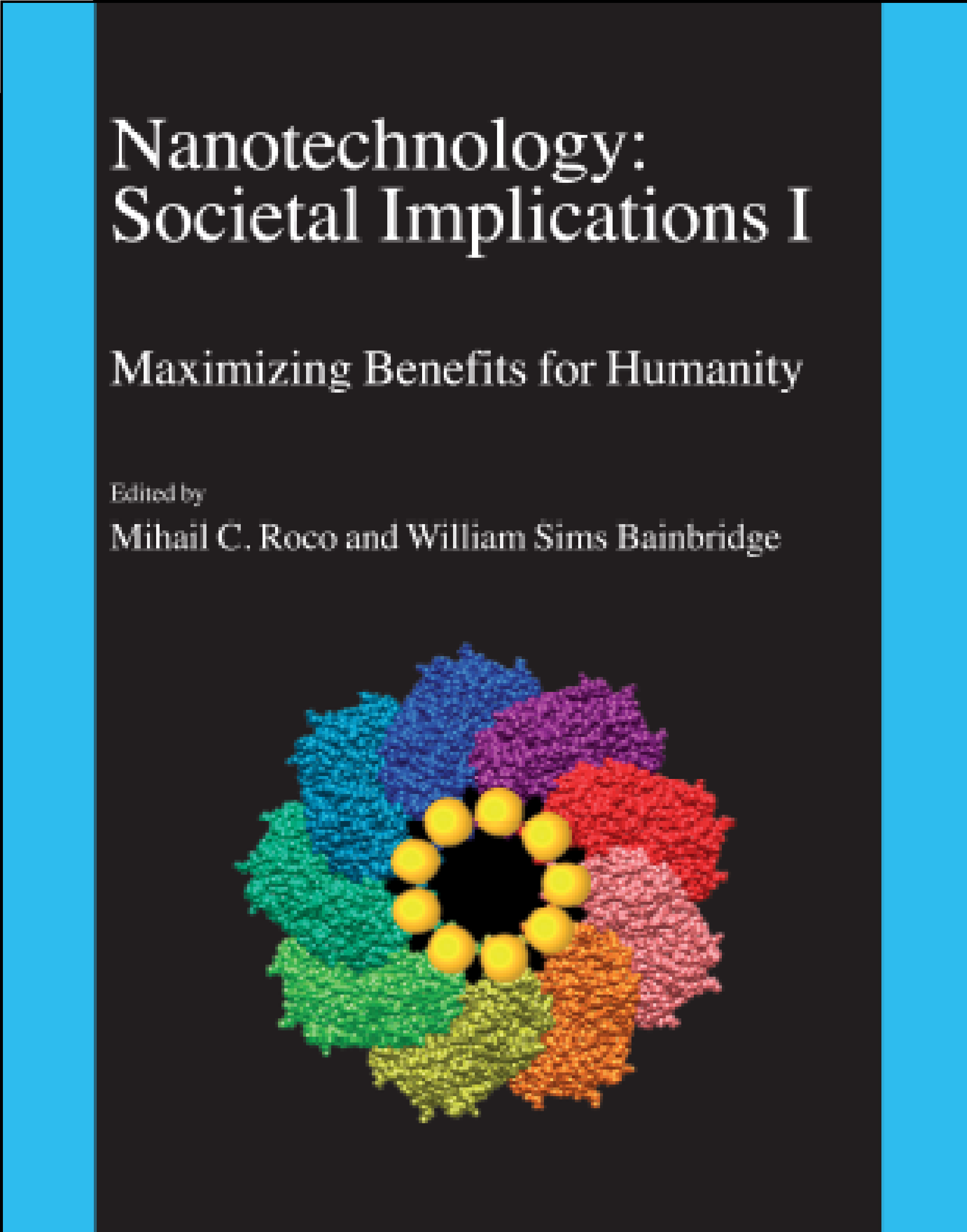
(Estimation made in 2000 after international study in > 20 countries)





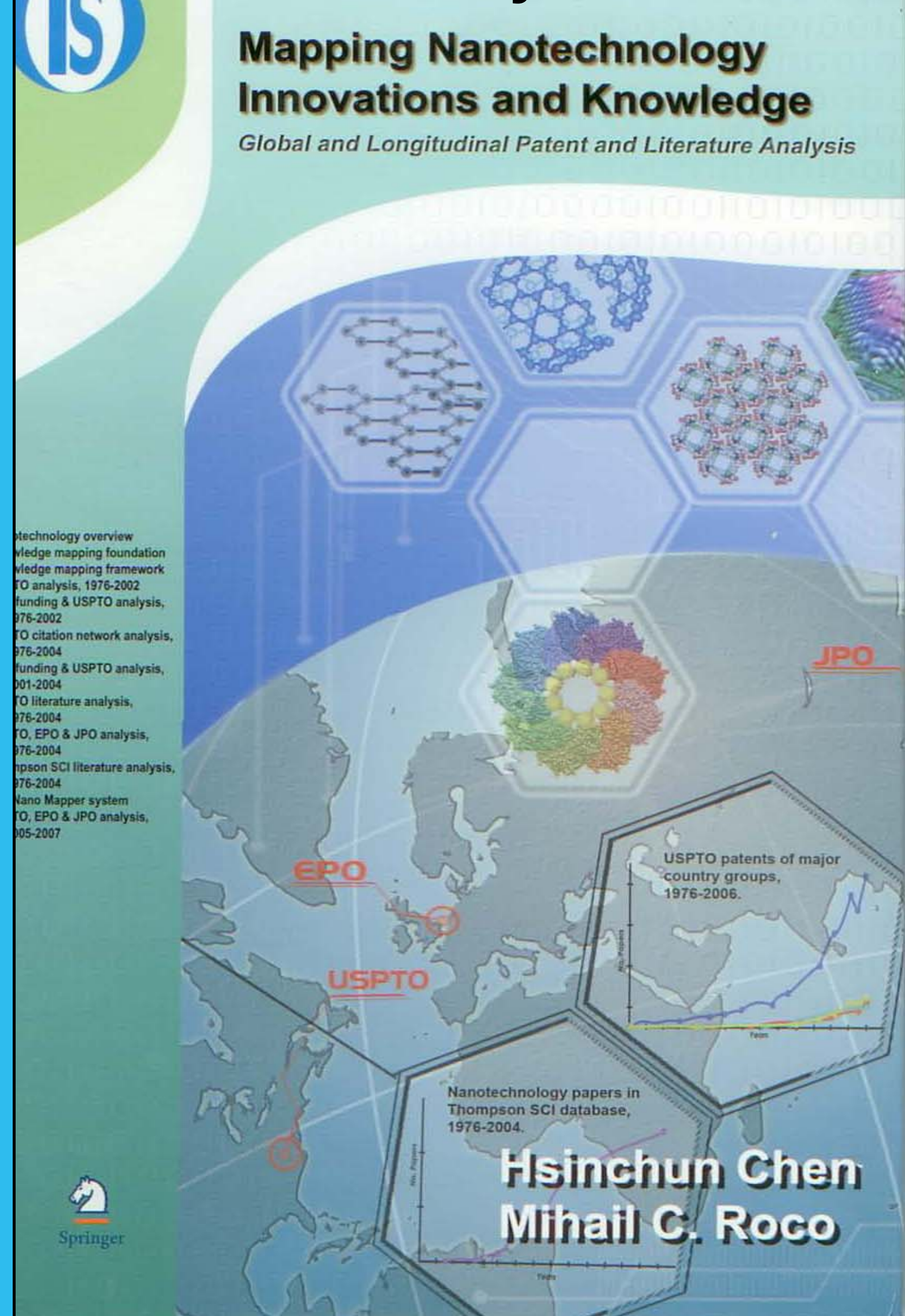
Reference: Roco and WS Bainbridge, Springer, 2001

MC Roco, 2010 04 06



March 2007

January 2009



2000-2010
Expanding nanotechnology domains

2000-2001: nano expanding in almost all disciplines;
by 2009: 11% of NSF awards; 5% papers; 1-2% patents

2002-2003: industry moves behind nano development
by 2009: ~ $200B products incorporating nano worldwide

2003-2004: medical field sets up new goals

2004-2005: media, NGOs, public, organizations -involved

2006-2007: new focus on common Earth resources - water, food, environment, energy, materials

2008-2010: increased relevance to economy – policies - sustainability

The World is NOT Currently Achieving Sustainable Development

Every major ecosystem is under threat at different time scales: food, water, risk of climate change, energy, biodiversity, mineral resources

Nanotechnology may offer efficient manufacturing with less resources, less waste, better functioning products

Need for global governance of converging technologies

.

