National Renewable Energy Laboratory
Innovation for Our Energy Future

The importance of basic science in addressing the challenges of organic photovoltaics

Venue:
Plastic Electronics
Berlin, Germany

Presenter:
Garry Rumbles

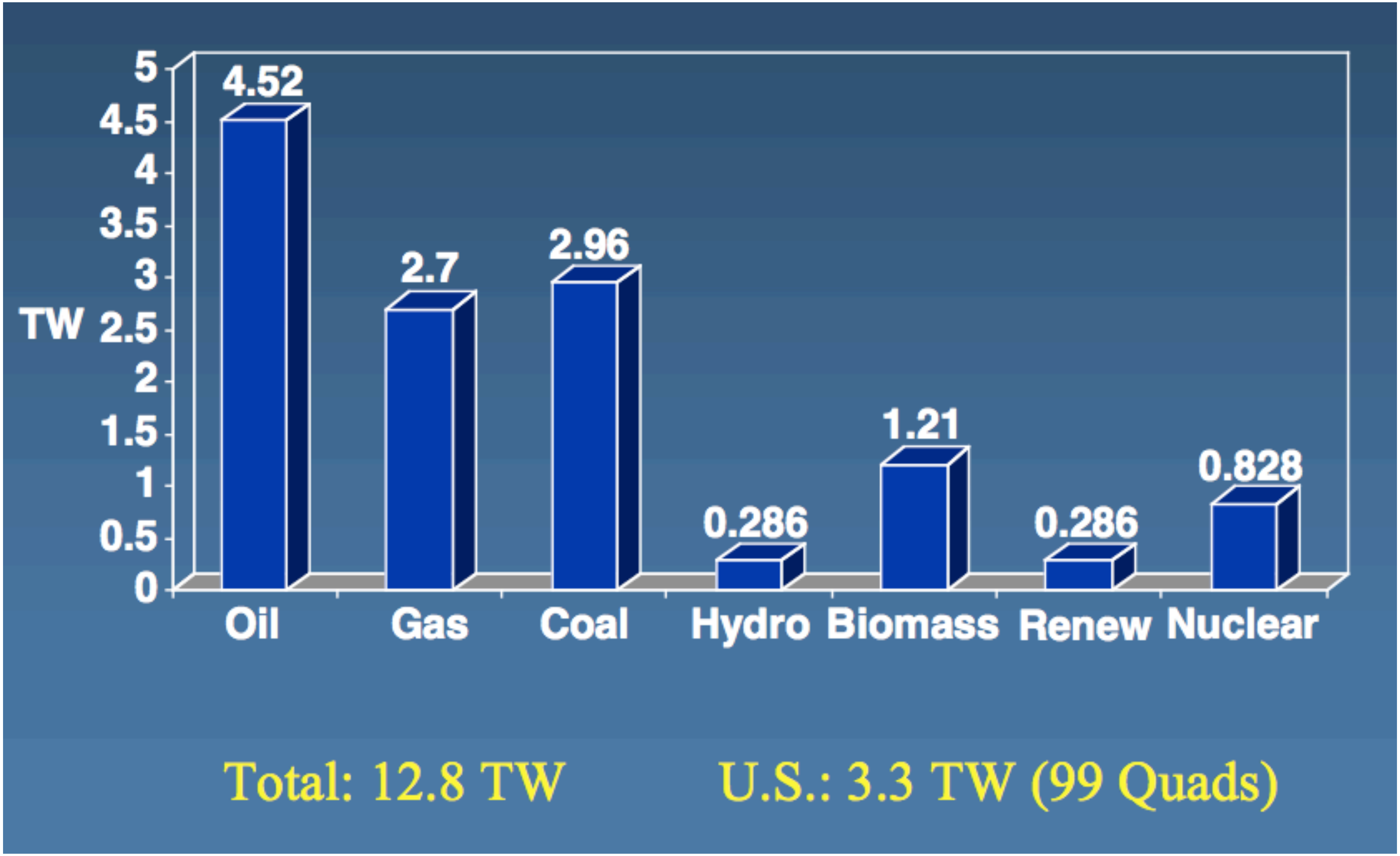
Date:
29th October, 2008

NREL/PR-2A0-44449
NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC

Outline:

- The Energy issue
- Photovoltaics
- Why organics?
- Technologies
- Basic issues

Energy Usage



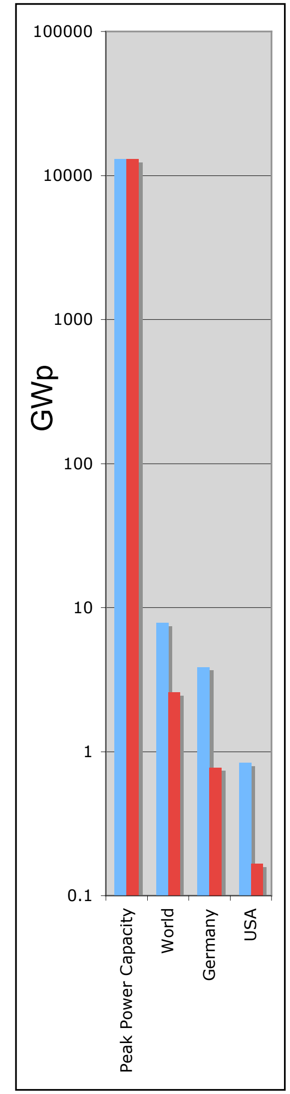
Renewables

	Theoretical	Practical	Comments
Wind	50 TW	2 TW	Offshore and Demographics
Geothermal		1.3 GW	Needs drilling breakthrough
Hydro	4.6 TW	1 TW	0.3 TW currently
Biomass	20 TW	6 TW	31% of land, 0.3% efficient, Water
Solar	1.2×10^5 TW	600 TW	Photosynthesis = 90 TW

Installed capacity!

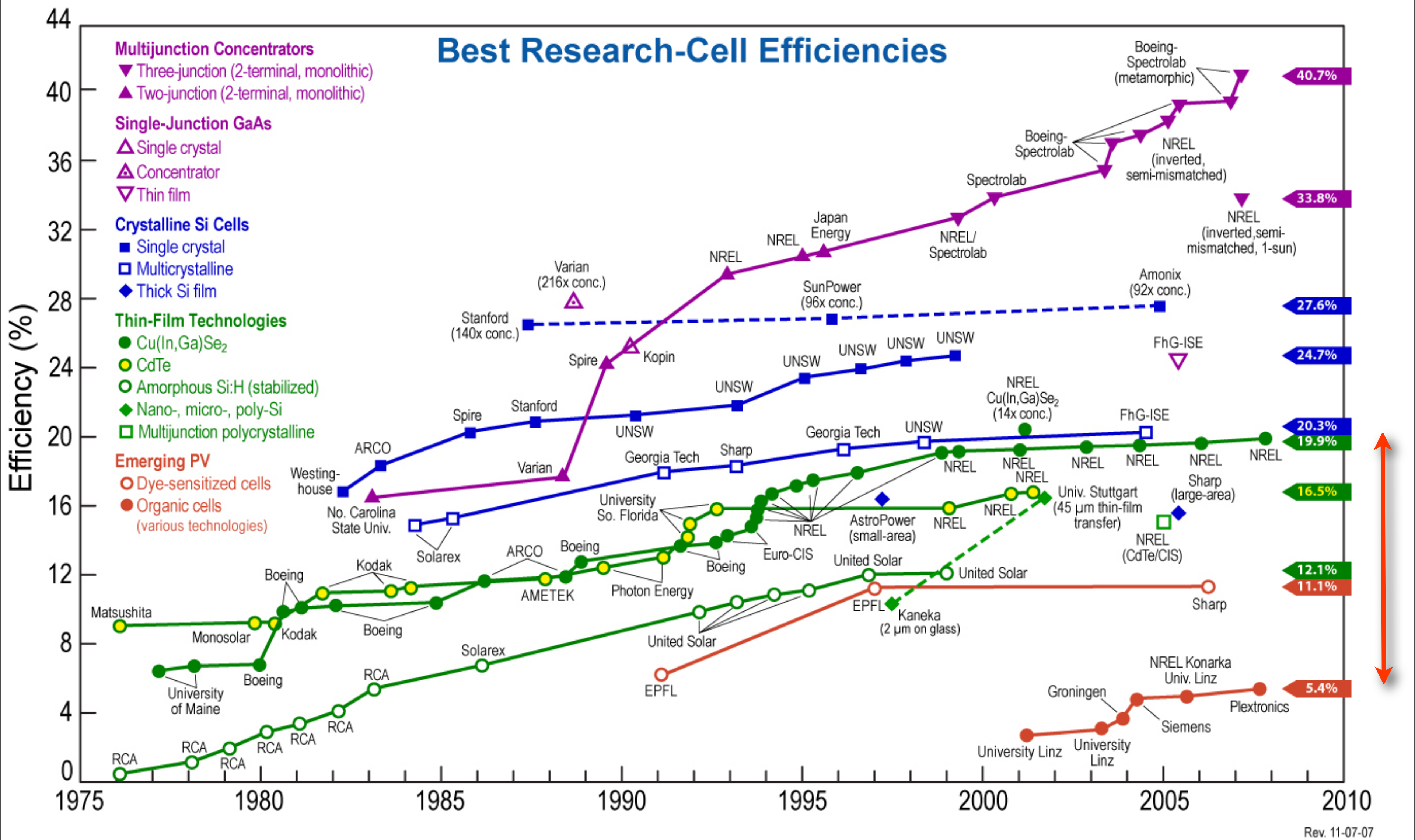
Produced, Installed & Total Photovoltaic Peak Power Capacity (MWp) as of the end of 2007

