Low Cost "Plastic" Solar Cells

Solar cells --- Power from the Sun --- must be and will be ---

a significant contribution to our energy needs.

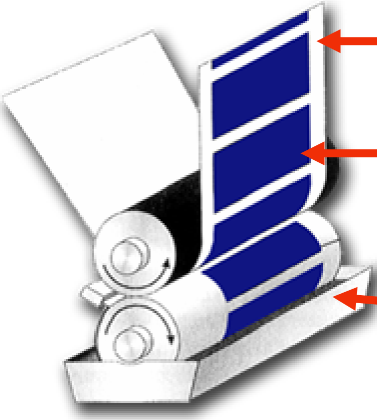
Two problems that must be solved with solar:

1. Cost
2. Area

Semiconducting and Metallic Polymers

"inks" ---- with electronic functionality!

The Dream →



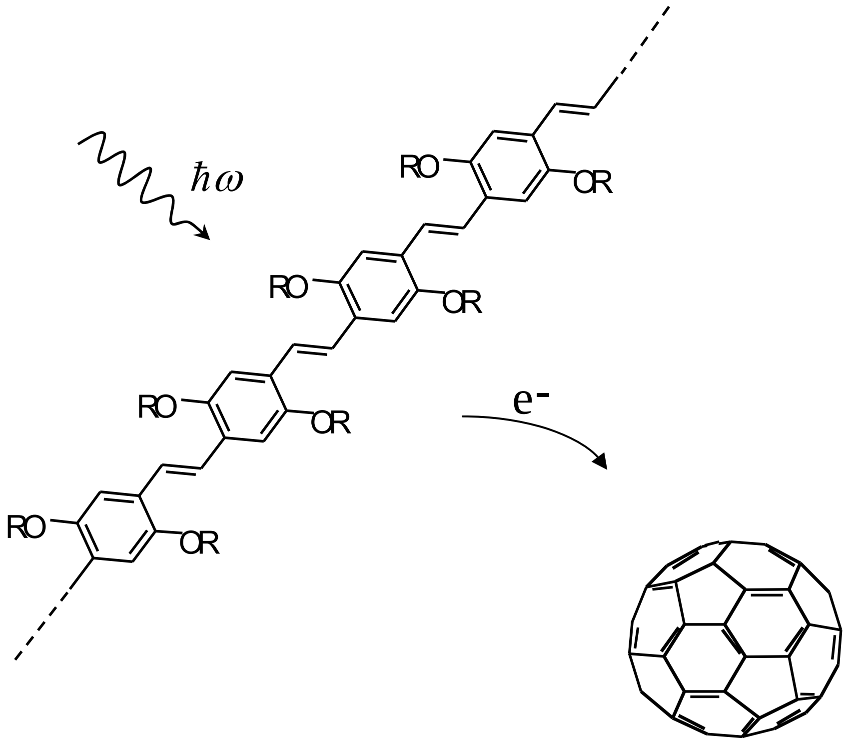
→


TiOx

“Plastic” Solar Cells

Ultrafast charge separation with quantum efficiency approaching Unity !

1992



50 femtoseconds!!

Ultrafast electron transfer is important ---

Charge transfer is 1000 times faster than any competing process,

and

Back charge transfer is inhibited

Therefore,

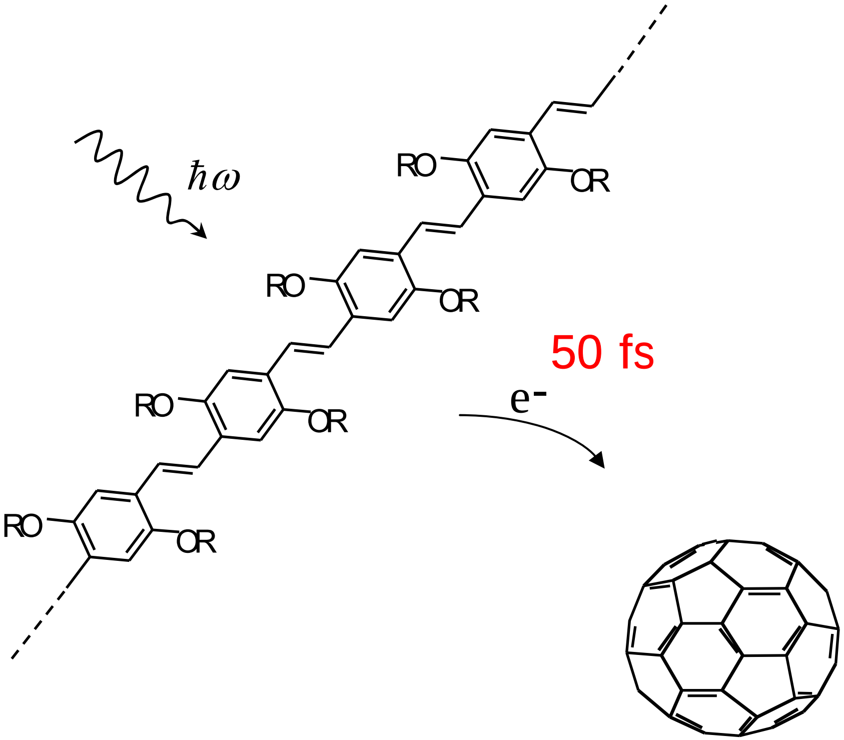
Quantum efficiency for charge separation approaches unity!

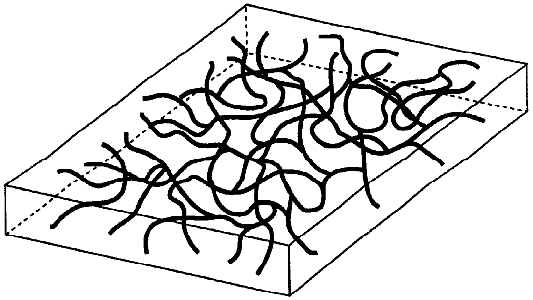
Every photon absorbed yields one pair of separated charges!

(Route to photovoltaics and photodetectors)

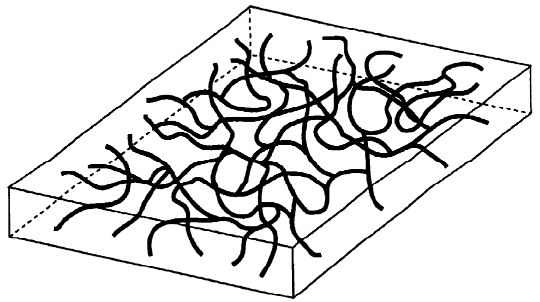
Ultrafast photo-induced charge separation ----

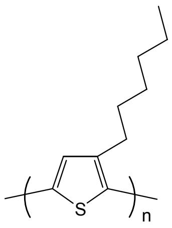
But how do we create a material with charge-separating junctions everywhere??



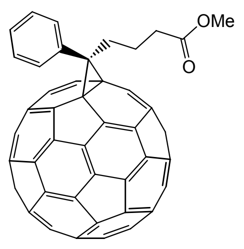


All must be accomplished at nanometer length scale!

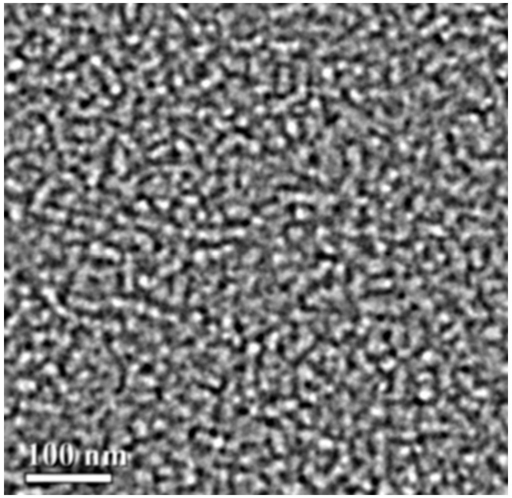




P3HT



PCBM



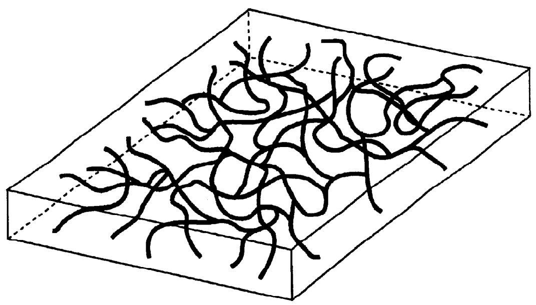
Bulk Heterojunction Material

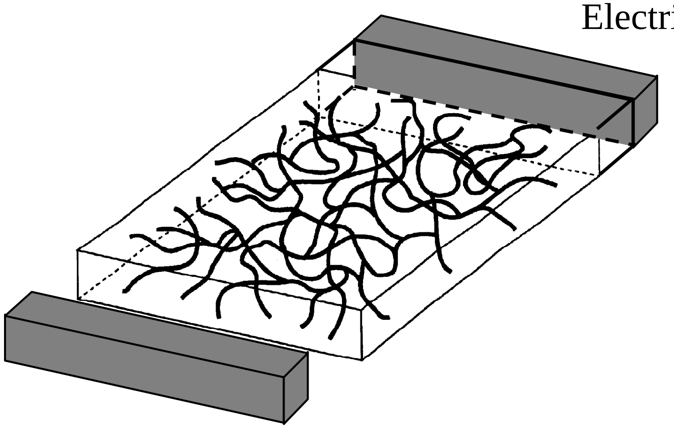
Bicontinuous interpenetrating network

Self-assembled nanoscale material with charge-separating junctions everywhere!

