Thin Films: Materials Choices & Manufacturing

Lecture 11 – 2.626

Tonio Buonassisi
General Matters

• Exam
• Homework #2
• Class Project next steps
Further Reading

• Visit http://www.knovel.com from an on-site computer (or with certificates).
• Search for “Handbook of Photovoltaic Science and Engineering”.
• Suggested Chapters:
  – 12: Amorphous Silicon Thin Films
  – 13: CIGS Thin Films
  – 14: CdTe Thin Films
  – 15: Dye-Sensitized Solar Cells
• Harvard Folks: If you have difficulty accessing this content, please email Sarah or me.
Thin Films: General Issues
Diversity in the PV Market

Future technologies must consider:
• Cost ($/kWh)
• Resource availability
• Environmental impact
Record laboratory efficiencies of various materials

NOTE: These are record cell efficiencies under ideal conditions (25°C, ~1000 W/m²)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.
Thin Films

Advantages
- 1 µm layers ➔ less material used ➔ potential cost decrease.
- Potential for lower thermal budget ➔ potential cost decrease.
- Potential for roll-to-roll deposition on flexible substrate.
  - Technology transfer with TFT, flat panel display industry.
- Good for BIPV applications.
- Radiation hardness.

Disadvantages
- Lower efficiencies ➔ potentially larger module costs.
- Potential for capital-intensive production equipment.
- Potentially scarce elements sometimes used.
- Spatial uniformity a challenge during deposition.
Thin Films

Advantages:

Roll-to-roll deposition of μm-sized layers ➔ potentially high throughput, large-area deposition, and cheap.

امج ومضبطة

Building-integrated solutions

http://www.inhabitat.com/images/bipv1.jpg
Radiation hardness of different compounds

Space payloads cost $1400–$6000/pound (~$2866–$13228/kg) ➔ Key parameter not $/W. Instead, it’s W/kg and reliability!
Grain Size and Efficiency

Images removed due to copyright restrictions. Please see Fig. 1 and 2 in Bergmann, R. B. “Crystalline Si thin-film solar cells: a review.” Applied Physics A 69 (1999): 187-194.


See also:
Heterostructures and Lattice Matching

To prevent interface recombination and achieve high carrier mobilities, atoms in the different layers must line up (adjacent hetero-epitaxial layers must be lattice matched). Otherwise, defects form at these interfaces.

An good example of a heteroepitaxial system is Ge / GaAs / InGaP / AlAs, in order of increasing bandgap.
### Material Abundances

Table 1. Materials requirements and indicators for the solar cells in four solar energy systems, each based on a specific thin-film technology supplying 100,000 TWh/yr.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total material requirements (g/m²)</th>
<th>Total material requirements (Gg)</th>
<th>Total material requirements/max. resources (%)</th>
<th>Annual material requirements/analyzed material (%)</th>
<th>Potential losses/weathered amounts (%)</th>
<th>Material cost share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-SiGe³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>3.3</td>
<td>1700</td>
<td>0.20</td>
<td>0.004</td>
<td>0.079</td>
<td>2</td>
</tr>
<tr>
<td>Ge</td>
<td>0.22</td>
<td>110</td>
<td>Negligible</td>
<td>0.0003</td>
<td>21</td>
<td>0.1</td>
</tr>
<tr>
<td>Si</td>
<td>0.54</td>
<td>270</td>
<td>Negligible</td>
<td>Negligible</td>
<td>0.0031</td>
<td>0.000002</td>
</tr>
<tr>
<td>Al</td>
<td>2.7</td>
<td>1400</td>
<td>0.0032</td>
<td>Negligible</td>
<td>0.00075</td>
<td>0.00005</td>
</tr>
<tr>
<td>CdTe</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sn</td>
<td>0.66</td>
<td>330</td>
<td>0.056</td>
<td>0.0009</td>
<td>0.016</td>
<td>0.4</td>
</tr>
<tr>
<td>Cd</td>
<td>4.9</td>
<td>2400</td>
<td>4.6</td>
<td>0.03-0.1</td>
<td>1.2</td>
<td>10-50</td>
</tr>
<tr>
<td>Te</td>
<td>4.7</td>
<td>2400</td>
<td>110</td>
<td>1-20</td>
<td>120</td>
<td>500-10,000</td>
</tr>
<tr>
<td>Mo</td>
<td>10</td>
<td>5100</td>
<td>0.93</td>
<td>0.01</td>
<td>0.47</td>
<td>6</td>
</tr>
<tr>
<td>CIGS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>9.1</td>
<td>4600</td>
<td>0.030</td>
<td>0.0003</td>
<td>0.0062</td>
<td>0.1</td>
</tr>
<tr>
<td>Cu</td>
<td>1.8</td>
<td>880</td>
<td>0.0017</td>
<td>0.0009</td>
<td>0.00098</td>
<td>0.04</td>
</tr>
<tr>
<td>In</td>
<td>2.9</td>
<td>1400</td>
<td>650</td>
<td>0.03-0.4</td>
<td>110</td>
<td>10-200</td>
</tr>
<tr>
<td>Ga</td>
<td>0.53</td>
<td>270</td>
<td>25</td>
<td>0.00007</td>
<td>48</td>
<td>0.03</td>
</tr>
<tr>
<td>Se</td>
<td>4.8</td>
<td>2400</td>
<td>30</td>
<td>0.3</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>Cd</td>
<td>0.19</td>
<td>95</td>
<td>0.18</td>
<td>0.001-0.005</td>
<td>0.048</td>
<td>0.4-2</td>
</tr>
<tr>
<td>Mo</td>
<td>10</td>
<td>5100</td>
<td>0.93</td>
<td>0.01</td>
<td>0.47</td>
<td>6</td>
</tr>
<tr>
<td>Grätzel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ru</td>
<td>0.1</td>
<td>50</td>
<td>7.5</td>
<td>0.3-3</td>
<td>88</td>
<td>100-1000</td>
</tr>
<tr>
<td>Pt</td>
<td>0.05</td>
<td>25</td>
<td>0.83</td>
<td>0.01-0.1</td>
<td>2.4</td>
<td>6-60</td>
</tr>
<tr>
<td>Ti</td>
<td>1.2</td>
<td>600</td>
<td>0.0021</td>
<td>Negligible</td>
<td>0.0024</td>
<td>0.0002</td>
</tr>
<tr>
<td>Sn</td>
<td>5.5</td>
<td>2800</td>
<td>0.47</td>
<td>0.007</td>
<td>0.13</td>
<td>3</td>
</tr>
</tbody>
</table>

