2.626 Fundamentals of Photovoltaics
Fall 2008

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

		Common Deposition/Growth Method	Sample Companies	Typical Commercial Cell Efficiencies
Wafer-Based	Monocrystalline Silicon (sc-Si)	Czochralski (CZ)	SunPower, REC, Sanyo…	17-22%
	Multicrystalline Silicon (mc-Si)	Directional solidification (Bridgman)	Q-Cells, Suntech, REC, Solarworld…	15.5-16.5%
	Ribbon Silicon	String Ribbon (SR) and Edge-defined Film-fed Growth (EFG)	Evergreen Solar, SCHOTT Solar, Ever-Q…	~15.5%
Thin Film	Cadmium Telluride (CdTe)	Chemical vapor deposition (CVD) on glass	First Solar...	~11%
	Amorphous Silicon (a-Si) and variants	Plasma-enhanced chemical vapor deposition (PECVD) on glass or metal substrates	Energy Conversion Devices, Oerlikon, Applied Materials…	~6-9%
	Copper Indium Gallium Diselenide (CIGS)	Variety: CVD, physical vapor deposition (PVD) on glass, metals.	Numerous start-ups: Nanosolar, Miasolé, Heliovolt…	Pre-commercial: 6-10% reported.

emerging pv technologies

Goals:

- Very low cost PV (~\$0.20/W_p).

Challenges:

- In R&D stage (appropriate materials and technologies not yet developed).

Emerging PV Technologies: Driving Motivation

Image removed due to copyright restrictions. Please see Fig. 1 in Lewis, Nathan. "Toward Cost-Effective Solar Energy Use." *Science* 315 (2007): 798-801.

N. Lewis, *Science* **315** (2007) 798

The "High Road": "3rd generation" PV

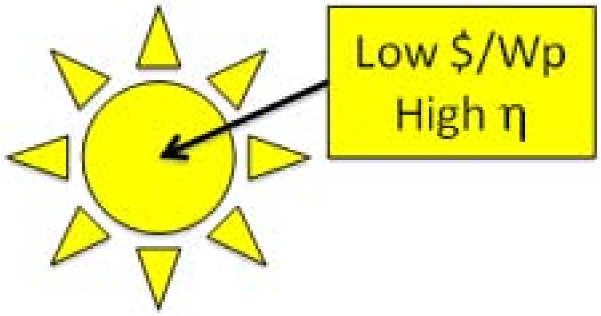
Advantages:

- Theoretical η > 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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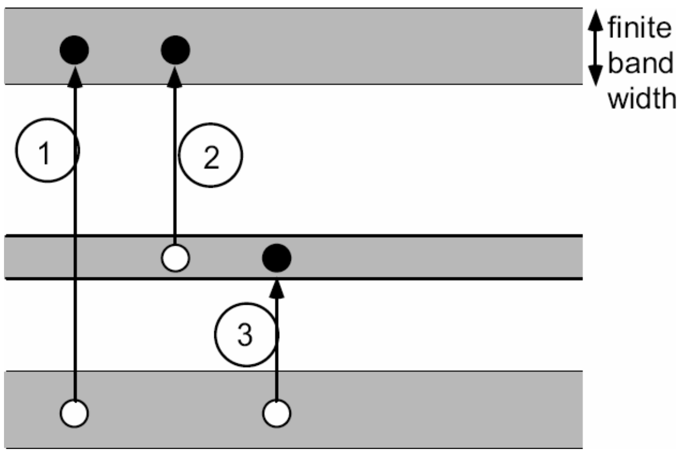
Multiband materials



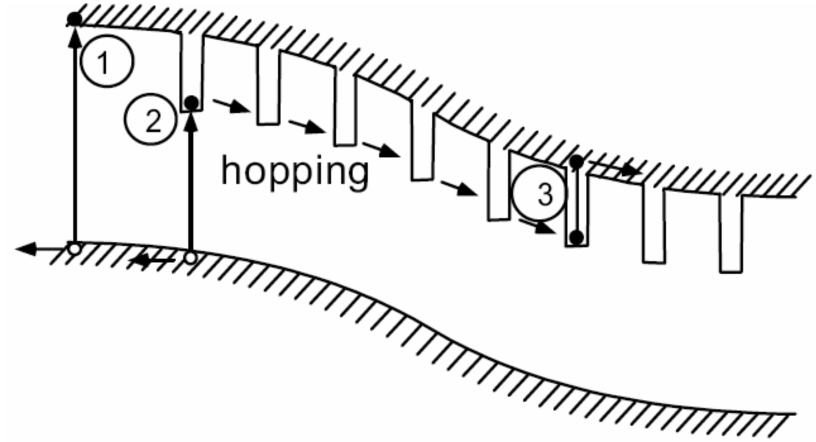


Fig. 7. Multiple quantum well solar cell meeting the constraints of three-band theory.

M.A. Green, *Physica E* **14** (2002) 65
A. Luque and A. Martí, PRB 78, 5014 (1997)

- 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

N. Lewis, *Science* **315** (2007) 798

Multiband materials

Multiband concepts: First reduction to practice

Image removed due to copyright restrictions. Please see Fig. 1 in Martí, A., et al. "Production of Photocurrent due to Intermediate-to-Conduction-Band Transitions: A Demonstration of a Key Operating Principle of the Intermediate-Band Solar Cell." *Physical Review Letters* 97 (2006): 247701.

A. Martí et al., *Phys. Rev. Lett*. **97**, 247701 (2006)

Multiband materials

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

A. Martí et al., *Phys. Rev. Lett*. **97**, 247701 (2006)

Hot carrier cells

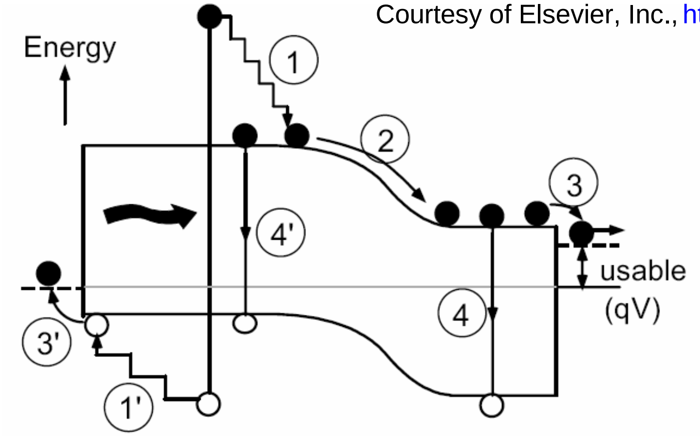


Fig. 1. Loss processes in a standard solar cell: (1) thermalisation loss; (2) and (3) junction and contact voltage loss; (4) recombination loss.

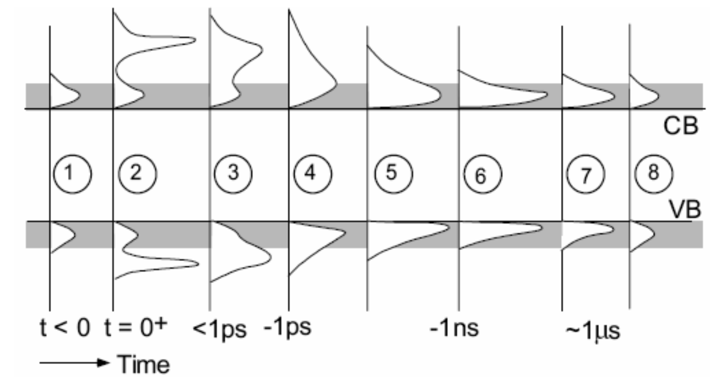


Fig. 4. Energy relaxation of carriers after a short, high-intensity laser pulse at $t = 0$.