"Bulk" D-A Heterojunction Material

A self-assembled nanomaterial



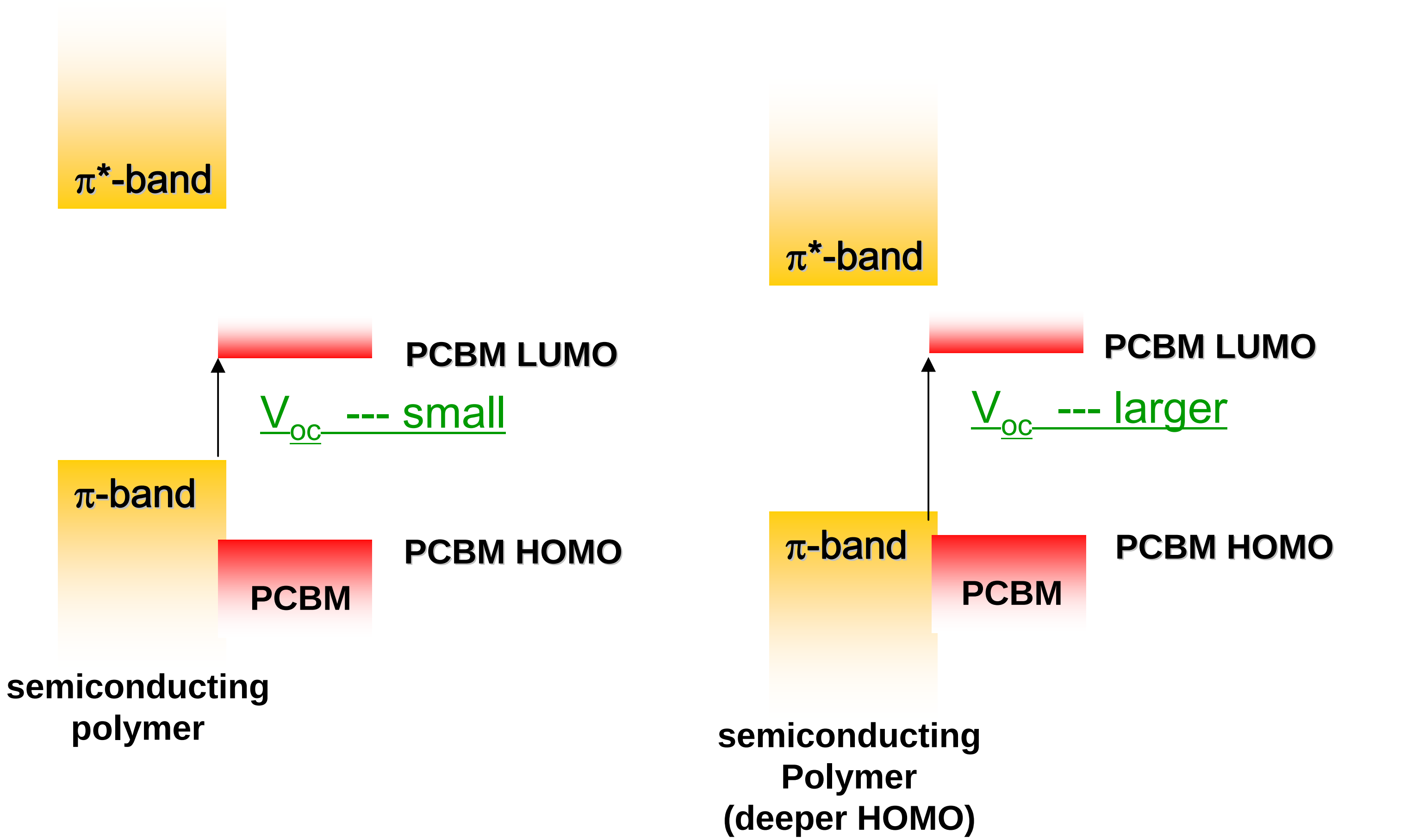


Must break the symmetry --- use two different metals with different work functions.

Electrons will automatically go toward lower work function contact and holes toward higher work function contact

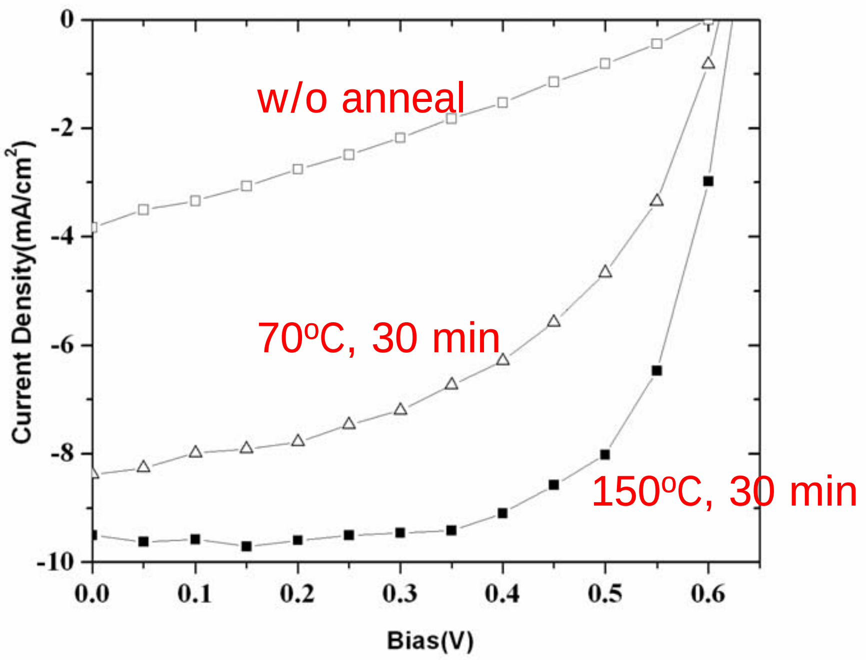
Origin of V_{oc} --- when irradiated with high light intensity, Fermi levels must be equal (holes in the π-band and electrons in PCBM LUMO):

$$V_{oc} \approx E_{PCBM\ LUMO} - E_{polymer\ homo}$$



Solar Cell Performance

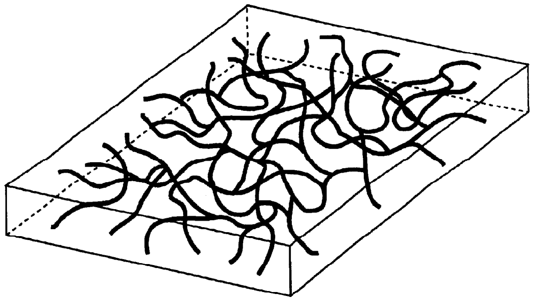
Device structure: ITO/PEDOT/P3HT:PCBM/Al.

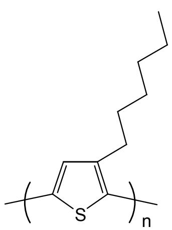


Eff = 5.0 %
V_{OC} = 0.625 V
FF = 68 %

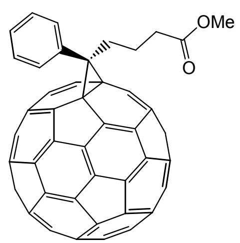
Series resistance decreased from 113 Ω to 7.9 Ω