Deposition Technologies

Vacuum Based: Large capex   Non-Vacuum Based: Small(?) capex

Images removed due to copyright restrictions. Please see
http://i236.photobucket.com/albums/ff105/sanjaykram/PDP_Large/PECVD_png.png

and any photo of chemical bath deposition, such as
http://www.cranfield.ac.uk/cds/departments/dassr/images/22179_lg_solar%20cbd%20growth%20of%20cds_580x200.jpg
Thin Films: Technology Choices
Record laboratory efficiencies of various materials

**NOTE:** These are record cell efficiencies under ideal conditions (25°C, ~1000 W/m²)! Actual commercially-available silicon solar cells are typically 14-17% efficient. Modules are typically around 11-13%.


Amorphous Silicon (a-Si)

Advantages:
- Potentially very cheap, low-temperature.

Challenges:
- Overcoming the Staebler–Wronski effect (SWE)
- Uniform (thickness, quality, grain size) film deposition.
- TCO expensive.
- Challenges to scaling

Energy Band Diagram of a-Si


a-Si heterostructures

Image removed due to copyright restrictions. Please see Fig. 4 in Rech, B., and H. Wagner. “Potential of amorphous silicon for solar cells.” Applied Physics A 69 (1999): 155-167.

Staebler–Wronski effect (SWE)


The a-Si (μ-Si) \( \rightarrow \) nc-Si transition...

...is determined by deposition temperature...

Fig.5 SEM images of the film deposited at different substrate temperature; (a) 150 and (b) 133°C.
**...ambient gas content, and other factors.**


http://www.nrel.gov/docs/fy05osti/38355.pdf

Image removed due to copyright restrictions. Please see Fig. 5 in Srinivasan, Easwar, and Gregory N. Parsons. "Hydrogen elimination and phase transitions in pulsed-phase plasma desposition of amorphous and microcrystalline silicon." Journal of Applied Physics 81 (1997): 2847-2855.

Commercialization of a-Si / μ-Si

Applied Materials SunFab: Turnkey production lines.

Images removed due to copyright restrictions. Please see

Movie at:
Commercialization of a-Si / µ-Si

Oerlikon

Uni-Solar
Heterojunction with Thin Intrinsic layer (HIT) Cells

Advantages:
- Less surface recombination.
- Higher maximum voltages ($V_{oc} > 710$ mV).
- Efficiency less temperature sensitive.
- High efficiencies (21.5% on 100 cm$^2$ cell)

Challenges:
- Deposition: doping, nano-to-micro-crystalline phase transition
- Optimizing the c-Si and a-Si interface, low-damage plasma.

http://www.sanyo.co.jp/clean/solar/hit_e/hit.html
Energy Band Diagram of HIT Cell

Images removed due to copyright restrictions. Please see Fig. 1 and 5 in Taguchi, Mikio, et al. "Obtaining a Higher Vpc in HIT Cells." Progress in Photovoltaics: Research and Applications 13 (2005): 481-488.