Renewable Energy Emphasis Areas using nanoscale processes

Biomass Conversion, Biofuels & Bio-Energy

Renewable Natural Resources

Renewable Energy Technologies

Environmentally Benign Materials & Processes

Wind & Wave Power

Solar Photovoltaic Power & Fuels

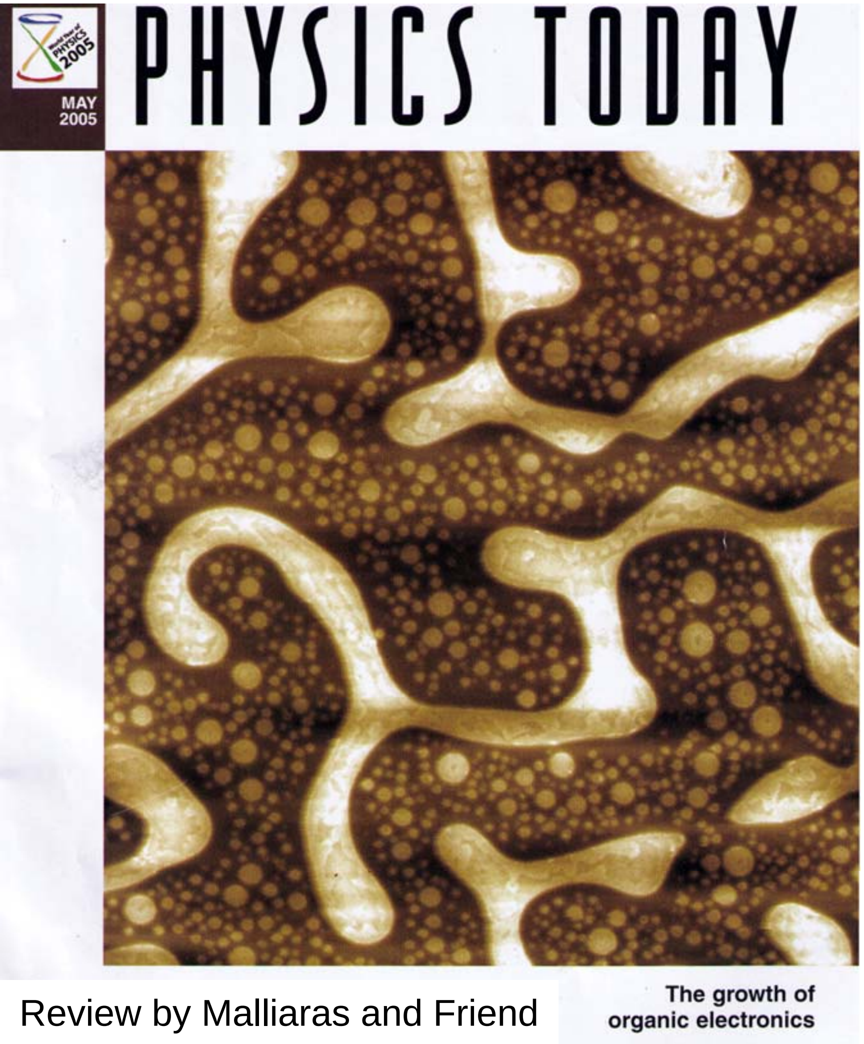
Nanotechnology Impact Areas in Energy

- *solid-state lighting (LED)*
- *low-power displays*
- *fuel cells*
- *battery materials*
- *solar power*
- *catalysis*
- *weight reduction*
- *propellants and explosives*
- *hydrogen storage*
- *nanoscale energy (ATP motors, etc.)*
- *…..*

Example: Polymer solar cells are intrinsically nanostructured devices

In a bulk heterojunction solar photovoltaic a nanostructured donor/acceptor interface is used to dissociate excitons while providing co-continuous transport paths

Hierarchical assembly – can we control molecular to nanoscale structure over large areas, in scalable processes?



Review by Malliaras and Friend

Trajectory

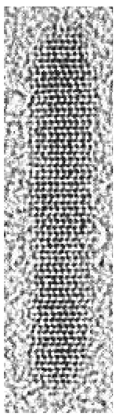
2000 Efficiency <1%
Lifetime= ~hours
crazy to discuss as viable technology

2010 Efficiency ~8% (certified lab scale)
Lifetime= unknown: months-years?
Industrial startups

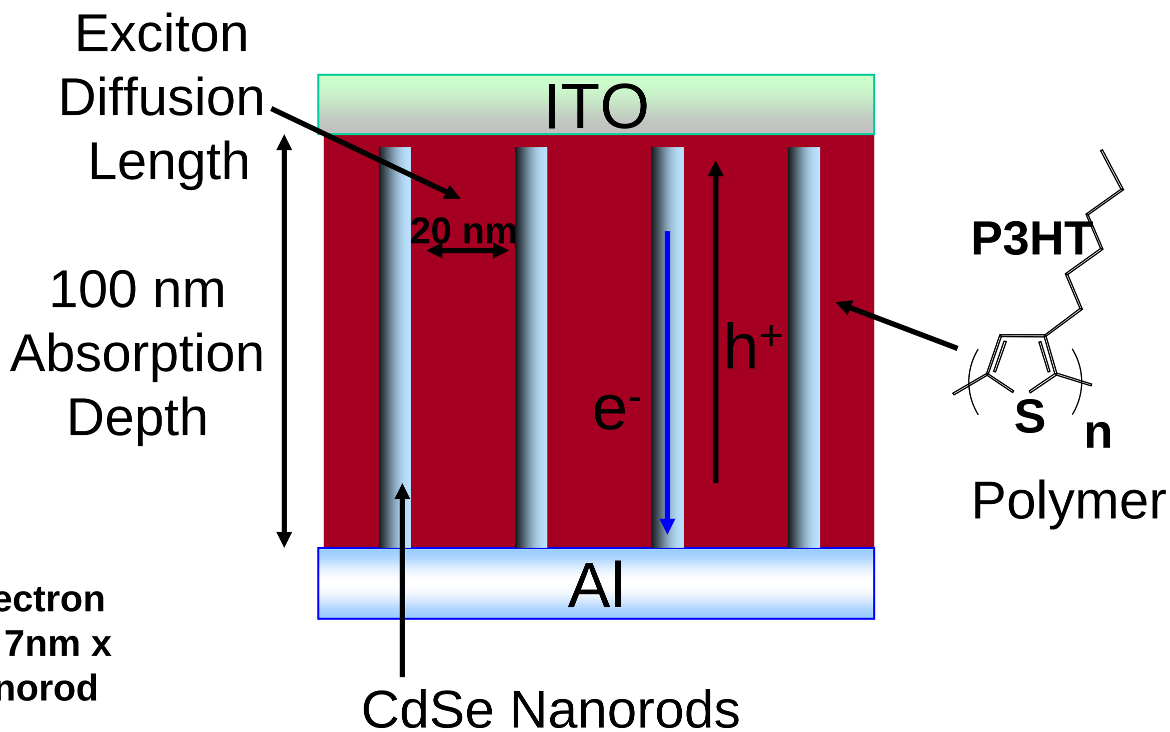
2020 Efficiency 10-15% (in production)
Lifetime= years+
Successful, transformative technology

Polymer/Nanorod Structures for Novel Solar Cells

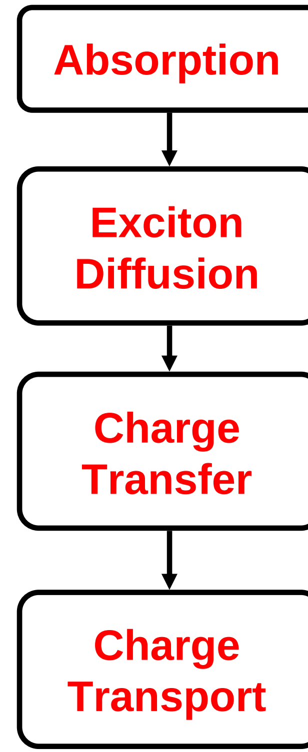
- **Nanoscale volume of rods reduces amount of inorganic semiconductor needed**
- **Potential for low cost, ultra-light weight, and flexible cells**
- **Nanorods can be tailored to absorb certain wavelengths via quantum size effects**



transmission electron micrograph of a 7nm x 30 nm CdSe nanorod



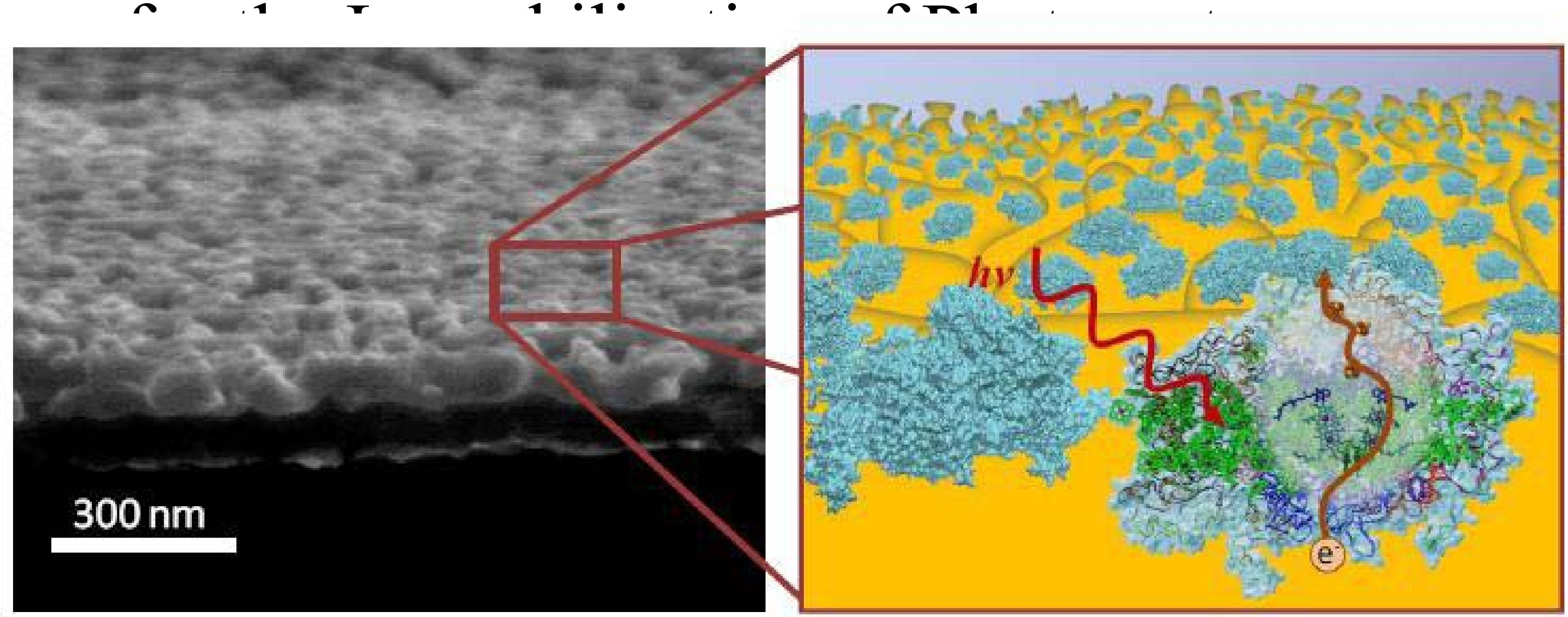
Transport: Bicontinuous Network



P. Alivisatos et al., LBNL/UC-Berkeley

Biomimetic Solar Cells

P. N. Ciesielski, A. Scott, C. J. Faulkner, B. J. Berron, D. E. Cliffel, and G. K. Jennings, —Functionalized Nanoporous Gold Leaf Films



