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Renewable Energies for a Global Economy
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Energy & Nanostructured Materials: Scientific Challenges In the Hydrogen Economy

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Collaborators H_2 big picture

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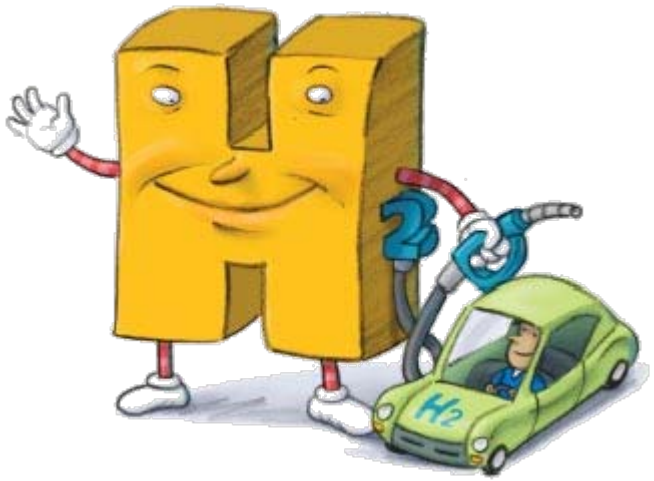


Energy & Nanostructured Materials: Scientific Challenges In the Hydrogen Economy

- Overview of nanostructured materials
- Overview of the hydrogen initiative and of the role that nanoscience and nanotechnology might play
- Concluding Remarks

Hydrogen: A National Initiative

“Tonight I'm proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles… With a new national commitment, our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom, so that the first car driven by a child born today could be powered by hydrogen, and pollution-free.”

President Bush, State-of the-Union Address, January 28, 2003

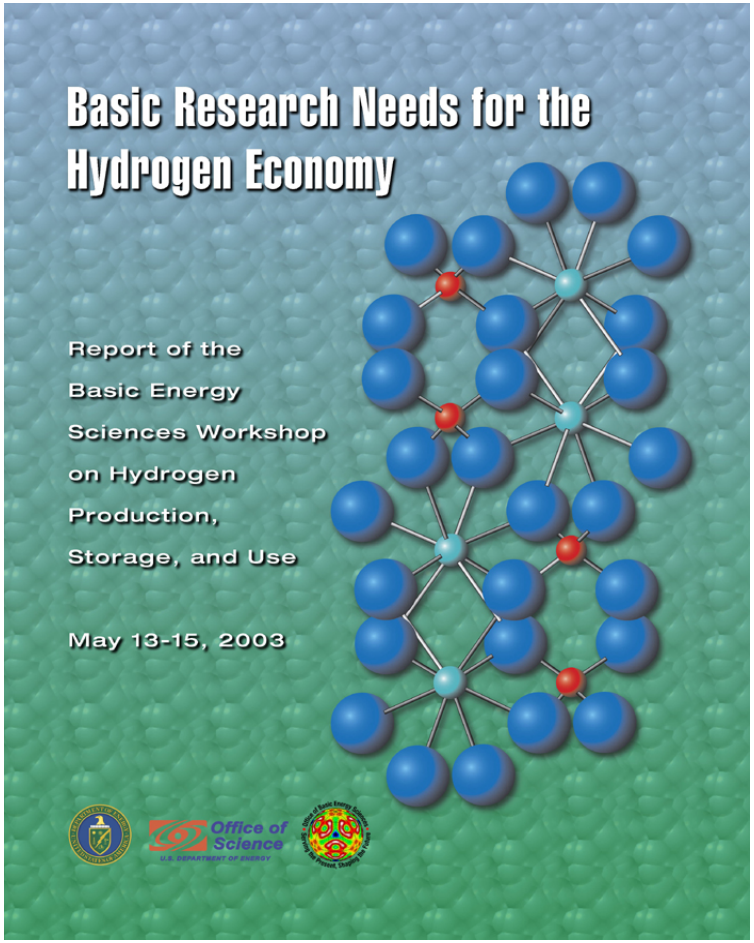
"America is addicted to oil, which is often imported from unstable parts of the world,“

“The best way to break this addiction is through technology..”

“..better batteries for hybrid and electric cars, and in pollution-free cars that run on hydrogen’

President Bush, State-of the-Union Address, January 31, 2006

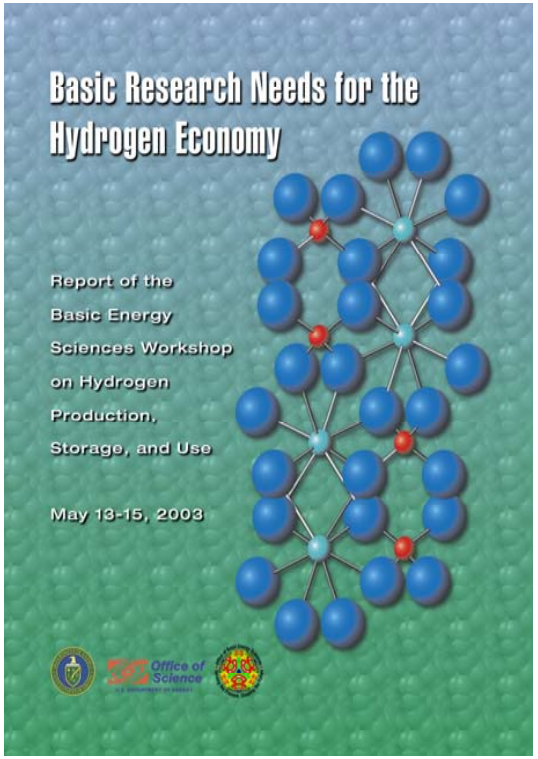
2003: Basic Research Hydrogen Workshop Report



"Bridging the gaps that separate the hydrogen- and fossil-fuel based economies in cost, performance, and reliability goes far beyond incremental advances in the present state of the art. Rather, fundamental breakthroughs are needed in the understanding and control of chemical and physical processes involved in the production, storage, and use of hydrogen. Of particular importance is the need to understand the atomic and molecular processes that occur at the interface of hydrogen with materials in order to develop new materials suitable for use in a hydrogen economy. New materials are needed for membranes, catalysts, and fuel cell assemblies that perform at much higher levels, at much lower cost, and with much longer lifetimes. Such breakthroughs will require revolutionary, not evolutionary, advances. Discovery of new materials, new chemical processes, and new synthesis techniques that leapfrog technical barriers is required. This kind of progress can be achieved only with highly innovative, basic research."

Chair: Mildred Dresselhaus, MIT
Co-Chairs George Crabtree, Argonne National Laboratory, Michelle Buchanan, Oak Ridge National Laboratory
Dates: May 13–15, 2003

Hydrogen Studies



THE HYDROGEN ECONOMY: OPPORTUNITIES, COSTS, BARRIERS AND R&D NEEDS

Committee on Alternatives and Strategies for Future Hydrogen Production and Use

Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF ENGINEERING
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December 2004 PHYSICS TODAY

The Hydrogen Economy

If the fuel cell is to become the modern steam engine, basic research must provide breakthroughs in understanding, materials, and design to make a hydrogen-based energy system a vibrant and competitive force.

George W. Crabtree, Mildred S. Dresselhaus, and Michelle V. Buchanan

Since the industrial revolution began in the 18th century, fossil fuels in the form of coal, oil, and natural gas have powered the technology and transportation networks that drive society. But continuing to power the world from fossil fuels threatens our energy supply and puts enormous strains on the environment. The world's demand for energy is projected to double by 2050 in response to population growth and the industrialization of developing countries.[1] The supply of fossil fuels is limited, with restrictive shortages of oil and gas projected to occur within our lifetimes (see the article by Paul Weisz in PHYSICS TODAY, July 2004, page 47). Global oil and gas reserves are concentrated in a few regions of the world, while demand is growing everywhere; as a result, a secure supply is increasingly difficult to assure. Moreover, the use of fossil fuels puts our own health at risk through the chemical and particulate pollution it creates. Carbon dioxide and other greenhouse gas emissions that are associated with global warming threaten the stability of Earth's climate.

A replacement for fossil fuels will not appear overnight. Extensive R&D is required before alternative sources can supply energy in quantities and at costs competitive with fossil fuels, and making those alternative sources available commercially will itself require developing the proper economic infrastructure. Each of those steps takes time, but greater global investment in R&D will most likely hasten the pace of economic change. Although it is impossible to predict when the fossil fuel supply will fall short of demand or when global warming will become acute, the present trend of yearly increases in fossil fuel use shortens our window of opportunity for a managed transition to alternative energy sources.

Hydrogen as energy carrier

One promising alternative to fossil fuels is hydrogen[2,3] (see the article by Joan Ogden, PHYSICS TODAY, April 2002, page 69). Through its reaction with oxygen, hydrogen releases energy explosively in heat engines or quietly in fuel cells to produce water as its only byproduct. Hydrogen is abundant and generously distributed throughout the world without regard for national boundaries; using it to create a hydrogen economy—a future energy system based on hydrogen and electricity—only requires technology, not political access.

Although in many ways hydrogen is an attractive replacement for fossil fuels, it does not occur in nature as the fuel H_2. Rather, it occurs in chemical compounds like water or hydrocarbons that must be chemically transformed to yield H_2. Hydrogen, like electricity, is a carrier of energy, and like electricity, it must be produced from a natural resource. At present, most of the world's hydrogen is produced from natural gas by a process called steam reforming. However, producing hydrogen from fossil fuels would rob the hydrogen economy of much of its raison d'être: Steam reforming does not reduce the use of fossil fuels but rather shifts them from end use to an earlier production step, and it still releases carbon to the environment in the form of CO_2. Thus, to achieve the benefits of the hydrogen economy, we must ultimately produce hydrogen from non-fossil resources, such as water, using a renewable energy source.

Figure 1 depicts the hydrogen economy as a network composed of three functional steps: production, storage, and use. There are basic technical means to achieve each of these steps, but none of them can yet compete with fossil fuels in cost, performance, or reliability. Even when using the cheapest production method—steam reforming of methane—hydrogen is still four times the cost of gasoline for the equivalent amount of energy. And production from methane does not reduce fossil fuel use or CO_2 emission. Hydrogen can be stored in pressurized gas containers or as a liquid in cryogenic containers, but not in densities that would allow for practical applications—driving a car up to 500 kilometers on a single tank, for example. Hydrogen can be converted to electricity in fuel cells, but the production cost of prototype fuel cells remains high: $3000 per kilowatt of power produced for prototype fuel cells (mass production could reduce this cost by a factor of 10 or more), compared with $30 per kilowatt for gasoline engines.

The gap between the present state of the art in hydrogen production, storage, and use and that needed for a competitive hydrogen economy is too wide to bridge in incremental advances. It will take fundamental breakthroughs of the kind that come only from basic research.

Beyond reforming

The US Department of Energy estimates that by 2040 cars and light trucks powered by fuel cells will require about 150 megatons per year of hydrogen.[3] The US currently produces about 9 megatons per year, almost all of it by reforming natural gas. The challenge is to find inexpensive

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December 2004 Physics Today 39

Basic Energy Sciences
Department of Energy
July 2003/February 2004
http://www.sc.doe.gov/bes/hydrogen.pdf

National Research Council
National Academy of Sciences
February 2004
http://www.nap.edu/catalog/10922.html

G. W. Crabtree, M. S. Dresselhaus, M. V. Buchanan
Physics Today **57**(12), 39-44, 2004
http://www.physicstoday.org/vol-57/iss-12/p39.html

