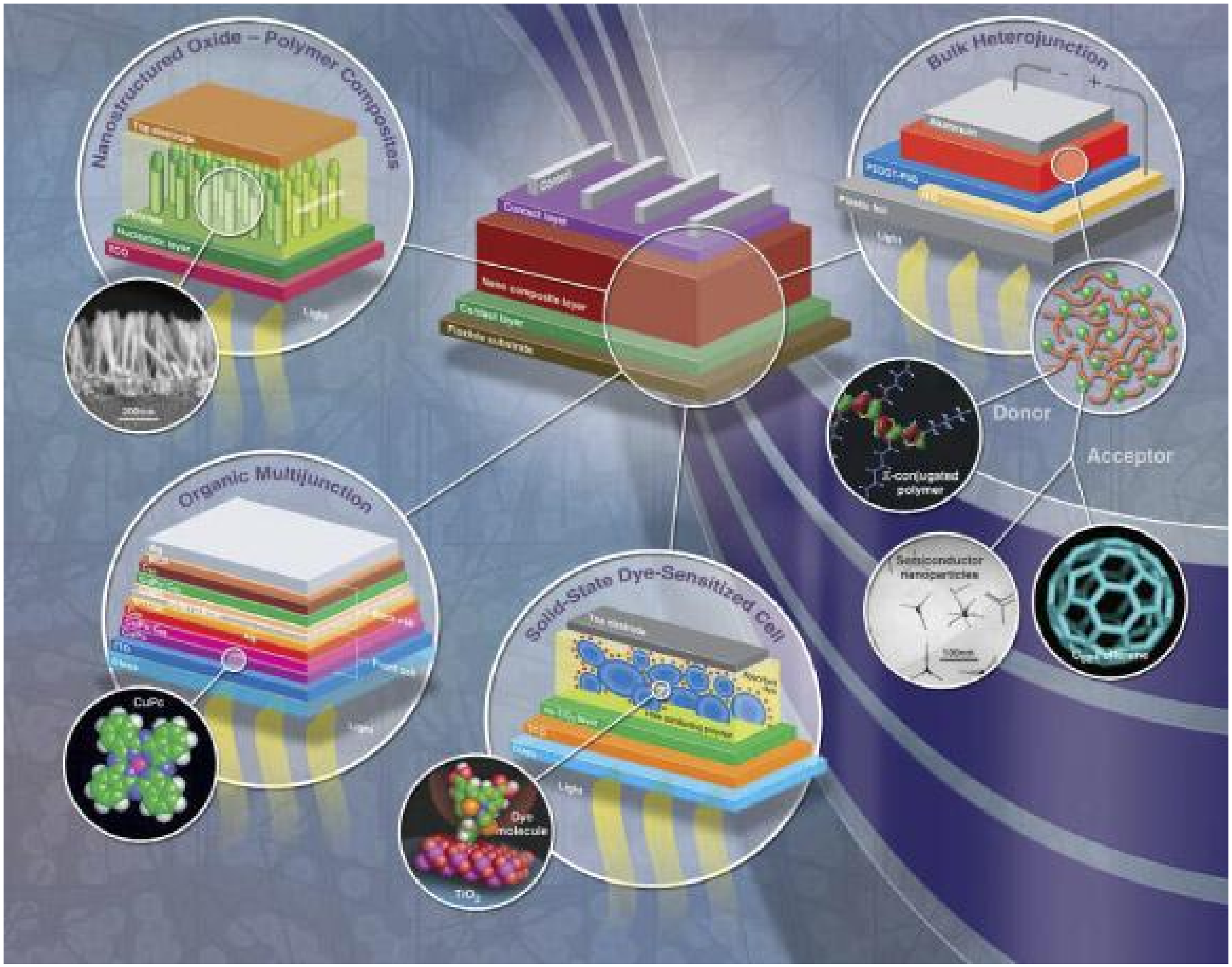
Low-Cost Nanostructured Solar Cells



Mike McGehee Stanford University

DOE workshop on solar energy in April 2005

• Over 200 scientists met in Maryland to assess the potential of utilizing solar energy to provide power for our country and to prioritize research directions.

• We wrote a report titled *Basic Research Needs for Solar Energy Utilization.*

Why solar cells are likely to provide a significant fraction of our power

- We probably need to generate ~ 30 TW of power without emitting carbon in 2050.

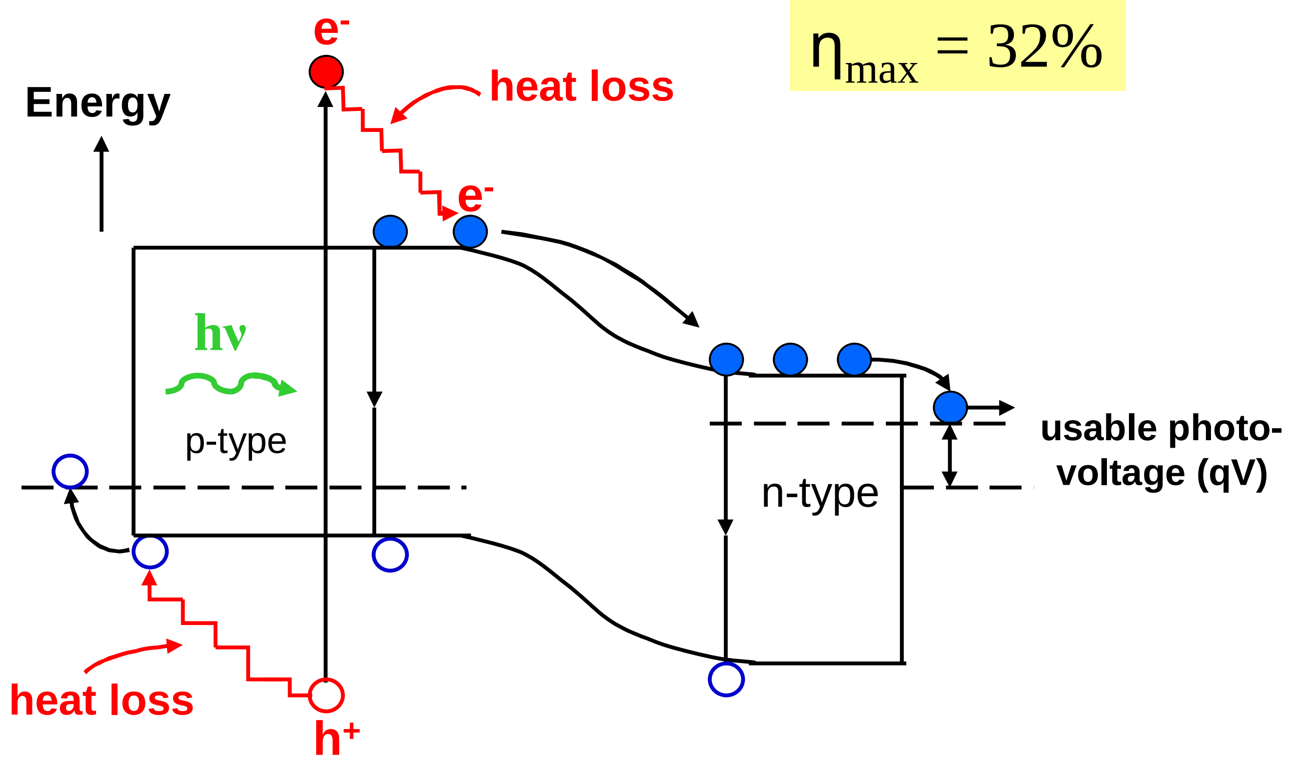
- The sun gives us 120,000 TW.

- Most other renewables probably can't provide 30 TW.

- Solar cells are safe and have few non-desirable environmental impacts.

- Using solar cells instead of burning coal to generate electricity is a much easier way to reduce carbon emissions than replacing gasoline in vehicles.

Conventional p-n junction photovoltaic (solar) cell



$\eta_{max} = 32\%$

Jenny Nelson, *The Physics of Solar Cells*, 2003.

