Emerging PV Technologies

Lecture 14 – 2.626

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General Matters

• Exam #2
• Group Project Check-In
## Last Classes: Summary of the Most Common Commercial and Nearly-Commercial PV Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Common Deposition/Growth Method</th>
<th>Sample Companies</th>
<th>Typical Commercial Cell Efficiencies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wafer-Based</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocrystalline Silicon (sc-Si)</td>
<td>Czochralski (CZ)</td>
<td>SunPower, REC, Sanyo...</td>
<td>17-22%</td>
</tr>
<tr>
<td>Multicrystalline Silicon (mc-Si)</td>
<td>Directional solidification (Bridgman)</td>
<td>Q-Cells, Suntech, REC, Solarworld...</td>
<td>15.5-16.5%</td>
</tr>
<tr>
<td>Ribbon Silicon</td>
<td>String Ribbon (SR) and Edge-defined Film-fed Growth (EFG)</td>
<td>Evergreen Solar, SCHOTT Solar, Ever-Q...</td>
<td>~15.5%</td>
</tr>
<tr>
<td><strong>Thin Film</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cadmium Telluride (CdTe)</td>
<td>Chemical vapor deposition (CVD) on glass</td>
<td>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>Energy Conversion Devices, Oerlikon, Applied Materials...</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>Numerous start-ups: Nanosolar, Miasolé, Heliovolt...</td>
<td>Pre-commercial: 6-10% reported.</td>
</tr>
</tbody>
</table>
emerging pv technologies

Goals:
- Very low cost PV (~$0.20/Wp).

Challenges:
- In R&D stage (appropriate materials and technologies not yet developed).
Emerging PV Technologies: Driving Motivation

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The “High Road”: “3rd generation” PV

Advantages:
- Theoretical $\eta > 85\%$

Challenges:
- Practical implementation difficult.
- Appropriate materials and technologies not yet developed.
Vision of “3rd Gen” PV: High Efficiencies, Low $/W_p

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Multiband materials

Electrons can be excited either in one step by a single high-energy photon (1), or by a combination of steps using two lower-energy photons (3+2).
- Theoretical efficiency limit for $n$-band multiband cell: 86.8%

Challenges:
- Practical implementation difficult.
- Low carrier mobilities in highly defective materials.
- High recombination rates (step down).
- N- and P-type doping.
Multiband materials

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N. Lewis, Science 315 (2007) 798
Multiband materials

Multiband concepts: First reduction to practice

Multiband materials

State-of-the-art: Demonstration of intraband transitions

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


Fig. 1. Schematic and band diagram of an ideal hot carrier solar cell. The absorber has a hot carrier distribution at temp $T_A$. Carriers cool isentropically in the monoeenergetic contacts to $T_A$. The difference of the Fermi levels of these two contacts is manifested as a difference in chemical potential of the carriers at each contact and hence an external voltage, $V$.

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.


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.


Multiple Exciton Generation (MEG)

- One photon creates multiple electron-hole pairs, each with the energy of the bandgap. Thermalization losses are avoided.
- Physical mechanisms: Raman luminescence, impact ionization.
- Theoretical $\eta$ limit for these devices, with bandgap $\rightarrow 0$ eV: 85.9%

Challenges:

- Practical implementation difficult.
- Must compete with highly-efficient processes (e.g., thermalization).
- Controversy...

Recent pubs by R.J. Ellingson
Photon Cascade

- High energy photons are converted into multiple lower-energy, bandgap-matched photons. Thermalization losses reduced.

Challenges:
- Practical implementation, conversion layer material choice.
- Conversion layer must directionally emit lower-energy photons into, not away from, the absorber material. Self-assembled nanorod arrays?
Plasmon Surface Resonance

Potential advantages: Enables use of very thin material layers.

References:

http://gcep.stanford.edu/research/factsheets/plasmonic_photovoltaics.html

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Plasmon Surface Resonance

http://gcep.stanford.edu/research/factsheets/plasmonic_photovoltaics.html

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The “Low Road”: Low-cost Nanostructured PV

Advantages:
- Potentially cheaper.
- Potentially more scalable.

Biggest challenge:
- Increasing efficiencies.
Vision: Low Efficiencies, Low \$/W_p, Massively Scalable

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Vision of Nanostructured PV: Fast Scaling!

