Review of Photovoltaic Solar Cells

Optics for Energy Course
11/5/13
Liz Lund
Outline

• Solar electricity production
• How Photovoltaics (PV) work
• Types of PV
• Emerging technologies
Solar Electricity Production

http://www.nrel.gov/docs/fy13osti/54909.pdf
Renewables in US

~10% Renewable Energy in US

Solar is a small fraction 0.1%
Global vs. US Renewable Energy

- Same trends for PV global and in US
- Wind and solar are fastest growing renewables in US
  - Wind 17%
  - Solar 86%

http://www.nrel.gov/docs/fy13osti/54909.pdf
Solar Growth is Exponential

Solar electricity generation grown by a factor of 9 (2000 to 2011)
Who’s Making It?

Global Solar Module Production 2011:
34,788 MW

**By Country**
- China 61% 21,265 MW
- Europe 14% 4,815 MW
- Japan 5% 1,590 MW
- United States 4% 1,333 MW
- Rest of World 1% 386 MW
- Rest of Asia 16% 5,399 MW

**By Manufacturer**
- First Solar 5.7%
- Suntech Power 5.8%
- Yingli Green Energy 4.8%
- Trina Solar 4.3%
- Canadian Solar 4.0%
- Tianwei New Energy 2.8%
- SunPower 2.8%
- Hanwha-SolarOne 2.7%
- Sharp 2.7%
- LDK Solar 2.5%
- Hareon Solar 2.5%
- Others 59.4%
Where is it Installed?

Solar Electricity Installed Capacity (2011) – Select Countries

- Belgium: 1,603 MW
- France: 2,715 MW
- Spain: 5,310 MW
- United States: 4,527 MW
- Germany: 24,562 MW
- Czech Republic: 1,933 MW
- Austria: 1,323 MW
- Italy: 12,785 MW
- China: 2,995 MW
- Japan: 4,944 MW

Sources: SEIA/GTM, Bloomberg New
Where in US?

States with extensive incentives lead PV deployment
Solar Prices

99% cost drop since 1977

Swanson’s Law: PV costs drop 20% for every doubling of shipped volume

How Photovoltaics Work
Photovoltaic Solar Cells: Light In, Electricity Out

3 Necessary Functions:

1. Generate charge carriers from light semiconductor + sunlight

2. Separate charge carriers p-n junction (diode)

3. Collect charge carriers to do electrical work carriers reach front and back contacts
Solar Cell, Module, Array

Solar Cells
(4 Cells)

Solar Panel
(Module)

Solar PV Array
(Multiple modules)
n- and p-type semiconductors

Undoped Si Lattice

P Doped Si

B Doped Si

Silicon

Phosphorous

Boron

“Extra” electron

“Missing” electron Hole

n-Type extra electrons

p-Type extra holes

Si

P

B
Making a Diode

1. n- and p-type materials separate are neutral
2. Place materials together
   • Free electrons and holes diffuse and recombine
   • Leave behind charged nuclei (localized)
3. Create charged interface
   • Charge build-up repels complete diffusion
   • At equilibrium, establish space charge region
4. Built in voltage potential
   • Diode behavior of pn junction
The Band Gap: Energy barrier to generating charge carriers

Individual Atoms
Discrete Energy States

Atoms in a Crystal
Energy Bands

Conduction Band

Energy Gap

Valence Band

Band Diagram

Valence band (of states):
Lower energy state
Electrons are localized around atomic nuclei
Formed from bonding orbitals in crystal

Conduction band (of states):
Higher energy state
Electrons are delocalized
Free to move throughout crystal
Formed from anti-bonding orbitals in crystal

http://pveducation.org/pvcdrom/pn-junction/band-gap
Generating Charge Carriers-Absorption of Light

http://pveducation.org/pvcdrom/pn-junction/absorption-of-light

Semiconductor only absorbs light with energy equal or greater than the band gap (lower wavelength)

Ideal band gap: 1.1 eV

Lower band gaps give lower voltage (current losses)
Absorption Coefficient-PV Material Property

http://www.pveducation.org/pvcdrom/pn-junction/absorption-depth
Schockley-Quiesser Limit

\[ \eta = 33.7\% \] theoretical maximum for single pn junction cell with no concentration

Plotted with actual record efficiencies of different materials

What limits this? (33% example)
- 47% to heat.
- 18% not absorbed.
- 2% local recombination of holes and electrons.