Silicon solar cells: The current industry leader

Modules
- 12 % efficiency
- $350/m^2
- \$3/W_p (from manufacturer)
- \$6/W_p (installed)

Average cost of PV cell electricity: $.27/kW-hr

Today's grid electricity: $0.06/kW-hr

Area and cost needed to power the country

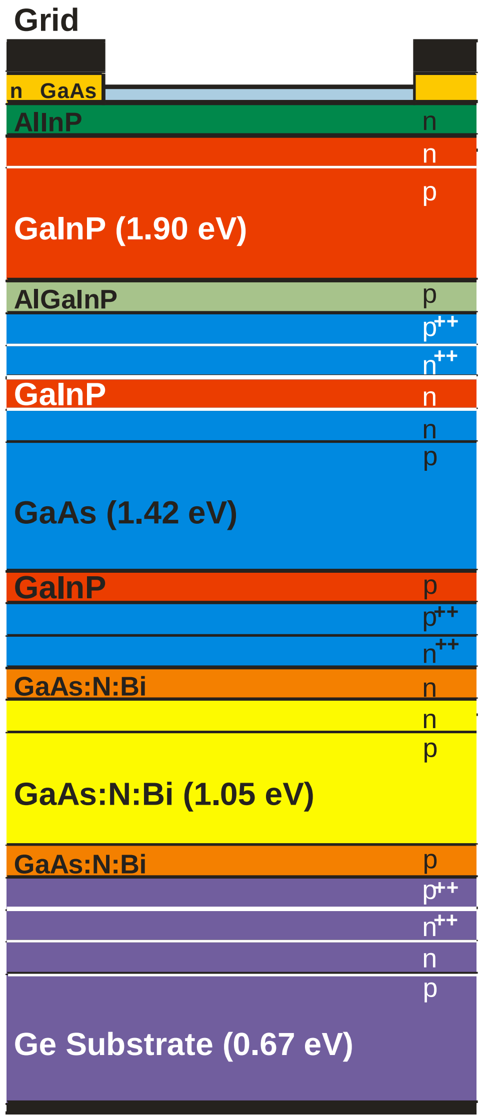
$(150\ km)^2$ of Nevada covered with 15 % efficient solar cells could provide the whole country with electricity

At $\$350/m^2$, we would have to spend \$8 trillion to do this.

Additional \$ would be needed for storage technology.

J.A. Turner, *Science* **285** 1999, p. 687.

Multijunction cells



SpectroLab has achieved 37 % efficiency

Costs are estimated at $50,000/m^2, so concentrators must be used.

The cheapest option

Efficiency: 0.3 %

We don't have the land and water to provide the world with energy this way.

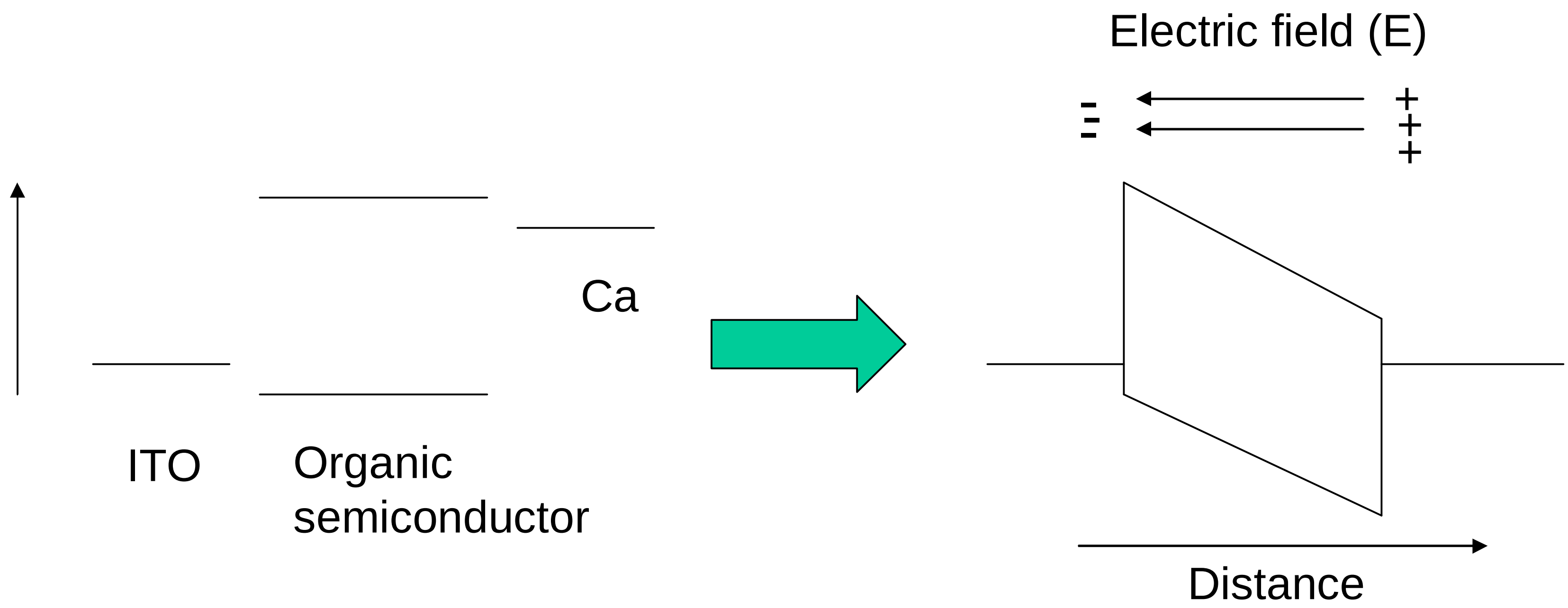
Can we artificially improve the efficiency?

Roll-to-Roll coating: A route to taking the costs below \$50/m^2

and keeping efficiency > 10 %.