M.A. Green, *Physica E* **14** (2002) 65

- 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

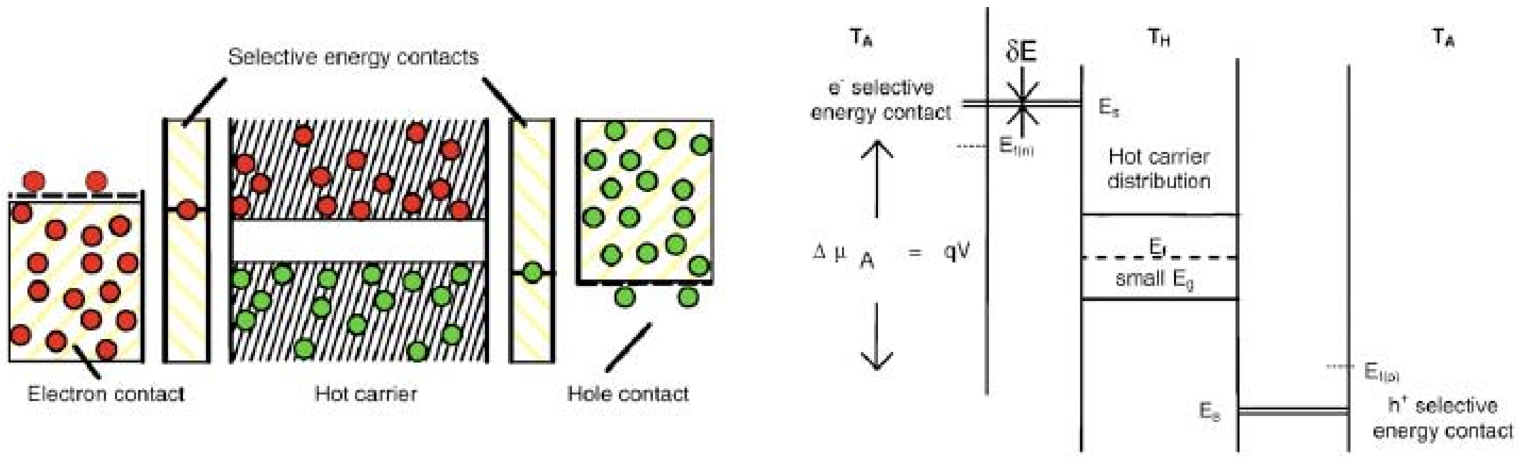


Fig. 1. Schematic and band diagram of an ideal hot carrier solar cell. The absorber has a hot carrier distribution at temp T_H. Carriers cool isoentropically in the mono-energetic contacts to T_A. The difference of the Fermi levels of these two contacts is manifested as a difference in chemical potential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

G.J. Conibeer et al., *Thin Solid Films*. **516**, 6948 (2008)

Hot carrier cells

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

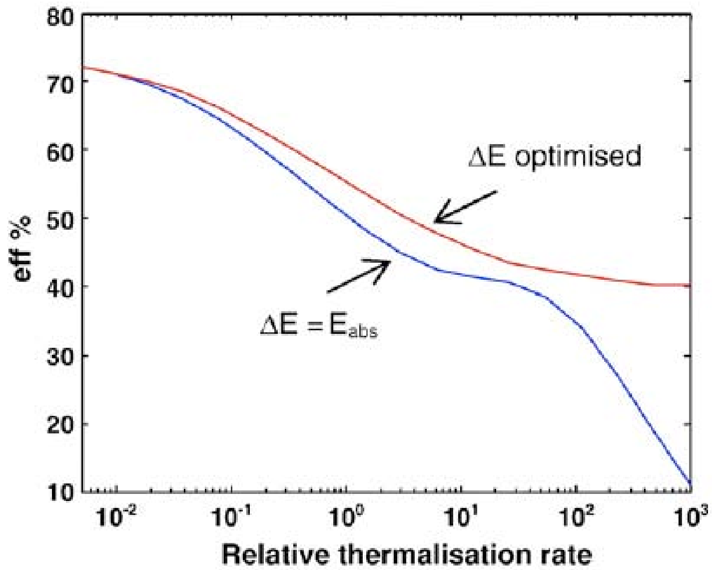


Fig. 7. Dependence of hot carrier cell efficiency on thermalisation rate. A rate of 1 corresponds to that measured in GaAs quantum wells [15,16]. In addition the importance of optimising the extraction energy ΔE is emphasised.

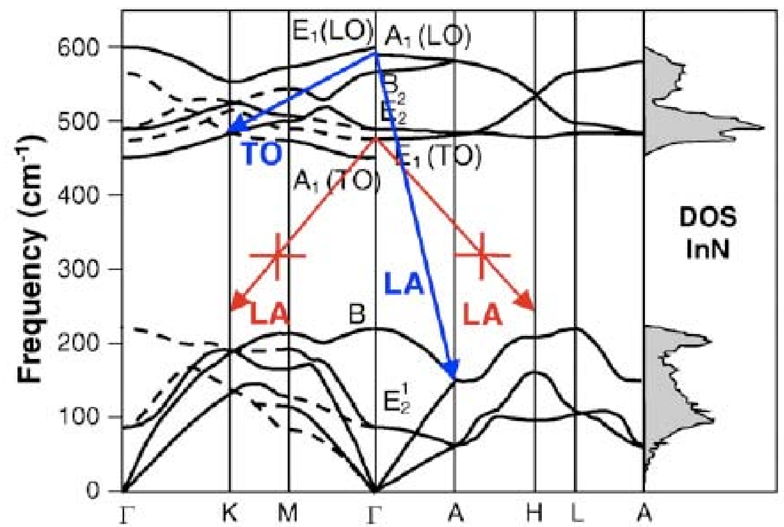


Fig. 3. Phonon energy as a function of phonon momentum and density of states (DOS) for InN redrawn from [12] in which $E_{LO} > 2E_{LA}$ such that LO→2LA (Klemens mechanism) is forbidden, whereas the LO→TO+LA (Ridley mechanism) can occur, although it is normally less likely and involves smaller loss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

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

G.J. Conibeer et al., *Thin Solid Films*. **516**, 6948 (2008)

Hot carrier cells

Approach #2: Selective Energy Contacts

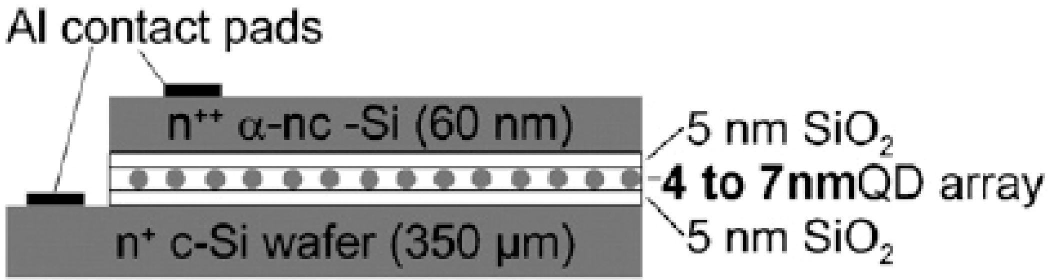


Fig. 3. Sample structure for SEC experiments.

G.J. Conibeer et al., *Thin Solid Films* 516 6968 (2008)

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

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 η limit for these devices, with bandgap → 0 eV: 85.9%

Challenges:

