Wafer Silicon-Based PV

Lecture 9 – 2.626
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General Announcements

• Quiz #1
• Class Projects
Outline of Today’s Lecture

• Illuminated IV Curves: Efficiency, $J_{sc}$, $V_{oc}$
• Notes about Efficiency
• Overview of PV Technologies
• Manufacturing of Silicon-Based Solar Cells
Reading Assignment

• Read: PVCDROM: Chapters 5 and 6
Efficiency Calculations

\[ I = I_o \left( e^{\frac{qV}{kT}} - 1 \right) - I_L \]
Efficiency Calculations

\[ I = I_o \left( e^{qV/kT} - 1 \right) - I_L \]
Efficiency Calculations

Industry Convention: Quadrant flipped!

[Diagram showing Illuminated IV Curve with labels for $I_{SC}$, MPP, and $V_{oc}$]
Efficiency Calculations

\[ \text{Efficiency} \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi} \]

**V_{oc}**

**MPP**

**I_{sc}**

**Illuminated IV Curve**

*Current (A), Power (W)*

*Voltage (V)*

0 0.1 0.2 0.3 0.4 0.5 0.6
Efficiency Calculations

Fill Factor $\equiv FF = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$
Efficiency Calculations

By combining equations 1 and 2...

Efficiency \( \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi} \)

Fill Factor \( \equiv FF = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{V_{\text{oc}} \cdot I_{\text{sc}}} \)

We obtain:

Efficiency \( \equiv \eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{V_{\text{mp}} \cdot I_{\text{mp}}}{\Phi} = \frac{FF \cdot V_{\text{oc}} \cdot I_{\text{sc}}}{\Phi} \)
Efficiency Calculations

This is a higher-efficiency device compared to... [next slide]
Efficiency Calculations

This is a lower-efficiency device, compared to the previous slide.

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.
Efficiency of a solar cell is an important parameter

\[ \eta = \frac{\text{generated electrical power}}{\text{incident light power}} \]

100% efficiency (impossible to achieve)

33% efficiency (space-grade solar cells)

20% efficiency (monocrystalline silicon solar cells)

10% efficiency (amorphous silicon solar cells)

Expensive material

Very Expensive material

Relatively Inexpensive material
Solution-processed PbS quantum infrared photodetectors and optoelectronics

Under −5 V bias and illumination from a 975 nm laser, our detectors show an internal quantum efficiency of 3%, a ratio of photocurrent to dark current of 630, and a maximum responsivity of $3.1 \times 10^{-3} \text{ A W}^{-1}$.

The photovoltaic response under 975 nm excitation results in a maximum open-circuit voltage of 0.36 V, short-circuit current of 350 nA, and short-circuit internal quantum efficiency of 0.006%.

Technical Terms:
- Solar Conversion Efficiency
- External Quantum Efficiency
- Internal Quantum Efficiency

Courtesy of Edward H. Sargent. Used with permission.
Solar Conversion Efficiency

\[
\eta = \frac{\text{Power Out}}{\text{Power In}} = \frac{J_{mp} \cdot V_{mp}}{\Phi} = \frac{FF \cdot J_{sc} \cdot V_{oc}}{\Phi}
\]

Typical values are 12–20% for established technologies, <10% for most emerging technologies.

\(\eta\) and \(\Phi_F\): Vary with illumination intensity (e.g., 1 Sun)
External Quantum Efficiency

\[ \text{EQE} = \frac{\text{Electrons Out}}{\text{Photons In}} \]

Typical peak values are 60–90%, depending on reflectivity.

EQE highly wavelength- and illumination-dependent!
Internal Quantum Efficiency

\[
IQE = \frac{\text{Electrons Out}}{(\text{Photons In}) \cdot (1 - \text{Reflectivity})}
\]

Typical peak values are 80–98%, depending on reflectivity.

EQE highly wavelength- and illumination-dependent!
When an efficiency quoted, think about:

- What “efficiency” is being measured?
- What is the nature of the light being used?
  - What spectrometer to simulate solar spectrum?
  - If monochromatic, what wavelength?
  - What intensity (photon flux)?
- What used car are they trying to sell me?
An example of honest efficiency reporting


Module Efficiency Tables


Diversity of PV Devices
Photovoltaic Device Fundamentals

(1) Charge Generation: Light excites electrons, freeing them from atomic bonds and allowing them to move around the crystal.

