David Ginley, Research Fellow
NREL
Progress, Trends and Challenges for PV
Towards the Terrawatt Challenge

With Help From:

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Organic based Photovoltaics

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PLEXTRONICS
Light. Power. Circuitry.™

Konarka®

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APS physics

Solarmer

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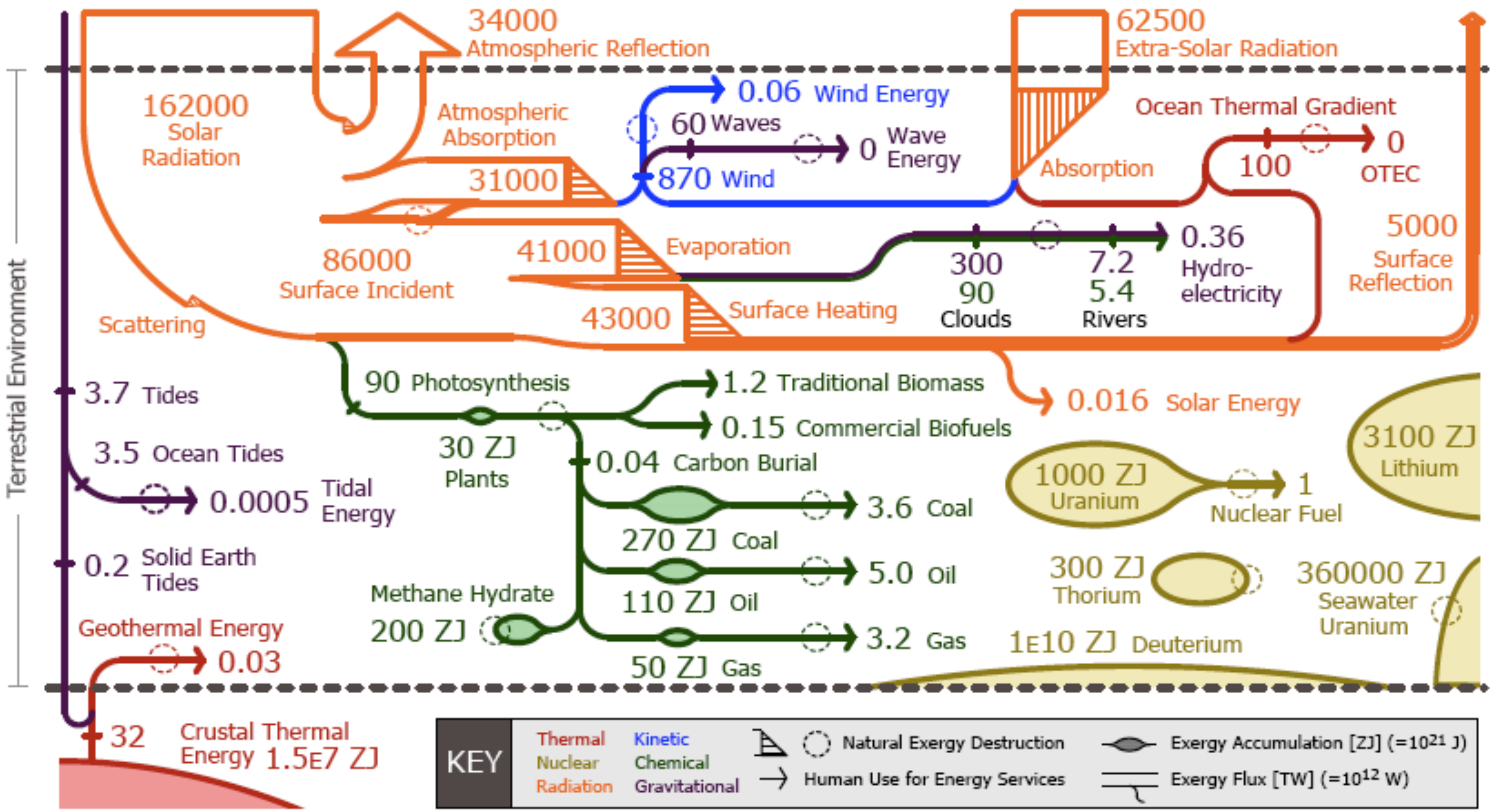
GCEP

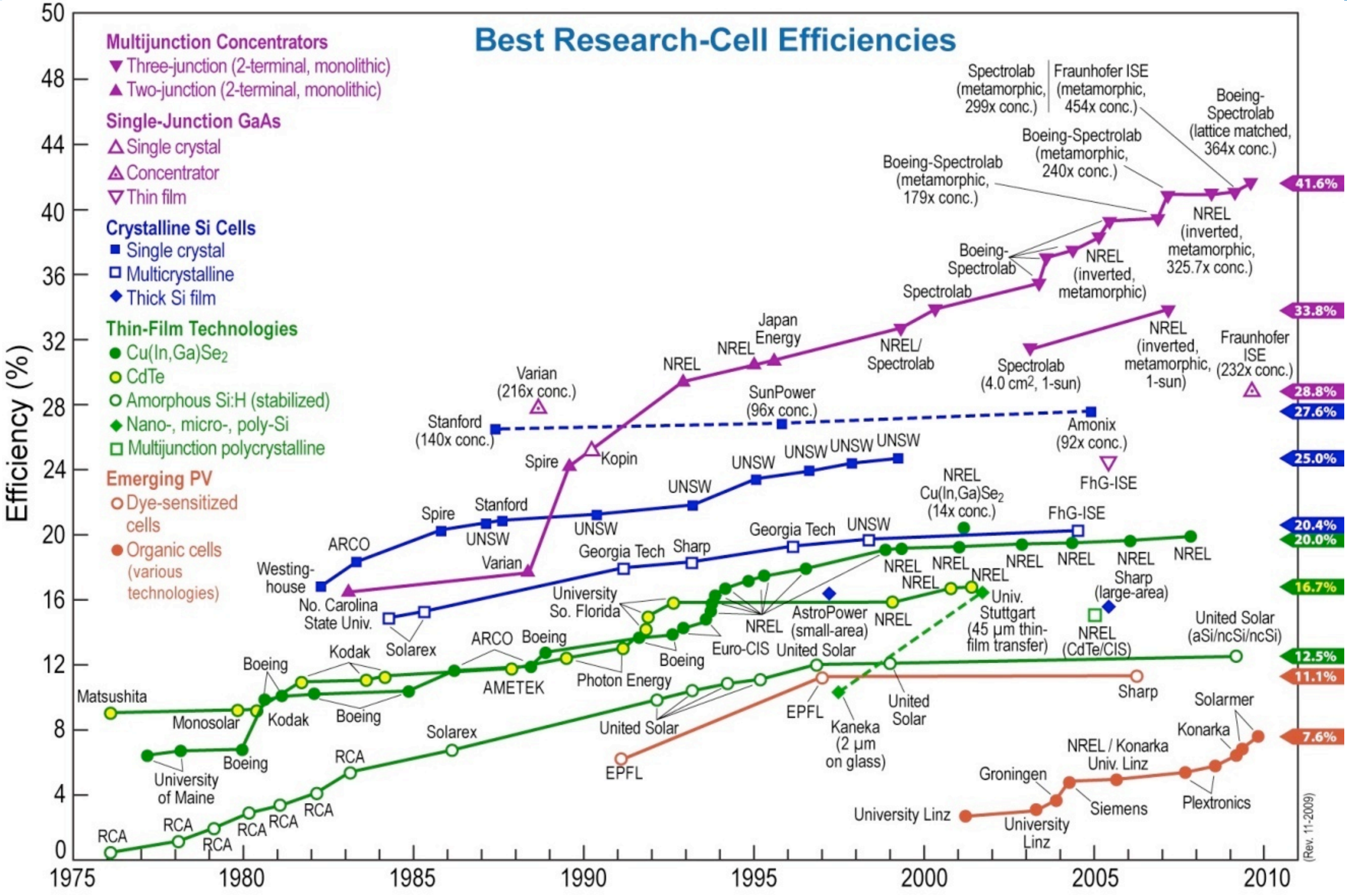
Global Exergy Flux, Reservoirs, and Destruction



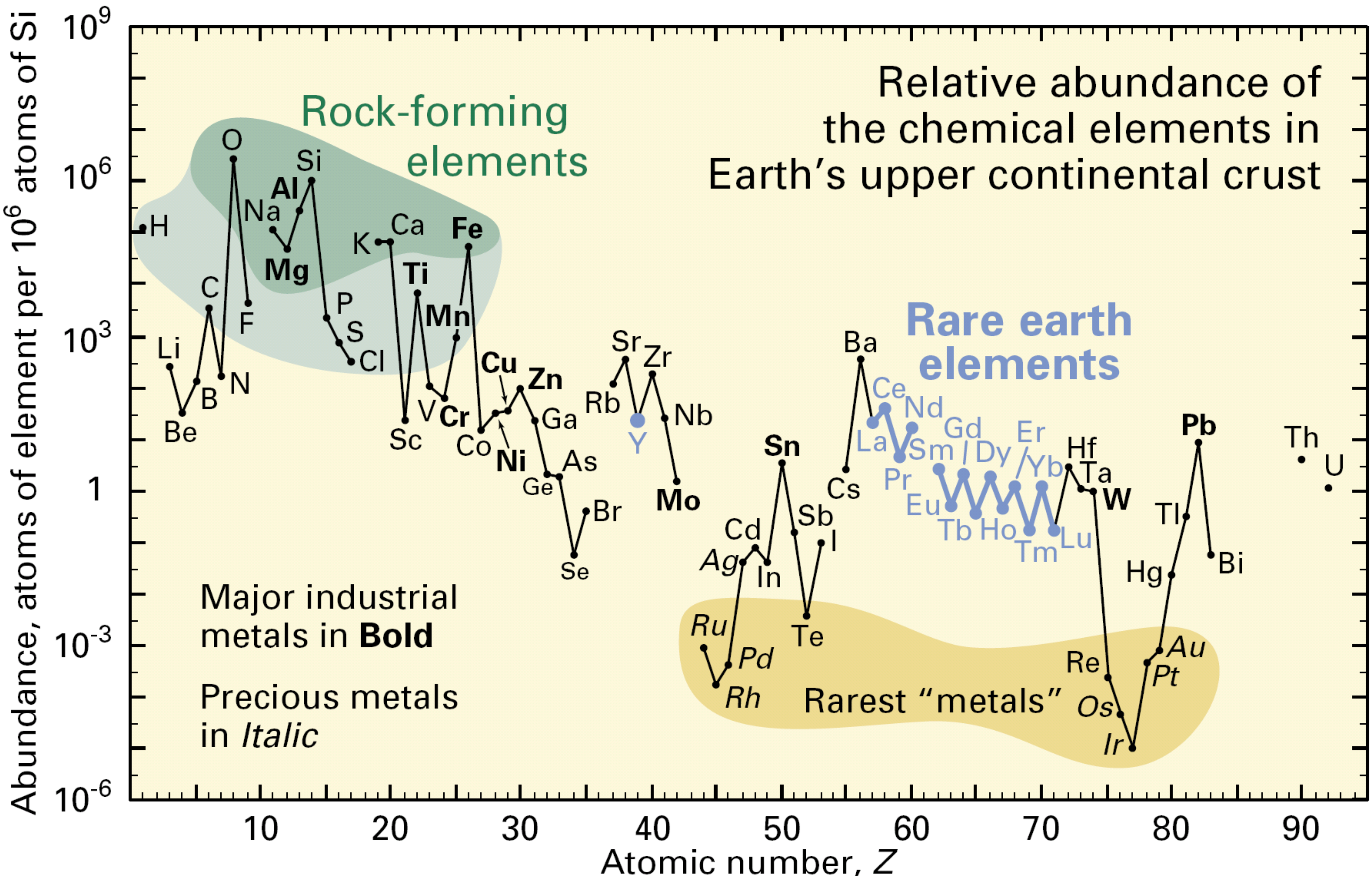
Exergy is the useful portion of energy that allows us to do work and perform energy services. We gather exergy from energy-carrying substances in the natural world we call energy resources. While energy is conserved, the exergetic portion can be destroyed when it undergoes an energy conversion. This diagram summarizes the exergy reservoirs and flows in our sphere of influence including their interconnections, conversions, and eventual natural or anthropogenic destruction. Because the choice of energy resource and the method of resource utilization have environmental consequences, knowing the full range of energy options available to our growing world population and economy may assist in efforts to decouple energy use from environmental damage.

Prepared by Wes Hermann and A.J. Simon
Global Climate and Energy Project at Stanford University (http://gcep.stanford.edu)

A story of many possibilities



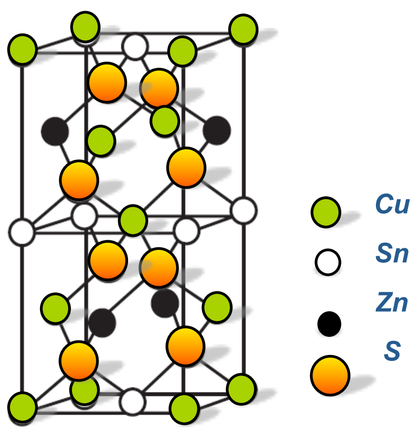
But for Terrawatts - abundance is key



Approaches to Abundant Green Systems

Green Systems

- $CuInGaSe_2$ – 19.5% efficient – thin film architecture
- Cu_2ZnSnS_4 (CZTS)
  - 6.7% efficiency (Katagiri et al.)
  - 1.45 eV Eg
- CZTS has kesterite structure



Raw Material Costs	Relative Abundance
Cu - $3.35/lb	Cu - 6.0×10^{-5}
Zn - $1.59/lb	Zn - 7.0×10^{-5}
Sn - $6.61/lb	Sn - 2.3×10^{-6}
S – $0.02/lb	S - 10^{-4}
Ga - $209/lb	Ga - 1.9×10^{-5}
In - $361/lb	In - 2.5×10^{-7}
Se - 2002 $4, 2007 $33/lb	Se - 5×10^{-8}

Source: www.usgs.gov (2007 data)

APS physics

Thin/Thick Film Si on Glass

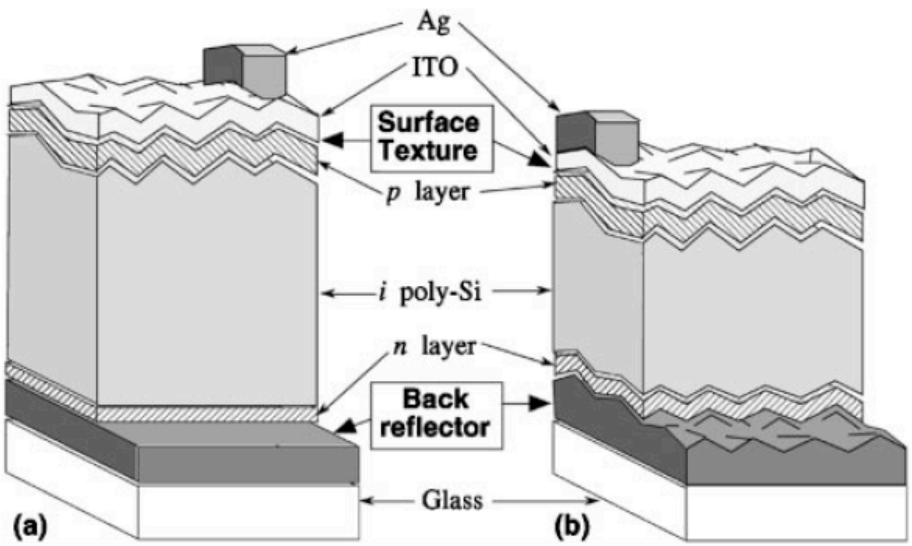


Fig. 1a,b. Schematic view of our thin-film poly-Si solar cell with STAR (natural surface texture and enhanced absorption with back reflector) structure. **a** First generation of poly-Si cell with flat back reflector. **b** Second generation of poly-Si cell with rough back reflector for thinner cell

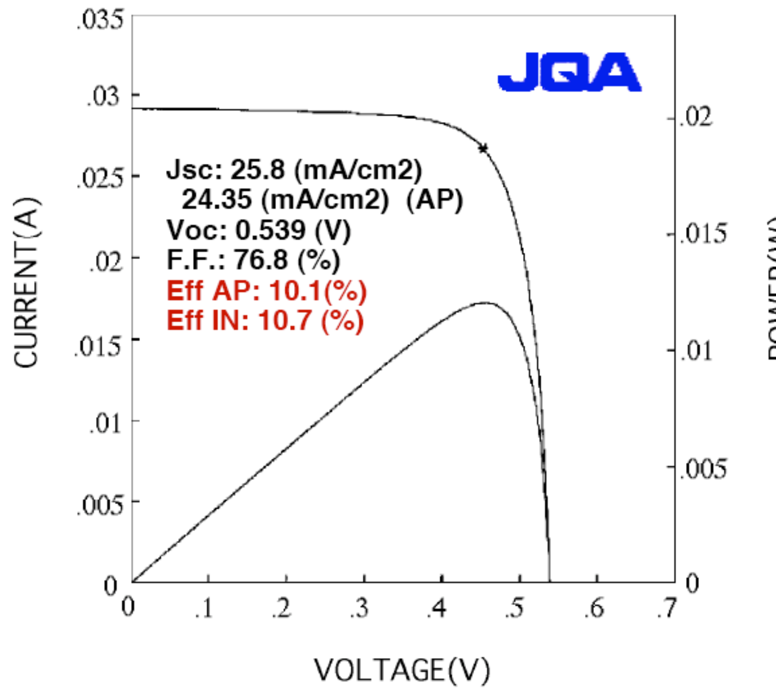


Fig. 3. The performance of the 2.0-µm-thick poly-Si solar cell with STAR structure as independently confirmed by Japan Quality Assurance (JQA). The numbers for η_{int} and η_{ap} represent the intrinsic and the aperture efficiency, respectively. The difference between the intrinsic and aperture efficiency originates from the Ag grid electrode on the ITO

Appl. Phys. A 69, 179–185 (1999) / Digital Object Identifier (DOI) 10.1007/s003399900066

OPV for Low Cost Power Production

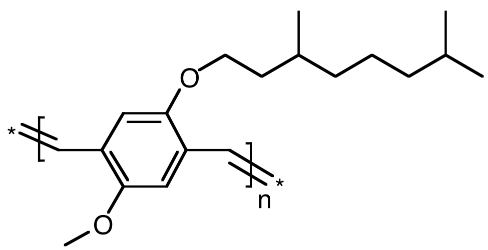
Efficiency, Lifetime and Scalability The Challenges

Excitonic Solar Cells

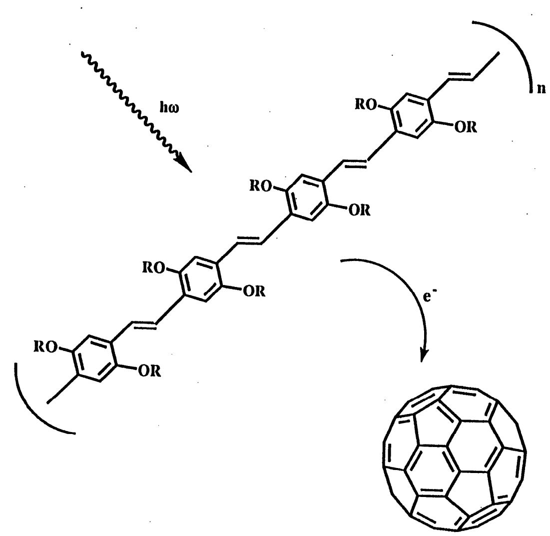
The Basis for Polymer Organic Solar Cells

Ultrafast photoinduced electron transfer between a conjugated polymer and a fullerene was discovered in 1992*.