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

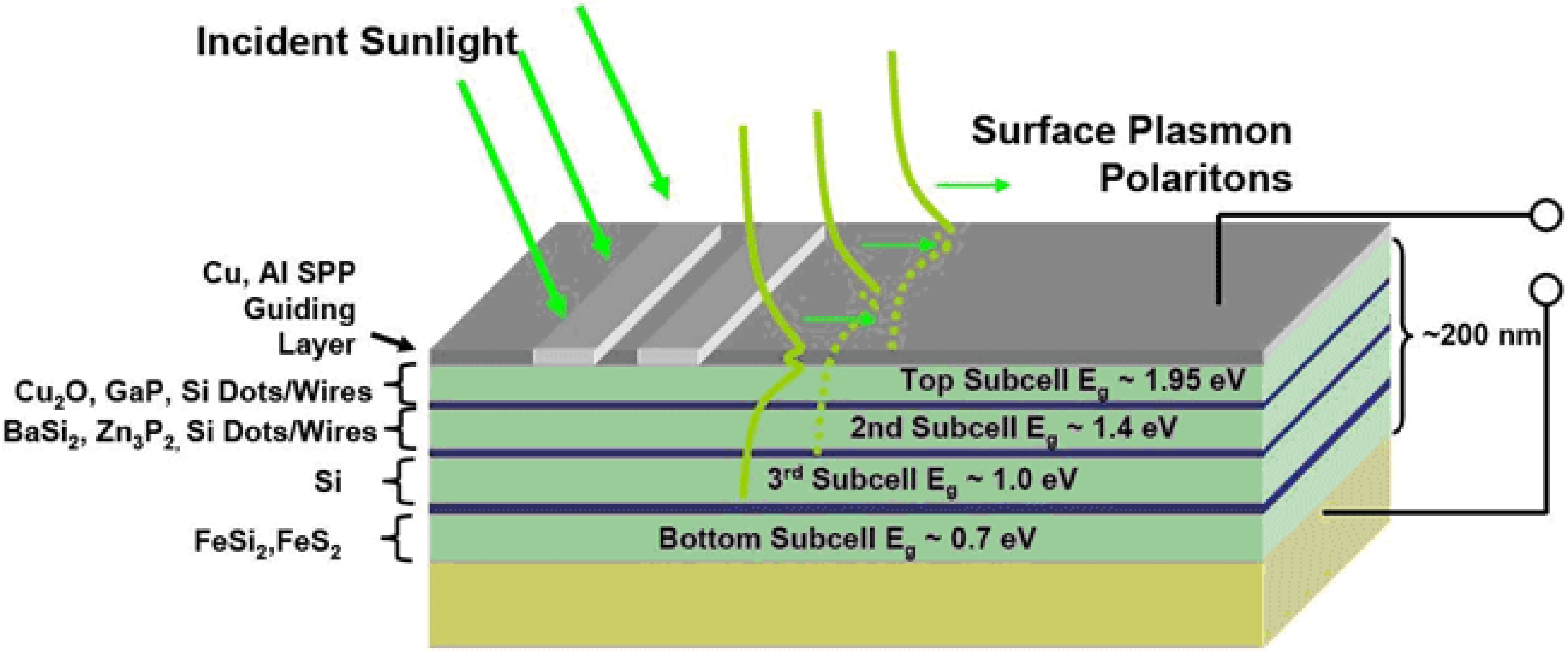
R.D. Schaller, V.I. Klimov, *Phys. Rev. Lett.* **92**, 186601 (2004)
Recent pubs by R.J. Ellingson

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



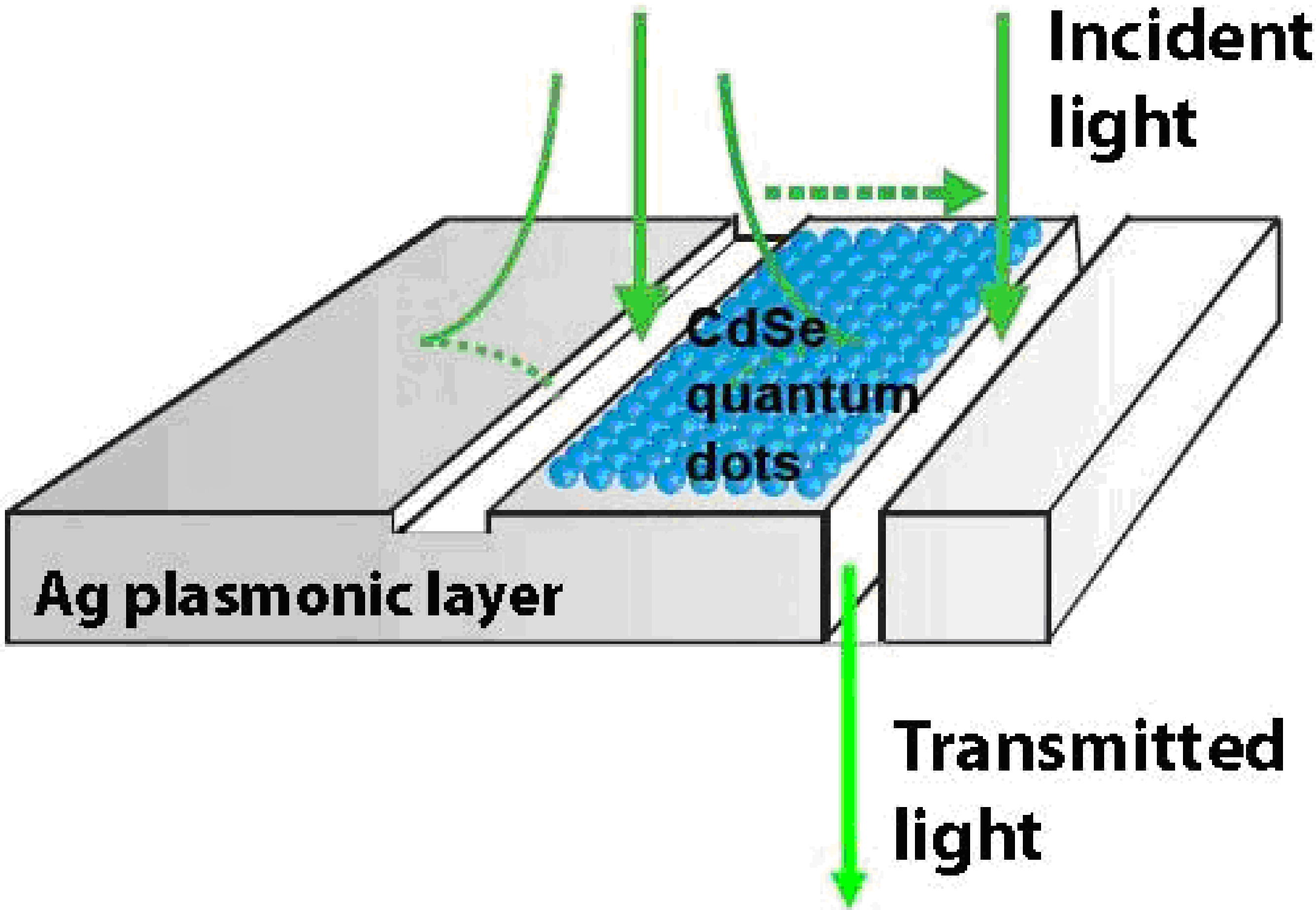
http://gcep.stanford.edu/research/factsheets/plasmonic_photovoltaics.html

Potential advantages: Enables use of very thin material layers.
Challenges: Performance (cost/benefit). Large-scale manufacturing.

References:

W.L. Barnes et al., *Nature* **424**, 824 (2003).
S.A. Maier and H.A. Atwater, *J. Appl. Phys*. **98**, 011101 (2005).
E. Ozbay, *Science* **311**, 189 (2006).
S.A. Maier, Plasmonics: Fundamentals and Applications. Springer Verlag (2007).

Plasmon Surface Resonance



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

The "Low Road": Low-cost Nanostructured PV

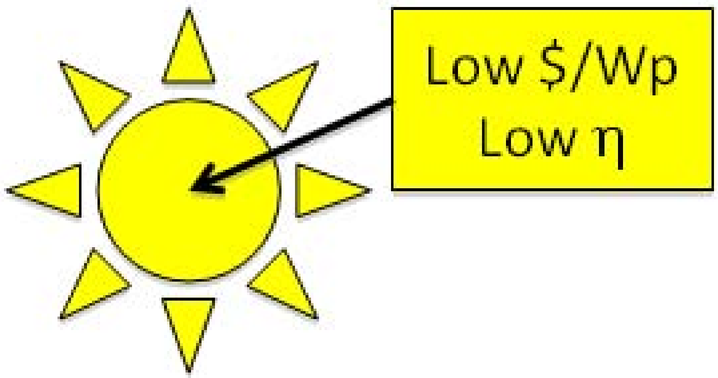
Advantages:

- Potentially cheaper.
- Potentially more scalable.

Biggest challenge:

- Increasing efficiencies.

Vision: Low Efficiencies, Low $\$/W_p$, Massively Scalable



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N. Lewis, *Science* **315** (2007) 798

Vision of Nanostructured PV: Fast Scaling!

Graph of project global solar cell production removed due to copyright restrictions.

