Thin-film Photovoltaics:

Opportunities and Challenges

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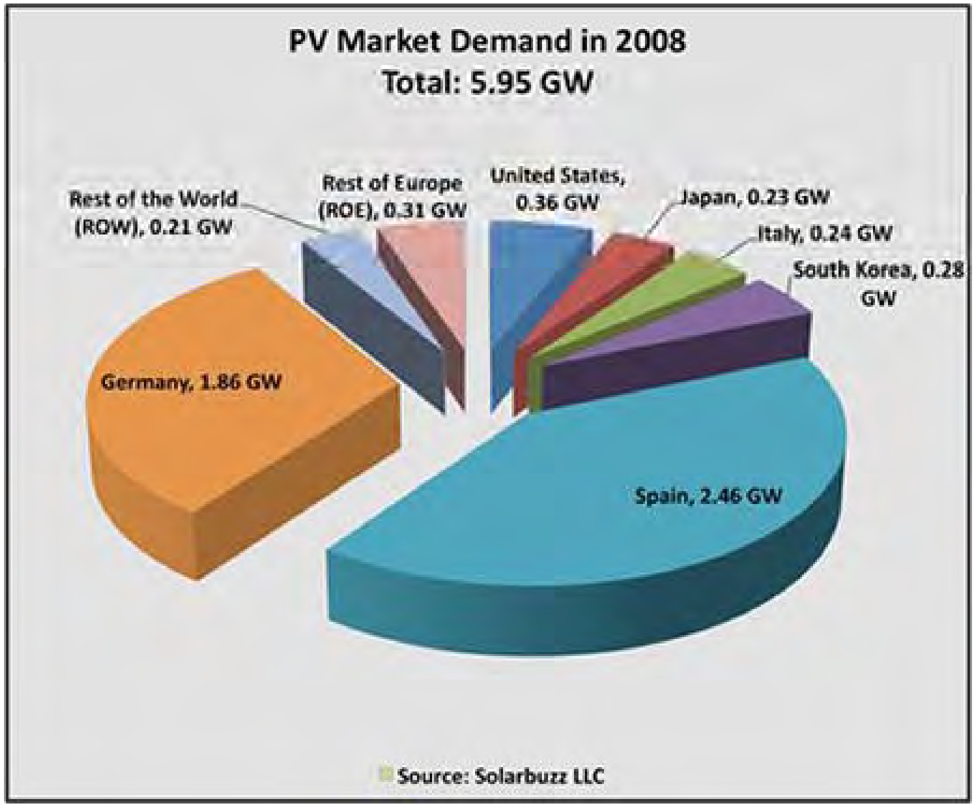
Photovoltaic Industry



Source: Solarbuzz.com

2008 Statistics:

- PV installation: 6 GW (mostly silicon)
- Thin-film: 0.9 GW (15%)
- Growth rate: 110% over 2007
- Europe accounts for 82%
- U.S. accounts for 6%
- Global revenue ~ US$37 billions
- China/Taiwan produces 44%

World's Largest Photovoltaic Farm, Jumilla, Spain

20 MW, 247 acres, 2008

Solar Thermal Electricity Generation

Parabolic Trough Systems

The world's largest solar plant

- **Location: Gila Bend, near Phoenix (Arizona)**
- **Capacity: 280 MW, CPS Trough Plant**
- **To be built by Abengoa, a Spanish company**

Solar Roofing Tiles and Sheets

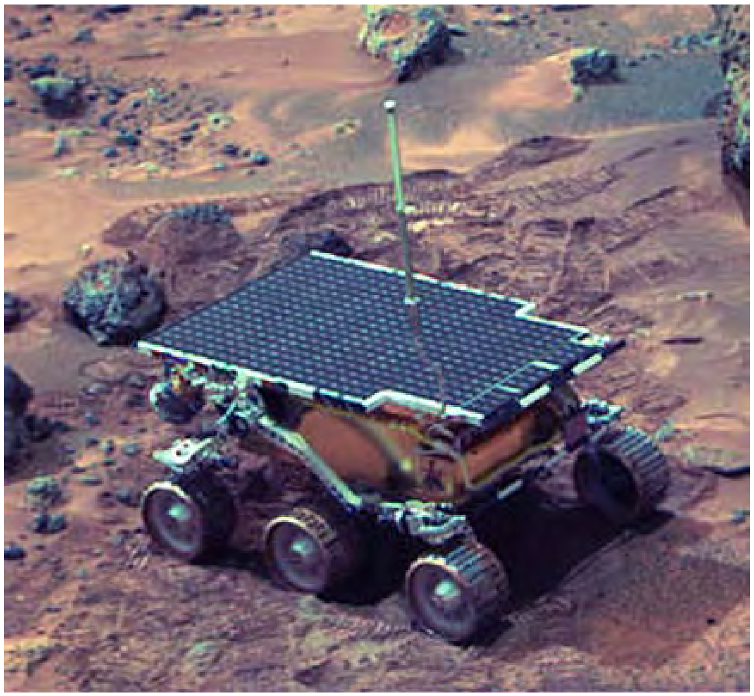
Altantis Energy Systems

http://www.nrel.gov/data/pix/

United Solar

PV: Space and other applications

Sojourner, Mars exploration, 1997
16W PV power



Mariner 5

University of Massachusetts's
photovoltaic car, 1995

http://www.nrel.gov/data/pix/

PV powered “gadgets” or Smart PV power

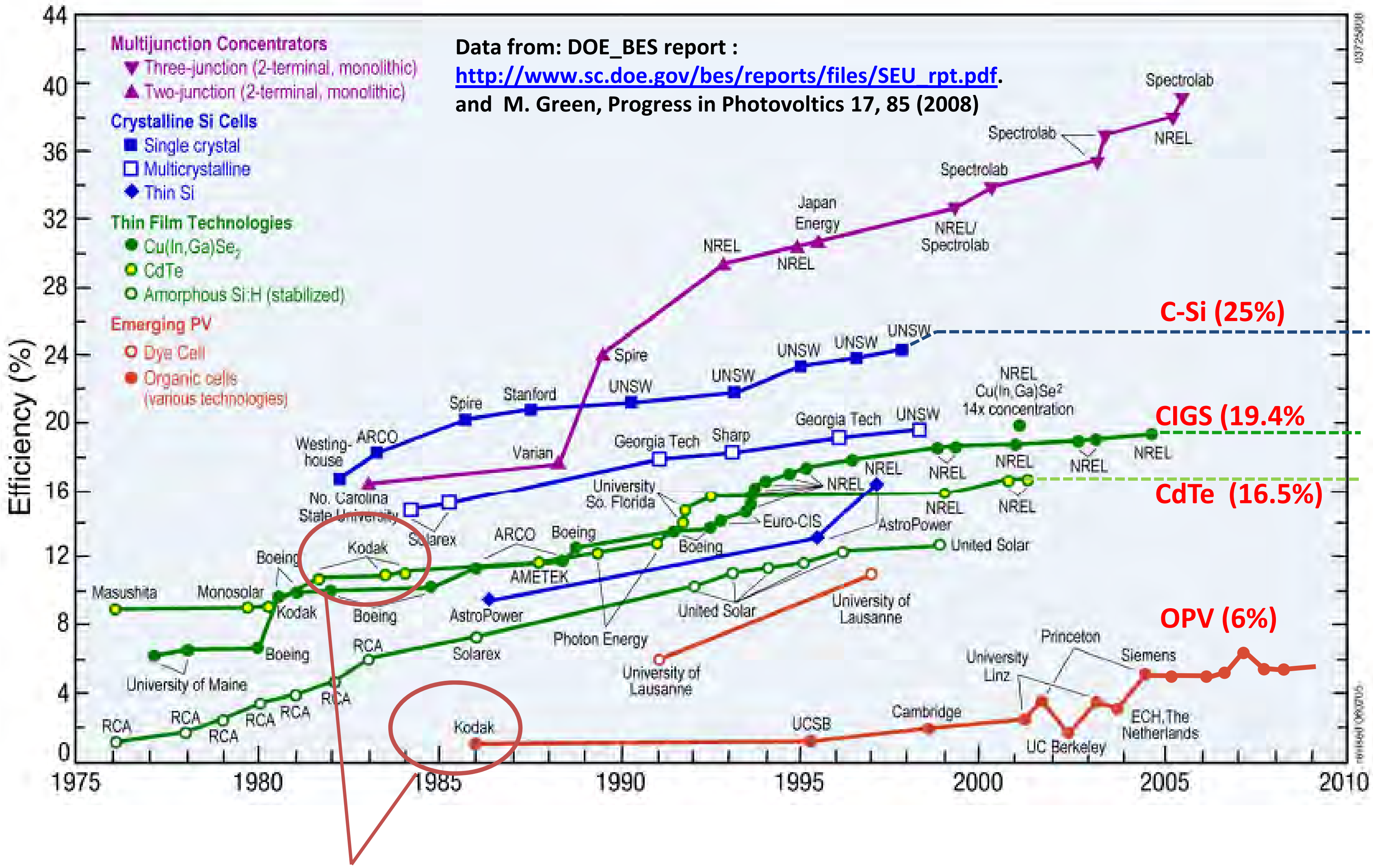
Solar bonsai tree

Solar powered bikini
Treehugger.com

Flexible OPV (Konarka)

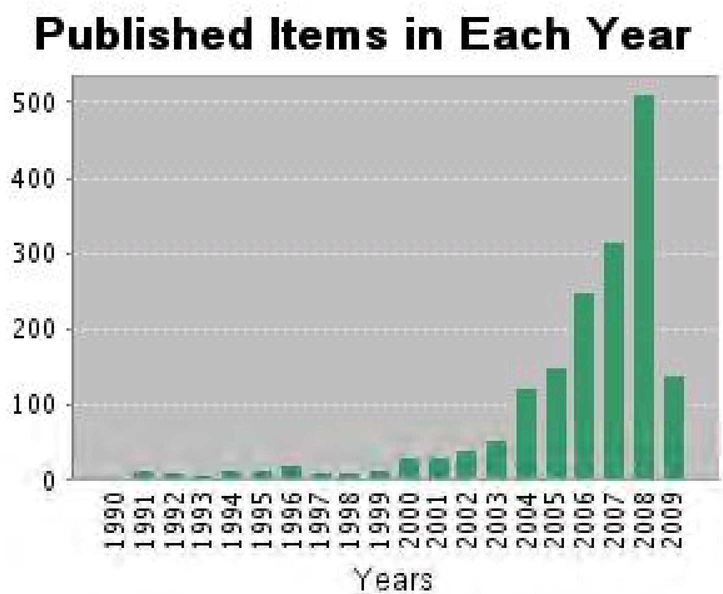
Solar backpack
($219 , Amazon.com)

Historical Data and Highest Confirmed Efficiencies for Solar Cells

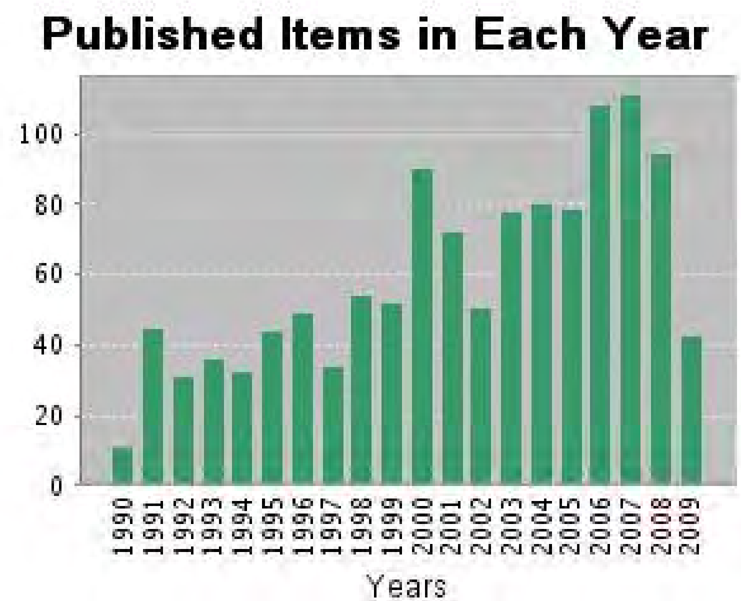


Kodak : CdTe and OPV

Organic Photovoltaics



CdTe solar cells

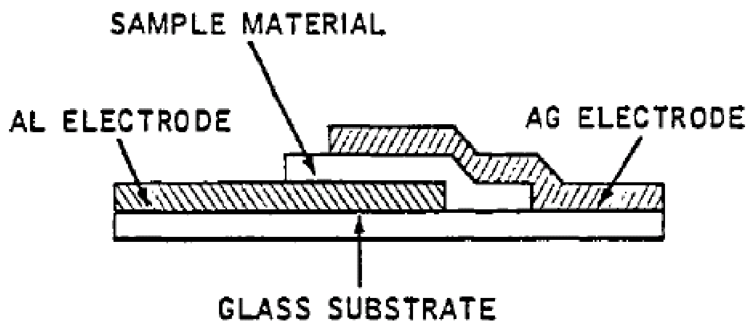


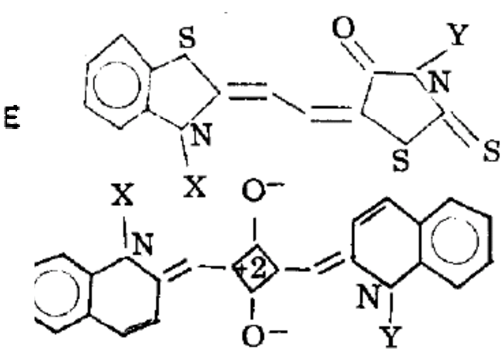
Recent progress in organic solar cells

Year	Research location	Eff(%)	Year	Research location	Eff (%)
2004	Princeton	5.7	2007	UCSB (Tandem)	6.5
2005	Princeton	5.0	2007	UCSB	5.5
2005	UCSB	5.0	2008	Osaka Univ.	5.3
2006	UCSB	5.0	2008	Northwestern	5.2
2007	Konarka	5.24	2008	South China Univ. of Tech.	5.4
2007	Plextronics	5.42	2009	Univ. of Chicago	5.6