"Bulk" Heterojunction Material --- Optimize Nanomorphology



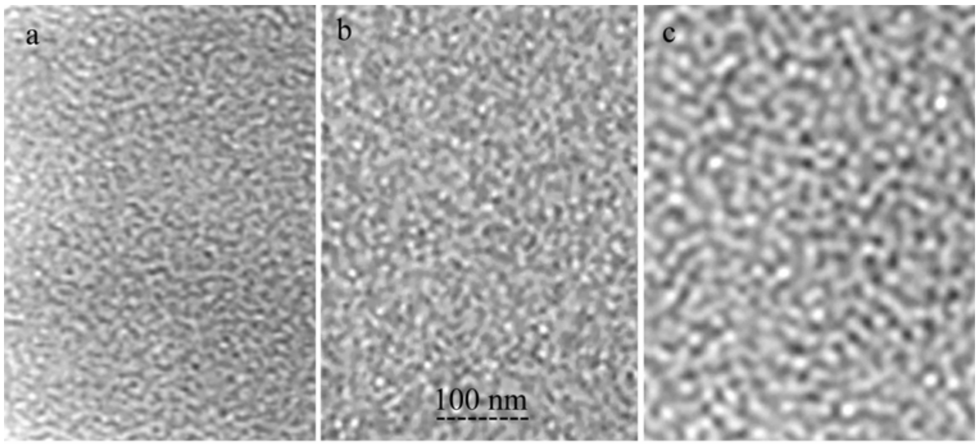


P3HT



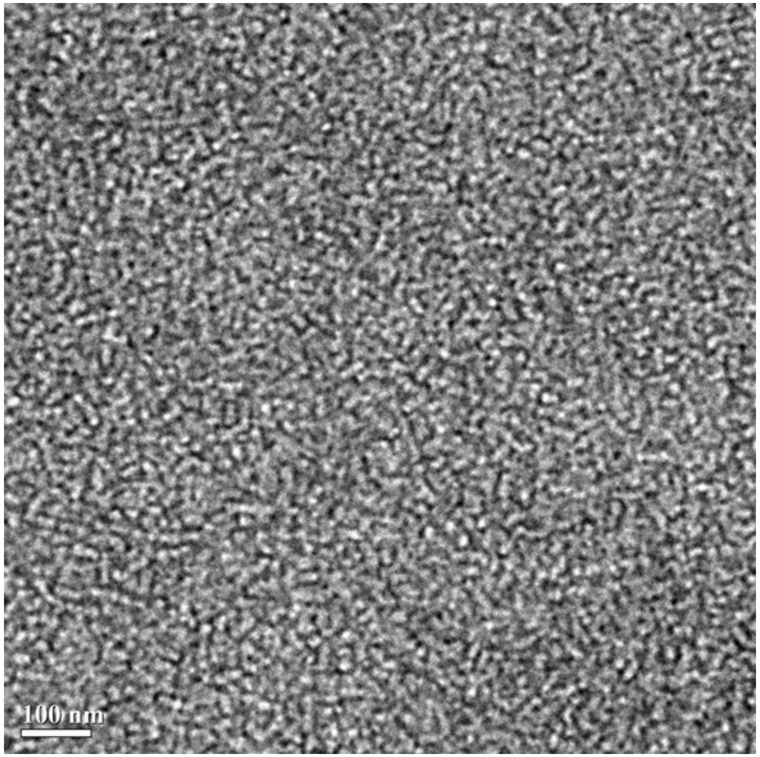
PCBM

Before 150°C anneal	150°C anneal 30 min	150°C anneal 2 hours

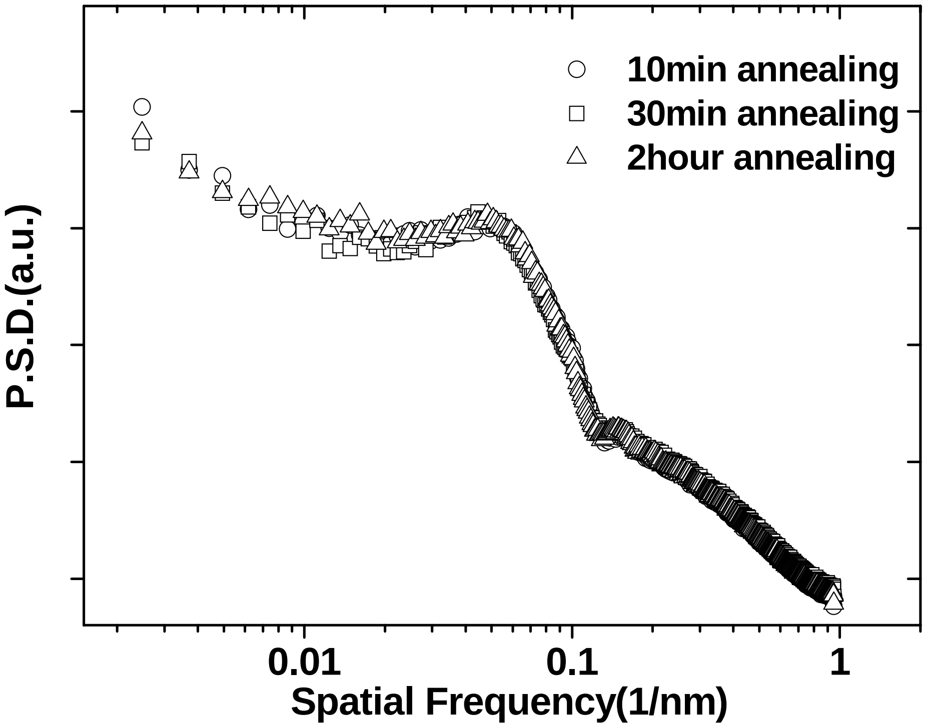


TEM images of the P3HT/PCBM interpenetrating network

After annealing for 10 minutes at 150^{o}C



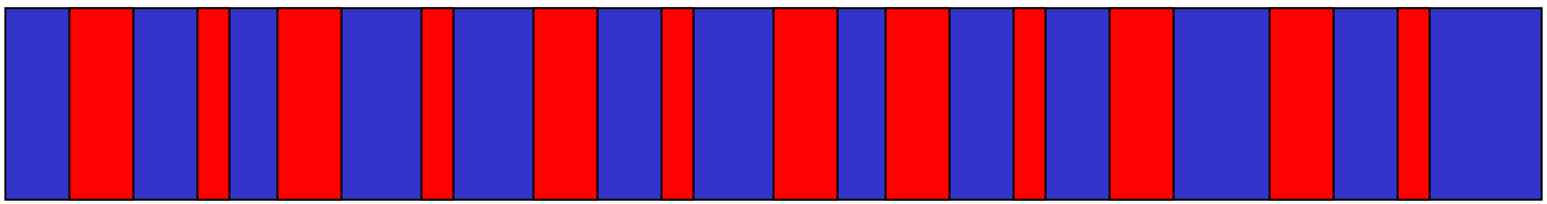
Spatial Fourier Transform



High temperature annealing --- 150^{o} C

1. Stable for long times at High-T
2. 10 minutes sufficient to lock in the nano-scale morphology

Quasi-periodic with "periodicity" of 16-20 nm



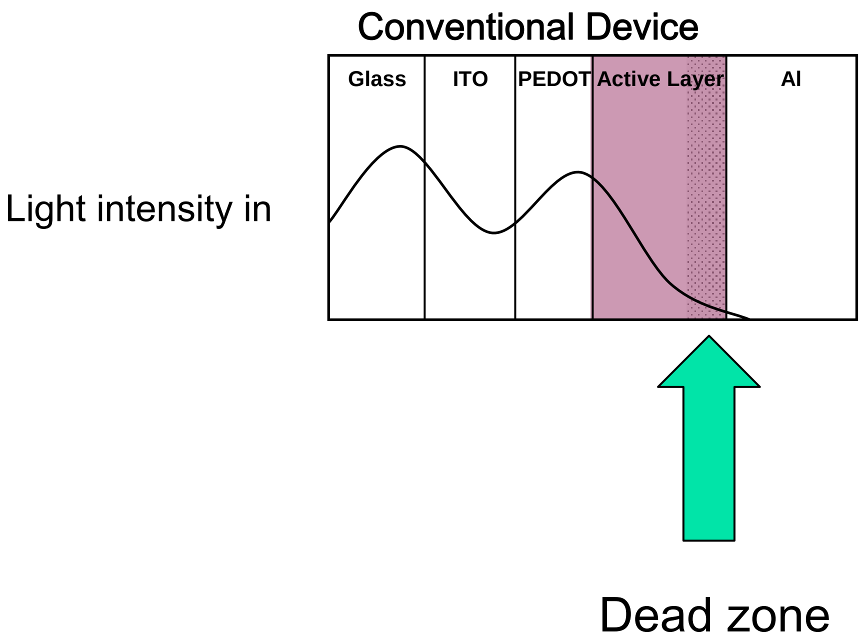
80 nm

|”Period” 160 -200 Å|

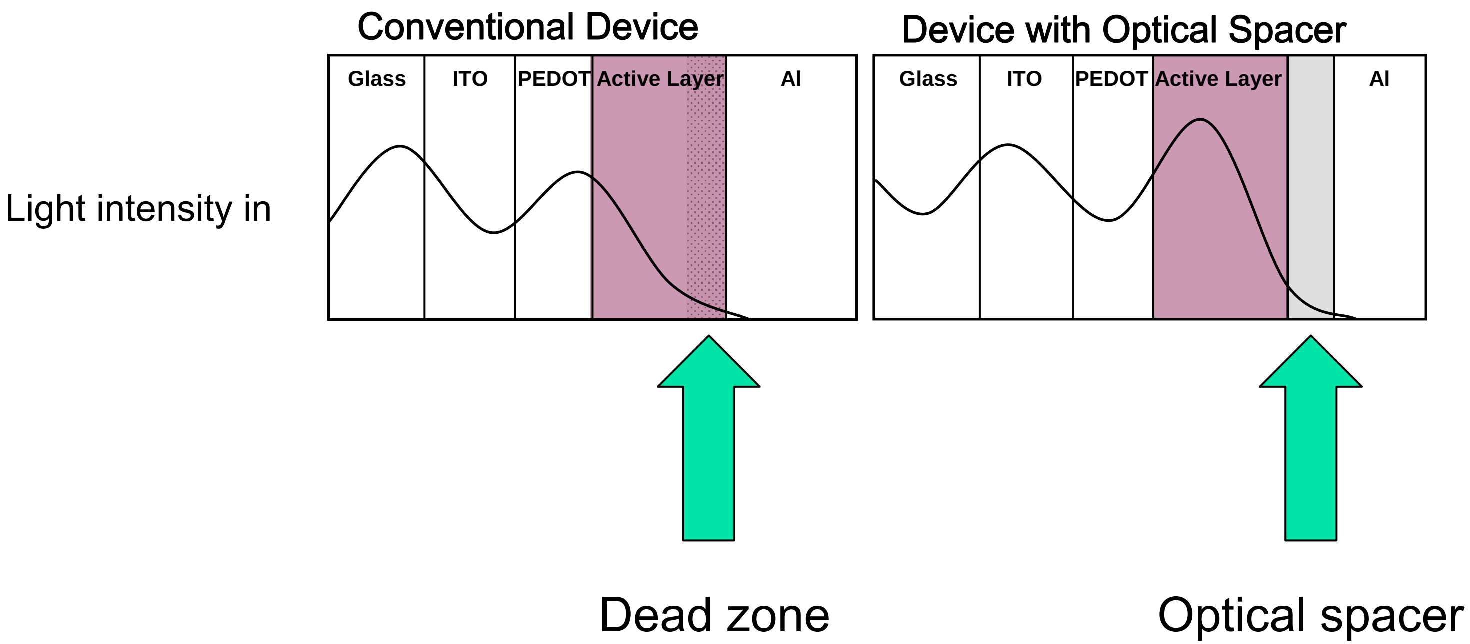
Distance from any point in the material to a charge separating interface ≈ 40-50 Å

Less than the mean exciton diffusion length --- High efficiency for charge separation.

