Advanced Concepts, Part 1

Lecture 15 – 11/3/2011
MIT Fundamentals of Photovoltaics
2.626/2.627
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Cells are done!
Contact Firing

Please see the lecture 15 video for lab equipment visuals.
Effect of Shadowing Losses

4mm spacing

$I_{SC} = 0.62A$

2mm spacing

$I_{SC} = 0.60A$
What’s Limiting Performance?

What are the different forms of series resistance?
Performance in the Field: Temperature, Shading, and Mismatch
Why Temperature Matters

- Solar cell efficiency measurements are performed at 25°C
- Most Semiconductor simulations occur at 300K (27°C)
- Typical Solar Cell operate at 50-65°C
Effect of Temperature

Recall:

\[ I = I_L - I_0 \left( \exp\left( \frac{qV}{kT} \right) - 1 \right) \]

\[ I_0 = \frac{qADn_i^2}{LN_D} \]

What do you think will happen with \( V_{oc} \) with temperature?
DEMO!

$V_{oc}$

HEAT
V_{oc} Decreases with Temperature

\[ V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{I_0} \right) = \frac{kT}{q} \left[ \ln I_{sc} - \ln I_0 \right] = \frac{kT}{q} \ln I_{sc} - \frac{kT}{q} \ln \left[ B'T^\gamma \exp \left( - \frac{qV_{G0}}{kT} \right) \right] \]

\[ = \frac{kT}{q} \left( \ln I_{sc} - \ln B' - \gamma \ln T + \frac{qV_{G0}}{kT} \right) \]

\[ \frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{G0}}{T} - \gamma \frac{k}{q} \]

\[ \frac{dV_{oc}}{dT} = - \frac{V_{G0} - V_{oc} + \gamma \frac{kT}{q}}{T} \approx -2.2 \text{mV per } ^\circ C \text{ for Si} \]

***Where \( V_{G0} = qE_{G0} \), where \( E_{G0} \) is the band gap at absolute zero

0.09V decrease if operating at 65°C!

Source: PV CDROM

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Effect of Temperature

Recall:

\[ I = I_L - I_0 \left( \exp \left( \frac{qV}{kT} \right) - 1 \right) \]

\[ I_0 = \frac{qADn_i^2}{LN_D} \]

What do you think will happen with \( I_{SC} \) with temperature?
DEMO 2!
$I_{SC}$ increases with Temperature

- Recall:
  - $I_{SC} \approx I_L$

- $I_L$ increases with the flux of photons of energy greater than the $E_G$.

- $E_G$ decreases with increased temperature.

$$\frac{1}{I_{SC}} \frac{dI_{SC}}{dT} \approx 0.0006 \text{ per } ^\circ\text{C for Si}$$

VERY SMALL EFFECT!
Band Gap Dependence on Temperature

![Graph showing the dependence of band gap on temperature. The x-axis represents temperature in Kelvin (K) and the y-axis represents band gap in electron volts (eV). The graph shows a downward trend as temperature increases.]
Temperature Decreases Overall Efficiency

\[
\frac{1}{P_M} \frac{dP_M}{dT} = \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} + \frac{1}{FF} \frac{dFF}{dT} + \frac{1}{I_{SC}} \frac{dI_{SC}}{dT}
\]

\[
\frac{1}{FF} \frac{dFF}{dT} \approx \left( \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} - \frac{1}{T} \right) \approx -0.0015 \text{ per } ^\circ\text{C for Si}
\]

\[
\frac{1}{P_M} \frac{dP_M}{dT} \approx -(0.004 \text{ to } 0.005) \text{ per } ^\circ\text{C for Si}
\]

\(\eta\) decreases \(\sim 0.5\%\) per \(^\circ\text{C}\) for Si

Source: PV CDROM. Used with permission.

Effect of Light Intensity \((C)\)

To first order:

Linear dependence of \(I_{sc}\) on \(X\):
\[ I_{sc} = C \cdot I_L \]

Log dependence of \(V_{oc}\) on \(X\):
\[ V_{oc} \approx \frac{k_B T}{q} \ln \left( \frac{C \cdot I_{sc}}{I_o} \right) \]

Dependence of Efficiency:
\[ \eta \propto J_{sc} V_{oc} \propto C \ln(C) \]

*Beware the increased impact of series resistance!*

Module vs Cell Efficiency

Cells in **Series** in a Module are matched by cell with the lowest current. Voltages add.
Effect of Shading
Module vs Cell Efficiency

Cells in **Parallel** in a Module are matched in voltage.

Currents add.
Effect of Inhomogeneities

Efficiency (%) vs. Area, log scale (cm²)

- GaInP/GaInAs/GaSb (100x)
- Si (96x)
- GaInP/GaAs
- GaAs/CIS
- GaAs/GaSb (57x, submodule)
- Si (FZ)
- Si (CZ)
- Si (FZ)
- Si (80x, module)
- CIGS
- Si (multi)
- Si (film)
- a-Si (multi)
- a-Si (film on glass)
- a-Si (thin film on glass)
- a-Si (submodule)
- a-Si/Ge (tandem)
- a-Si/CIGS (thin film)
- CdTe (submodule)
- CdTe
- CIGS
- Nanocrystalline Dye
- Photoelectrochemical

Source: PV CDROM

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Effect of Inhomogeneities

Larger samples tend to have greater inhomogeneities. → “Good regions” and “bad regions” connected in parallel.