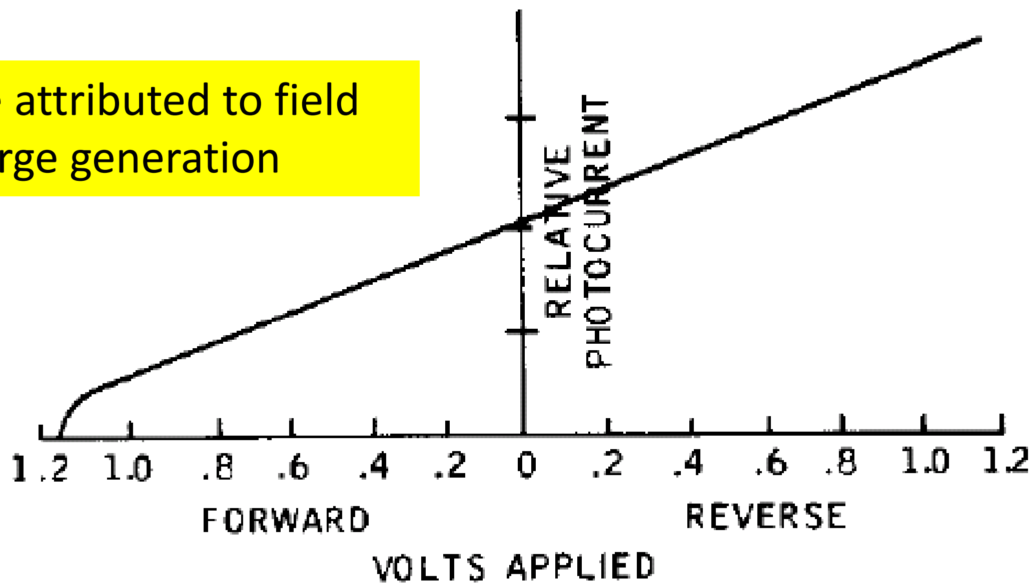
Historical OPVs: Morel et al. (Exxon), Appl. Phys. Lett. 32, 495 (**1978**)
Single-layer of organic absorber sandwiched between electrodes of different work function

Eff	0.7 %
Voc	1.2 V
Isc	1.8 mA/cm^2
FF	25%





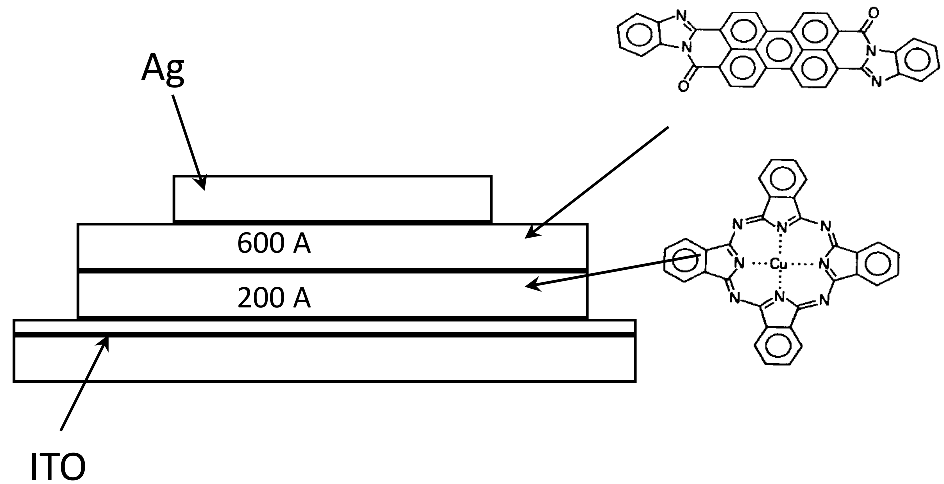
Poor F.F. can be attributed to field dependent charge generation

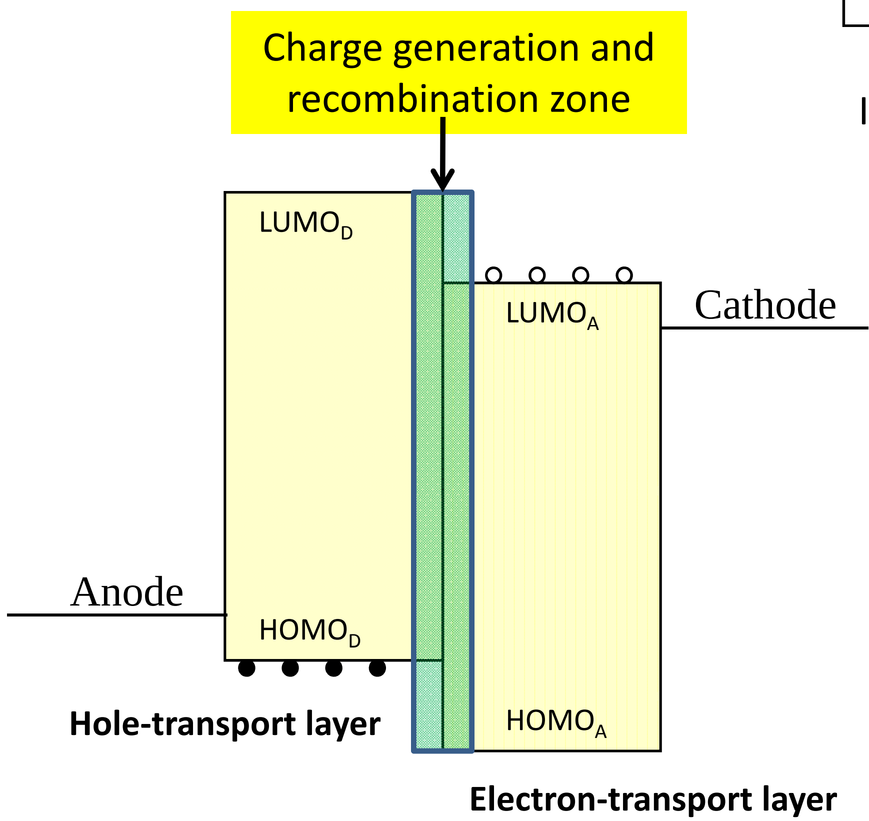


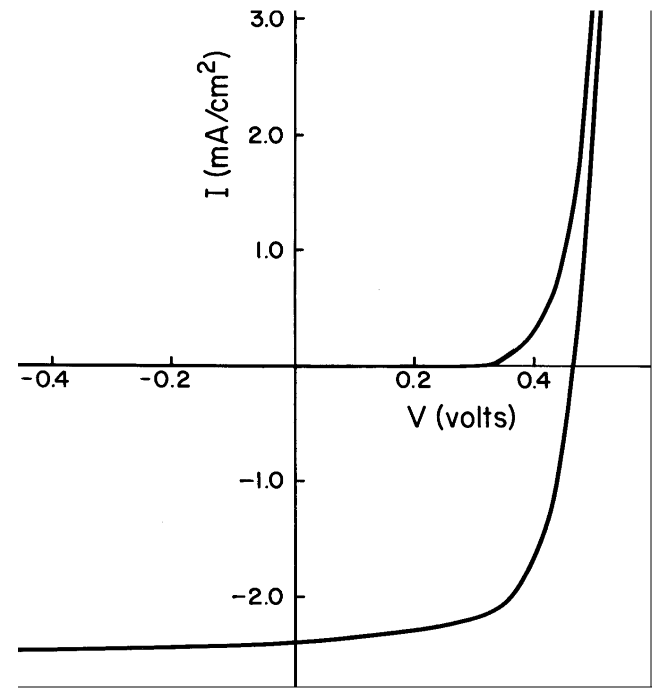
Historical OPVs: **Tang (Kodak)**, Appl. Phys. Lett. 48, 183 (**1986**)

First bi-layer heterojunction organic solar cell

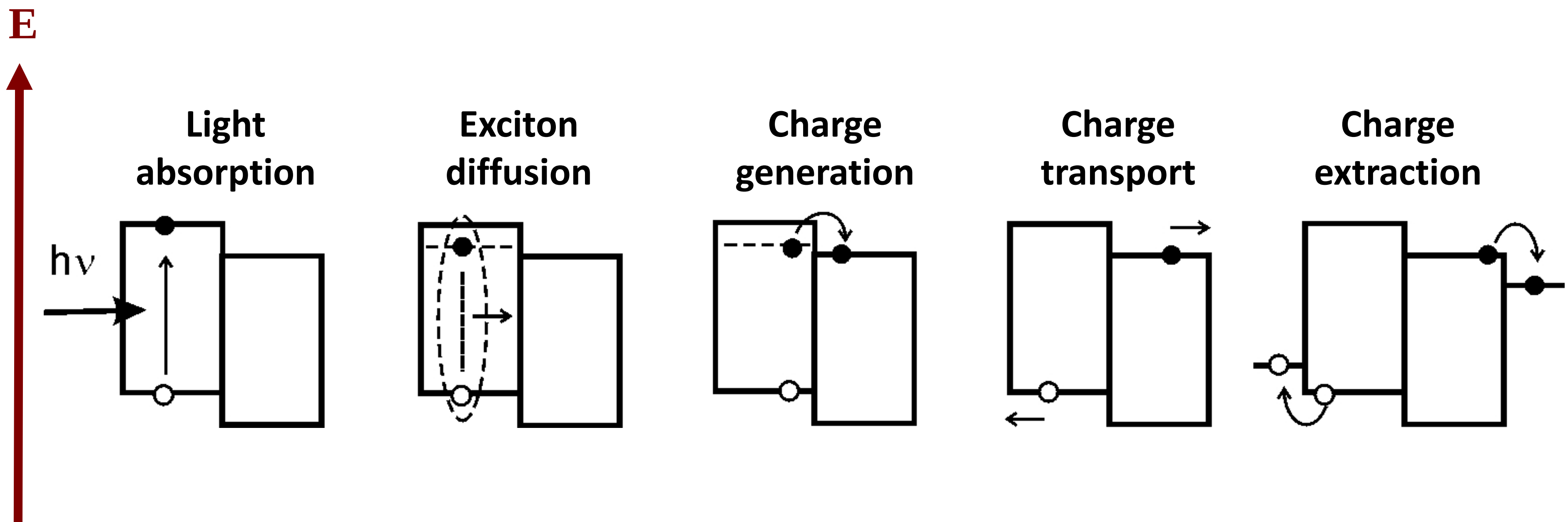
Eff	1.0 %
Voc	0.45 V
Isc	2.3 mA/cm^2
FF	65%







Organic Photovoltaic Processes and Issues



Light absorption

- Narrow band width
- J_{sc} limitation
- UV instability

Exciton diffusion

- Too short
- Thickness limitation
- J_{sc} limitation

Charge generation

- Electric field dependent generation
- V_{oc} limitation

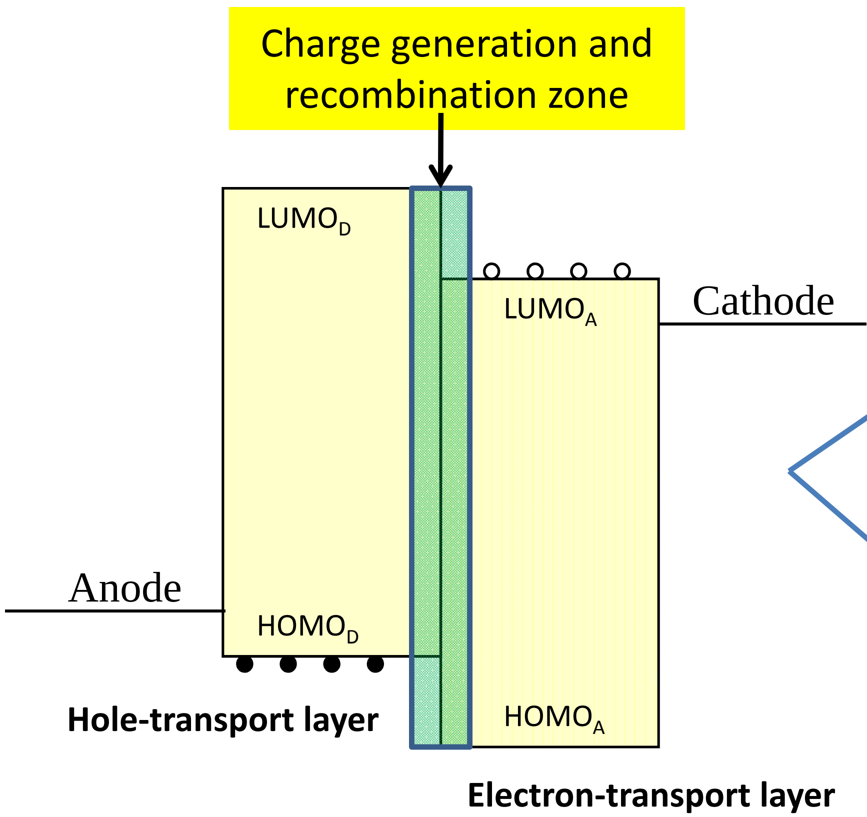
Charge transport

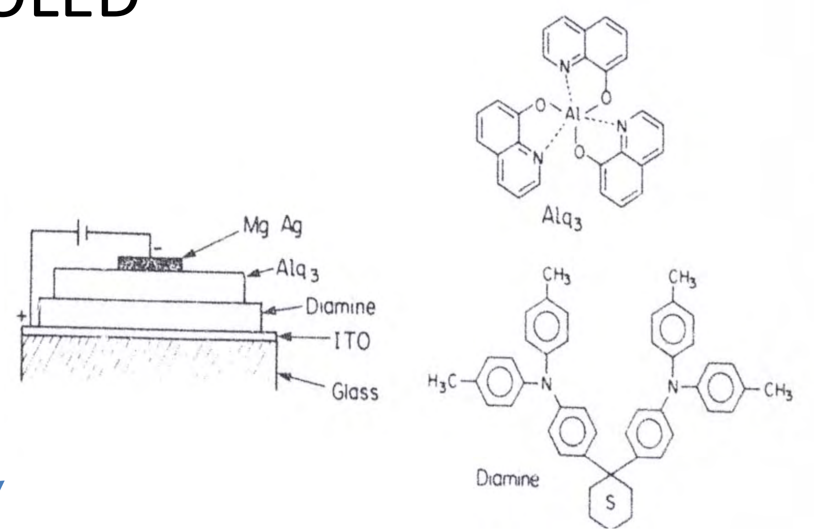
- Electric field dependent mobility
- Dispersive transport