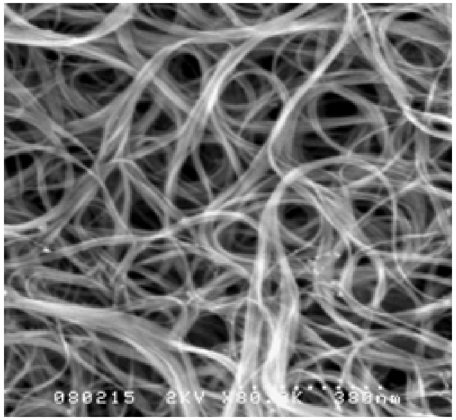
Scanning electron micrograph of a ~100 nm thick nanoporous gold electrode

Nanotechnology to Improve Lithium-Ion Battery Storage Capacity

Landi, B.J., Rochester Institute of Technology, 2009

Three time increase in battery performance through the addition of single wall carbon nanotubes (SWCNT) in the anode, cathode, and carbonaceous materials of Lithium-Ion batteries.

Applications to automotive batteries and space

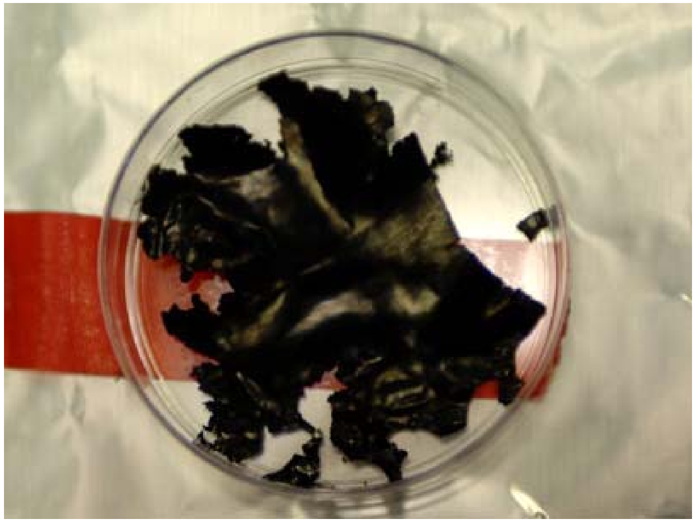


Single wall carbon nanotubes created by laser ablation

SWCNT paper that is used to make an anode

Battery Materials for Ultra-fast Charging and Discharging

- Kang, B. and G. Ceder. *Nature* **458**: 190–193, 12 March 2009. NSF Award # 0819762
- Lithium (Li) batteries: In order to speed the diffusion of Li ions from the cathode surface into the bulk of the crystal - use $LiFePO_4$ and a processing scheme that leaves a glassy, fast ion conductor on the surface, thereby leading the lithium ions rapidly to the proper "tunnels" for more efficient movement into the material.

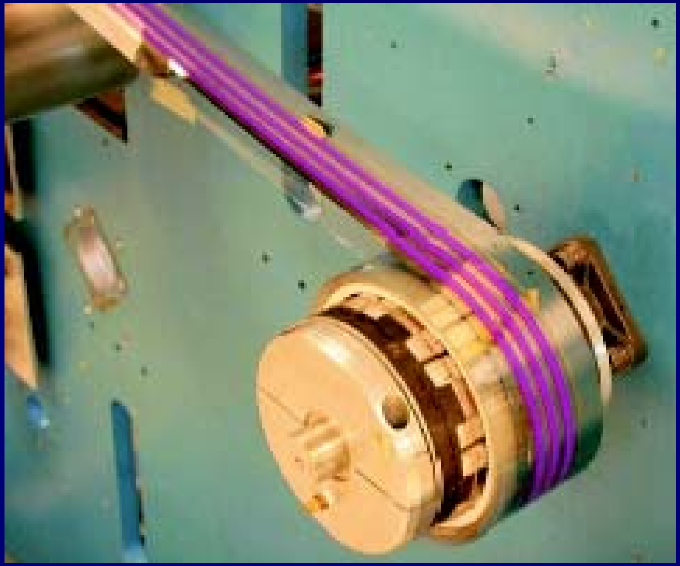


Film of ($LiFePO_4$) that allows quick charging and discharging of lithium ion batteries.

Photovoltaics : Nanoparticle co-sensitizers for increased efficiency.

NSF SBIR Award to Konarka, Inc

From Light to Power



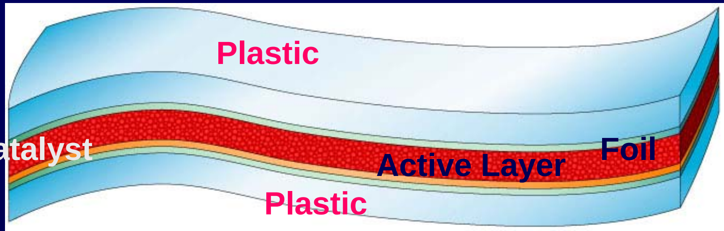
Polymer photovoltaic products in a variety of form factors for commercial, industrial, military and consumer applications

- **Uses photoactive dyes & conducting polymers**
- **High-speed manufacturing processes**
- **Low temperature environment**
- **Uses low cost materials**
- **Highly scaleable**

- **Mass customization from a single source**
- **World solar PV market: CAGR > 35%**
- **20+ patents pending**

Schematic of Dye Sensitized Titania Cell

Total thickness 0.01 inch



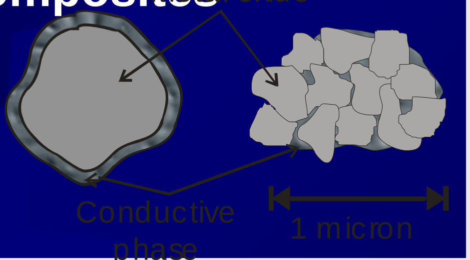
Transparent Conductor + Catalyst

NSF SBIR Award to T/JTechnologies, Inc.

Lithium Ion Batteries

Technology:

High Rate, High Capacity Anodes for Rechargeable Li Batteries Based on Metal Oxide Nano Composites



Goals:

- Reduce irreversible capacity to <15%

→

- >300 mAh/g reversible capacity

→

>10C at 80% rated capacity and 80% DOD

→Achieve projected material costs of <$10/kg

→

Outside Investment

NASA Contract: $2,200,000
Acquired by A123 Company

Commercialization Strategy:

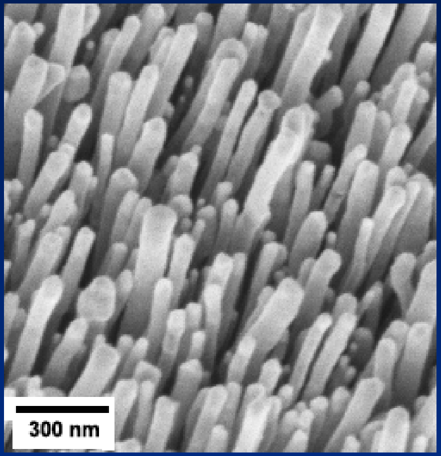
- System payoff:
  30-50% reduction in large format lithium-ion battery size

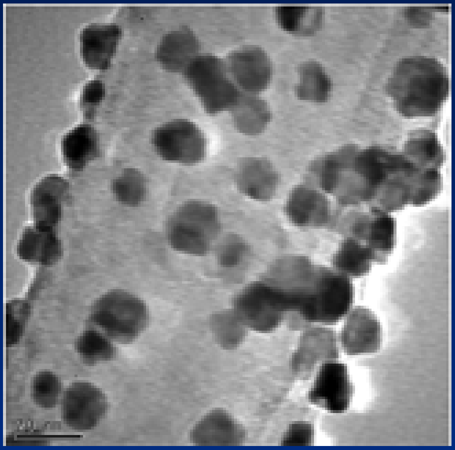
- Develop a cost-competitive battery suitable for HEV, UPS, military and aerospace applications

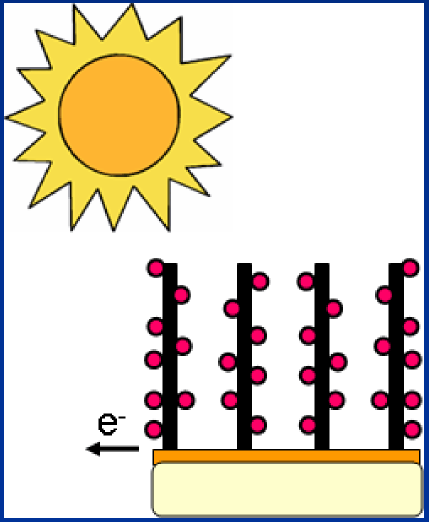
- Strategic Partnerships for joint development of new materials:
  materials production and battery manufacturing