Other hydrogen studies reach similar conclusions

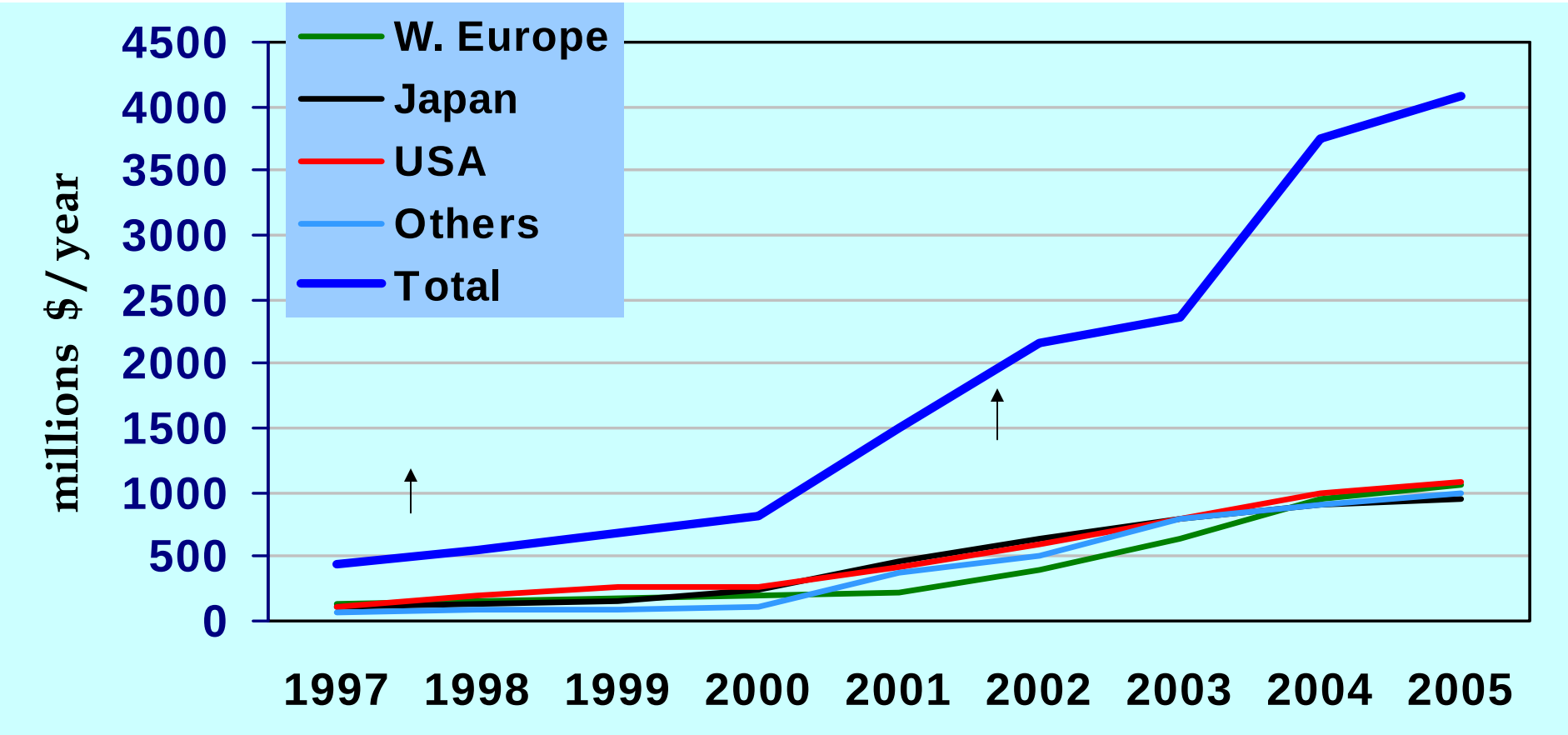
Why Nanostructural materials are important for energy-based applications

- New desirable properties are available at the nanoscale but not found in conventional 3D materials e.g., higher diffusion coefficient to promote hydrogen release

- Higher surface area – promotes catalytic interactions

- Independent control of nanomaterials parameters which are interdependent for 3D materials.

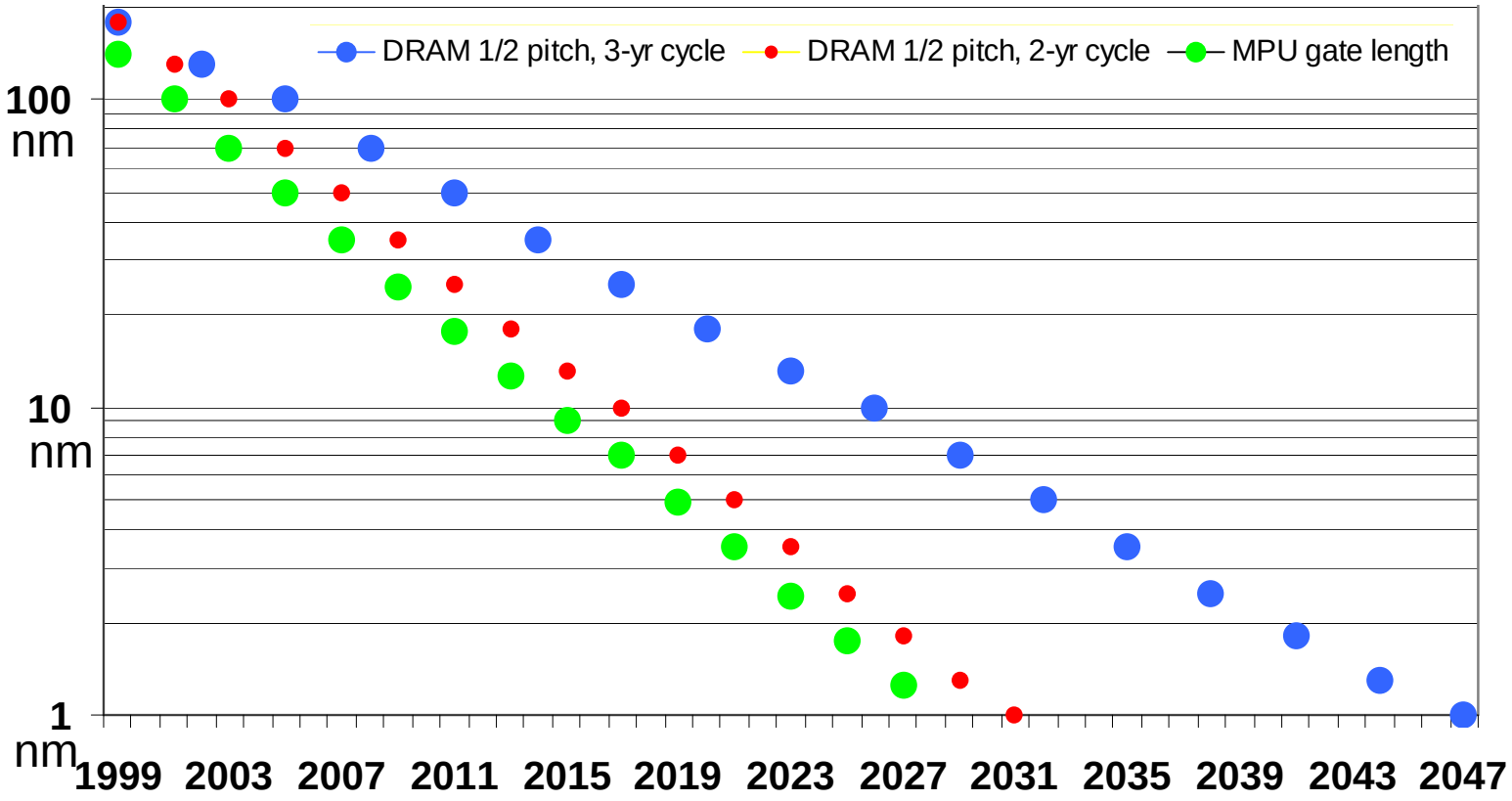
Context – Nanotechnology in the World Government investments 1997-2005



The Worldwatch Institute, State of the World 2006: a Worldwatch Institute report on progress toward a sustainable society.

Moore's Law for semiconductor electronics

soon, all microchips will be nanoscale devices

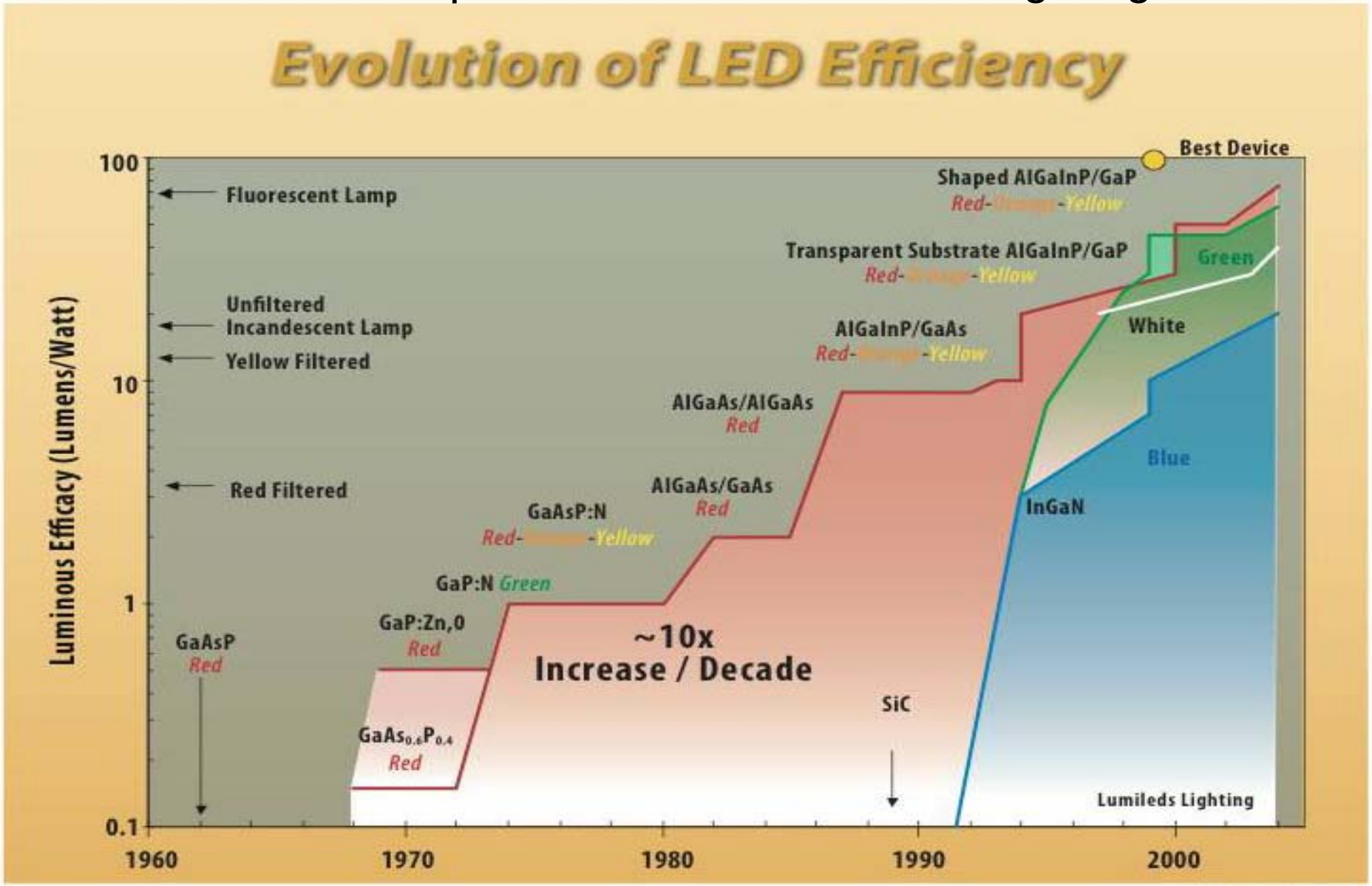


CONCLUSION: *Moore's law continues for this decade regarding future size, device performance and cost for semiconductor electronics industry.*

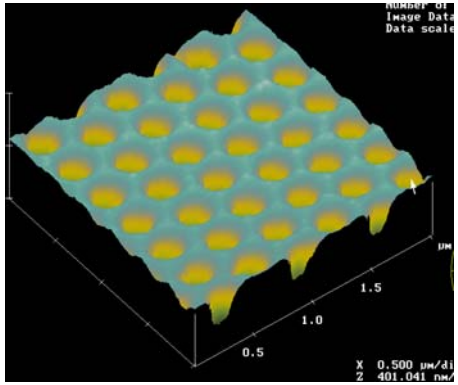
Extension of Moore's Law to the Energy Industry

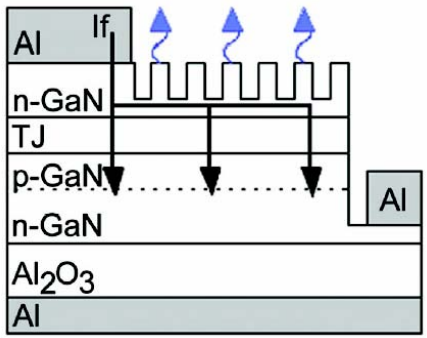
- Moore's law has for many years been working to set goals for electronics, opto-electronics, and magnetics industries.
- We now need to apply Moore's law to set goals for the energy industry.

Moore's law for Solid-State Lighting at Half the Energy Consumption as for Conventional Lighting

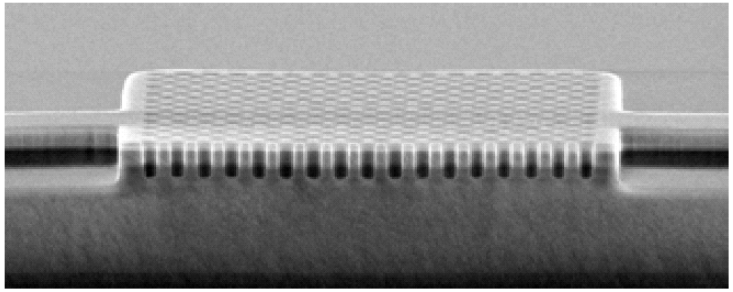


Emerging Nanotechnologies will further increase Solid State Lighting energy efficiency





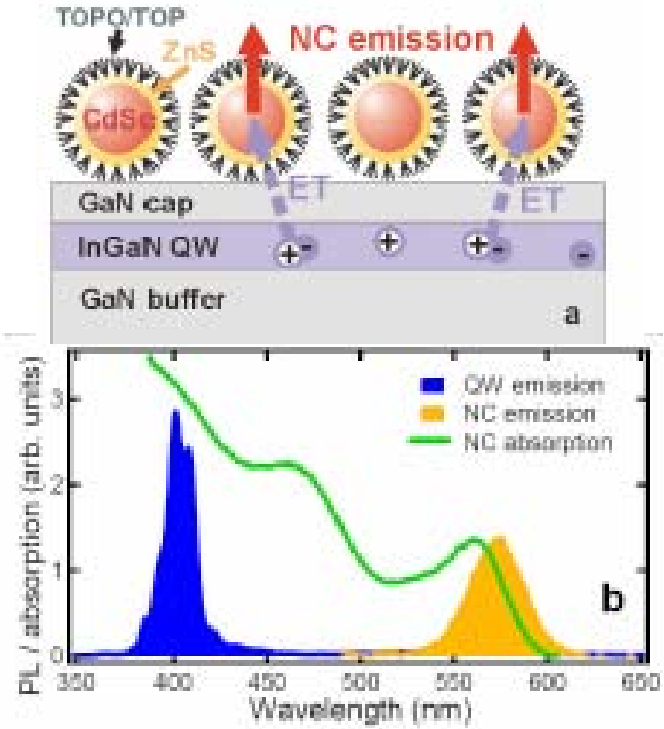
AFM Image courtesy of Lumileds & Sandia



Photonic Crystal LEDs

Patterning of LEDs with 2D photonic lattices could force all emission to be normal to the surface and could double the efficiency of LEDs.