Charge extraction

- Contact resistance
- metal/organic issues

From OPV to OLED



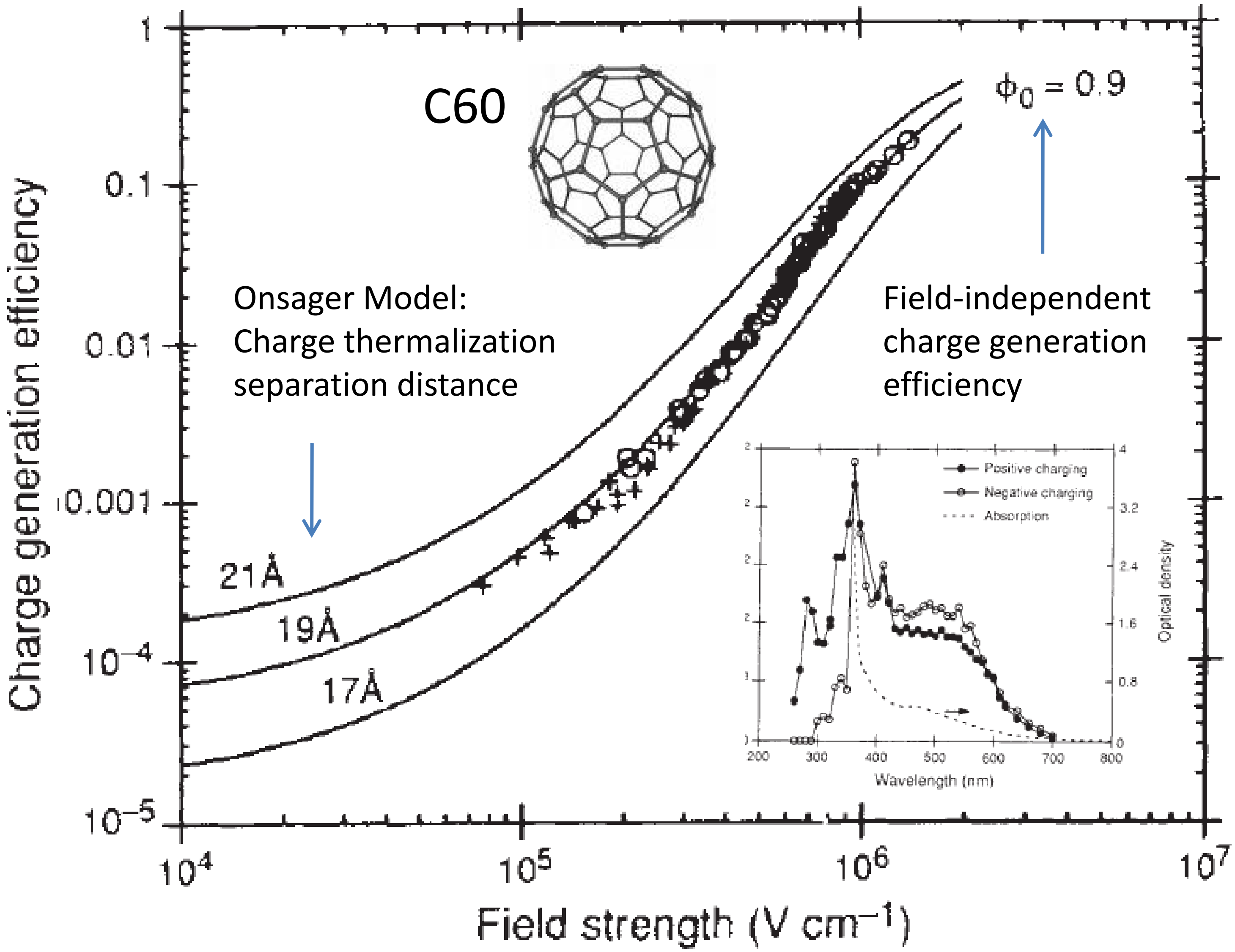


Appl. Phys. Lett 51, 913 (1987)

SONY OLED-TV (Model XEL1)

Historical OPVs: Y. Wang (DuPont), Nature 356, 585 (1992)

First use of C60 in organic photoconductor (PVK:C60)



Historical OPVs: Yu/Heeger (UCSB) SCIENCE 270, 1789 (**1995**)

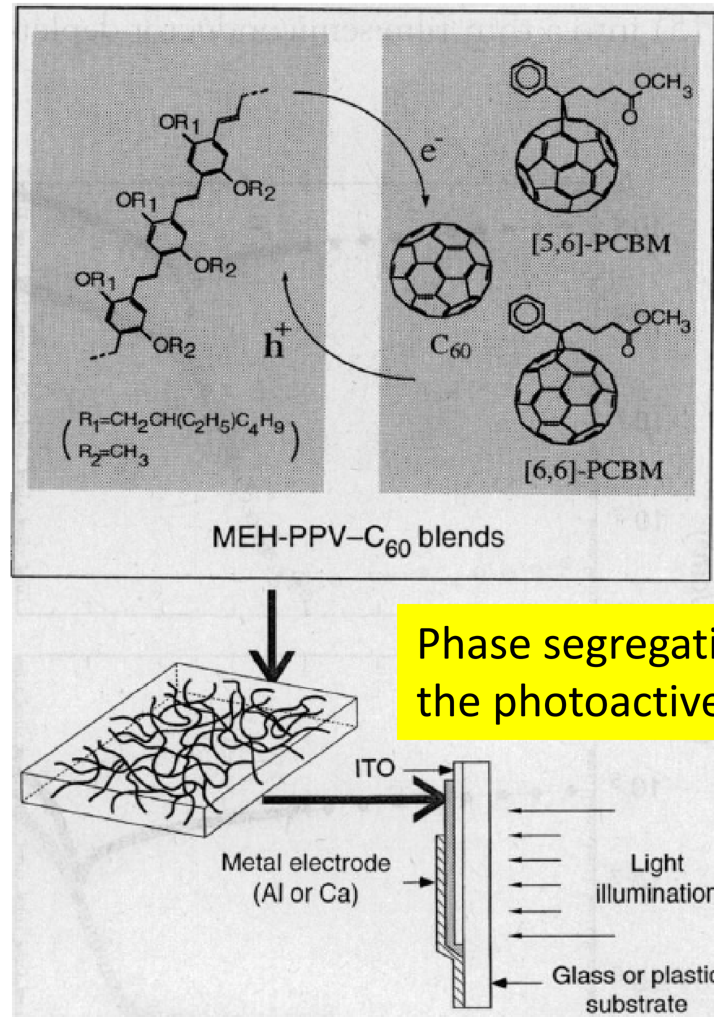
Bulk heterojunction: MEH-PPV:PCBM

ITO/MEH-PPV:PCBM/Ca

Eff	~ 3% @ 20mW/cm^2 (430nm)
Voc	~ 0.68 V
Isc	~ 2 mA/cm^2
FF	48%

Soluble conjugated polymer as donor

Soluble C60 as electron acceptor

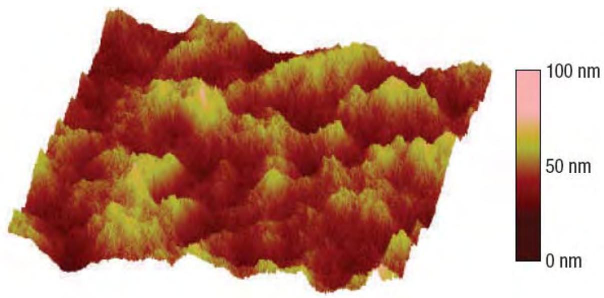


Phase segregation in the photoactive layer

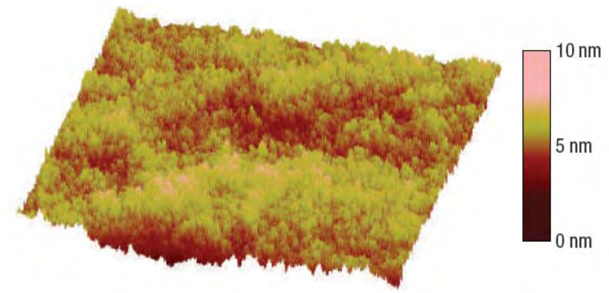
Recent OPVs: **Li/Yang**, Nature Materials 4, 864 (**2005**)