P. Fairley, *IEEE Spectrum.* Jan. 2004 p.28

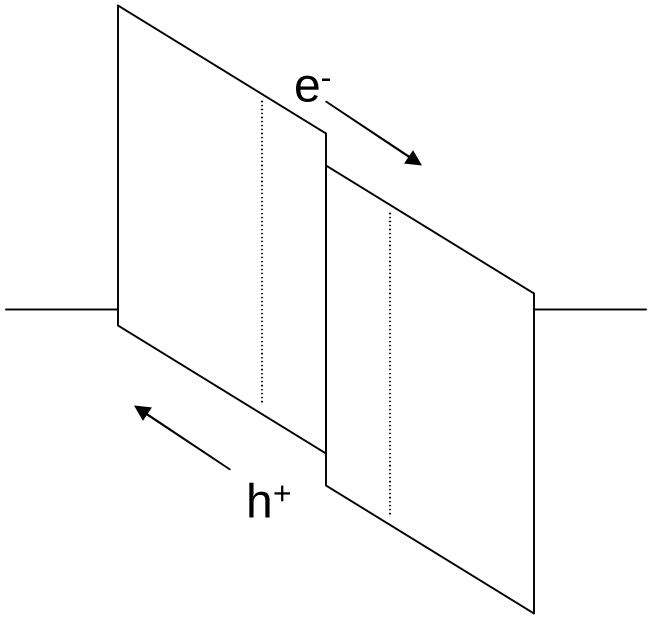
Single semiconductor organic PV cells



High exciton binding energy
Low mobility

Quantum efficiency < 1 %

Flat bilayer organic PV cells



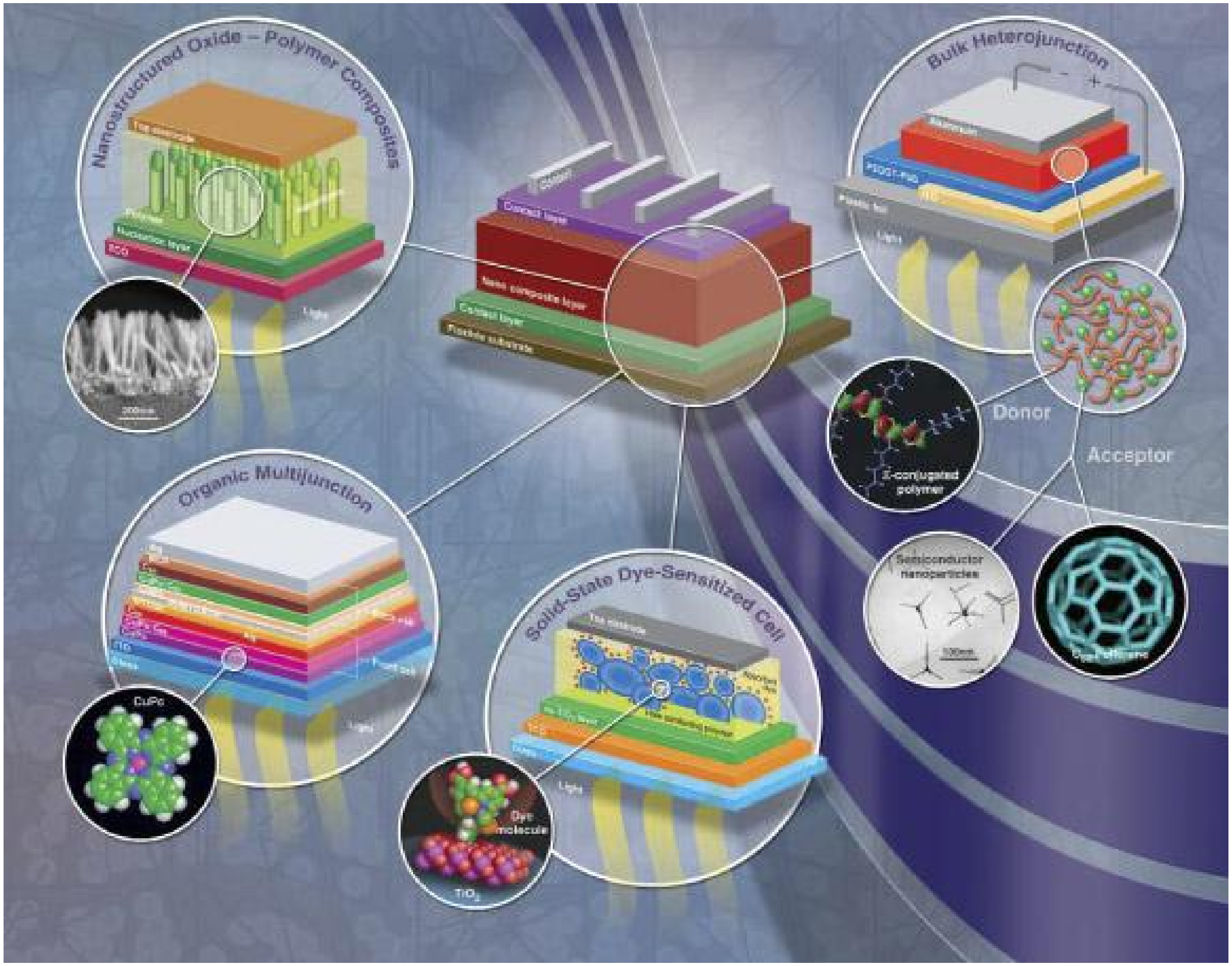
• Carriers are split at the interface.[1]

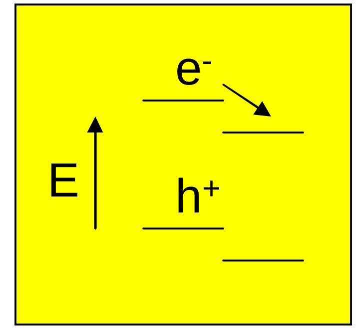
• They selectively diffuse to the electrodes.[2]

• Exciton diffusion length ~ 4-20 nm
• Absorption length ~ 100-200 nm

[1] C.W. Tang, *APL* **48** (1986) p. 183.
[2] B.A. Gregg, *J. Phys. Chem. B* **107** (2003) p. 4688.

Nanostructured Cells



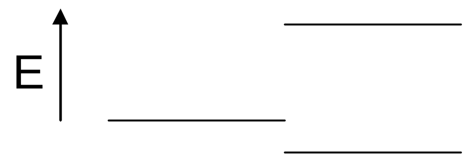


Excitons are split at interfaces.

Separating the electrons and holes enables the use of low quality materials

January 2005 *Materials Research Society Bulletin*

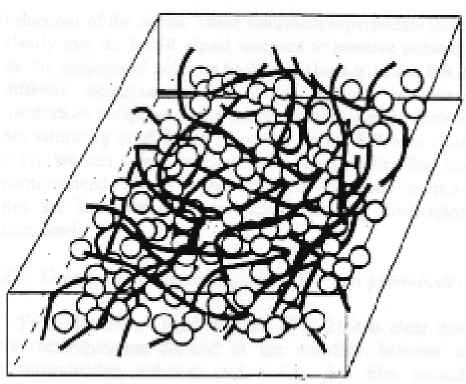
Bulk heterojunction PV cells made by casting blends



Polymer Electron acceptor

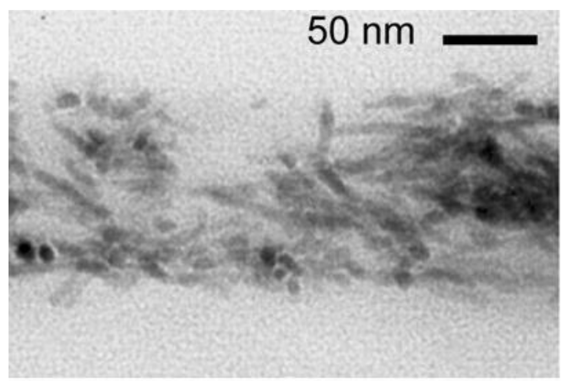
absorber	electron acceptor		Energy conversion efficiency (AM 1.5)
Polymer	C_{60} derivative	Heeger	4.9 %
Polymer	polymer	Friend	1.9 %
Polymer	CdSe nanorods	Alivisatos	1.7 %
Polymer	ZnO nanocrystal	Janssen	1.6 %

polymer/C_{60} blend



Heeger et al. *Science* **270** (1995) p. 1789.

polymer/nanorod blend



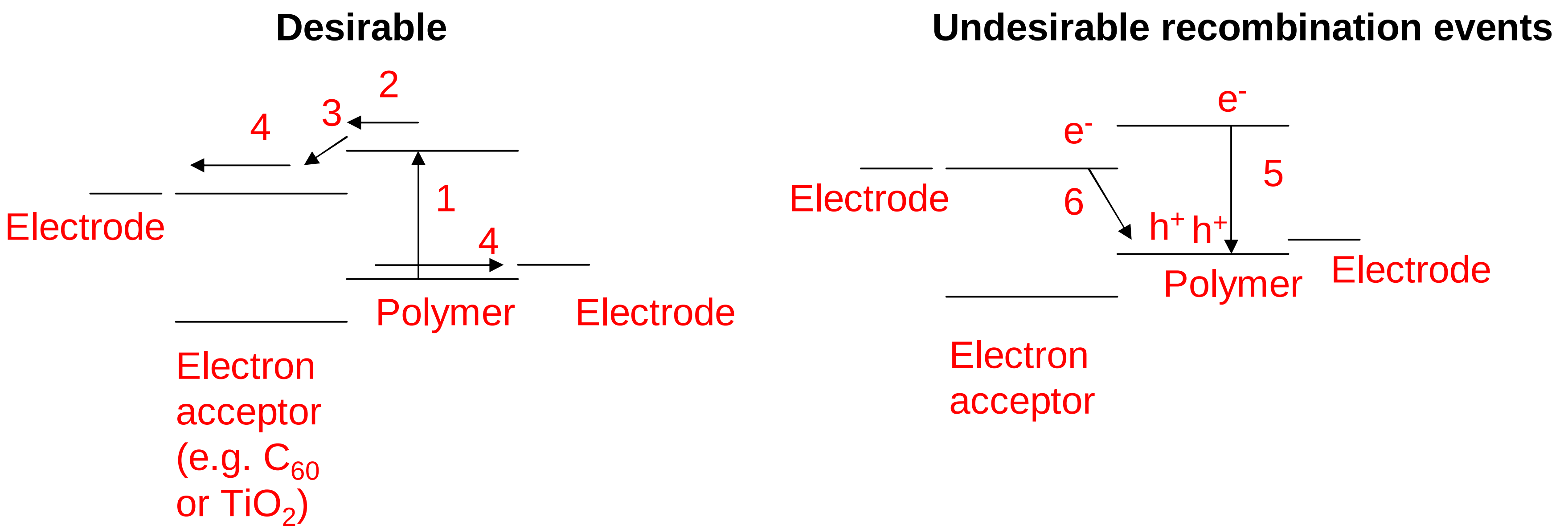
Alivisatos et al., *Science* **295** (2002) p. 2425

J fabrication is simple

L not all excitons reach at interface

L there are deadends

Processes in bulk heterojunction PV cells



1 Absorption

2 Exciton diffusion
3 Forward electron transfer $\xleftrightarrow{\text{competing}}$ 5 Geminate recombination (1 ns)

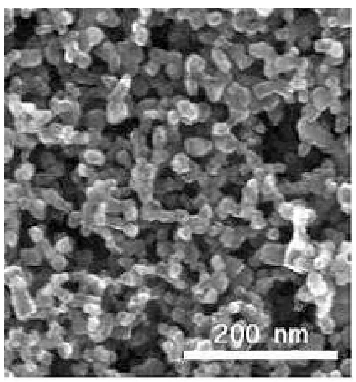
4 Charge transport to electrodes $\xleftrightarrow{\text{competing}}$ 6 Back electron transfer (1 µs ?)