(J. Weirer et al., APL 84, 3885, (2004))



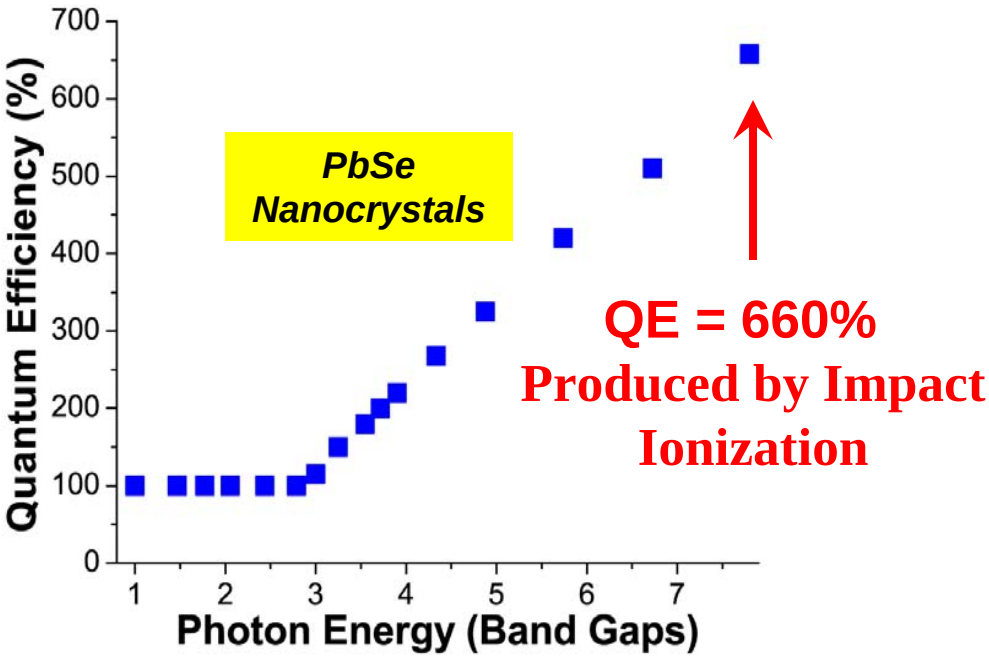
Nanocrystalline Quantum Dots as Phosphor Alternatives

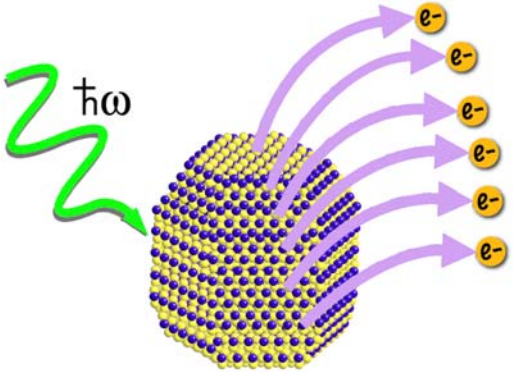
Nanoscale dimensions of the quantum dots allow for an efficiency of more than 50% and also output tunable in wavelength.

(M. Achermann et al., Nature 429, 642, (2004))

Discovery of Ultra-Efficient Carrier Multiplication in Semiconductor Nanocrystals

- **Observation of more than 6 e-h pairs produced by 1 photon**

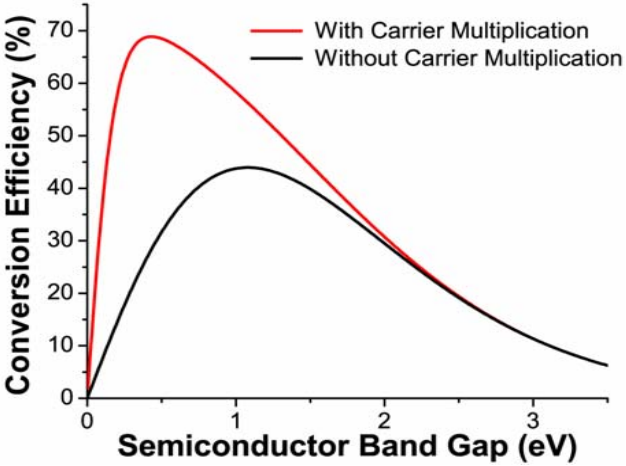




R. D. Schaller & V. I. Klimov, *Phys. Rev. Lett.* 92, 186601 (2004)

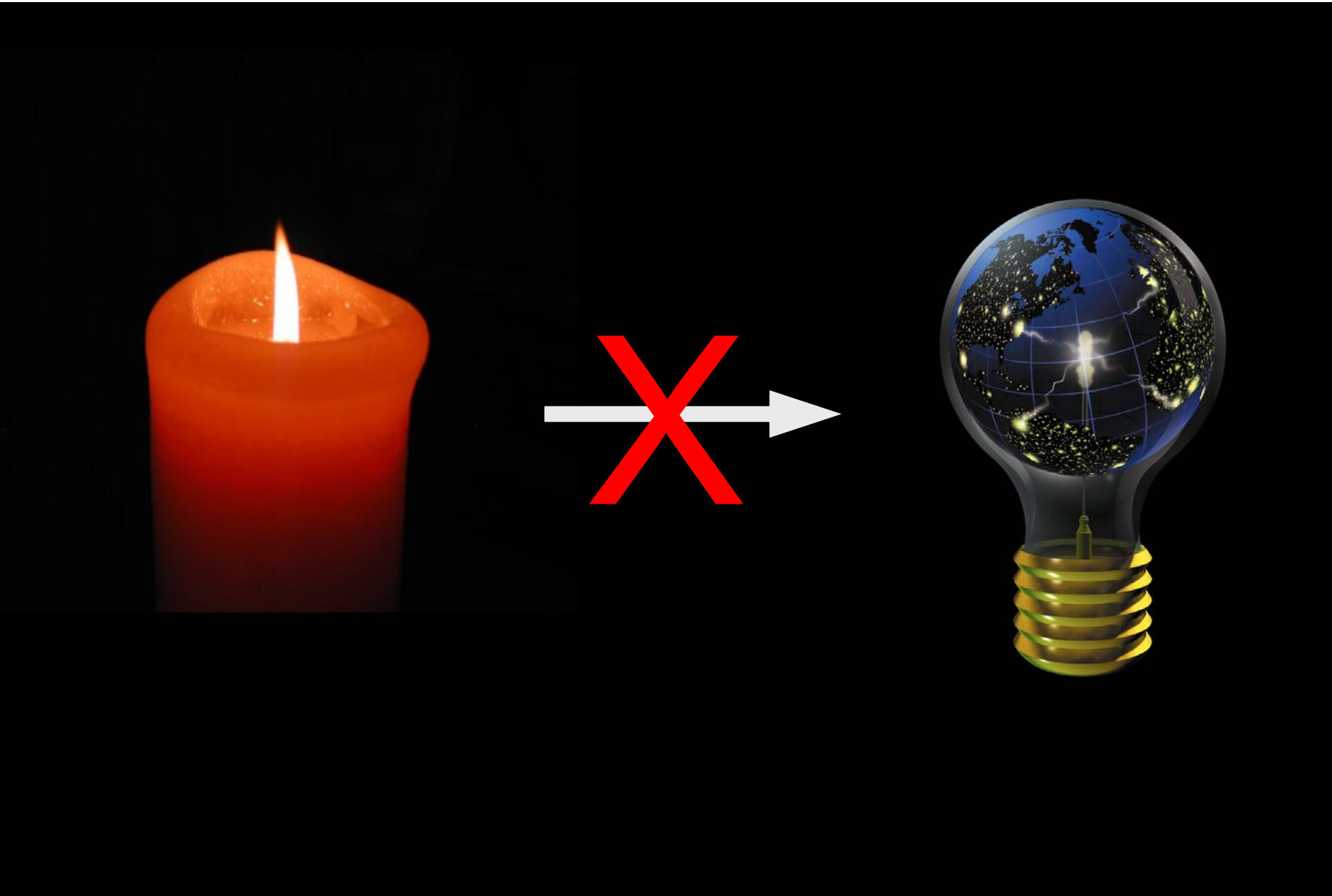
- **Single Band-Gap "Ultimate" Conversion Efficiency of Solar Cells:**

Potential increase up to ~70% !



Los Alamos

... but electricity was not discovered via incremental improvements to the candle



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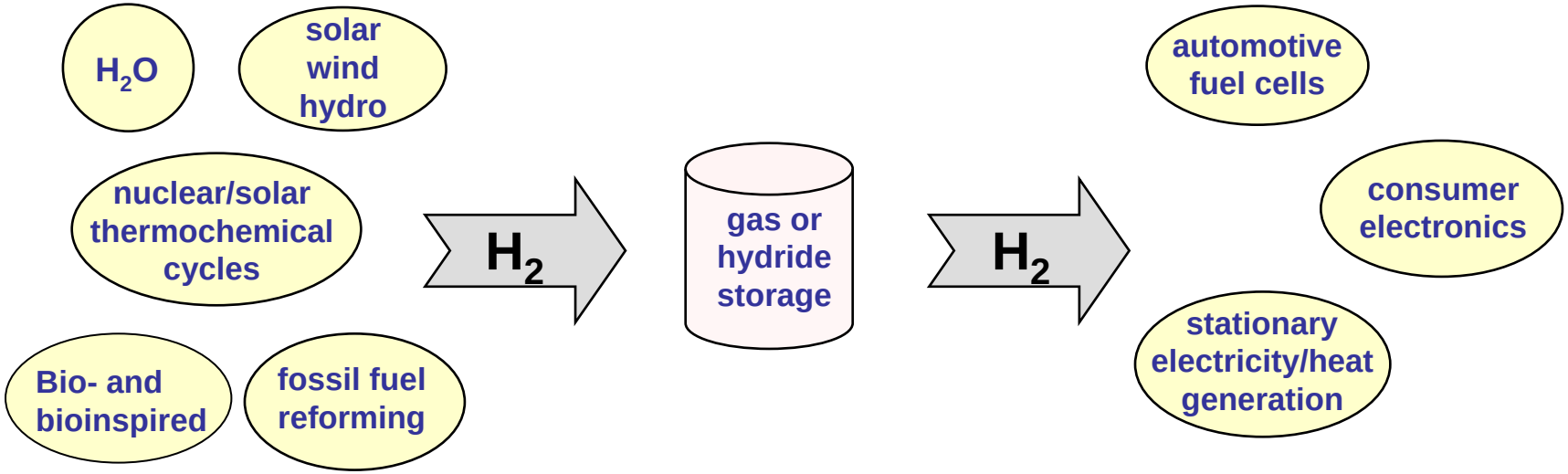
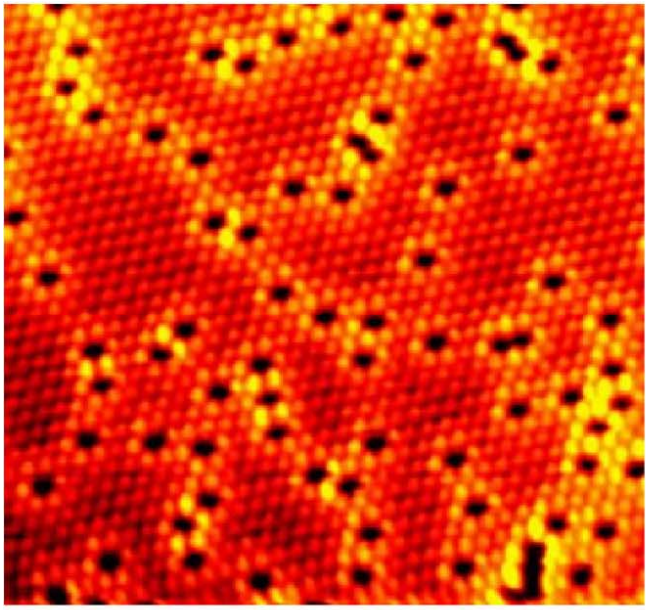
Hydrogen as an Energy Carrier
The Technology Gaps