Morphology control through solvent annealing processes

Eff	4.4%
Voc	0.61 V
Isc	10.6 mA/cm^2
FF	67.4%

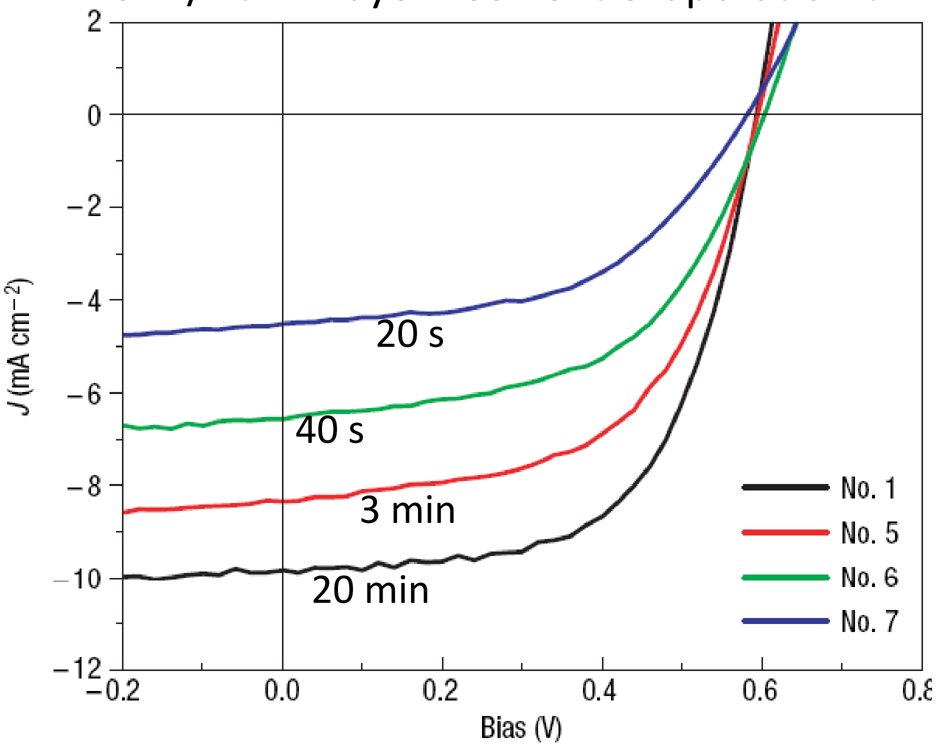


20 min

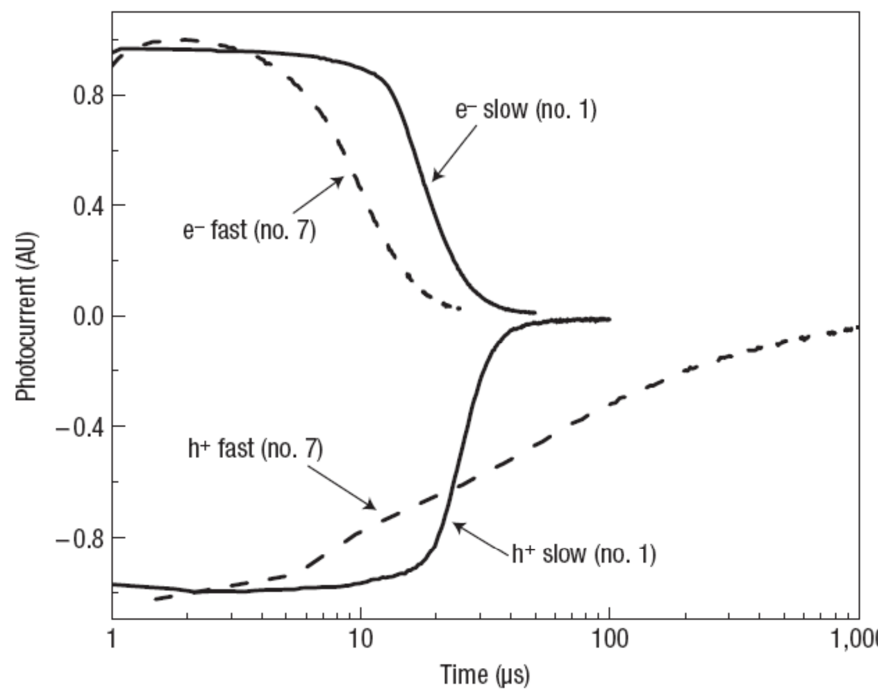


20 s

P3HT/PCBM layer - solvent evaporation time



Carrier mobility enhancement

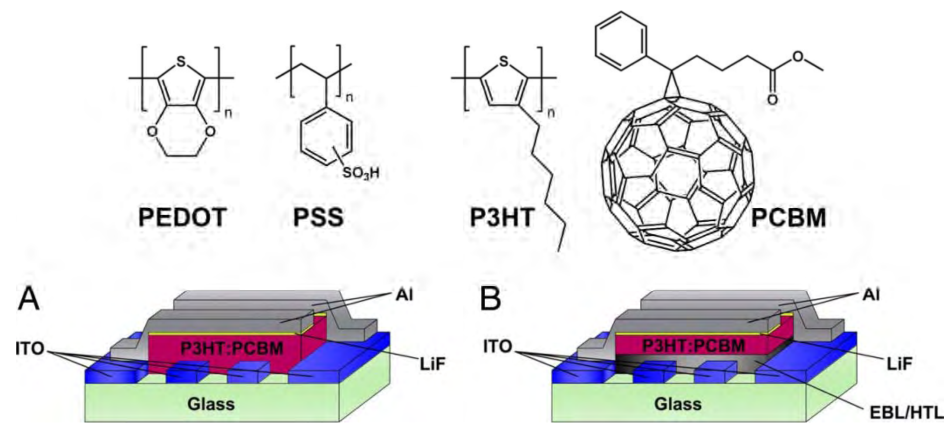


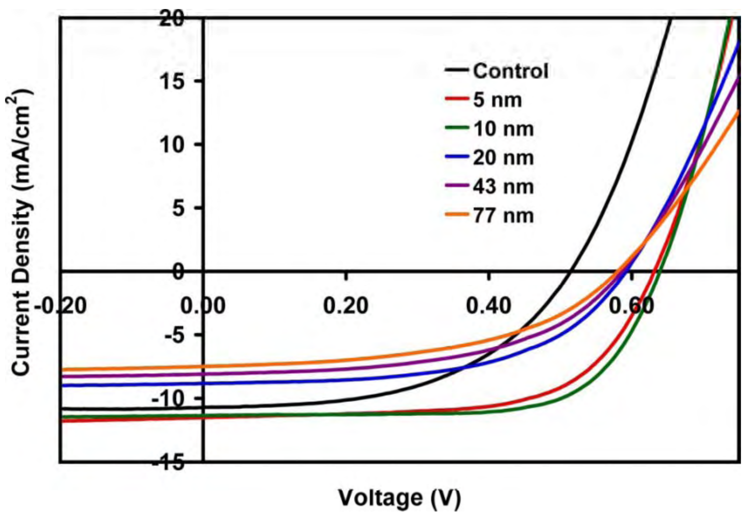
Recent OPVs: **Tobin Mark**'s group: PNAS **2008**; 105:2873-2787

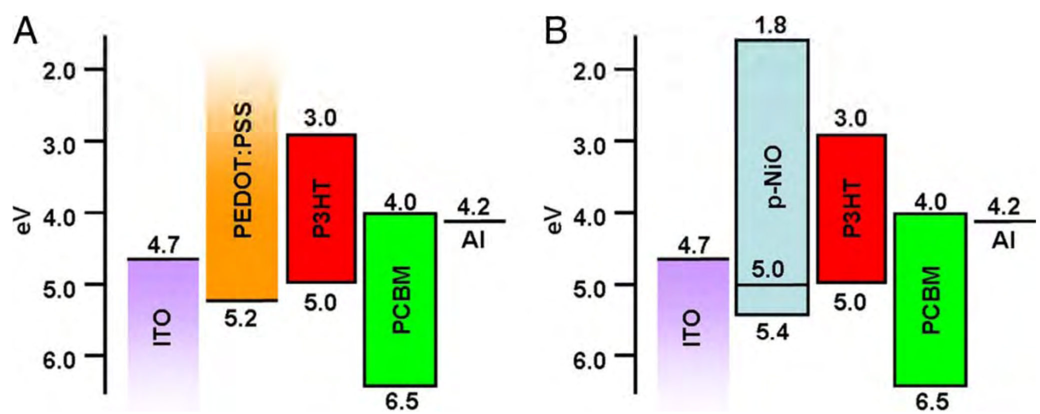
NiO as p-type contact layer instead of PEDOT

Eff	5.16%
Voc	0.638 V
Isc	11.3 mA/cm^2
FF	69.3%

Uncertified





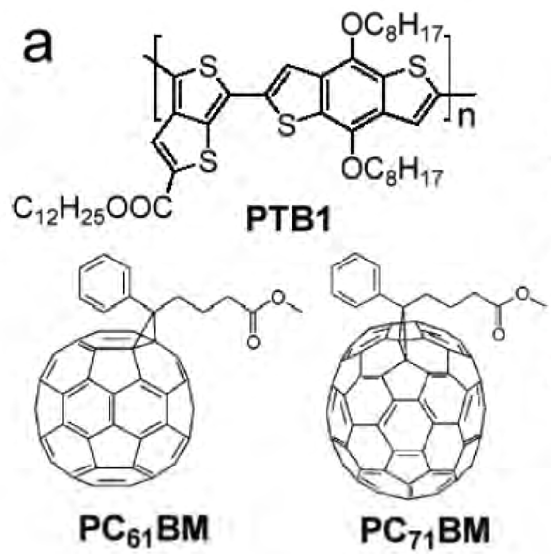


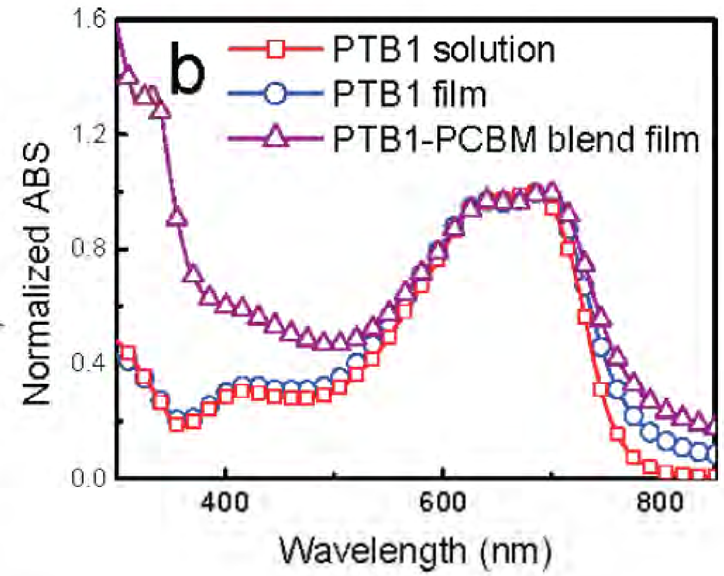
Recent OPVs: **Luping Yu**'s group, *J. Am. Chem. Soc.*, ***2009, 131 (1), 56-57***

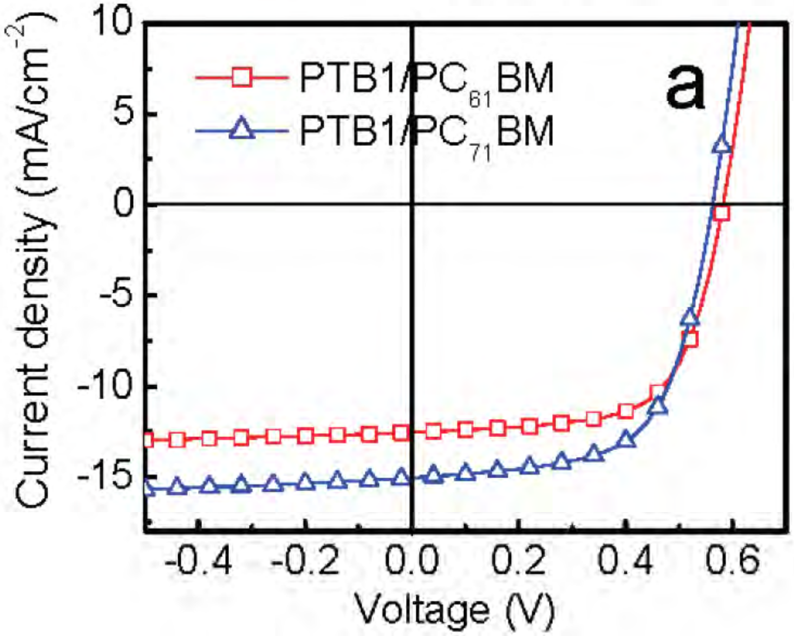
New polymers with extended absorption band and C71

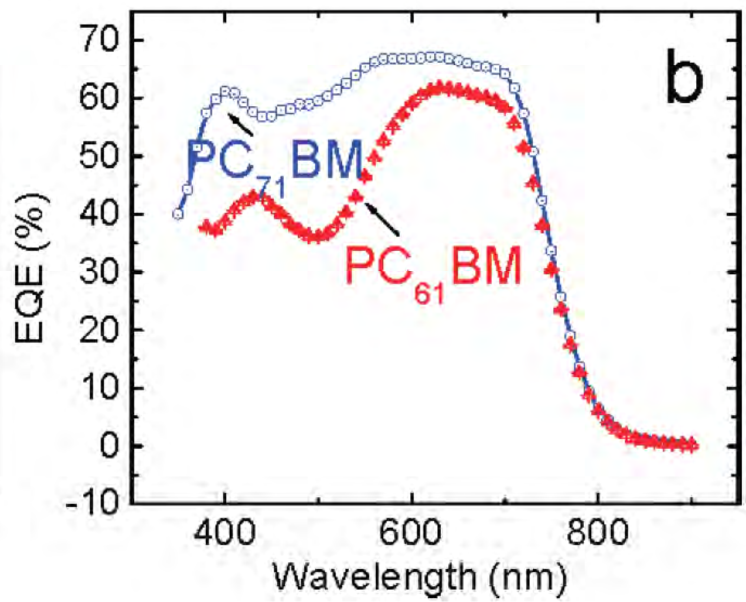
Eff	5.6%
Voc	0.56 V
Isc	15.6 mA/cm^2
FF	65%

Uncertified





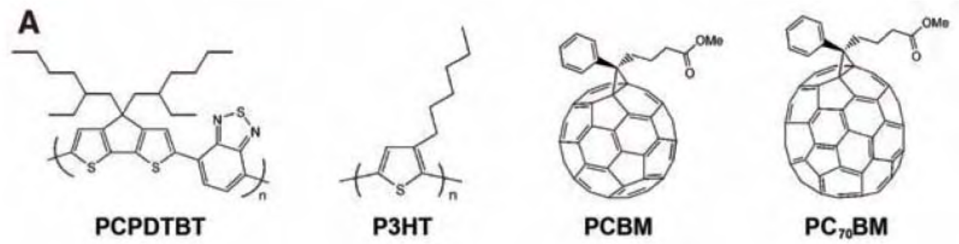




Recent OPVs: **K. Lee** (Gwangju Institute of Science and Technology, Korea

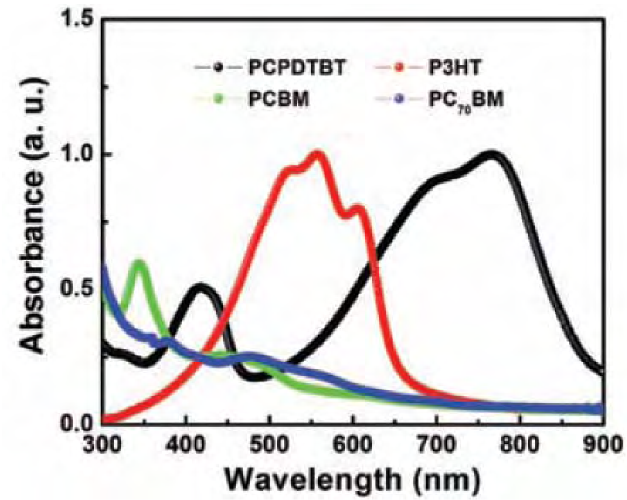
A. Heeger, UCSB, SCIENCE 317, 222 (**2007**)

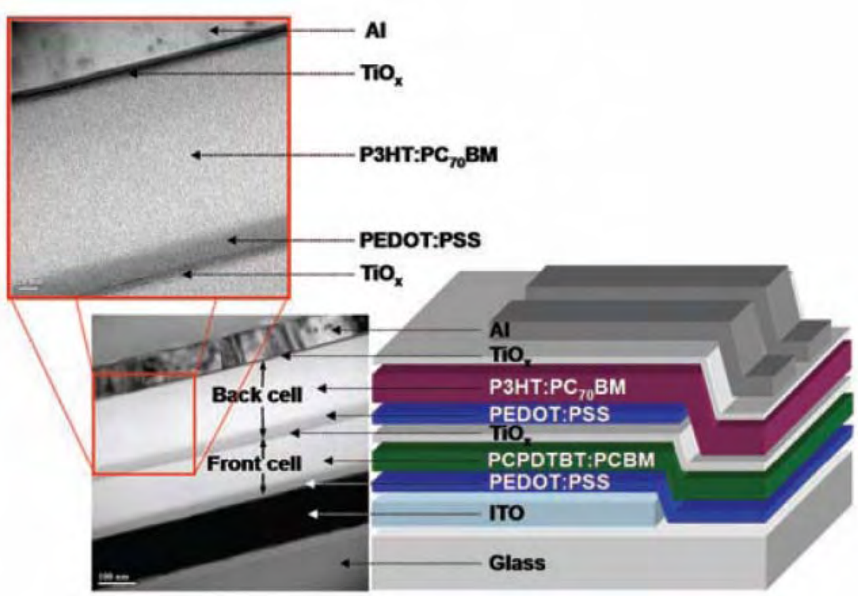
Tandem OPV with TiOx as interconnect layer