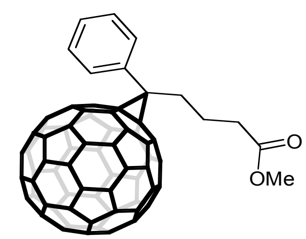
Donor



OC_1C_{10}-PPV
3,7 - dimethyloctyloxy methyloxy PPV



Acceptor



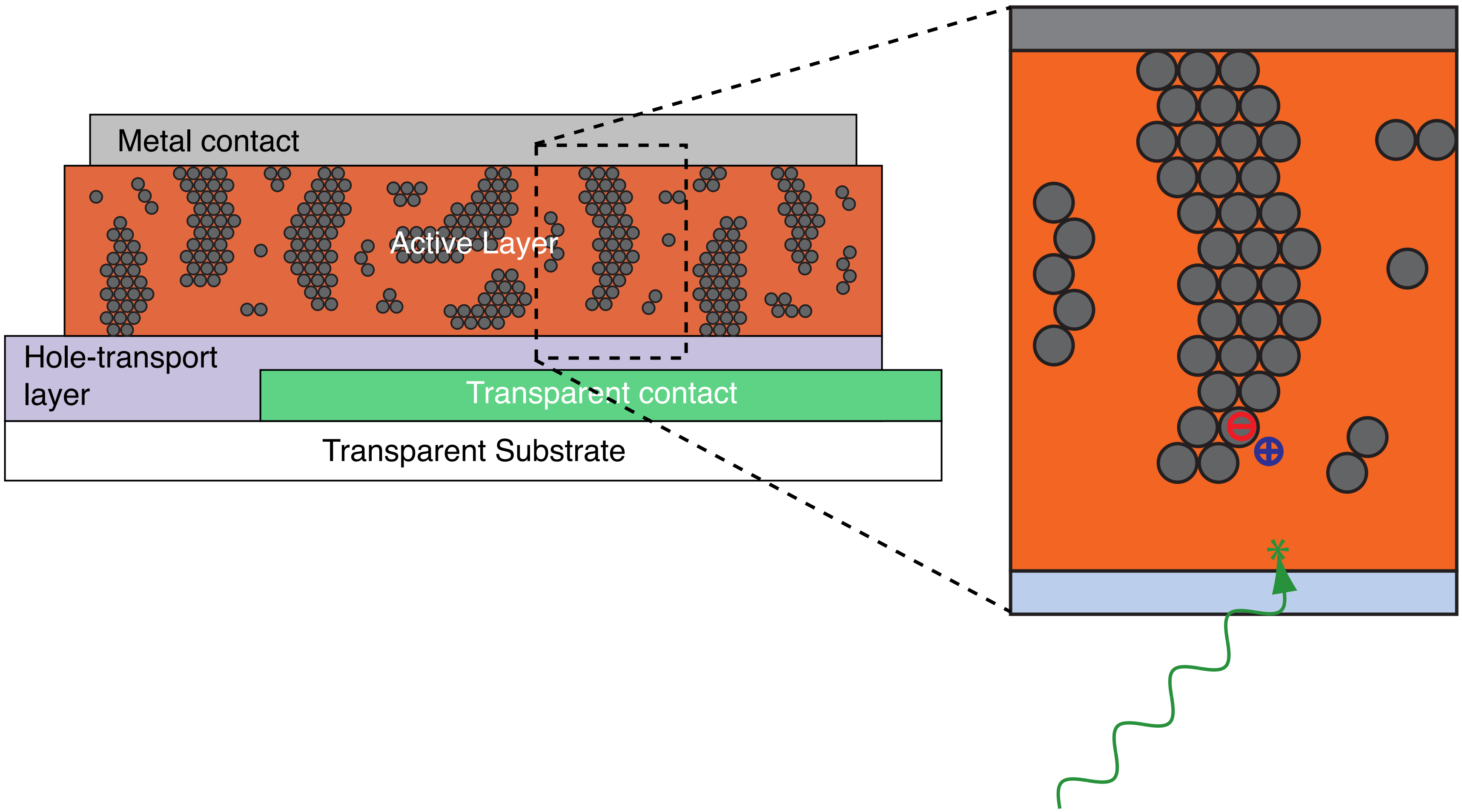
PCBM
1-(3-methoxycarbonyl) propyl-1-phenyl $[6,6]C_{61}$

Forward electron transfer rate: 45 fs†

Backward electron transfer rate: ~1 μs

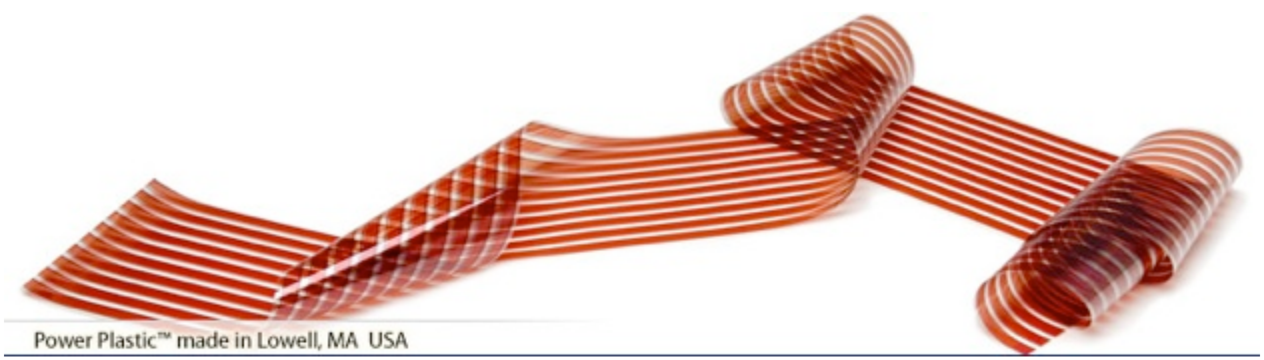
*N. S. Sariciftci, L. Smilowitz, A. J. Heeger, and F. Wudl, *Science* **258**, 1474 (1992).
†C. J. Brabec, G. Zerza *et al.*, *Chem. Phys. Lett.* **340**, 232 (2001).

How Do Organic Solar Cells Work?



What are the Drivers for Organic Solar Cells

- Terrawatt Power Production from Solar will require a number of key features:
  - Very high production capacity - **Konarka and DTU have proof of principle**
  - Reasonable Efficiency - rapid progress in devices and modules - update this talk
  - Lifetime sufficient to Commercialize - update this talk - is the paradigm different?
  - Low energy payback times -- low temperature processing - **Konarka, NREL, DTU, Plextronics - as low as 2 months possible**
  - Low capital investment - still to be proven
  - Abundant Materials - **yes** but cost still being resolved
  - Green Processing - yes a possibility
  - Low Balance of Systems Cost - **Konarka and Plextronics new ways to make cells**
  -

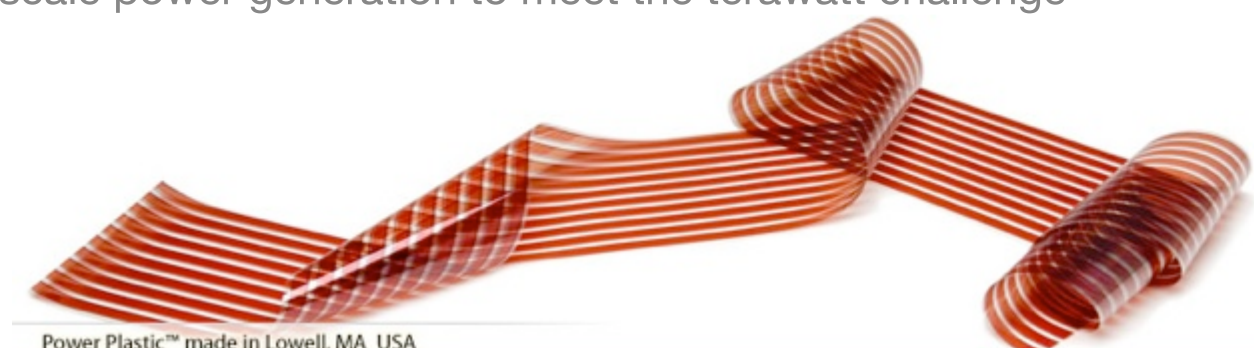


Power Plastic™ made in Lowell, MA USA

Konarka Technologies, http://www.konarka.com/

Progress in Organic Solar Cells

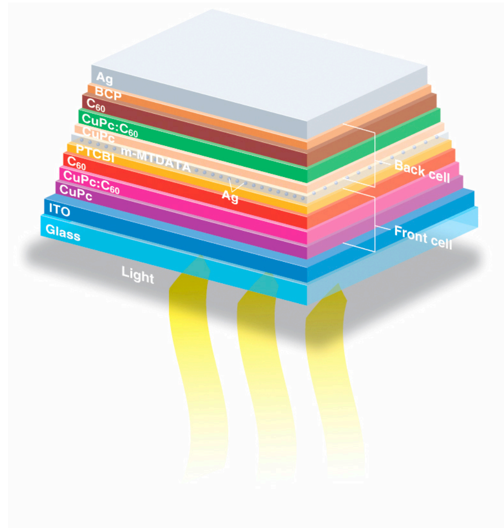
- Demonstration of low cost organic photovoltaic (OPV) devices
  - Printed or solution processed at high speed on flexible substrates
  - Using roll-to-roll processing for dramatic reduction in production costs
  - Low materials and balance of systems costs
- Near term goal: 5 - 10% efficiency, lifetime up to 10,000 hours
  - "Niche" applications in consumer electronics, autonomous sensors, RFID, etc.
- Long term goal: 15% efficiency, lifetime > 5 years
  - Grid connected - roof top power generation & solar farms
  - Building Integrated PV
  - Large scale power generation to meet the terawatt challenge

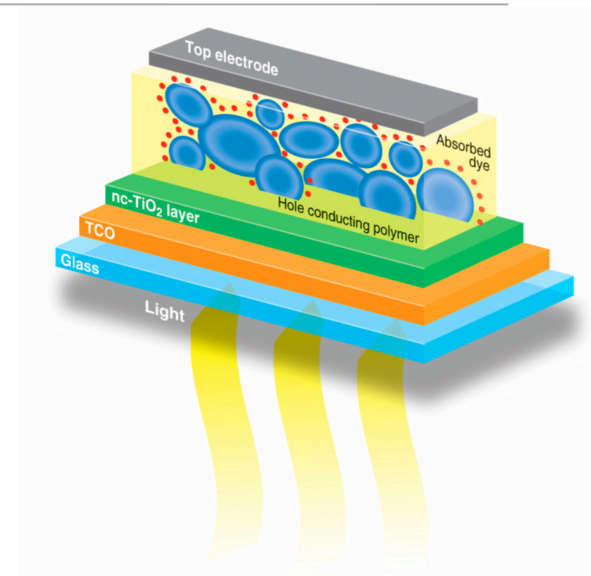


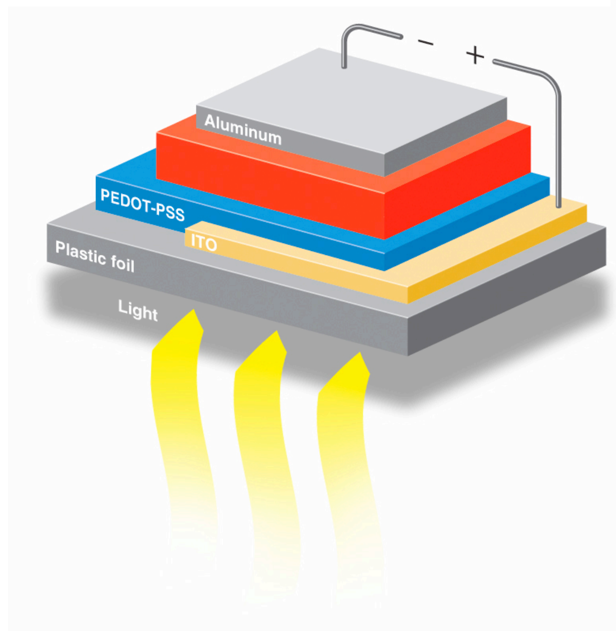
Konarka Technologies, http://www.konarka.com/

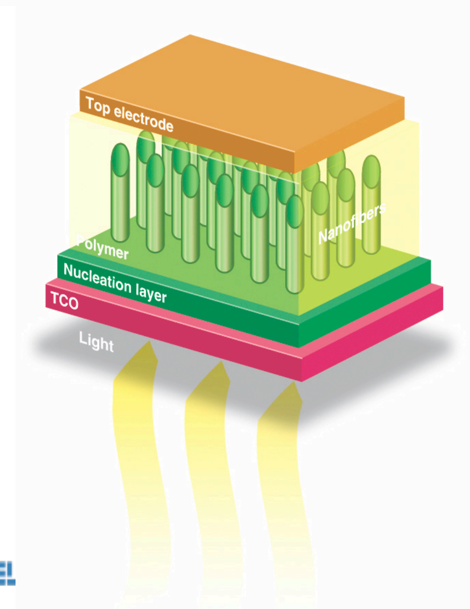
What are Excitonic Solar Cells?
A wide range of possibilities!!

- Dye Sensitized Solar Cell (DSSC)
- Planar - Small Molecule
- Polymer - Fullerene Bulk Heterojunction
- Hybrid Polymer - Inorganic Ordered Bulk Heterojunction

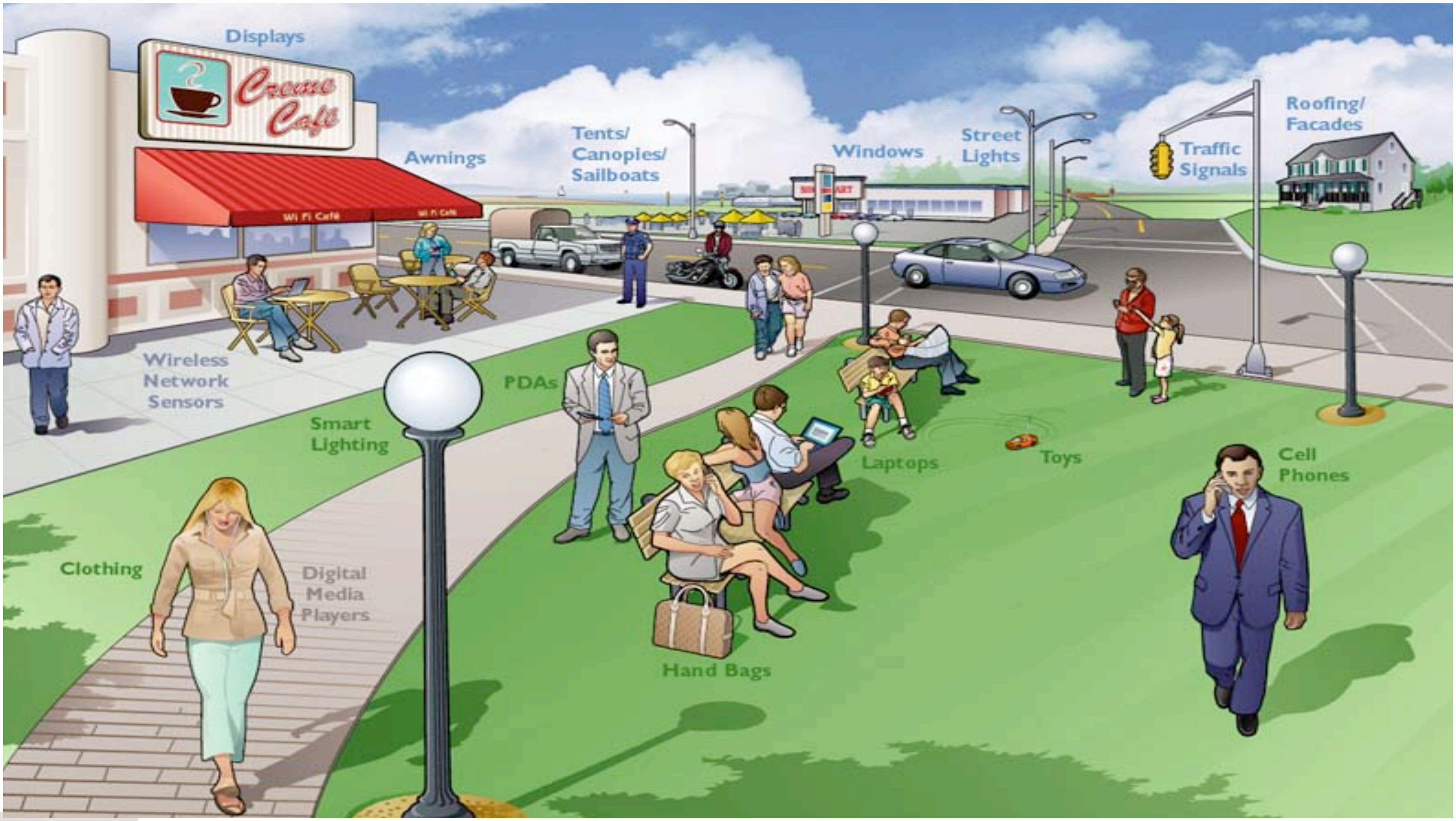




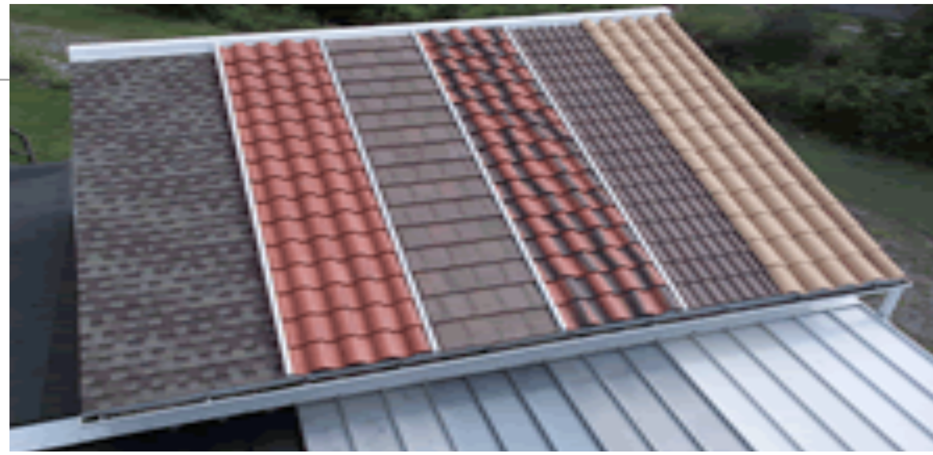




Power Plastic® Portable to BIPV to Rooftop Applications

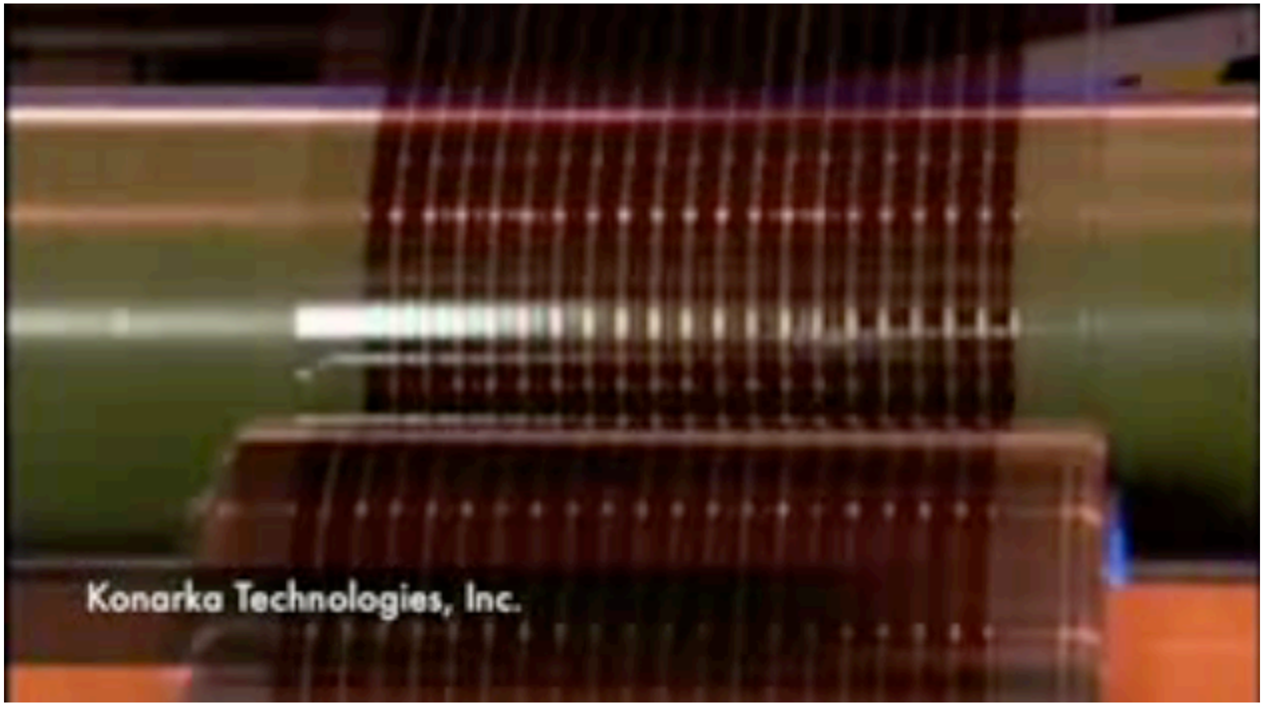


BIPV Systems and Structures



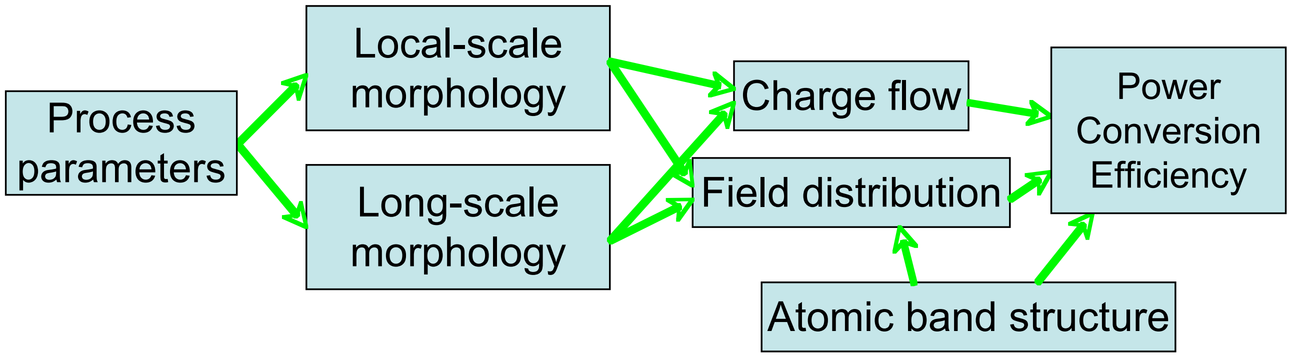
power plastic ™

Low Capital, Highly Scalable, Flexible or . . .