Chemical and Biochemical Surface Functionalization of Group IV Materials

Robert Hamers, University of Wisconsin-Madison CHE-0613010





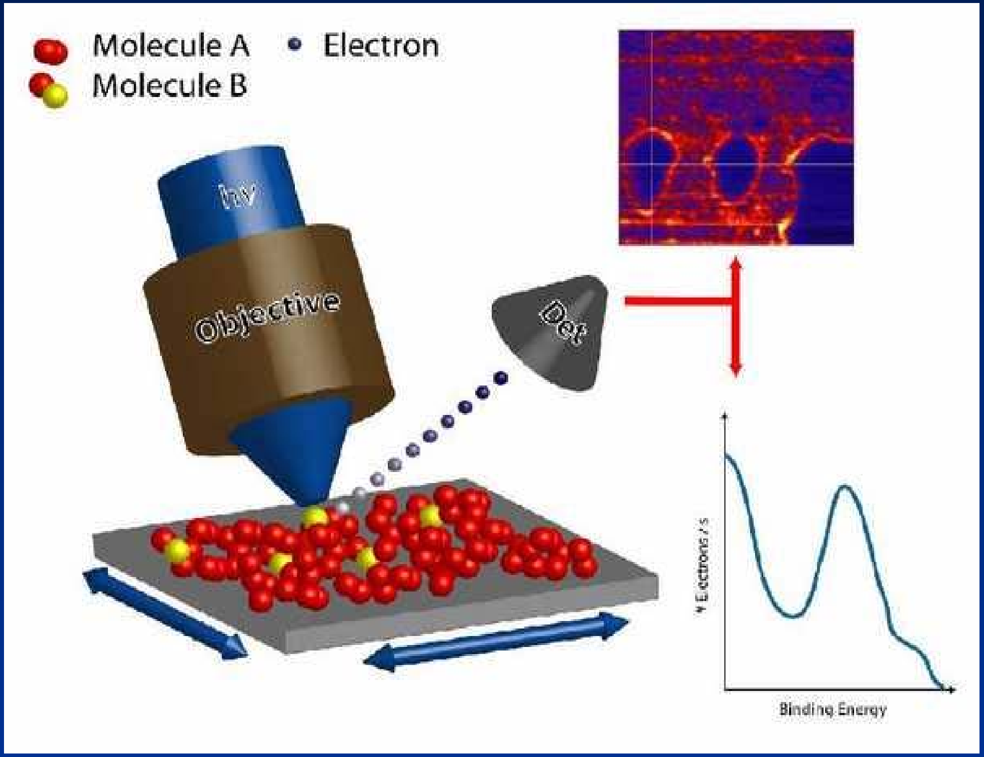


Carbon nanofiber materials offer extremely high surface areas and individual fibers can conduct electricity. Hamers and his group are developing new energy related chemistry technologies based on vertically aligned carbon nanofibers (VACNFs). They have discovered ways to grow nanometer scale catalysts such as platinum onto the VACNFs in unprecedentedly high densities. Catalysts can accelerate chemical reactions, and since the platinum nanocrystals are in electrical contact with the carbon nanofiber, the VACNF forest can collect sunlight and generates electricity. Alternatively, the forest can generate hydrogen fuel (sunlight + water => H_2 + O_2).

Development of a Spatially Resolved Photoionization Microscope for Chemically Selective Mesoscale Spectroscopy in Organic Photovoltaic Cells

Francis Oliver Monti, University of Arizona CHE-0618477

Organic solar cells have the potential to make solar energy conversion widely economically viable, thereby reducing dependence on fossil fuels. This group has successfully developed a complete experimental platform for the study of organic photovoltaic devices. The platform includes a novel approach to ultrafast, simultaneous data acquisition from eight detectors in parallel to obtain spatially resolved chemical and electronic information at near micron length-scales. Enabling the collection of imaging data on a submicron length-scale allows data to be gathered that will help guide the development of more efficient organic solar cells.



Schematic of a scanning photoionization microscope to investigate the electronic structure of heterogeneous interfaces in organic photovoltaic cells.

ACC-F Variable Band-gap Block Co-Polymers Made from n-type Organoborane Polymers and p-type Thiophene Polymers for Photovoltaics

Diane Hinkens, South Dakota State University

CHE-0836082

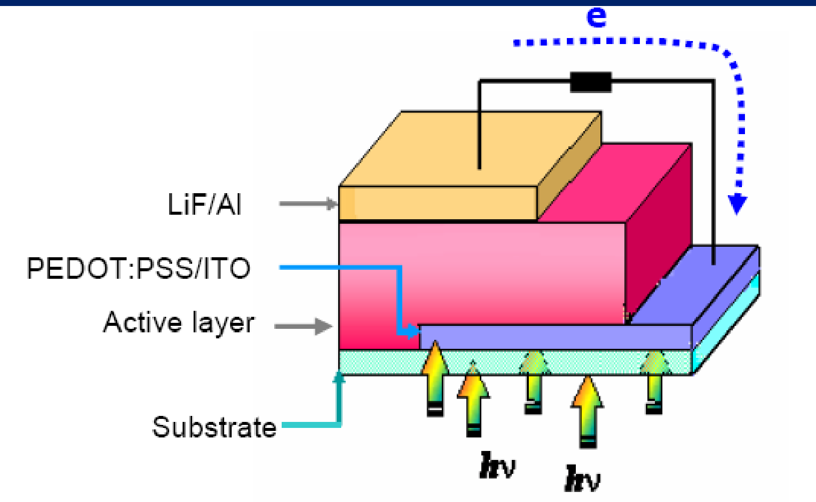
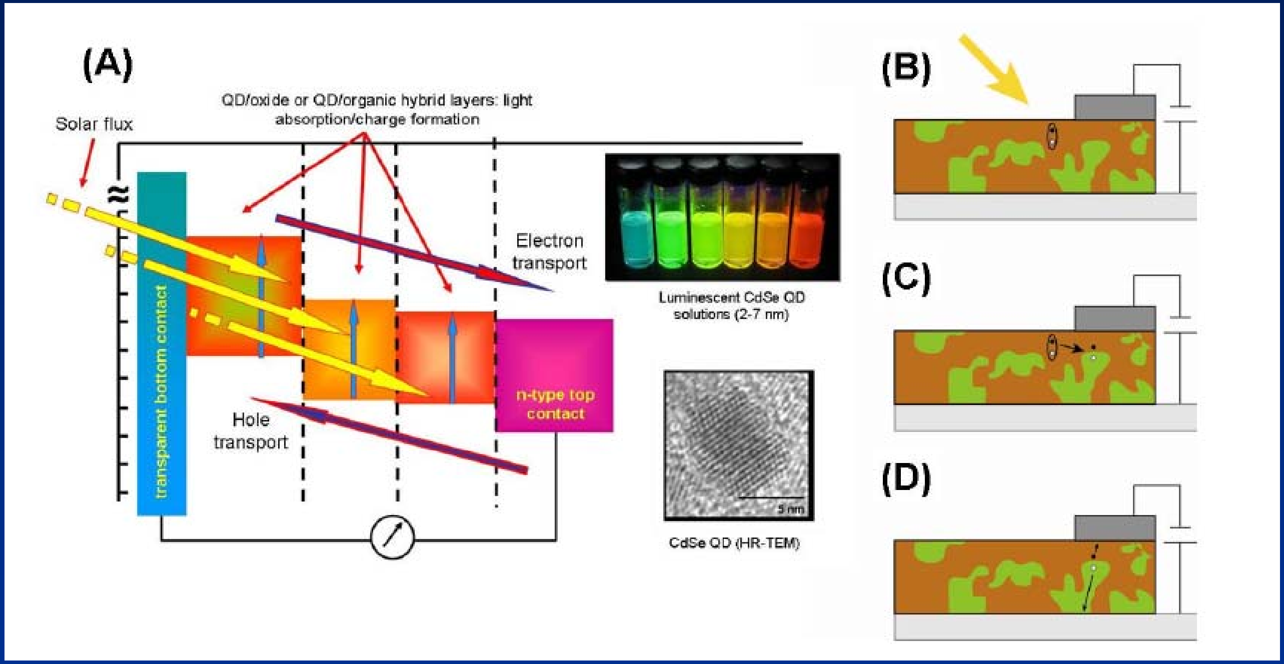


Figure 4. Schematic diagram illustrating the photovoltaic device architecture. Four different active layers will be used: (1) p-type polymer / n – type polymer; (2) p - type polymer / C60; (3) n - type polymer / C60; (4) p - n block polymer / C60.

Dr. Hinkens will synthesize and study the properties of new types of variable band gap block copolymer materials for phtovoltaic applications. Hinkens will work with scientists at Argonne National Laboratory. In her plan for broadening participation, she will develop hands-on activities describing photovoltaic materials for inclusion in the mobile science laboratory "Science on the Move" that travels across South Dakota, reaching small rural schools as well as schools on Native American reservations. In addition, she will develop a photovoltaic laboratory for the Chemistry Van of the Chicago Science Alliance -- which supports science teachers in the Chicago Public Schools.

ACC-F: Investigating the Energy Levels of Semiconductor Nanocrystal-Polymer Hybrid Materials

Andrea Munro, University of Arizona CHE-0836096



Dr. Munro will synthesize and study the properties of semiconductor nanocrystals (CdSe) embedded in a polymer matrix. Dr. Munro will work in collaboration with scientists at the National Renewable Energy Laboratory. In her plan for broadening participation, she will develop hands-on materials with associated curriculum to be used by teachers of grades K-6 in the Tucson and Sunnyside school districts. Some of these materials may be modified for use in the University of Arizona Biosphere II for outreach to the general public.