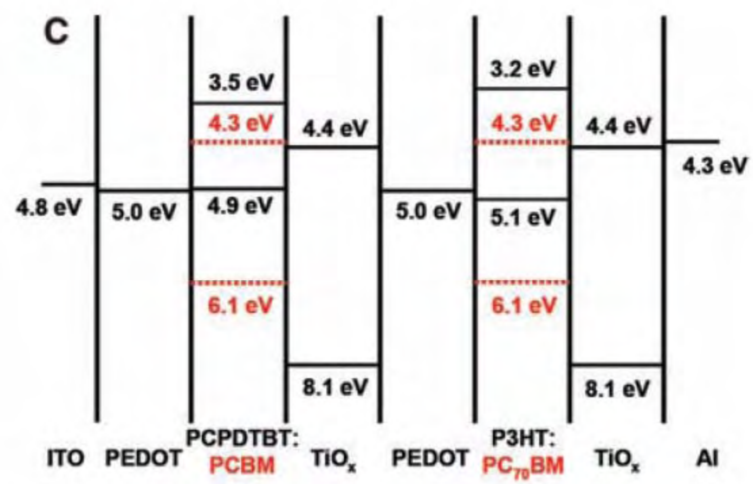


Eff	6.5%
Voc	1.24 V
Isc	7.8 mA/cm^2
FF	67%

Uncertified



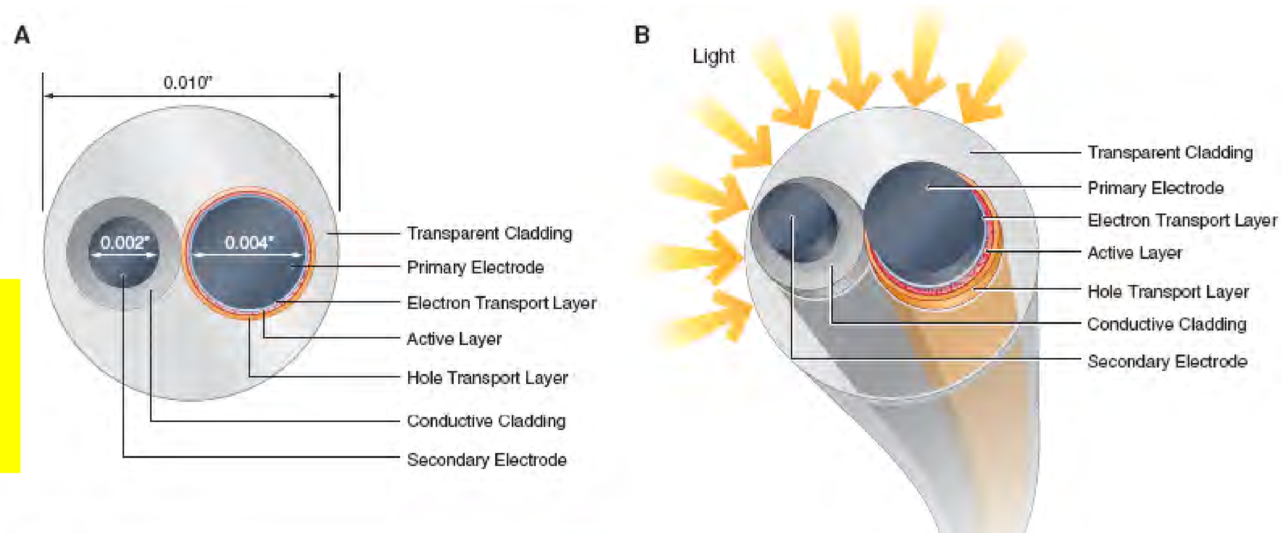


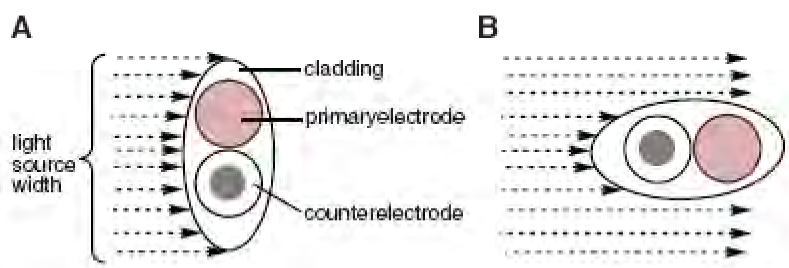


Recent OPVs: **R. A. Gaudiana (Konarka)** , Science 324, 232 (**2009**)

OPV Wires

Efficiency values of the wires range from 2.79% to 3.27%.





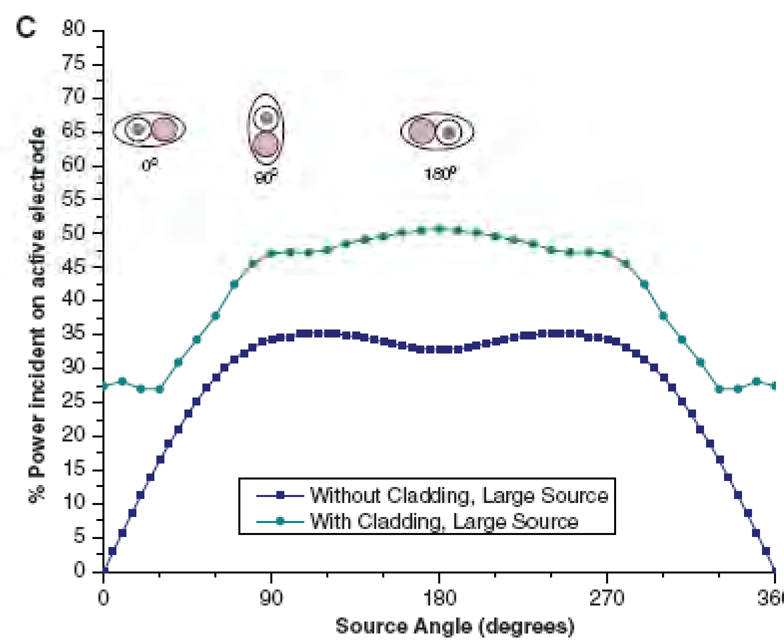
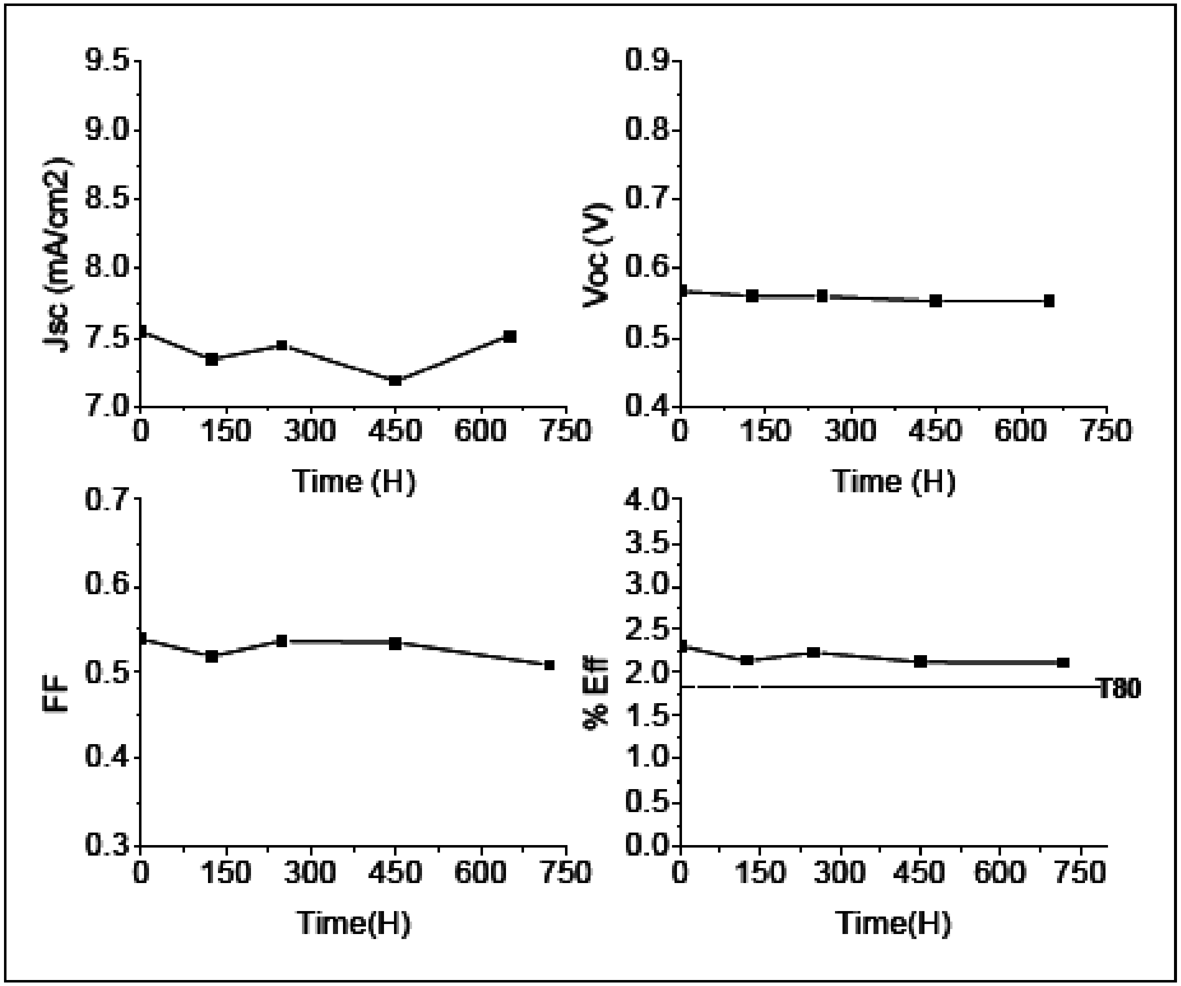


Fig. 3. (**A**) Light source equal to long axis of cladding ellipse. (**B**) Width of light source remains constant as the spiral-wrapped counter electrode wire rotates through 360°. (**C**) The power absorbed by the primary electrode wire as a function of the position of the spiral-wrapped counter electrode wire.

Recent OPVs: **DW Laird (Plextronics)**, SPIE (**2007**), Vol. 3, P6656-12

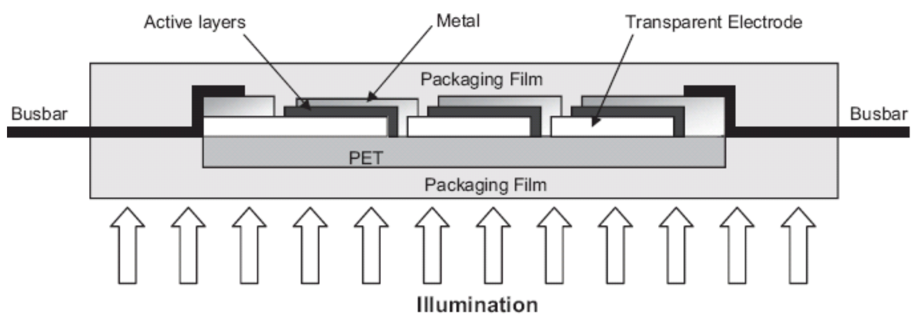
OPV Lifetime Data from Plextronics – Rooftop test (Pittsburg, PA) 7/07

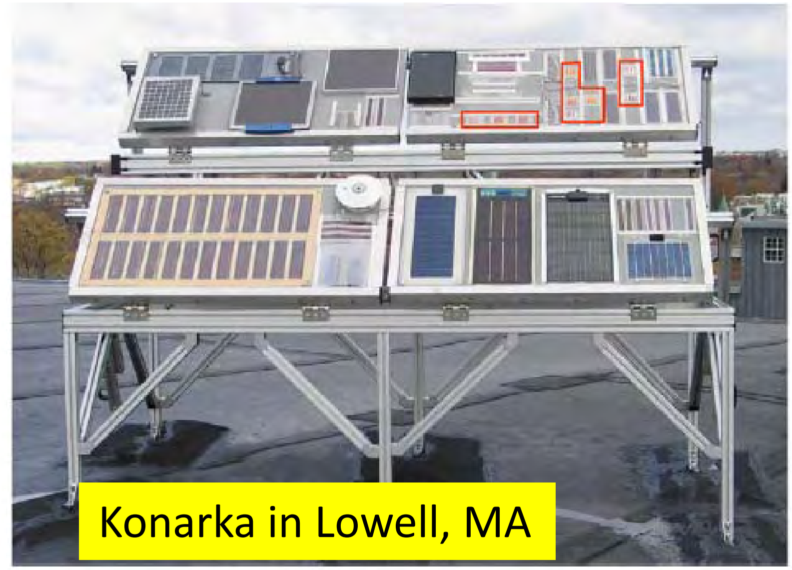
OPV: P3HT:PCBM



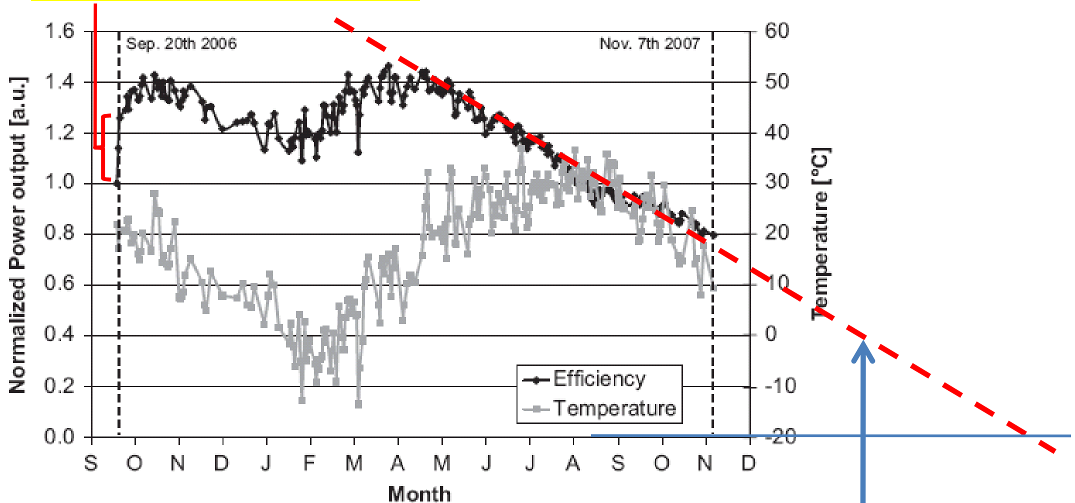
Recent OPVs: Solar Energy Materials and Solar Cells 92, 727 (**2008**)

