Quantum Dot Solar Cells

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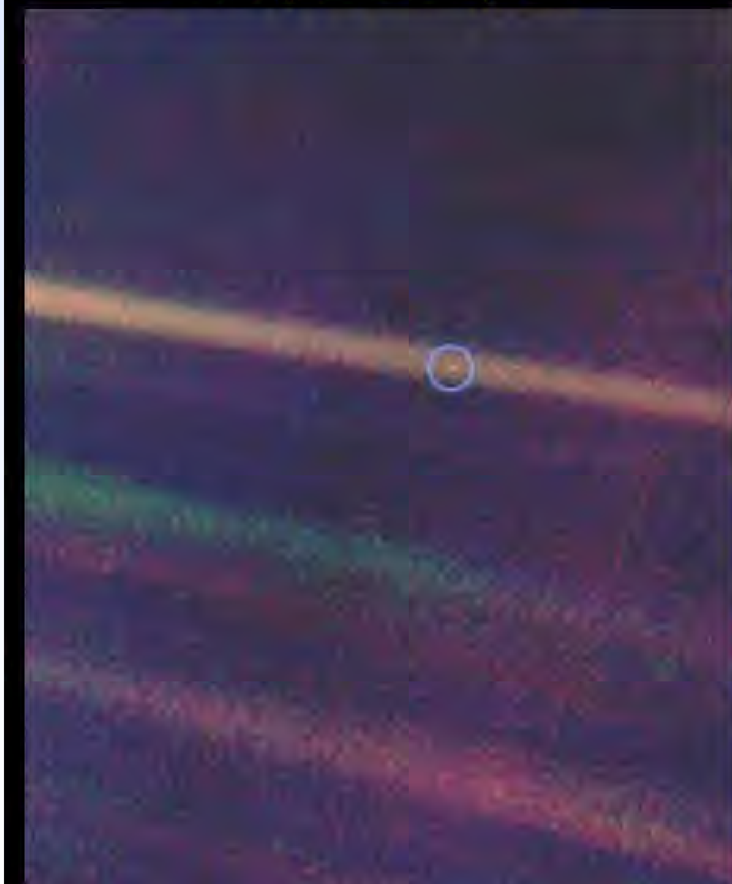
Condensed Matter Seminar, Department of Physics

Case Western Reserve University

Our little dot

In 1990, Carl Sagan convinced NASA engineers to turn Voyager for one last, homeward look before leaving the solar system



"Look again at that dot. That's here. That's home. That's us. On it, everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives …. Every hunter and forager, every hero and coward, every creator and destroyer of civilization, every king and peasant, every young couple in love, every mother and father, hopeful child, inventor and explorer, every teacher of morals, … every saint and sinner in the history of our species lived there--on a mote of dust suspended in a sunbeam."

"….The Earth is the only world known so far to harbor life. There is nowhere else, at least in the near future, to which our species could migrate … Like it or not, for the moment the Earth is where we make our stand."