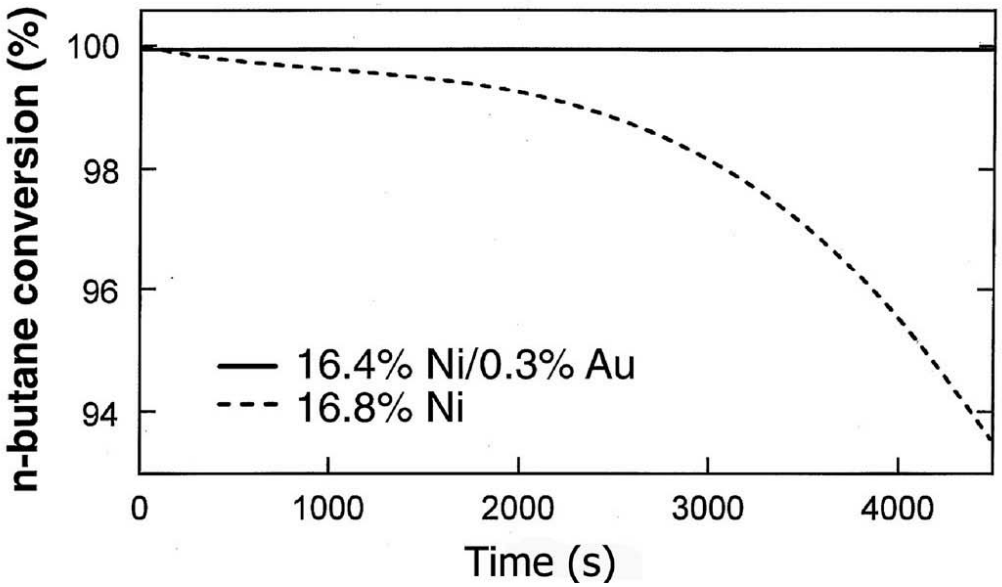


production	*storage*	*use (in fuel cells)*
9M tons/yr	**4.4 MJ/L (Gas, 10,000 psi)** **8.4 MJ/L (LH2)**	**$200-3000/kW**
Gap	*Gap*	*Gap*
150M tons/yr **(Light Cars and Trucks in 2040)**	**9.7 MJ/L** **(2015 FreedomCAR Target)**	**$30/kW** **(Internal Combustion Engine)**

Fossil Fuel Reforming in Hydrogen Production

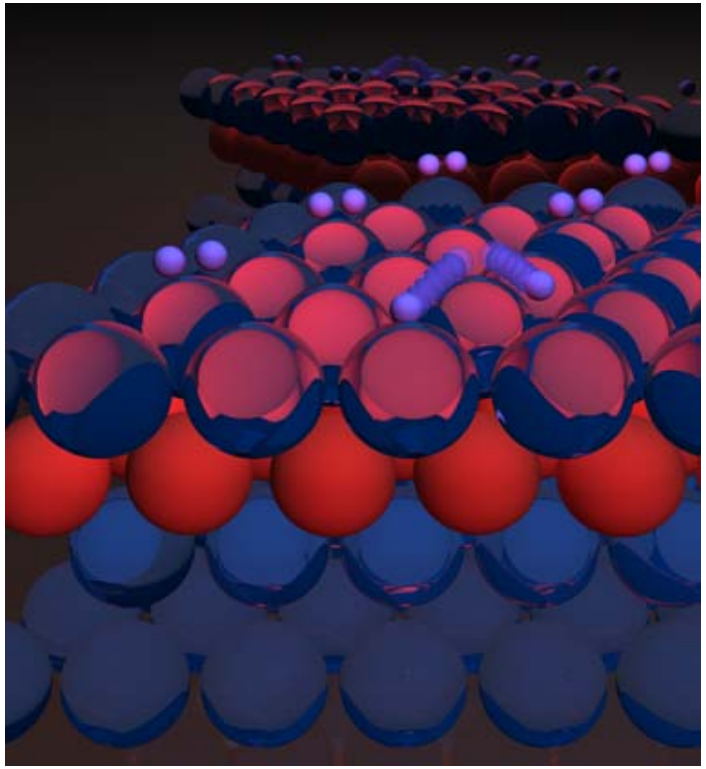
- **For the next decade or more, hydrogen will mainly be produced using fossil fuel feedstocks.**
- **Development of efficient inexpensive <u>catalysts</u> will be key.**
- **<u>Modeling and simulation</u> will play a significant role.**





Inspired by quantum chemical calculations, Ni surface-alloyed with Au (black) on the left is used to reduce carbon poisoning of catalyst, as verified experimentally on the right.

Catalysts: Predicting Catalysts for Hydrogen Production, Storage or Fuel-Cell Utilization



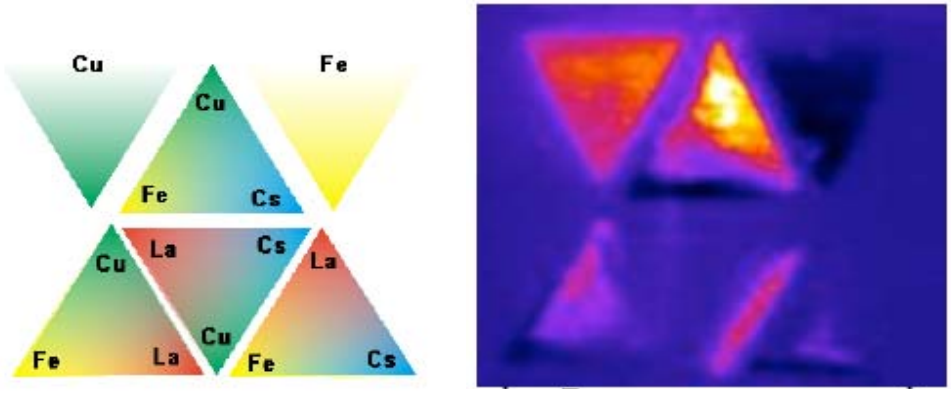
Theoretical calculation of molecular hydrogen undergoing dissociation over near-surface alloys.

- Small purple spheres: hydrogen
- Blue spheres: platinum atoms
- Red spheres: nickel atoms
- Bicolor blue and red spheres: platinum atoms whose electronic properties have been dramatically altered by the underlying nickel.

- There is a need for low-temperature, highly efficient and durable catalysts for large scale hydrogen production.
- New catalyst structures and compositions are now being predicted *a priori* using quantum chemistry and molecular dynamics.
- Single metallic layers of one metal embedded within a matrix of another metal produce low-energy hydrogen scission and recombination.
- Nickel within platinum can attach atomic hydrogen weakly like copper and gold, while dissociating molecular hydrogen rapidly like platinum and rhodium.
- This study may lead to breakthroughs in hydrogen production, storage and combustion in fuel cells.

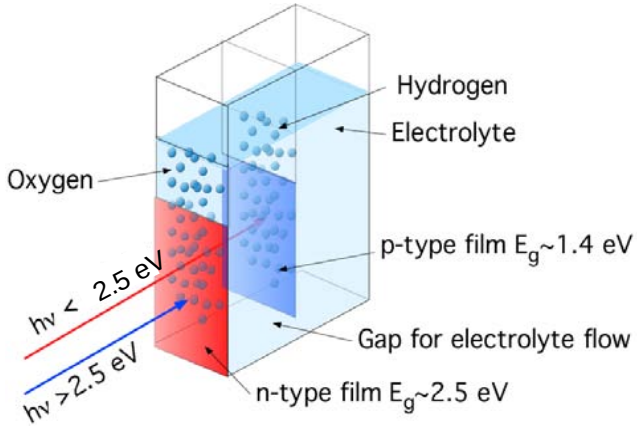
J. Zhang, et al, Angew. Chem. Int Ed. **44**, 2132 (2005)

Solar Hydrogen Production: The Search for the Ideal Mixed-Metal Oxide Photoelectrode



Ink jet patterning of metal oxides

Operational cell for solar water splitting



G.S. Herman and B.A. Parkinson, Chem. of Materials **17**, 4318 (2005)

- Solar water splitting by semiconductor electrodes is the ideal method for production of hydrogen fuel.
- A novel high-throughput search seeks to find a semiconductor with the band gap of 1.6eV to 2.0 eV needed for simultaneous hydrogen and oxygen evolution.
- This search seeks compound metal oxides for water splitting that contain up to four different metals. Some metals provide structure and stability, some the color of light absorption, and others provide charge compensation and recombination suppression.
- The high throughput search is made possible with the use of a three-cartridge ink jet printer where the cartridges are filled with different metal nitrate precursor solutions.
- A triangular pattern with all possible variations of the three metal inks is printed on a conductive glass where each position contains a different combination of metals.
- The triangle is scanned point by point with a laser to assess the potential of each combination for water splitting.

High Throughput Combinatorial Screening

Materials Fabrication

Proof of concept

Science **268**, 1738 (1995).

Combinatorial Materials Screening

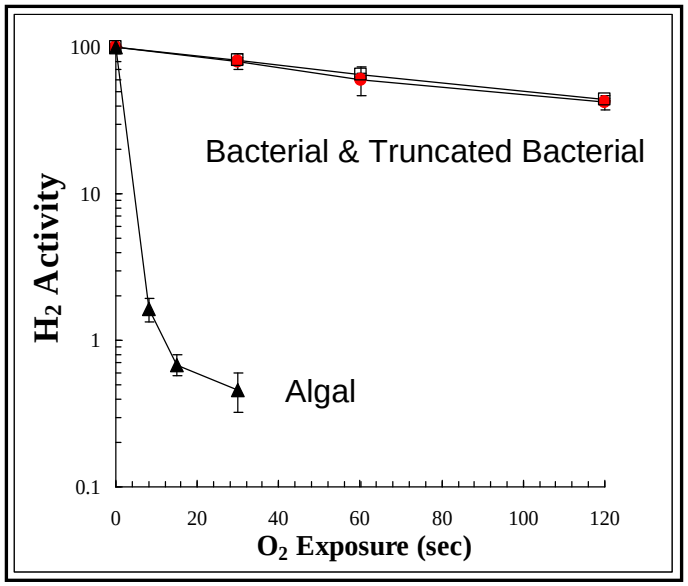
Series Process vs. **Parallel Process**

(one at a time) **(up to a thousand at a time)**

High throughput combinatorial screening methods are widely applicable for optimizing alloying of nanostructures for enhancing specific properties

Bio-Inspired Processes: Effects of structure truncation on Oxygen Tolerance of Hydrogenase

Bacterial | Truncated Bacterial (Genetically Modified) | Algal



P. W. King, et al, Proc. SPIE Vol. 6340, 63400Y (2006)

- Large scale production of hydrogen by mimicking the processes used either in algae or in bacteria.
- [FeFe]-hydrogenase from bacterium is >100 times more tolerant of oxygen than algal enzyme.
- Natural hydrogenases (e.g., bacterial enzyme) are typically not robust enough to operate under non-biological conditions.
- A truncated bacterial enzyme with a simpler structure has been developed and exhibits oxygen tolerance similar to natural systems.
- Subtle structural differences between truncated bacterial and algal enzymes provide important insights into the origins of oxygen-tolerance.
- Simplified and robust synthetic mimics of bacterial hydrogenase are essential for the development of a commercial hydrogen-producing system that is cost effective, scalable to large production, non-polluting, and self-sustaining.

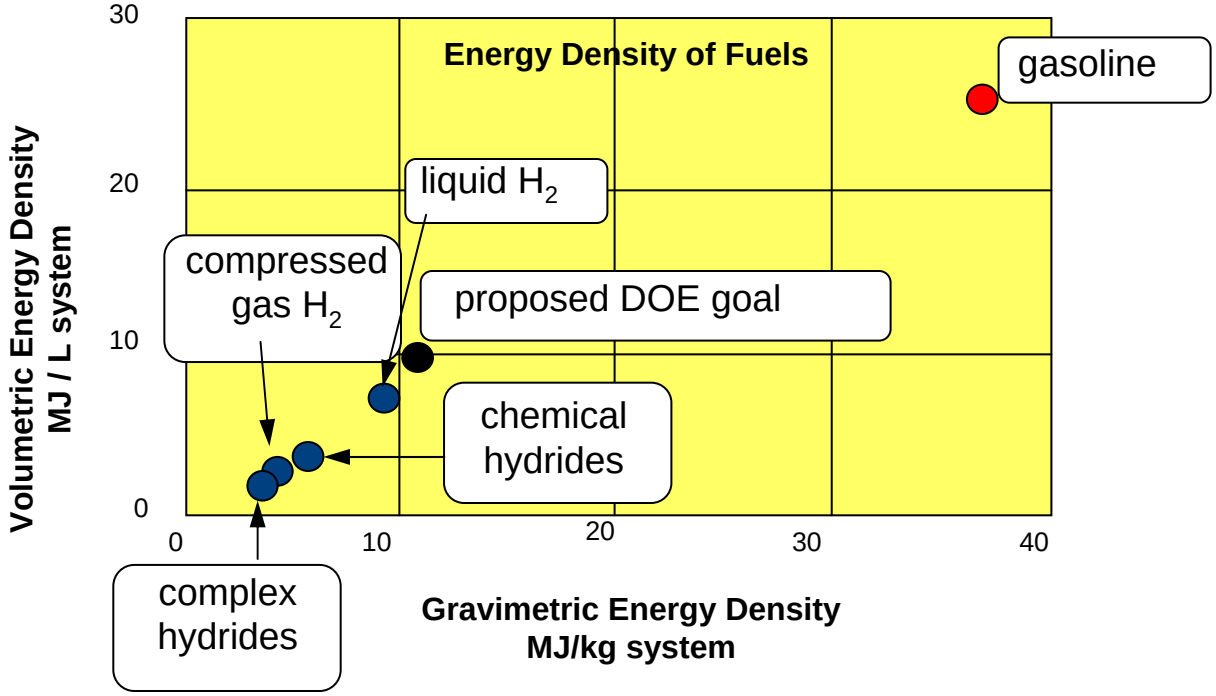
Hydrogen Storage

Current Technology for automotive applications

- Tanks for gaseous or liquid hydrogen storage.
- Progress demonstrated in solid state storage materials.