OPV lifetime data from Konarka Technologies

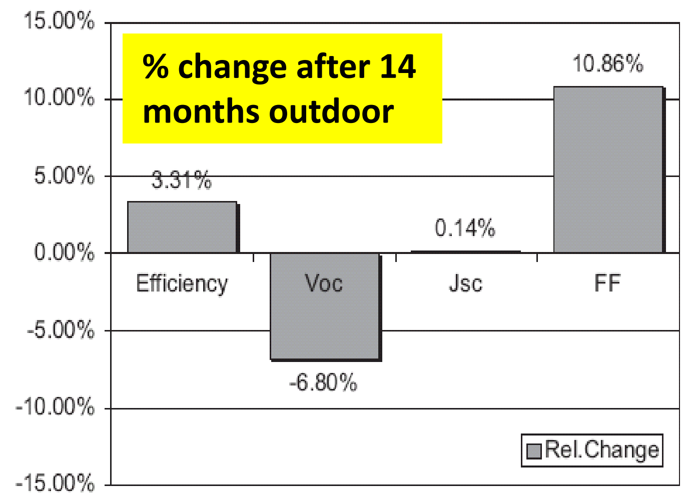




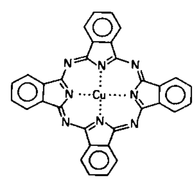
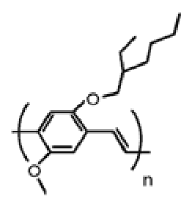
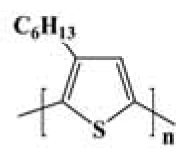
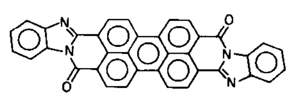
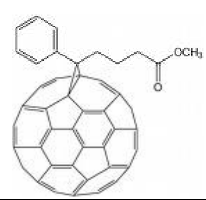
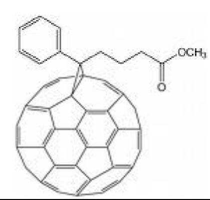
14% jump initially



Eff. degradation: 10% per month

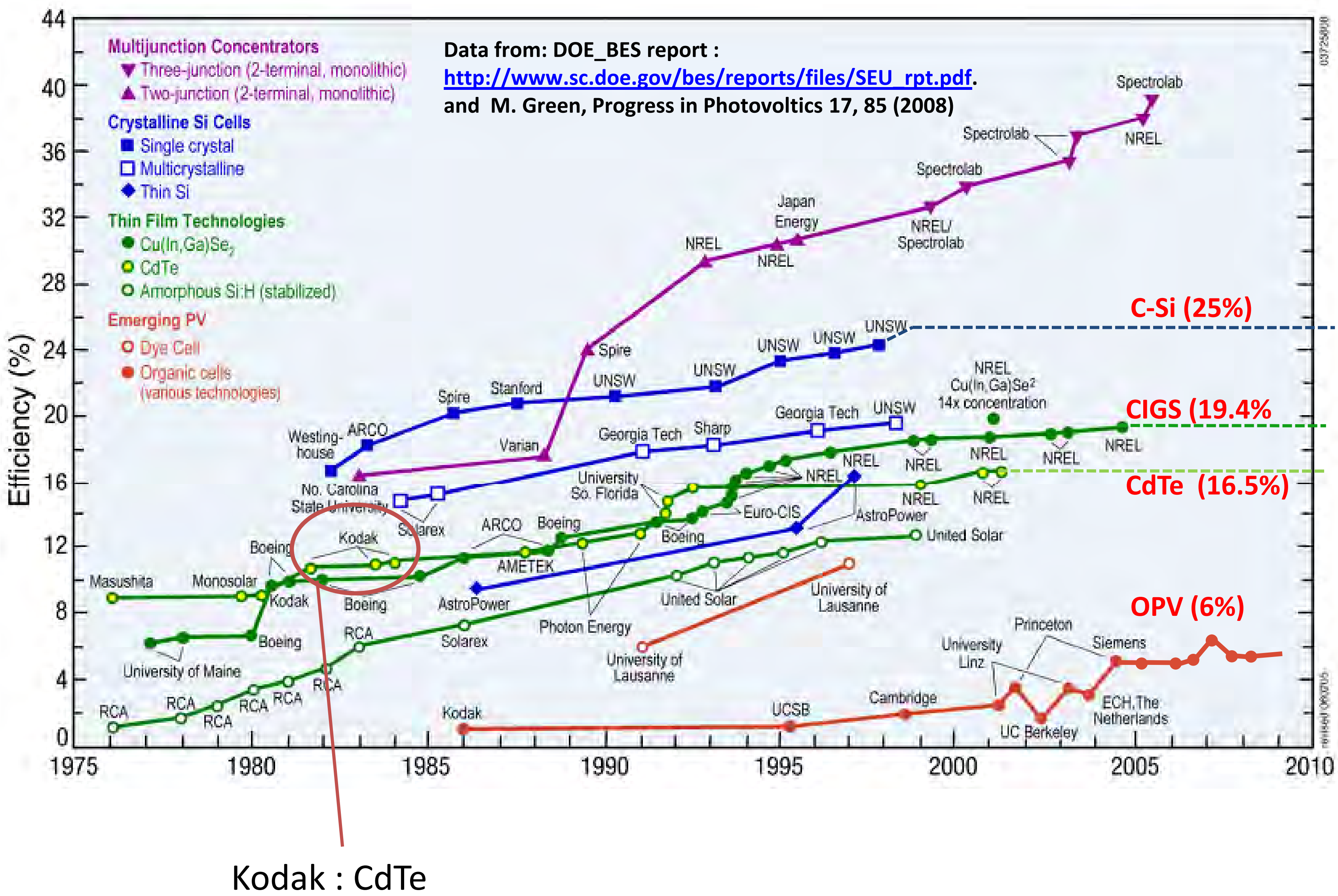


Organic Photovoltaic cells

Year	1986	1995	2005	2015
Device Structure	Heterojunction	Bulk heterojunction	Bulk heterojunction	TBD
Efficiency	1%	1%	5%	>10%
Materials donor				TBD
Materials acceptor				TBD

Will need major breakthroughs!!

Historical Data and Highest Confirmed Efficiencies for Solar Cells



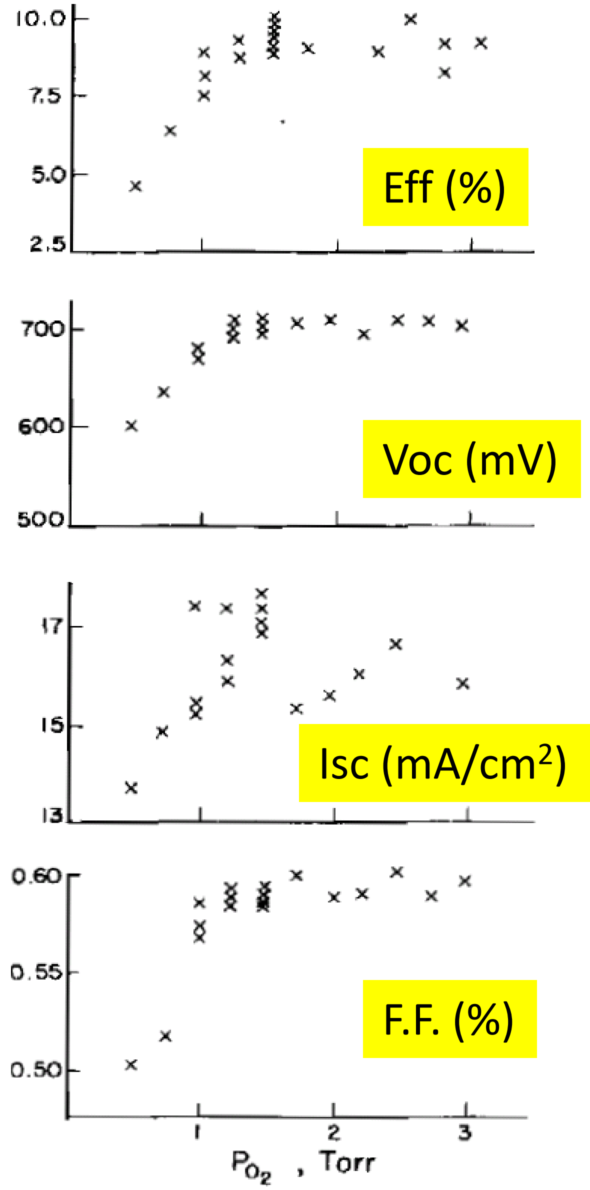
Historical CdS/CdTe: **Tyan (Kodak)**, IEEE Photovoltaic Specialists Conf., p840 (**1984**)

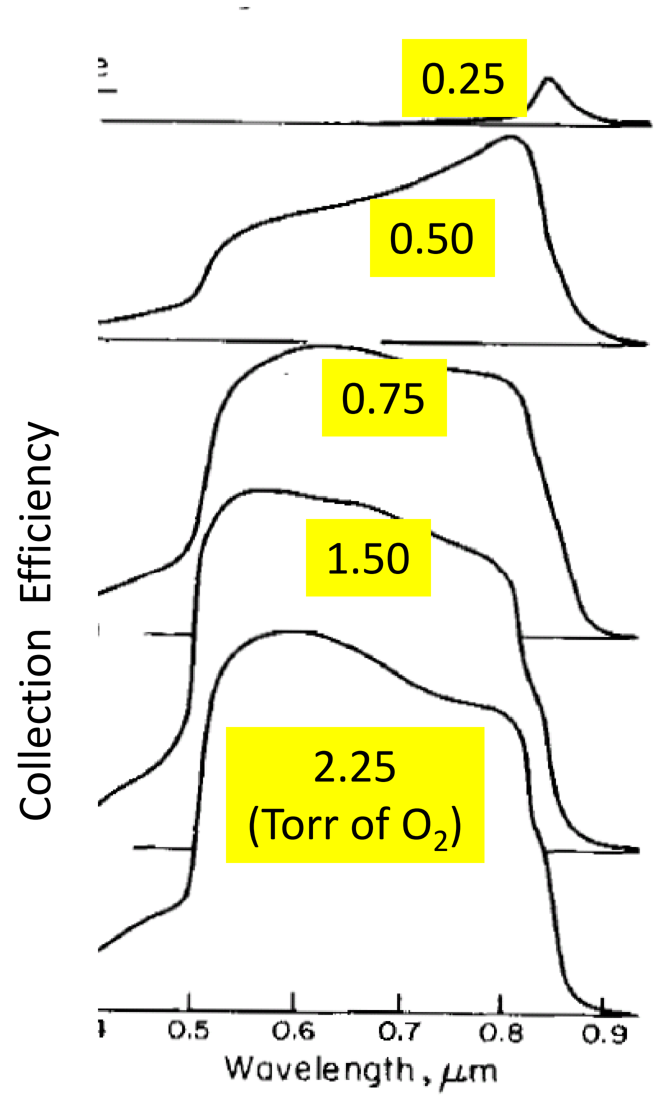
Discovery of oxygen doped p-CdTe and efficient n-CdS/p-CdTe solar cells