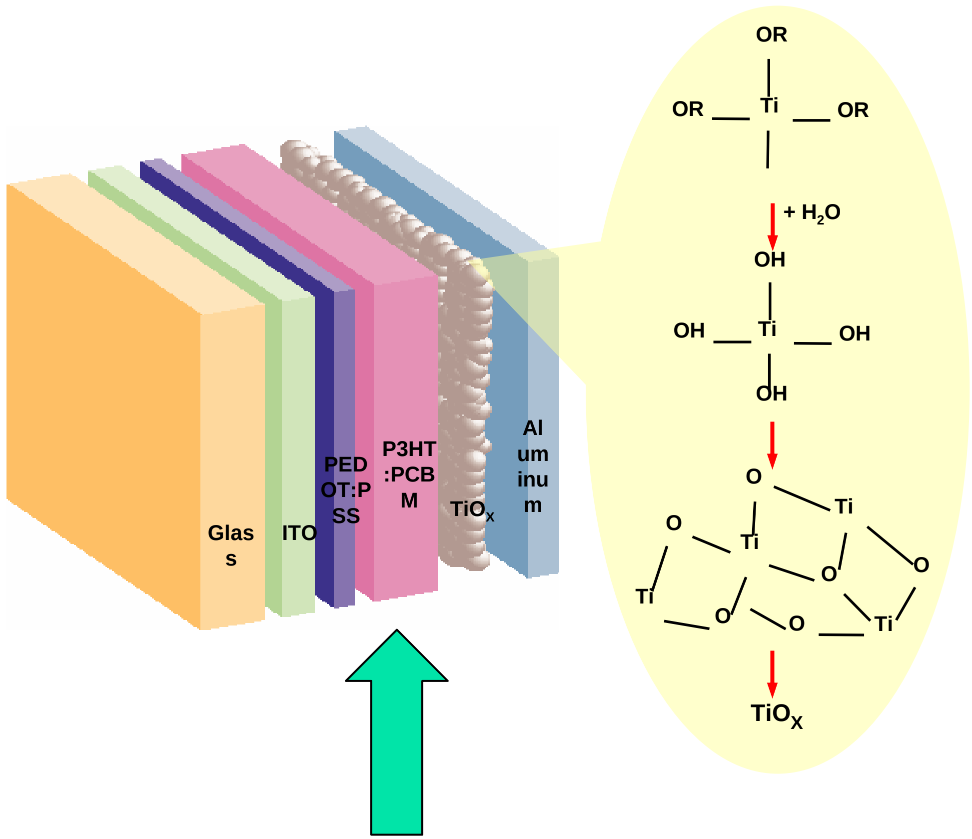
New Device Architecture: Optical Spacer



New Device Architecture: Optical Spacer



Device architecture: Optical spacer

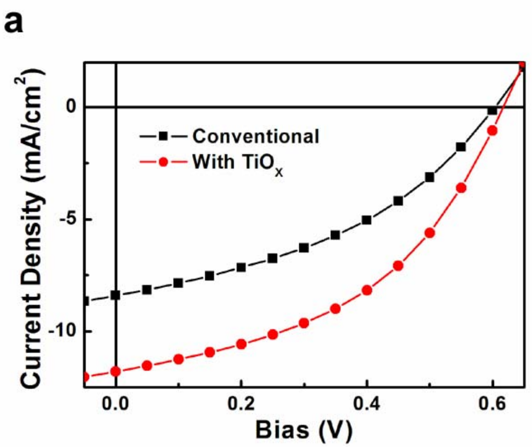


Charge separation layer

Optical Spacer can improve the Power Conversion Efficiency

Green light (532 nm)
Efficiency

η_e = 8.1% $\longrightarrow$ 12.6%



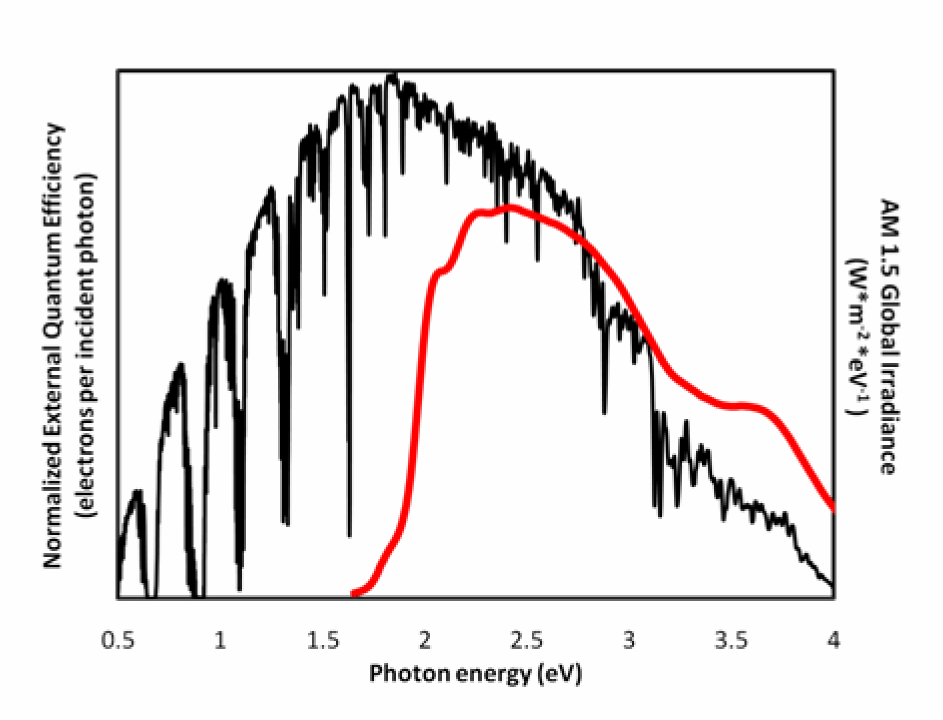
25 % - 50% increase in efficiency

Optical spacer important for low mobility materials where simply making the active layer thicker is not an option

What can we expect to achieve??

Single layer with efficiency > 5% demonstrated with P3HT

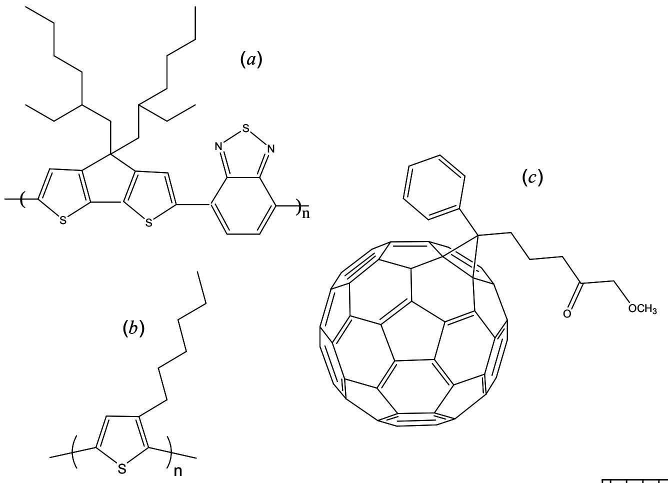
Band gap too large ---Missing more than half the solar spectrum



Opportunity: Potential for factor of 2 improvement using polymer with smaller band gap.

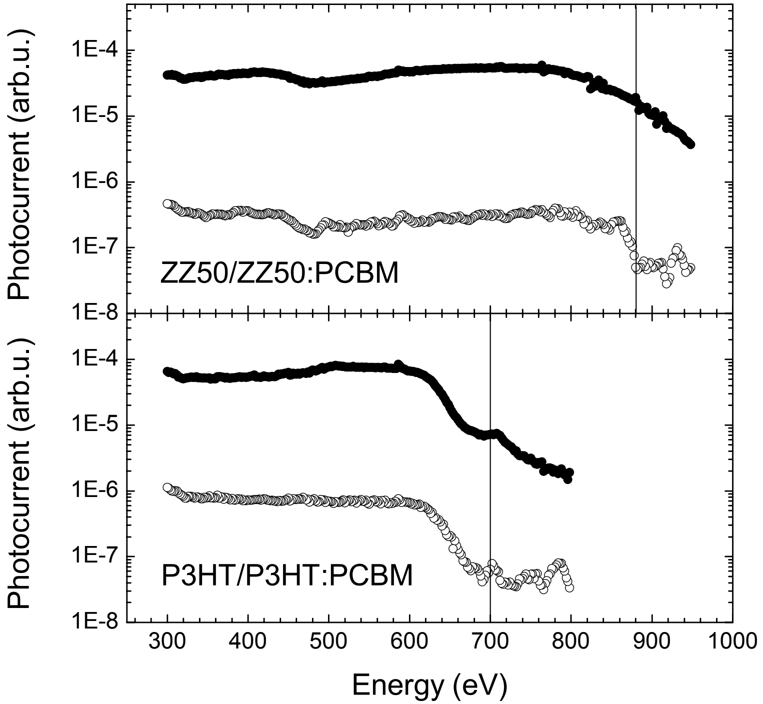
Semiconducting polymers with smaller band gap?

Zhengguo Zhu
(ZZ50)

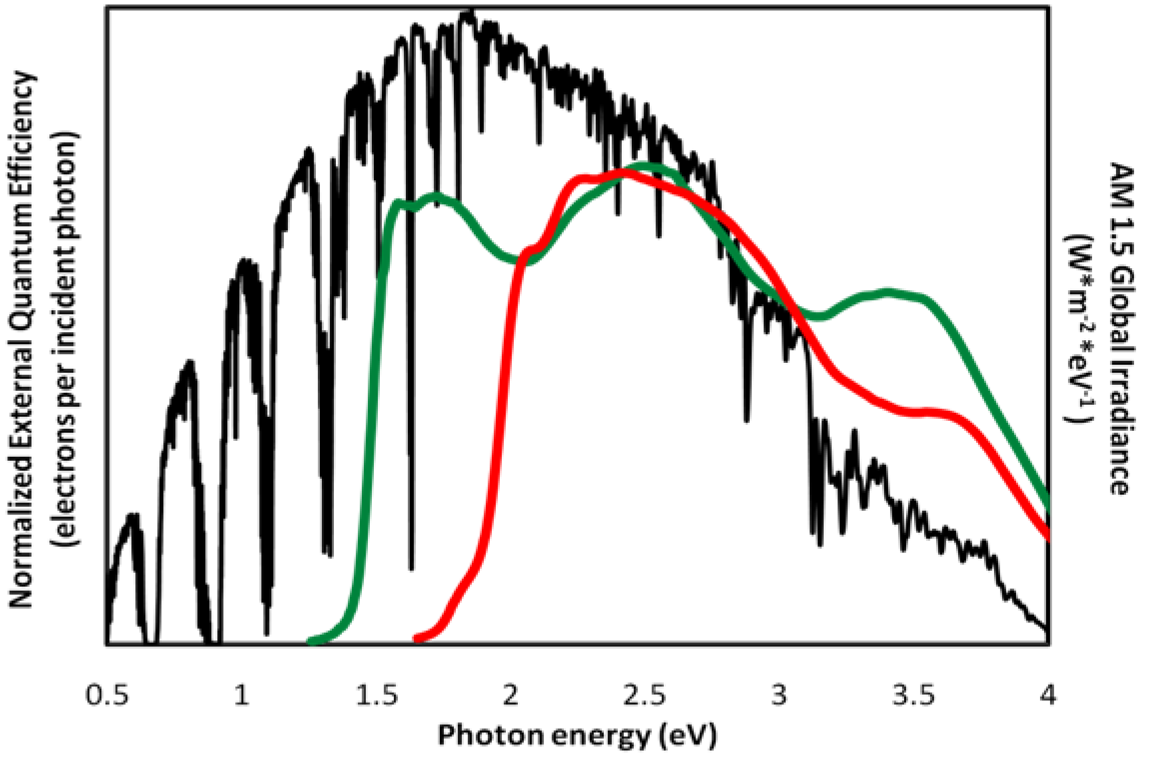


Absorption and photoresponse
out to 900 nm in the IR.

Should be capable of 7% in single cell
and >10% in a Tandem Cell with P3HT



With ZZ50 ---



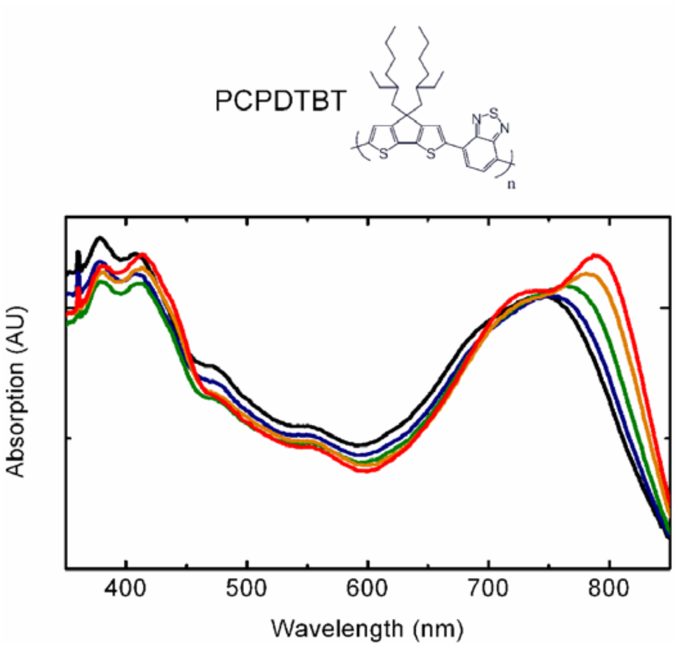
Progress --- but still missing all incident power in the IR beyond 900 nm.
Need smaller gap materials

Morphology Control withAlkane-dithiols as Processing Additives

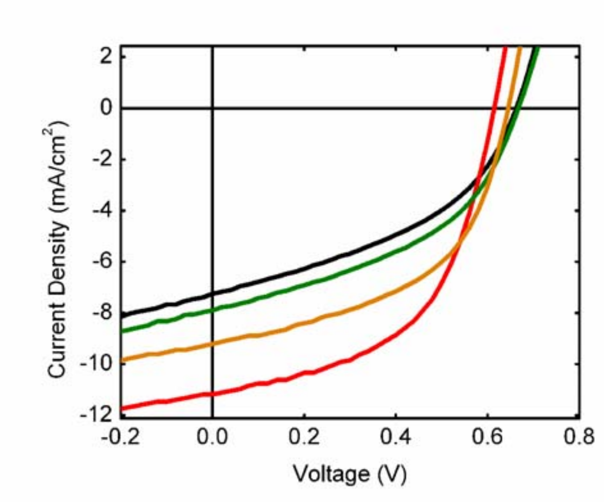
(Nature Materials, Published online May 27. 2007)