Country or Region Report Nat. Int.	off grid Δ	on grid Δ	Installed 2007	off grid Σ	on grid Σ	Total 2007	Wp/capita Total	Module Price €/Wp	kW·h/kWp·yr Insolation	Feed-in Tariff EU¢/kW·h
World	127.9	2,130	2,258	662.3	7,178	7,841		2.5-11.2	0800-2902	0-59.3
Germany[26][27]	35	1,100	1,135	35	3,827	3,862	46.8	4.0-5.3	1000-1300[28]	51.8-56.8
Japan[29][27]	1.562	208.8	210.4	90.15	1829	1919	15	2.96	1200-1600	Ended(2005)
United States[30][27]	55	151.5	206.5	325	505.5	830.5	2.8	2.98	0900-2150[28]	1.2-31.04(CA)
Spain ?[27]	22	490	512	29.8	625.2	655	15.1	3.0-4.5	1600-2200	18.38-44.04
Italy[31][27]	0.3	69.9	70.2	13.1	107.1	120.2	2.1	3.2-3.6	1400-2200	36.0-49.0
Australia[32][27]	5.91	6.28	12.19	66.45	16.04	82.49	4.1	4.5-5.4	1450-2902[33]	0-26.4(SA'08)
South Korea[34][27]	0	42.87	42.87	5.943	71.66	77.60	1.6	3.50-3.84	1500-1600	56.5-59.3
France[35][27]	0.993	30.31	31.30	22.55	52.68	75.23	1.2	3.2-5.1	1100-2000	30.0-55.0
Netherlands[36][27]	0.582	1.023	1.605	5.3	48	53.3	3.3	3.3-4.5	1000-1200	1.21-9.7
Switzerland[37][27]	0.2	6.3	6.5	3.6	32.6	36.2	4.9	3.18-3.30	1200-2000	9.53-50.8
Austria ?[27]	0.055	2.061	2.116	3.224	24.48	27.70	3.4	3.6-4.3	1200-2000	>0
Canada[38][27]	3.888	1.403	5.291	22.86	2.911	25.78	0.8	3.76	0900-1750	0-29.48(ON)
Mexico ?[27]	0.869	0.15	1.019	20.45	0.3	20.75	0.2	5.44-6.42	1700-2600	None
United Kingdom[39][27]	0.16	3.65	3.81	1.47	16.62	18.09	0.3	3.67-5.72	0900-1300	0-11.74(exprt)
Portugal ?[40]	0.2	14.25	14.45	2.841	15.03	17.87	1.7		1600-2200	
Norway[41][27]	0.32	0.004	0.324	7.86	0.132	7.992	1.7	11.2	0800-0950	None
Sweden[42][27]	0.271	1.121	1.392	4.566	1.676	6.242	0.7	3.24-7.02	0900-1050	None
Denmark[43][27]	0.05	0.125	0.175	0.385	2.69	3.075	0.6	5.36-8.04	0900-1100	None
Israel[44][27]	0.5	0	0.5	1.794	0.025	1.819	0.3	4.3	2200-2400	13.13-16.40
Country or Region Report Nat. Int.	off grid Δ	on grid Δ	Installed 2007	off grid Σ	on grid Σ	Total 2007	Wp/capita Total	Module Price €/Wp	kW·h/kWp·yr Insolation	Feed-in Tariff EU¢/kW·h



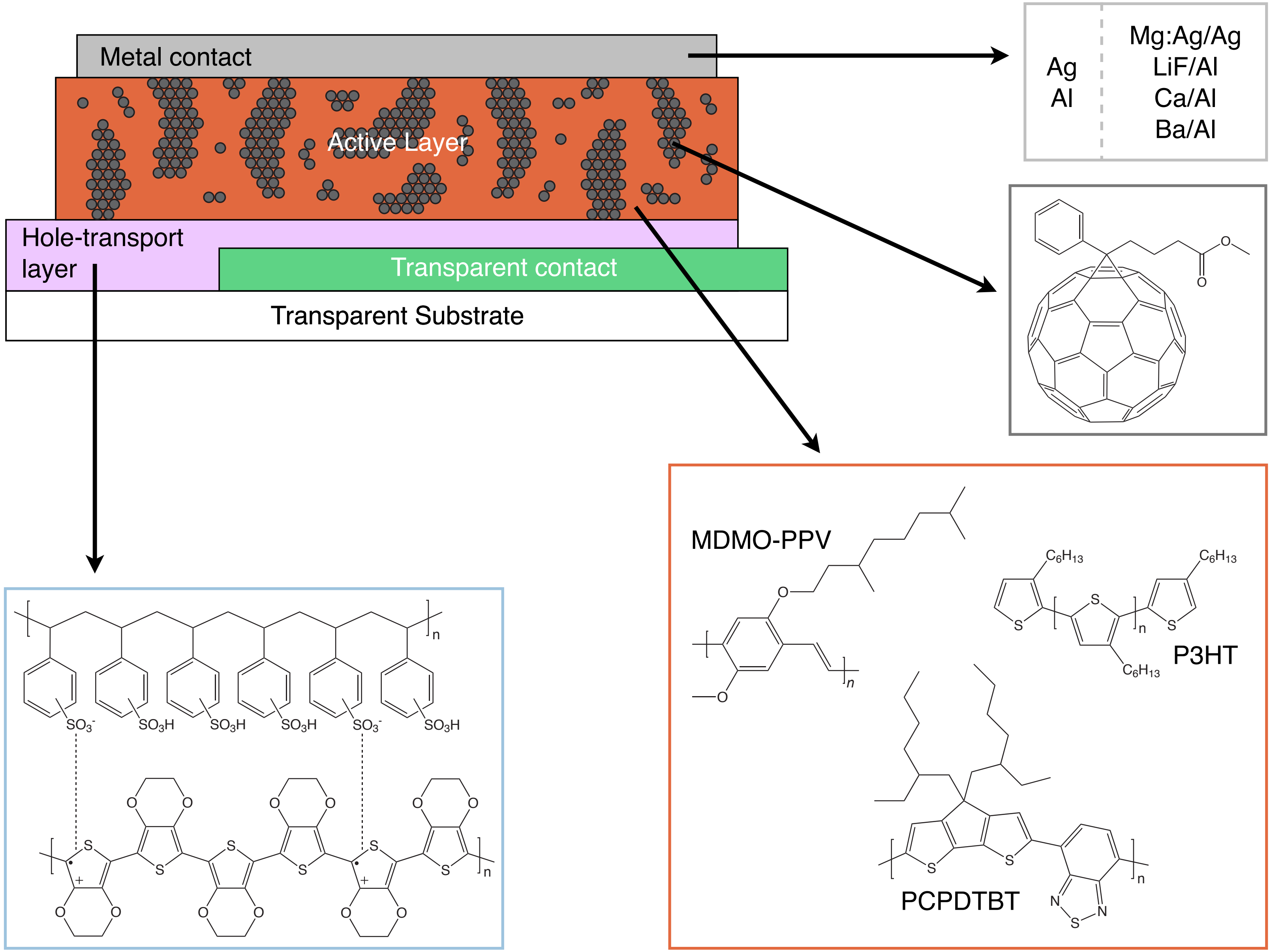
http://en.wikipedia.org/wiki?Photovoltaics

PV Research cell efficiencies

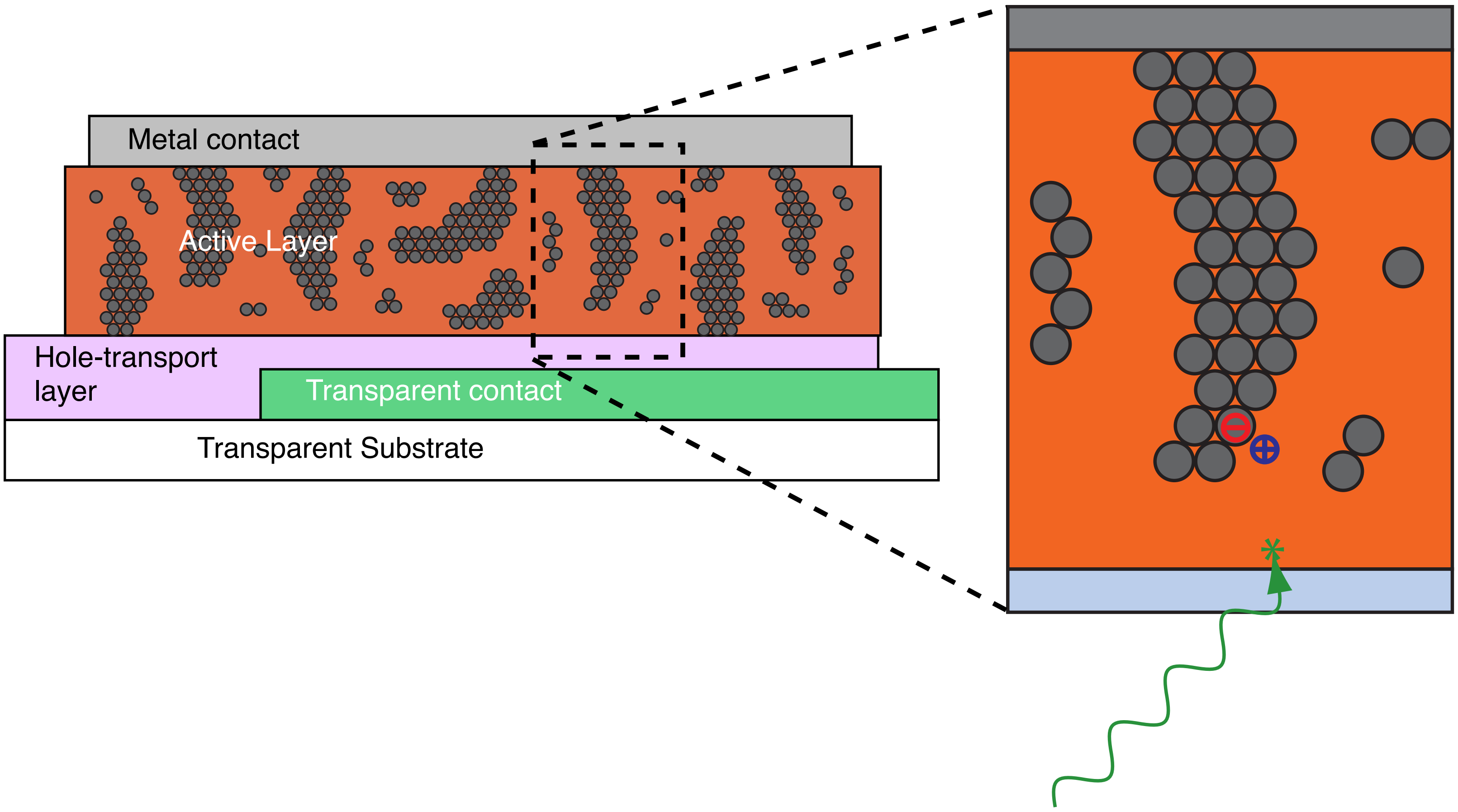


http://en.wikipedia.org/wiki/Solar_cell

Generic bulk heterojunction device



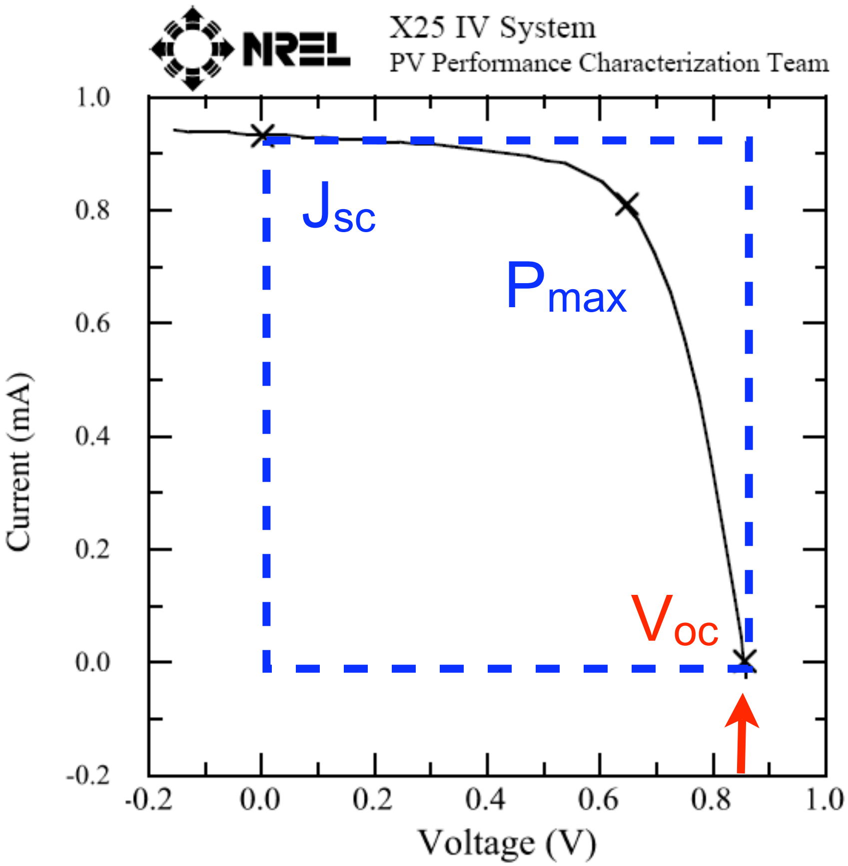
Fundamental understanding - Is this how it works?