CAREER: Synthetically Tuned Luminophoric Materials: 3D Displays, Solar Energy Conversion and Beyond

Stefan Bernhard, Princeton University CHE-0449755

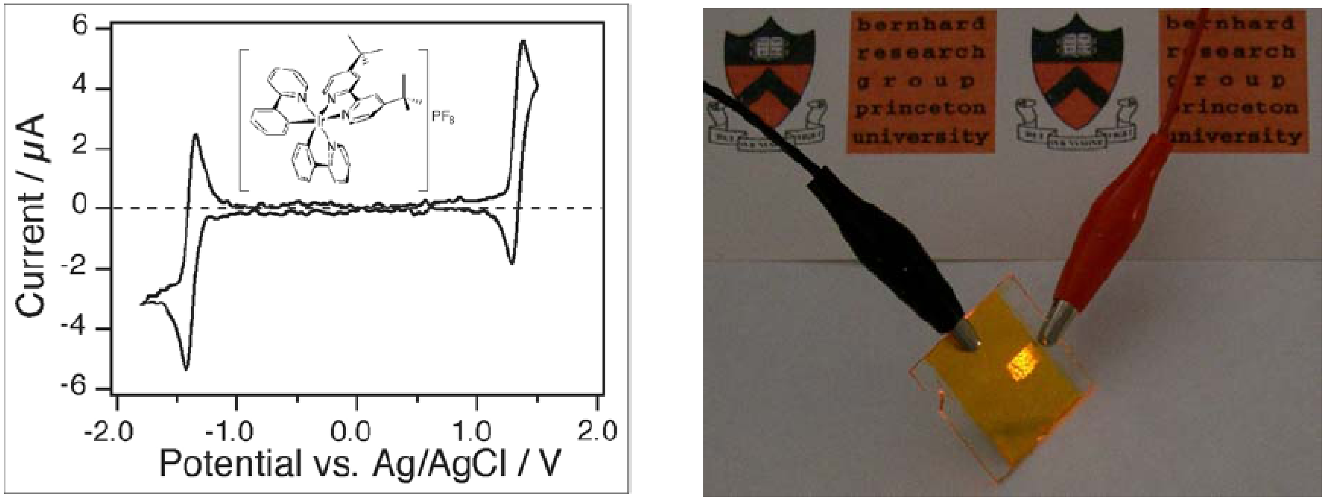


Figure 3: The libraries will be screened for complexes with redox behavior similar to the cyclic voltamogram depicted above. Efficient electro-luminophores possess a gap between the 2 redox waves that exceeds the energy of the excited state and exhibit excellent reversibility for both redox couples (left) An electroluminescent device in air prepared in 30 min employing gilding techniques (right).

Parallel synthetic techniques and parallel screening techniques for photochemical and electrochemical properties will target photoconversion efficiency and stability of photoactive materials. Rigid cage structures will be utilized to inhibit non-radiative decay processes. Combinatorial techniques will be employed to screen the excited state properties of new coordination based materials for both light emitting diode and solar energy conversion applications. Ionic transition metal luminophores will be investigated for light emitting diode development, chiral metal complexes with mesogenic tails will be employed to generate dissymmetric emission (circularly polarized luminescence). Materials with long lived excited states will be identified and examined for electron transfer quenching with redox mediating reagents to explore photolytic cleavage of water using high throughput analysis of gaseous products.   An outreach program at Princeton High School that exposes students to optoelectronics will be extended to additional schools, and visits to elementary schools will be expanded to urban New Jersey sites.

CAREER: Rationally Assembled Nanoparticles for Multi-Electron Transfer Processes

Sherine Obare, University of North Carolina at Charlotte

CHE-0811026

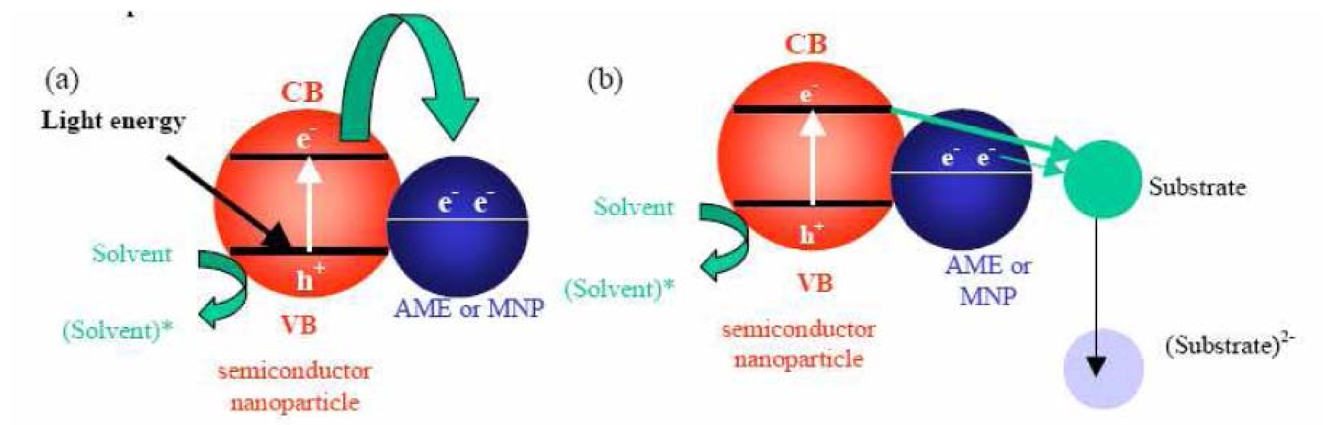


Figure 1. Proposed mechanism (a) Semiconductor irradiation promotes an electron from the valence band (VB) to the conduction band (CB). The holes in the valence band react with the solvent to produce the oxidized solvent (solvent *). Electrons transfer from the conduction band to the interface. (b) Reactive electrons from both the semiconductor and the metal are transferred to the substrate.

The goal of this work is to design, synthesize and characterize nanoscale multi-electron transfer catalysts. Using stopped flow kinetic measurements, coupled with radical clock methods, the complex flow of electrons in these transfer catalysts are being examined. The work provides a unified framework for multi-electron transfer at the nanoscale, which will impact both fundamental scientific understanding and applications in solar energy conversion, electrocatalysis, and photonics. A well integrated program to incorporate this research into the education of graduate, undergraduate, and high school students is underway, and will result in the dissemination of information about nanomaterials and nanoscience and engineering to the general public.

Center for Powering the Planet

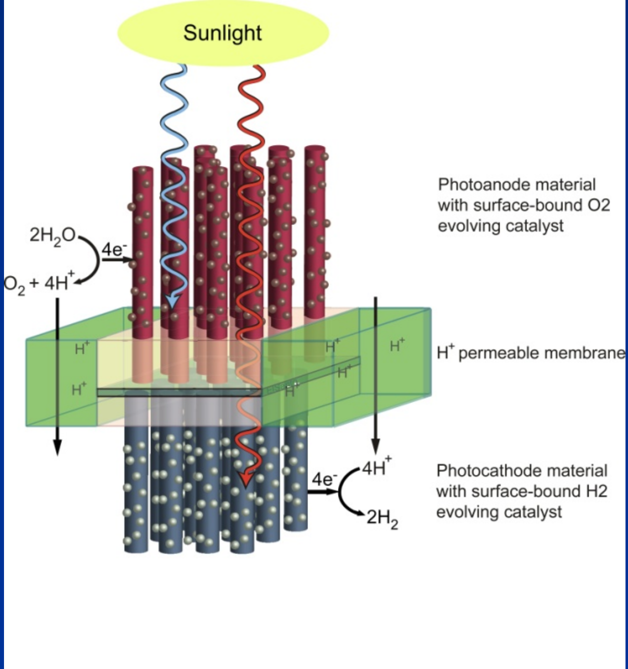
Harry B. Gray, California Institute for Technology

CHE-0802907

Grand challenge- efficient and economical conversion of solar energy into chemical fuel (H_2, O_2)

- Focus on developing the components for a solar water splitting system
  - membrane-supported assembly that captures sunlight and transports charge,
  - two-electron catalyst that reduces water to H_2 and
  - four-electron catalyst that oxidizes water to O_2.

- Involves 16 academic researchers across 10 institutions with NIST, NREL, and Brookhaven as partners

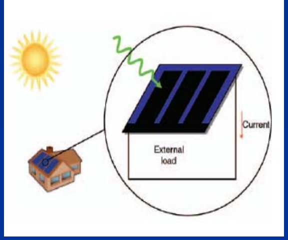


Renewable Energy Materials Research Science and Engineering Center

- MRSEC at the Colorado School of Mines (CSM), Sept. 2008, PI: Craig Taylor
- Focus on renewable energy applications: *photovoltaic materials* and *fuel-cell membranes*
- Education of the next generation of energy professionals
- $9.3M over 6 years: DMR and OMA
- Collaborations
  - NREL
  - 20 industrial companies







Examples 3rd generation –nanosystems integrated with microtechnology

Solar Energy Cells with focused energy

Consortium led by the University of Delaware has developed a high-performance crystalline silicon solar cell platform (focusing the light) that has achieved 42.8 percent solar efficiency in 2007 at standard terrestrial conditions.

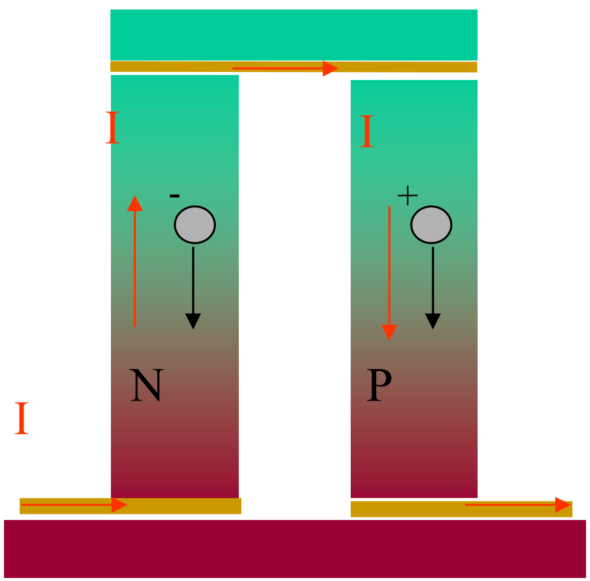
Working under way to achieve 50 percent efficiency (production planned by 2010) http://www.azonano.com/news.asp?newsID=4546