Add 2.5% alkanedithiol into solvent (chlorobenzene)

1,3-propanedithiol (blue), 1,4-butanedithiol (green),
1,6-hexanedithiol (orange) and 1,8-octanedithiol (red)

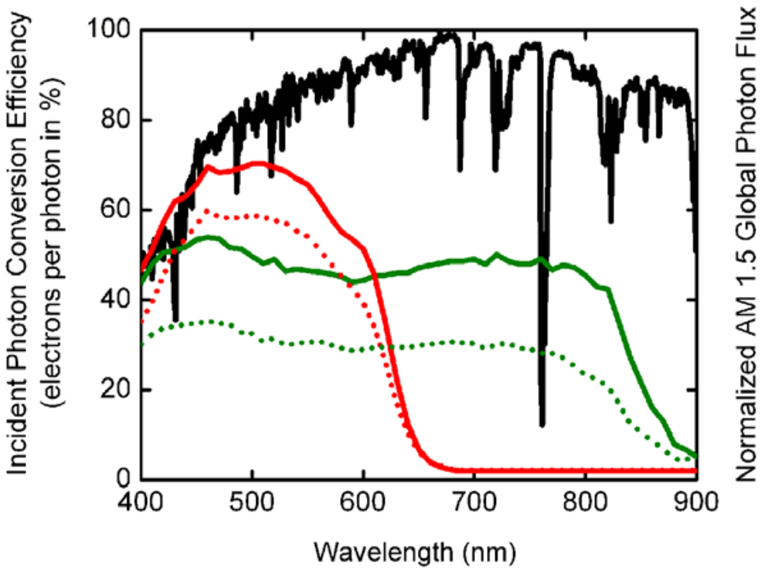


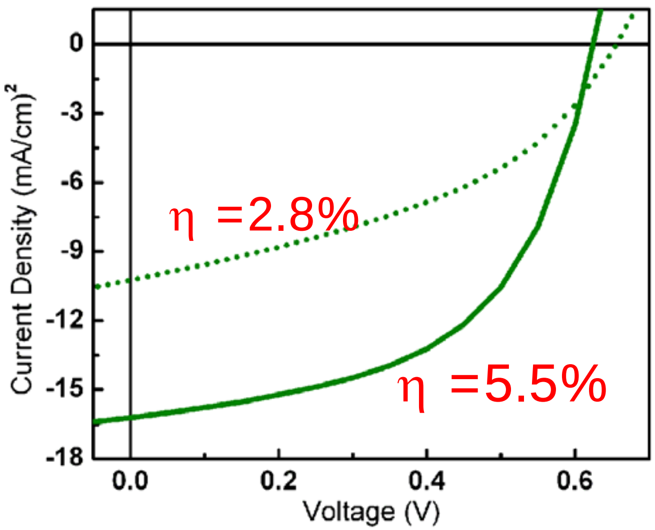
Spectra sharpen and red-shift



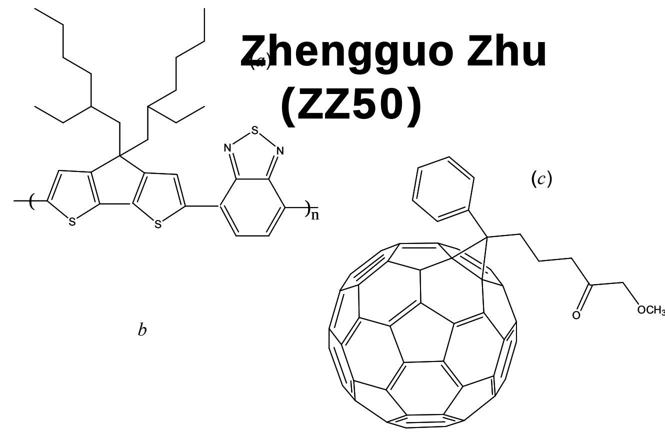
Higher j_{sc} --- higher efficiency

Processing Additives for Morphology control





Zhengguo Zhu (ZZ50)



Factor of 2 Improvement by using octane-dithiol as processing additive

Nature Materials
Published online May 27. 2007

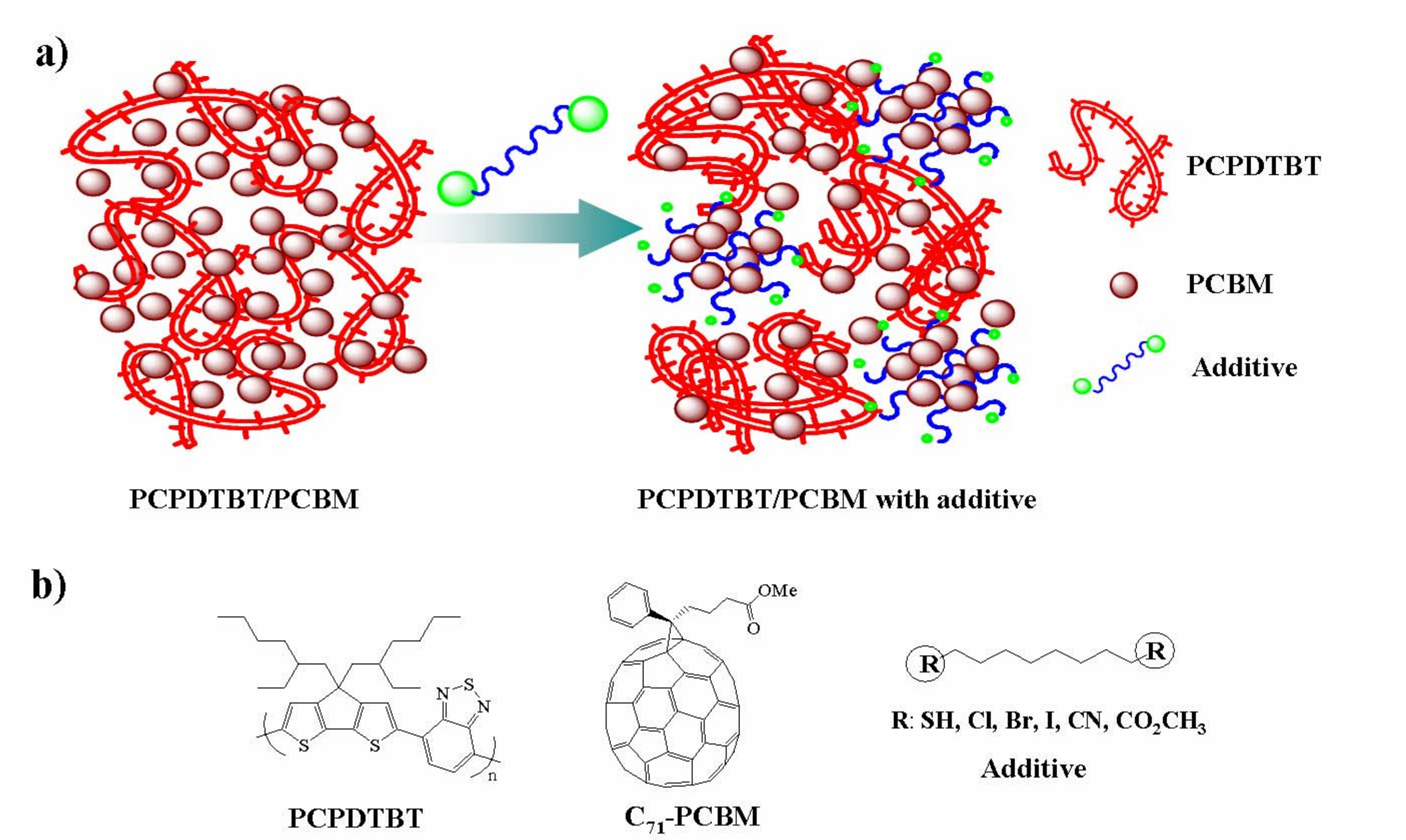
Best performance for a single cell architecture

Processing Additives for Morphology Control of Bulk Heterojunction Materials

Mechanism:

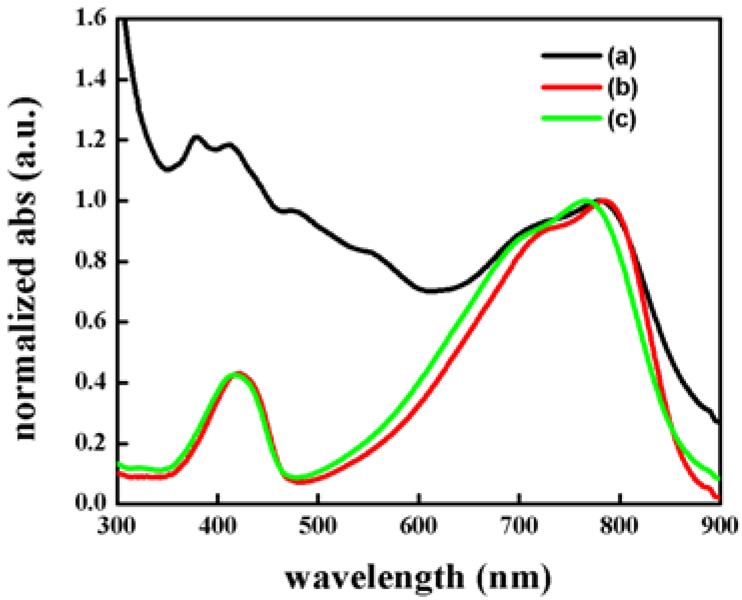
(i) Selective (differential) solubility of the fullerene component

(ii) Higher boiling point than the host solvent.