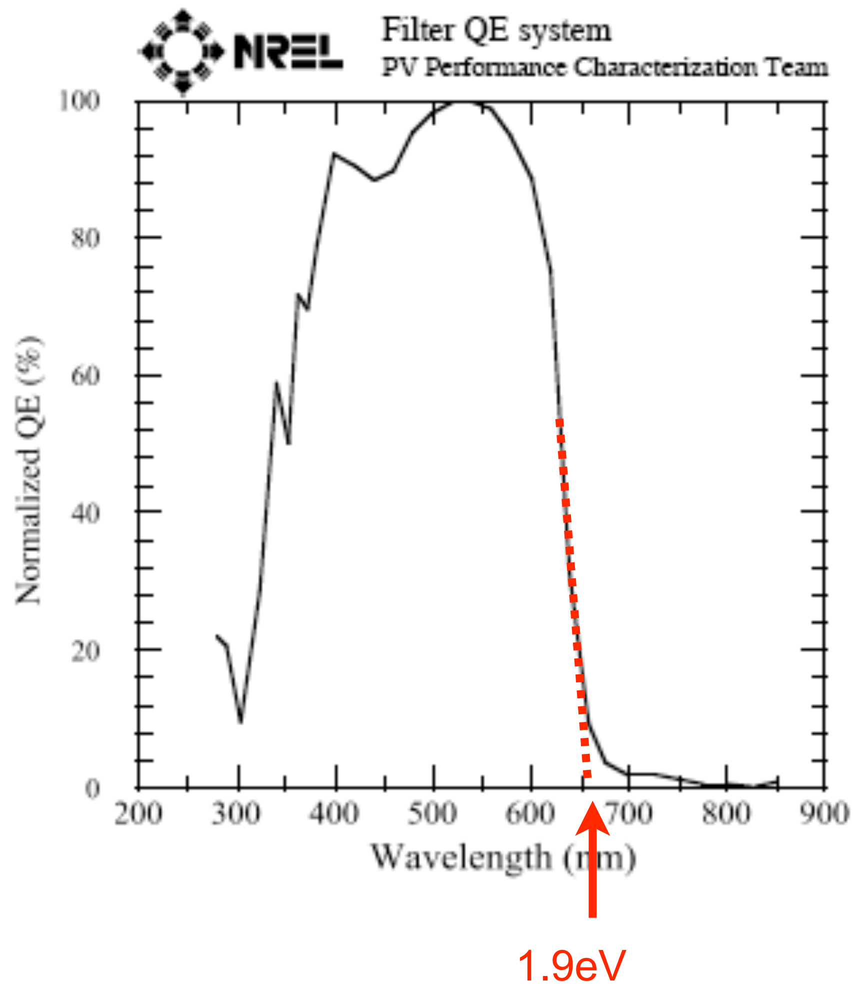


Plextronics - Plexcore® PV NREL-Certified Performance

Jul 17, 2007 11:50 Device Area: 0.096 cm^2

Spectrum: AM1.5-G (IEC 60904) Irradiance: 1000.0 W/m^2





V_{oc} = 0.8563 V

I_{sc} = 0.93132 mA

J_{sc} = 9.7013 mA/cm^2

Fill Factor = 65.26 %

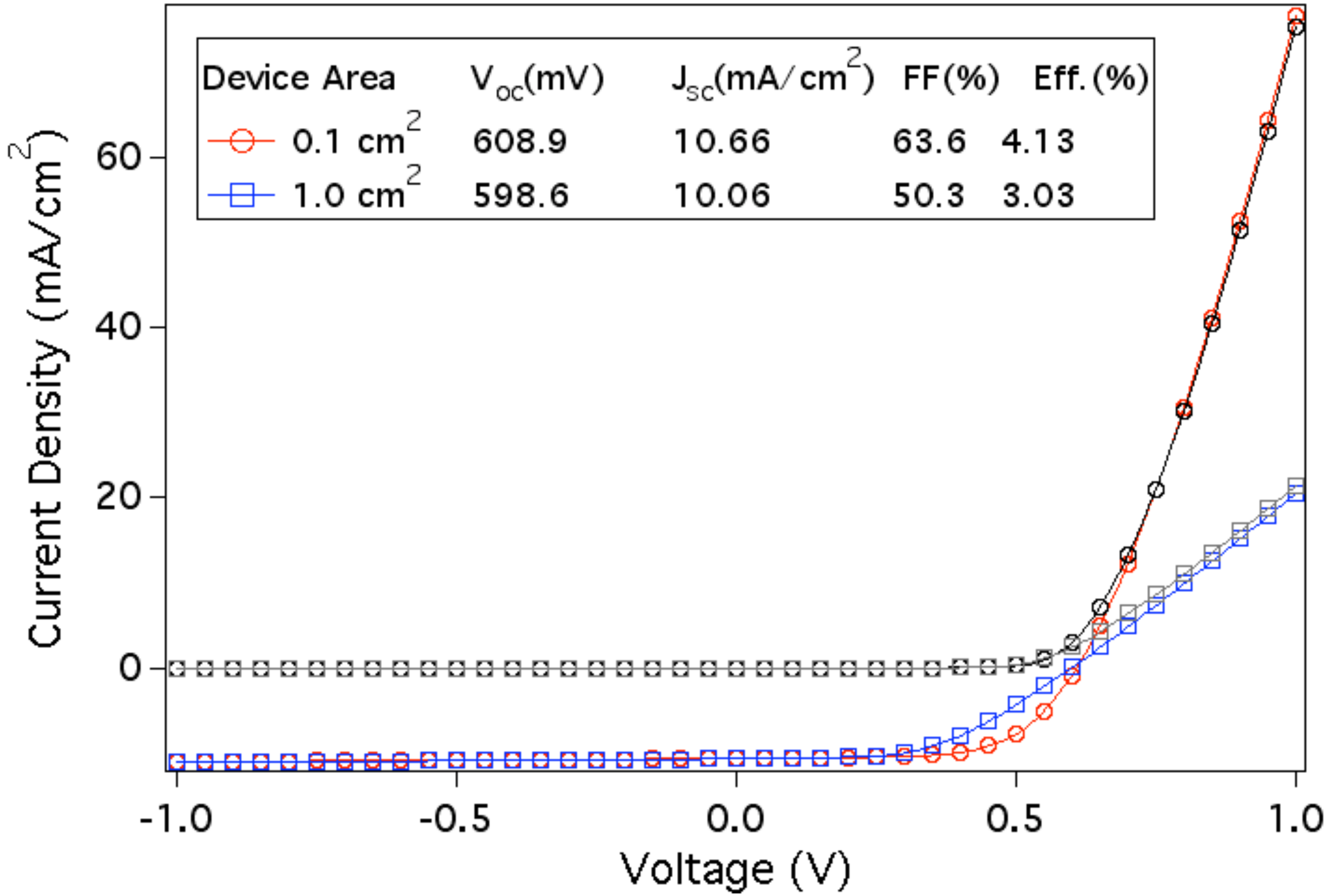
I_{max} = 0.80664 mA

V_{max} = 0.6452 V

P_{max} = 0.52048 mW

Efficiency = 5.42 %

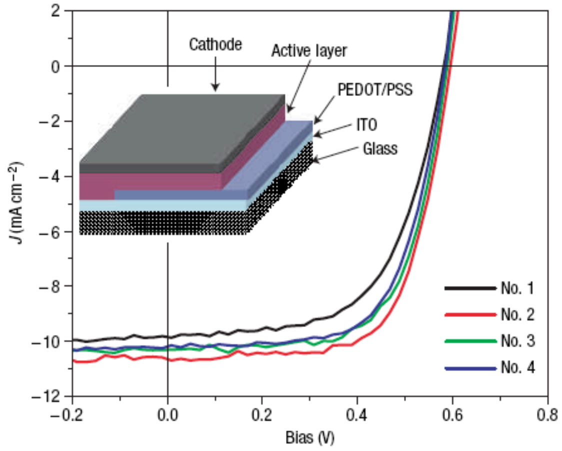
Size matters



Champion devices (P3HT:PCBM)

	Now	Realistic	Plan*	How?
V_{oc} (V)	0.62	0.65	1.1	Lower LUMO (and HOMO)
J_{sc} (mA/cm^2)	10	14	25	Shift absorption to red
FF (%)	67	75	80	Improve transparent electrode
Efficiency (%)	(4.2)	6.8	22	Larger carrier mobilities

Device development v Fundamental understanding



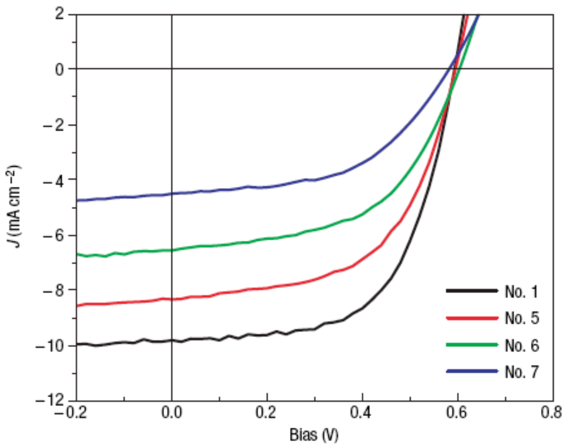
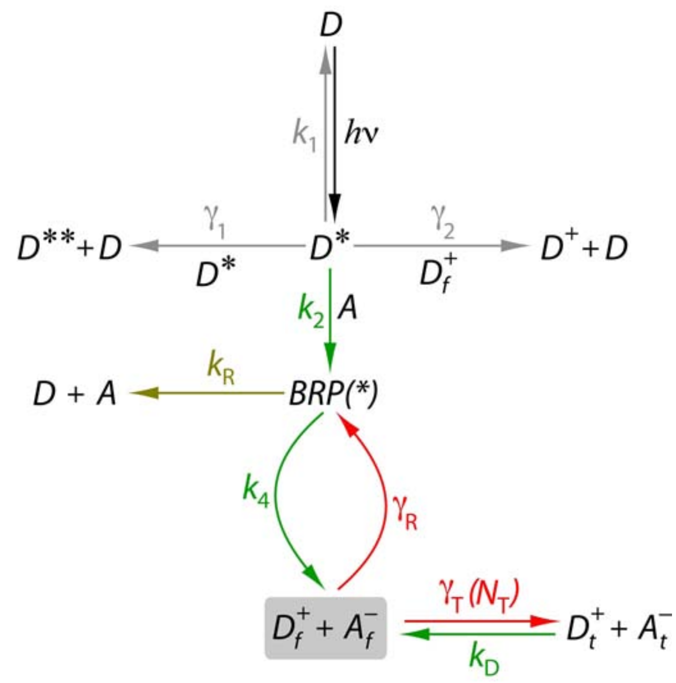


Table 1 Summary of device performance for various PV devices in the work.