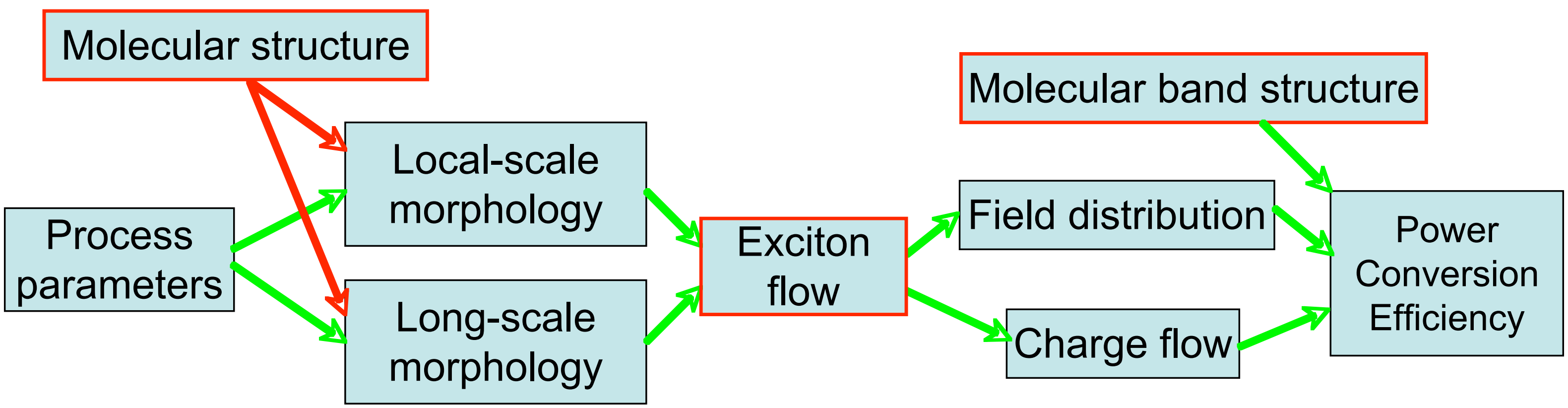


Conventional vs. Organic Semiconductors in PV

Conventional semiconductors (vacuum processing)

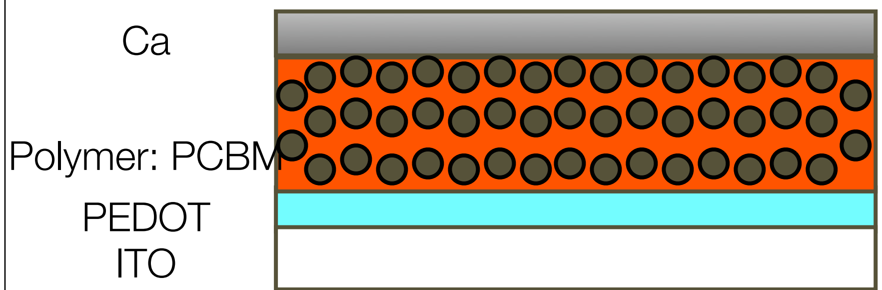


Molecular semiconductors (solution processing)

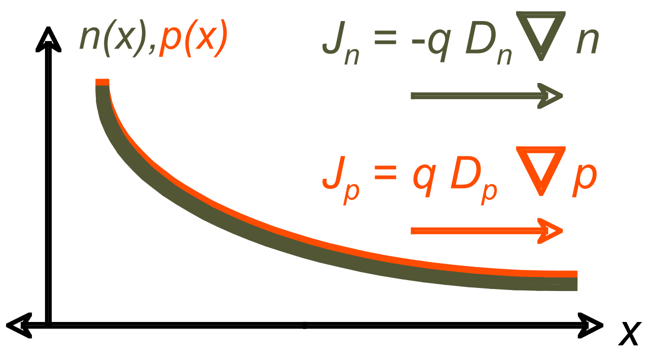


Organic an immense plus for tunability and a minus for rapid optimization

Bulk Heterojunction Devices



(6,6)-phenyl C_{61} butyric acid methyl ester (PCBM)



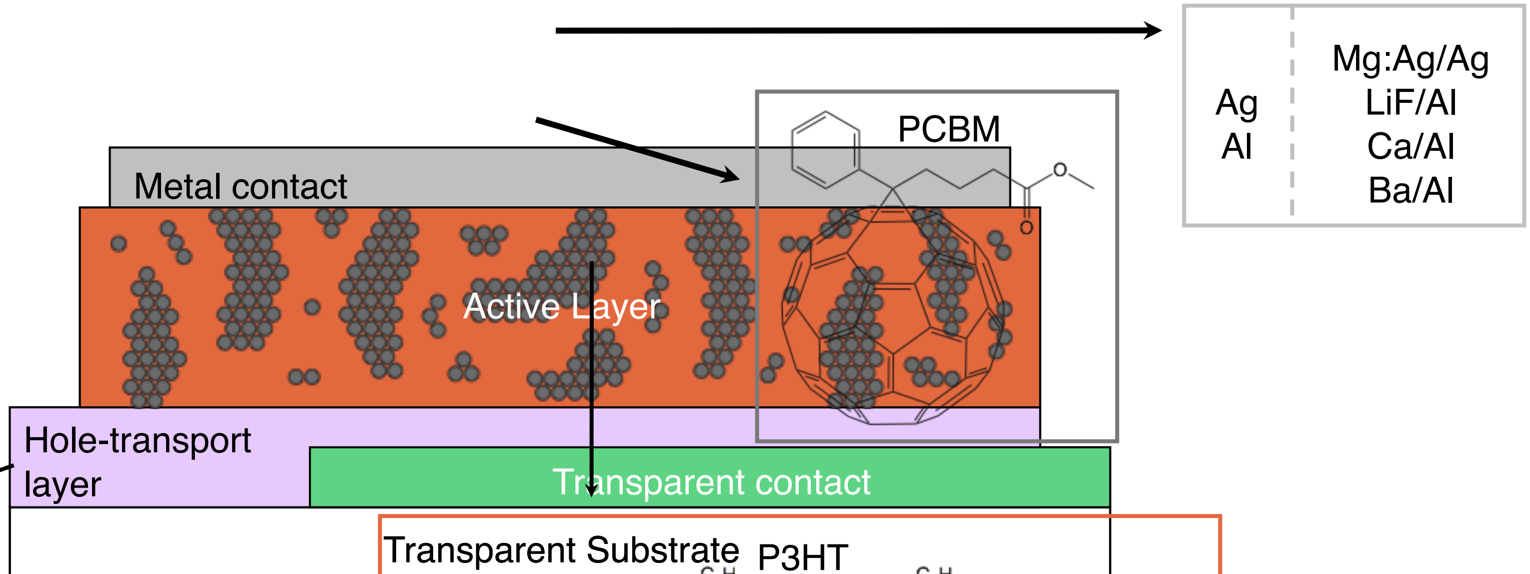
Chemical potential gradients for both charges are in the same direction

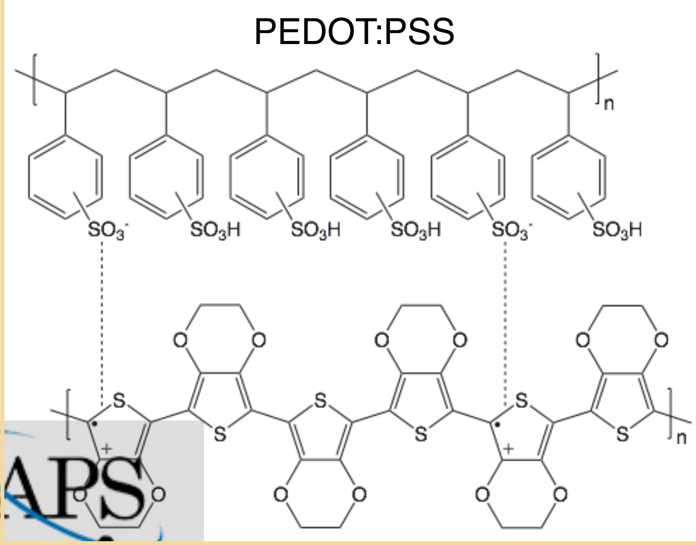
- **Strengths**
  - All excitons are effectively dissociated
  - Solution processing by spin coating from a common solvent
- **Weaknesses**
  - Chemical potential gradients do not yield diffusion current
  - Recombination can occur in the bulk
  - Little control over morphology

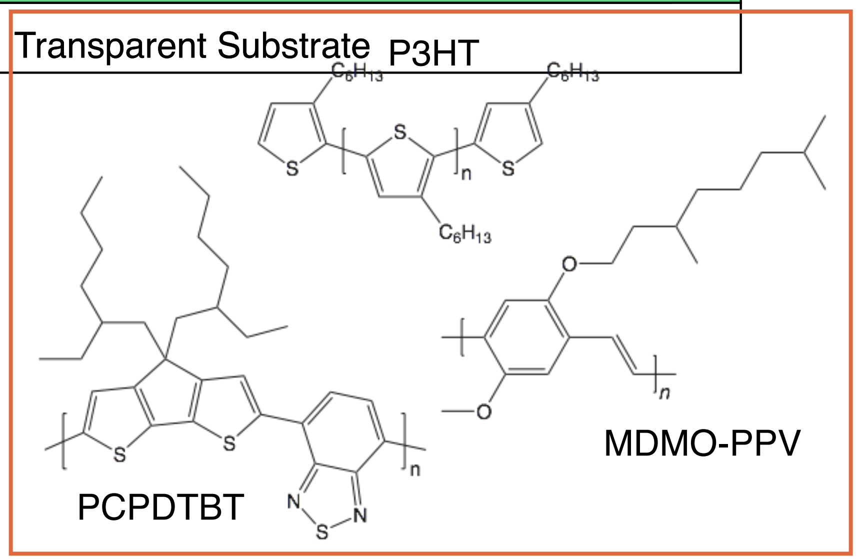
Model Bulk Heterojunction OPV Device

Interfaces are key-- understanding is just developing!

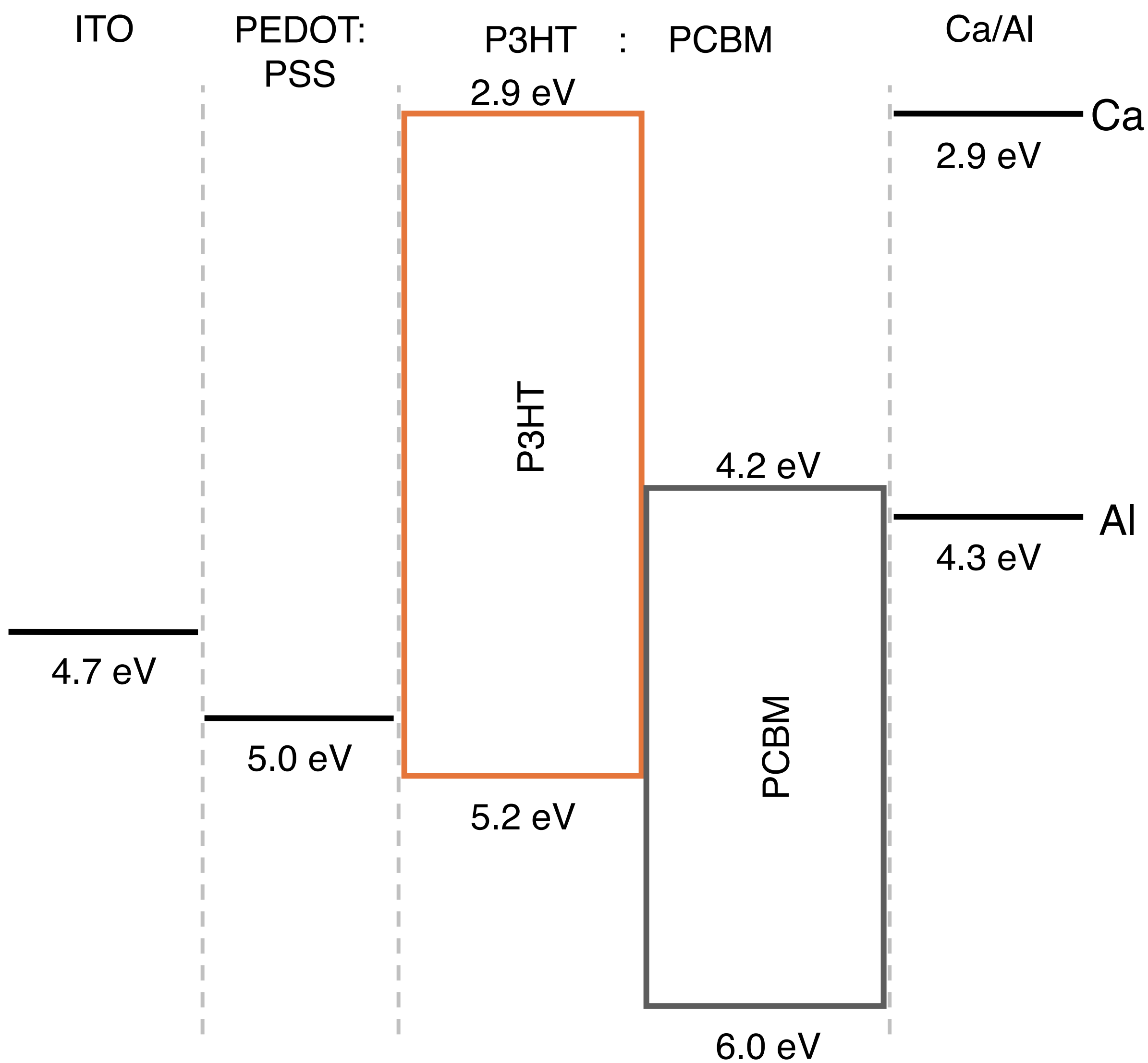
Note that Plexcore OC represents a non-acidic HTL alternative as do various oxides such as NiO





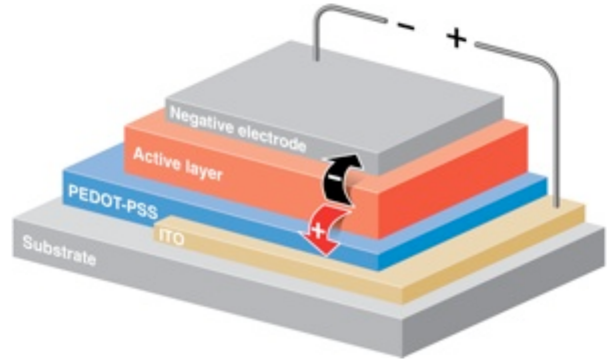


‘Band Diagram‘ for OPV Devices

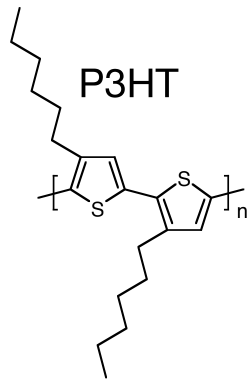


Bulk Heterojunction Solar Cells - NREL Devices

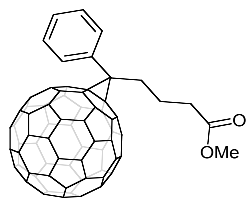
glass / ITO / PEDOT:PSS / P3HT:PCBM (1:1) / Ca
(active layer slow dried from ODCB)



P3HT

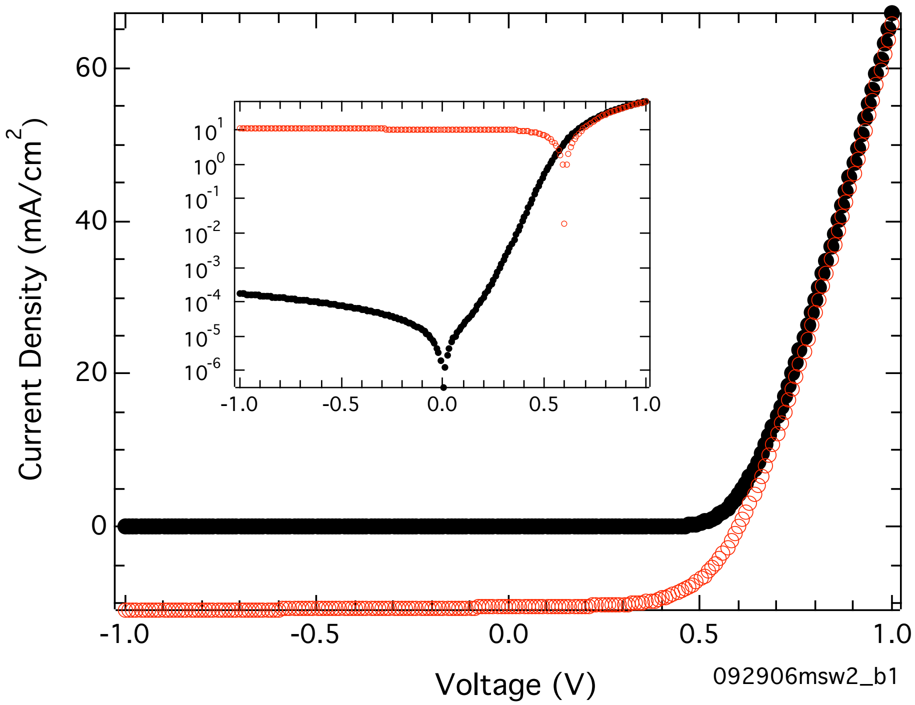


PCBM



V_{OC} = 0.605 V
J_{SC} = 9.3 mA/cm^2
FF = 65.5%
η = 3.7% (NREL certified)

$$\eta = \frac{V_{OC} J_{SC}}{P_{in}} FF$$



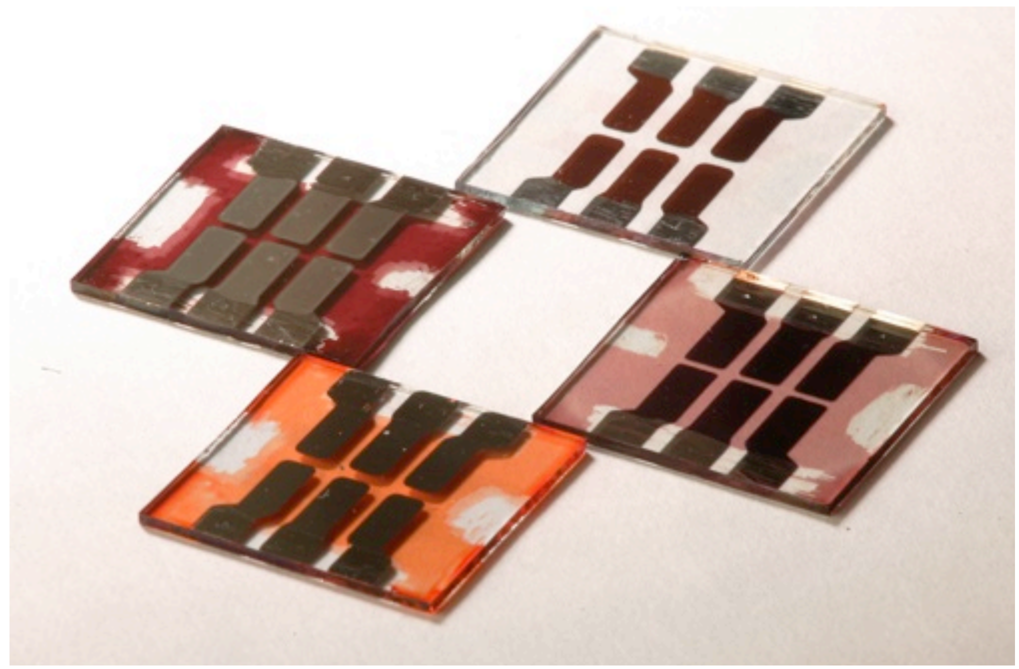
M.O. Reese, M.S. White, G. Rumbles, D.S. Ginley, and S.E. Shaheen, *Appl. Phys. Lett*. 92, 053307 (2008).