Courtesy of
V. Bulovic

To survive as a technology NANOSTRUCTURED PVs need to:

- ACCELERATE OVER THE Si-PRODUCTION
- REACH HIGHER EFFICIENCIES and/or LOWER INSTALLATION COSTS

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)

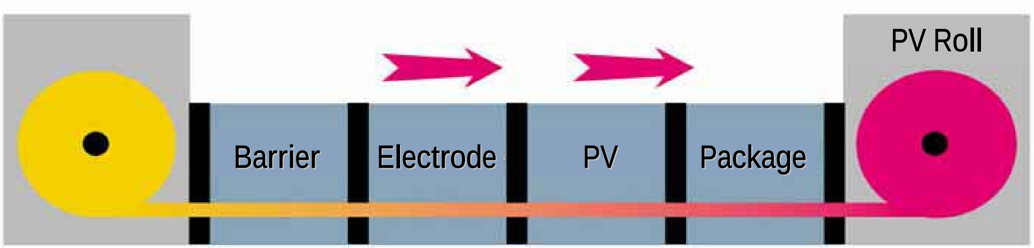
- TUNABLE SPECTRAL ABSORPTION -

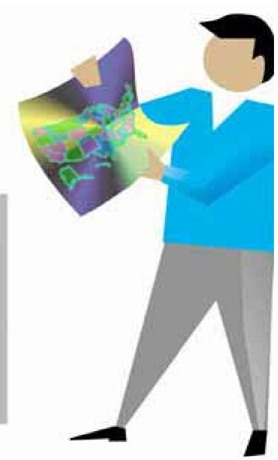
- EFFICIENT MATERIALS USE -

- ROOM TEMPERATURE DEPOSITION –
(on an arbitrary form factor)

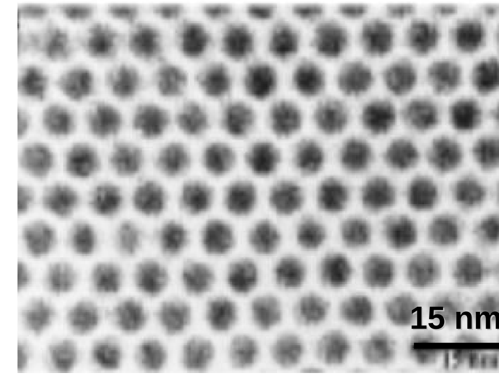
Thin Film Nanostructured PV efficiency ~6 %
Nanocrystalline dye electrochemical PV ~8 %

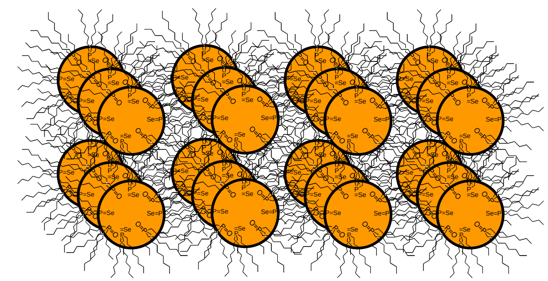
MANUFACTURING PARADIGM SHIFT

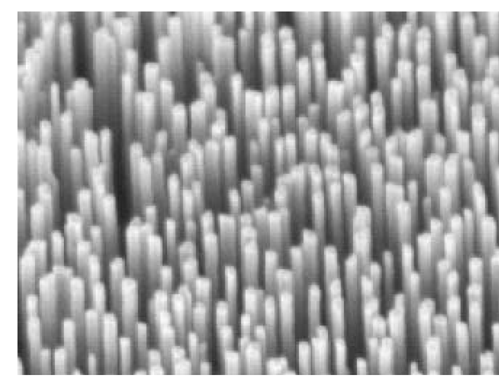




Courtesy of Vladimir Bulovic. Used with permission.

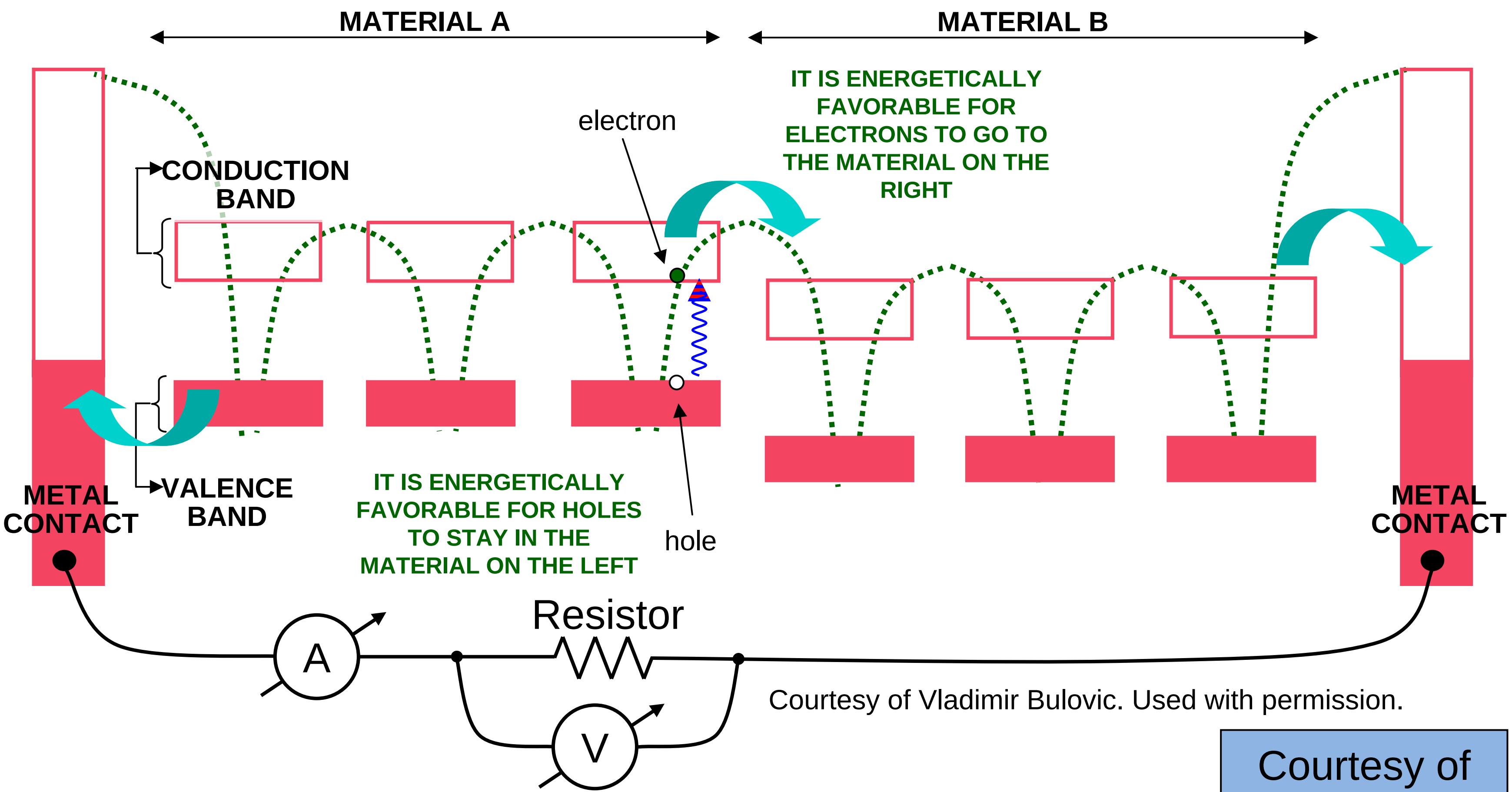






Courtesy of V. Bulovic

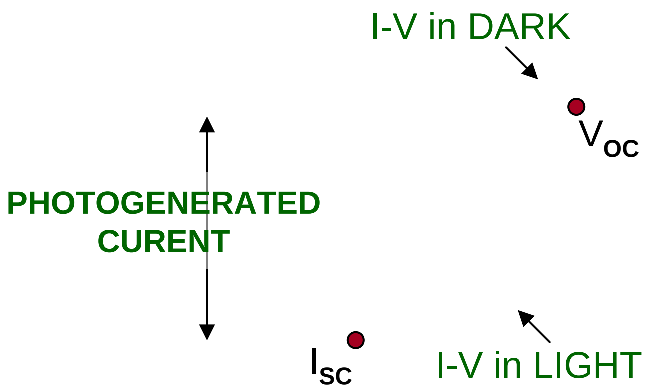
Semiconductor Heterojunction Solar Cell

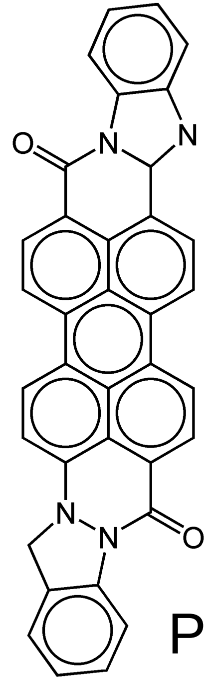


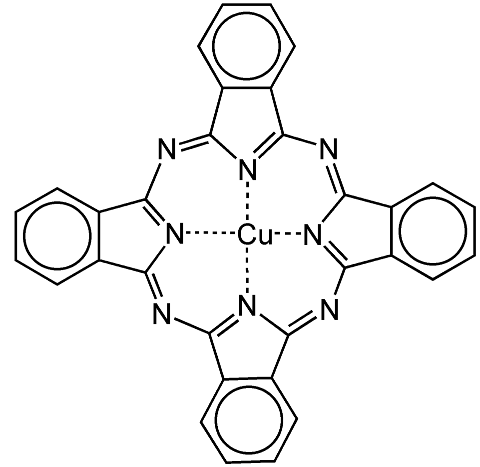
1. Photon can excite an electron from Valence Band (ground state) to Conduction Band (excited state)
2. At the heterojunction the electron and hole can separate, resulting in buld-up of electrons on the right and build-up of holes on the left → WE GENERATED PHOTOVOLTAGE
3. If solar cell is connected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