Temperature Dependence of HIT Cells

CIS and its variants

Basic Facts:
- CIS = Copper Indium Diselenide = CuInSe$_2$ = Chalcopyrite
- Zincblende-like structure
- Record efficiencies: 19.2% lab; 13.4% large area

Figure by MIT OpenCourseWare.
Thin-film polycrystalline CIGS

A. Klein, Proc. 31st IEEE PVSC
(Lake Buena Vista, FL, 2005) p.205
CIS Band Structure Debated


CIGS Characteristics

**Advantages:**
- High efficiencies (~20%)

**Challenges:**
- Uniform deposition (stoichiometry & thickness) over large areas, quickly
- Defects, Interface States are complex, poorly understood.
- Replacing n-type emitter with Cd-free material.
CIGS Commercialization

Start-ups: Nanosolar (above), Heliovolt, Miasolé...

Images removed due to copyright restrictions. Please see
http://www.nanosolar.com/media/firstpanelsshipped_web.jpg
Cadmium Telluride (CdTe)


Cadmium Telluride (CdTe)

Back Contact
- Metal
- Buffer Layer
- p⁺ - Te-rich Layer
- p - CdTe
- absorber
- n - CdS
- window
- Glass
- substrate

Irradiation

~ 50 nm
~ 10 nm
3-5 μm
0.5-1 μm
0.3 μm
1 mm

Courtesy of M. Terheggen. Used with permission.

A. Klein, Proc. 31st IEEE PVSC
(Lake Buena Vista, FL, 2005) p.205
CdTe Characteristics

Advantages:
- Technology developed for application on glass → BIPV.
- Radiation hardness.

Challenges:
- Cadmium
- Marketability (Greenpeace opposed, banned in Japan)
Environmental Concerns: Cadmium

Arguments Against:
- Suspected carcinogen.
- Industrial emissions tightly regulated, esp. in E.U.
  - Cradle-to-grave requirement.

Arguments in Favor:
- By-product of Zn, Cu mining [1].
  - “Better to tie it up in CdTe than dump it in the ground.”
- “Negligible” Cd released during fires [2].
- “Public fear a perception issue” [3].
- CdTe is a stable compound.
  - Much less Cd released per kWh than a battery [4].
- Safe production.
- Full recycling guaranteed (by law in Europe).

CdTe Commercialization

Images removed due to copyright restrictions. Please see
http://www.firstsolar.com/images/large_pp5.jpg

First Solar: Proven Technology!
Announced Production Capacities by Technology

- Silicon based
- CdTe
- CIS
- Dye + others

Production Capacity [MW]

2006 2007 2009 2010

Renewable Energies

Courtesy Arnulf Jäger-Waldau. Used with permission.
Announced Capacity Increases: Regional Differentiation by Technologies

- Dye + others
- CIS
- CdTe
- silicon based

Joint Research Centre

Production Capacity [MW]

Europe | USA | Japan | China | ROW | Europe | USA | Japan | China | ROW | Europe | USA | Japan | China | ROW

2006 | 2007 | 2009 | 2010

Courtesy Arnulf Jäger-Waldau. Used with permission.
Average Thin Film Cost Structure

Technology dependent Drivers
- Deposition Process: Dominates Energy
- Deposition Materials: Dominates Depreciation
- Package/Assembly: Dominates Materials

Common Drivers
- Material Cost: Volume, Efficiency
- Depreciation: Throughput, Efficiency
- Labour: Throughput, Automation, Efficiency
- Energy: Throughput, Efficiency

Courtesy Arnulf Jäger-Waldau. Used with permission.
Materials Availability

Most experts agree: not enough In, Te to produce TW of PV.

Development of new TCO materials may reduce costs.


Tandem (Heterostructure) Cells

- Stack of lattice-matched materials with decreasing bandgaps.
- SpectroLab Cells: GaInP₂/GaAs/Ge. Eff\(_{\text{max}}\)=32\%, Eff\(_{\text{ave}}\)=28\%. 375 kW in orbit!
- Theoretical efficiency limit for infinite tandem cell: 86.8%
- *Heteroepitaxial growth slow and expensive!*

Materials Availability

Most experts agree: not enough Ge to produce TW of PV.

Development of new low-bandgap materials.