APS physics

NREL National Renewable Energy Laboratory

How efficient are they?

- Certified measurements of >7% in polymer / fullerene bulk heterojunction devices
- Efficiency greater than 4% with poly(3-hexylthiophene) (P3HT) donor material, Eg ~ 1.9 eV
- Chemistry and materials development are important tools for increasing performance
  - Synthesis of new active layer materials
  - Development of new contact and electrode materials



Practical Efficiency Targets for OPV devices

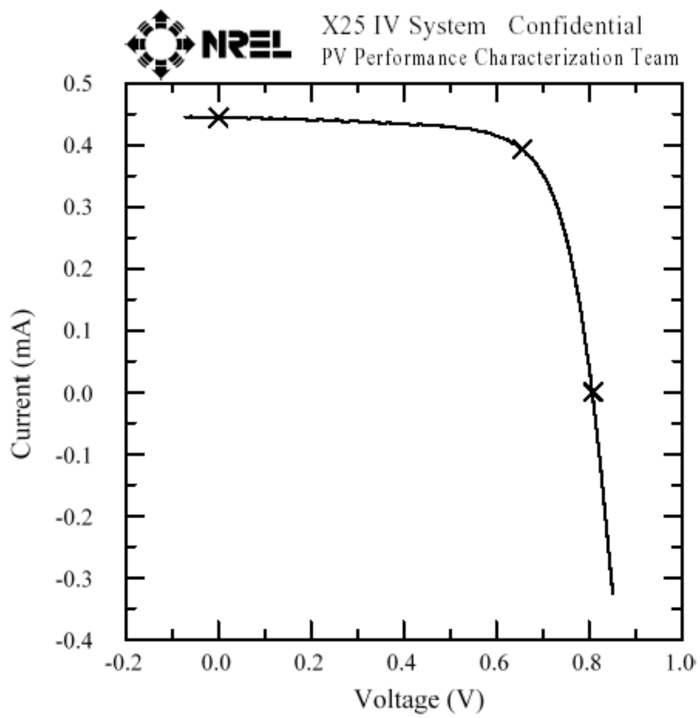
Paper	Practical Efficiency Target
i) "Conjugated Polymer Photovoltaic Cells", K.M Coakley and M.D. McGehee, *Chem. Mater.* **16** (2004).	10+%
ii) "Design Rules for Donors in Bulk-Heterojunction Solar Cells - Towards 10% Energy-Conversion Efficiency", M.C. Scharber, D. Mühlbacher, M. Koppe, P. Denk, C. Waldauf, A.J. Heeger, and C.J. Brabec, *Adv. Mater.* **18** (2006).	10%
iii) "Ultimate Efficiency of Polymer/Fullerene Bulk Heterojunction Solar Cells", L.J.A Koster, V. D. Mihailetchi, and P.W.M. Blom, *Appl. Phys. Lett.* **88** (2006).	11%

How efficient do they need to be to be practical???

NREL-Certified World-Class Performance through New Development

Device ID: 3393-2 pxl 1
Aug 14, 2008 23:17
Spectrum: AM1.5 Global

Device Temperature: 25.0 ± 1.0 °C
Device Area: 0.043 cm^2
Irradiance: 1000.0 W/m^2



Polymer-based OPV Solar Cell

Single Photoactive Layer OPV Cell

NREL Certified at 5.98%

Aperture = 0.043 cm^2
Cell Size ~ 0.1 cm^2

V_{oc} = 0.8079 V
I_{sc} = 0.44438 mA
J_{sc} = 10.321 mA/cm^2
Fill Factor = 71.67 %

I_{max} = 0.39258 mA
V_{max} = 0.6553 V
P_{max} = 0.25724 mW
Efficiency = 5.98 %

X25 IV System
PV Performance Characterization Team

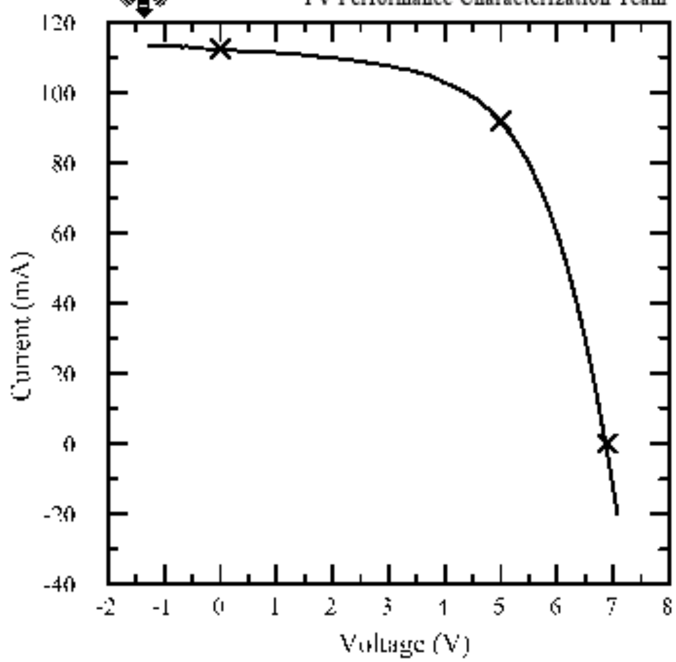
NREL-Certified OPV Module Efficiency using Plexcore® PV 2100 Active Layer

PLEXTRONICS Light. Power. Circuitry.™

Device ID: 4103
Jan 28, 2009 12:11
Spectrum: ASTM G173 global

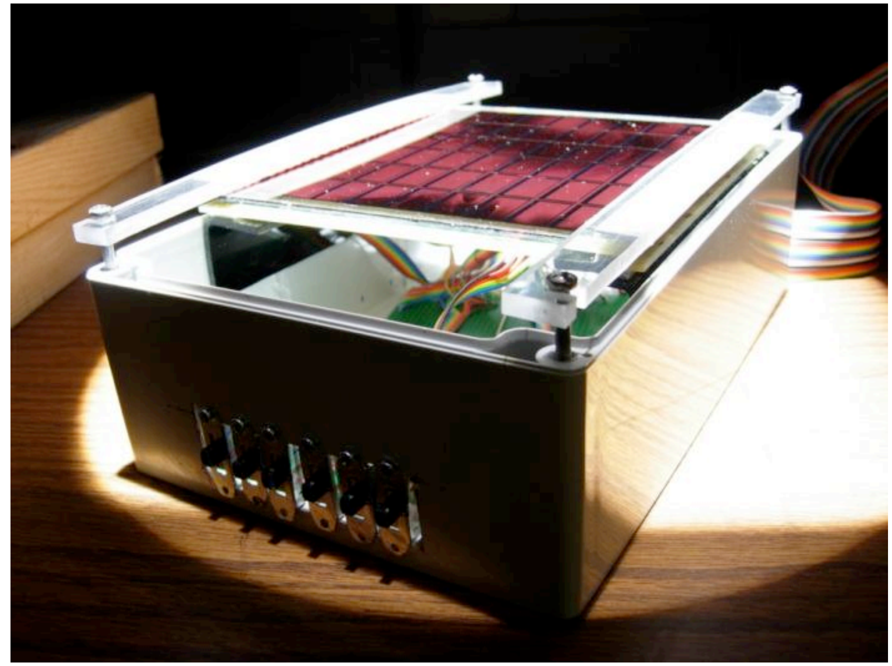
Device Temperature: 24.6 ± 0.5 °C
Device Area: 223.5 cm^2
Irradiance: 1000.0 W/m^2

NREL X25 IV System Confidential
PV Performance Characterization Team



V_{oc} = 6.9025 V
I_{sc} = 0.1123 A
J_{sc} = 0.502 mA/cm^2
Fill Factor = 59.09 %

I_{max} = 91.700 mA
V_{max} = 4.9952 V
P_{max} = 0.4580 W
Efficiency = 2.05 %



Largest OPV Module certified at NREL

- 152mm x 152mm Module
- Total Area Certified at 2.05%
- Active Area coverage = 48%
- Active Area efficiency = 4.24%

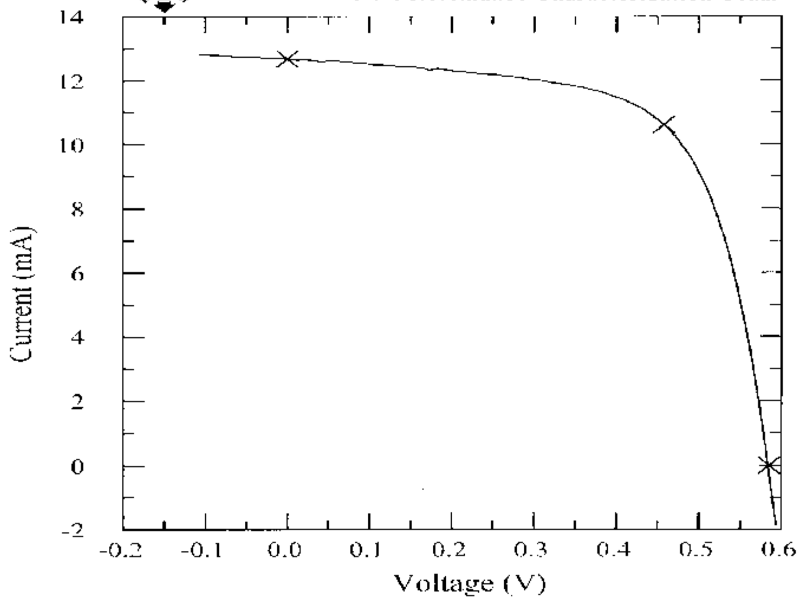
APS physics

Konarka Technologies
organic Cell

Device ID: EC02
Dec 11, 2008 22:18
Spectrum: AM1.5 Global

Device Temperature: 25.0 ± 1.0 °C
Device Area: 0.759 cm^2
Irradiance: 1000.0 W/m^2

NREL X25 IV System Confidential
PV Performance Characterization Team



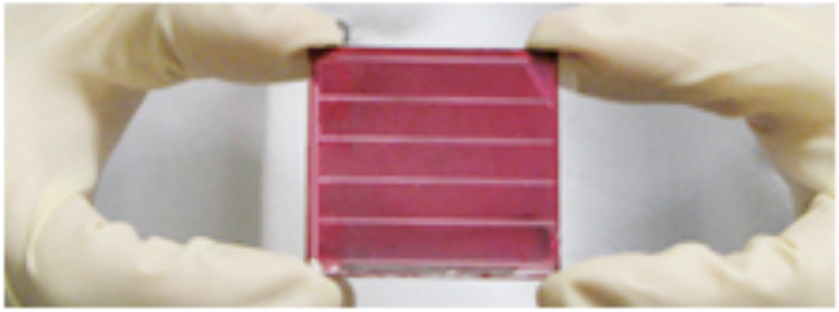
V_{oc} = 0.5851 V
I_{sc} = 12.670 mA
J_{sc} = 16.693 mA/cm^2
Fill Factor = 65.47 %

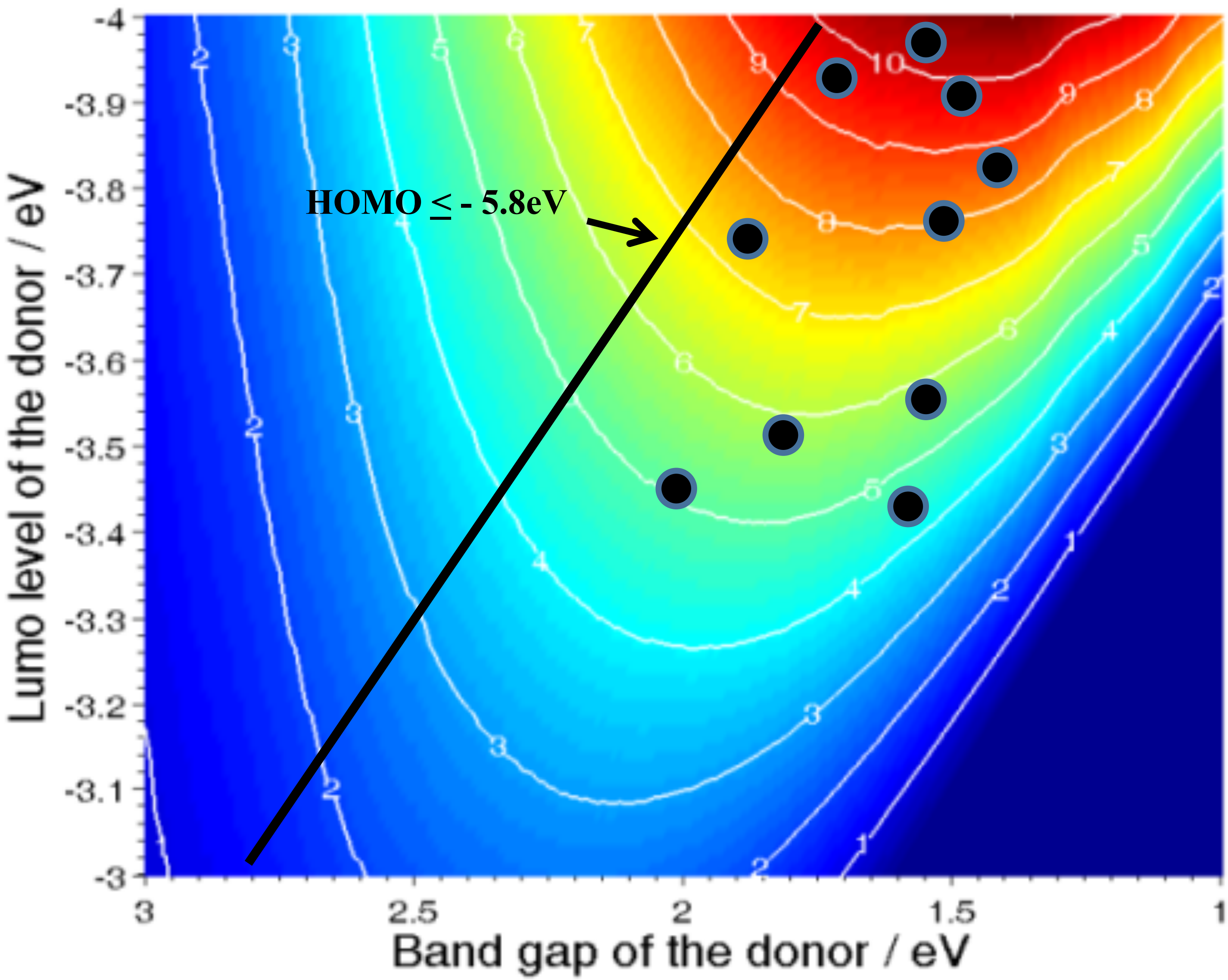
I_{max} = 10.610 mA
V_{max} = 0.4573 V
P_{max} = 4.8530 mW
Efficiency = 6.39 %

Konarka

Performance sufficient for initial applications has already emerging

Solarmer breaks organic solar PV cell conversion efficiency record, hits NREL-certified 7.9%





Single Junction Devices

Contour Plot showing the calculated conversion efficiency and the relationship of the donor LUMO level and bandgap

Assumption: EQE = 0.65; FF = 0.65

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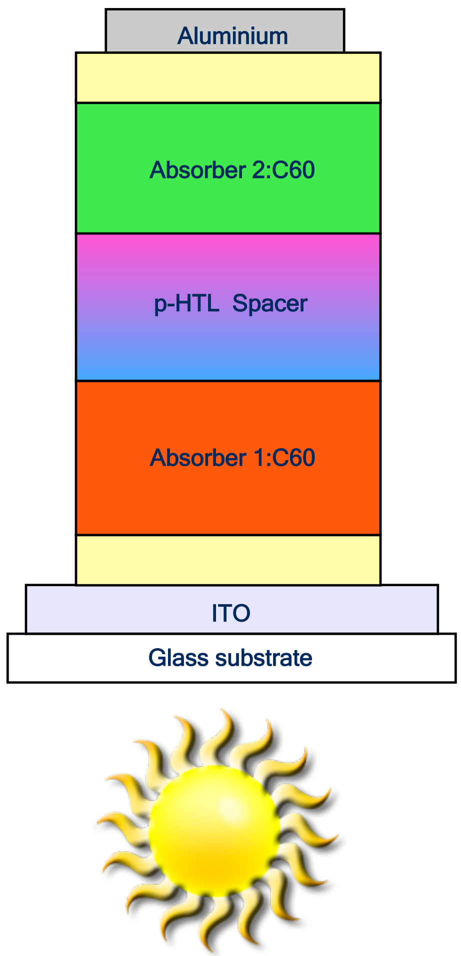
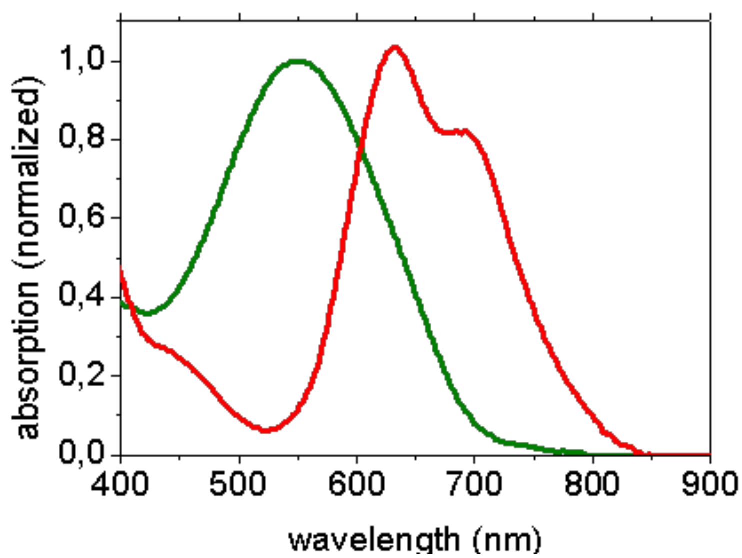
Technology: p-i-n tandem solar cells



tandem solar cell technology:

➔ **optimum harvesting of complete sun spectrum**



APS physics

NREL National Renewable Energy Laboratory

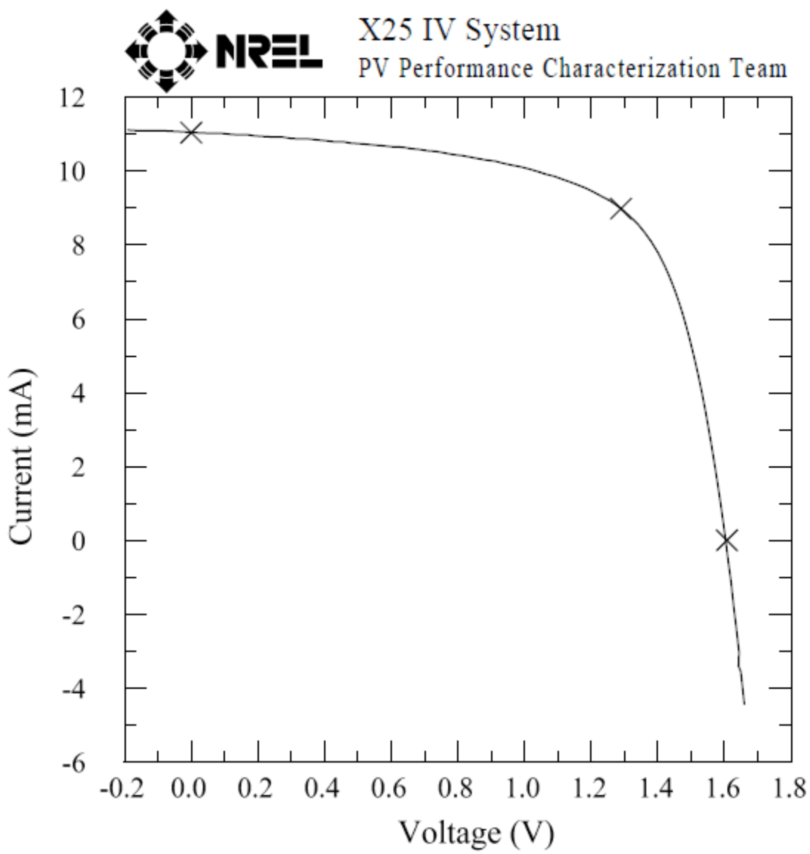
Record Tandem Device heliatek/IAPP/BASF

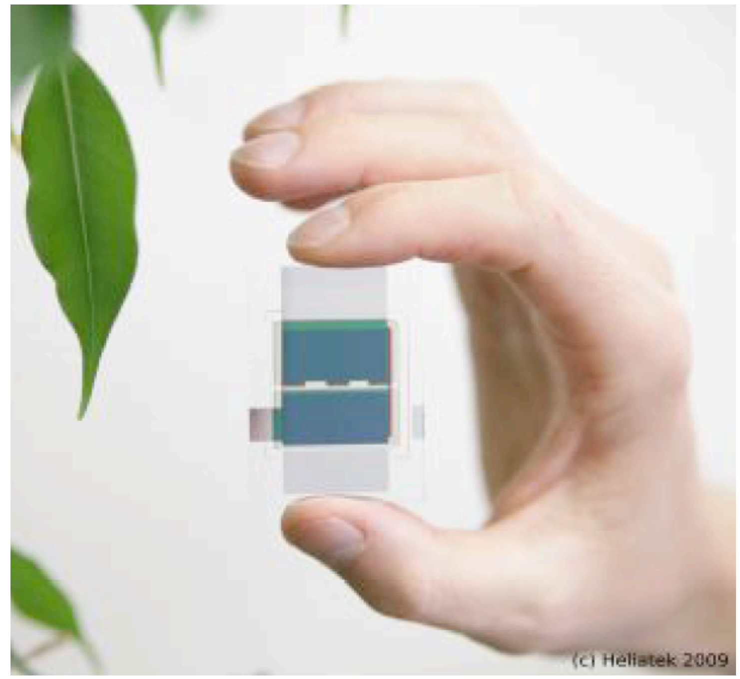
heliatek
Organic based Photovoltaics

iapp

Device ID: PV17 11 e1
Apr 24, 2009 19:04
Spectrum: ASTM G173 global

Device Temperature: 24.9 ± 0.5 °C
Device Area: 1.974 cm^2
Irradiance: 1000.0 W/m^2





V_{oc} = 1.6076 V
I_{sc} = 11.045 mA
J_{sc} = 5.5952 mA/cm^2
Fill Factor = 65.24 %

I_{max} = 8.9829 mA
V_{max} = 1.2896 V
P_{max} = 11.585 mW

Efficiency = 5.87 %
Device Area: 1.974 cm^2

How good can a practical double junction cell be?

Assumptions

• Two cells are stacked in series. The total current is given by that of the subcell with the lower current.

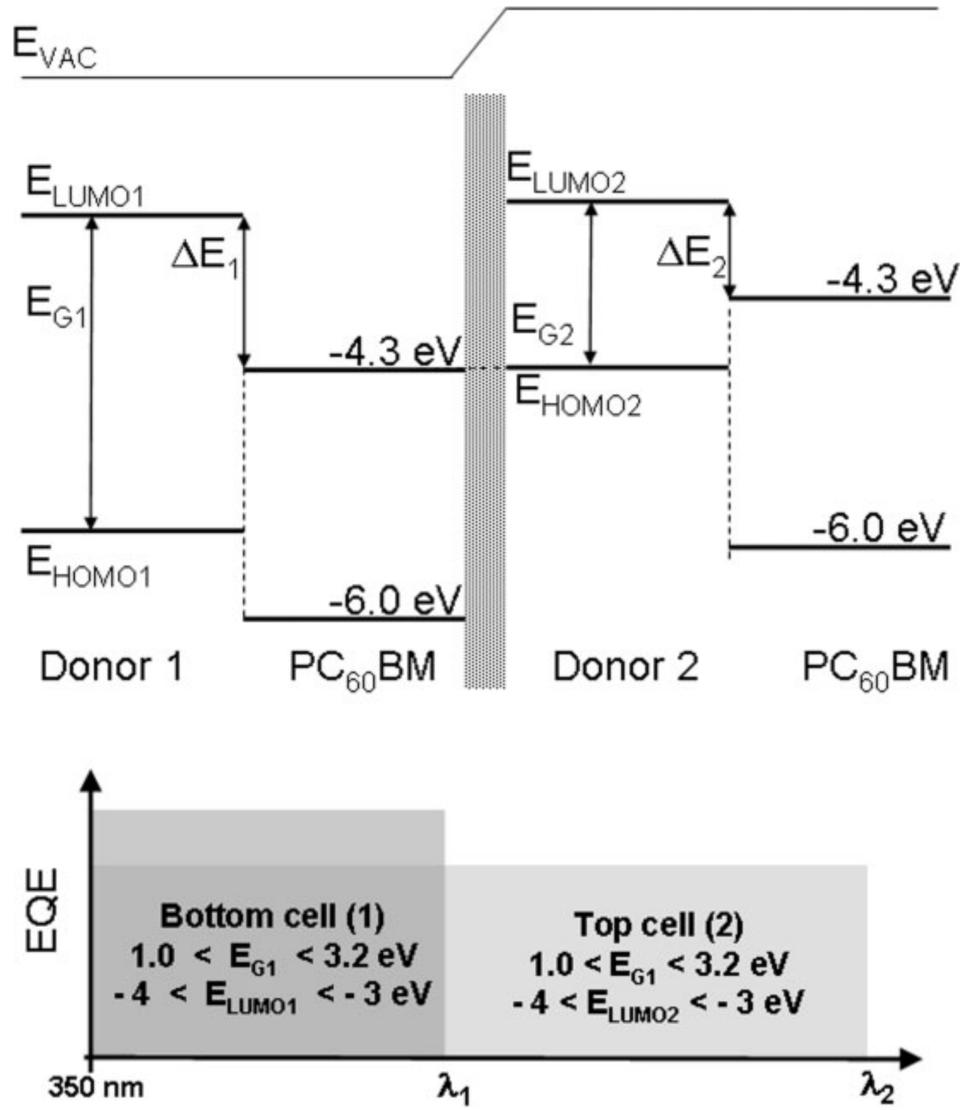
• Fill Factor = 0.65.

• EQE is approximately 85 % (see the paper for details)

•The acceptor is PCBM

• The Donor LUMO is at -4.0 eV

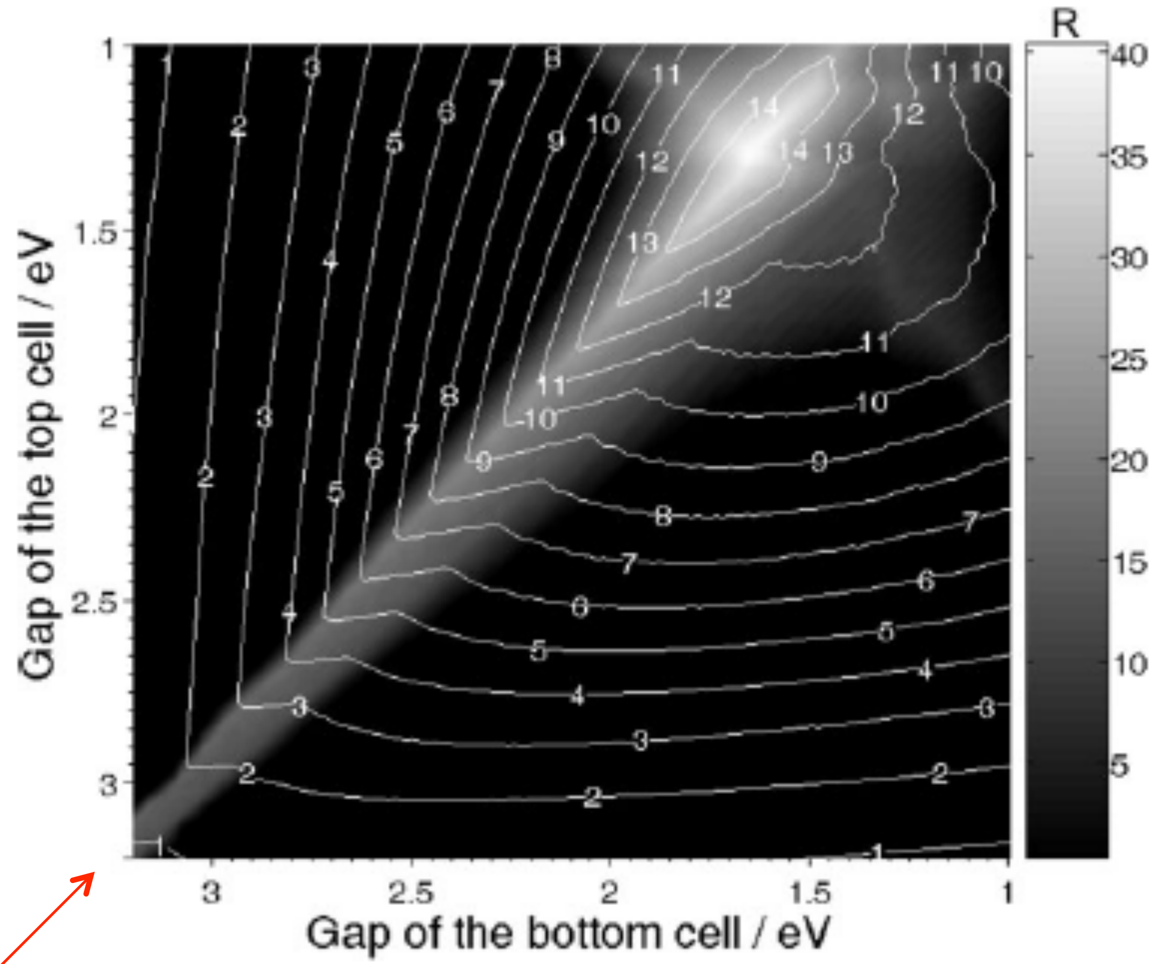
$$Voc = \frac{1}{e}\left(\left|E^{Donor}_{HOMO}\right| - \left|E^{PCBM}_{LUMO}\right|\right) - 0.3$$



Dennler, Brabec et al. *Advanced Materials* 20 (2008) 579.

Efficiency of double junction cells from previous slide

The two band gaps should be 1.3 and 1.7 eV.

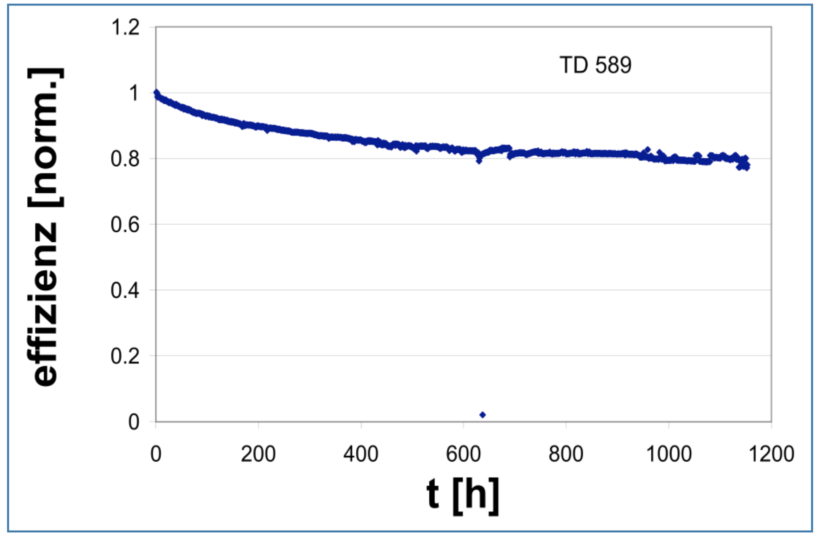


The current is matched along this diagonal.

Dennler, Brabec et al. *Advanced Materials* 20 (2008) 579.

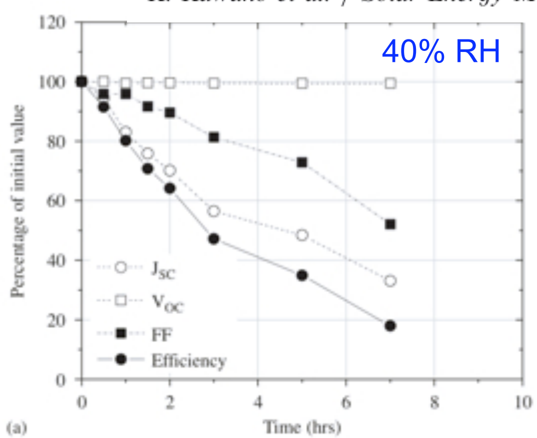
The Next Big Question - Degradation in Organic Solar Cells

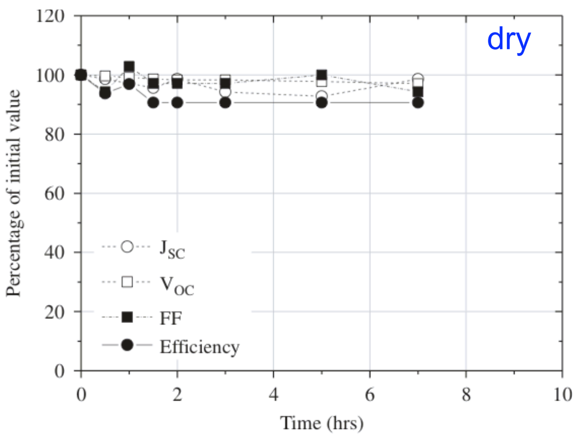
- Many pathways possible for OPV device degradation:
  - Delamination
  - Inter-diffusion of electrodes
  - Morphology changes of donor-acceptor
  - Interfacial degradation
  - Photo-oxidation of organic
  - Oxidation of electrode



Accelerated testing at 85 ºC, Konarka Technologies
Christoph Brabec, MRS Bulletin January 2005.

K. Kawano et al. / Solar Energy Materials & Solar Cells 90 (2006) 3520–3530





PEDOT:PSS is very hygroscopic

Plexcore OC, is not hydroscopic and maintains weight, resistive, and chemical stability in air and under light

NiO, WO_3 offer alternatives as well

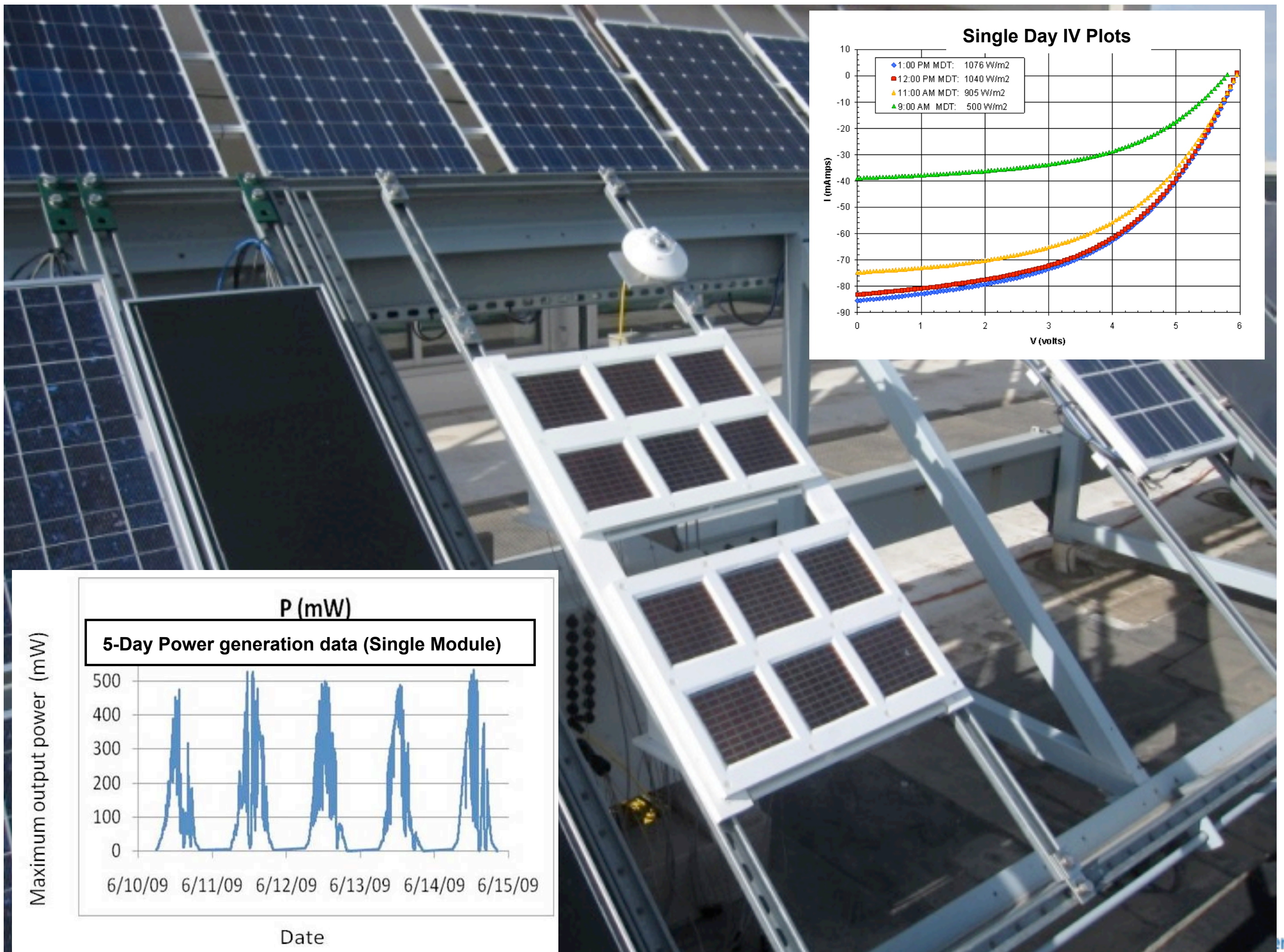
physics

NREL National Renewable Energy Laboratory

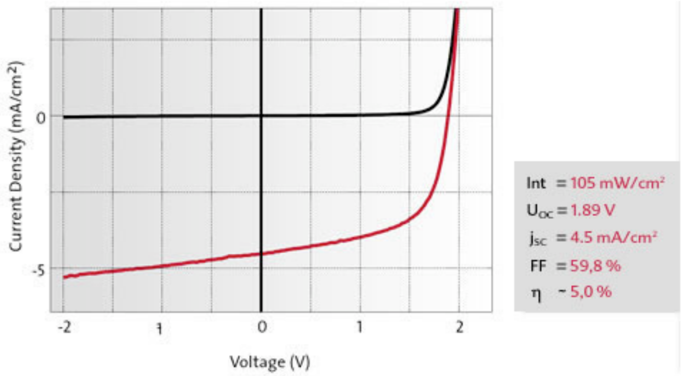
Lifetime -- OPV outdoors

PLEXTRONICS Light. Power. Circuitry.™

First OPV Modules at NREL Outdoor Testing Site



APS physics



Source: Heliatek, based on Novaled PIN OLED[TM] technology

novaled

Organic Photovoltaics (OPV)

The application of Novaled materials to solar cells allowes for highest efficiencies, just the way it does for OLEDs. It allowes easy integration of tandem architecture (stacking of two solar cells on top of each other) with excellent performance:

- 5% efficiency (1cm² active area, Heliatek tandem architecture based on Novaled p- and n-dopants combining absorber materials from Heliatek and BASF)
- High open circuit voltage (1.9V)
- High fill factor (60%, improved fill factor with NDP9)
- Lifetime for pin-type Heliatek solar cells with Novaled dopants: up to 16.000h (exposed to 100mW/cm² white light), very good thermal stability.

