The Present and Future of Photovoltaic Manufacturing

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Outline

Energy: Resources & Needs
  – Survey of Conventional and Renewable Resources
  – The Scope of the Sustainable Energy Challenge
  – A Little Science

Status & Prospects for PV Manufacturing Technologies
  – Single and Multi-crystalline Silicon
  – Thin Film: (CdTe, a-Si, CIGSS)
  – Dye-sensitized Solar Cells (DSC)

Meeting the Terawatt Challenge
  – Areas for Research Investment
  – Broader Issues
Humanity’s Top Ten Problems for next 50 years

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION

2003  6.3  Billion People
2050  8-10 Billion People

Source Richard Smalley Energy & Nanotechnology Conference
Rice University, Houston  May 3, 2003

see also R.E. Smalley, MRS Bulletin 30 412 (2005)
Current Energy Portfolio

Global Total ~ 15 Terawatts

- 1 TW = $10^{12}$ W
- Predominantly through the combustion of fossil fuels

N. S. Lewis, *MRS Bulletin* 32, 808 (2007)
Conventional Energy Resources

How much is left?

- Oil: 40 – 125 years
- Natural Gas: 65 - 210 years
- Coal: 250 – 360 years
- Nuclear: 80 – 300

More Difficult/Costly

CO₂ & Climate Change


**Carbon Dioxide Variations**

- The Industrial Revolution has caused a dramatic rise in CO₂.
- Ice Age Cycles

**Global Temperatures**

- Annual Average
- Five Year Average

**CO₂ output per kilowatt-hour (liters)**

| 26 | 21 | 6.7 | 8.4 | 11 | 530 | 330 | 500 | 17 |

*Source:* DOE, AWEA, DOE-EPA, Electricity from Renewable Resources, NAS (2010); (bottom) DOE, AWEA.
Population & Wealth

2050: > 10 Billion


To Stabilize CO₂: 30 TW of carbon-free energy by 2050

Renewable Energy Resources

- Hydroelectric
- Wind
- Biomass
- Geothermal
- Ocean/Tides
- Solar

Global Potential
- Current: ~2 TW
- Practical: ~10 TW

Source: WEA 2000
Renewable Energy Resources: Solar

Solar Energy Potential
- Solar Flux: $1.1 \times 10^5$ TW
- 1 hour Sunlight = Annual Global Consumption
- Practical Potential: 600 TW
- Infinite Supply

Solar Energy Conversion Options
- Solar Thermal: Photons to Heat
- **Solar Photovoltaic: Photons to Electrons**
- Solar Fuels: Photons to Chemicals
  - Water Splitting: $2\text{H}_2\text{O} + h\nu \rightarrow 2\text{H}_2 + \text{O}_2$
  - CO$_2$ Reduction: $\text{CO}_2 + 2\text{H}_2\text{O} + h\nu \rightarrow 2\text{CH}_3\text{OH} + \text{O}_2$
Terawatt Challenge

- 30 TW of clean, renewable energy by 2050
- Require 1 TW/year capacity
Growth of the PV Market

- Is 20% growth sustainable?
- What about costs?


MW

1988 - 2003

2004 - 2009

Future?

- 2009
  - 8 GW
- 2010*
  - 16 GW
PV Costs are Dropping

The Experience Curve: 80%

- x-Si: $2/W_p, $1.3/W_p (China)
- CdTe (First Solar): $1/W_p

Electricity from solar PV is becoming cheaper...

...and grid costs are rising

Periodic over-supply is inevitable

Potential for explosive growth in demand upon convergence

Grid cost convergence

No technical breakthroughs are required to achieve solar PV cost reduction curve(s)

Source: Deutsche Bank estimates

US - Average price of electricity in 2009 est: 9.5 cents/kWh

Source: Deutsche Bank estimates

Market poised for explosive growth this decade

Are we ready for it?

Workshop Goal

“Identify the potential technologies and innovations that offer low-cost, high-conversion-efficiency and sustainable photovoltaic materials.”

Reviewed Each Technology

- Current Status
- Identify the short/long term needs
- Recommend/prioritize areas for R & D Investment
Solid State $pn$ Junction: The Electron Pump

- Join to dissimilar semi-conductors: A diode
- Absorb Photon: Generate Electron-Hole Pair
- Junction provides a internal bias

\[ h\nu > E_g \]
Why is Solar so Inefficient?