Absorption Spectra

PCPDTBT film (green)



PCPDTBT:C71-PCBM films processed with 1,8-octanedithiol ---

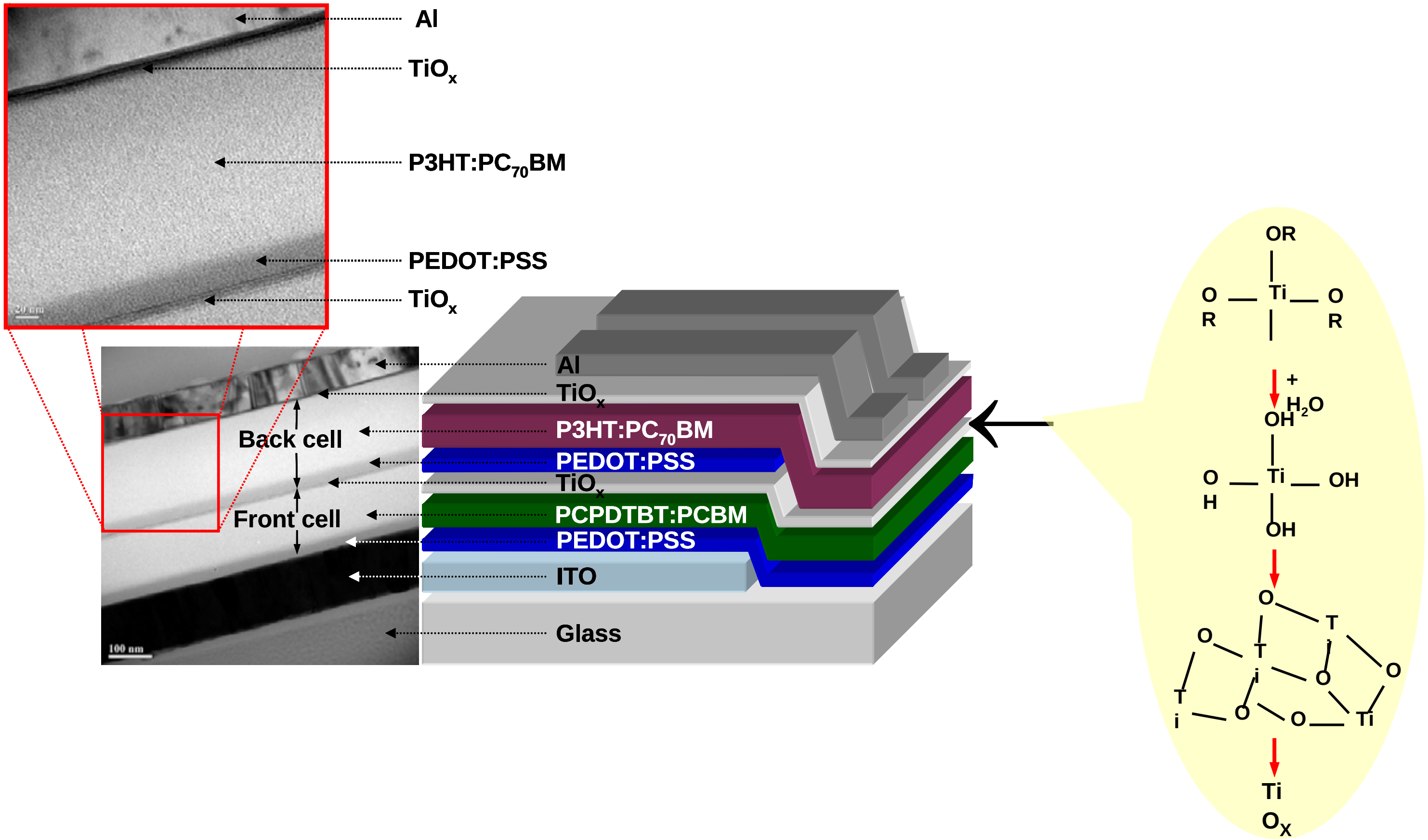
Before removal of C71-PCBM with alkanedithiol (black),

After removal of C71-PCBM with alkanedithiol (red)

The PCBM is completely removed by the alkane-dithiol!

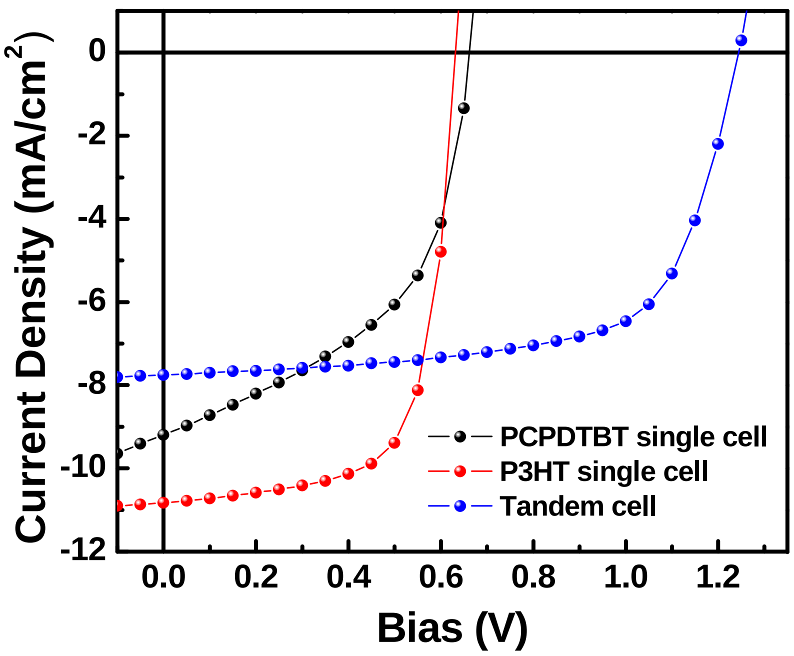
Multi-layer Tandem Cell

(equivalent to two solar cells in series)



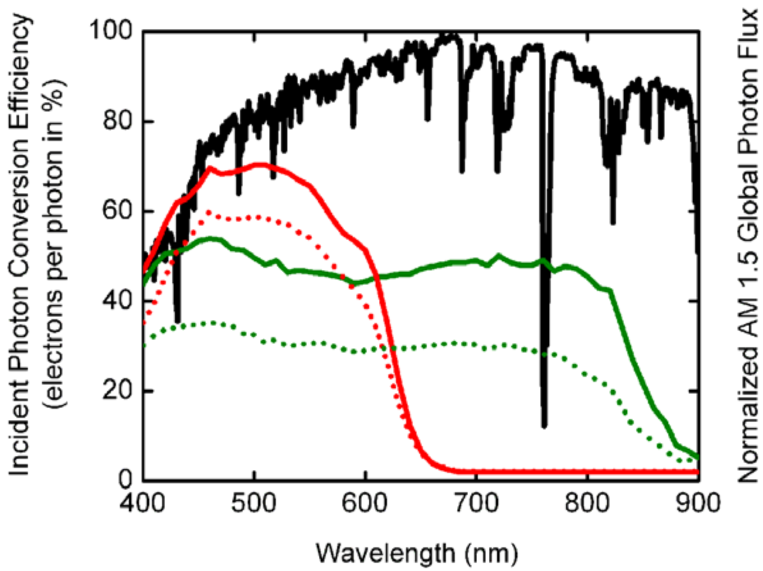
Tandem Cell

(Multilayer architecture equivalent to two solar cells in series)



Open circuit voltage doubled --- Efficiency 6.5%

We can do even better ----



Increased performance of
each of the two subcells ---

Already demonstrated
(using the Processing Additive).

Goal for coming months: 8-10 %

In the Tandem Cell, the TiOx layers serve six separate functions:

1. Optical spacer that redistributes the light intensity
   to optimize the efficiency of the back cell.

2. With TiOx layer between the charge separating layer and
   the aluminum cathode --- much improved air stability

3. The TiOx functions as a low resistance electron transport layer

4. TiOx layer breaks the symmetry and thereby creates
   the open circuit voltage.

5. TiOx functions as a hole blocking layer
   (top of the valence band at - 8.1 eV)

6. TiOx layer enables the fabrication of tandem cells. The transparent
   TiOx layer is used to separate and connect
   the front cell and the back cell.

Polymer Solar cells: Present status --- 5 - 6 % with P3HT (and with several other materials with similar spectra)

What can we expect (hope) to achieve??

New Architecture --- optical spacer --- 25-50% improvement

New Polymers with energy gap well matched to the solar spectrum
Opportunity for x2 improvement

Better charge collection efficiency (optimize morphology)
Opportunity for 25% improvement

Increased open circuit voltage (deeper HOMO for semiconducting polymer)
Opportunity: Potential for > 50% improvement

Tandem Cell ---
Opportunity: Potential for > 50% improvement

Reality of each of these has been demonstrated.

Goal: Achieve all these advances in the same system

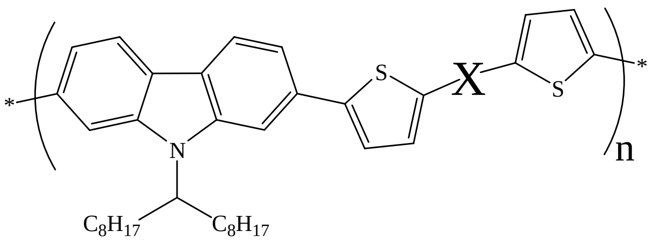
(1.25 x 2 x 1.25 x 1.5 x 1.5 = 7)

Clear vision of technology pathway to BHJ solar cells with efficiencies exceeding 20%

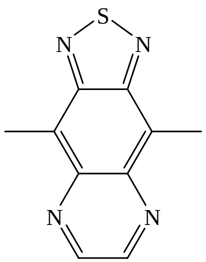
New materials are the key to progress

Examples:

LeClerc and colleagues (JACS published on the web 12/21/07)

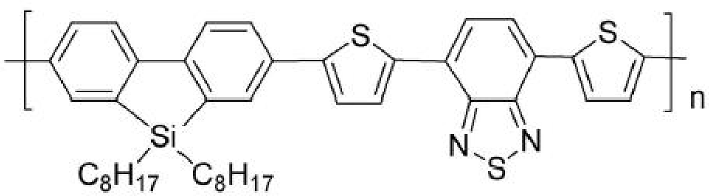


With X = acceptor such as



3.6% with PCBM

Yong Cao and colleagues (in press)



PSiF-DBT

5.4% with PCBM

Note: Both have high V_{oc} --- 0.9 V Deeper HOMO

Air-stable polymer electronic devices

Thin layer of amorphous TiO_x ($x<2$) improves performance

and

Enhances Lifetime

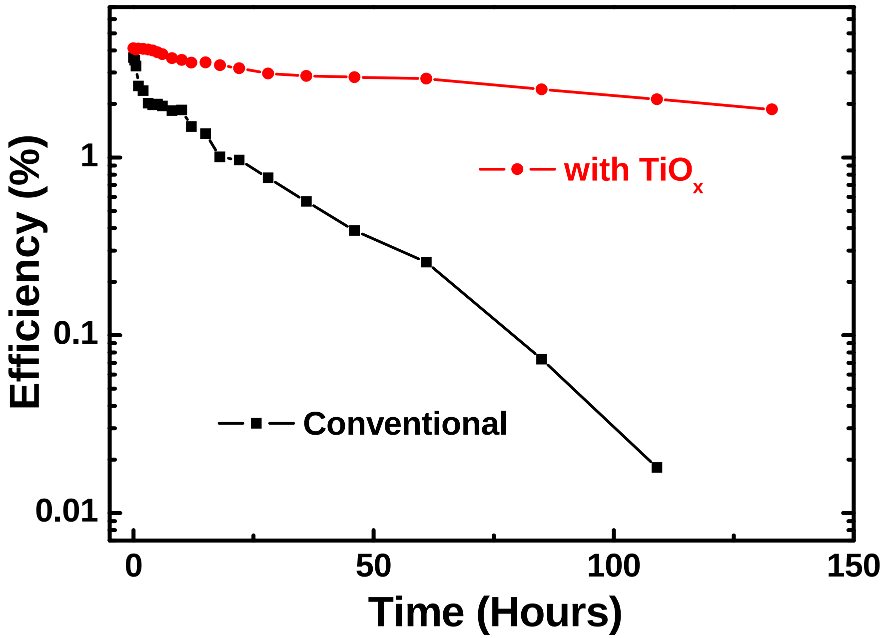
Polymer Based Solar Cells
Polymer LEDs
Polymer FETs