"Nano-generator" fabric with zinc oxide nanowires

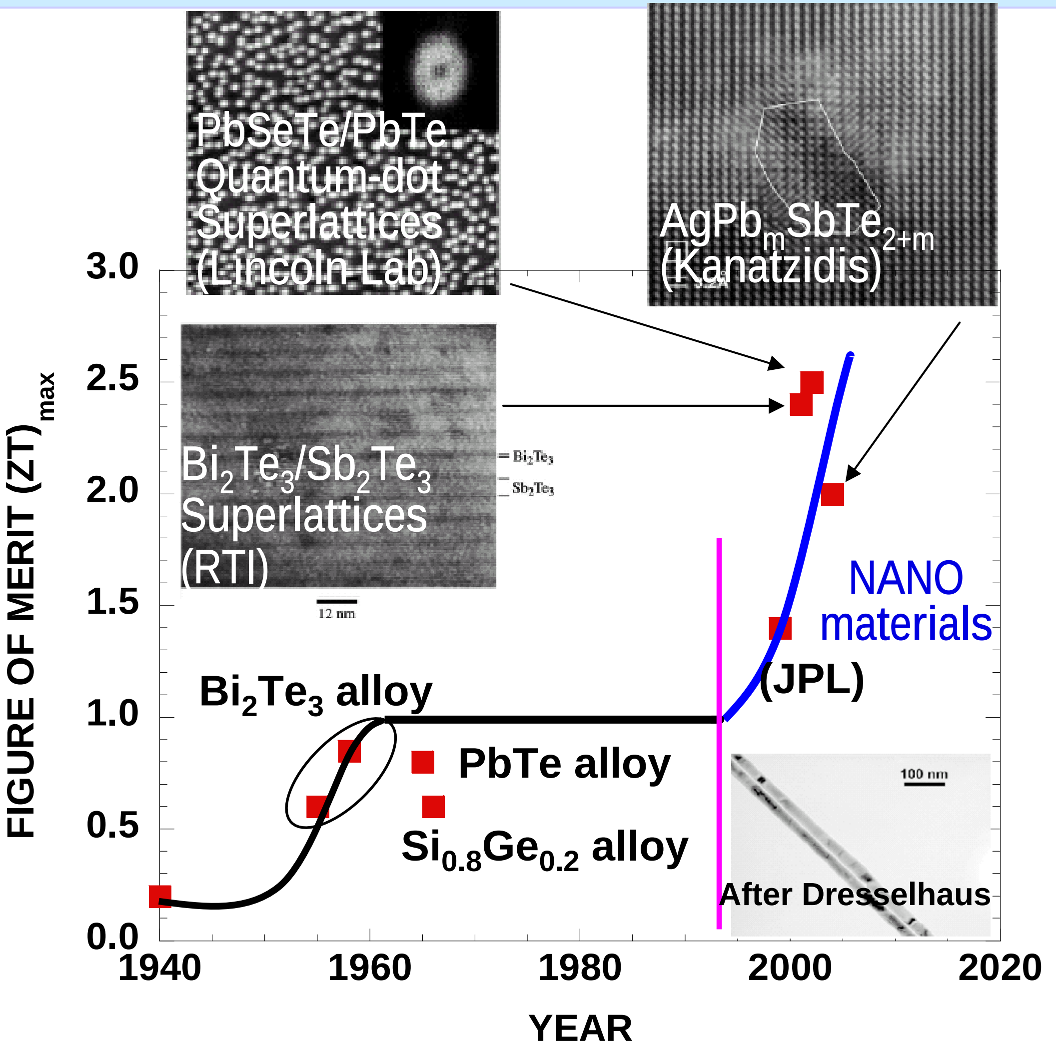
Converts low-frequency vibrations into electricity: nanowires in the fabric generate electricity by rubbing together when set in motion by disturbances such as heartbeats and footsteps (currently 80 milliwatts per m^2 of fabric). Zhong Lin Wang, Georgia Tech.

Example 3rd generation – nanosystems integrated with microtechnology

Direct thermo-electric energy conversion



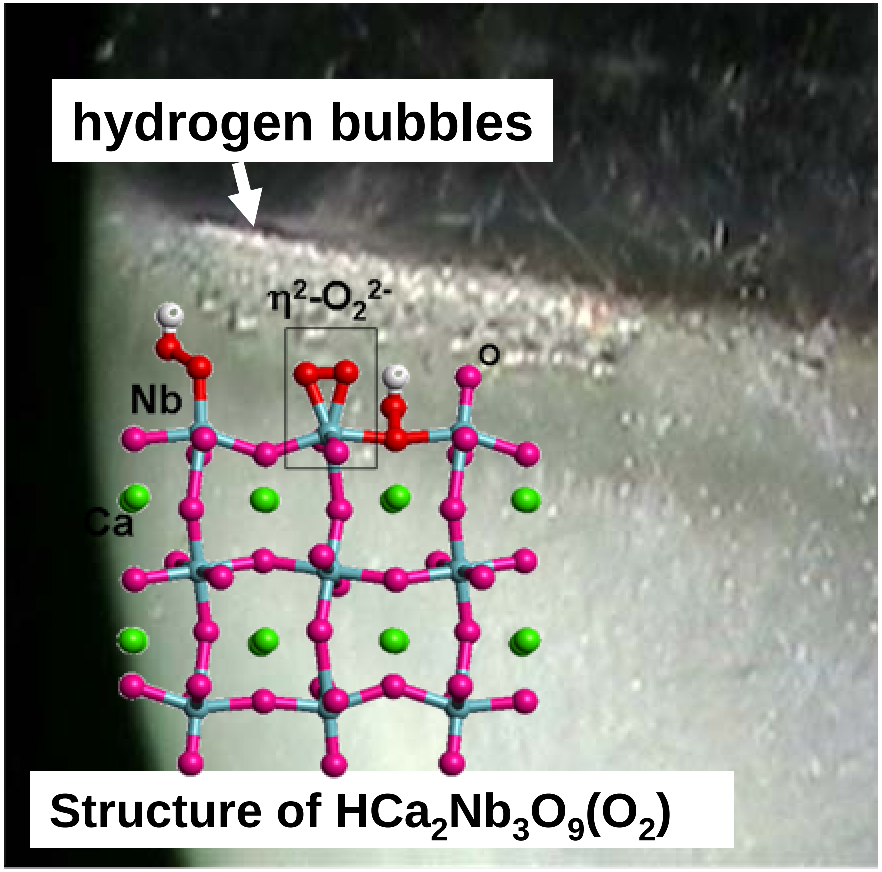
Electron flux versus phonon flux



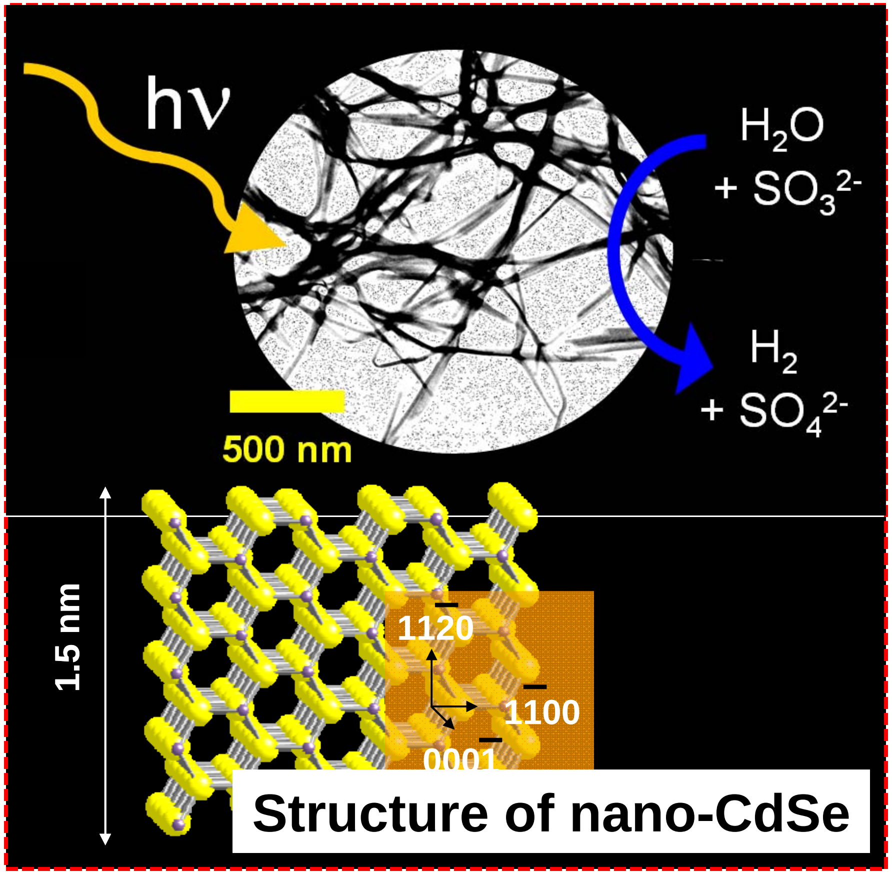
Using nanostructures promises figures of merit up to ZT =10 Chen, MIT)

Solar Fuels: Modular Construction of Nanostructured Catalysts for Solar H_2 Generation from Water