(2) Charge Separation: An electric field engineered into the material (pn junction) sweeps out electrons.

Advantages: There are no moving parts and no pollution created at the site of use (during solar cell production, that’s another story).

Disadvantages: No output at night; lower output when weather unfavorable.

For full animation, see:
http://micro.magnet.fsu.edu/primer/java/solarcell/
Technological Diversity


Silicon Ribbon

Heterojunction Cells

Copper Indium Diselenide (CIS)

Amorphous Silicon

Monocrystalline Silicon

Multicrystalline Silicon

SunPower Back-contacted

Organics

http://site.novatechgadgets.com/evtechfeat.jpg

http://www.atp.nist.gov/eao/sp950-1/astropw1.jpg

http://www.iea-pvps.org/ar/ar00/images/aus03.jpg


http://commons.wikimedia.org/wiki/File:Multicrystallinewafer_0001.jpg

http://electronicdesign.com/Files/29/11527/Figure_01.jpg

http://www.livescience.com/images/0412_solar_panels_03.jpg

http://www.triplepundit.com/nanosolar.jp

http://www.triplepundit.com/nanosolar.jp

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Photovoltaics: State of the Art

Slide courtesy of Gerhard Willeke, Fraunhofer ISE (Freiburg, Germany)

Courtesy of Gerhard Willeke. Used with permission.
Silicon Photovoltaics – Wafer Substrates
Worldwide PV Production

- Sustained 25-40% industry growth rates.
- PV now a $10+ bi industry.


US Market Share:
1980: 75%
1990: 33%
2000: 26%
2005: 10%

Silicon is the second most abundant element on Earth after oxygen (28% of the Earth’s crust). Its most familiar forms are sand and quartzite (the latter one is more pure).

Human-made Monocrystalline Silicon

Human-made Multicrystalline Silicon

Monocrystalline Silicon

Multicrystalline Silicon
Crystalline silicon growth technologies used in PV

- Single crystalline ingot growth
  (Czochralski (CZ) and float zone (FZ) technologies)
  → Sunpower, Siemens Solar

- Casting of multicrystalline silicon
  - Sharp, Kyocera, BP Solar, Shell Solar

- Ribbon growth of multicrystalline silicon
  → Evergreen,
  RWE Schott Solar (former ASE Americas)

- Sheet growth of multicrystalline silicon
  → General Electric (former Astropower),
  ECN

Courtesy of A. A. Istratov. Used with permission.
Czochralski (CZ) crystal growth

1916, Polish physicist Jan Czochralski

Melting of polysilicon, doping
Introduction of the seed crystal
Beginning of the crystal growth
Crystal pulling
Formed crystal with a residue of melted silicon

Si melting point 1414°C
Growth rate approx. 5 cm/hour
Typical crystal size:
10-30 cm in diameter,
1-2 meters long

This type of silicon is the standard for integrated circuit industry. Very high quality ingots. Partial dissolution of quartz crucible introduces oxygen and carbon into the melt.
Principles of CZ growth process

Images of the Czochralski method removed due to copyright restrictions. Please see:
- http://semiconductor-nano.com/images/Czochralski_2a.gif
- http://semiconductor-nano.com/images/Czochralski_2c.gif

Courtesy of A. A. Istratov. Used with permission.
Float-zone silicon growth

Crystal grows without contact with crucible and has the lowest possible impurity content (particularly low oxygen and carbon content). However, FZ growth appears to be more expensive than CZ growth and is used only for the most demanding applications.

Courtesy of A. A. Istratov. Used with permission.
Crystalline silicon

**Single crystalline silicon**

FZ, CZ

**Multicrystalline silicon**

Cast, ribbon, sheet techniques

Each silicon atom is bonded to four neighbouring atoms.

The grain size in multicrystalline silicon is from several microns to several millimeters or even centimeters. The fundamental physical properties such as bandgap and absorption properties are similar. The difference between c-Si and mc-Si is primarily the density of defects and impurities – and cost, cost, cost.

Courtesy of A. A. Istratov. Used with permission.  

Courtesy Christiana Honsberg and Stuart Bowden. Used with permission.
Multicrystalline silicon is very easy to distinguish from single crystalline silicon: \emph{grains in mc-Si are clearly visible in reflected light}.
Casting/directional solidification of mc-silicon

Silicon can be solidified either in a separate crucible after it is poured from a melting crucible, or can be melted and directionally solidified in the same crucible. Crucibles are usually made of quartz or graphite, often with Si₃N₄ coating.