Thermodynamic Limit: 30% Conversion

– Photons below band gap are not absorbed
– Photon energy in excess of band gap wasted

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UV NIR


Technology Classification

1st Generation
- Crystalline silicon, relatively thick (100s $\mu$m)
- Higher efficiency, relatively expensive

2nd Generation
- Thin Film Technology (1 – 10 $\mu$m)
- Flexible, low cost, lower efficiency
- CdTe, CIGS, a-Si, DSC

"Next Generation"
- Organic PV (OPV), plastic solar cells
- Earth abundant inorganics (CZTS, pyrite)
- Quantum-dot (3rd Generation)

Courtesy Richard van de Sanden, TU Eindhoven
Crystalline Silicon

“1st Generation” Photovoltaics

- Invented 1954
- Dominates Market (~85%)
- Single Crystal (c-Si)
- Multi-crystalline (mc-Si)
- Mature, Earth Abundant
- 10 Companies Dominate

PERT Cell, UNSW

Chapin, Fuller & Pearson, JAP 25, 676 (1954)
Crystalline Silicon

Cast Brick

Cut & Grind Bricks

Wire-Cut Wafers

Clean & Polish

Czochralski Growth

Ingot

Big Problem

50% Loss

Improve Feedstock

Metallurgical 99%

Solar Grade ???

Electronic < 1 ppb

mc-Si

c-Si
**Ribbon Silicon**

**EFG Si**
Edge-defined film-fed growth

**String Si**

**Kerfless Wafers**
- Invented in the 1970s
- mc-Si: 200-300 μm thick
- Passivation of defects critical
- Record Cells ~18%, Modules 14.5%
- **Energy payback < 1 year**
- Reduce thickness, improve throughput

Ultrathin Silicon (5 – 50 µm)

- Current wafers: ~200 µm
- Optimum Thickness: ~40 µm
- **10X Improvement Possible**

Maintain High Efficiency

- Optical Enhancement
- Surface Passivation
- Wafer Handling

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*Graph showing efficiency vs. thickness with an optimal thickness of about 40 um.*

*Kerr et al., 29th IEEE PVSC, 2002*
Production of Ultrathin Silicon

Strategies for Production

Liftoff

Hetero-epitaxy

Unanswered Questions

- Reduce T requirements?
- Low cost sacrificial substrate?
- Throughput?
- **Economics**
- Trading Process vs. Material Costs?

Photon International, p.116 (May, 2009)

J. Poortmans, IMEC
Thin Film CdTe

“2nd Generation” Photovoltaics

- Invented 60s, developed 80s, 90s
- Major Player (~12% of market)
- First Solar + Dozen Startups
- Ideal band gap, high absorption
- Simple deposition: Evaporation
- Compatible with float line glass
- **Low Cost Leader ($1/Wp)**


Thin Film CdTe Manufacturing

First Solar
CdTe: Opportunities & Challenges

Improve Efficiency
- Advanced front contact, $J_{sc}$
- Need to Increase $V_{oc}$
- Carrier Lifetime/Density
- Understand/Control of Grain Boundaries

Concerns about Toxicity/Availability
- Hotly debated questions
- Not volatile, no leaching
- Recycling programs in place
- Cd byproduct of Zn Mining
- PV panels: Cd Sequestration
- Te is a relatively scarce material

Practical Potential
- Research
- Development
- Process Integration
- Current Production

Simulated $V_{oc}$ [$V$]

Amorphous-Nanocrystalline Silicon

Synthesis & Attributes

- Carlson and Wronski (1976)
- Sharp, United Solar, Oerlikon
- Plasma-enhanced CVD using SiH₄/H₂
- Low temperature (<150 °C)
- Low weight, flexible laminates
- Multi-junction compatible

Carlson & Wronski, APL 28, 671 (1976)
a-Si/nc-Si: Opportunities & Challenges

High Rate Manufacturing
- a-Si Unstable: Staebler-Wronski Effect
- nc-Si Stable: Slow rate, low absorption
- VHF (100 MHz) plasma, new linear sources

Advanced Photon Management
- Increase light collection
- Reduce thickness requirements
- Texturing, plasmonics, index matching

Increase Efficiency
- Triple junction cells
- Introduce SiGe alloys
- Targeting 15%

