The Horse Race Among Silicon, Thin Film and Concentrator PV
(and where should a corporate research lab play?)

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About PARC

• Founded as Xerox PARC in 1970; incorporated 2002

• Recognized leader in research-based innovation
  – ~30 new businesses from PARC, innovation in nearly every Xerox product, licensing and co-development agreements with companies around the globe
  – Home of much of modern computing – Ethernet, laser printing, GUI, ubiquitous computing…

• Today: Open center for commercial innovation
  – Strategic focus on industry – 85% of revenue
  – Help our clients grow new revenue

“…one of the most innovative commercial research labs in the world.”
Kiplingers.com, June 2008
**Learning Rate** = % price decrease for every doubling in cumulative capacity

LR (module) = 19-20%

Source: Ken Zweibel, NREL
Module Price is Not the Only Factor

Typical Breakdown:
Silicon PV Commercial System in 2006
Learning Rates for Other Elements

Inverter

Experience curve for inverter list prices (1995 – 2002)


Learning Rate = 7-9%
Versus Microelectronics

• DRAM Bits:
  – CAGR (1964-1992) = 120%
  – Learning Ratio = 0.7
  – Driven by: Transistor Shrink & Wafer Size
  – Time to cut cost in half = 1.5 years (Moore’s Law)

• Crystalline Silicon PV Modules:
  – CAGR (1976-2003) = 40%
  – Learning Ratio = 0.8
  – Driven by continuous, incremental improvement
    • Efficiency, Si thickness, wafer size (somewhat)
  – Time to cut cost in half = 6 years
Options to Accelerate (1)

Crystalline Silicon:
- Accelerate innovations
Options to Accelerate (2)

Thin Film:
- Reduce semiconductor material (in thickness)
- Process larger substrates

K. Zweibel, NREL, 2004
Concentrators:
- Reduce semiconductor material (in area)
- Use most efficient III-V cells
Observations

• When efficiency is lower, the price goes up for all things that scale with $m^2$
  – Land, framing, shipping, interconnections

• Provides a strong argument for high efficiency approaches
  – Backside contact silicon, PERL, HIT, tracking
  – III-V concentrators

• However, even assuming a BOS penalty of 50%, thin films can dominate in the long run and reduce the total investment to reach grid parity
PARC Innovation Path

• Reduce the amount of semiconductor (in thickness)
  – Conventional thin films (α-Si, CdTe, CIGS)
  – Organic & dye-sensitized cells
    – New inorganic materials

• Reduce the amount of semiconductor (in area)
  – Low concentration PV
  – High concentration PV

• Innovations for silicon PV
Approach

• Look only at materials that are:
  – Abundant and low cost (e.g. transition metals: Zn, Cu, W, Fe)
  – Environmentally friendly (i.e. not Cd, As, Se)
  – Processed at low temperature (electrodeposition, etc)

• Use nano-structuring to mitigate effects of imperfect material quality (e.g. low $\mu \tau$)

![Diagram of solar cell layers](image)

- **Transparent Electrode** (e.g. ITO)
- **Transparent Metal Oxide** (e.g. TiO$_2$ or WO$_3$)
- **Inorganic Semiconductor** (e.g. CuO)
- **Metal Electrode**

Energy gaps:
- $E_g = 3-5$ eV for Transparent Metal Oxide
- $E_g = 1.2 – 1.7$ eV for Inorganic Semiconductor
### Some Materials of Possible Interest:

**Oxides, Sulphides and Phosphides of Transition Metals**

<table>
<thead>
<tr>
<th>Material</th>
<th>Gap</th>
</tr>
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<tbody>
<tr>
<td>WS₂</td>
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<tr>
<td>SnS</td>
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<tr>
<td>Zn₄Sb₃</td>
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<tr>
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<tr>
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<tr>
<td>CuO</td>
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<td>ZrS₂</td>
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<tr>
<td>Sb₂S₃</td>
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<tr>
<td>Cu₂O</td>
<td>2.19</td>
</tr>
</tbody>
</table>

Search for Published Papers (INSPEC, 2005)
Single Junction Efficiencies
Existence Ratios of Elements in Earth’s Crust

Some Materials of Interest

- Deviation from Ideal Gap (eV)
  - c-Si
  - FeS$_2$
  - Zn$_3$P$_2$
  - CuP$_2$
  - Cu$_2$O
  - ZrS$_2$
  - Cu$_2$S
  - ZnS

- Gap(Ideal) – Gap(Actual)
- log(Existence Ratio)

Single Junction
But, Need to Consider the Timeframe

And this is research cell efficiency. Best modules are about 80% of these numbers.