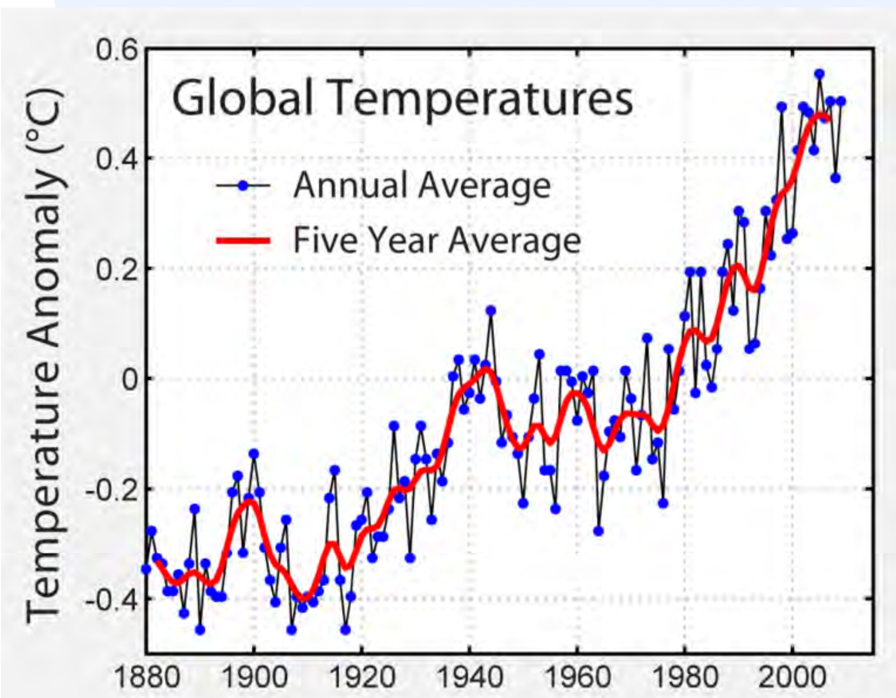
-- Energy Secretary, Steve Chu

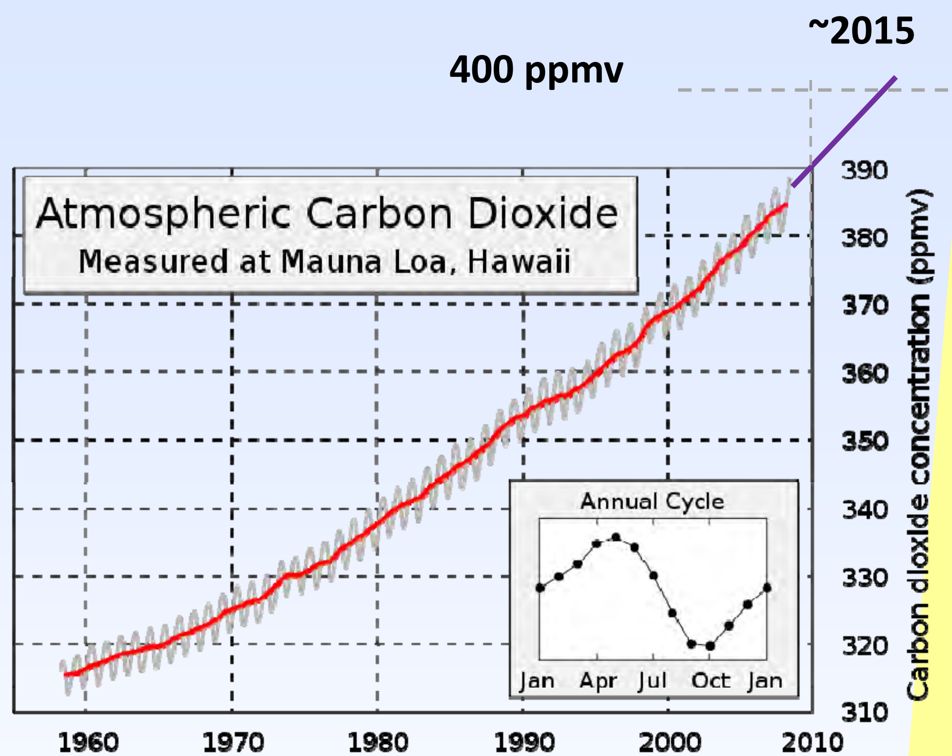
$ per Watt Workshop held Aug. 11-12, 2010 [http://www1.eere.energy.gov/solar/dollar_per_watt.html].

http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf

On watch: global temperatures, atmospheric CO_2

Global average temperatures from NASA's *Goddard Institute for Space Studies* (Columbia University). Data set follows methodology developed by J. Hansen.





Keeling curve, data from Mauna Loa, Hawaii.

Hansen, J., et al. (2006) "*Global temperature change*", PNAS 103: 14288-14293.

Need for clean energy

NATURE |VOL 395 | 29 OCTOBER 1998
Energy implications of future stabilization of Atmospheric CO_2 content
M. Hoffert et al.