Example: First Organic Heterojunction Solar Cell

Power conversion efficiency ~ 1%





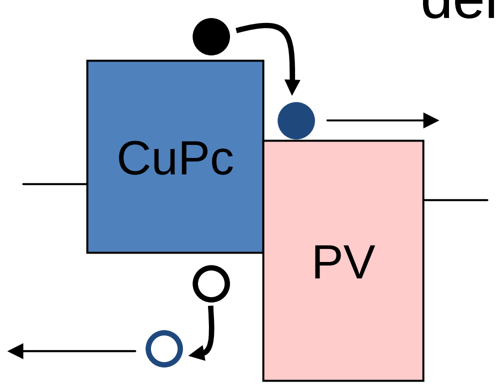


CuPc

Perylene tetracarboxylic derivative (PV)

Need interface to maximize exciton dissociation

Courtesy of V. Bulovic



V_{OC} = open-circuit voltage

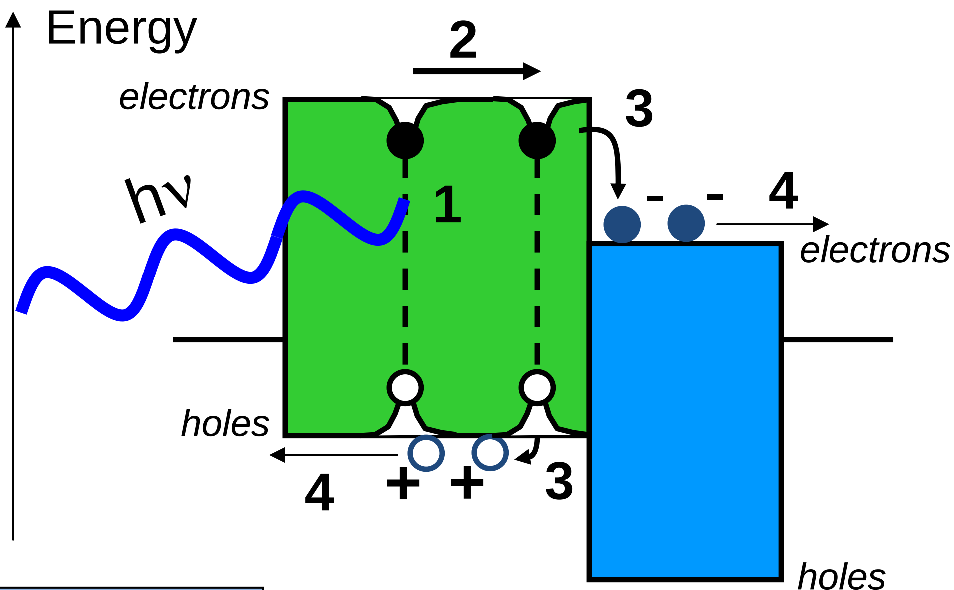
I_{SC} = short-circuit current

*from Tang, Applied Physics Letters, **48** 183 (1985)*

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



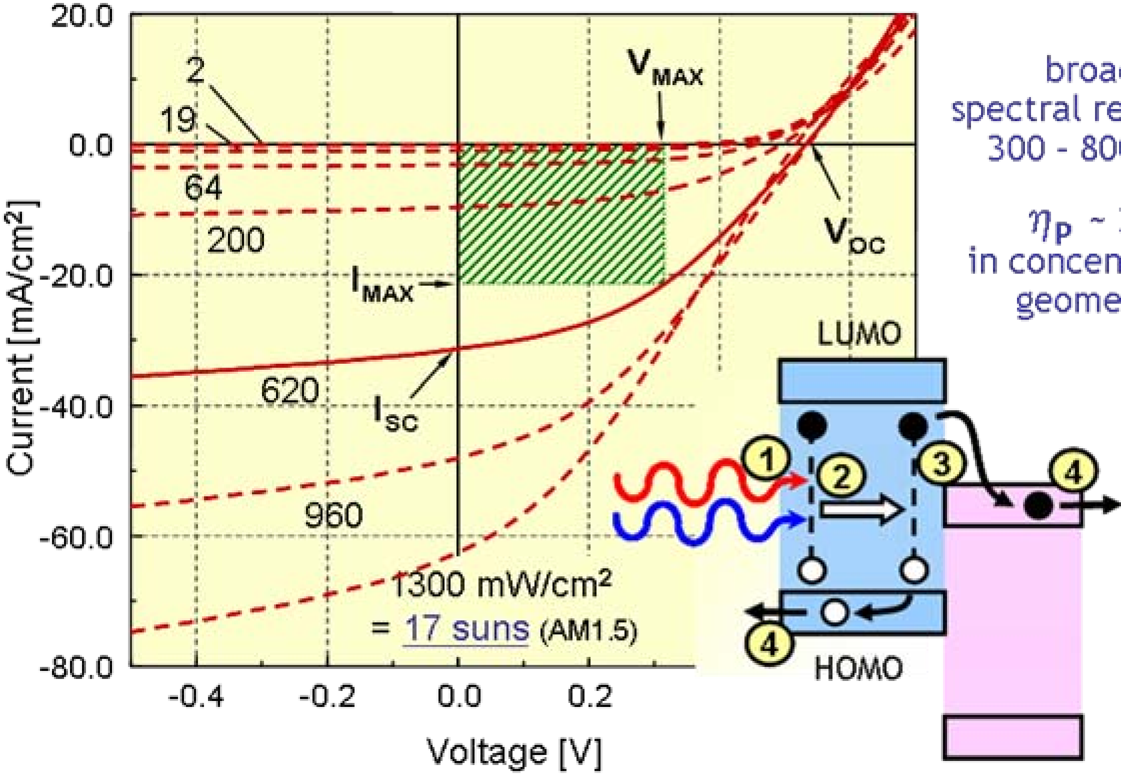
1. Photon absorbed
2. Excited state diffuses
3. Charge formed at interface
4. Charge diffuses out