Frank E. Osterloh - University of California-Davis



Structure of $HCa_2Nb_3O_9(O_2)$



Structure of nano-CdSe

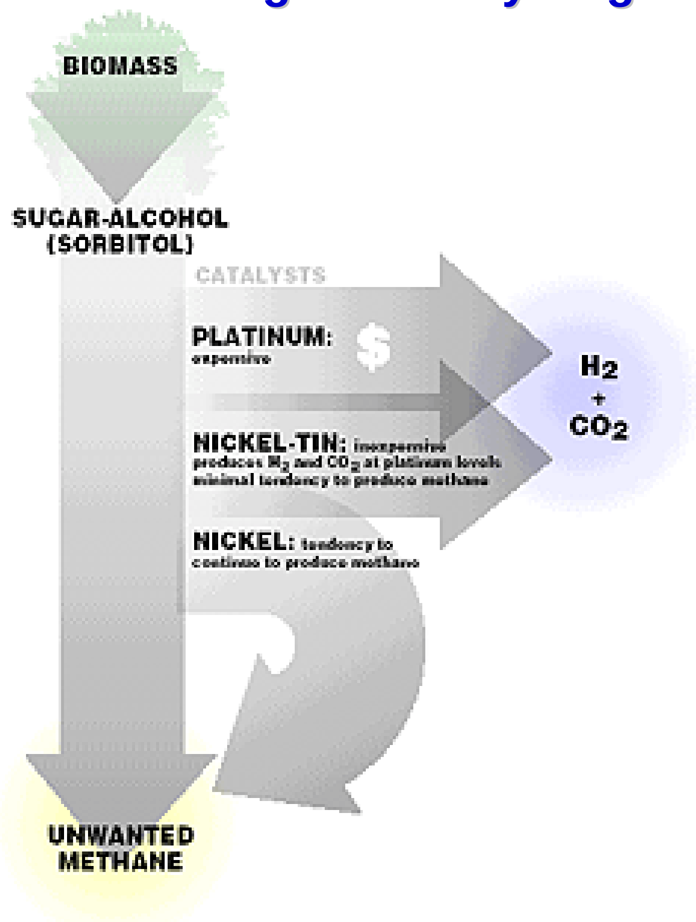
New Catalyst: Catalyst-Bound Peroxide Identified as Deactivating Reagent

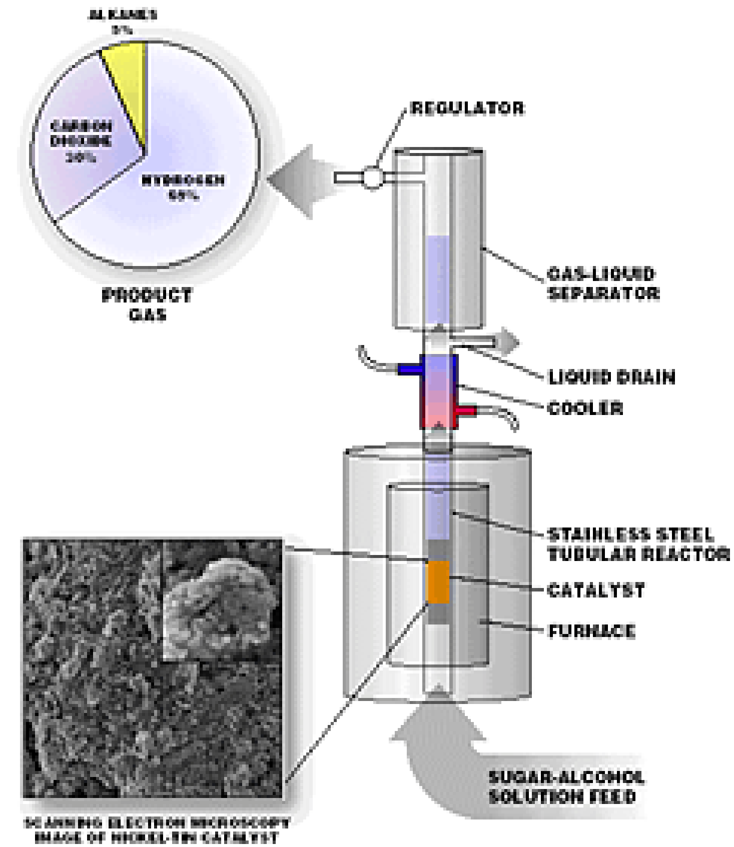
New Phenonema: Quantum Size Effect Activates nano-CdSe for Photocatalytic H_2 Evolution under Visible Light

CBET 0829142

Hydrogen from Biomass via a Nanostructured Catalyst

The goal was to find a catalyst to convert sugar alcohol to high-value hydrogen fuel.

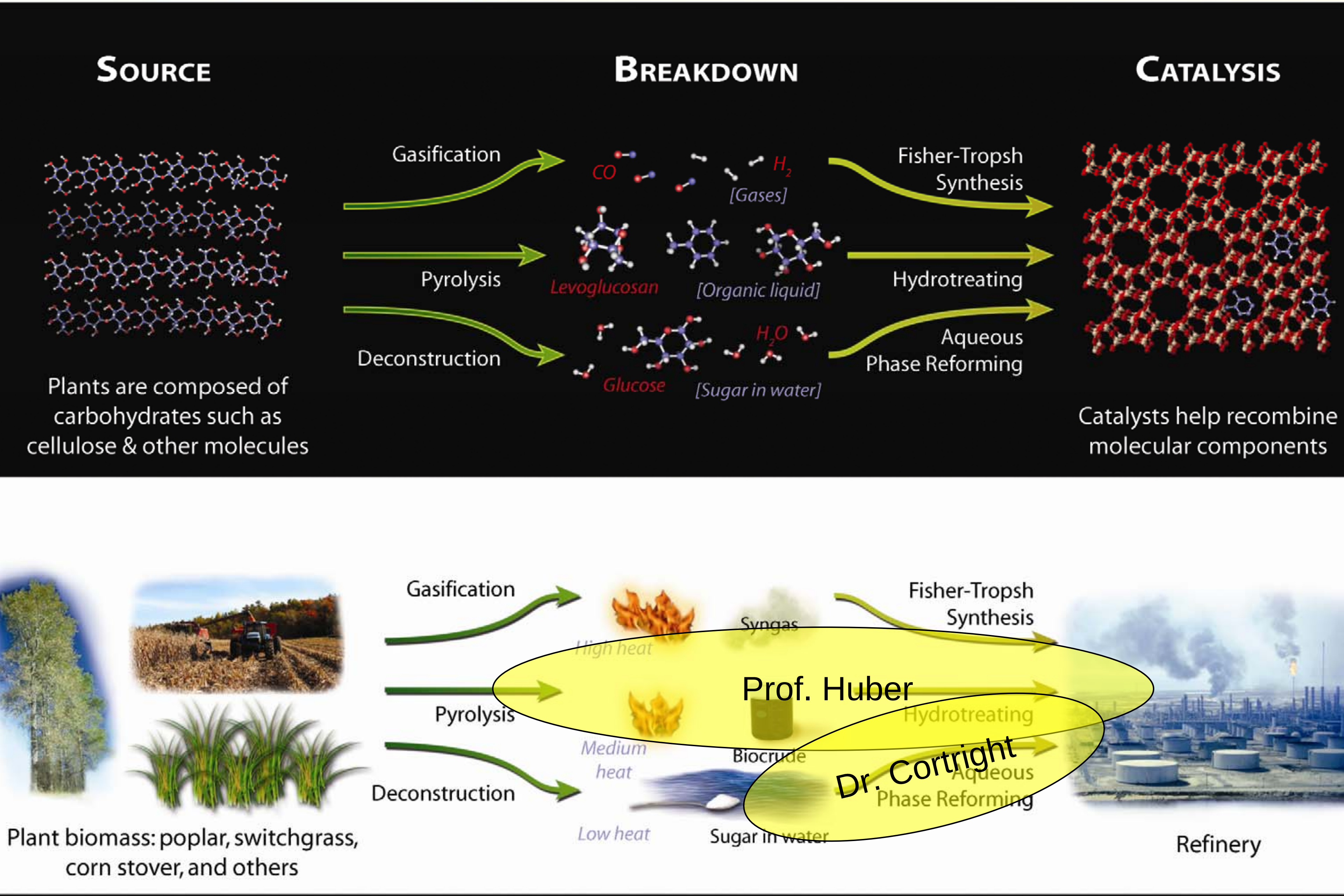




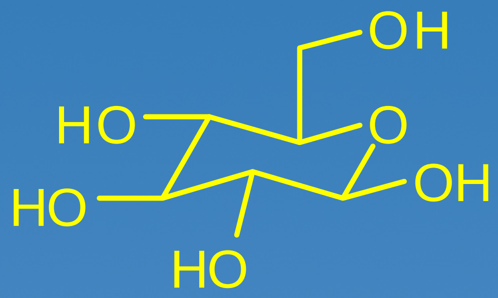
J. Dumesic et al., University of Wisconsin at Madison

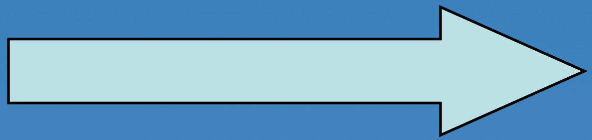
Raney-NiSn catalyst for renewable production of hydrogen for fuel cells by aqueous-phase reforming of biomass-derived hydrocarbons

Green Gasoline: A Renewable Petroleum Alt

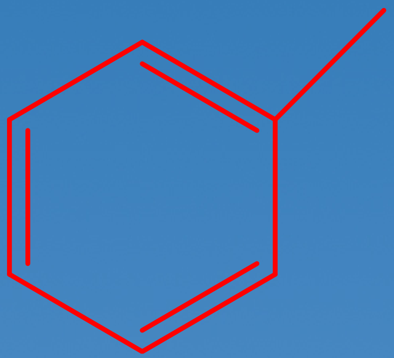


Green Gasoline by Catalytic Fast Pyrolysis





Catalytic Fast Pyrolysis



Woody Biomass:
wood waste,
agricultural wastes
(corn stover, sugarcane
waste), paper trash,
energy crops.