Device no.	J_{SC} (mA cm^{-2})	V_{OC} (V)	PCE (%)	FF (%)	R_{SA} (Ω cm^2)
1	9.86	0.59	3.52	60.3	2.4
2	**10.6**	**0.61**	**4.37**	**67.4**	**1.7**
3	10.3	0.60	4.05	65.5	1.6
4	10.3	0.60	3.98	64.7	1.6
5	8.33	0.60	2.80	56.5	4.9
6	6.56	0.60	2.10	53.2	12.5
7	4.50	0.58	1.36	52.0	19.8

G. Li et al (UCLA) *Nat. Mat.*, **4(11)** 864 (2005)



$$\frac{dD^*}{dt} = L(t) - (k_1 + k_2')D^* - \gamma_1 (D^*)^2 - \gamma_2 . D^* . D_f^+$$

$$\frac{dBRP}{dt} = k_2' . D^* - (k_4 + k_R) BRP + \gamma_R . A^- . D_f^+$$

$$\frac{dD_f^+}{dt} = k_4 . BRP - \gamma_R . A^- . D_f^+ - \gamma_T . D_f^+ (N_T - D_t^+) + k_D . D_t^+$$

$$\frac{dD_t^+}{dt} = \gamma_T . D_f^+ (N_T - D_t^+) - k_D . D_t^+$$

Tandem Organic Solar Cells

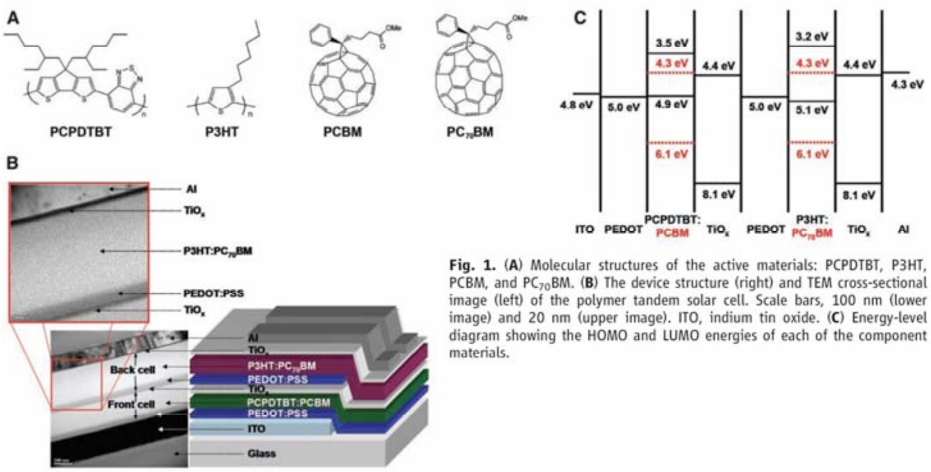
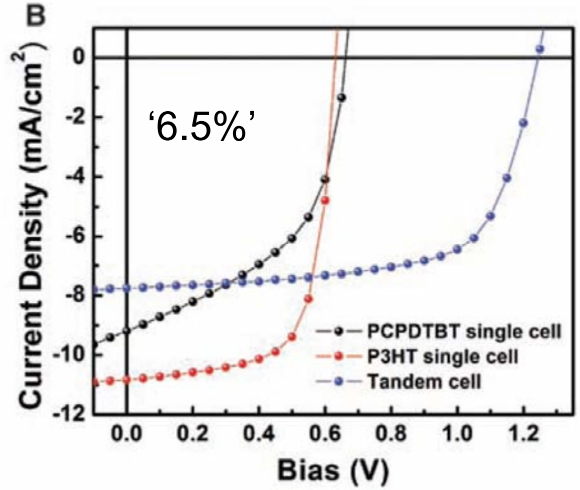
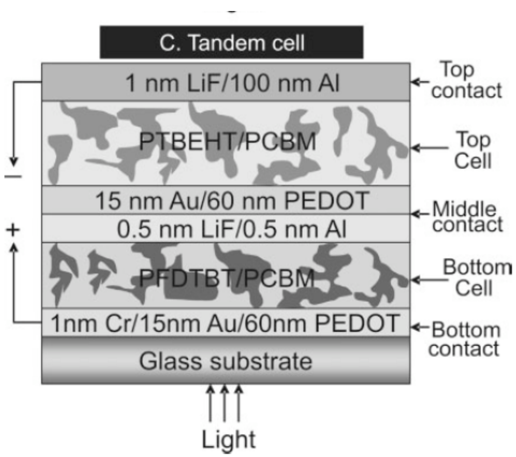


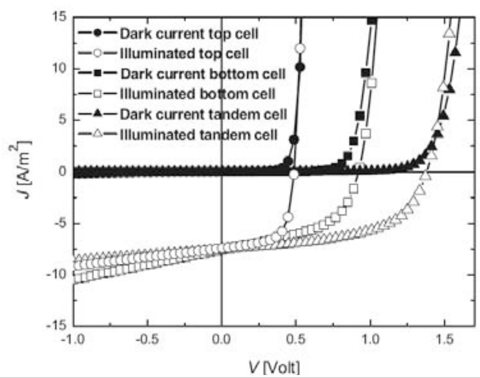
Fig. 1. (**A**) Molecular structures of the active materials: PCPDTBT, P3HT, PCBM, and $PC_{70}BM$. (**B**) The device structure (right) and TEM cross-sectional image (left) of the polymer tandem solar cell. Scale bars, 100 nm (lower image) and 20 nm (upper image). ITO, indium tin oxide. (**C**) Energy-level diagram showing the HOMO and LUMO energies of each of the component materials.



J-Y Kim et al (UCSB) *Science*, **317** 222 (2007)

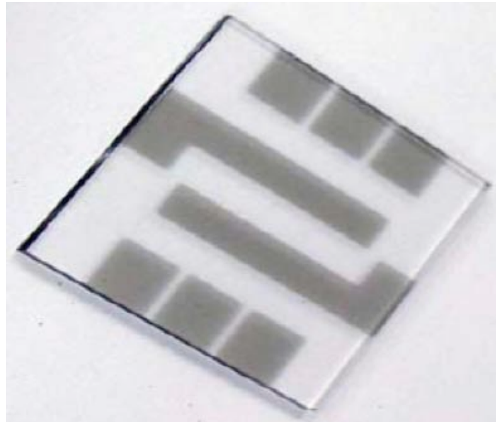


A. Hadipour et al (NL), *AFM*, **16(14)** 1897 (2006)

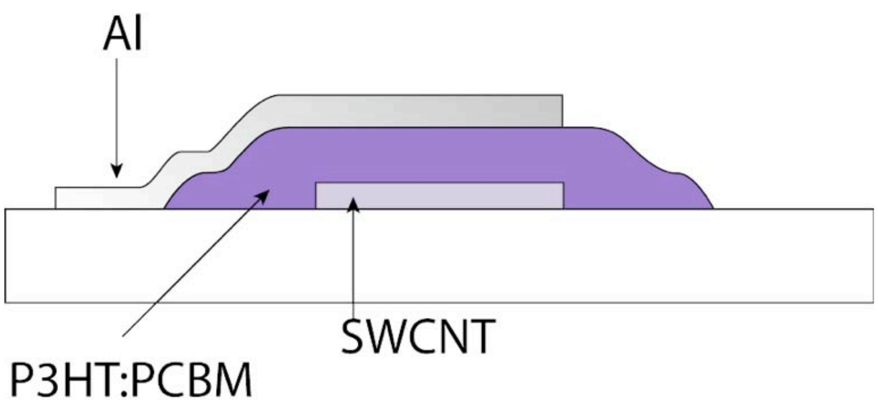


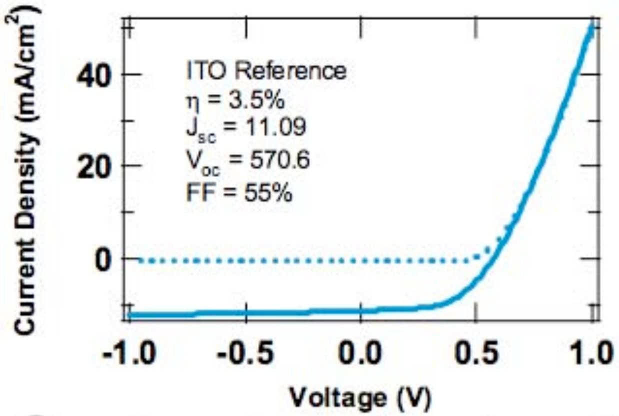
Cells	V_{OC} [V]	J_{SC} [A m^{-2}]	FF [%]	η [%]
Bottom	0.9	~10	50	0.35
Top	0.5	~9	64	0.23
Tandem	1.4	~9	55	0.57

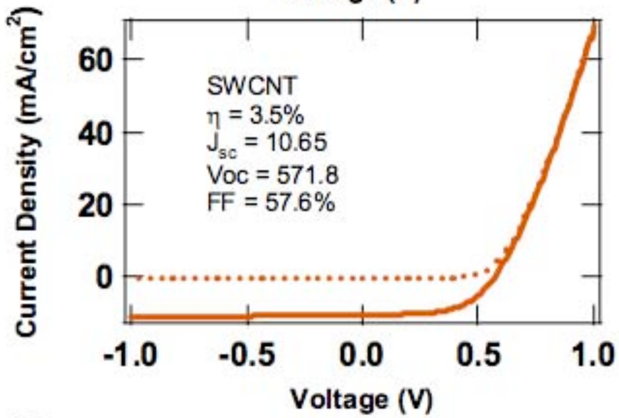
Doped, single-walled carbon nanotube electrodes