Bulk heterojunctions made by filling nanoporous films

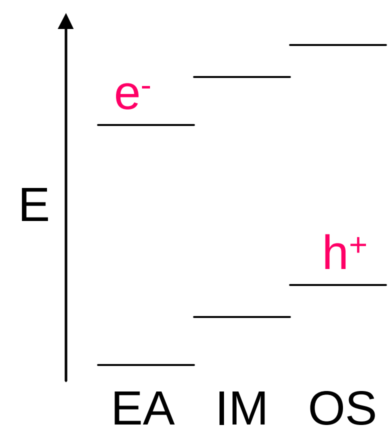
Light absorber	**Electron acceptor**		**Efficiency**
Polymer	sintered TiO_2 nanocrystals	Carter	0.2 %
Ru Dye	sintered TiO_2 nanocrystals	Grätzel	4 %*

*with solid state hole transporter

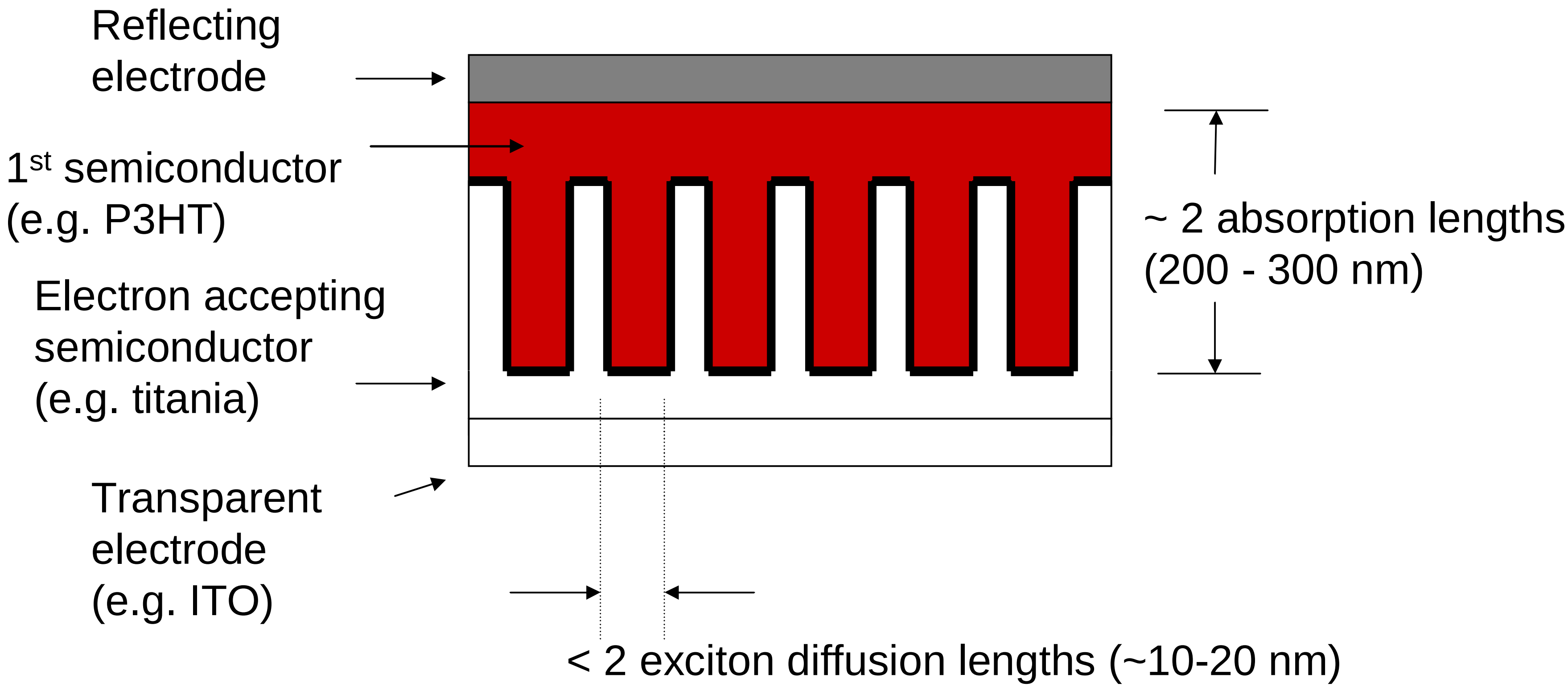
titania nanocrystals



Modifying the interface can be used to slow down back electron transfer.



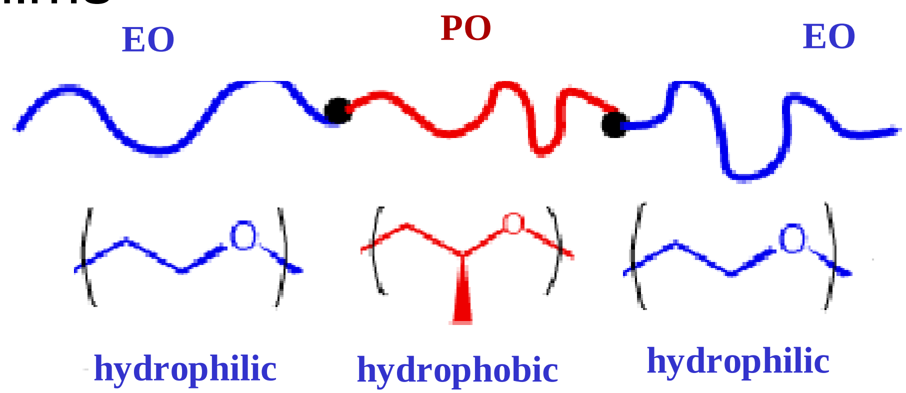
Ordered bulk heterojunctions



- Almost all excitons can be split
- No deadends
- Polymer chains can be aligned

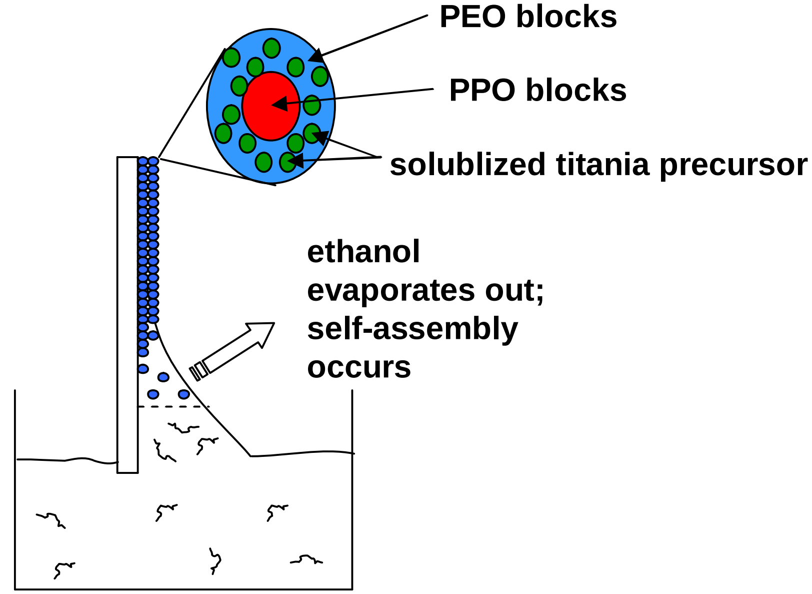
- Easy to model
- Semiconductors can be changed without changing the geometry.