Sopori et al, NREL/CP 520-33435 (2002)

Universal Improvement Curve?

4%/decade!
Given the pace of PV deployment, and the competitive advantage inferred by having a large manufacturing base...

- CdTe, CIGS, $\alpha$-Si: good prospects
- Organic solar cells: most likely won’t succeed
- Dye sensitized cells: questionable
- New inorganic devices: most likely won’t succeed (single junction)

However, 3rd Generation (hot carrier, intermediate band, etc) inorganic devices with very high efficiency (>50%) are future contenders.
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• Innovations for silicon PV
Concentrators: Many System Concepts
Solfocus Technology – 1st Generation

• Tailored Imaging Concentrator
  – 500 suns on 1cm² Spectrolab Cells
  – Passive Cooling
Solfocus 500KW Deployment in Spain
PARC Design for Gen 2

Single glass-molded optic

Purely Reflective, light enters at normal incidence, no chromatic aberration

No: coverglass, gas seals, spacers, mechanical alignment

5-12 mm

20-40 mm

PV Cell

Reinforcement

Mirror coatings
$R_{\text{primary}} = 15.0 \text{ mm}$
$R_{\text{secondary}} = 3.351 \text{ mm}$
$n_{\text{glass}} \approx 1.5$

$D_{\text{primary}} = 28.0 \text{ mm}$
$D_{\text{secondary}} = 6.8 \text{ mm}$

Throughput = 93.8%
Solar disk diameter = 0.54° = 9.425 mrad
Concentrator PV has a Roadmap for Continuous Improvement

World-record of 34.2% Achieved in 2001, Recognized As One of the Top 100 Achievements by R&D Magazine and One of the Top 50 Achievements by Scientific American Magazine

New world-record of 36.9% achieved in 2003

New world-record of 37.3% achieved in 2004

Spectrolab Terrestrial Concentrator Solar Cell Technology Roadmap

PARC Innovation Path

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• Innovations for silicon PV
To Rapidly Increase Domain Knowledge, Bring in a Visiting Technologist

Visiting Solar Energy Technologist

Steve Shea
Previously Director of R&D
at BP Solar

+ parc®
Palo Alto Research Center
Solar Metallization: Shadowing Challenge

Screen-Printed Gridlines
Fired Aspect Ratio = 1:10

PARC Gridlines
~50 µm x ~50 µm
Fired Aspect Ratio = 1:1

Opportunity: Net Efficiency
Increase of 6% Relative at
Similar Manufacturing Cost
Key Features/Results

• Non-contact printing approach
• Uses silver inks that are almost identical to current screen printing inks
• Uses same “fire-through” furnace process with glass frit
• Process speed enables 1 wafer/sec
• Have completed split lots with a PV manufacturer
• Roadmap to extend technique for other silicon PV process steps
Status for Gridline Printing

• PARC has signed an exclusive development contract with one PV manufacturer, effective through 1Q2009

• After the development/pilot phase, co-extrusion printers and the materials will be sold commercially by a spinout company that PARC is creating
Other Silicon PV Work: Laser Ablated Vias

Very clean vias in SiN layer
Application Example: In-Line Approach Using Laser, Inkjet and Gridline Printing

- Common conveyor for registration

Laser ablate vias
Inkjet silicide forming precursors
Printed gridlines

Patents filed
PARC Cleantech Innovation Program

Optical Design
- Laser Printing
- Solar concentrators

Direct Printing
- Inkjet
- High Aspect Ratio PV Gridlines
- Inkjet to Form Silicide PV Contacts
- Low cost membranes for CO2 extraction

Particle Manipulation
- Toner Powder Control
- Bioagent concentrator

Adaptive Control
- Model Based Printer Control

Other Technologies
- Data Center Optimization
- Demand Response