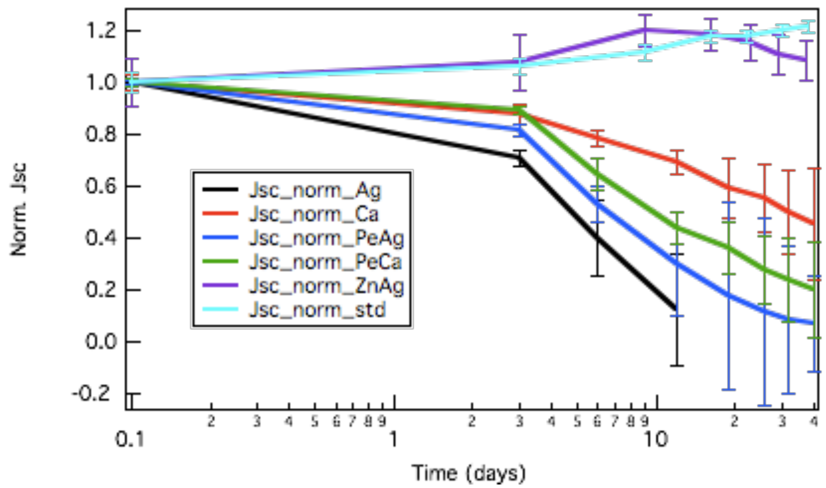
Use of doped transport layers allowes for optical engineering and thus for optimized efficiency. Novaled technology is proven for highest OLED stability and this also holds for organic solar cells.

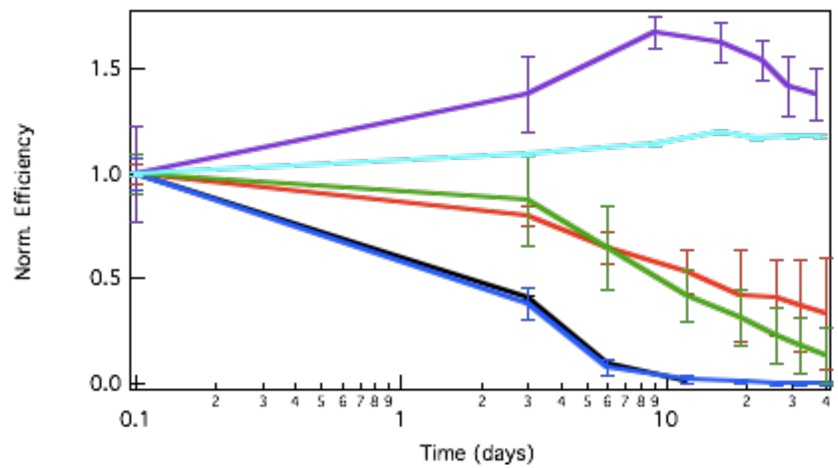
APS physics

Device and Packaging Reliability and Lifetime

Effect of Device Architecture on Shelf Life

- Shelf life study on devices that haven't been encapsulated
- Traditional vs. inverted device architectures





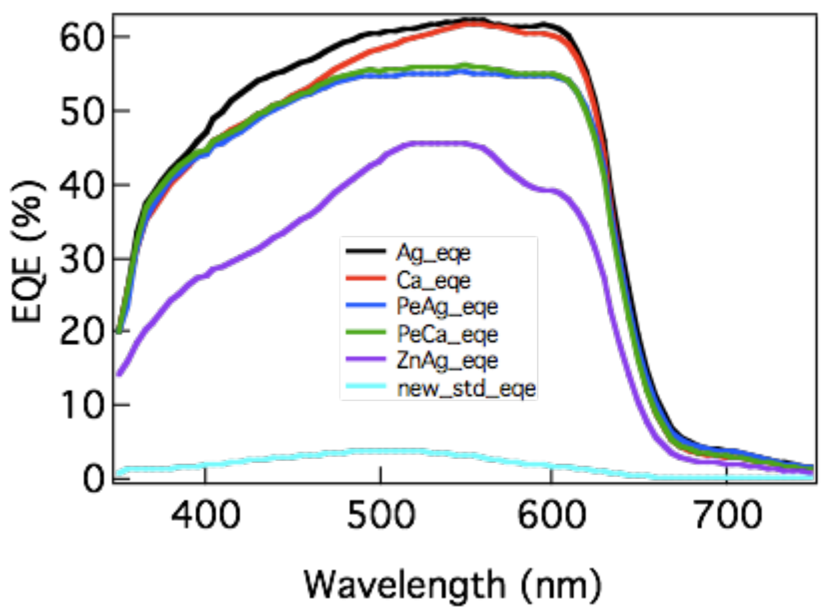
- Ca/Al electrode fails quickly, whereas inverted device is less susceptible to oxidation of the electrode materials
- Active layer is relatively stable in air when not illuminated

Device and Packaging Reliability and Lifetime

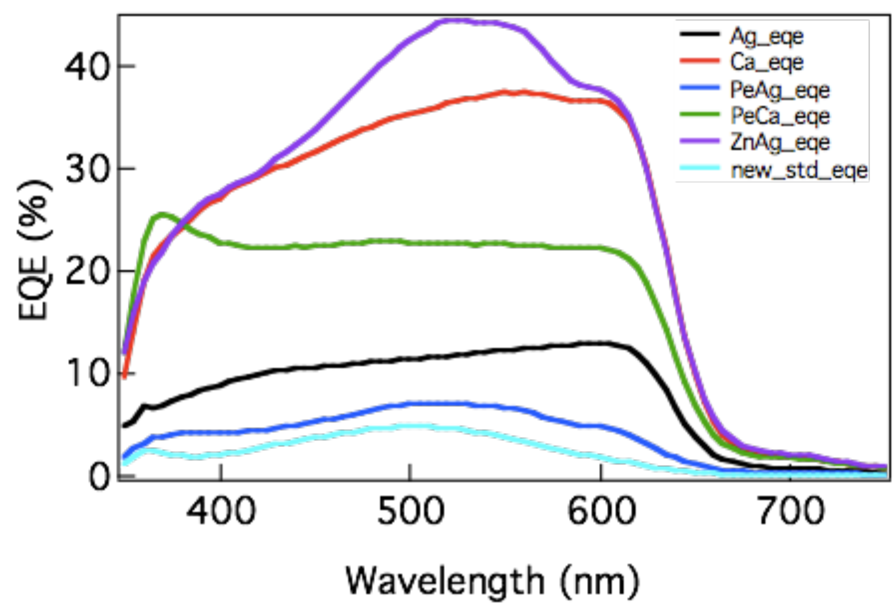
Effect of Device Architecture on Shelf Life

Initial & final EQE measurements (Sandia) for shelf life study

Initial measurement



Final measurement

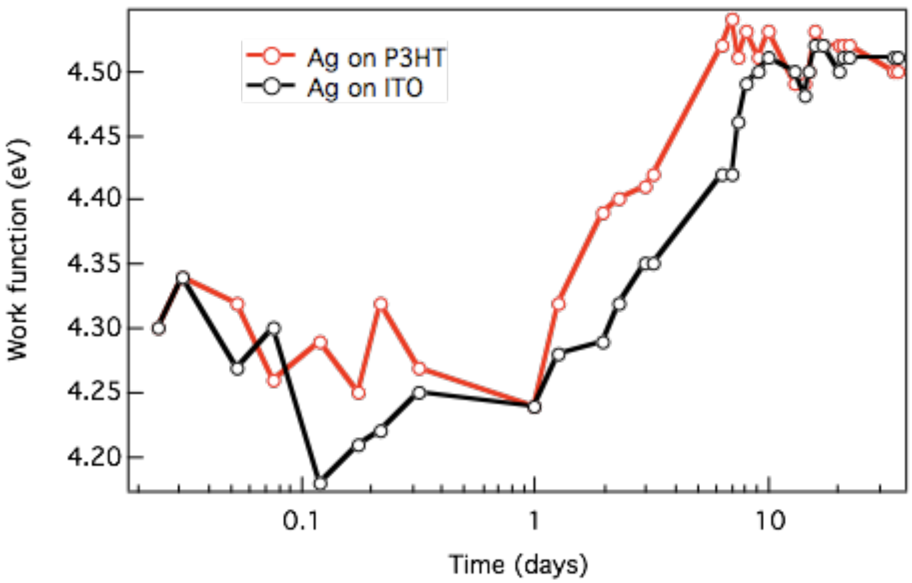


- No changes observed in current extraction efficiency from inverted (ZnAg) device after 40 days of exposure to air - large changes observed in Ca/Al (PeCa) device.
- No changes in active layer when exposed to air - electrode choice is paramount!

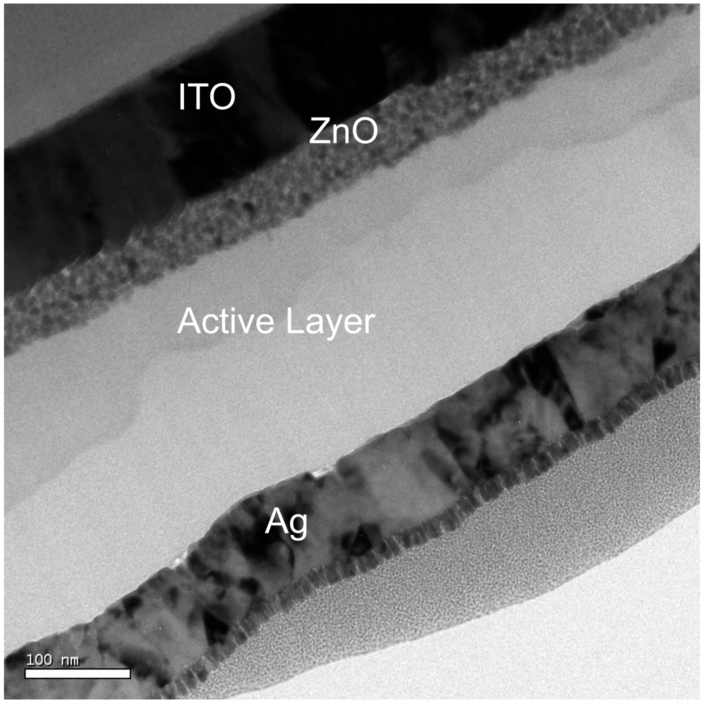
Device and Packaging Reliability and Lifetime

Effect of Air Exposure on Inverted Silver Electrode

Kelvin probe measurement for Ag electrode over time exposed to air



Inconel reference, assuming a work function of 4.3 eV

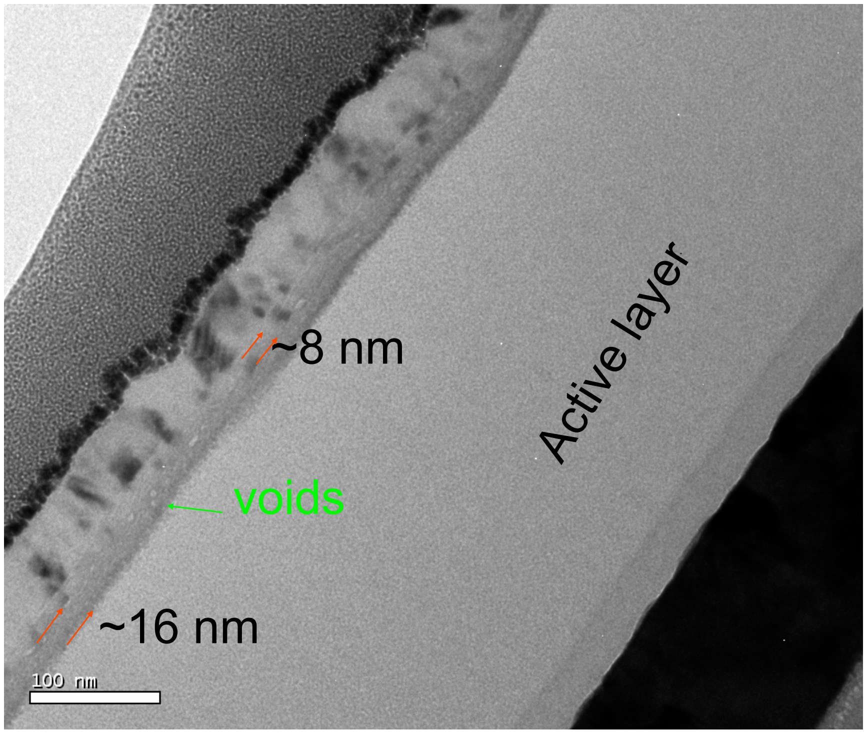


- Ag work function increases over time, improving contact to donor material
- Interface between Ag and the active layer is very sharp, with little/no sign of Ag oxidation

Device and Packaging Reliability and Lifetime

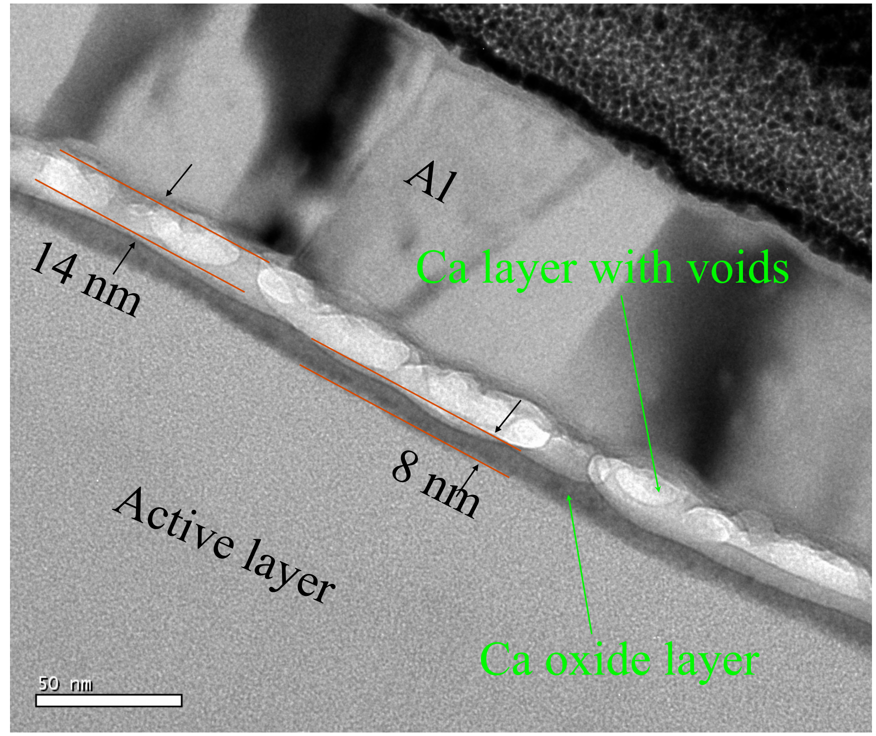
Effect of Air Exposure on Calcium Electrode, TEM

New Sample



- At Al/Ca interface, it forms a transition layer of ~ 8nm, made of mainly Al.
- Tiny voids are often present at the interface of the transition layer and the Ca layer.
- The Ca/polymer interface is also not very sharp.

Sample After Air Exposure



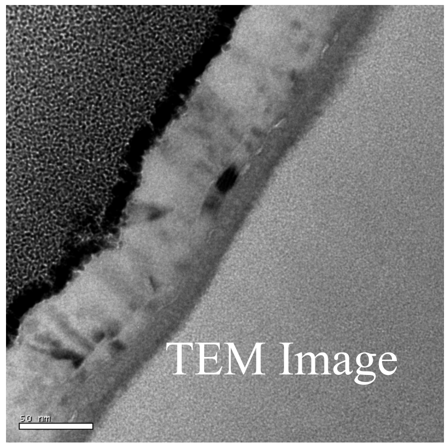
- All of the Ca layer is oxidized. Very large voids are present at the interface of the transition layer and the Ca layer.
- Ca is fully oxidized after exposure to air resulting in dramatically reduced performance.

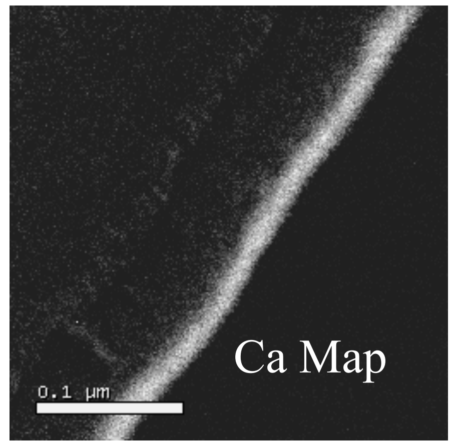
Device and Packaging Reliability and Lifetime

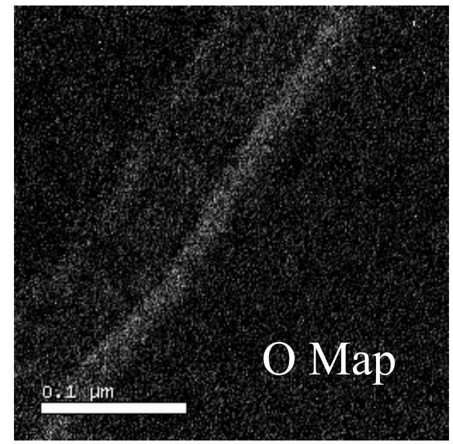
Effect of Air Exposure on Calcium Electrode, EELS Mapping

New Sample

- The actual Ca layer thickness is about 17 nm. The Ca layer has a significant tail into the Al layer.
- O content in the Ca layer appears to be insignificant!

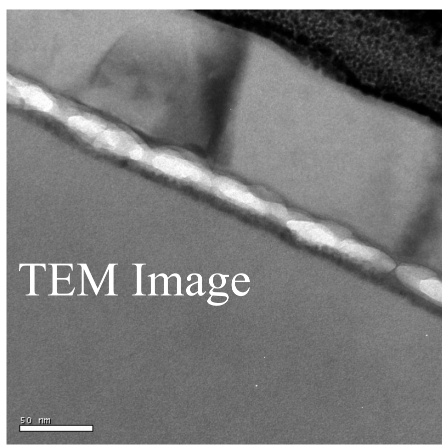


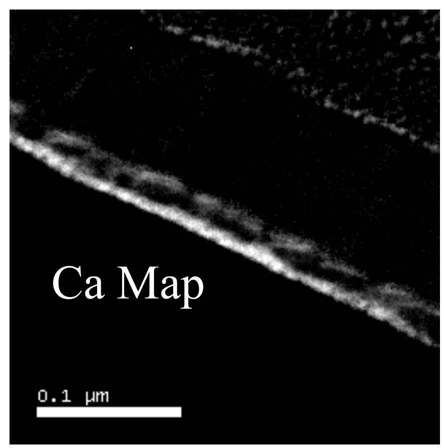


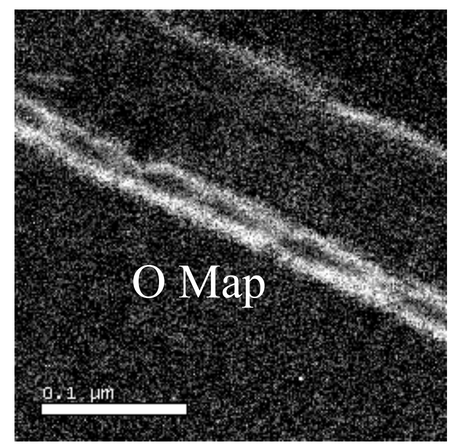


Sample After Air Exposure

- The actual CaO layer thickness is about 8 nm. The Ca layer has a significant tail into the Al layer.
- O content in the Ca layer is significant, suggesting the Calcium is fully oxidized!

