Materials Science Innovations in Energy Efficiency and Generation

UC Santa Barbara Summit on Energy Efficiency, Materials for a Sustainable Energy Future
1 May, 2013
Innovation in energy technologies and high technology manufacturing are intimately connected with materials science, industrial processing, device and system design.

The best engineering requires integrated expertise in all these areas.
Materials for Energy Applications

- High-strength, lightweight materials for transportation
- Materials for power electronics, generators and motors
  - Wide band gap semiconductors (SiC, ZnO, diamond, ...)
  - Hard and soft magnetic materials
- Photovoltaic materials and processes
- Energy storage materials
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New materials and manufacturing methods can change the landscape of energy solutions.

In 1884, the price of aluminum was $1/oz and the price of gold was $20/oz. The highest skilled craftsman working on the Washington Monument was paid $2/day.

Today’s prices: Al = 6¢/oz, Au about $1776/oz.
Can we develop an electrolytic process for titanium?

**Kroll (conventional)**
- TiO₂
- Convert to TiCl₄
- Reduction to element
- Re-melt (>1660° C) (3 times for aero-grade)
- Ingot breakdown
- Forging
- Component

**Electrolytic (next generation)**
- TiO₂
- Electrolytic reduction (475-525° C)
- Consolidation
- Component

**Comparison of Process Energy (KBtu/kg):**
- Kroll: 900 KBtu/kg
- Electrolytic: 100 KBtu/kg

- 9x reduction of process energy
- Potentially 5x savings
- Titanium powder permits additive manufacturing
Additive manufacturing
The Boeing 787 uses only 30% of the fuel as the 707. Improved aerodynamics, engines and materials (carbon composites)
Out-of-the-Autoclave Composites

Autoclave (conventional) → Out-of-the-Autoclave

The manufacturing of inexpensive carbon composites that can be molded as a thermo-plastic?
Pratt & Whitney “Virtual Testing” of Jet Engine Designs Accelerate Improvements

Computer simulations using Argonne National Lab computer resources enabled virtual testing of a turbofan drive gear system.

- 12-15% improved fuel burn
- 3,000 tons less carbon emissions
- $1.5M savings/airplane/year
- 50% quieter
Jet engines have become 50% more efficient

Increase in turbine inlet temperature enabled by changes in SIZE and CONFIGURATION of nickel alloy STRUCTURE and NOT Chemistry

![Graph showing turbine inlet temperature over years with labels for different crystal structures and configurations]
Evolution of Advanced High Strength Steels in Automotive Applications

Jody N. Hall
General Motors Company
Chair, Joint Policy Council, Auto/Steel Partnership
May 18, 2011
Safety

Steels for Passenger Compartment Zone
- Highest Strength
- Martensite, and Boron Steels Preferred

-conventional HSS
-AHSS

www.autosteel.org
The major high tensile strength steel manufacturers in the world

- **ArcelorMittal**: Indian-based company
- **Severstal**: Russian-based
- **ThyssenKrupp**: German-based
Relationships between processing, structure and properties of high-tensile strength martensitic steels
We understand the structural changes at the nano- and meso-scale by forming processes, but don’t yet have a *fundamental* understanding of how alloying or thermal treatments create those properties.

• Electron microscopy (TEM and analytical)
• X-ray scattering
• Neutron scattering
• Scanning probe microscopy

• Computational design tools have been used to calculate interfacial boundary energies, precipitation rates, etc.

• Perhaps high performance computer simulations can help us design better manufacturable materials.
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The size of transformers for inverters (DC ⇔ AC), converters (DC ⇔ DC), and for step up and down voltage scales roughly as the inverse of switching frequency.

Today

10,000 lbs

Future

100 lbs

2010: 30% of all electric power flows through power electronics
2030: 80% of all electric power will flow through power electronics
Miniature (Fast) Magnetics Needs Fast Switches

- Bandgap (energy to ‘free electron’) increases
- Breakdown voltage increases
- Drift region can be decreased

Wide Bandgap Materials: SiC, GaN, etc.

Reduces transit time
Increases frequency
Reduces on-resistance

Power (VA) vs. Operation Frequency (Hz) chart:
- GTO
- TRANSISTOR MODULES
- IGBTMOD™ MODULES
- MOSFET MOD
- TRI-MOD
- IGBT-MOD DISCRETE MOSFET

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SiC power modules operate at 1200V and 880 amps. (1MW)

1.2 kV/100A SiC module

Internal view: 2 80 A SiC MOSFETs and 2 50 A SiC JBS diodes

A > 1 kV, 1 MW single SiC transistor has been demonstrated.
In addition to high power transistors, we need improved “soft” and “hard” magnetic materials.
ENERGY LOSS IN ELECTROMAGNETIC MATERIALS

Energy lost in rotating recalcitrant domains...  
- requires soft magnets, low coercive fields,  
  *little or no domain wall movement*  

Energy lost induced electrical current  
- requires *poor electrically conductivity* or  
  insulating material (no eddy-currents)
Efficient transformer and high field magnets

Metglas is a thin amorphous metal alloy ribbon produced by using rapid ($10^6$ °C/s) solidification. AlliedSignal began research in the 1970s. The Advanced Technology Program of NIST provided 50% cost share in a research program in the 1990s.