System Requirements

- Compact, light-weight, affordable storage.
- System requirements set for FreedomCAR: 4.5 wt% hydrogen for 2005, 9 wt% hydrogen for 2015.
- No current storage system or material meets all targets.



Ways to Store Hydrogen

- Compressed gas
- Liquid hydrogen
- Condensed state

Issues

- Volumetric density
- Gravimetric density
- Kinetics, release temperature
- Refueling rate and Heat transfer
- Energy efficiency
- Reversibility
- Cost

U.S. DOE Targets

Table 1 FreedomCAR Hydrogen Storage System Targets

Targeted Factor	2005	2010	2015
▶Specific energy (MJ/kg)	5.4	7.2	10.8
Hydrogen (wt%)	4.5	6.0	9.0
▶Energy density (MJ/L)	4.3	5.4	9.72
System cost ($/kg/system)	9	6	3
Operating temperature (°C)	-20/50	-20/50	-20/50
Cycle life-time (absorption/desorption cycles)	500	1,000	1,500
Flow rate (g/s)	3	4	5
Delivery pressure (bar)	2.5	2.5	2.5
Transient response (s)	0.5	0.5	0.5
Refueling rate (kg H_2/min)	0.5	1.5	2.0

[a] Source: Milliken (2003).

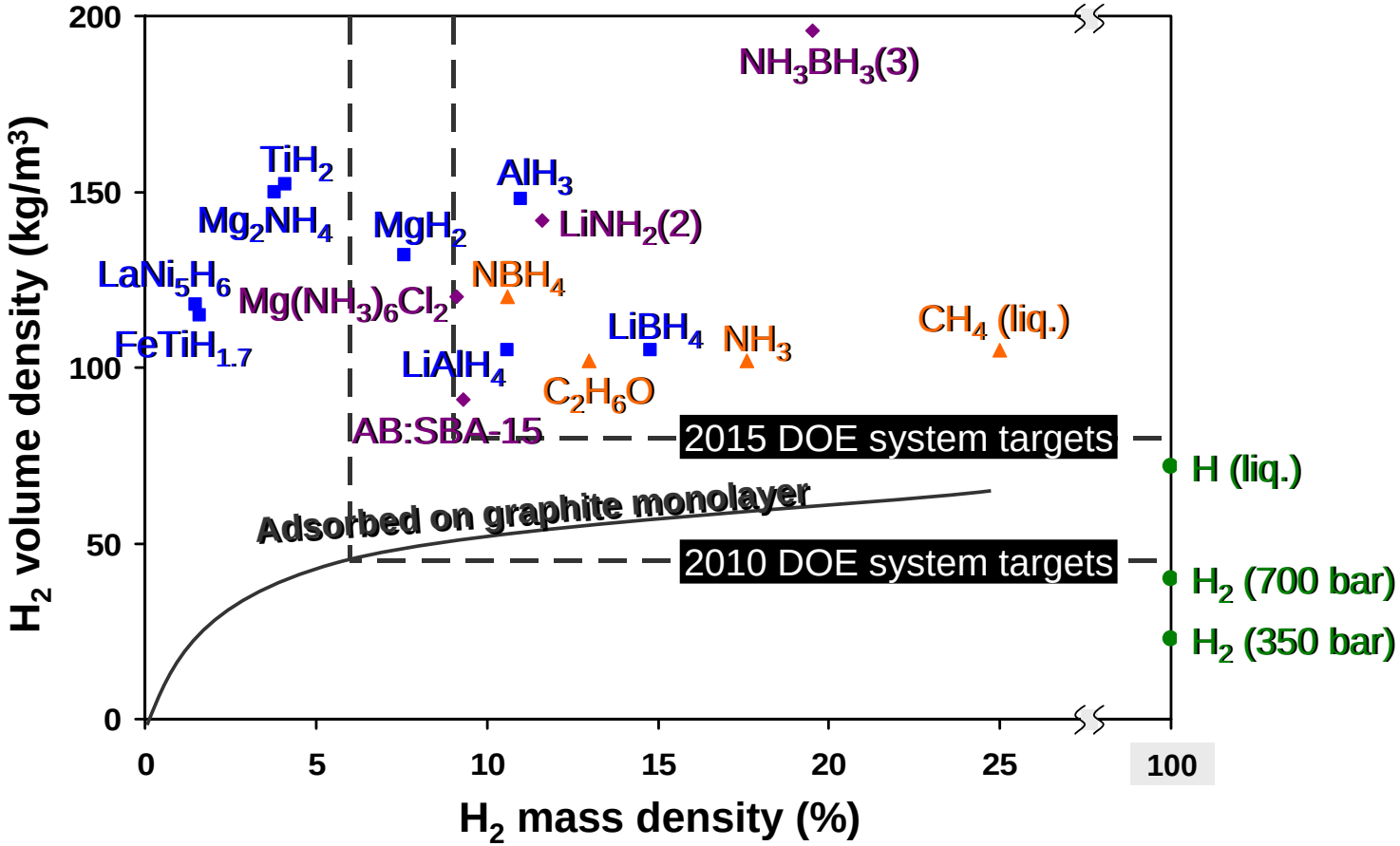
Hydrogen Storage Options

Metal/complex hydrides:

- Slow kinetics
- Heat management issues
- High release temperature

Chemical hydrides:

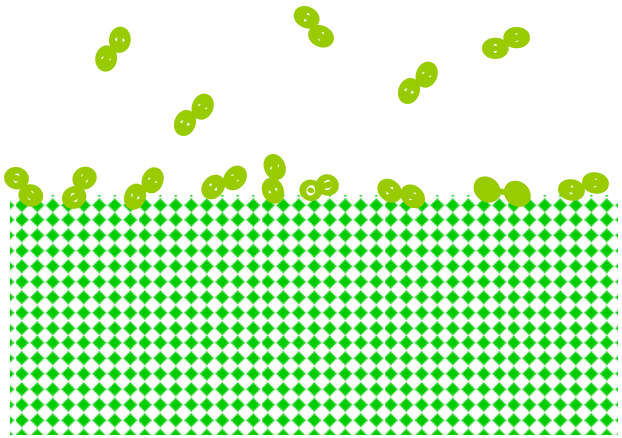
- Not reversible (on-board)



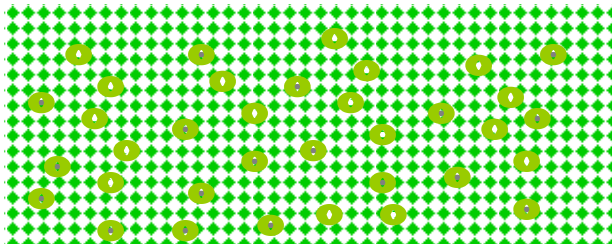
Carbon structures:

- Low temperature
- Too low wt. % for 2015
- Low energy barrier for hydrogen release

Hydrogen Storage in Condensed States



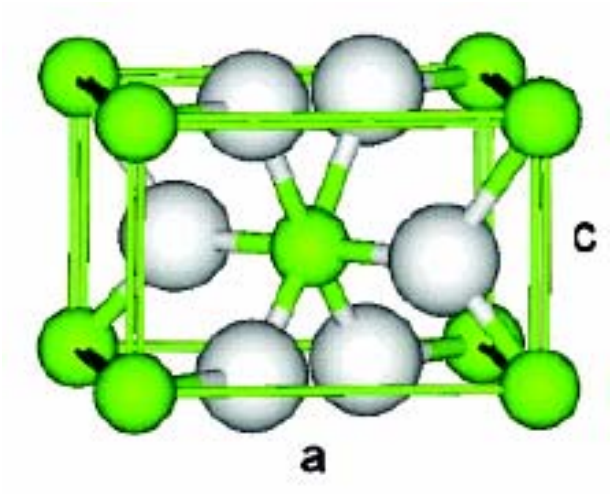
Physisorption
Adsorption on Surface



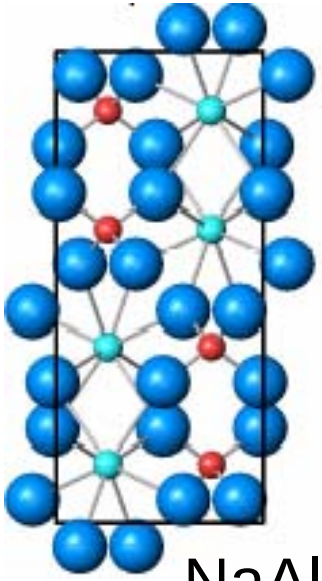
Chemisorption
Absorption into Matter

Chemisorption Categories

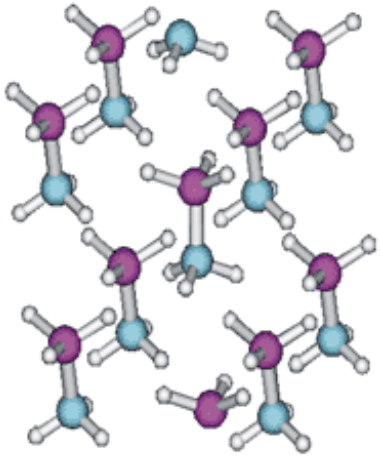
- Metal hydrides: MgH_2
- Complex hydrides: $NaAlH_4$
- Chemical hydrides: $LiBH_4$, NH_3BH_3



MgH_2



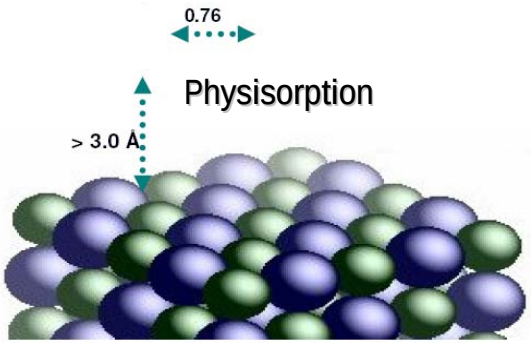
$NaAlH_4$



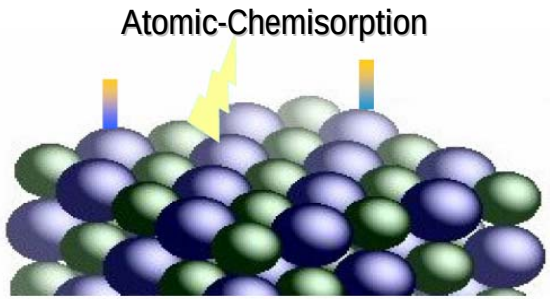
NH_3BH_3

Nature of Hydrogen Bonding

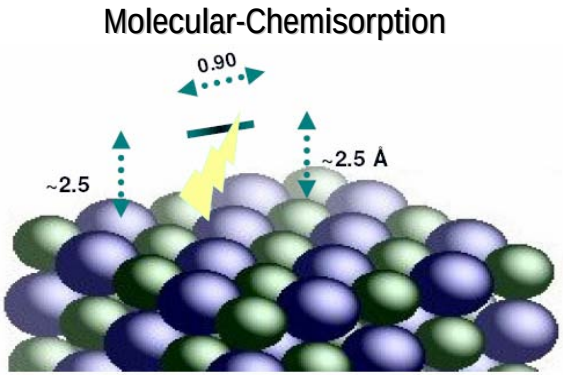
• **Physisorption:** Hydrogen binds in molecular form with a binding energy of the order of a few meV's/ H_2 molecule – Binding is too weak and hydrogen desorbs at low temperatures.



• **Chemisorption:** Hydrogen binds dissociatively with a binding energy of the order of 2 – 4 eV/H_2 molecule – Binding is too strong and hydrogen desorbs at high temperatures.