Close-space sublimation deposition – high-rate deposition of CdTe

Eff	10 %
Voc	705 mV
Isc	17.3 mA/cm^2
FF	60%

Uncertified, 75 mW/cm^2

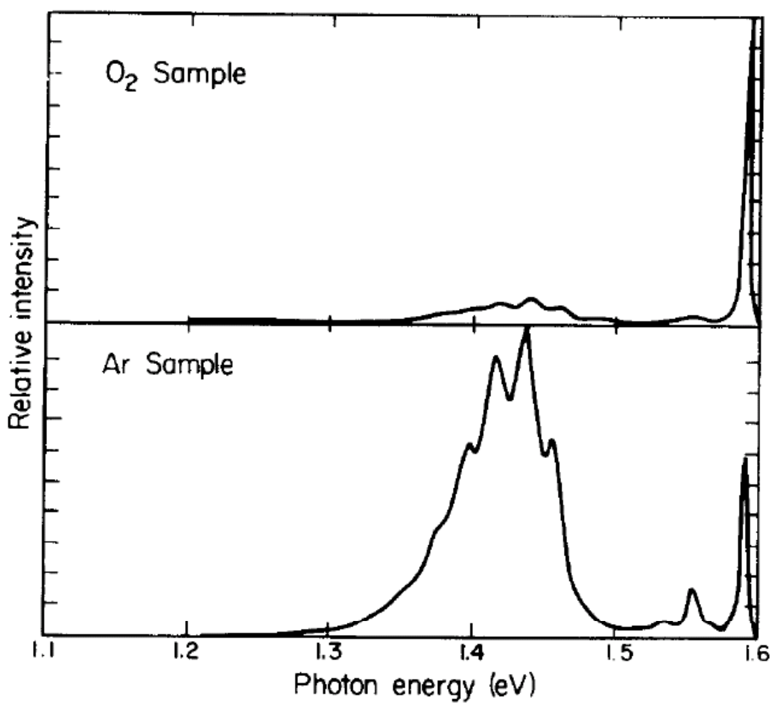




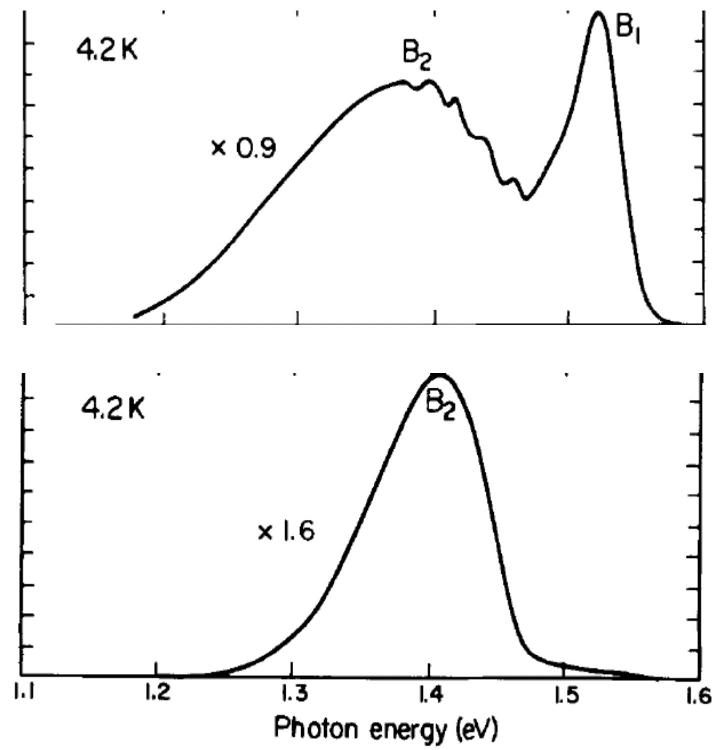
Historical CdS/CdTe: **Tang (Kodak)**, J. Appl. Phys. 55, 3866 (**1984**)

Oxygen doping in CdTe – deep-level defects

PL: Excitation at free CdTe surface



PL: Excitation at CdS/CdTe interface

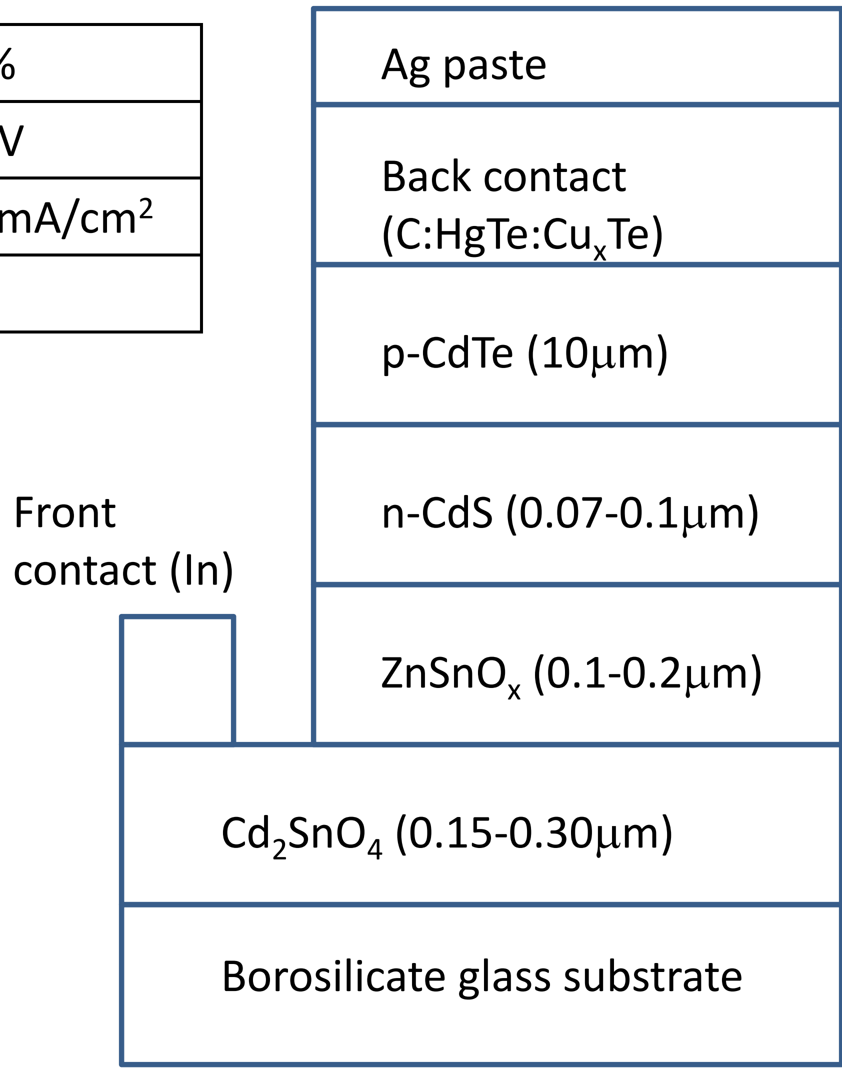


Recent CdTe papers: **Wu (NREL),** Solar Energy 77, 803 (**2004**)

Record efficiency of 16.5%

Critical processes for making record-efficiency CdS/CdTe solar cells:

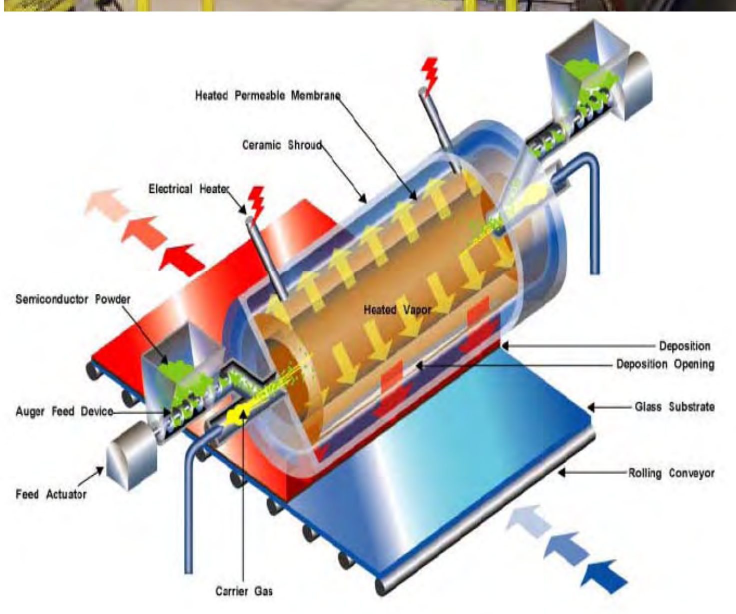
Eff	16.5 %
Voc	845 mV
Isc	25.88 mA/cm^2
FF	77.5%



Annealing of CdTe with $CdCl_2$, a critical step in producing "quality" CdTe and CdS/CdTe junction

Bi-layer TCO – low resistivity Cd_2SnO_4 electrode and high resistivity ($ZnSnO_x$) buffer layer

Thin-film CdTe Photovoltaic Production



- First Solar's total production capacity for CdS/CdTe solar cells will reach **1 GW** in 2009
- Less than 20% is produced in the U.S.

Key enabling technology:
Vapor transport deposition process capable of **1 micron / s rate**

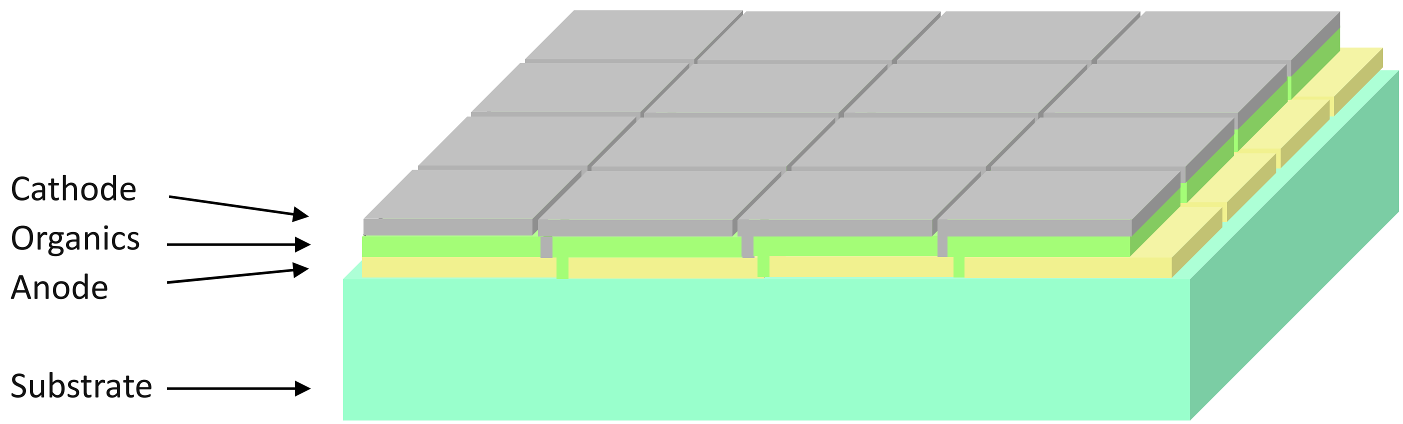
Subcontract Report : NREL/SR-520-39669 April 2006

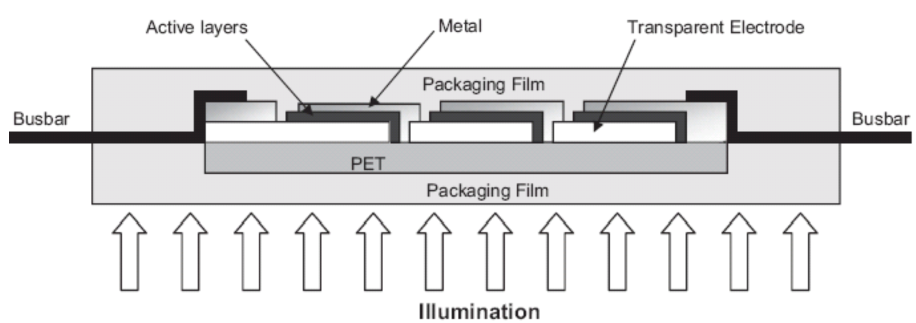
OLED Thin-Film Deposition Technology
Kodak's Vapor Injection Source Technology (VIST)

- **Scalable linear source – demonstrated at Gen 5**
- **Multi-component co-deposition**
- **Excellent material utilization – up to 90%**

http://www.kodak.com/eknec/PageQuerier.jhtml?pq-locale=en_US&pq-path=11689

Monolithic Serially Connected Segments for Large-area OLED Panels: To reduce IR losses and current load

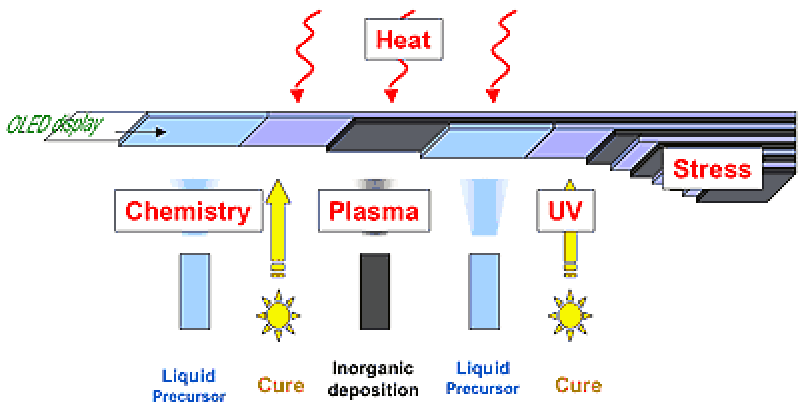




- ➢ Three-scribe process – to isolate anode, organic layer, cathode
- ➢ For OLEDs and OPVs – serially connected cells

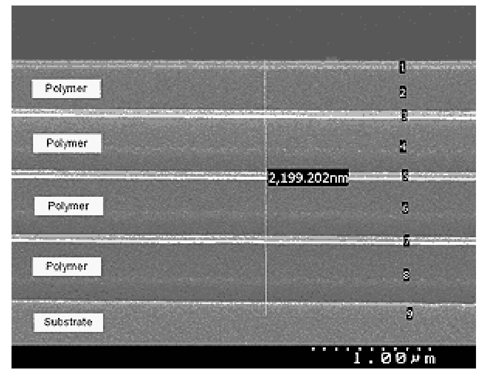
OLED / OPV encapsulation and packaging – e.g. barrier coat from Vitex Systems