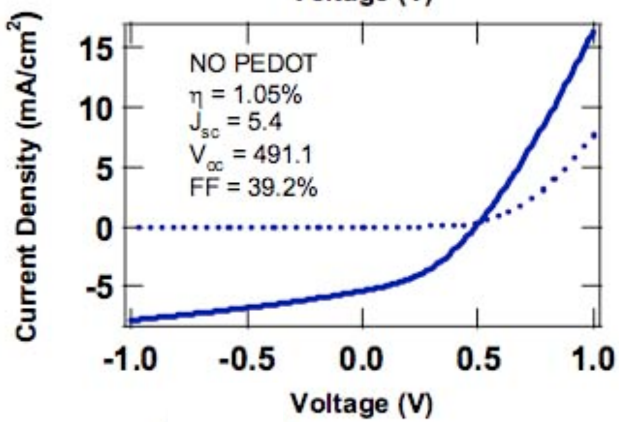


50 Ω/sq electrode
Deposited by ultrasonic spray RMS Roughness ~ 3nm



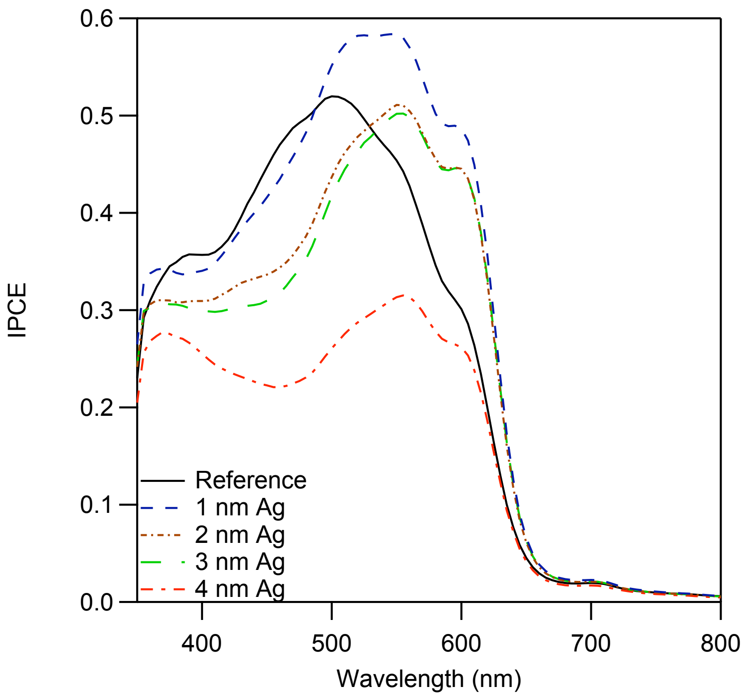






van de Lagemaat et al (NREL). *APL*, **88** 233503 (2006)

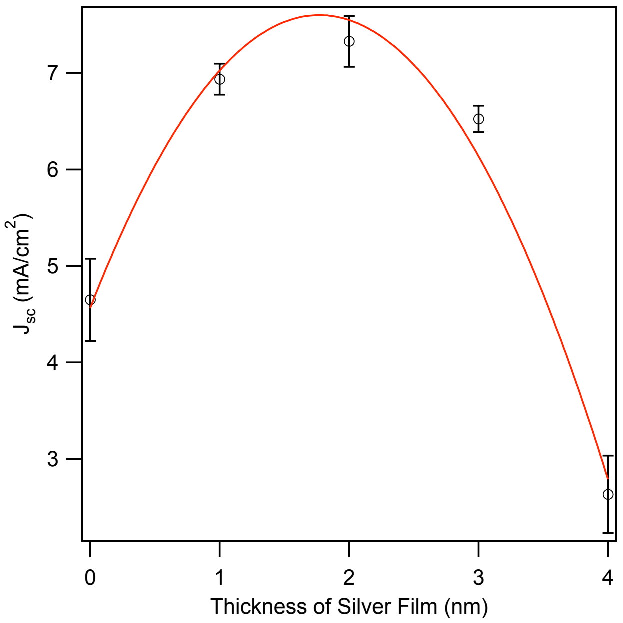
Plasmon enhancement effects

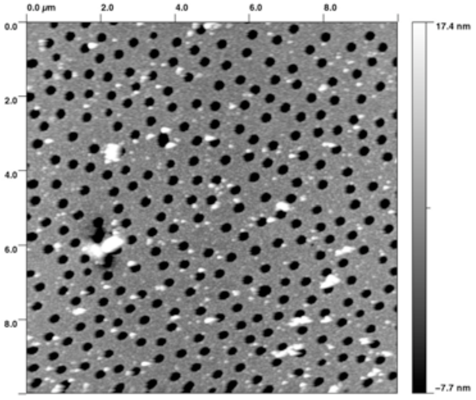


Silver nanoparticles on ITO:
Enhancement due to increased light absorption induced by the plasmonic effect on the particles.
Almost doubling of current and efficiency

A. Morfa et al, *APL,* **92** 013504 (2008)
and *APL,* **92** 243304 (2008)

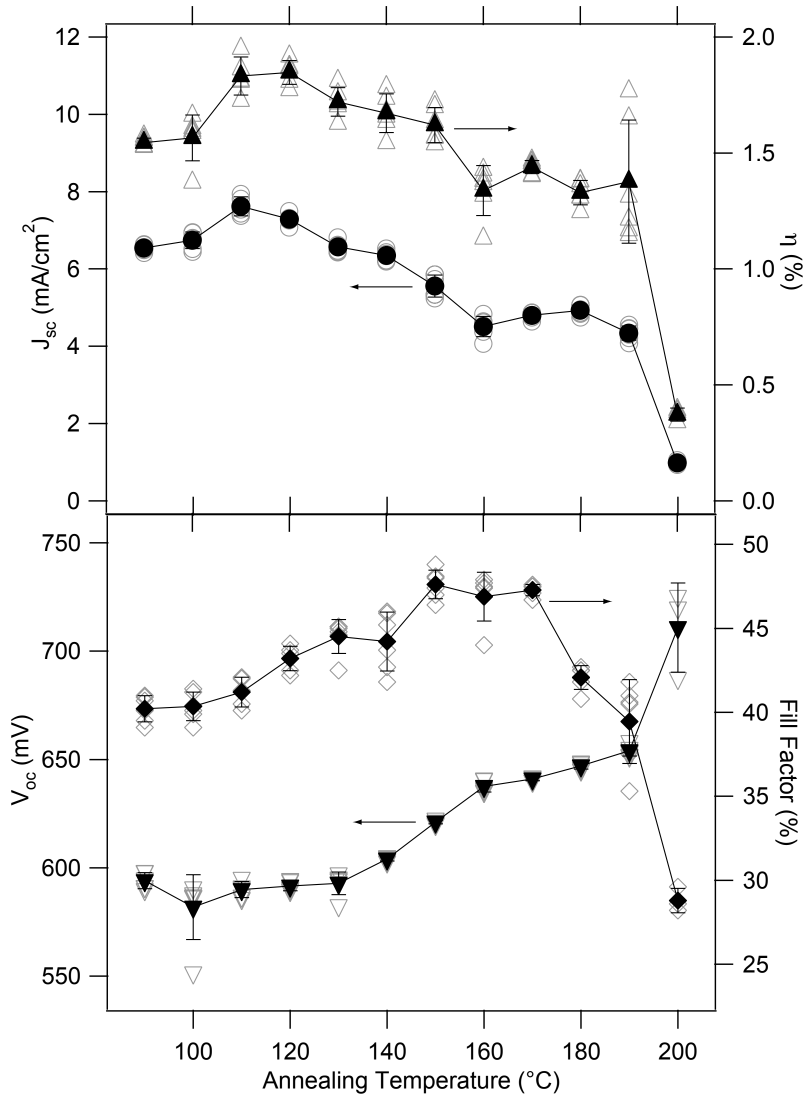
Also on silver nanohole arrays:

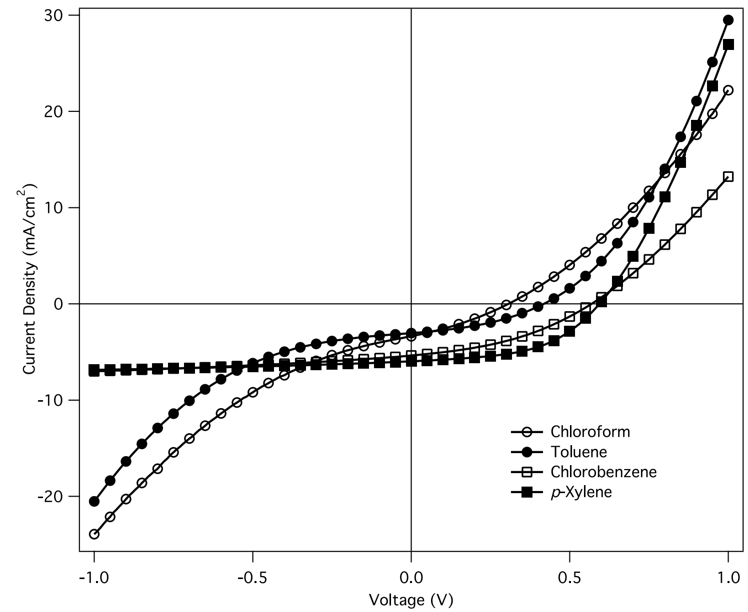


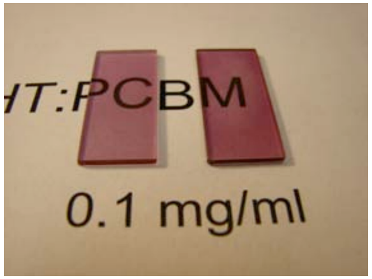


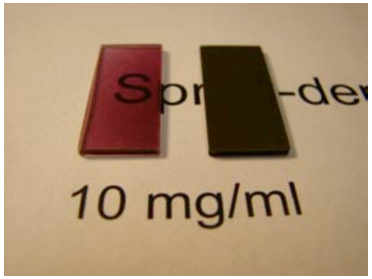
T. Reilly et al. *APL* **92**, 243304 (2008)