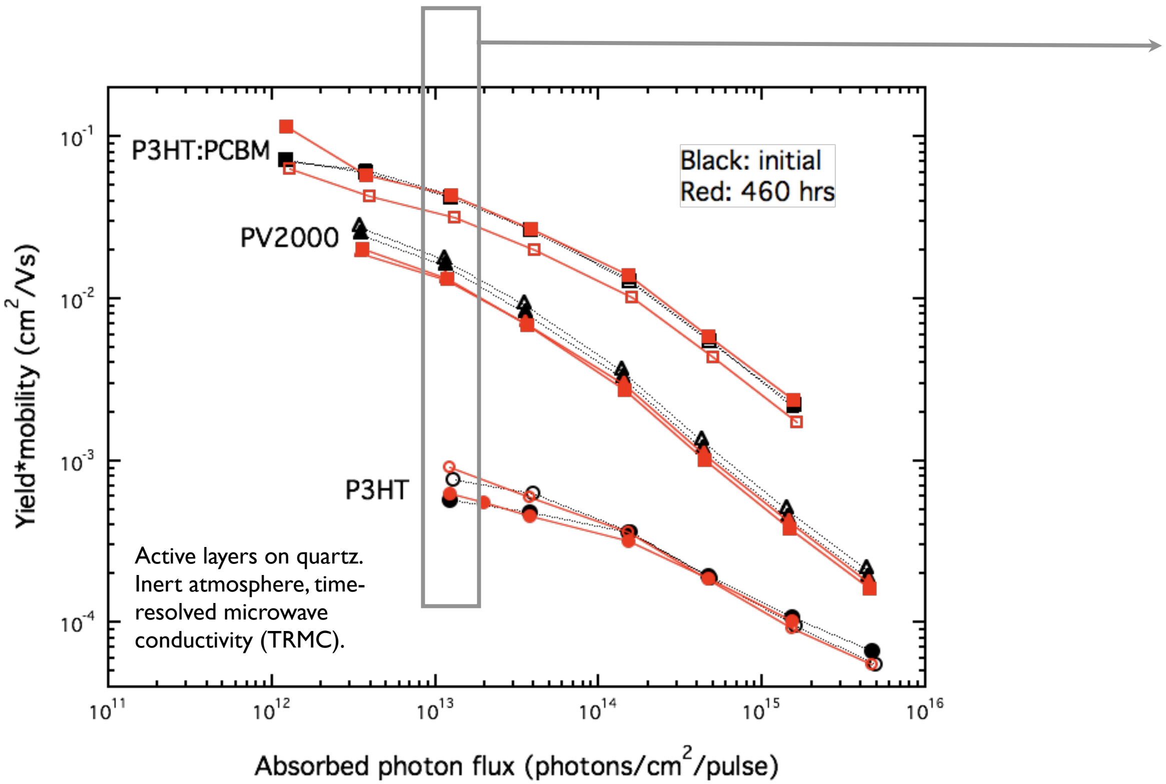


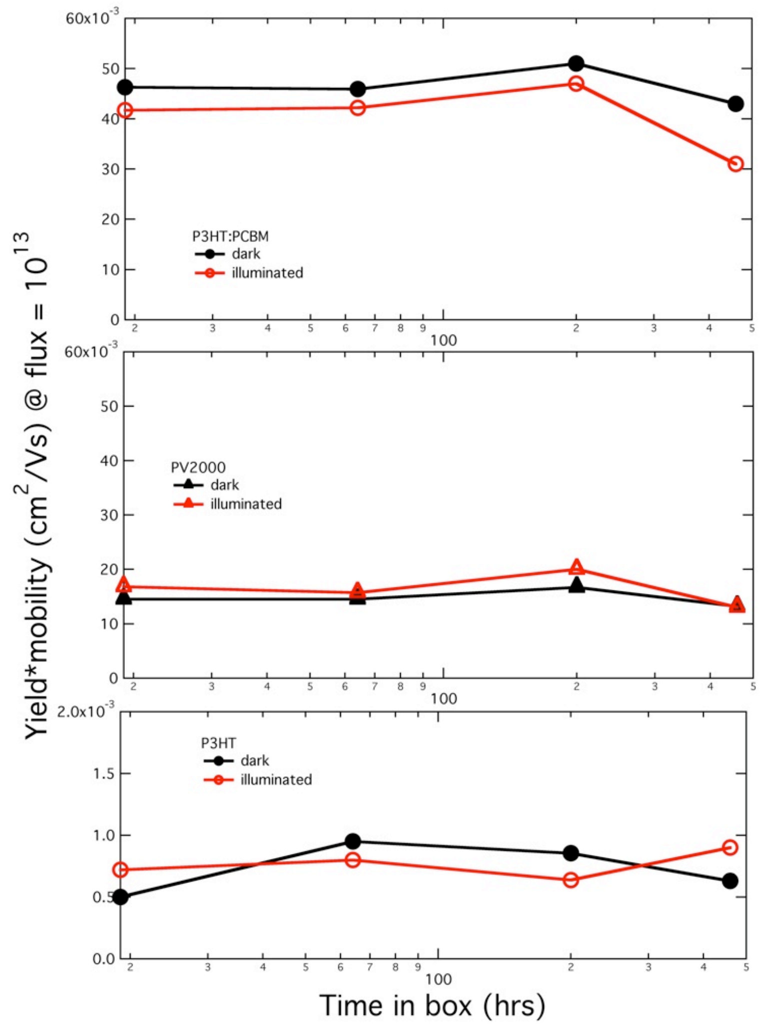




Materials Characterization Specific to OPV

Active Layer Degradation Studies Using TRMC



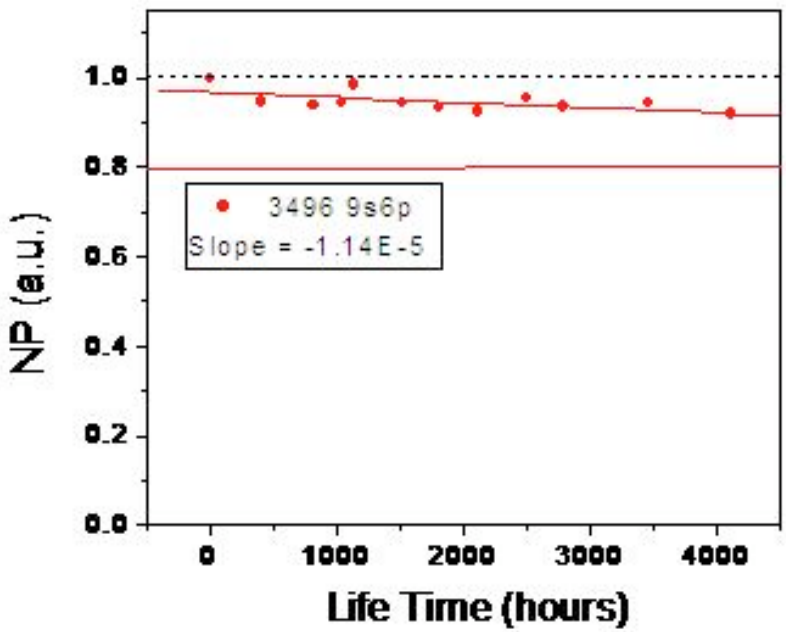


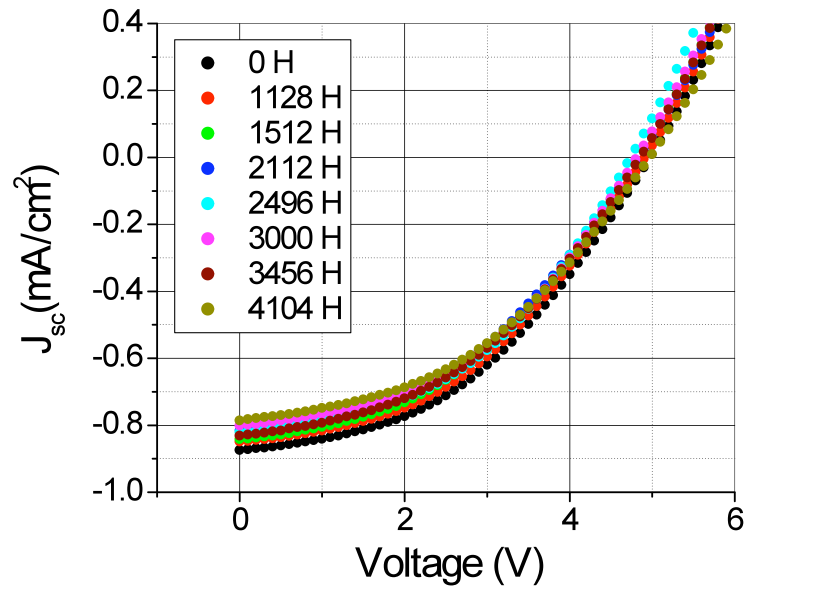
- Unique capability to assess intrinsic stability of the active layer.
- No photobleaching observed in UV-vis absorption.
- Stable active layer photoconductivity and carrier lifetimes ~ 500 hrs.
- To be compared with illumination under ambient conditions.

APS physics

NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Champion OPV Module Lifetime
Continuous Xe Light Soaking



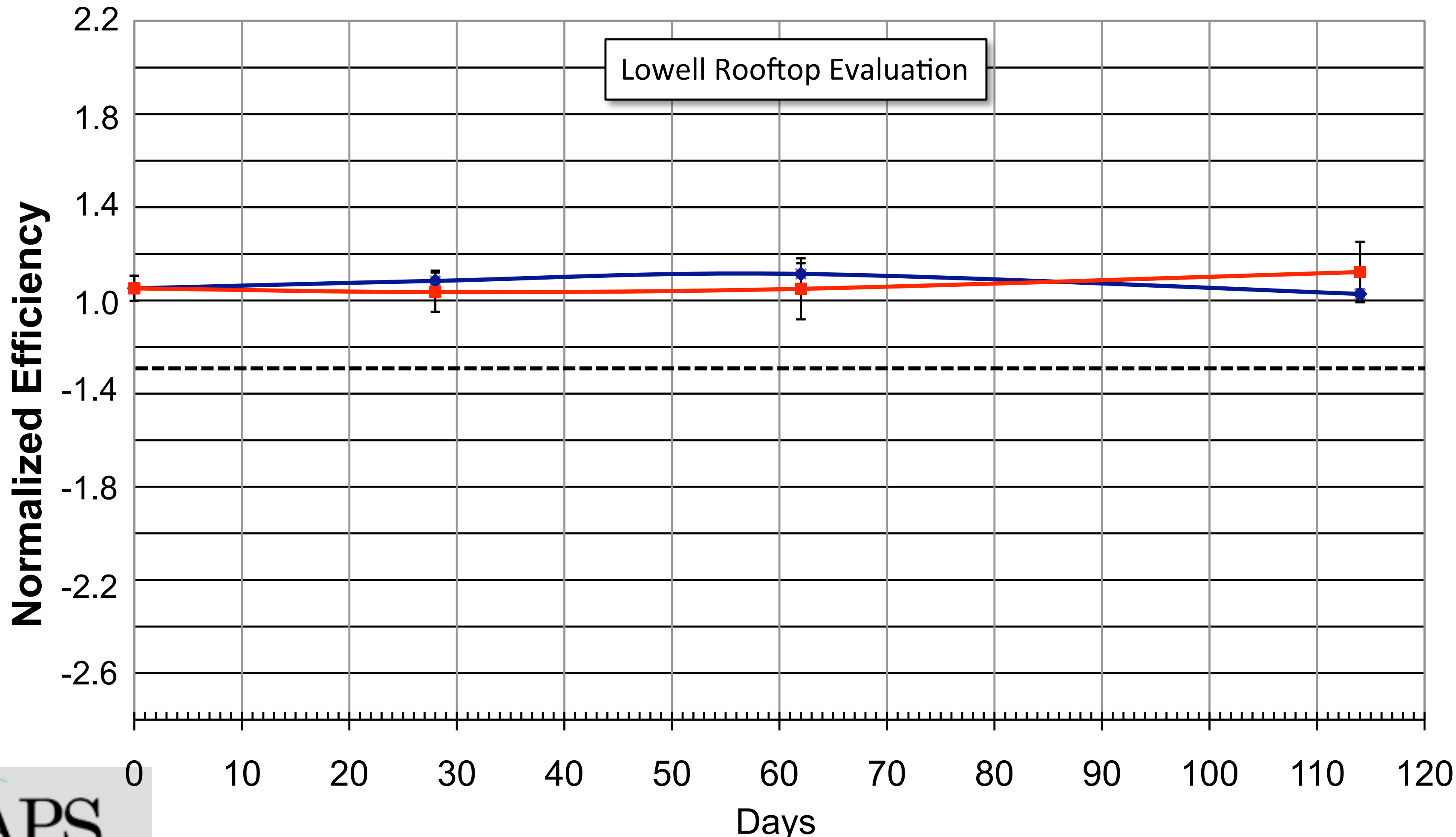


AM1.5G solar simulation JV characteristics

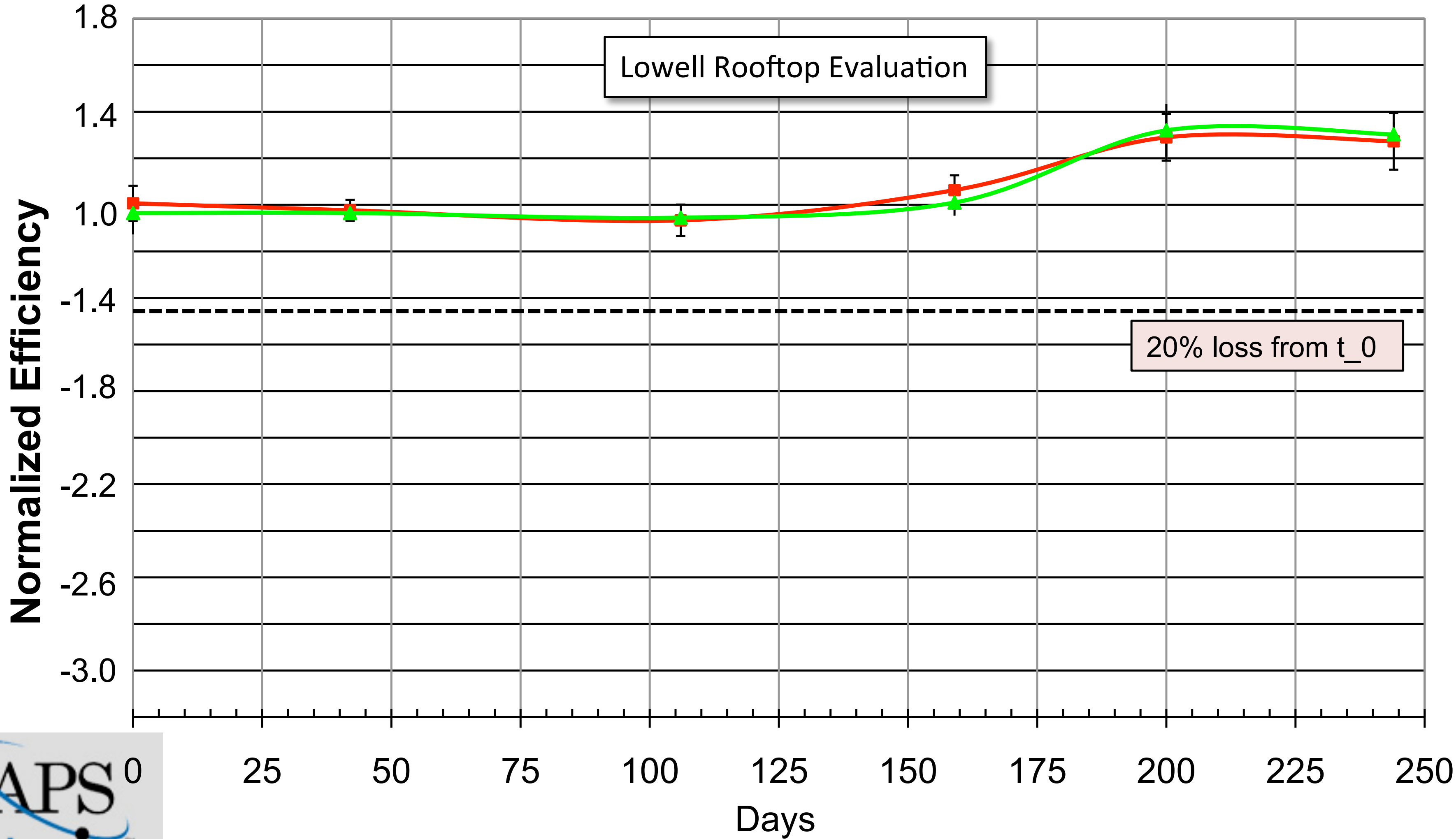
Extrapolates to > 3 yr (27 kh) of outdoor lifetime*

- > 4100 hrs to date (Xe-lamp, continuous, 25C)
- ~ 1.1%/1000h decay rate (stabilized efficiency, 100% duty cycle)
- 32 kWh/m^2/day (6.5x ave. US insulation)

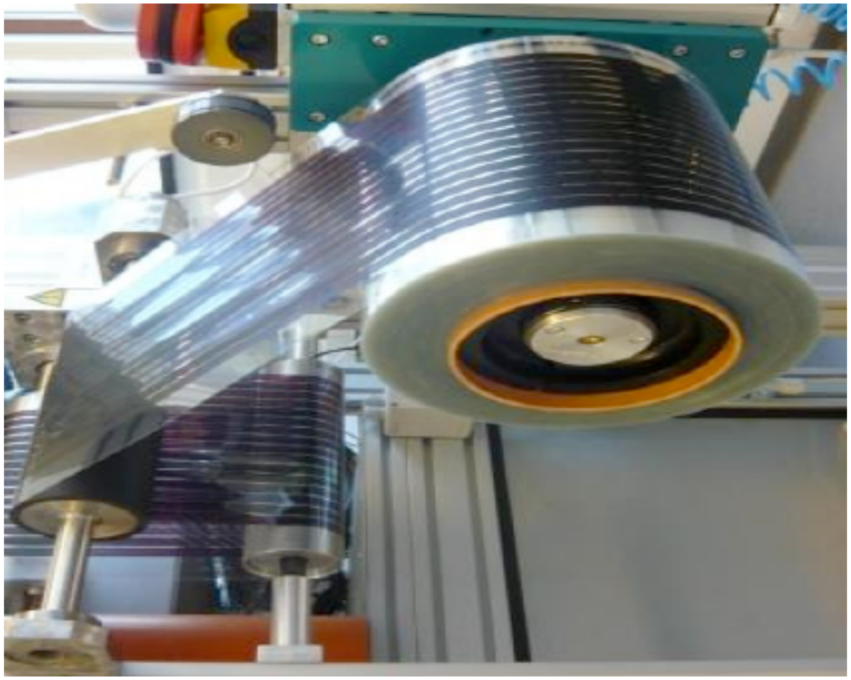
Estimate based on irradiation energy input which may be primary driver for degradation; comparison of irradiance of continuously operated indoor Xe lamp with continuous vs. average outdoor irradiance of the US