To survive as a technology NANOSTRUCTURED PVs need to:
- ACCELERATE OVER THE Si-PRODUCTION
- REACH HIGHER EFFICIENCIES and/or LOWER INSTALLATION COSTS

Graph of project global solar cell production removed due to copyright restrictions.
**Advantages of Nanostructured PVs**

Absorption constant for organic and nanostructured materials is **10-fold larger** than for inorganic thin films (due to large dipole moments in organics and quantum size effects in quantum dots and rods)

- **TUNABLE SPECTRAL ABSORPTION** -
- **EFFICIENT MATERIALS USE** -
- **ROOM TEMPERATURE DEPOSITION** – (on an arbitrary form factor)

Thin Film Nanostructured PV efficiency ~6 %
Nanocrystalline dye electrochemical PV ~8 %

**MANUFACTURING PARADIGM SHIFT**

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1. Photon can excite an electron from Valence Band (ground state) to Conduction Band (excited state)
2. At the heterojunction the electron and hole can separate, resulting in build-up of electrons on the right and build-up of holes on the left \( \rightarrow \) WE GENERATED PHOTOVOLTAGE
3. If solar cell is connected to a resistor, the photo-voltage will drive current through the resistor

(Courtesy of Vladimir Bulovic. Used with permission.)
Example: First Organic Heterojunction Solar Cell

Power conversion efficiency ~ 1%

Need interface to maximize exciton dissociation

I-V in DARK

PHOTOGONERATED CURRENT

V_{oc}

I_{sc}

I-V in LIGHT

CuPc

Perylene tetracarboxylic derivative (PV)

V_{oc} = open-circuit voltage
I_{sc} = short-circuit current


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**ORGANIC SOLAR CELLS**

Room temperature deposition – **organics are compatible with plastic substrates**

- Disorder causes strong localization.
- Carrier pairs strongly bound – not easily broken by field.
- Must use interface between two materials to dissociate carrier pairs

1. Photon absorbed
2. Excited state diffuses
3. Charge formed at interface
4. Charge diffuses out

Performance peaks at 5% power conversion efficiency (cf. Si ~ 25%)

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Molecular Organic Photovoltaics

Organic Solar Cells
I-V Response Under Solar Illumination

- Broad spectral response: 300 - 800 nm
- $\eta_p \approx 3\%$ in concentrator geometry

Peumans, Bulovic, Forrest,

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**Solar Cell Characteristics**

Critical parameters:

- $V_{OC}$, open circuit voltage
- $I_{SC}$, short circuit current
- $FF$, fill factor = area max. power rectangle

$V_{OC} \cdot I_{SC}$

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Fundamental Efficiency Limits of Solar Energy Conversion in Photovoltaics

Excess energy above $E_g$ → heat

Conduction band

$E_g = \text{max. } V_{OC}$

Valence band

As band gap increases, the maximum open circuit voltage increases, but the fraction of the solar spectrum absorbed decreases.

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Multiple Junction Cells

Connect solar cells in series.
Usually wide gap cells in series with narrow gap cells.

Voltage of cells adds.
But need same current through each cell. Must carefully tune absorption.

Advantage: highest performance cells made this way.

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6 Multijunction Cells

Principle

LIMITATIONS TO EFFICIENCY OF PLANAR HETEROJUNCTION CELLS

Organic PV cells must simultaneously maximize absorption and exciton dissociation.

\[ \eta_{\text{ABSORB}} \times \eta_{\text{DIFFUSE}} \approx 10\% \]

1. Photon absorbed
2. Excited state diffuses
3. Charge formed at interface
4. Charge diffuses out

Efficiency:
\[
\begin{align*}
\text{THICK device} &= \text{high absorption, lots of exciton losses} \\
\text{THIN device} &= \text{low absorption, few exciton losses}
\end{align*}
\]

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Tradeoff:
**Target: Increase the exciton dissociation interface**

Method 1 - Stack devices:

Power conversion efficiency 3%~6%.

**Challenges:** Multilayer stack is likely expensive, unless generated from folded structures.
Method 2 - Random Blends of nanostructures (polymers, molecules, and/or nanowires)

Blended polymer/nanorod PVs

Power conversion efficiency ~ 1%~3%.

Challenges: Charge extraction limited by trapping on disordered nanorods.
New Approaches:

Self-aligned nanowires, to reduce carrier hopping.

Combination with dye-sensitized solar cell approach.

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Please see Fig. 1d in Huang, Michael H., et al. "Room-Temperature Ultraviolet Nanowire Nanolasers." *Science* 292 (June 8, 2001): 1897-1899.

Courtesy of Peidong Yang. Used with permission.

Courtesy of Vladimir Bulovic. Used with permission.
Method 3 - Coat nanostructured semiconducting surfaces, and get the charges out using electrolyte (Grätzel PV cell)

Ex: Electrolytic PV Cell with absorbed organic dye on surface of colloidal TiO₂

Power conversion efficiency ~8% (the Best performing ‘organic’ PV)

Challenges: This is a wet cell – electrolyte leaks, dye desorbs, makes packaging expensive

Images removed due to copyright restrictions. Please see Fig. 3 and 4 in Grätzel, Michael. “Photoelectrochemical Cells.” Nature 414 (November 15, 2001): 338-344.
Challenges of emerging technologies
Challenges of Nanostructured PV: Efficiency

If (energy payback time) > (doubling time), then solar becomes net negative energy producer! (Remember the bad press for ethanol?)