One way to make nanoporous films

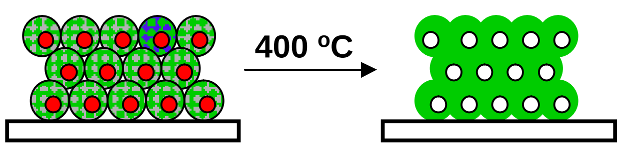


1 Titanium ethoxide,
HCl,
P123 tri-block copolymer
and ethanol are mixed
in a beaker

2 the mixture is dip coated
and the film is aged

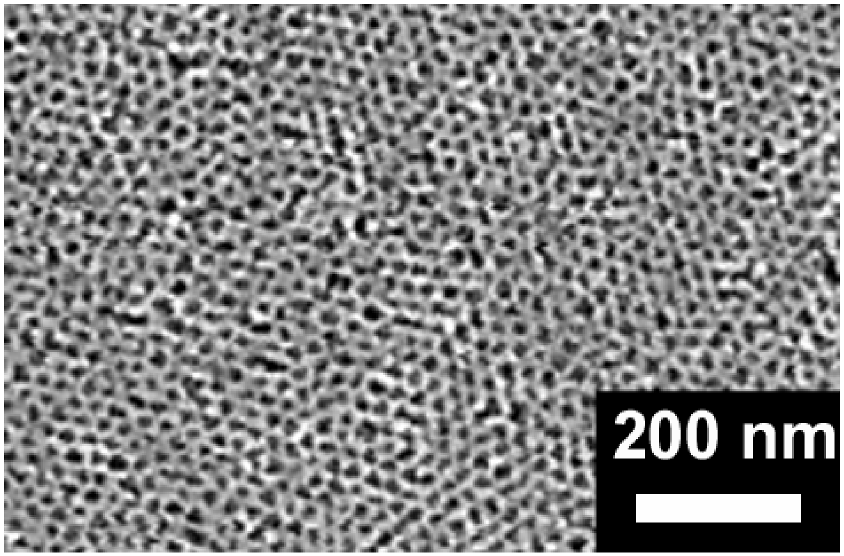


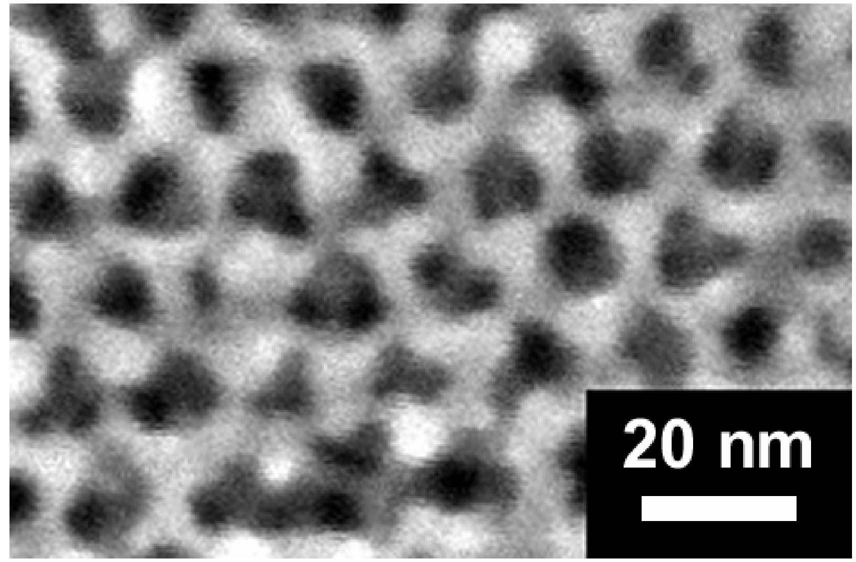
3 The film is calcined at 400 ^{o}C
to burn out the block copolymer



G.D. Stucky et al. *Chem. Mater.* **14** (2002) p. 3284.
C. Sanchez et al. *JACS* **125** (2003) p. 9770.

Mesoporous titania films



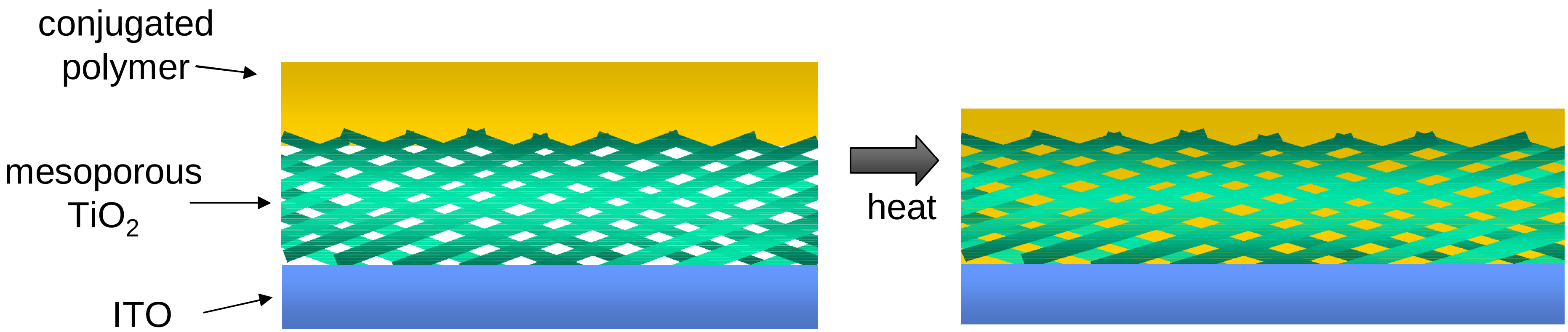


J Film thickness can be varied from 50 - 300 nm
J Pore radius: 4 nm in the plane and 2-3 nm perpendicular to the plane
J Film quality is very high