Gap Between Record Cells and Modules

Best Laboratory Cells

Commercial Modules

Projection

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Richard M. Swanson (SunPower)
Advanced Concepts
Third Generation Solar Cells

- **1\text{st} gen = single bandgap**
  - High cost
  - 15-20% efficient
- **2\text{nd} gen = thin films**
  - Low cost
  - 8-14% efficient
- **3\text{rd} gen = advanced concepts**
  - Low cost
  - >25% efficiency

\[
\frac{\$/W}{W} = \frac{\$/m^2}{\Phi\left(\frac{W}{m^2}\right) \cdot \eta \cdot Y}
\]

Intermediate Band Materials
Absorption of Photons in a Semiconductor
Added Absorption Pathway in IB Semiconductor
Theoretical Efficiency Gain From IB Solar Cells

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How to Create an IB?

- Three approaches:
  - Impurity band
  - Highly-mismatched alloys (Band Anti-crossing)
  - Quantum dot arrays
Impurity Band

$N_D < N_{\text{crit}}$

Impurity Band

\[ N_{\text{crit}}^{1/3} \times a_B \approx 0.26 \]

Quantum Dot/Well

Fig. 2. Possible methods of circumventing the 31% efficiency limit for thermalized carriers in a single–band gap absorption threshold solar quantum conversion system. (A) Intermediate-band solar cell; (B) quantum-well solar cell. [Adapted from (2)]

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Band-Anticrossing

Please see lecture 15 video or the references below for relevant band diagram visuals.


Hot Carrier Cells
Hot carrier cells

- Thermalization (pathway 1, left) accounts for a large efficiency loss, especially in small-bandgap materials.
- Hot carrier cells aim to collect carriers before they decay from an excited state. Carriers either move very quickly, and/or are inhibited from decaying. Band structure and contacts must also be properly designed.
- Theoretical efficiency limit for hot carrier cell: 86.8%.

Challenges:
- Practical implementation difficult.
- Must compete with highly-efficient processes (e.g., thermalization).
Hot carrier cells

Approach #1: Slow Carrier Cooling (e.g., by interruption of phonon modes)

Goal: To slow carrier cooling by modifying material parameters and geometry, to prolong excited charge states in the conduction band.


Fig. 7. Dependence of hot carrier cell efficiency on thermalisation rate. A rate of 1 corresponds to that measured in GaAs quantum wells [15,16]. In addition the importance of optimising the extraction energy $\Delta E$ is emphasised.

Fig. 3. Phonon energy as a function of phonon momentum and density of states (DOS) for lnN redrawn from [12] in which $E_{LO}>2E_{LA}$ such that LO→2LA (Klemens mechanism) is forbidden, whereas the LO→TO+LA (Ridley mechanism) can occur, although it is normally less likely and involves smaller loss of energy [13].

Hot carrier cells

Approach #2: Selective Energy Contacts

Goal: To extract hot carriers from devices, e.g., via resonant tunneling contacts.

Fig. 3. Sample structure for SEC experiments.


Emerging Tech: Bulk Thin Films
### Last Classes: Summary of the Most Common Commercial and Nearly-Commercial PV Technologies

<table>
<thead>
<tr>
<th>Wafer-Based</th>
<th>Common Deposition/Growth Method</th>
<th>Sample Companies</th>
<th>Typical Commercial Cell Efficiencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline Silicon (sc-Si)</td>
<td>Czochralski (CZ)</td>
<td>SunPower, REC, Sanyo...</td>
<td>18-22%</td>
</tr>
<tr>
<td>Multicrystalline Silicon (mc-Si)</td>
<td>Directional solidification (Bridgman)</td>
<td>Q-Cells, Suntech, REC, Solarworld...</td>
<td>16-17.5%</td>
</tr>
<tr>
<td>Ribbon Silicon</td>
<td>String Ribbon (SR)</td>
<td>Evergreen Solar, Sovello...</td>
<td>~15.5%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thin Film</th>
<th>Common Deposition/Growth Method</th>
<th>Sample Companies</th>
<th>Typical Commercial Cell Efficiencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>Chemical vapor deposition (CVD) on glass</td>
<td>Pureplays (First Solar)</td>
<td>~11%</td>
</tr>
<tr>
<td>Amorphous Silicon (a-Si) and variants</td>
<td>Plasma-enhanced chemical vapor deposition (PECVD) on glass or metal substrates</td>
<td>Pureplays (Energy Conversion Devices) Turnkey System Manufacturers (Oerlikon)</td>
<td>~6-9%</td>
</tr>
<tr>
<td>Copper Indium Gallium Diselenide (CIGS)</td>
<td>Variety: CVD, physical vapor deposition (PVD) on glass, metals.</td>
<td>Start-ups (Nanosolar, Heliovolt)</td>
<td>Pre-commercial: 6-14% reported.</td>
</tr>
</tbody>
</table>
Finding Earth-Abundant Thin Films

- **CuInGaSe**$_2$
  - Alternative: Cu$_2$ZnSnSe$_4$ (CZTS)
Materials Availability Limits Many PV Materials

**FIGURE 1.** Annual electricity production potential for 23 inorganic photovoltaic materials. Known economic reserves (also known as Reserve Base) and annual production are taken from the U.S. Geological Survey studies (27). Total U.S. and worldwide annual electricity consumption are labeled on the figure for comparison.

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Wadia et al. Materials availability expands the opportunity for large-scale photovoltaics deployment. Environmental science & technology (2009) vol. 43 (6) pp. 2072-2077
FIGURE 2. Minimum $c/W$ for 23 inorganic photovoltaic materials. Component cost contribution in $c/W$ is a strong indicator of value for future deployment. Calculated values for all 23 compounds evaluated are shown. The range of costs are between 0.32$c/W$ for Ag$_2$S and $<0.000002$c/W$ for FeS$_2$. While the actual dollar figure per watt for material extraction will appear small compared to the entire cost of an installed PV system, the cost of processing the material for PV grade applications is a larger cost contributor and should be evaluated further.
Many challenges in developing new materials. Obtaining right stoichiometry is key!