Adv Mater. 2007

Bulk Heterojunction Solar Cells

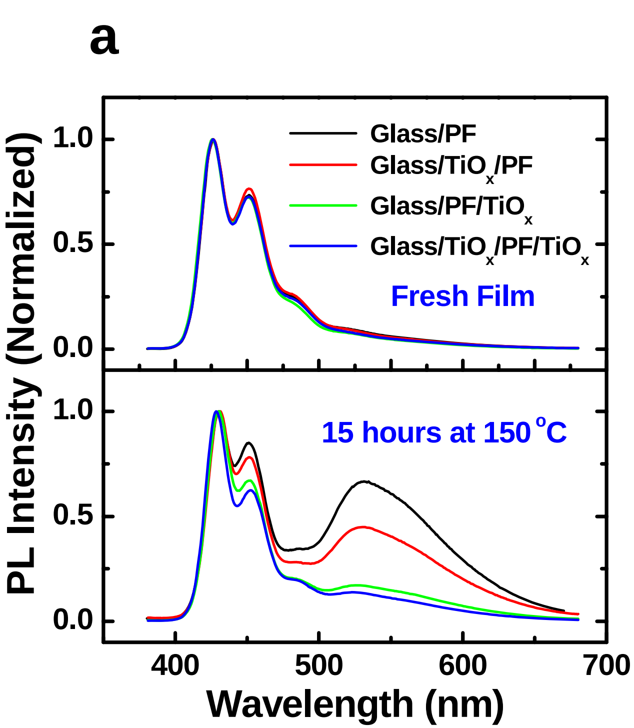
Single TiO_x passivation layer signficantly enhances the lifetime

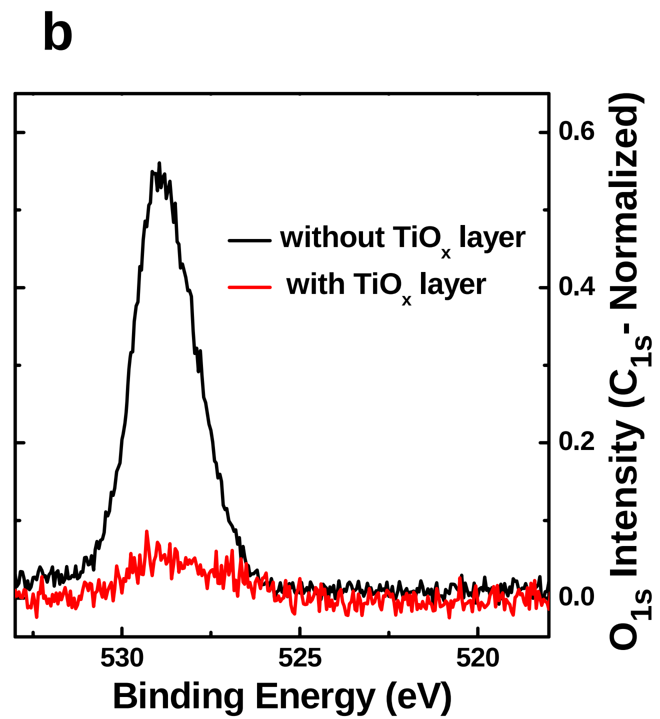
Factor of 100 !



Goal: Simple inexpensive barrier materials will be sufficient for achieving long lifetime.

Background scientific information



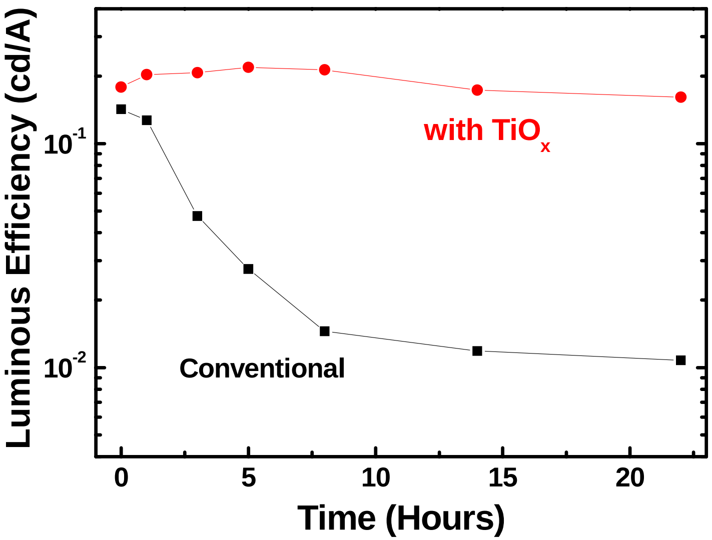


TiOx prevents oxidation of polyfluorene (PF)

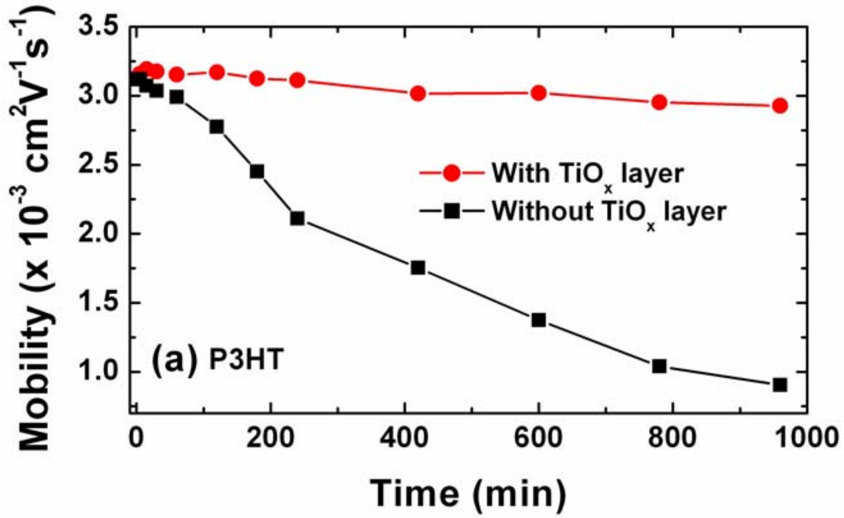
XPS of the O1s/C1s ratio in the PF after 48 hrs at 150°C in air

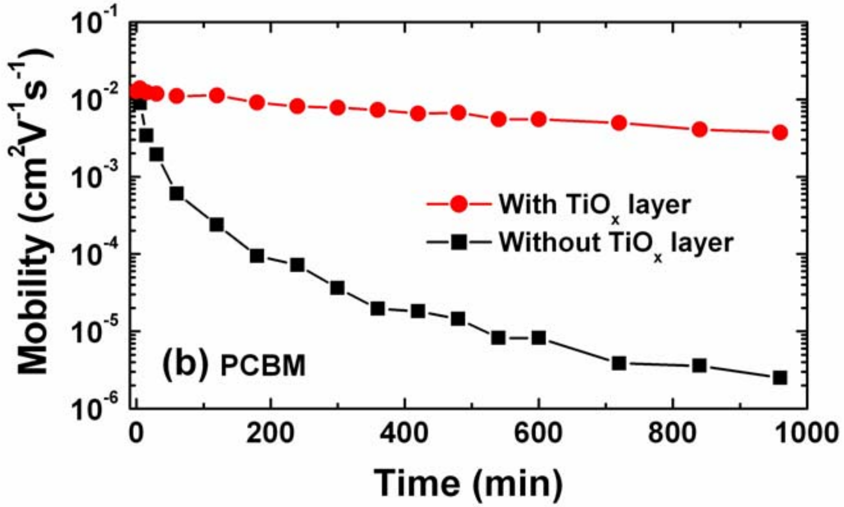
Similar enhancement in lifetime for LEDs and FETs