The best commercial metallic glass material has power losses of ~15% of the best silicon-iron grades.

China produces ~ 95% of the rare earth metals

Rare Earths are used in motors/generators, advanced batteries, displays, fluorescent and LED lighting
Critical Rare Earth Free Magnetic Materials – New Structures

Hard on Soft Nanoparticle

"Scalable Exchange Coupling"

$B_{\text{max}} = 50 - 100$ MGOe

Maintain Critical Dimensions and Anisotropy

BiMn on Fe

"Elevated Temperature Stability"

$B_{\text{max}} = 40$ MGOe (200C)

MnBi core / Fe shell
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Cost of PV modules are dropping below the power law experience curves

Source: (CdTe) First Solar Earnings Presentation, SEC Filings; (c-Si) Navigant, Bloomberg NEF, NREL internal cost models

Spot market price = $0.69
Opportunities in Silicon

Conventional approach

Standard

Pure Silicon

1. Cast Ingot
2. Cut Brick
3. Grind & Polish Brick
4. Saw Wafers

Wastes 50% of Silicon

I366 Direct Wafer

~6 g/W

~3 g/W
Epitaxial growth of single crystal Si on a reusable single-crystalline silicon template 35 µm thick.

Proven cell efficiency ~19%
23.5% cell efficiency
22% module efficiency.”
Photon-enhanced thermionic emission (PETE)

- 2% conversion efficiency with at least another 10-fold gain in the future.
- Applications in utility-scale concentrating solar power plants

Z.-X. Shen, N.A. Melosh, et. al., Nature 2013
Silicon Crystal Growth

Czochralski growth

Directional solidification
In 2007, the DOE supported research of BP Solar in the U.S. to make large single crystals of silicon in directional solidification method. A proto-type version of this technology achieved 20% efficiency.

Before the technology was taken to the manufacturing scale, intense competition with Chinese manufacturers caused BP Solar shut down operations in the US.
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Lithium air and Lithium Sulfur
Revolutionary specific energy and potential cost reduction
Changing the game: entirely new sensing modes for batteries

Safety and lifetime issues in batteries stem from dynamic and localized physical phenomena. Today’s battery use indirect measurements (V, I, T). New sensors to track physical phenomena directly could allow safer operation and better use of inherent capacity.

- In-line chemical sensing
- Gas sensing
- 2D or 3D sensor resolution
- Optical sensing
- Strain and pressure sensing
- Other disruptive sensing schemes?

Locally resolved sensing INTERNAL to the cell

Johns Hopkins University – App. Phys. Lab discovery enables the detection of potentially unsafe internal thermal conditions
New materials are a great enabler of new technologies

Invented and *made* in America, sold worldwide
END
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- Other disruptive sensing schemes?
Oh, power electronics and manufacturing engineers ...

Where art thou?
SunShot goal: Cost Competitive Solar by 2020
(L.C.O.E.: 6.5¢/KWh)

$1.70

$3.80/W

$1.88

Jan. 9, 2012
Spot market silicon module price ~ $0.93/watt

$0.22

Power Electronics

Reductions

$1.70

 Installed Systems Price ($/W)

2004 Systems Prices

2010 Systems Prices

Power Electronics Cost

BOS

PV Module

BOS Soft Reductions

Manufacturing Cost Reductions

Module Efficiency Improvements

$1/W Target

$0.72

Balance of Systems (BOS)

$0.76

$0.80

$0.40

$0.10

$0.40

$0.50

$1/W

0

2

4

6

8

$1/W
How to promote domestic manufacturing

• Regulations (mileage, appliance efficiency, pollution standards, etc.) drives innovation.

• Fiscal Polices that help companies that take the long term-view and to help guide on-shore investments.

• Corporate and labor leadership are essential.

• Government role as an “early adopter” and other methods (e.g. a clean energy standard) to create market draw.
A Materials Science Approach to Enhancing Cell and Module Efficiency

Cryst. Si 19 → 22 % efficiency
Poly-Si 14 → 16.5 %
CdTe 12→ 14.5 %
GaAs 26% efficient?

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Incident Solar Spectrum

Spectrum Splitting Photonic Structure

Optically-in-Parallel Subcells

Multijunction Photovoltaics with Many Subcells

Single Junction Cell

>> 3 Subcells \rightarrow Reduced Carrier Thermalization
Ultrahigh Efficiency Photovoltaics

ADVANCED ELECTRIC MACHINES FOR ELECTRIC VEHICLES

Enabling Larger, More Powerful Electric Vehicles

80 kW motor ~$1,500 ⇒ $320

and Order of Magnitude Reduction in Rare Earth Content: less than 0.33kg/kW
3rd Generation Advance high Strength Steels

we are researching a new generation of steels for the future.

For 2017-2025, new formable AHSS grades will enable more steel mass reduction.