Courtesy of V. Bulovic

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

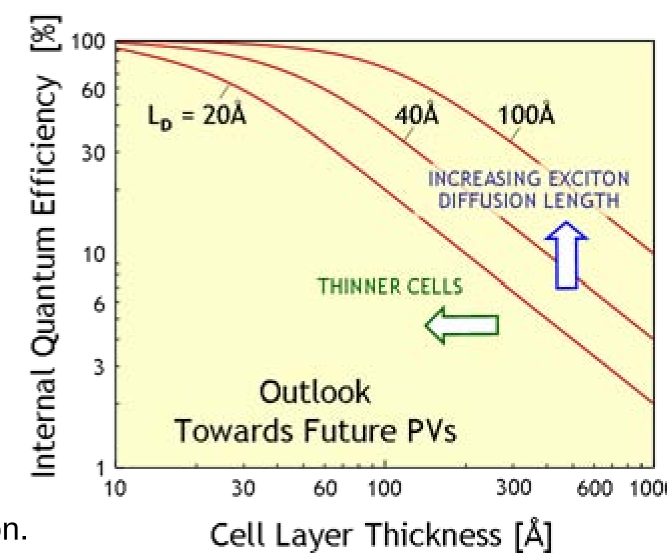
Molecular Organic Photovoltaics

Organic Solar Cells
I-V Response Under Solar Illumination



broad
spectral response
300 - 800 nm

η_P ~ 3%
in concentrator
geometry

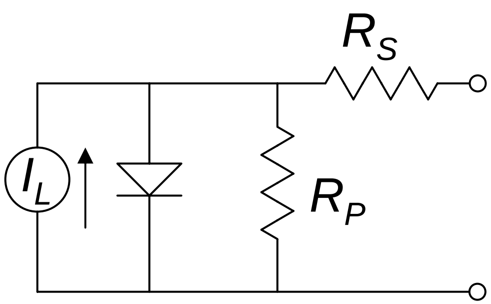


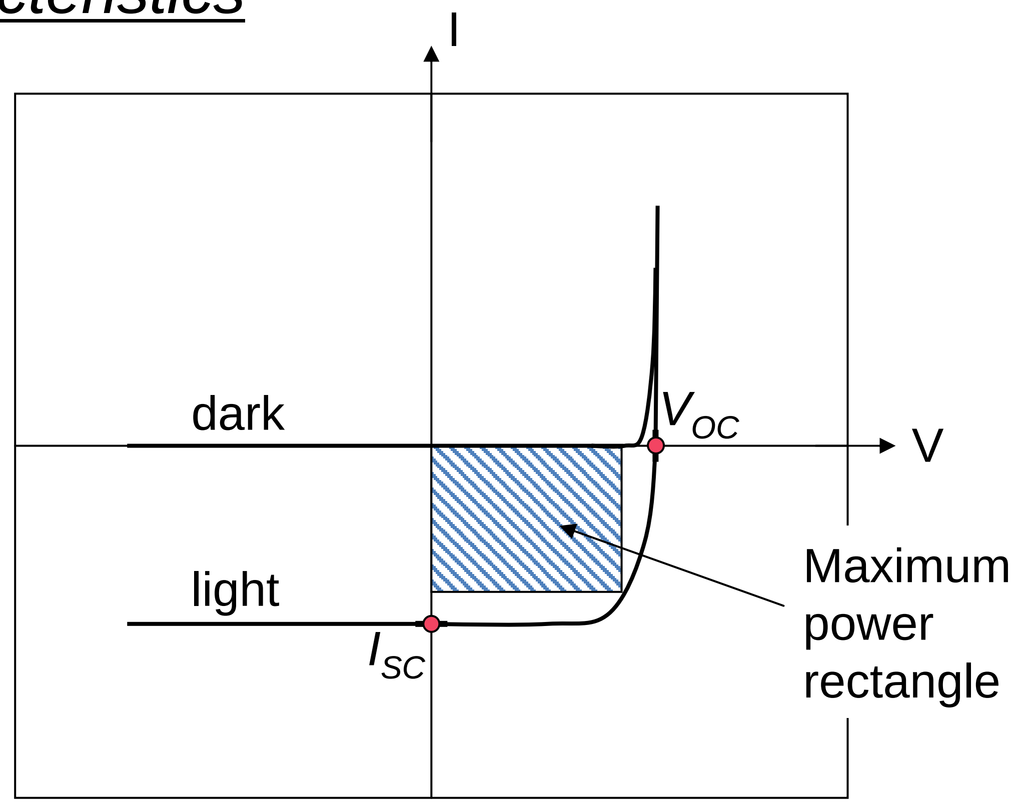
Peumans, Bulovic, Forrest,
Appl. Phys. Lett. *76, 2650 (2000).*

Courtesy of
V. Bulovic

Solar Cell Characteristics

Circuit model



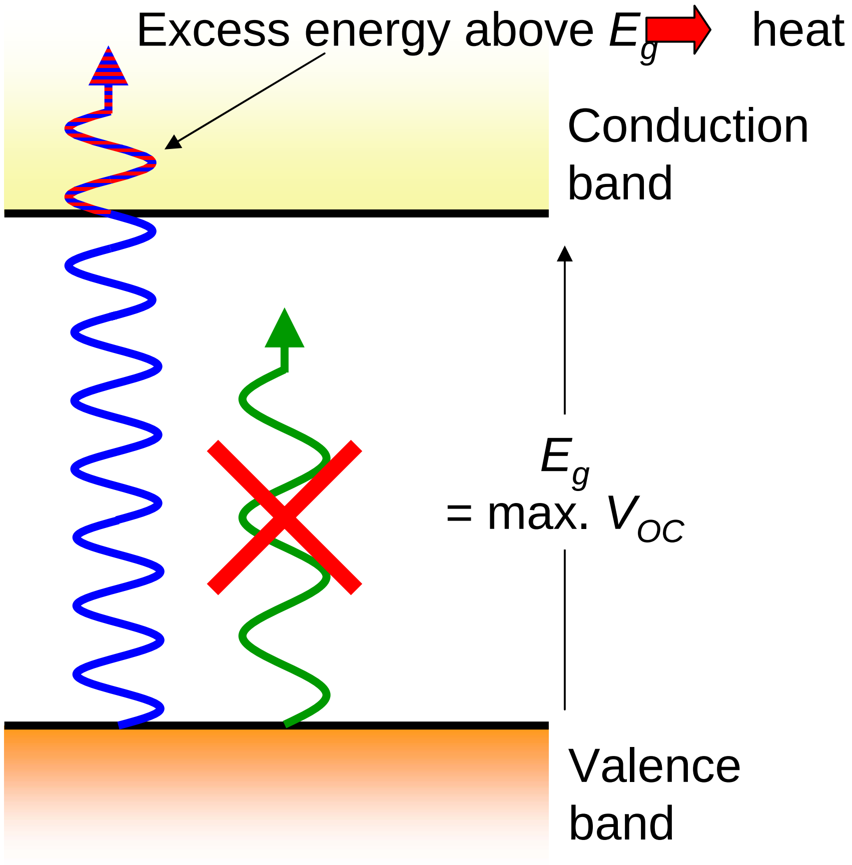


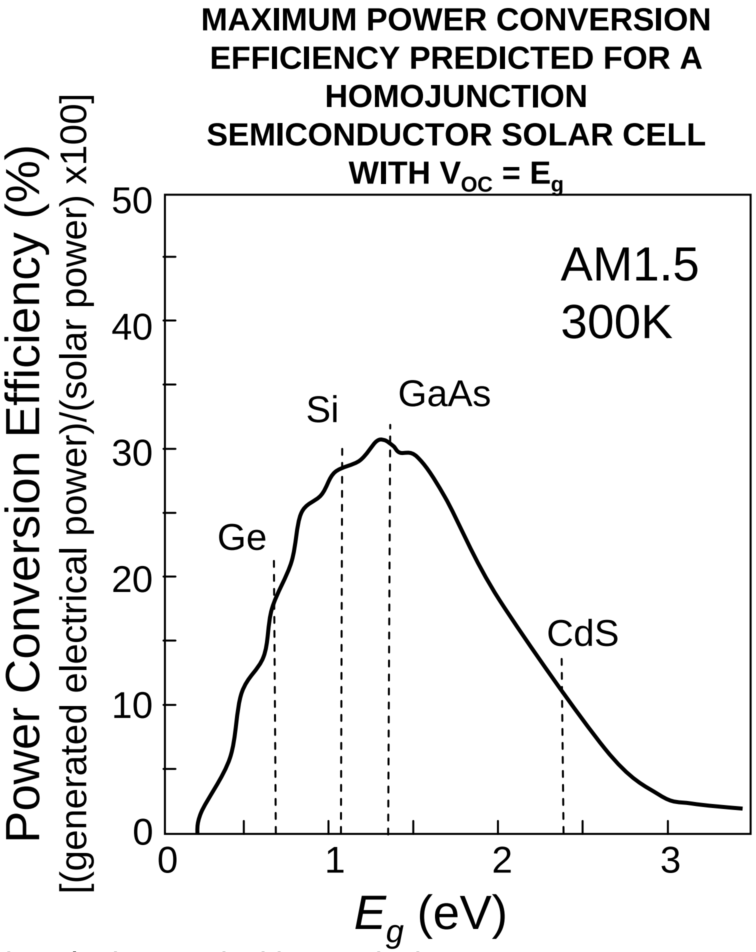
Critical parameters: V_{OC}, open circuit voltage

I_{SC}, short circuit current

FF, fill factor = $\dfrac{\text{area max. power rectangle}}{V_{OC} \cdot I_{SC}}$

Fundamental Efficiency Limits of Solar Energy Conversion in Photovoltaics





Courtesy of Vladimir Bulovic. Used with permission.