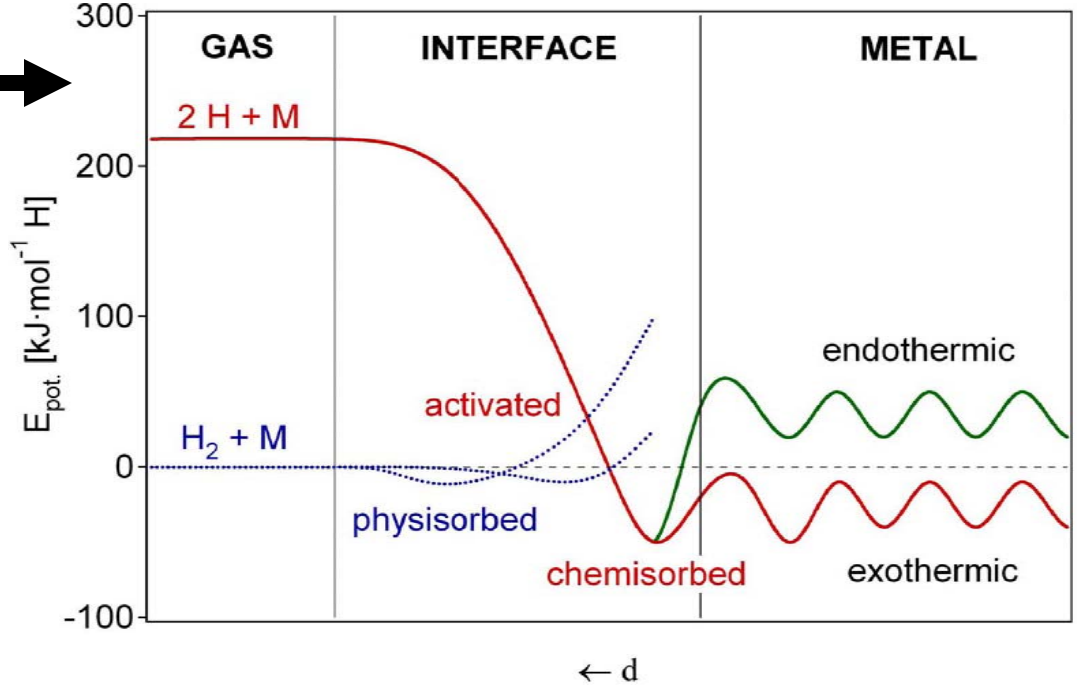
• **Ideal Hydrogen bonding:** Binding should be intermediate between physisorption and chemisorption with a binding energy in the range of 0.2 to 1.0 eV/H_2 molecule . Hydrogen can then be stored reversibly at near ambient thermodynamic conditions.



Desired binding energy range

Potential energy for molecular and atomic hydrogen absorption

Activated reaction increases release temperature if no catalysts are used



J. E.Lennard-Jones, Trans. FaradaySoc. 28 (1932),pp. 333.

Desirable range of binding energies: 10-60 kJ/mol (0.1 - 0.6 eV)

Carbon physisorption

AlH_3 MgH_2 TiH_2 LiH H-I H-SH $H-CH_3$ 2H H-OH

0 100 200 300 400 500

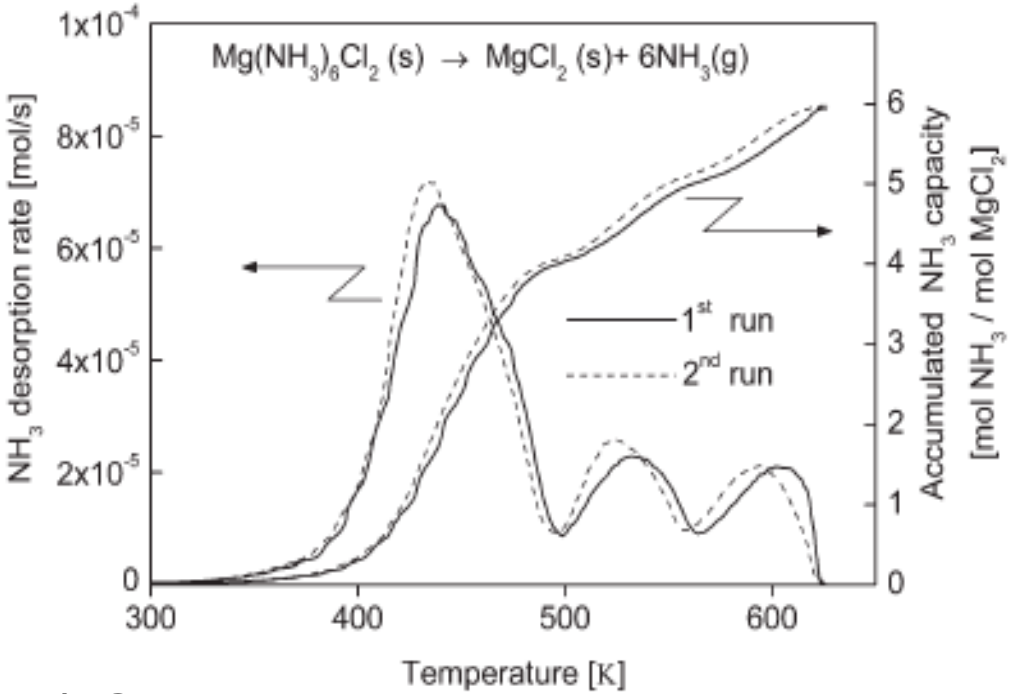
Physisorption
Low temperature
Molecular H_2

Bond strength [kJ/mol]

Chemisorption
High temperature
Atomic H

Metal ammine complexes

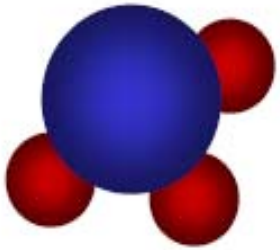
	Gravimetric H_2 density (% H_2)	Volumetric H_2 density/ (kg m^{-3})
$Mg(NH_3)_6Cl_2$	9.1	110
$Ca(NH_3)_8Cl_2$	9.7	120



- $Mg(NH_3)_6Cl_2 = MgCl_2 + 6NH_3$ (9.1%) @ T <620K
- NH_3 can be used in high T solid oxide fuel cells.
- High temperature of hydrogen release

$$2NH_3 \rightarrow 3H_2 + N_2 \text{ @ ~600K}$$

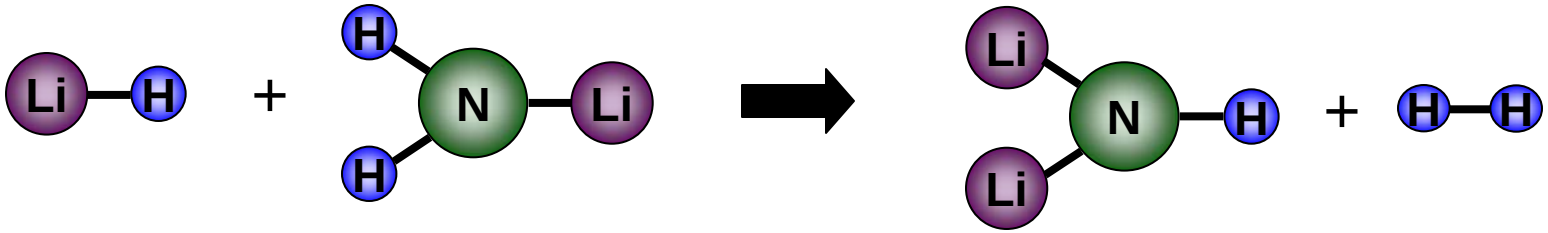
- Technology being developed for battery applications



Christensen et al., J. Mater. Chem., 2005, 15, 4106–4108

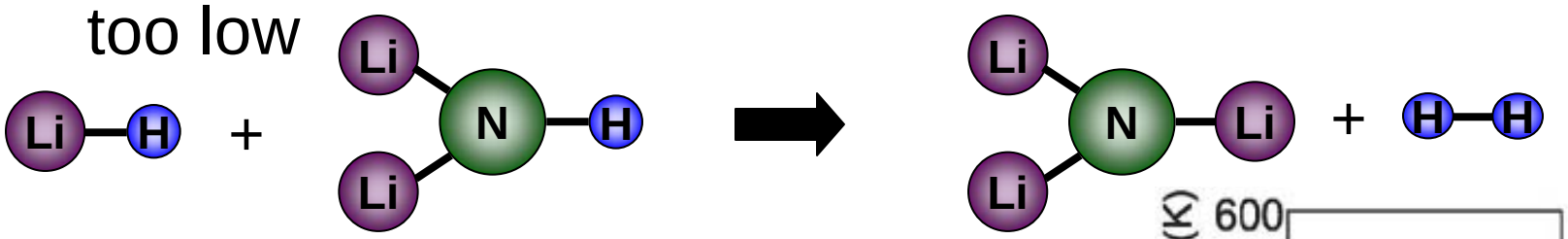
Imide (NH) and Amide (NH_2)

First step: $LiNH_2 + LiH \Leftrightarrow Li_2NH + H_2$ (6.55% @ 300C,1atm.)



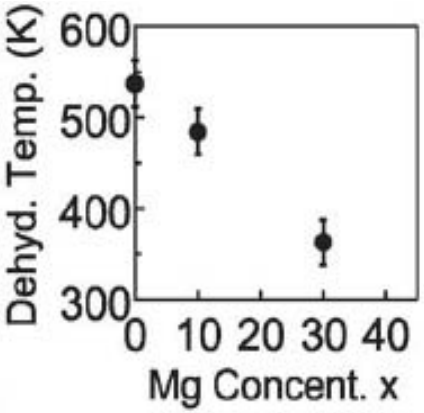
Second: $Li_2NH + LiH \Leftrightarrow Li_3N + H_2$ (5% @ 300C, 0.05atm)

- Release temperature is too high and release pressure is too low



Partial Mg substitution reduces release temperature using an alloying approach

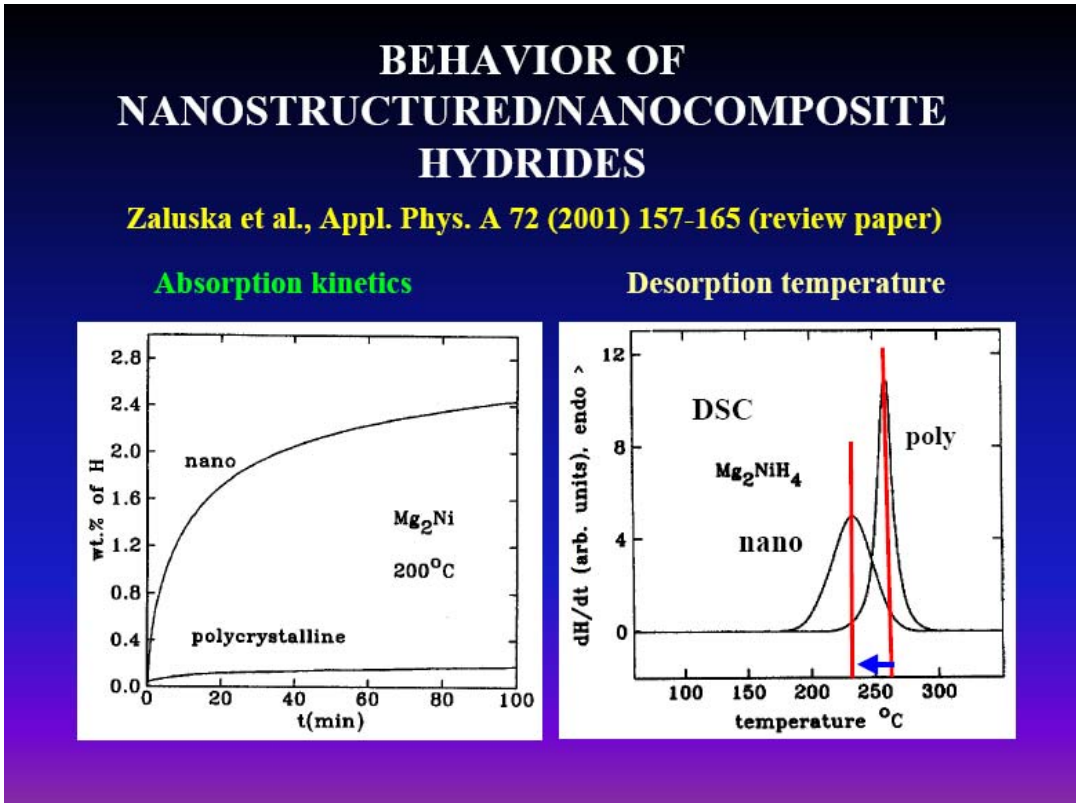
$Li_{1-x}Mg_xNH_2$

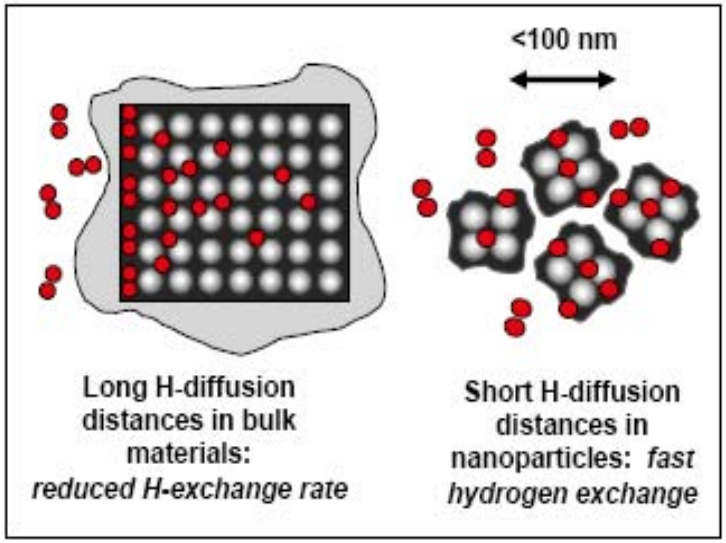


S. Orimo et al., Appl. Phys. A:Materials Science & Processing, Vol 79, No 7, p. 1765 - 1767.

Improving sorption properties with nanotechnology

- The bulk hydride sorption rate is prohibitively small and release temperature is too high.
- Poor heat transfer leads to process interruption.
- Reducing grain and particle size increases kinetics and hydrogen uptake.





•Increased porosity and smaller size increase diffusion rate.