5X Increase in Thickness

Plasmonics
CIGSS: $\text{CuIn}_x\text{Ga}_{1-x}\text{Se}_{2-y}\text{S}_y$

**Attributes**

- Kazmerski et al. (1976)
- Tunable Band gap (1 – 2 eV)
- Thin Film Efficiency Leader (20.1%)

**Many Companies/Many Techniques**

- Co-Evaporation
- Sputtering/Anneal in Se Vapor
- Screen Print /Anneal in Se Vapor

**References**

CIGS: Opportunities & Challenges

Robust Manufacturing Process
- Translate cell record into module performance
- Could compete with c-Si

Materials Chemistry
- Optimizing Chalcopyrite
- Replace CdS as window layer
- Reduce/replace In
- Understand the role of Na

Improved Stability
- Reduced sensitivity to moisture (replace ZnO?)
- New moisture barriers (WVTR < $10^{-6}$ g/m²/day)

DSC: Dye Sensitized Cell

Photoelectrochemical Cell

- Discovered by Becquerel (1839)
- Invented by Grätzel (1990)
- SolarPrint, G24i, Dye-sol
- **Works in diffuse light (indoors, cloudy)**
- Low T, Flexible, Lightweight

Many Steps

- Photon absorbed by dye
- e^- “hops” TiO₂ particles
- Redox Reaction
  \[ I_3^- + 2e^- \rightarrow 3I^- \]
- Diffuse across electrolyte
- Regenerate dye

DSC: Opportunities & Challenges

**Increase Efficiency: Stagnant at ~11%**
- Unchanged since 1995
- New Dyes: Improve \( J_{SC} \)
- New Redox Couple: Improve \( V_{OC} \)

**Improved Stability**
- New Dyes (>10^8 turnovers)
- New Electrolyte (Ionic liquids/Gels)
- Simultaneous Optimization

**R2R Processing**
- Eliminate Glass
- Encapsulation

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All Technologies Continue to Grow

- CdTe and Si Growing Fastest
- Other Technologies Getting Squeezed

Source: Navigant Consulting
3 Possible Future Scenarios

**Status Quo**
- Continued dominance by c-Si, mc-Si
- CdTe an important component of utility market
- Others: Niche markets in consumer/aerospace

**Transition to New Forms of Crystalline Silicon**
- Ribbon silicon
- Ultrathin silicon

**Breakthrough in Thin Film Technology**
- CIGS: Compete with x-Si, CdTe in power sector
- DSC: Consumer products, BIPV, selected climates
Revolution Through Evolution?

Adapted from M. A. Green, “3rd Generation Photovoltaics”, Prog. Photovolt.: Res. Appl. 9, 133 (2001)
Areas for Investment

NSF/DOE

– Predominantly supported 3rd Generation
– Little for x-Si, thin films

Fundamental Challenges Remain

– Developing thin Si (< 100 µm)
– Increase CdTe/DSC efficiency
– Improve CIGS/a-Si manufacturing

Cross Cutting Issues

– Advanced Photon Management
– Effective Encapsulation/Compatibility with R2R Processing
– Manufacturing Science: Metrology/Reliability
Transportation & Storage

Geographic/Diurnal Variations
- Common to most renewables
- Management challenge

New Grid
- From concentrated to distributed
- From continuous to variable
- Increased capacity
- Coal/Nuclear/Natural Gas
- Wind/ Hydroelectric/Solar

Energy Storage
- Batteries, Hydrostatic, Mechanical
- Solar Fuels: Chemical

Meeting the Sustainability Challenge

50% from New Energy Sources
- Solar PV, Solar Thermal
- Wind, Hydroelectric
- Nuclear: Bridge Technology

50% Increased Efficiency
- More with less
- Technology exists
- Maintain quality of life

Progress:
- < 2000
- > 2000

GDP/capita (000's 1997 $ PPP) vs. GJ/capita-yr
Solar Energy

- Critical contributor to a sustainable future
- PV poised for explosive growth

Future Outlook: No silver bullet

- x-Si: Leader in utility & residential markets, large upside remains
- CdTe: Fast growing, expect to increase share of utility market
- a/nc-Si: Improved deposition rate/cost critical to keep up with CdTe, low weight laminates a differentiator
- CIGS: Potential to challenge x-Si, awaiting a break through
- DSC: Consumer products, BIPV where weight and flexibility are key drivers and lifetime less of a concern

Renewables + Increased Efficiency = Sustainability
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