Passing the Limit:
Use multiple materials
Have multiple pn junctions
Concentrate sunlight
Harvest heat also
Use "quantum dots" to harvest excess photon energy
Device Parameters

- JV Curve
  - Jsc
- Voc
- Resistances
  - Series-contact and current movement
  - Shunt-manufacturing defects
- Fill Factor
  - Max Powerpoint
- Efficiency
  - IQE
  - EQE
JV Curve

- Series Resistance Slope of Line
- Shunt Resistance Slope of Line
- Maximum power point
Types of PV
Best Research-Cell Efficiencies

Multijunction Cells (2-terminal, monolithic)
- LM = lattice matched
- MM = metamorphic
- IMM = inverted, metamorphic

Three-junction (concentrator)
- Two-junction (concentrator)
- Four-junction (concentrator)

Single-Junction GaAs
- Single crystal
- Concentrator
- Thin-film crystal

Crystalline Si Cells
- Single crystal (concentrator)
- Single crystal (non-concentrator)
- Multicrystalline
- Thin-film crystal

Thin-Film Technologies
- CIGS (concentrator)
- CIGS
- CdTe
- Amorphous Si:H (stabilized)
- Nano- or micro-poly-Si
- Multijunction polycrystalline

Emerging PV
- Dye-sensitized cells
- Perovskite cells
- Organic cells (various types)
- Organic tandem cells
- Inorganic cells (CuZnSSe)
- Quantum dot cells

http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

NEED MORE BULLET POINTS
Classes of PV

• **Thin Film**
  – 1-2 um thick
  – “dirty” deposition methods
  – Optically thin-use optics to compensate
  – More defect tolerant
  – CIGS, CdTe, CZTS, a-Si
  – Deposit on flexible substrates

• **Thick**
  – 100’s of um thick
  – Typically c-Si
  – Must be very pure for carrier diffusion

• **Monocrystalline**
  – Continuous crystal lattice
  – Expensive production
  – Higher efficiencies in cells

• **Polycrystalline**
  – Many grains (um-cm size)
  – More grain boundaries=more defects
  – Most thin films

http://www.posterus.sk/?p=1247
Comparing PV Technologies

- Energy Payback Time
  - 10% CIGS, 4% OPV ...1 yr
  - c-Si ...2.7 yrs

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<th>2004</th>
<th>2009</th>
<th>2012</th>
<th>Record Cell</th>
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<tr>
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<td>µc-Si, a-Si</td>
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<td>a-Si (3-j)</td>
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<td>Organic</td>
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Emerging PV
Best Research-Cell Efficiencies

http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

NEED MORE BULLET POINTS
Perovskite Solar Cells

Dye-Sensitized Solar Cells

Organic/Inorganic Hybrid
Cheap to make
Lifetime?

3 different materials:
1. Light absorption
   Sensitizing (organic) dye
2. Electron transport
   Wide band-gap (inorganic) semiconductor
3. Hole transport/electron regeneration
   Electrolyte

Hardin et al., Nature Photonics (2012)
Multi-junction PV

- Thin top layers absorb shorter wavelengths
- Longer wavelengths in bottom cell
- Tunnel diode allows current flow but electrical field isolation of top and bottom cells
- Expensive to make
- Crystalline lattice and currents must match—really difficult and constrains materials!
- Currently only used in space
- World Record: 43% with 5-tandem cell UNSW
Concentrating PV (CPV)

Focus light using mirrors, lenses
Use small area, high efficiency cells

Additional requirements
• Non-imaging optics-focus on radiative rather than image transfer
• Trackers-2D east to west each day, north to south each season
• Cooling system

http://amonix.com/content/low-energy-production-costs-0
Advantages
• Very efficient, less space
• Low water usage, advantage over traditional solar thermal concentrators (4 vs. 850 gal/MWhr)
• Lower cost of materials, majority of infrastructure is not PV
• Well-suited for large power plant arrays
• Nearing grid parity now!

Disadvantages
• Requires direct sunlight
• New technology-late to the funding game
• Trackers are expensive

Suited for desert climates especially
Large-scale PV should use earth-abundant and industrially-available elements to avoid bottlenecks

“commodity elements”
PV materials cost - Red Herring

- First Solar: ‘Module shipping box cost higher than CdTe material cost’
- Glass for panel much more expensive than 1 cm$^3$ semiconductor film (>100x)
- Absolute semiconductor materials costs insignificant!
Winning Argument-TW Scale-Up Potential

- Sulfur: byproduct of Cu, Zn ores & fossil fuel production
- More cm$^3$/kg from light elements
- Many sulfides have right $E_{\text{Gap}}$

In or Te production limits:
CIGSe & CdTe: $\sim$150 GW$_p$/yr

CZTS-CIGS with no Indium

- Kesterite structure (like chalcopyrite)
- $E_{\text{Gap}} = 1.5$ eV, direct gap
- First PV investigations in late 1990’s
  - Katagiri
  - Friedlmeier

$\eta = 11\%$ for evaporated cells*

(IBM)

*Wang APL 97 143508 (2010)
Summary

• Photovoltaic solar cells needs 3 things
  – Generation of charge carriers-semiconductor with band gap
  – Separation of carriers-pn junction
  – Collection of current to do electrical work
• Variety of technologies that get the job done
• C-Si still dominate the market
• It’s getting cheaper faster