240 kg ingots with cross-section of 69x69 cm are grown in total cycle times of 56 hours.

Drawing from www.siliconsultant.com, Ted Ciszek

Courtesy of A. A. Istratov. Used with permission.
Casting of multicrystalline silicon

Images removed due to copyright restrictions.
Please see any photos of multicrystalline silicon ingots and blocks, such as
http://www.tkx.co.jp/english/solar/images/index_img_03.jpg

Ingots are initially cut into rectangular blocks, and then sliced into wafers. Ingots can weigh up to 200-250 kg. The major part of mc-Si used in PV is grown by casting.

Courtesy of A. A. Istratov. Used with permission.
Wafering (cutting ingots into wafers)

Possible configuration of a wire saw

Inner diameter slicing

Cutting wire spindle
Guiding Cylinders
Silicon Brick

Abrasive wire length may be up to several km.

Kerf loss during sawing is typically 30-40% of silicon

Courtesy of A. A. Istratov. Used with permission.
Ribbon growth (A)

EFG (Edge-Defined, Film-Fed Growth) – RWE Schott Solar

Growth rate: 1-3 cm/min

No sawing required!

Image removed due to copyright restrictions.
Please see Fig. 2 in Bell, R. O., and J. P. Kalejs. "Growth of Silicon Sheets for Photovoltaic Applications."
Ribbon growth (B)

String ribbon growth technique - Evergreen Solar

Similar technique:
T.F.Ciszek and J.L.Hurd, 1980

Edge-supported pulling

Growth rate: 1-3 cm/min

Courtesy of A. A. Istratov. Used with permission.
Sheet Growth (A)
RGS (Ribbon Grown on Substrate) – ENC

Growth rates from 4 to 9 meters/min

Sheet Growth (B)
Sheet ribbon – General Electric (former Astropower)

100 – setter material (a rigid board or a flexible thin belt made of, e.g., quartz graphite, silicon nitride, silicon carbide).

110 – release agent coating, e.g., silicon nitride, silicon oxynitride, silicon carbide, etc.

200 – granulated silicon, grain size: 20 to 1000 microns.

300 – melt zone in Ar/H mixture ambient to minimize Si oxidation

400 – controlled solidification and columnar growth from the top. Nucleation of grains is enhanced by addition of the “coating materials”, 305, which can be silicon carbides, nitrides, oxides, ...

U.S. Patent 6,111,191 (August 2000)
## Comparison of different growth techniques used in silicon technology

<table>
<thead>
<tr>
<th>Method</th>
<th>Width (cm)</th>
<th>Growth rate, mm/min</th>
<th>Throughput (m²/day)</th>
<th>Energy use (kWh/m²)</th>
<th>Typical, best efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Float zone</td>
<td>15</td>
<td>2-4</td>
<td>80</td>
<td>36</td>
<td>&lt;18%, 24%</td>
</tr>
<tr>
<td>Czochralski</td>
<td>15</td>
<td>0.6-1.2</td>
<td>30</td>
<td>21-48</td>
<td>&lt;17%, &gt;20%</td>
</tr>
<tr>
<td>Cast – directional solidification</td>
<td>69</td>
<td>0.1-0.6</td>
<td>70</td>
<td>9-17</td>
<td>&lt;16.5%, 20%</td>
</tr>
<tr>
<td>Ribbon Silicon</td>
<td>8-80 cm</td>
<td>15-20</td>
<td>20</td>
<td>20</td>
<td>15.5%, 18%</td>
</tr>
<tr>
<td>Sheet growth (substrate melt shaping)</td>
<td>20</td>
<td>1000-6000</td>
<td>&gt;1000</td>
<td>No data</td>
<td>&lt;12%, 16%</td>
</tr>
</tbody>
</table>

Courtesy of A. A. Istratov. Used with permission.


Source for energy use, growth rate, etc.: www.siliconsultant.com . **Disclaimer:** These numbers are outdated, and may not reflect actual commercial production values.
Materials Availability

Plenty of (oxidized) silicon in the Earth’s crust, but...

Not enough silver! New solar cell contact materials needed.


Next Class

• *From wafers to cells.*
• *Intro to thin film technology.*