L Pores are not straight

Adv.Func.Mat., **13** (2003) p. 301

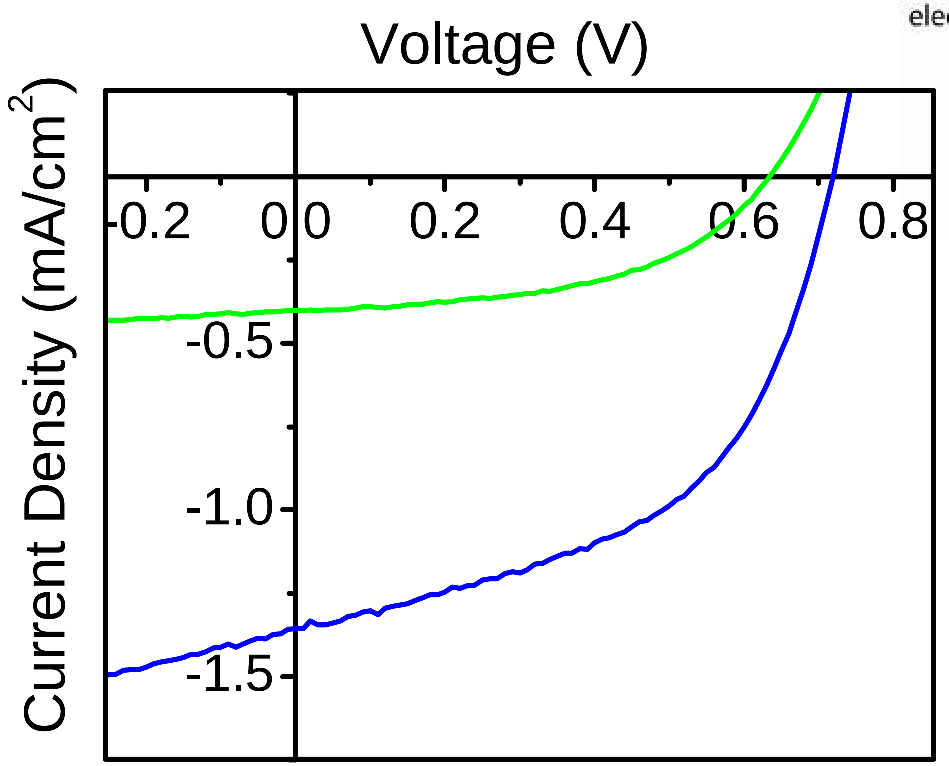
Melt infiltration



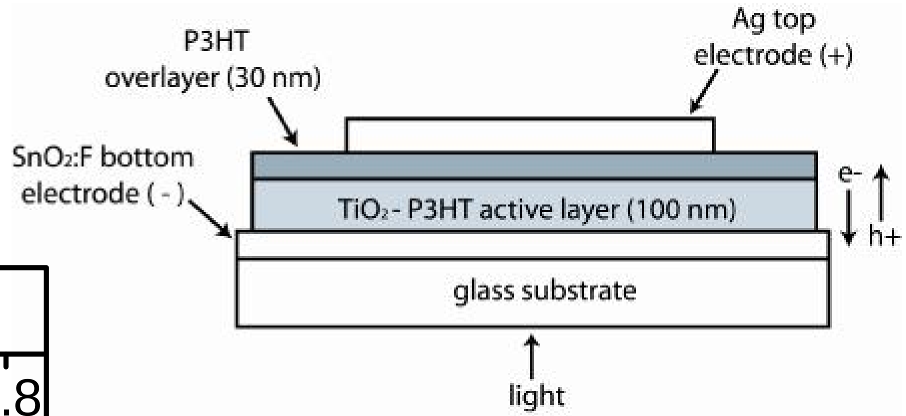
33 % of the volume of the film can be filled in several min.