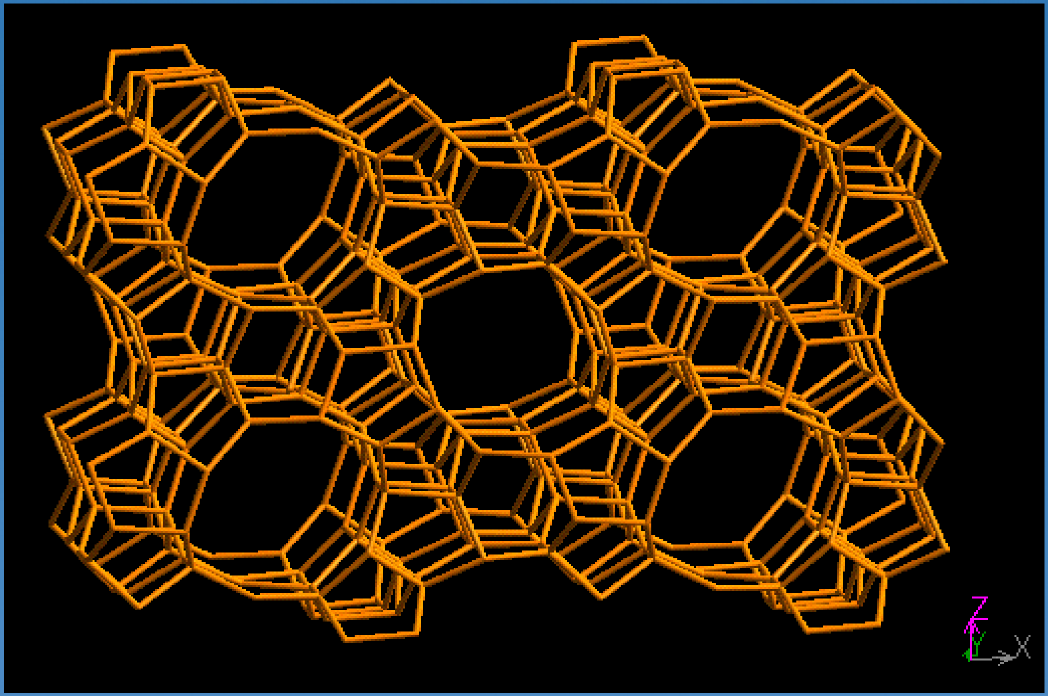
Green Gasoline:
Xylenes and Toluene

By Products:
Water, Carbon Dioxide

Carlson, Vispute, and Huber, Green Gasoline by Catalytic Fast Pyrolysis

Enabling Science: Zeolites

- Zeolites are workhorse of petrochemical industry.
- Zeolites have well defined pores (shape selective).
- Reaction is controlled by pore structure and catalytic sites.



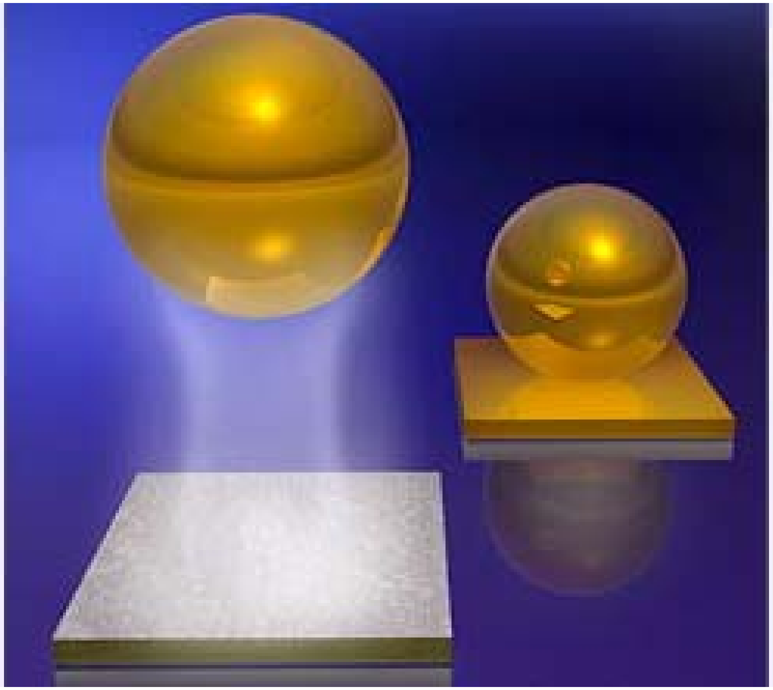
Zeolites: the jewel of nanotechnology.

Most proposed biomass crops are wild, undomesticated species

Photo credit: Jake Eaton, Potlatch Corporation

Discovery of Nanoscale Repulsion

Federico Capasso, Harvard University



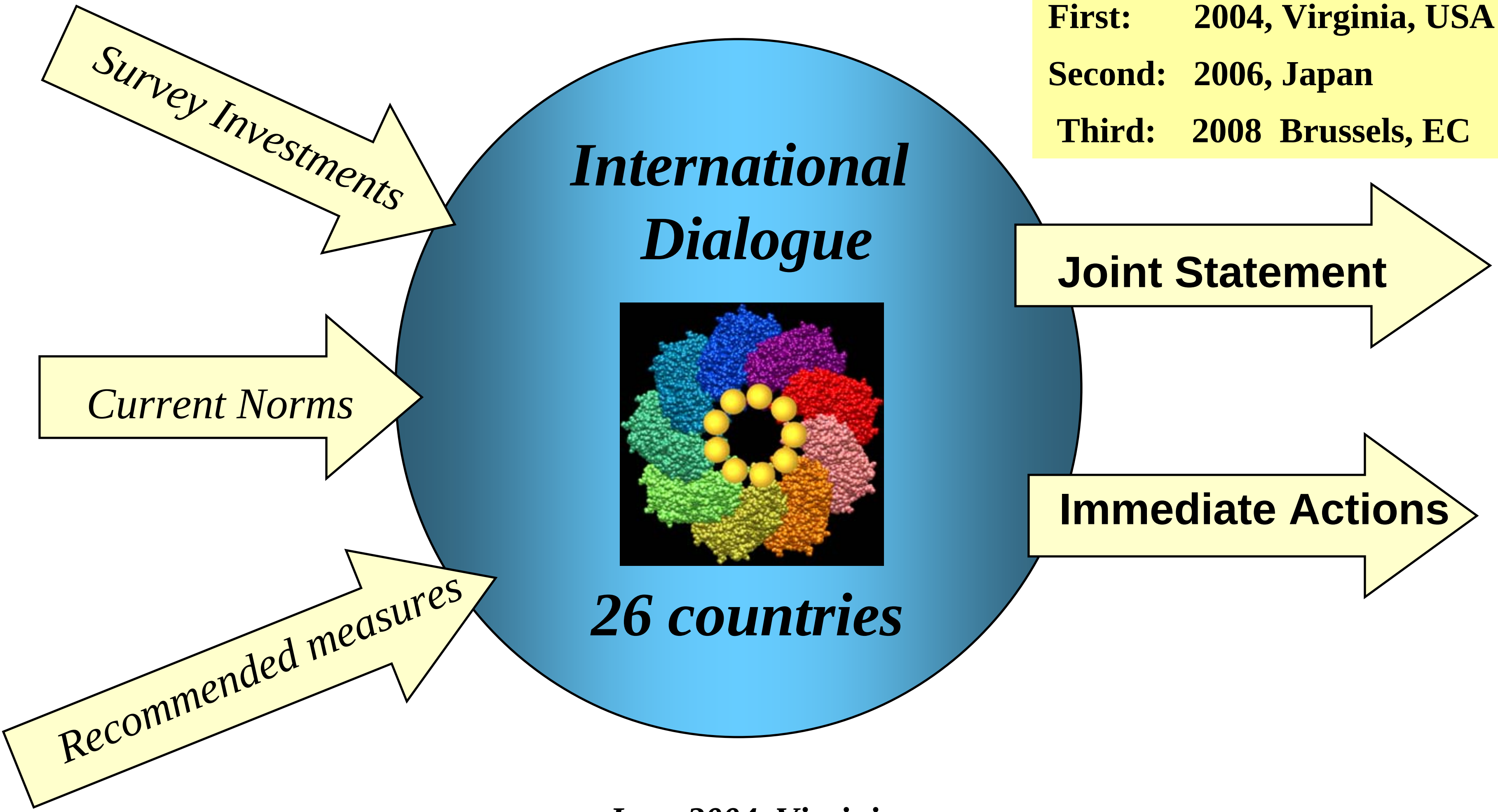
A repulsive force arising at nanoscale was identified similar to attractive repulsive Casimir-Lifshitz forces.

As a gold-coated sphere was brought closer to a silica plate - a repulsive force around one ten-billionth of a newton was measured starting at a separation of about 80 nanometers.

For nanocomponents of the right composition, immersed in a suitable liquid, this repulsive force would amount to a kind of quantum levitation that would keep surfaces slightly apart

Inclusive governance - Ex: International Dialogue on Responsible Nanotechnology R&D since 2004

First: 2004, Virginia, USA
Second: 2006, Japan
Third: 2008 Brussels, EC



June 2004, Virginia

http://www.nsf.gov/home/crssprgm/nano/dialog.htm

MC Roco, 2010 04 06

Follow up activities after the First International Dialogue on Responsible Nanotechnology R&D (2004)

Coordinated activities after the June 2004 International Dialogue

- October 2004 / October 2005 - Occupational Safety Group (UK, US,.)
- November 2004 - OECD / EHS group on nanotechnology begins
- December 2004 - Meridian study for developing countries
- December 2004 - Nomenclature and standards (ISO, ANSI)
- February 2005 - North-South Dialogue on Nanotechnology (UNIDO)
- May 2005 - International Risk Governance Council (IRGC)
- May 2005 - "Nano-world", MRS (Materials, Education)
- July 2005 - Interim International Dialogue (host: EC)
- **October 2005 - OECD Nanotechnology Party in CSTP**
- **June 2006 - 2nd International Dialogue (host: Japan)**
- **2006 Int. awareness for: EHS, public participation, education**
- **2007-2009 - new activities**

OECD, Chemicals Committee, WPMN

2005- (**http://www.oecd.org/env/nanosafety/**)

OECD: Working Party on Nanotechnology (WPN)

Working Party on Nanotechnology, 2007- (http://www.oecd.org/sti/nano)

A. Statistics and Measurement
B. Impacts and Business Environment
C. International Research Collaboration
D. Outreach and public engagement
E. Dialogue on Policy Strategies
F. Contribution of Nanotech to Global Challenges