Roll-to-roll process

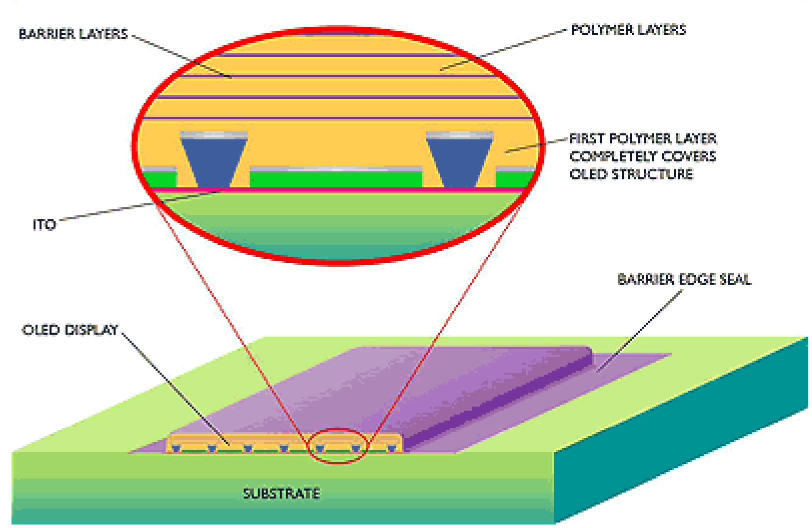


Deposition tool

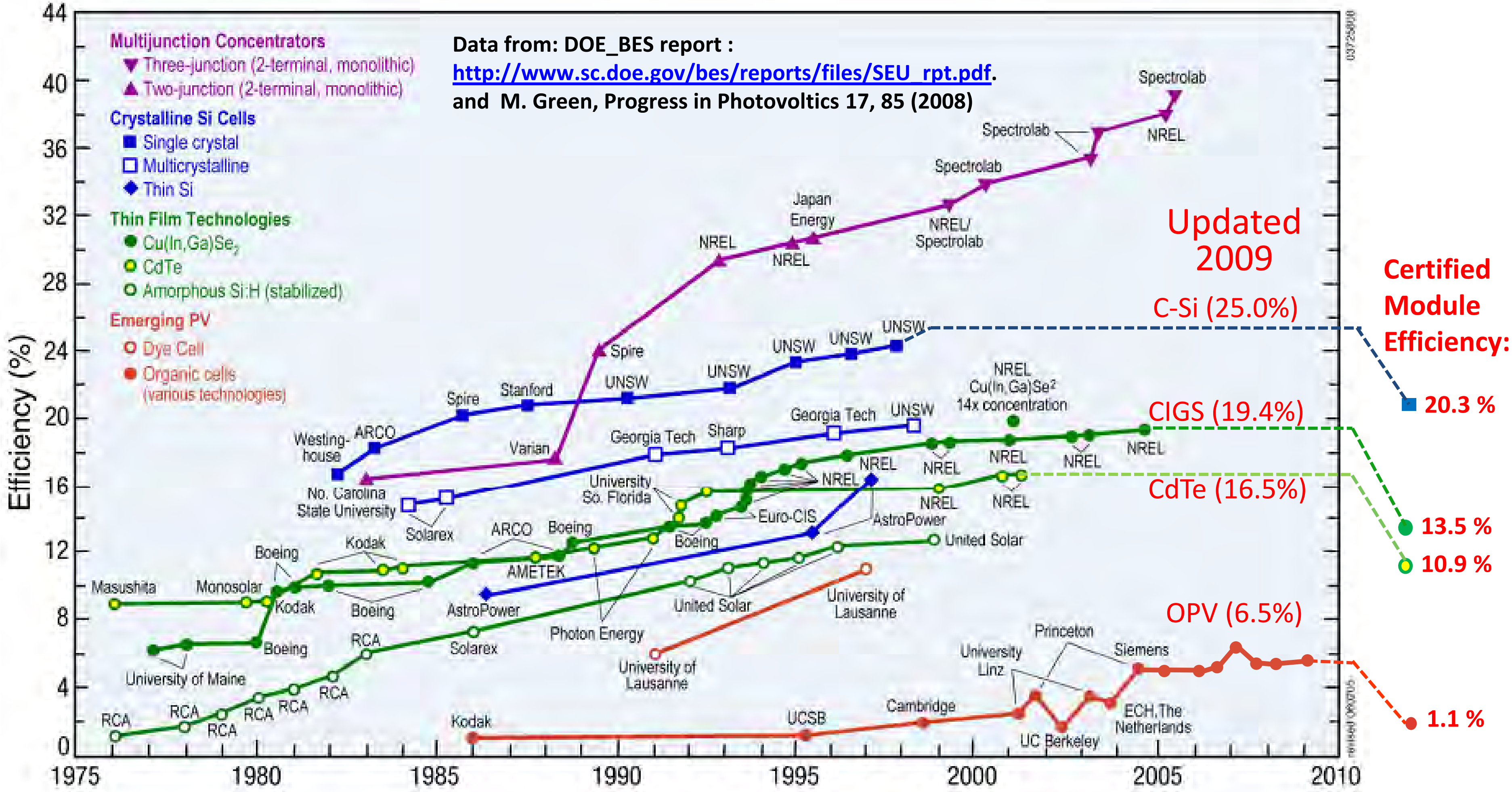
Multi organic/inorganic layers



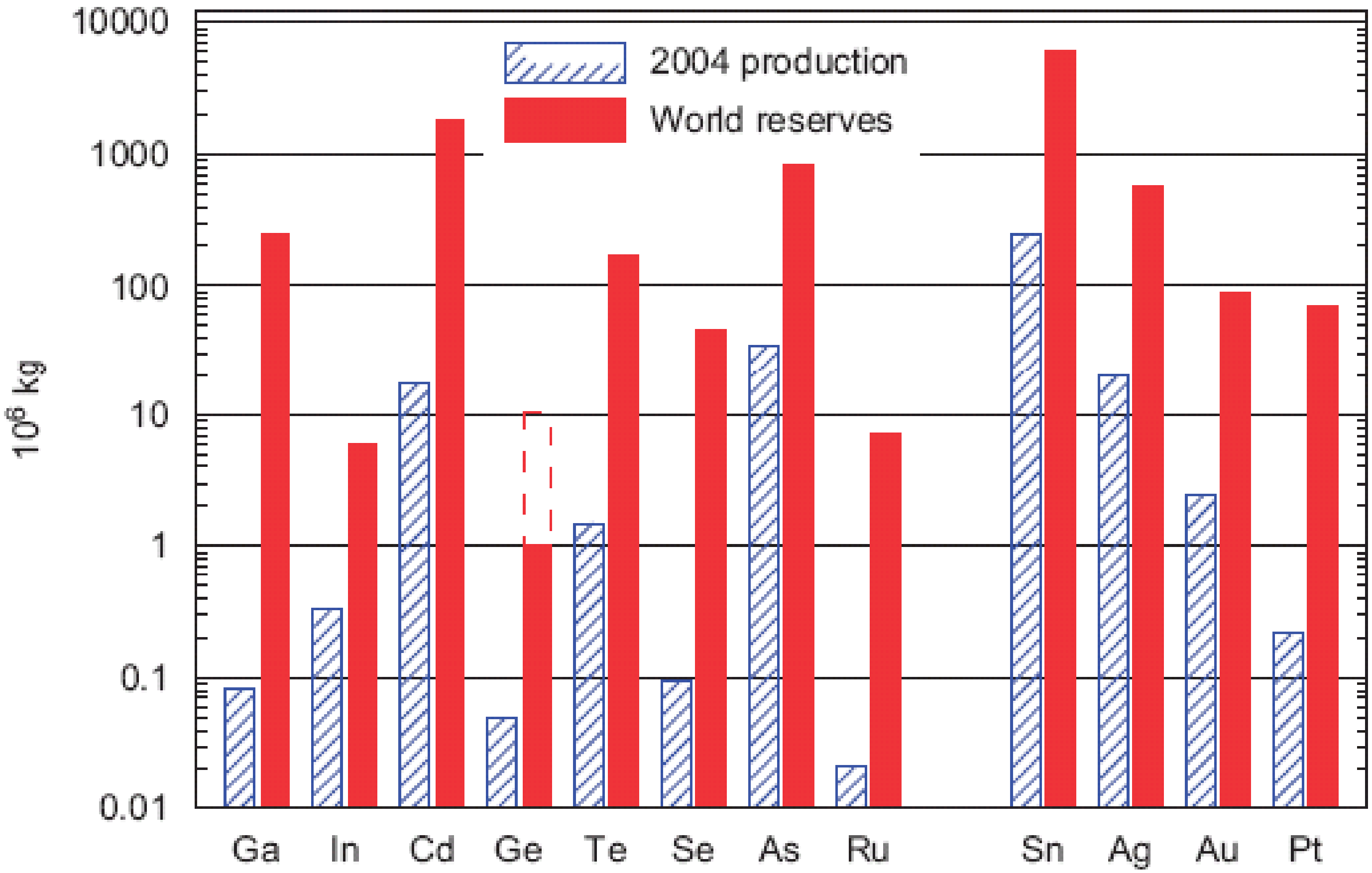
Encapsulated OLED



Historical Data and Highest Confirmed Efficiencies for Solar Cells and Modules

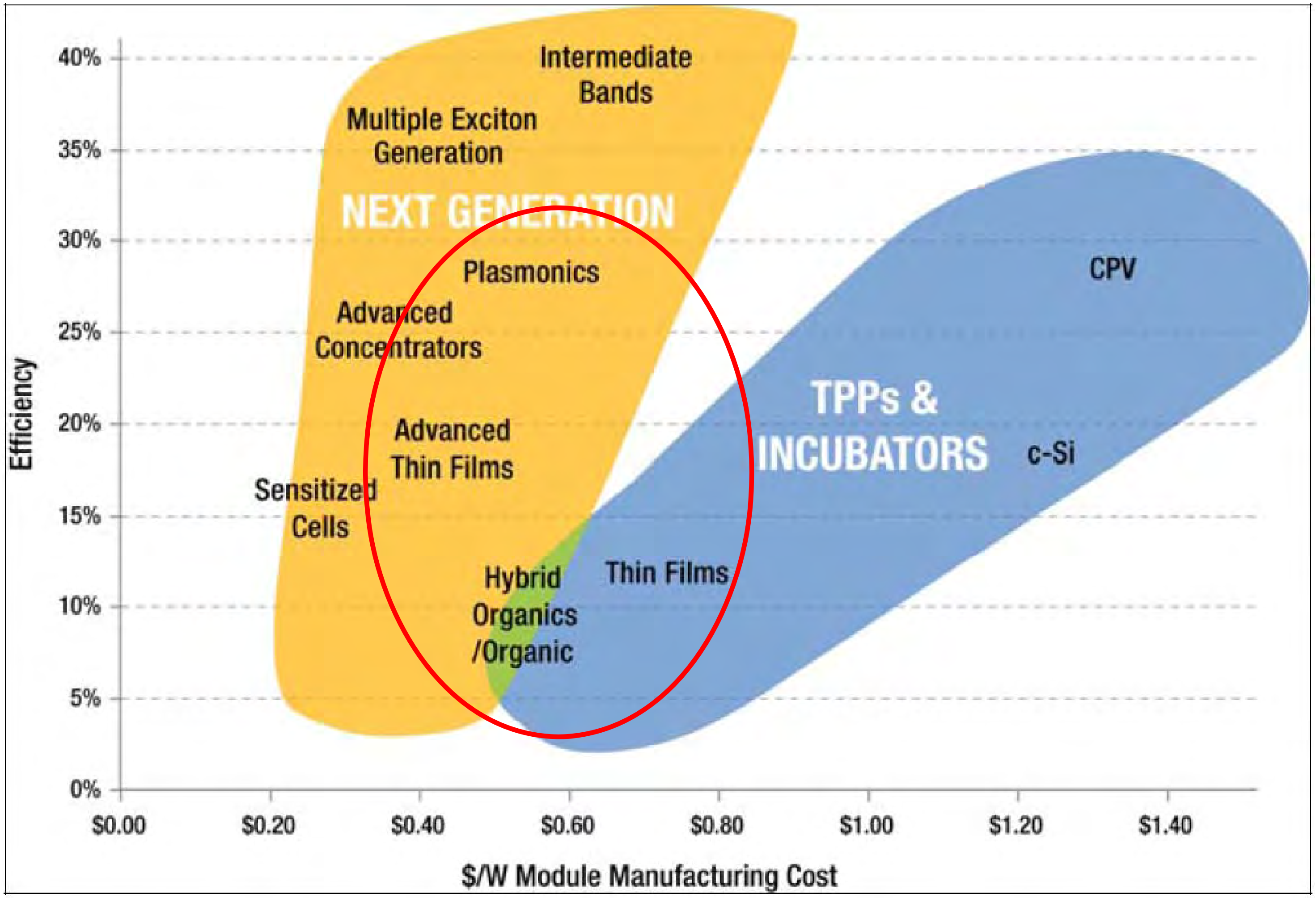


Materials Abundance Issues:



Freundlich etal, Renewable Energy 33 (2008) 180–185

Cost and Efficiency Potential – DOE Aims



Source: DOE Solar Energy Technologies Program – 2008-2012 MYPP

Solar Photovoltaics Challenges:

- Transformational PV technologies are needed – cost/kWh is the main driver
- CdTe and CIGS are potentially low-cost alternatives to silicon
- OPV faces uphill challenges and stiff competitions
- Low carrier mobilities and field dependent electronic processes are the key material issues with OPV