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

Courtesy of V. Bulovic

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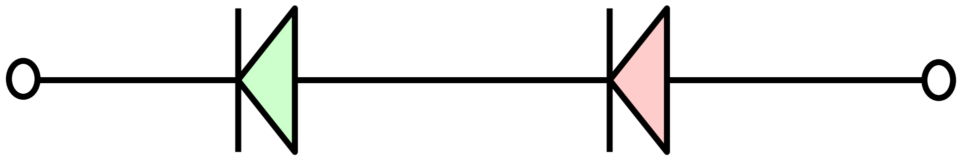
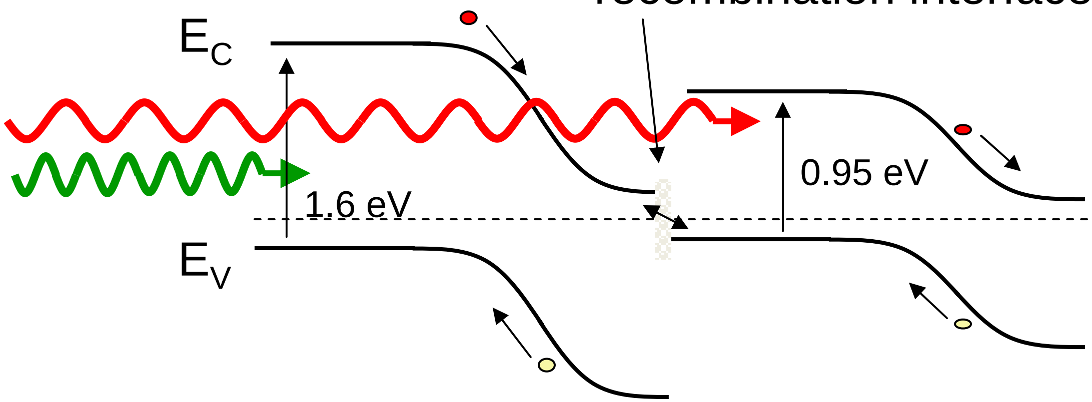
Multiple Junction Cells

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.

Courtesy of V. Bulovic

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6 Multijunction Cells

Principle

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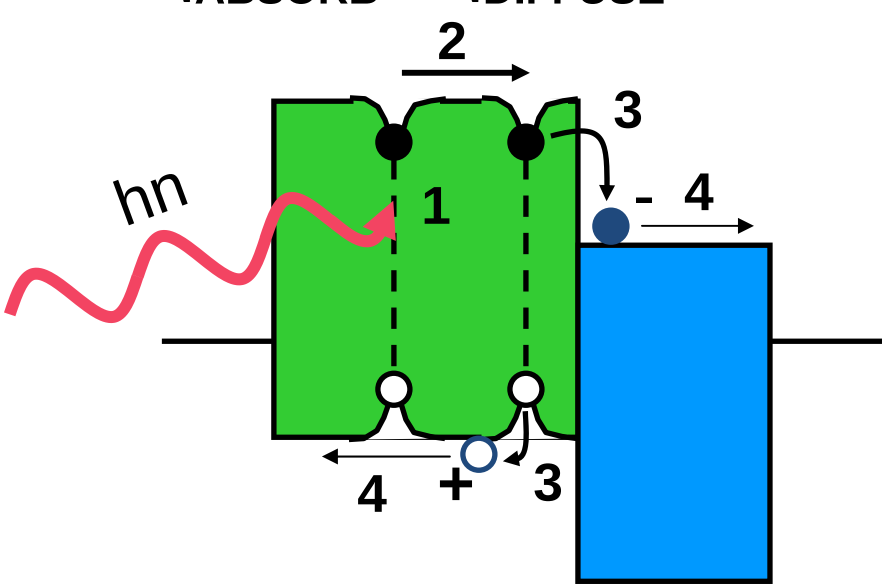
LIMITATIONS TO EFFICIENCY OF PLANAR HETEROJUNCTION CELLS

Organic PV cells must simultaneously maximize absorption and exciton dissociation

$\eta_{ABSORB} \times \eta_{DIFFUSE} \sim 10\%$



	efficiency
1. Photon absorbed	10% (1 and 2 combined)
2. Excited state diffuses	
3. Charge formed at interface	100%
4. Charge diffuses out	100%

Tradeoff:

THICK device = high absorption, lots of exciton losses
THIN device = low absorption, few exciton losses

Target: Increase the exciton dissociation interface

Method 1 - Stack devices:

Image removed due to copyright restrictions. Please see Fig. 23 in Peumans, Peter, Aharon Yakimov, and Stephen R. Forrest. "Small molecular weight organic thin-film photodetectors and solar cells." *Journal of Applied Physics* 93 (April 1, 2003): 3693-3723.

Bulović and Forrest,
US Patent 6,297,495 (2001)
US Patent 6,352,777 (2002)
US Patent 7,151,217 (2006)

Courtesy of V. Bulovic

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)

Example: Alivisatos, *et al*. Science (2002)
Blended polymer/nanorod PVs

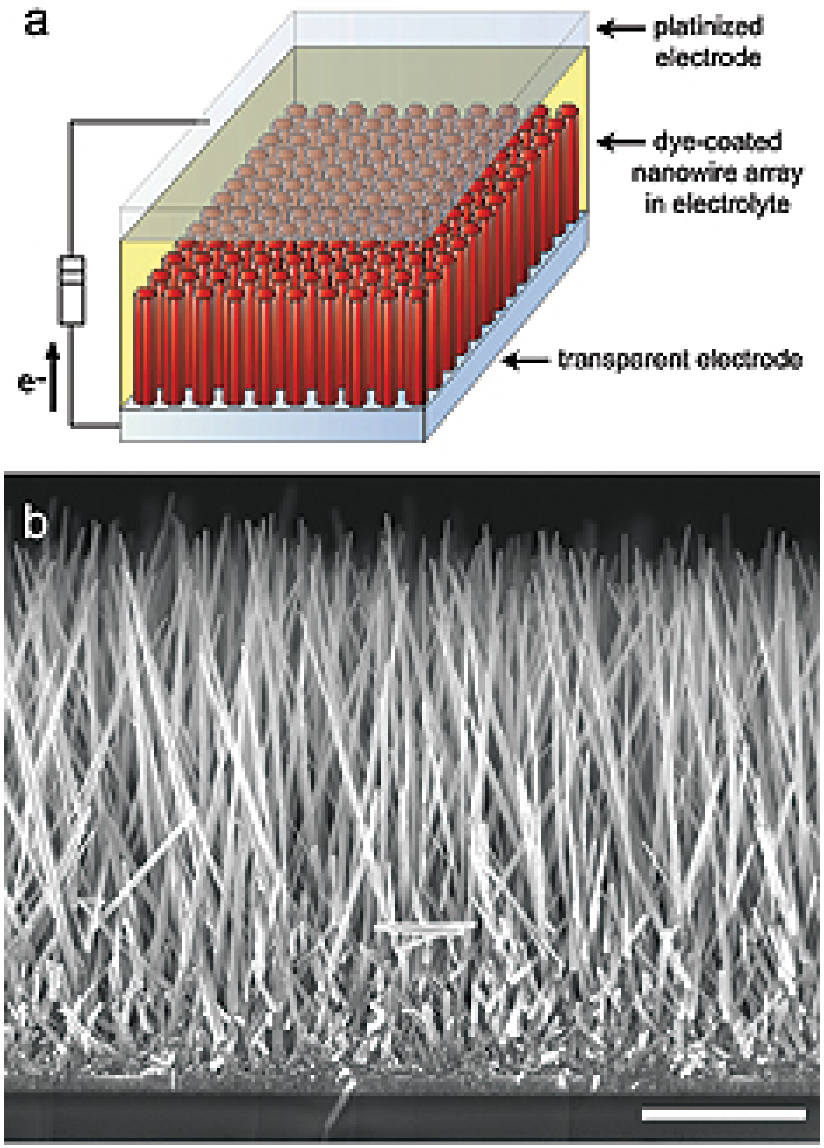
Images removed due to copyright restrictions. Please see Fig. 1, 2a, and 4a,c in Huynh, Wendy U., Janke J. Dittmer, and A. Paul Alivisatos. “Hybrid Nanorod-Polymer Solar Cells. *Science* 295 (March 29, 2002): 2425-2427.