Air-brushed devices

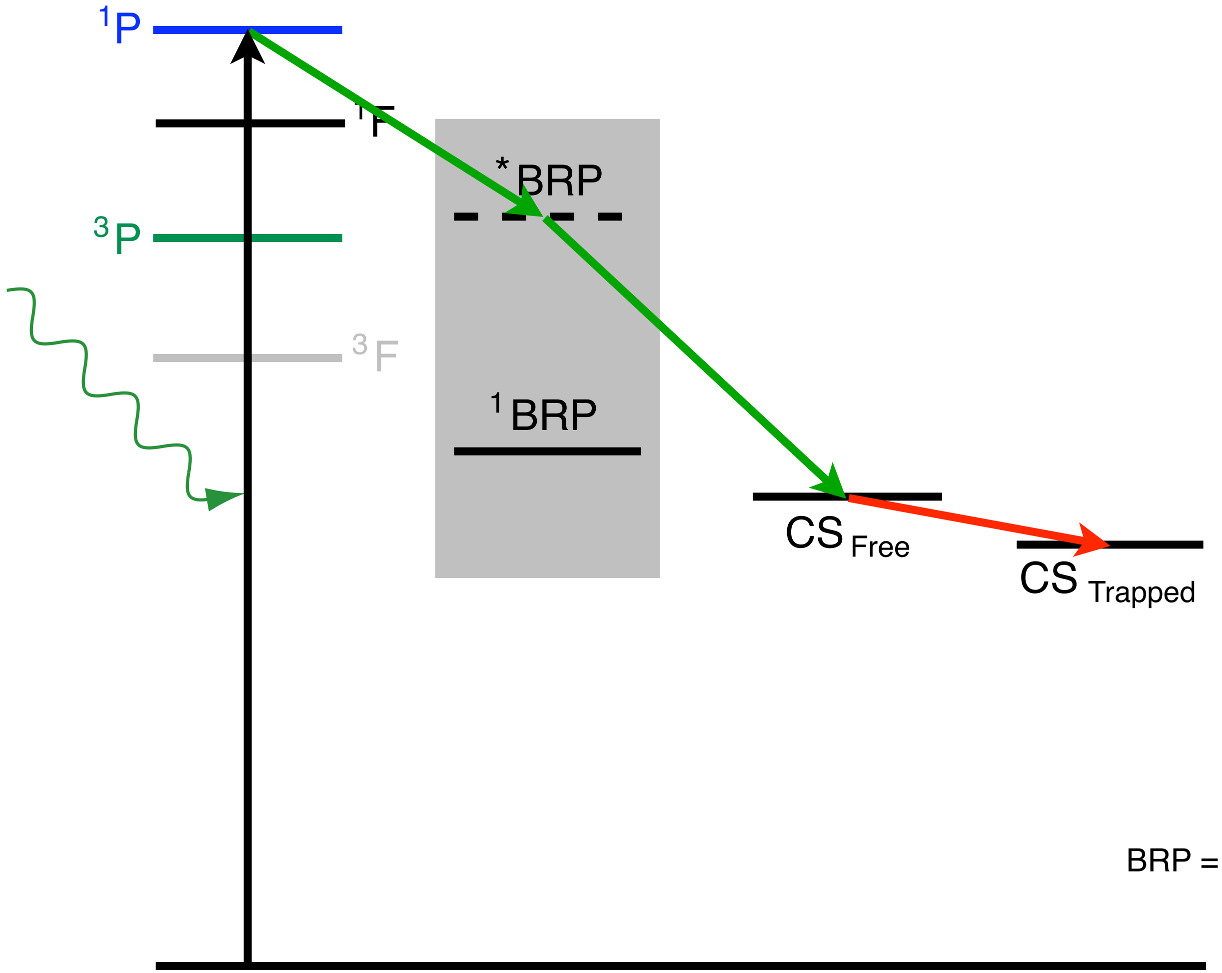


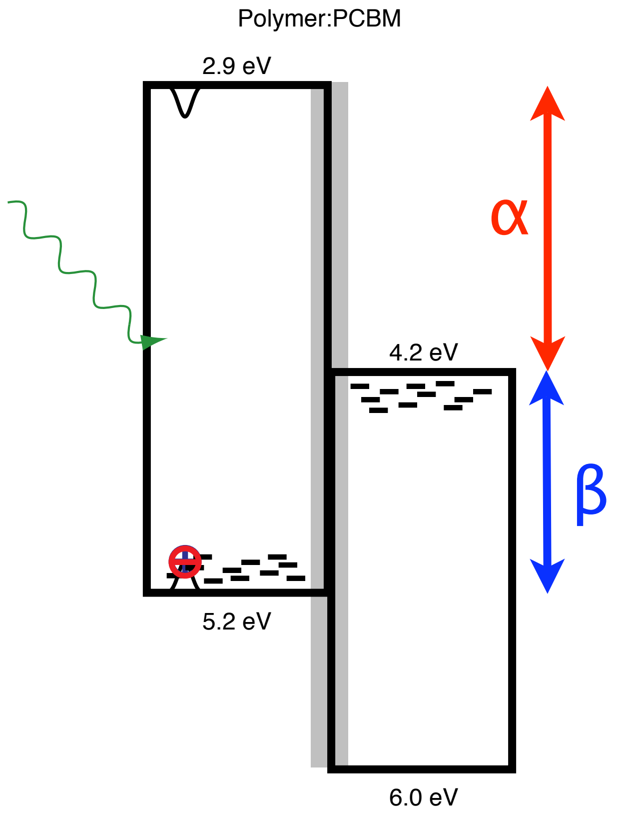






Ferguson et al. (NREL) *APL*, **92** 033301 (2008)

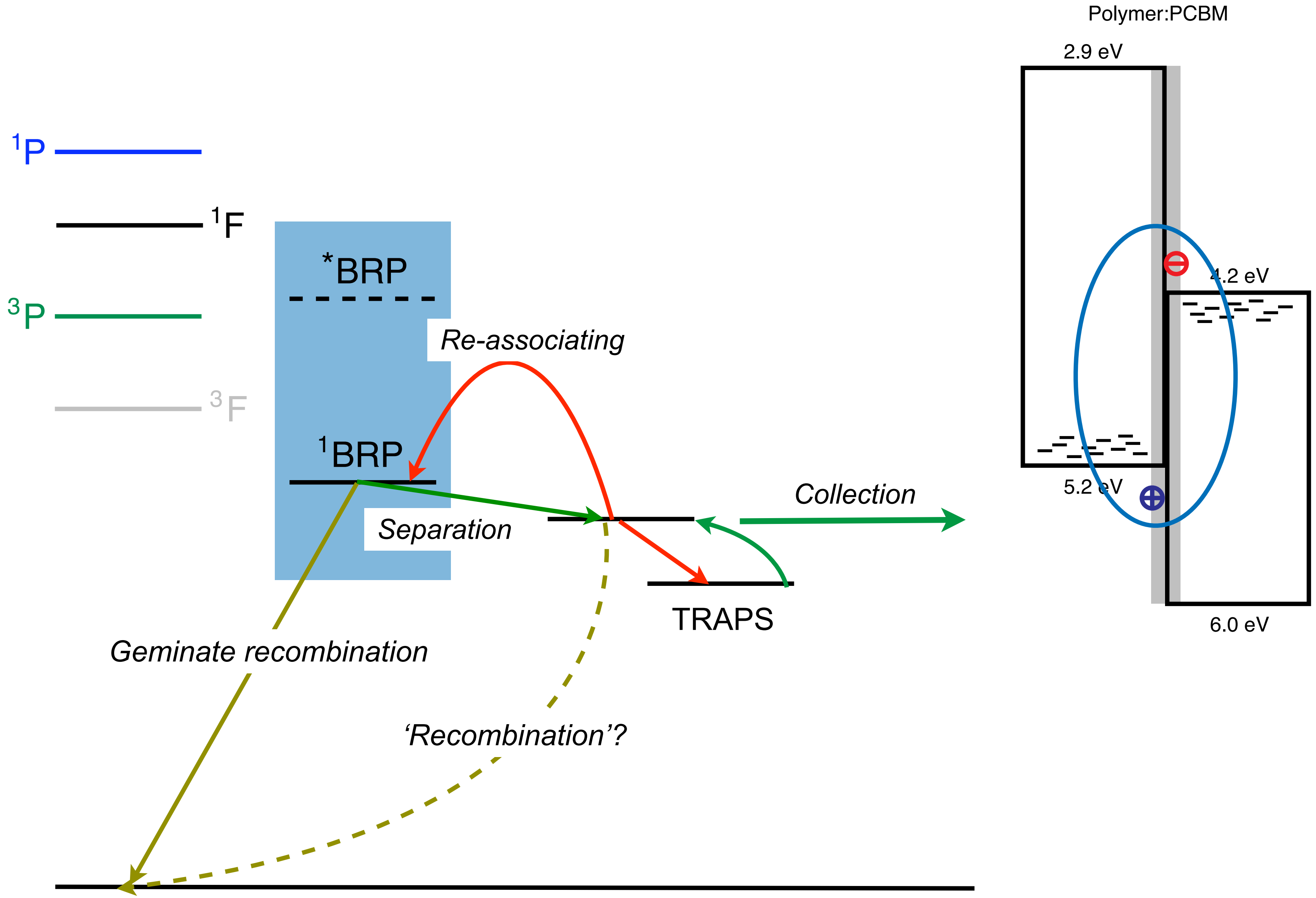




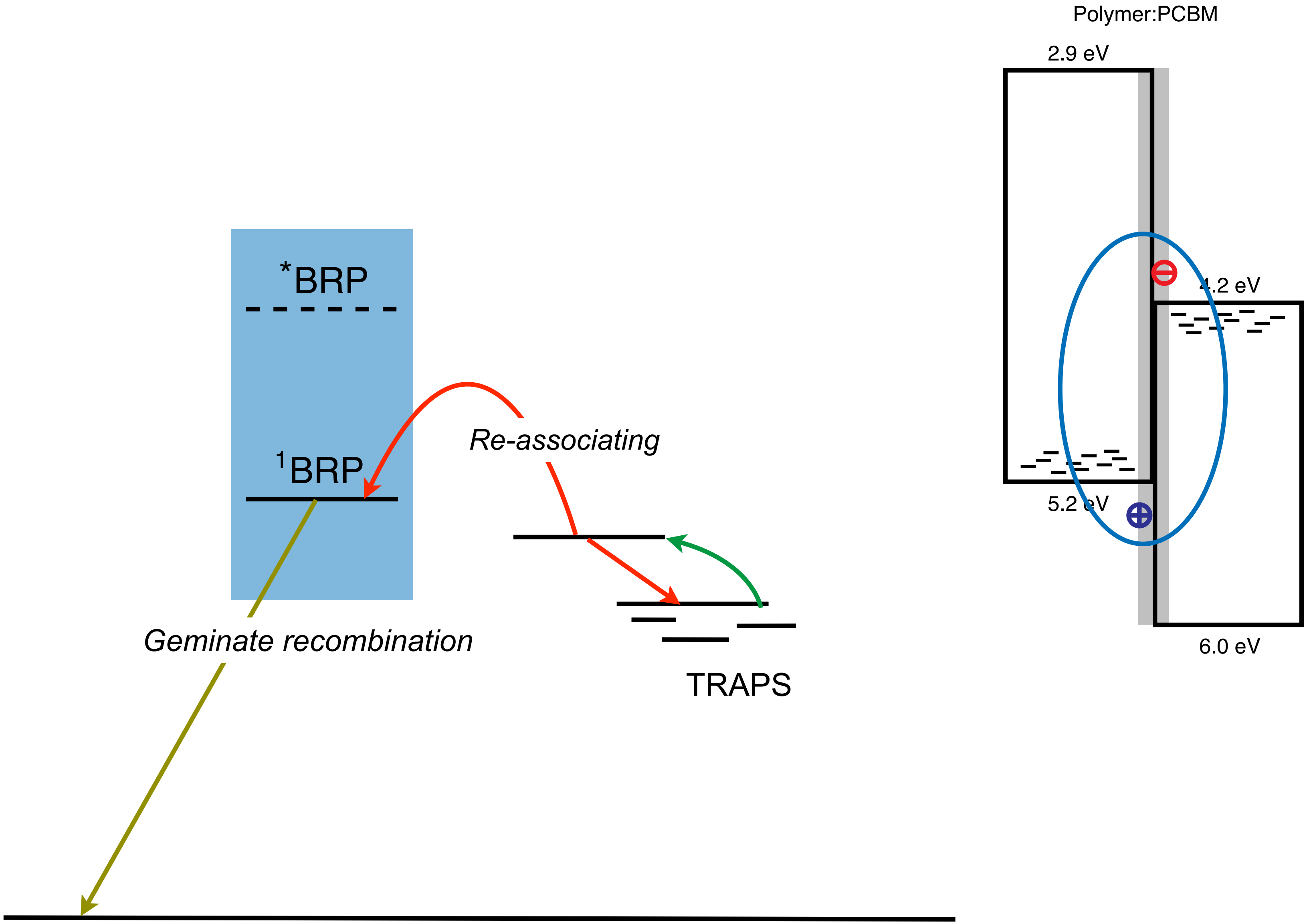
BRP = Bound Radical Pair ≡ D^+—A^- ≡ P^+—F^-