•Surface energies and materials properties at nanoscale offer ways to tune the energetics of absorption and desorption to reduce release temperature and to speed up release process.

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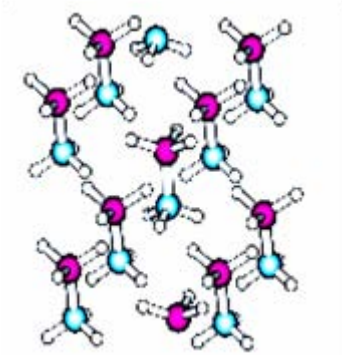
Hydrogen Storage: Chemistry and Nanoscience

NH_3BH_3

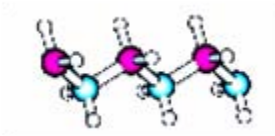


Ammonia Borane

solid: di-hydrogen bonds

$\Delta E \sim +8.8$ kcal/mole ~ 120°C

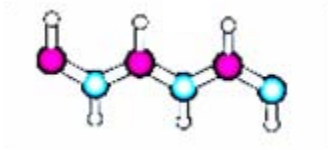
$(NH_2BH_2)_n + H_2$



solid

$\Delta E \sim -3.2$ kcal/mole ~ 120°C

$(NHBH)_n + H_2$

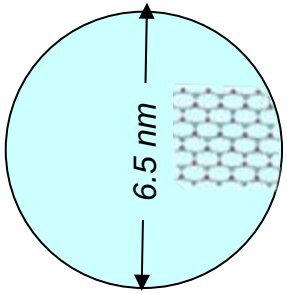


solid

> 12% mass released as H_2

simulation: ~ thermo-neutral

Stable, non-toxic



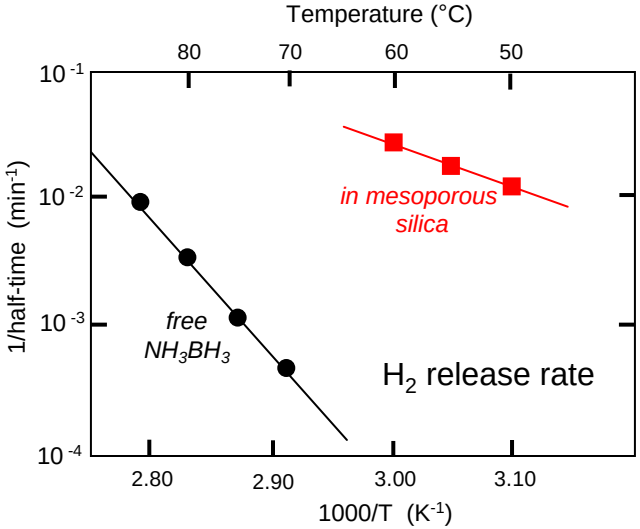
nano-phase trapping

NH_3BH_3 in mesoporous silica

SBA-15

release rate increased
1-2 orders of magnitude

undesirable borazine
eliminated



issues:
nanophase mechanism
reversibility

Gutowska, Autrey et al. ,Angew. Chem. Int. Ed. 2005, 44, 3578 –3582.

Van't Hoff plots

- At constant temperature, a change in free energy obeys

$$dG = VdP$$

$$G^{H_2} = G_o^{H_2} + RT\ln(\frac{P^{H_2}}{P_o})$$

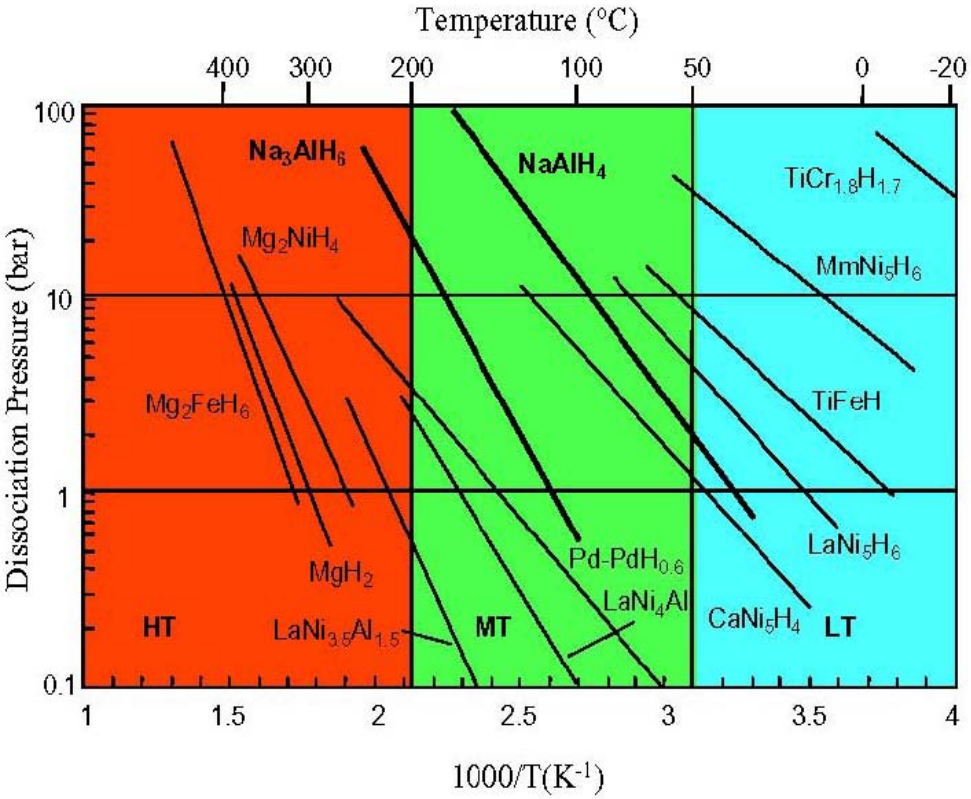
- Where P_o=1atm is the pressure at which the standard free energy G_o is measured.
- For a hydriding reaction we get

$$\Delta G^{reaction} = \Delta G_o^{reaction} - RT\ln P^{H_2}$$

- In equilibrium the change in free energy is 0

$$\Delta G_o^{reaction} = RT\ln(P_{eq}^{H_2})$$

$$\frac{\Delta H_o^{reaction}}{RT} - \frac{\Delta S_o^{reaction}}{R} = \ln P_{eq}^{H_2}$$



Van't Hoff plot showing dissociation pressure and temperature of various hydrides (Source: Bogdanovic and Sandrick 2002)

- The slope of a plot of $\ln(P_{eq})$ as a function of 1/RT gives the enthalpy of the reaction and the entropy change is given by the intersection with the ordinate axis.

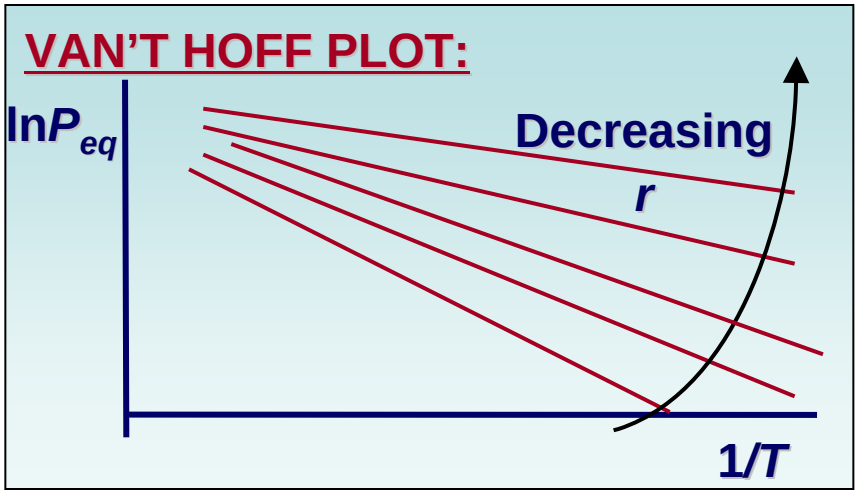
Size Effects on Thermodynamic Properties

Assuming the following reaction

$$M + H_2 \rightarrow MH_2$$

- At the nanoscale, the surface energy becomes important and it modifies the free energy.
- If the surface energy term Δ is positive, enthalpy of formation will be reduced for smaller particles.

Van't Hoff plot for a model MH_2 hydride



Bulk molar free energy of formation

$$\Delta G = \Delta G_o + RT \ln\left(\frac{a_{MH}}{a_M P_{H_2}}\right)$$

Van't Hoff relation

$$\ln P_{H_2}^{eq} = \frac{\Delta H_o}{RT} - \frac{\Delta S_o}{R}$$

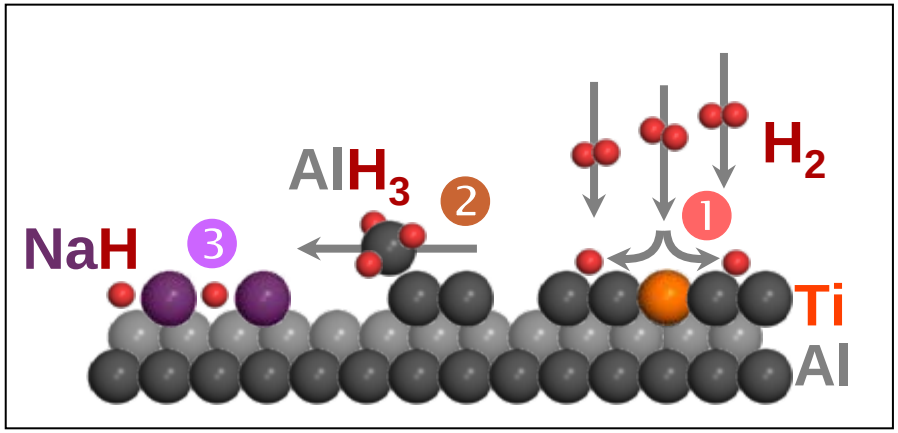
Nanoparticle molar free energy of formation

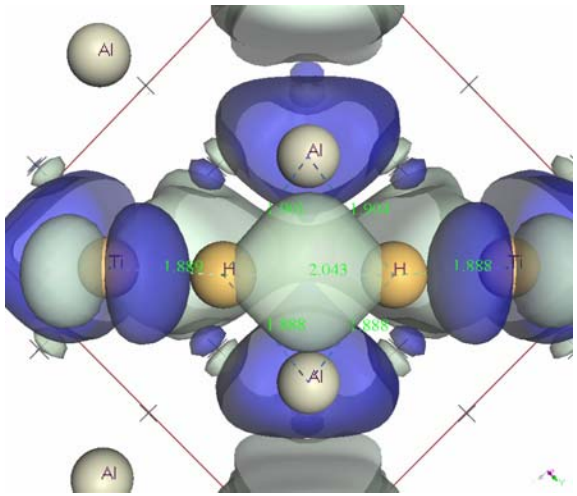
$$\Delta G(r) = \Delta G_o(r) + RT \ln\left(\frac{a_{MH}}{a_M P_{H_2}}\right) + \frac{3\overline{V_M}\Delta(\gamma_{Mg}, \gamma_{MgH_2}, r)}{r}$$

Nanoscale Van't Hoff relation

$$\ln P_{H_2}^{eq} = \frac{\Delta H_o}{RT} + \frac{3\overline{V_M}\Delta}{rRT} - \frac{\Delta S_o}{R}$$

Hydrogen Storage: Atomistic Transport Mechanisms in Reversible Complex Metal Hydrides





Molecular orbital model of the Ti-doped Al surface with hydrogen. The model shows the highest occupied molecular orbital (HOMO) configuration after the H_2 adsorption and dissociation.

- Titanium-doped sodium alanate ($NaAlH_4$) is one complex hydride material storing hydrogen reversibly at moderate temperature and pressure.

- Key: Hydrogenation ("fueling") reaction to $NaAlH_4$
  - ❶ Di-hydrogen (H2) adsorption & dissociation
  - ❷ Formation & diffusion of mobile surface species
  - ❸ Solid state reaction with sodium hydride (NaH).

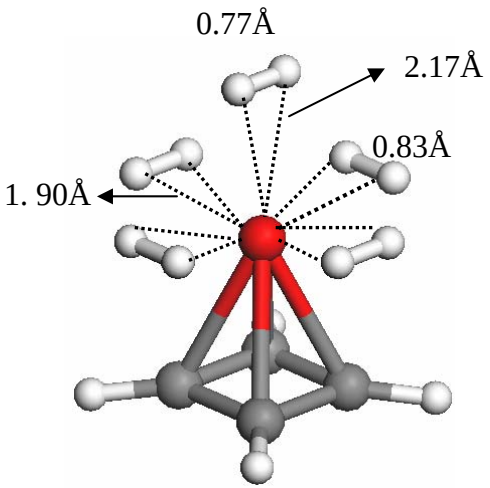
- Key step in the hydrogenation of $NaAlH_4$ identified

- Theory shows that a specific Ti:Al complex near the (001) surface of Al in the hydrogen-depleted storage material dissociates di-hydrogen (H_2) to atomic-H, part ❶ (above)

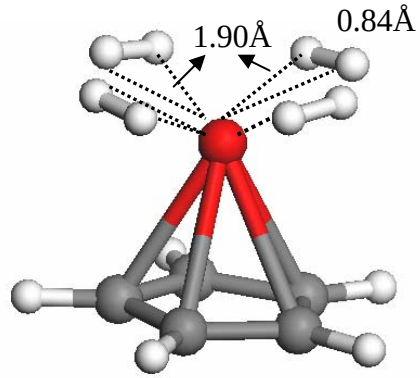
- This finding is an important step toward understanding how Ti catalysts enable fast hydrogen uptake and release in $NaAlH_4$.