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. http://industrial-innov.lbl.gov/images/nanolaser-1.jpg.

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 TiO_2

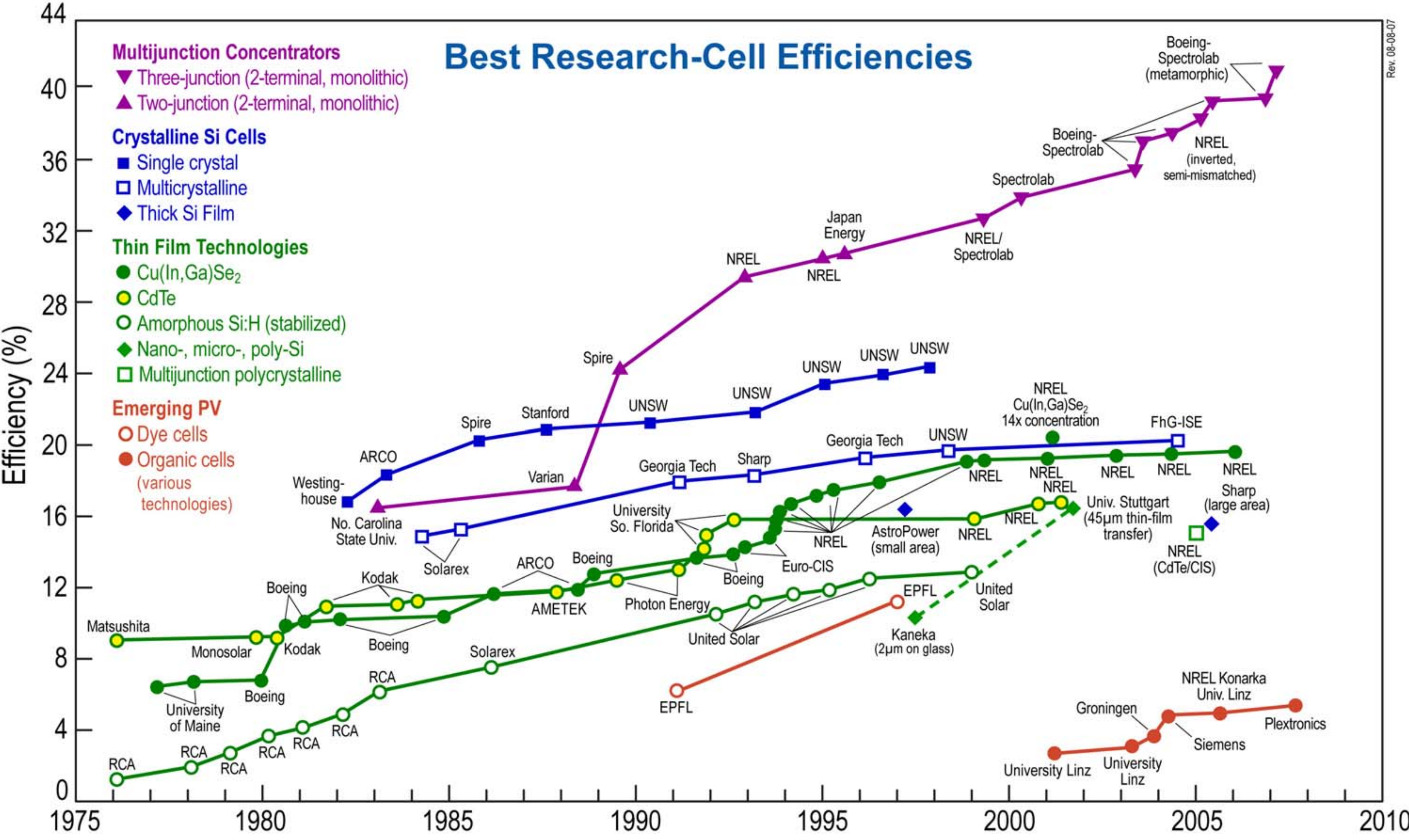
Power conversion efficiency ~8% (the Best performing 'organic' PV)

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

Courtesy of V. Bulovic

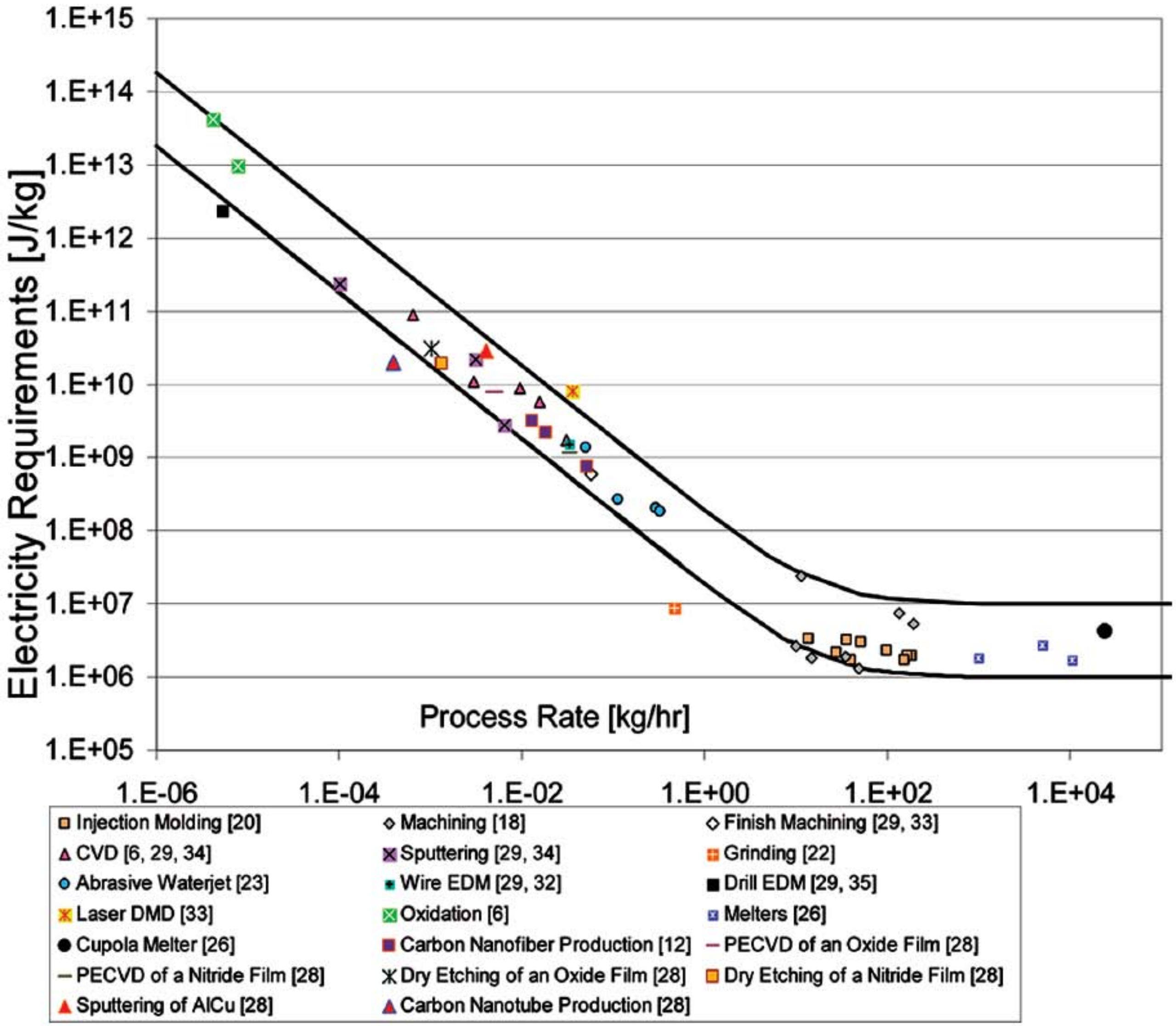
Challenges of emerging technologies

Challenges of Nanostructured PV: Efficiency



L.L. Kazmerski, Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135.
Updated version, private communication.

Challenges of Nanostructured PV: Manufacturing



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