Adv.Func.Mat., **13** (2003) p. 301

Photovoltaic cells



Blue: Mesoporous titania
Green: Solid (nonporous) titania



<u>At 33 mW/cm^2, 514 nm:</u>

η_{pwr} = 1.5 %

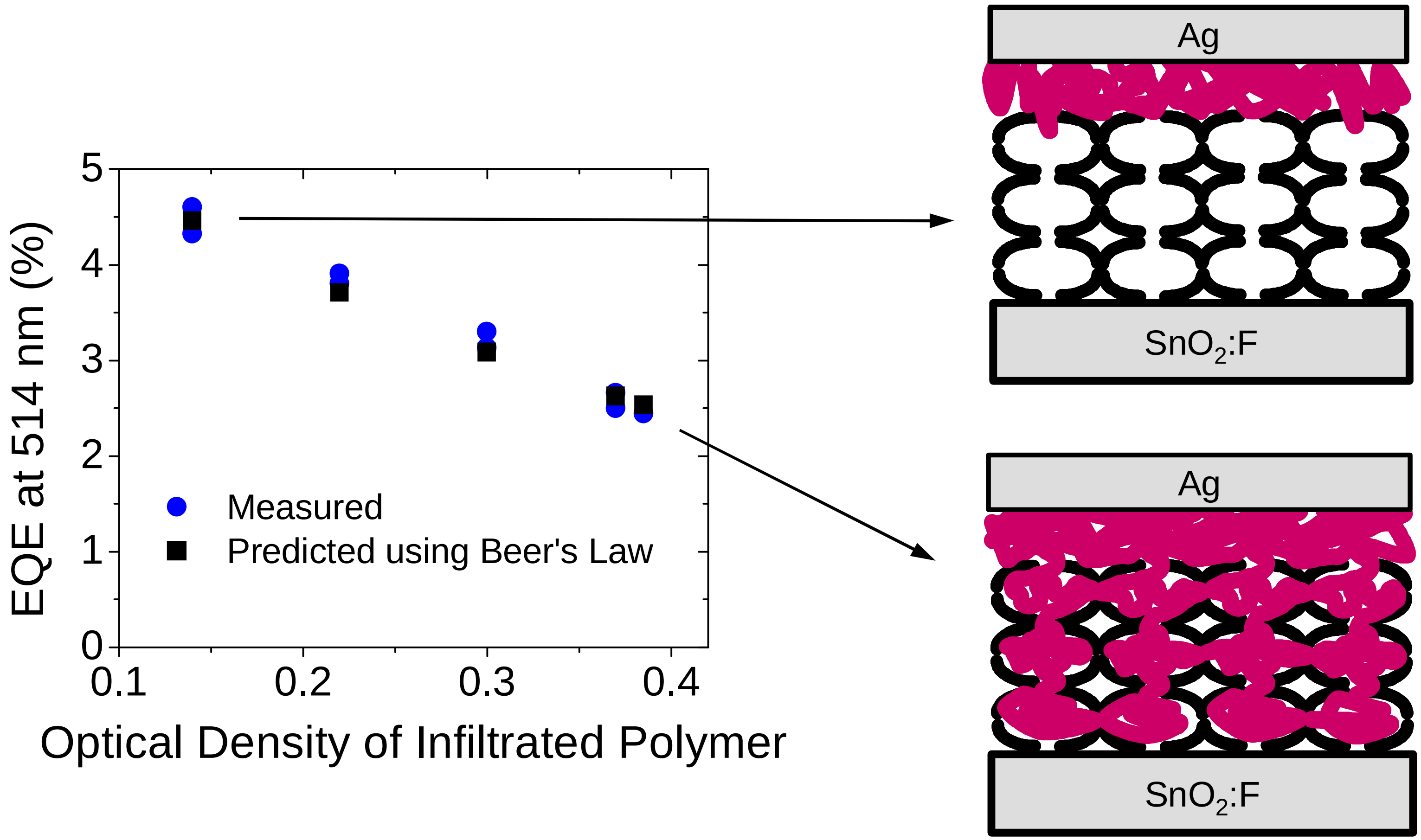
FF = 0.51

EQE = 10 %

η_{pwr} would be ~ 0.45% under actual sunlight

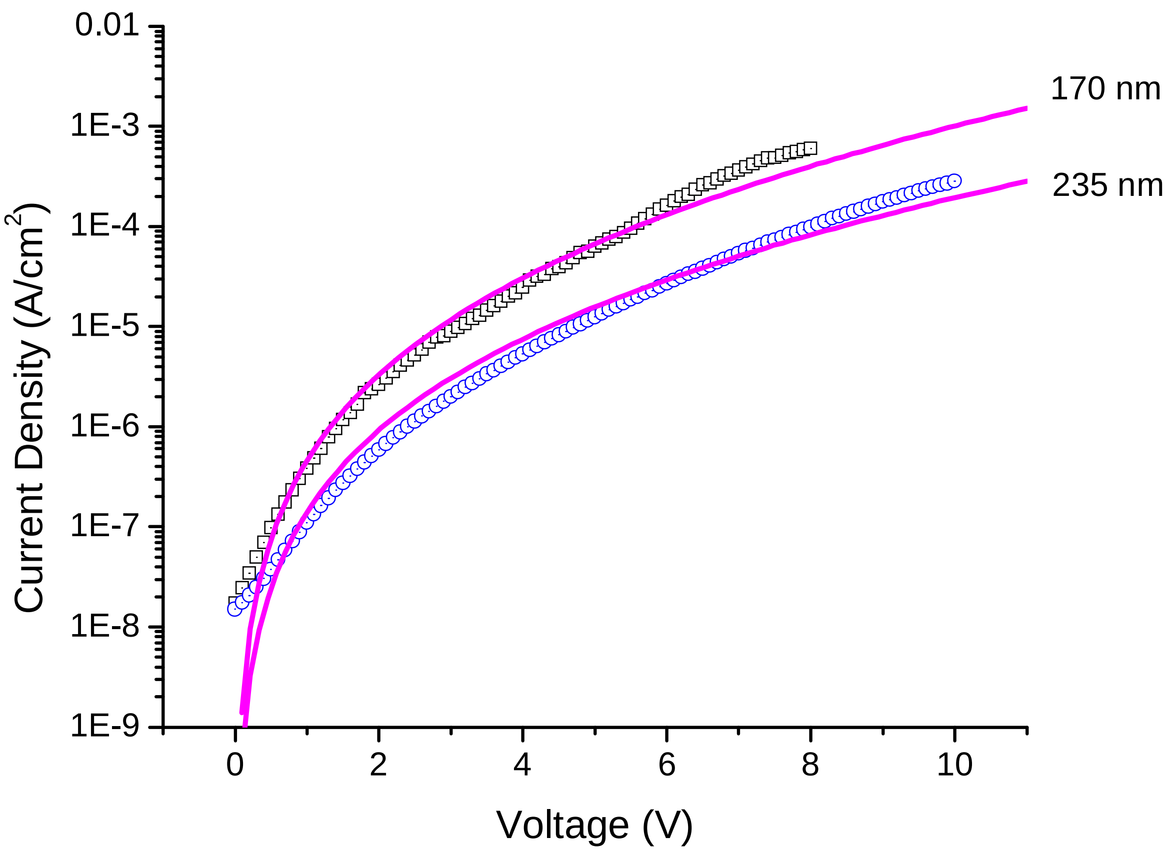
App. Phys. Lett. **83** (2003) 3380

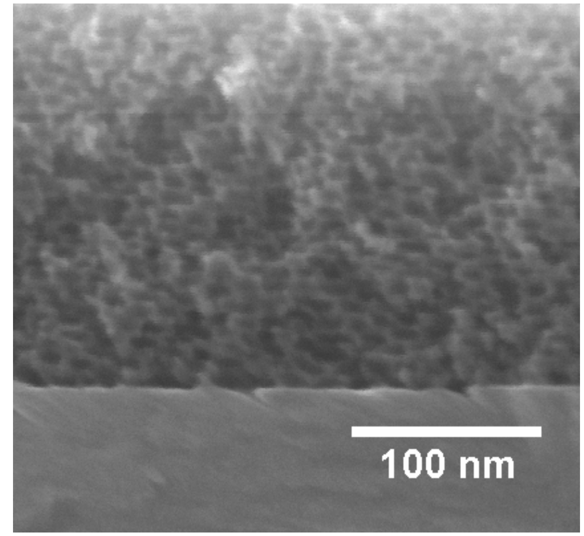
Photocurrent is only generated at the top



App. Phys. Lett. **83** (2003) 3380

Diodes with the polymer in mesoporous silica





$$J = \frac{9}{8} e_0 e_r m_{p0} \exp(g \sqrt{\tfrac{V}{L}}) \frac{V^2}{L^3}$$

$$g = 5.9 \times 10^{-4} \ (\mathrm{m/V})^{0.5}$$

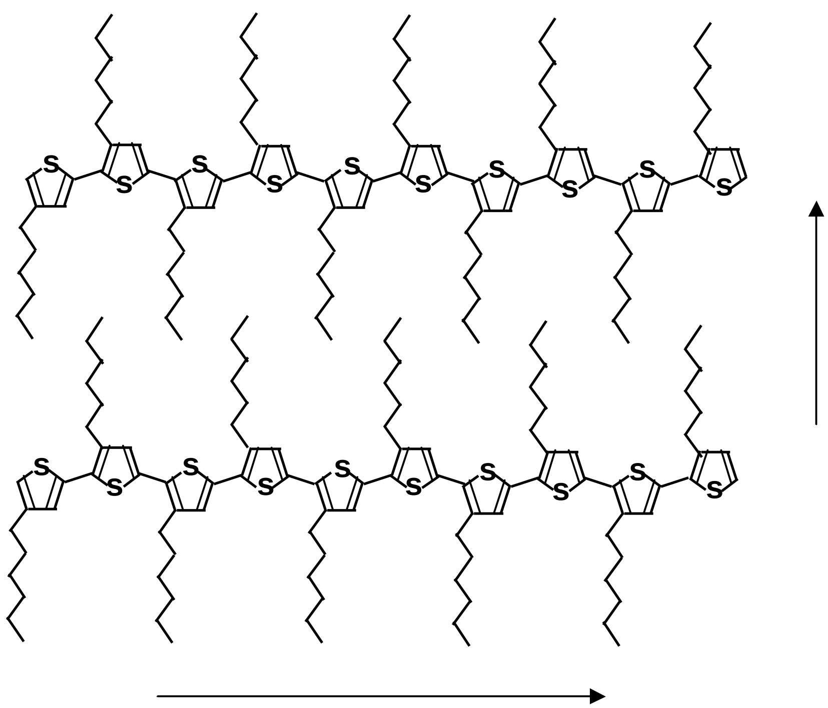
$$m_{p0} = 9.5 \times 10^{-9} \quad \mathrm{cm^2/Vs}$$

Fits to the SCLC current model yield very low mobilities.

How high does the hole mobility have to be?

If the films are 270-nm thick and $t_{\text{back transfer}} = 1\ \mu s$, then

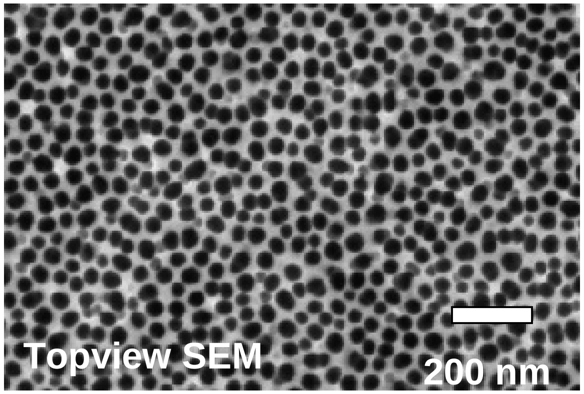
μ needs to be approximately **10^{-2} cm^2/Vs**.