H. Ohkita et al (Imperial) *JACS*, **130**, 3030 (2008)

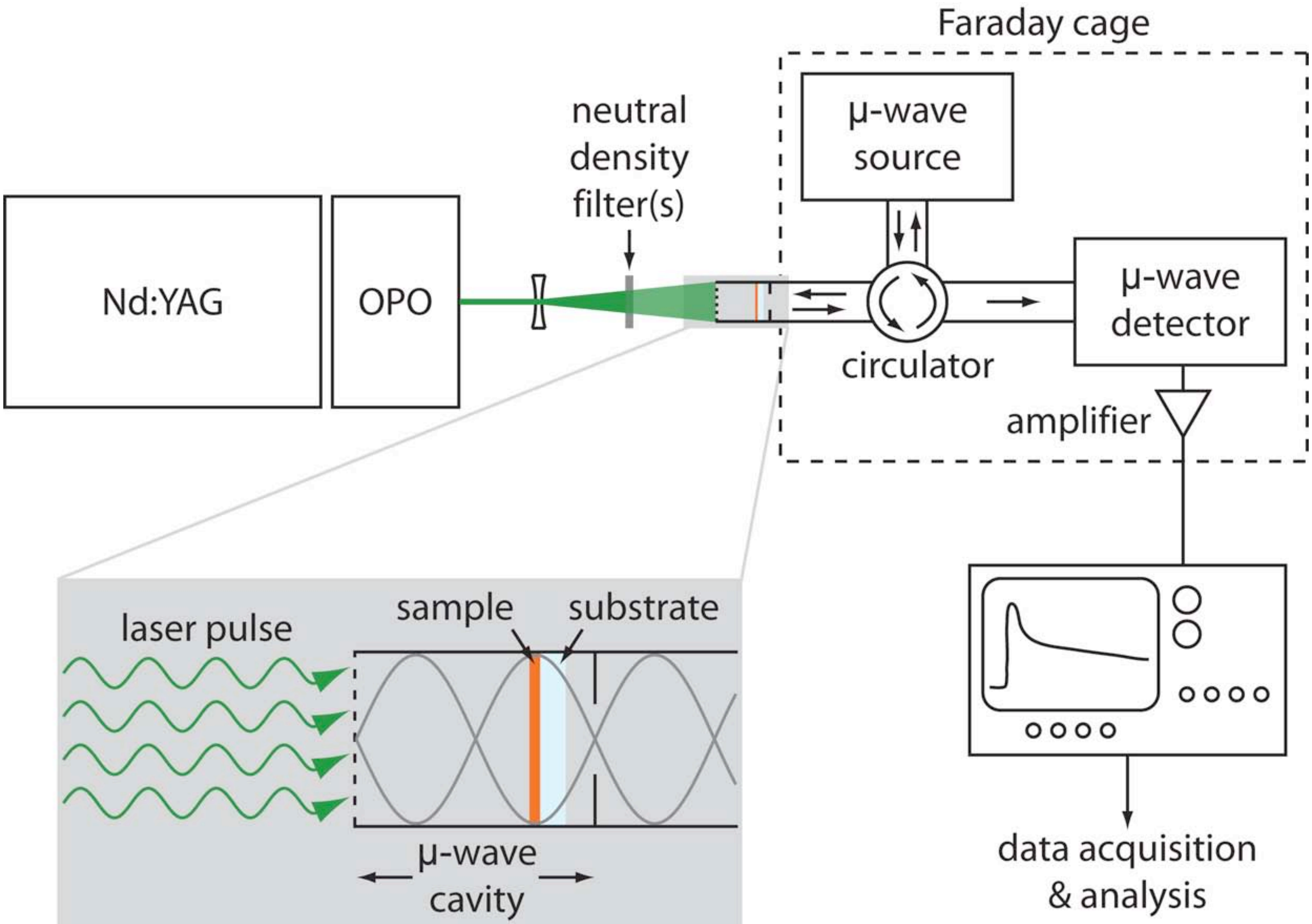
Competition with carrier collection



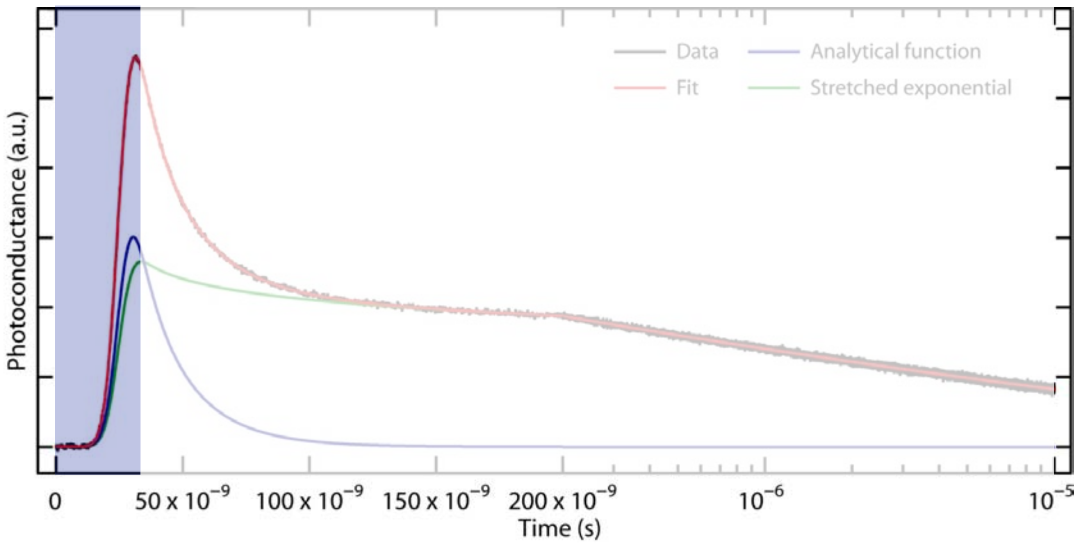
Competition with carrier collection

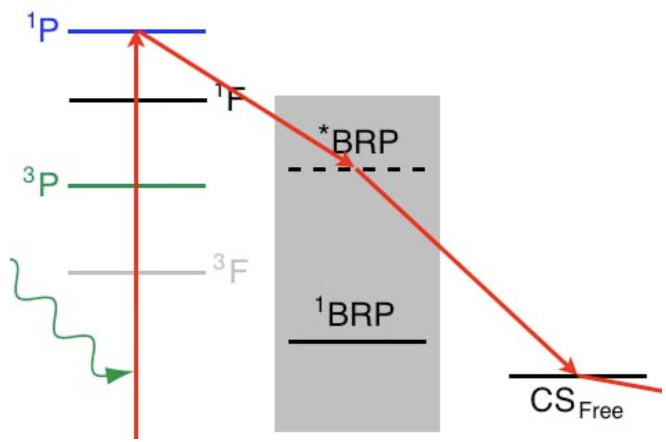


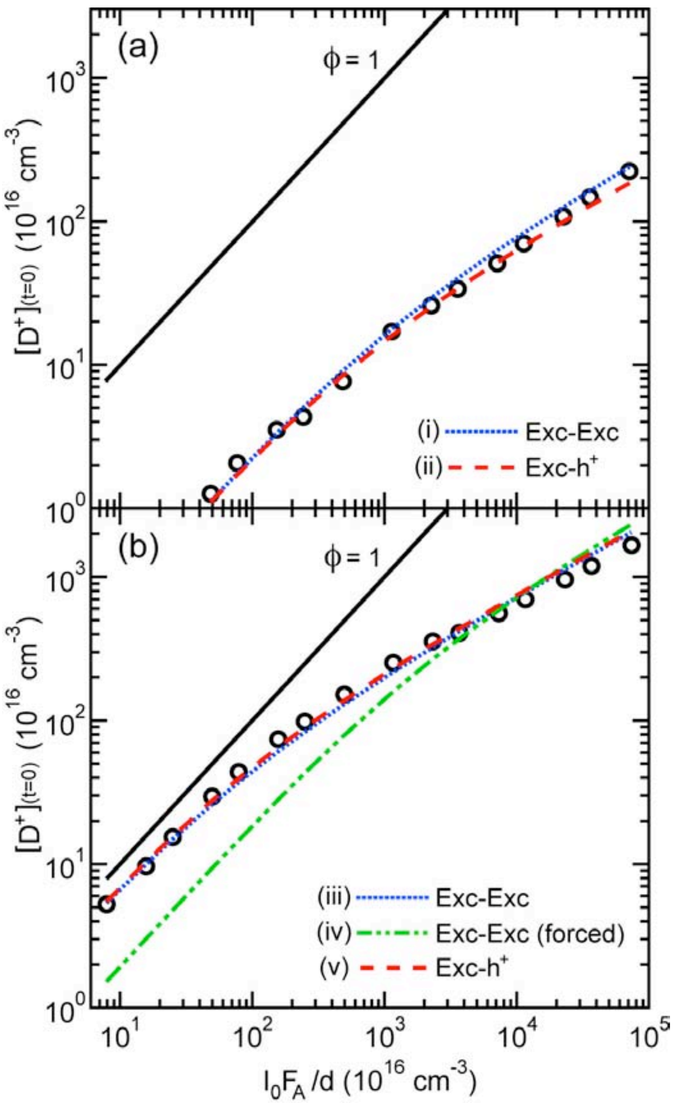
Transient Microwave Conductivity (TRMC)



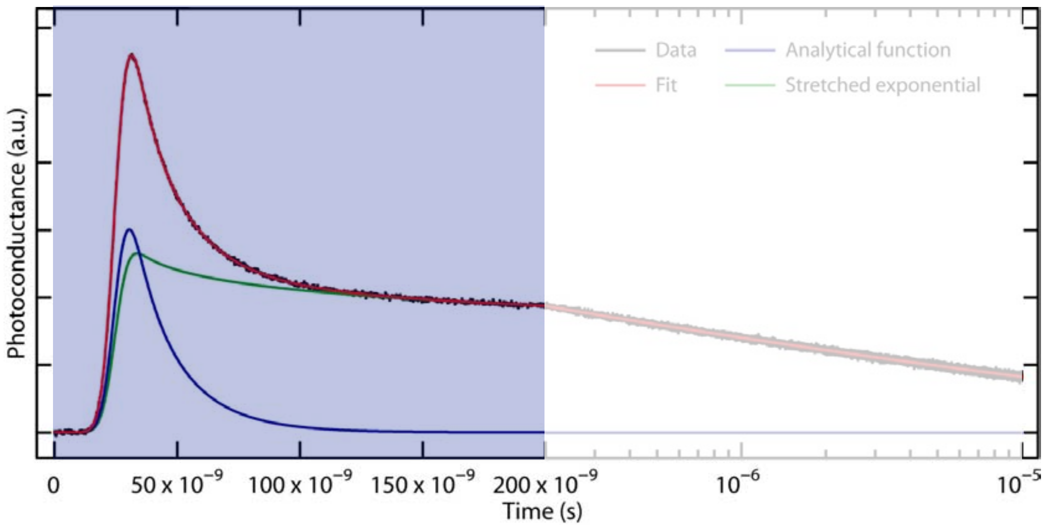
ΔG$_{max}$ (ΔG$_{t=0}$): Exciton (or BRP) dissociation efficiency