LEDs

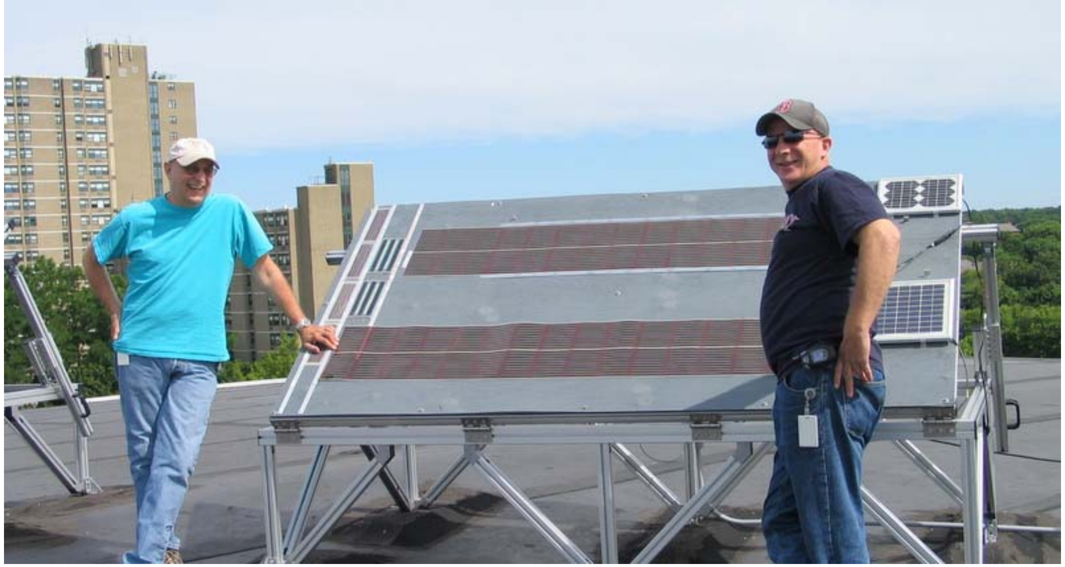


FETs



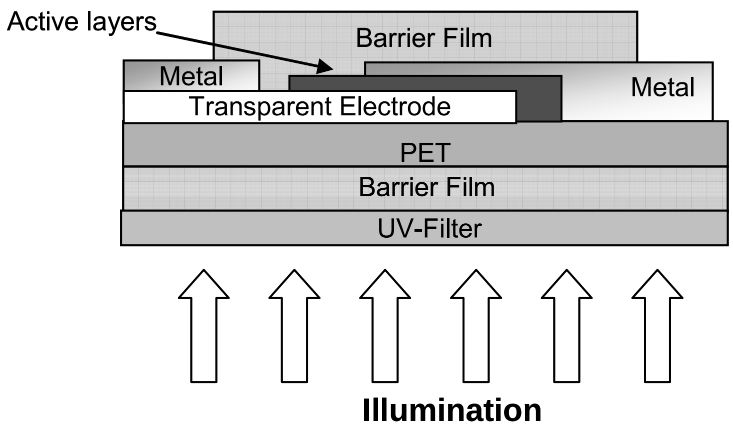


Rooftop testing of BHJ solar cells at KONARKA



Lifetime: Rooftop and Accelerated Degradation

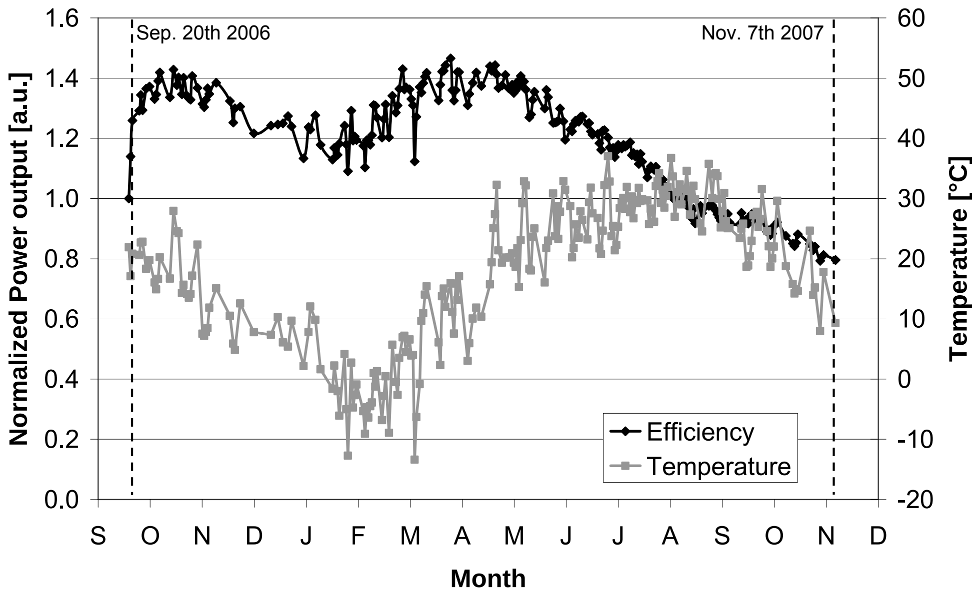
Flexible devices packaged with commercial, low cost barrier films (Konarka)

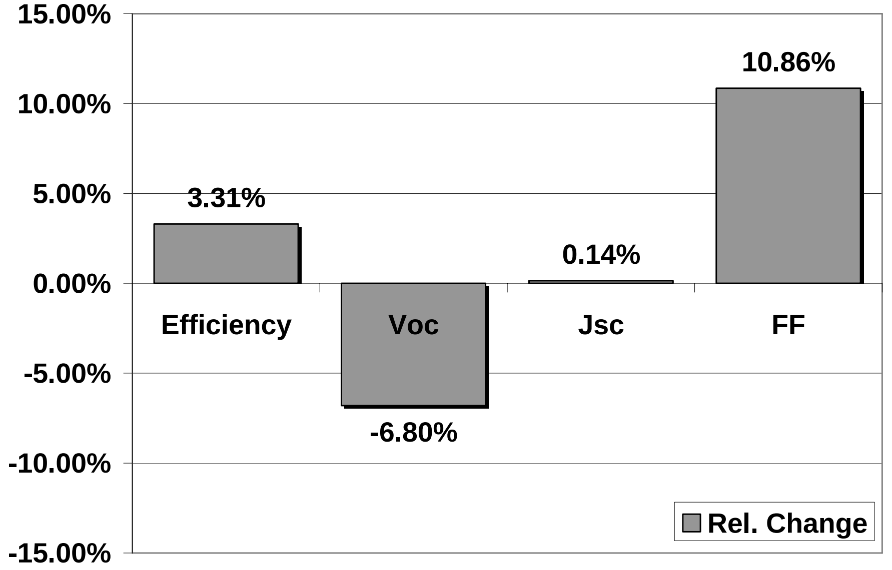


Flexible Organic P3HT:PCBM Bulk-Heterojunction Modules with more than 1 Year Outdoor Lifetime
Jens A. Hauch, Pavel Schilinsky, Stelios A. Choulis, Richard Childers, Markus Biele and Christoph J. Brabec

Long-Lived Flexible Organic Solar Cells
Jens A. Hauch, Pavel Schilinsky, Stelios C. Choulis, Sambatra Rajoelson and Christoph J. Brabec

Outdoor rooftop lifetime (Konarka)



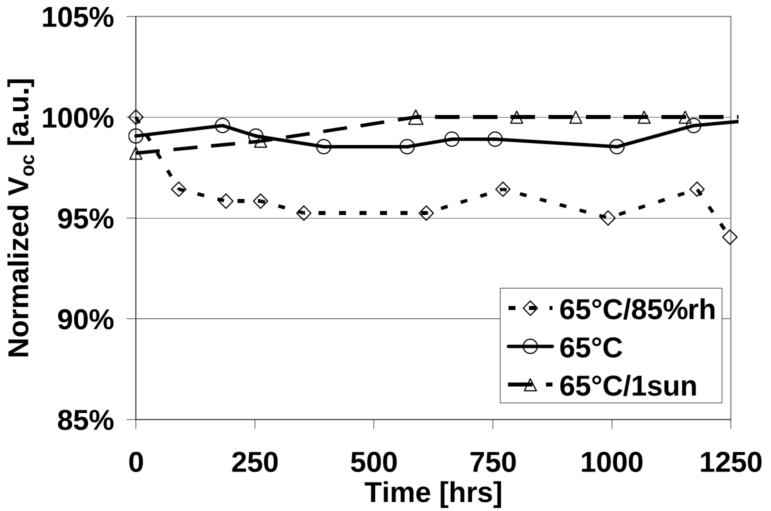


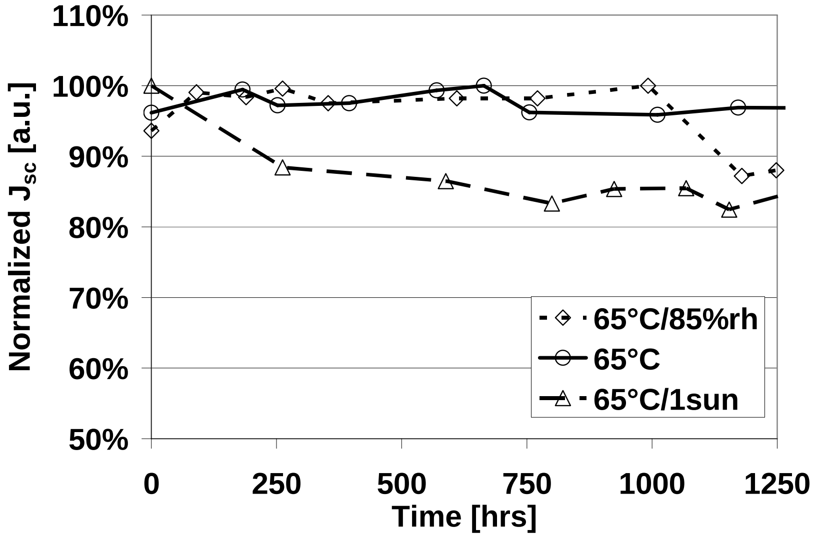
Efficiency actually increased ---

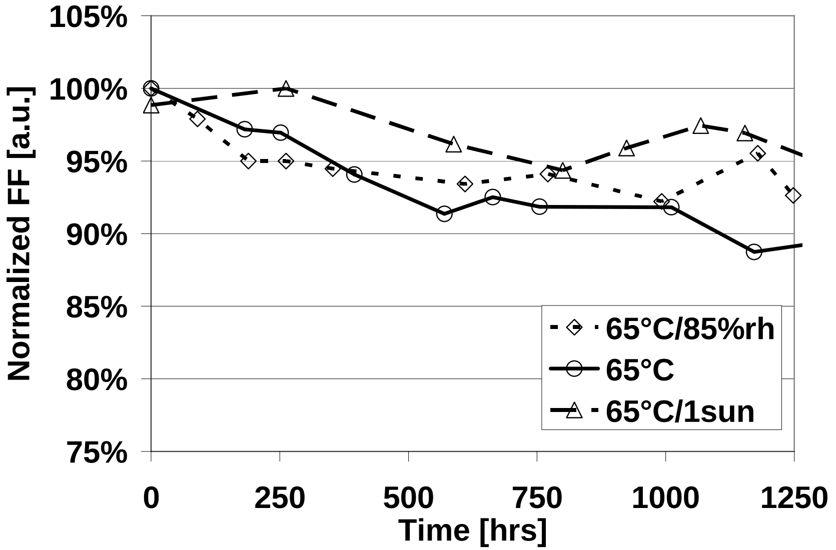
Drop in power output after 1 year due to small shift in the maximum power point (from 0.87V to 0.8V).

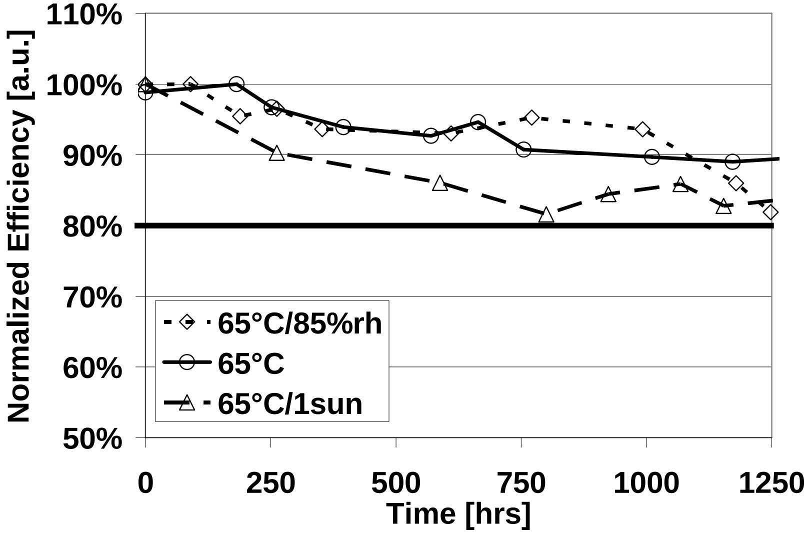
Accelerated Degradation ---

Flexible devices packaged with commercial, low cost barrier films (Konarka)









Goal: Efficiency > 10 - 15 % with polymer "bulk heterojunction" nano-materials

Low Cost Roll-to-Roll manufacturing by printing and coating technologies

Acknowledgement

Professor Kwanghee Lee ---UCSB and GIST (Korea)
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Christoph Brabec and colleagues at Konarka


SCIENCE