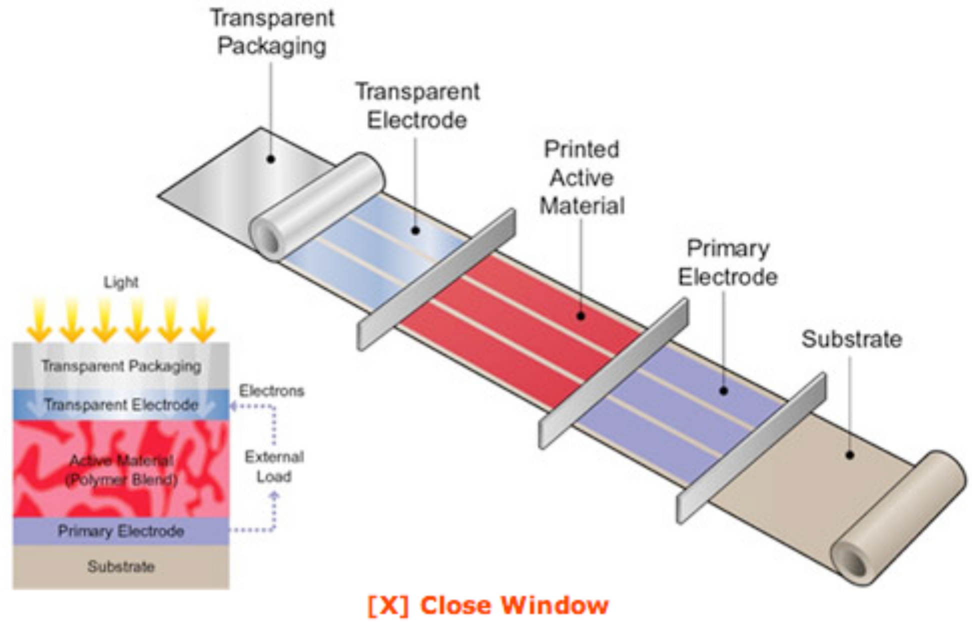


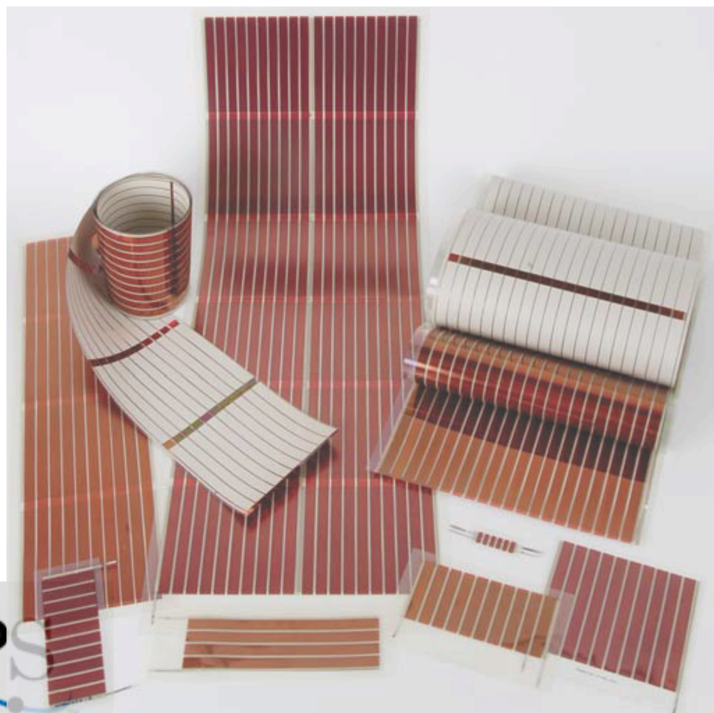
Lowell Rooftop Evaluation
Normalized Efficiency
2.2
1.8
1.4
1.0
-1.4
-1.8
-2.2
-2.6
0
10
20
30
40
50
60
70
80
90
100
110
120
Days


Lowell Rooftop Evaluation
20% loss from t_0
Normalized Efficiency
Days
1.8
1.4
1.0
-1.4
-1.8
-2.2
-2.6
-3.0
0
25
50
75
100
125
150
175
200
225
250

Technology is Scalability and at Low Temperature



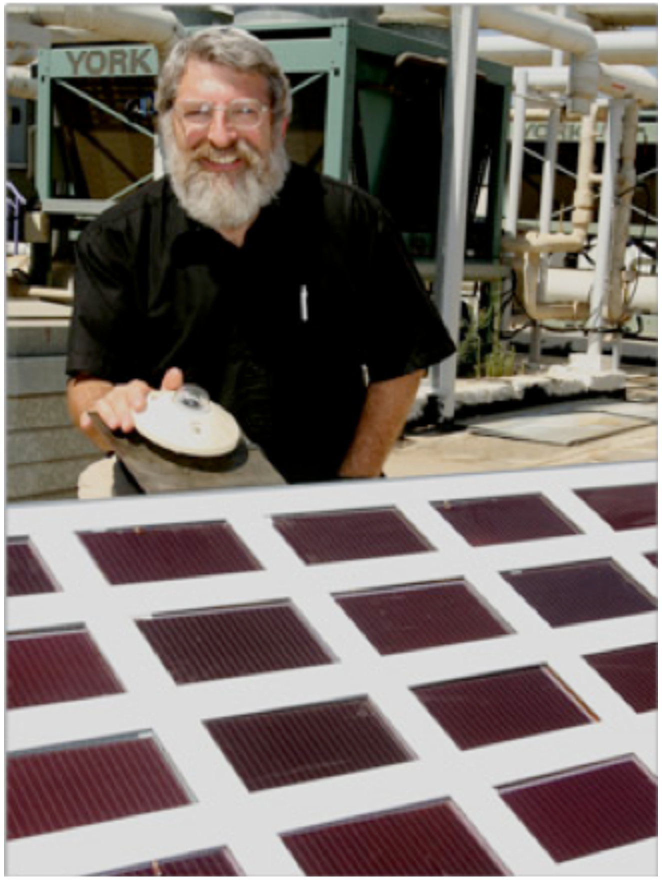


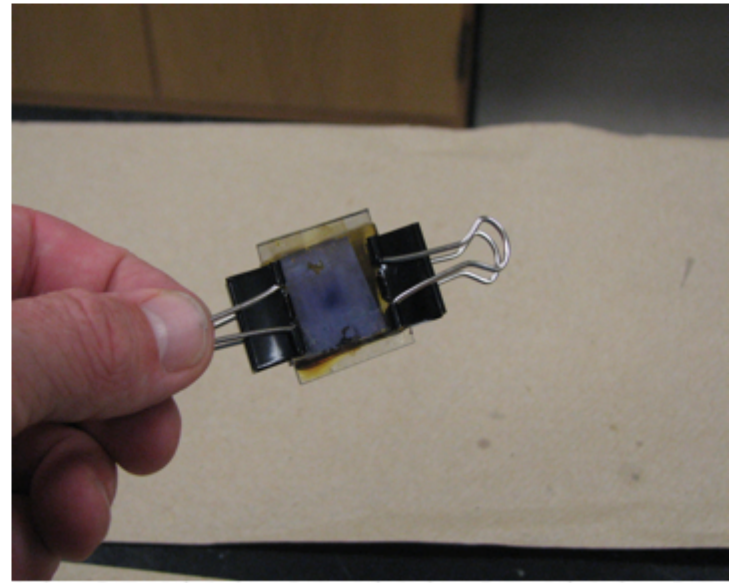


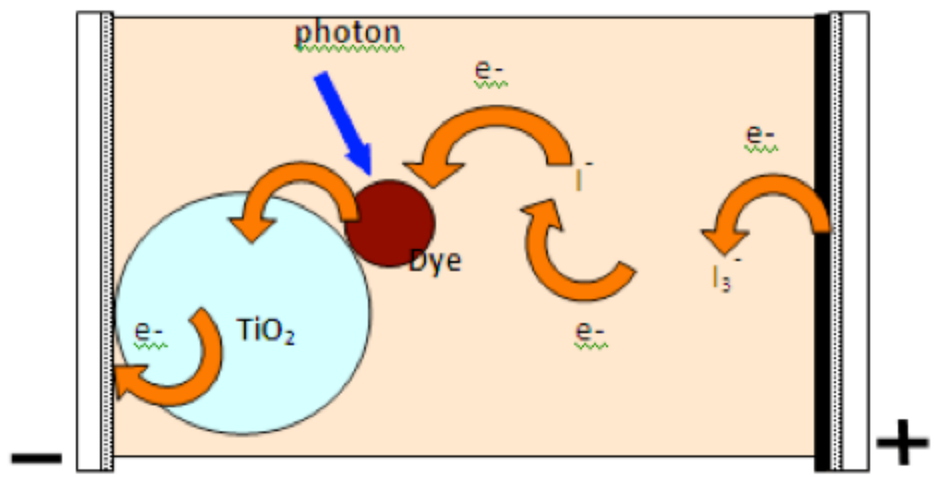
APS physics

What Else is Coming Along??

DSSC - The Dye Cell - Nanoscale PV







PV dye cell schematics

3GSolar

Beyond the Single Junction

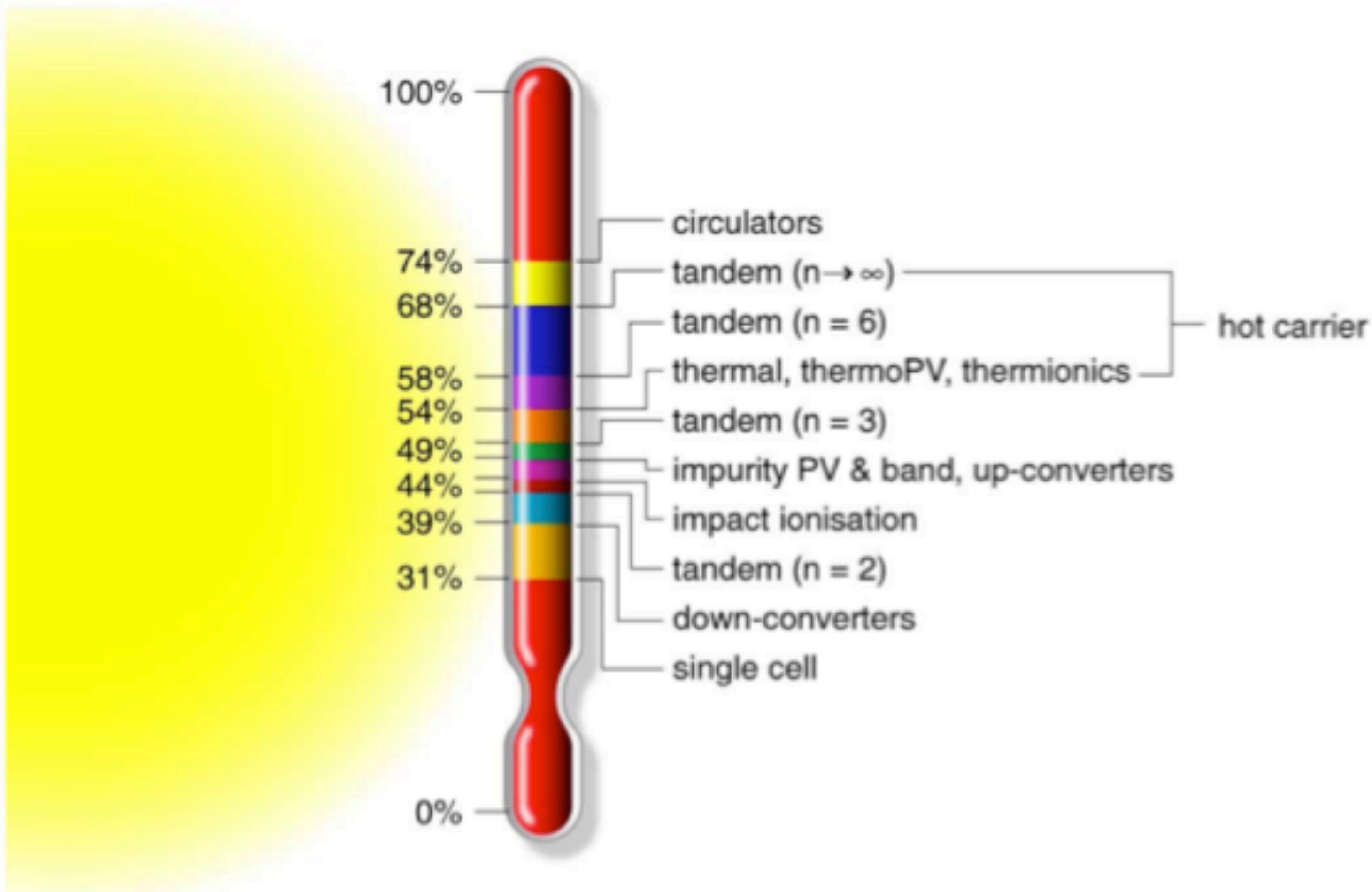
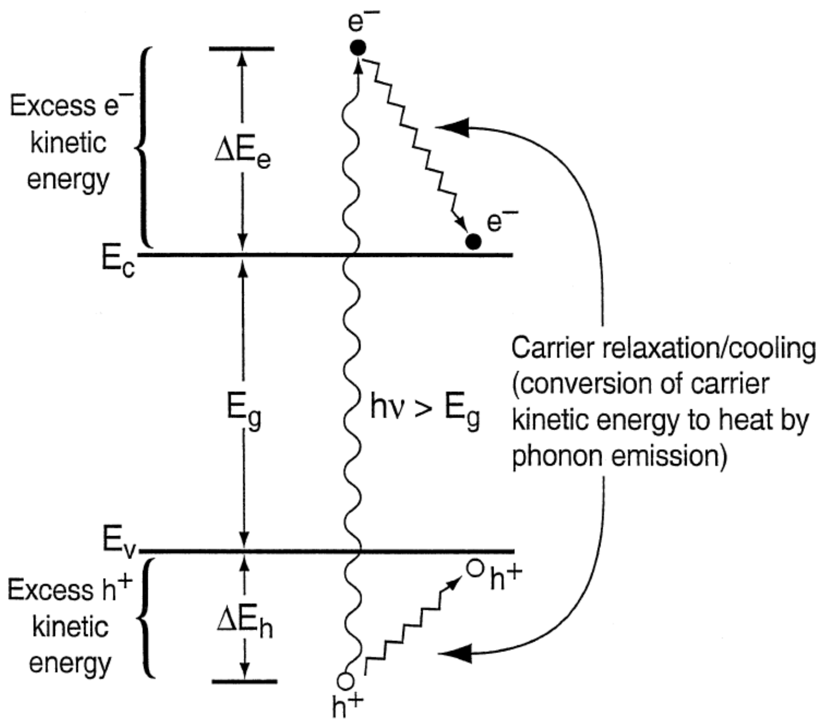
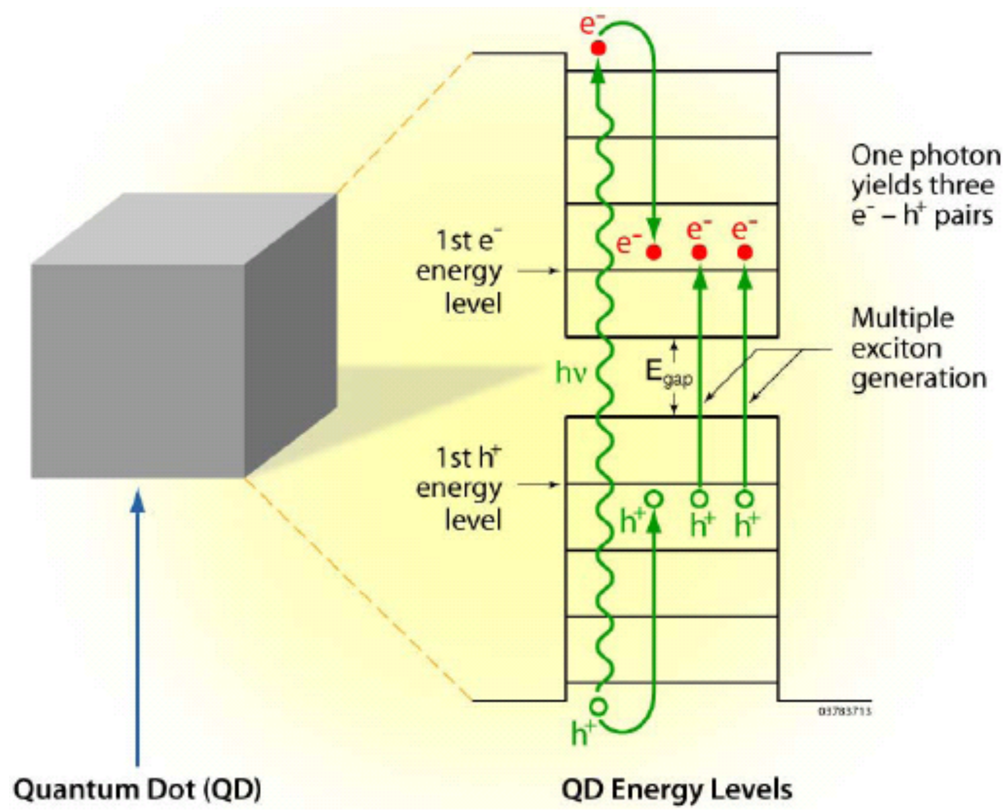


Figure 13. "Third Generation" options and thermodynamic limits on their efficiency.

Multiple Exciton Generation in nanocrystals





R. D. Schaller, V. I. Klimov, Physical Review Letters, 2004, Vol. 92.

Conclusions - solar cells by design!

- Terawatt production will require “green approaches”
- Organic photovoltaics offer a promising technology for future low-cost, large scale renewable energy production - Progress is very rapid toward this end with scalability being demonstrated so far by low cost approaches.
- Alternatives for Earth Abundant PV exist such as CZTS, Thick Film Si, Dye Cells, 3rd Generation approaches
- Materials by Design offers tremendous potential for real breakthroughs - ie new designed donor materials are being fabricated to allow for increased light absorption - tandem devices offer great potential in this technology
- Interfacial stability seems at present the most critical area even vs efficiency. Development of new contact and electrode materials allow for enhanced performance and stability and reduced cost with increased focus on flexible substrates will be needed for new materials.

Thank You

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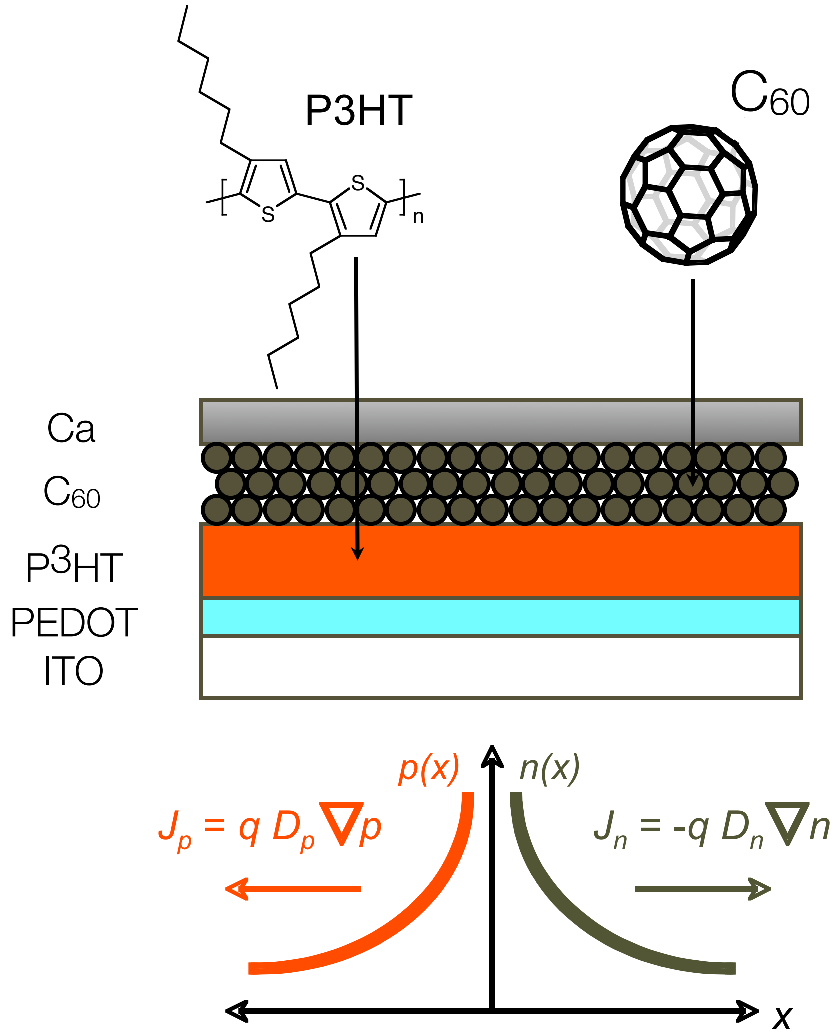
303-384-6573

Planar Bilayer Heterojunction Devices



Chemical potential gradients drive charges through device

- **Strengths**
  - Chemical potential gradients yield a net diffusion current
  - Efficiently separated charges, limited recombination
- **Weaknesses**
  - Requires large exciton diffusion lengths
  - Very little light absorption
  - Often thermally evaporated