Transition Metal decorated Organic Complexes

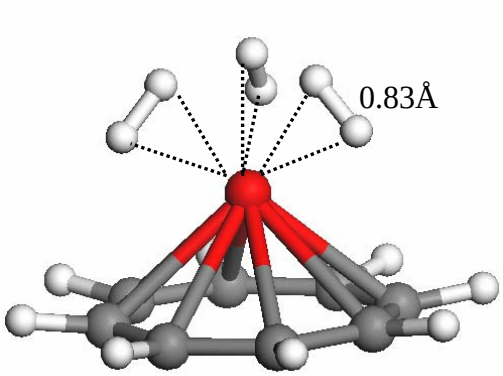
Some new approaches for designing molecules with high capacity and suitable binding energy.



$TiC_4H_4\ (H_2)_5$



$TiC_5H_5\ (H_2)_4$



$TiC_8H_8\ (H_2)_3$

Wt%	9.09	6.61	2.21
Avg. BE:	0.55 eV	0.72 eV	0.57eV

"Hydrogen Storage and the 18 electron rule", B. Kiran, A. K. Kandalam, and P. Jena
J. Chem. Phys. 124, 224703 (2006)

Summary of strategies to reduce release temperature

- Destabilize materials by forming ternary, quaternary and higher order alloys
- Doping to destabilize materials
- Ball milling of hydride or other methods to create nanoparticles
- Use of catalysts
- Use of templates

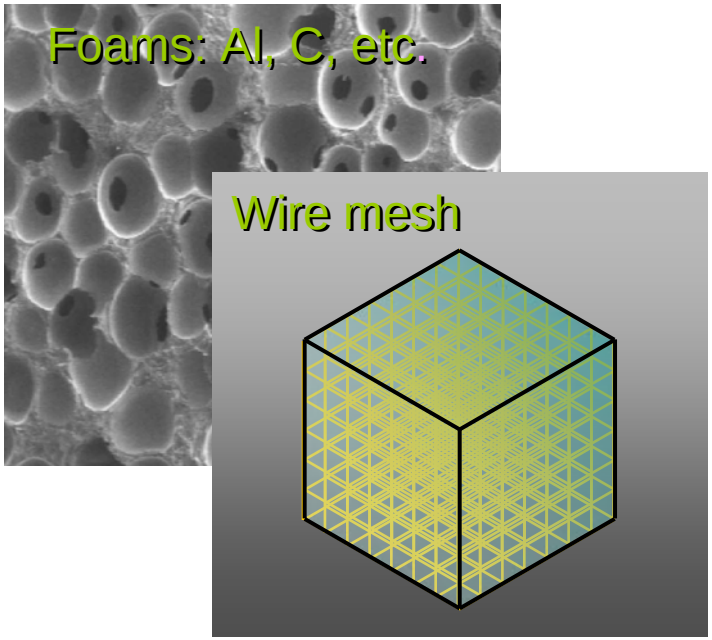
Thermal Management

- Forming hydride is exothermic:

~1 MW for 5 min.

- Temperature rise suppresses hydriding reaction
- For typical hydrides the thermal conductivity is: k~0.1 W/m-K
- Nanostructured materials impair heat transfer

SOLUTIONS



Klein et. al., Int. J. Hydrogen Energy 29 (2003) 1503-1511

Make composites by adding carbon foams, fins and meshes and carbon nanotubes to hydrides to increase thermal conductivity.

Expanded Graphite Compacts

See: Zhang et. al., J. Heat Transfer, **127** (2005) 1391-1399

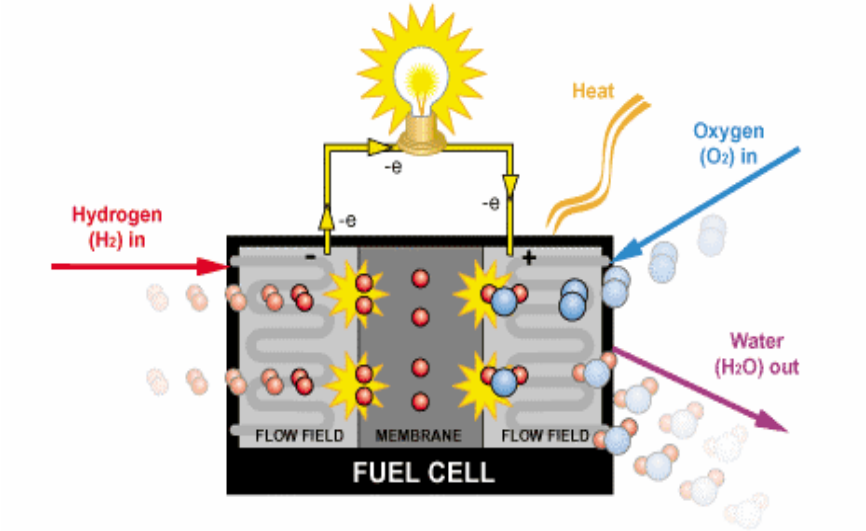
Conclusions on Hydrogen Storage

Nanostructures are key to improved performance – but it isn't easy

- Key Issue: Sufficiently high volumetric, gravimetric hydrogen capacity (DOE 2015)
  - Some candidate materials have been identified
- Thermodynamics:
  - Control of sorption/desorption temperature and reversibility are needed
  - Release temperature ~350K is desired
- Kinetics
  - Release rate should be fast enough and controlled
  - Strategies have been identified and progress has been made
- Thermal management mass and heat transfer
  - Minimize heat release and temperature rise during hydriding
  - Increase thermal conductivity of hydrogen storage material
  - Some strategies have been identified
- High energy efficiency and safety are prime considerations

Membranes: Micro- and Nano-Patterning Boost Power Output and Miniaturization of Fuel Cells

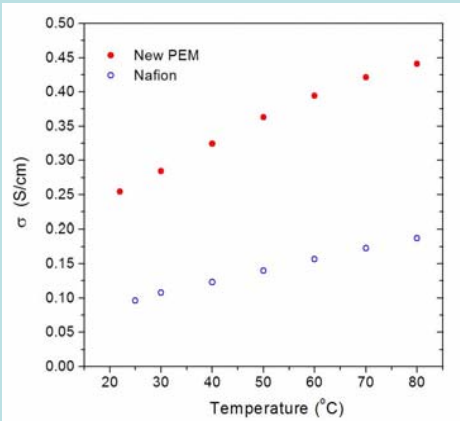
Fuel Cells: $2H_2 + O_2 \rightarrow 2H_2O$ + electrical power + heat



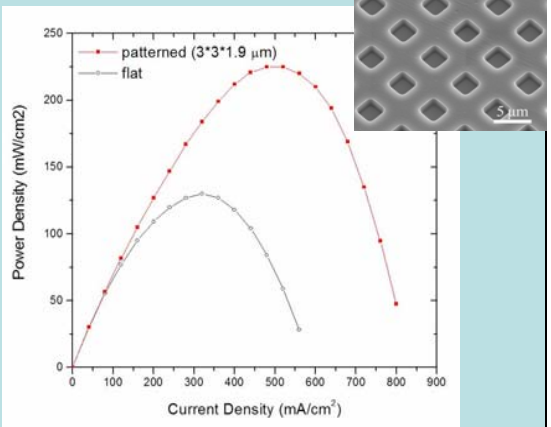
Membrane conducts protons from anode to cathode

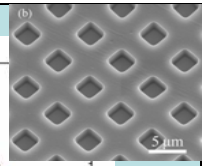
Traditional fuel cell proton exchange membranes (PEMs) such as Nafion™ , the current gold standard, have limitations:

- Have lower-than-desirable conductivity
- Require high humidity for optimal operation, which reduces durability
- Difficult to process, requiring high temperature melt extrusion, followed by exhaustive hydrolysis
- Has smooth surfaces and thus low active surface areas



New "liquid PEMs" have higher acid content and therefore higher conductivity than Nafion™





Lithographically patterned "liquid PEMs" lead to higher surface area of the membrane and the catalyst, and therefore, to higher power density of fuel cell

Advance in Photochemically cured "liquid PEMs" :

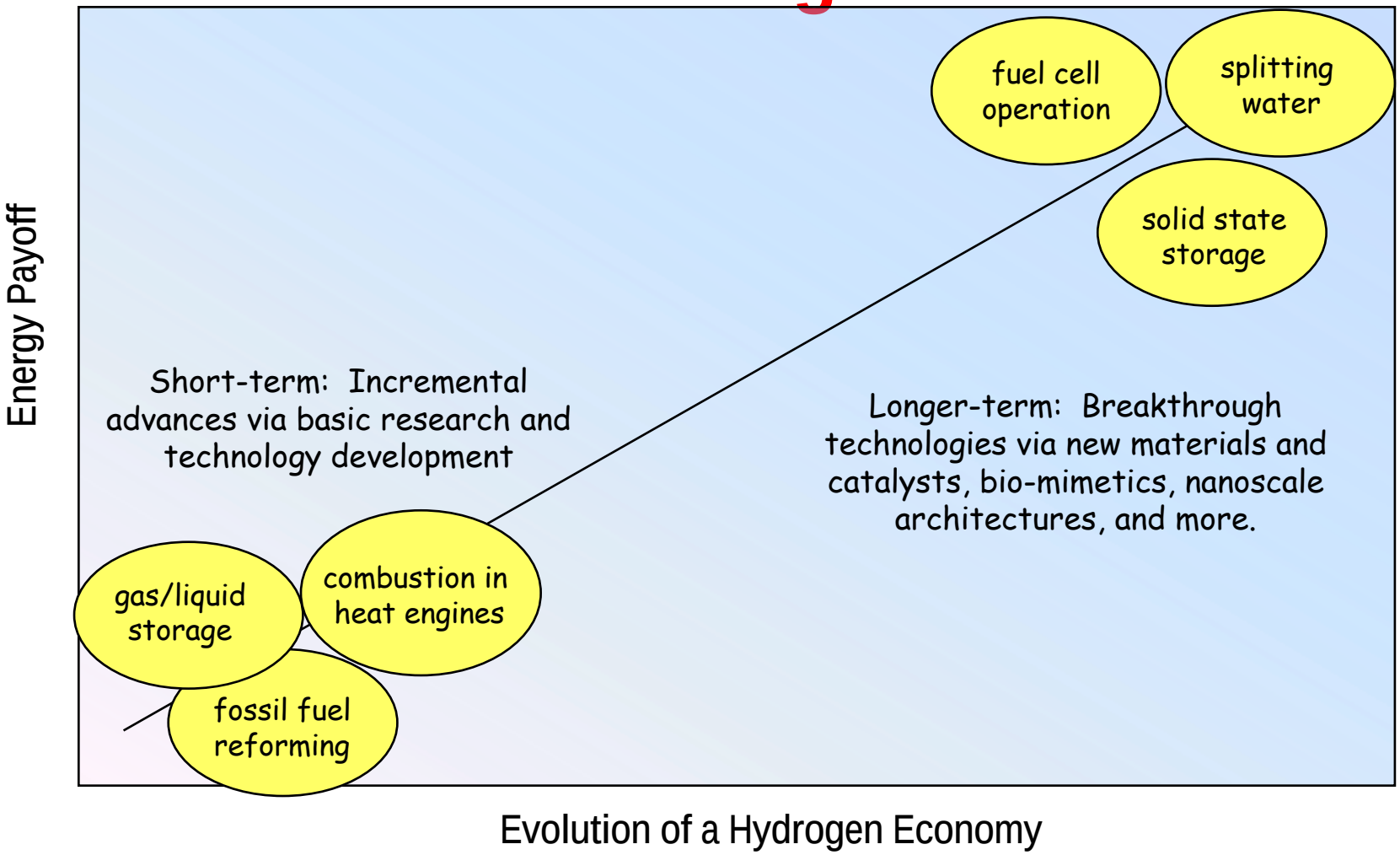
- Liquid precursors converted directly into membranes
- Can be cured into any desired shape including very thin films
- Can be chemically cross-linked
  Enables higher acid content
  ~ 250% increase in conductivity demonstrated
  Results in higher durability and better performance at lower humidity
- Can be patterned into high-surface area PEMs by soft lithography and micro-molding techniques
  ~ 200% increase in power density
  Could lead to significant size/weight reduction

Z. Zhou et. al., J. A.C.S. B**128** (2006) 12963

Energy & Nanostructured Materials: Scientific Challenges In the Hydrogen Economy

- Overview of nanostructured materials
- Overview of the hydrogen initiative and of the role that nanoscience and nanotechnology might play
- Concluding Remarks

Summary: Research for Short-term Showstoppers and Long-term Grand Challenges



Concluding Remarks

- Hydrogen is likely to be one of a mix of future sustainable energy conversion technologies
- New materials and nanoscience discoveries are necessary to its development
- Strong interplay between basic and applied sciences is key to success
- Interdisciplinary approaches, and coupling theory/experiment are vital
- Working with <u>industry</u> at all stages is a key factor

The END