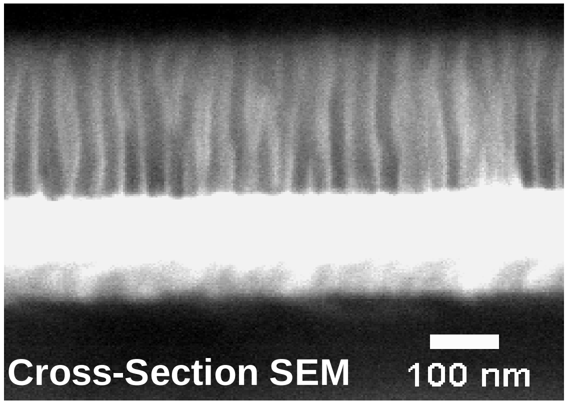


μ_{SCLC} as high as 3×10^{-4} cm^2/Vs

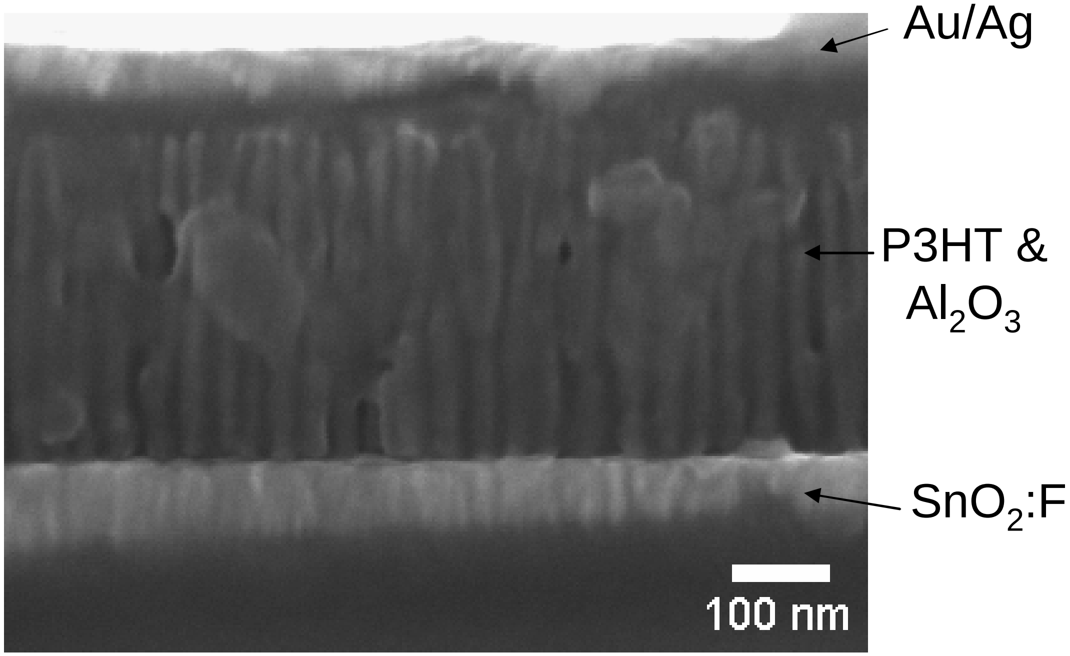
μ_{FET} as high as 0.1 cm^2/Vs

Hole-only P3HT diodes in anodic alumina





after Al anodization and pore widening to expose SnO_2:F

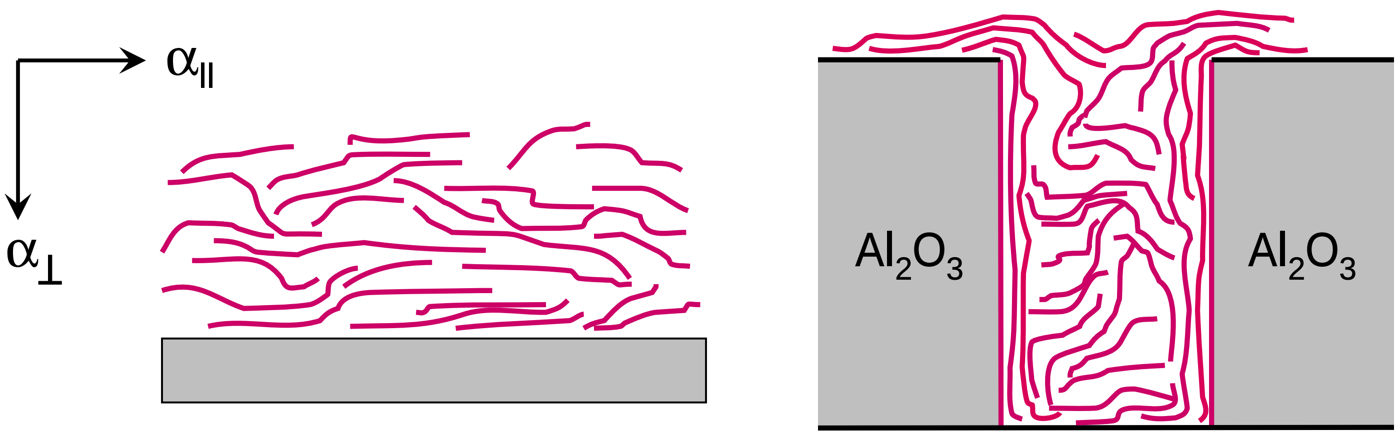


following P3HT infiltration and top electrode deposition

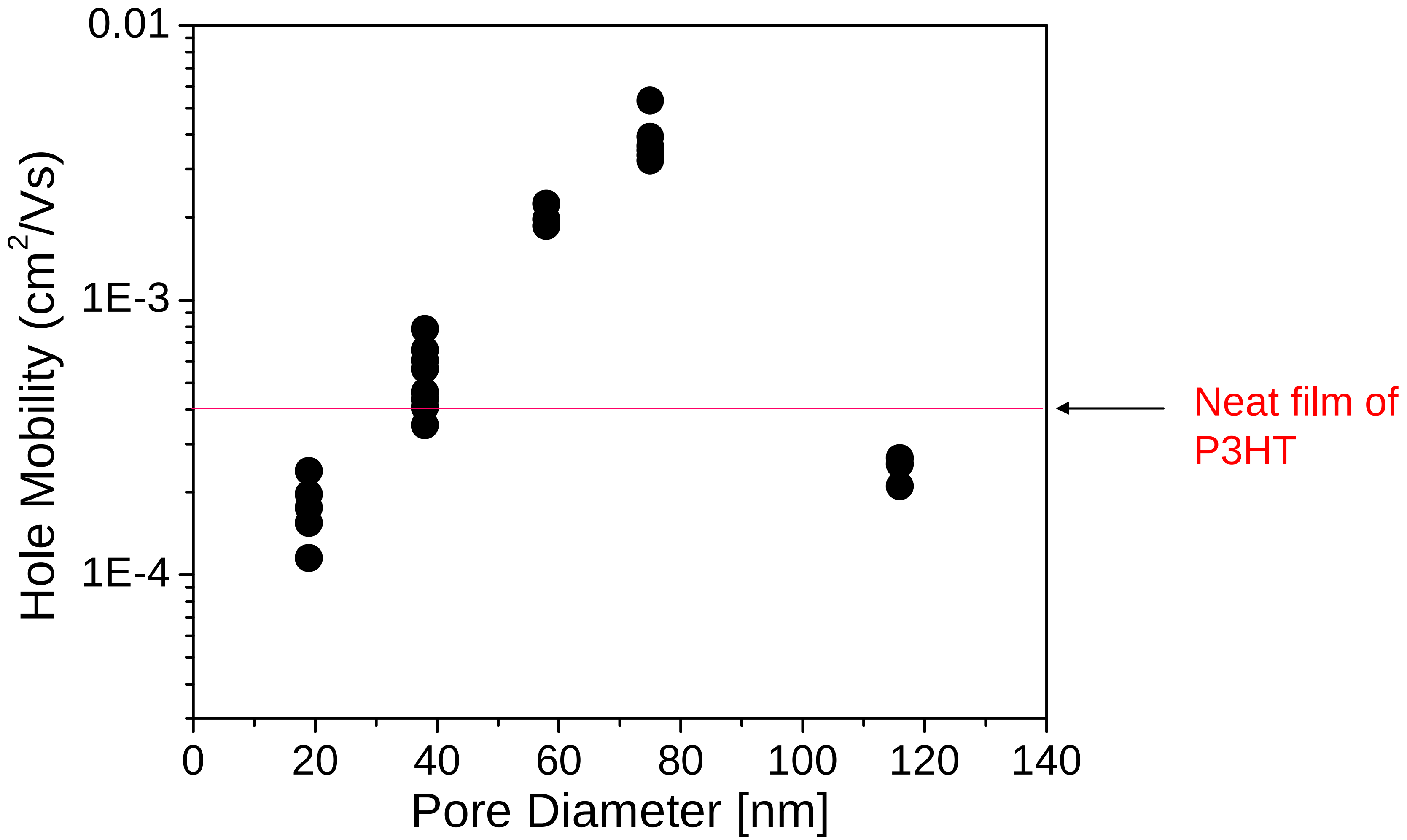
We have grown 20-120 nm diameter pores

Orientation of the chains

514 nm:	$\alpha_{\|\|}$ ($\times 10^5$ cm^{-1})	$\alpha_{\perp}$ ($\times 10^5$ cm^{-1})	ratio
neat film	1.64	0.31	0.19
in Al_2O_3	0.53	0.42	0.79



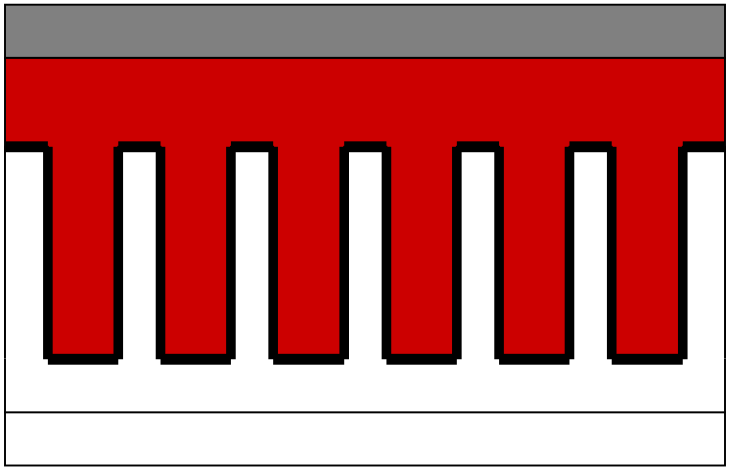
Hole mobility versus pore diameter



For 75-nm pores, μ is enhanced by 20x.

Conclusions

20 % efficiency can be achieve if



1.) We find a method for patterning 20 nm wide holes that are 200 nm deep in a suitable semiconductor.

2.) We reduce the bandgap to absorb more light.

3.) The energy loss associated with electron transfer is reduced.

4.) The charge carrier mobility is improved and the interface is engineered to almost eliminate recombination.

Review: Coakley and McGehee, *Chemistry of Materials*, 16 (2004) 4533-42.

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