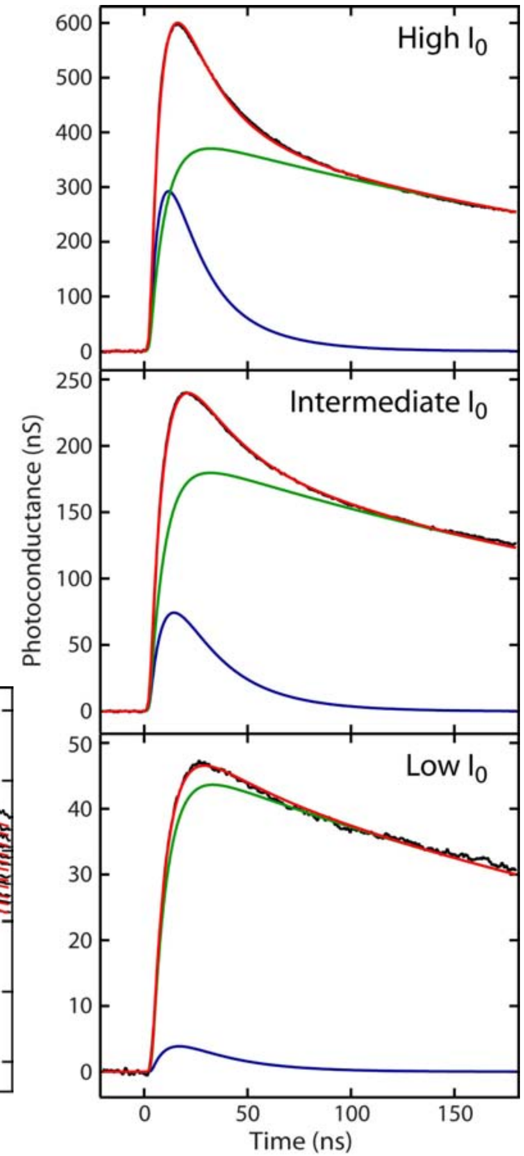


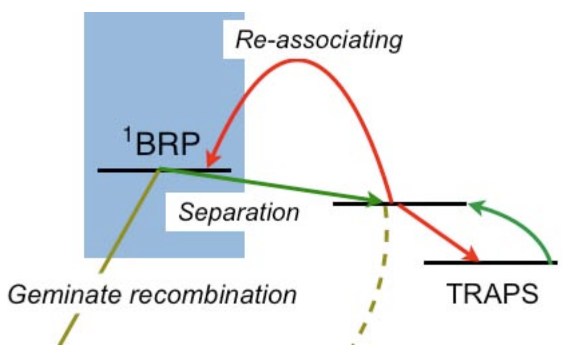


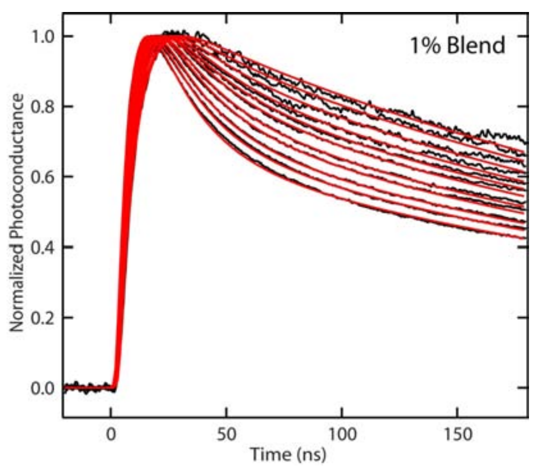
Free carrier decay (t = 0 to 200 ns)



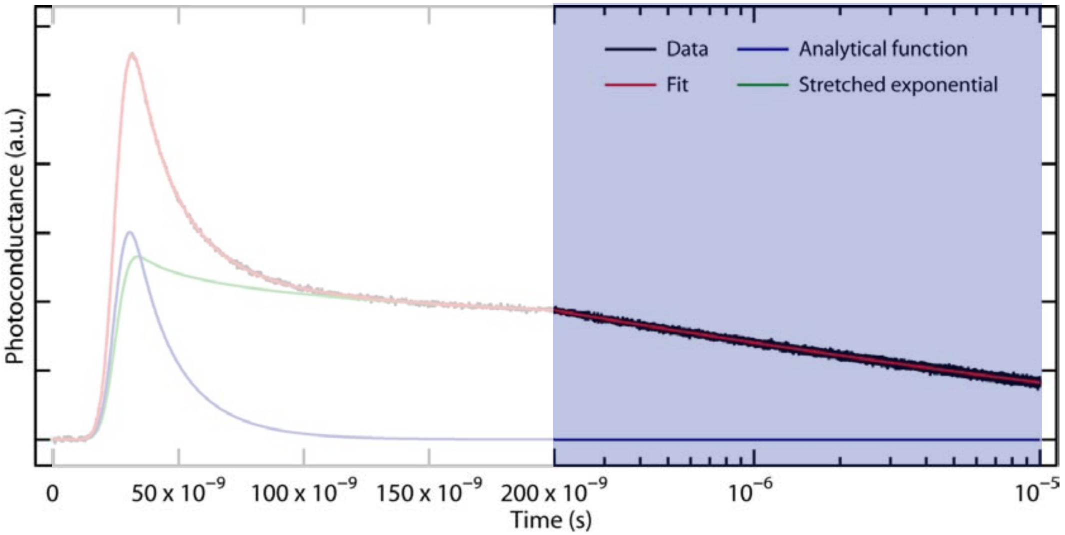
$$[D^+](t) = \frac{D_0 k}{(k + D_0\gamma)e^{kt} - D_0\gamma} + D_e.e^{-k_e t}$$



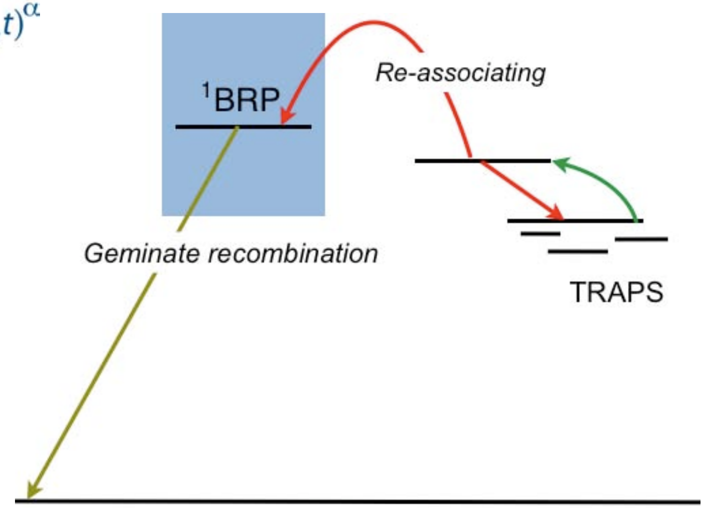




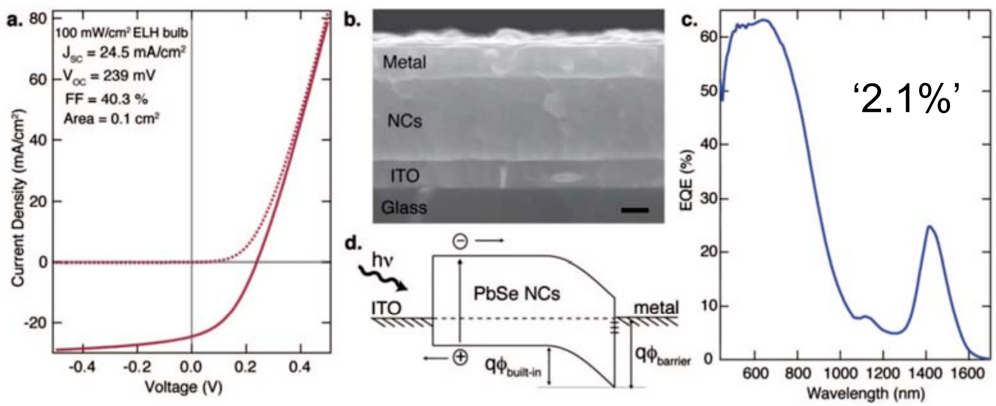
Trapping, de-trapping and recombination



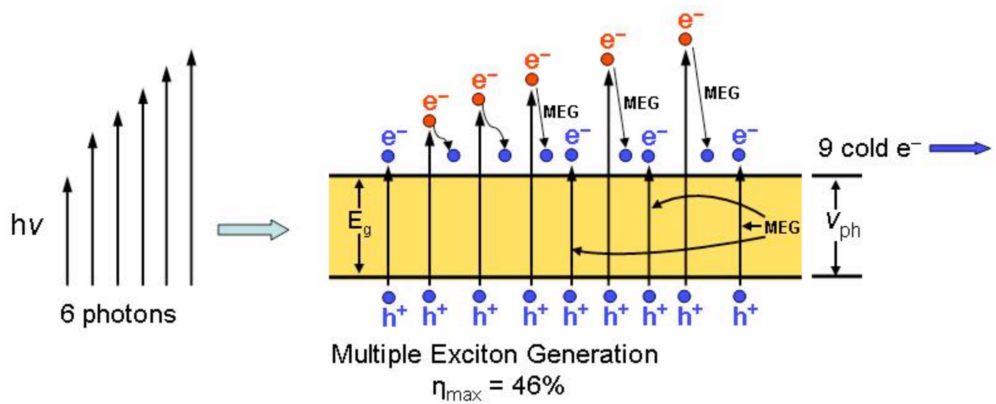
$$[D^+](t) = \frac{D_0 k}{(k + D_0\gamma)e^{kt} - D_0\gamma} + D_e.e^{-(k_e t)^\alpha}$$

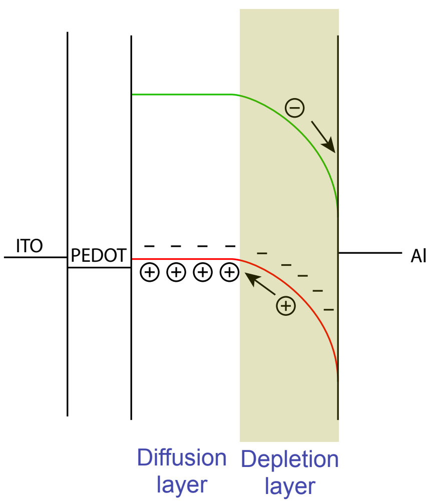


Dark carriers, MEG, Schottky devices



J.M. Luther et al (NREL), *Nano letters*, **8(10)** 3488 (2008)





Concluding remarks

- **The Energy issue**
  - We need to provide > 15TW
- **Photovoltaics**
  - This is a very good, perhaps the only, solution
- **Why organics?**
  - Chemistry
- **Technologies**
  - Poised and ready
- **Basic issues**
  - We need more understanding

Acknowledgments

- Nikos Kopidakis
- Sean Shaheen
- David Ginley
- Jao van de Lagemaat
- Teresa Barnes
- Jeff Blackburn
- Rob Tenent
- Brian Gregg
- Dana Olson
- Joe Berry
- Andrew Ferguson
- Matt Reese
- Tom Reilly
- Anthony Morfa
- Matt White
- Xerxes Steirer
- Alex Nardes
- Ben Rupert
- Erkan Kose
- Will Rance
- Smita Dayal
- Xin Ai
- Jeremy Bergeson

Funding: US DOE, Office of Science, Office of Basic Energy Sciences.