Growth

- Global energy consumption -- 1.6-1.7% per year.
- Includes for 1%/yr. efficiency improvement
- 28 TW global power consumption by 2050
- Population growth primarily in less-developed countries → increased C-intensity.
- **~15 TW of the ~30 TW should come from C-free sources in 2050.**

Health

Coal-fired power plants:

- 59% of total U.S. sulfur dioxide pollution
- 18% of total nitrous oxides every year
- largest polluter of toxic mercury pollution

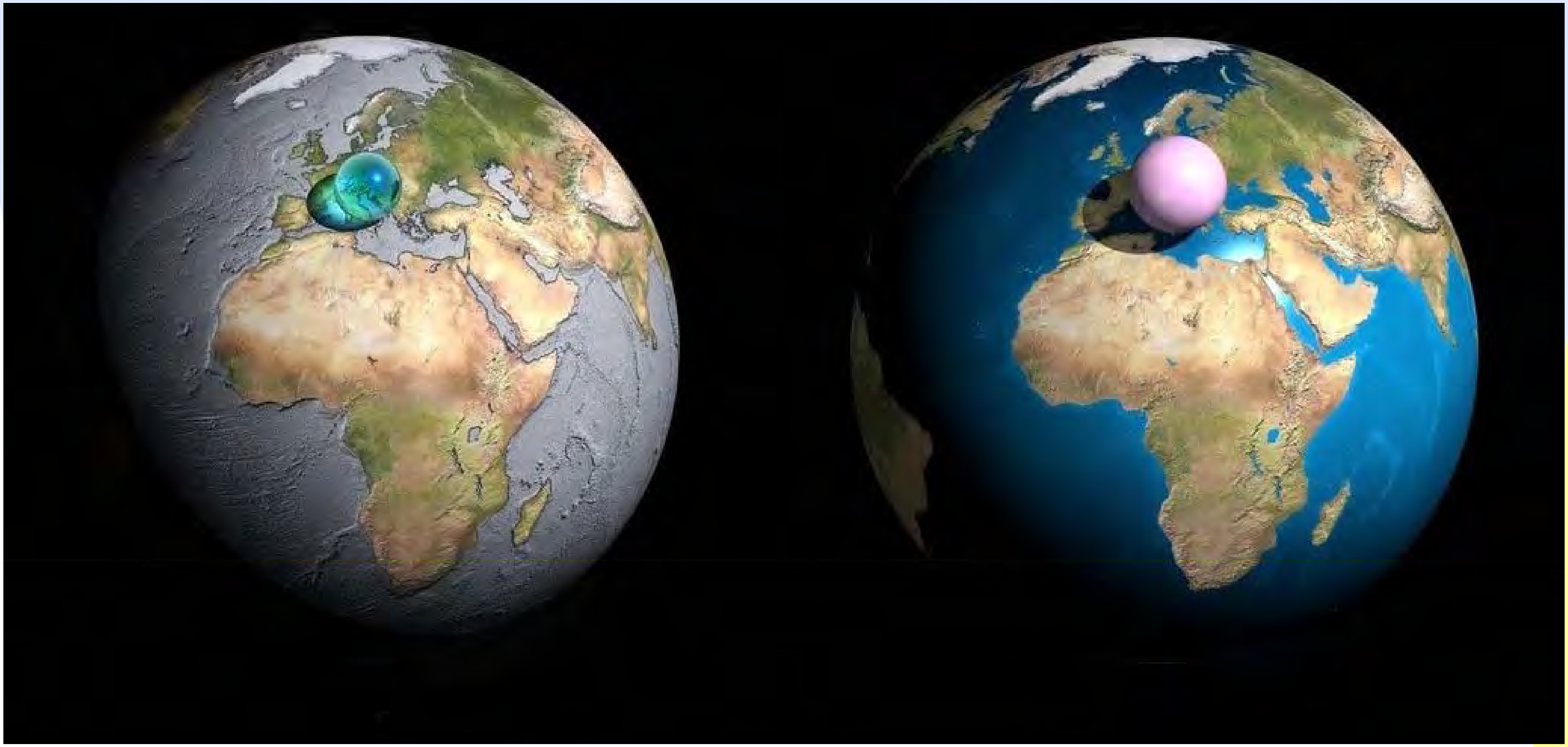
All U.S. power plants: release over 40% of U.S. CO_2

[Sources – U.S. DOE and U.S. EPA]

Acid rain, smog (ozone), soot → unhealthy ecosystems, respiratory problems, unhealthy lungs (incl. asthma)

A developmental toxin, affecting unborn children

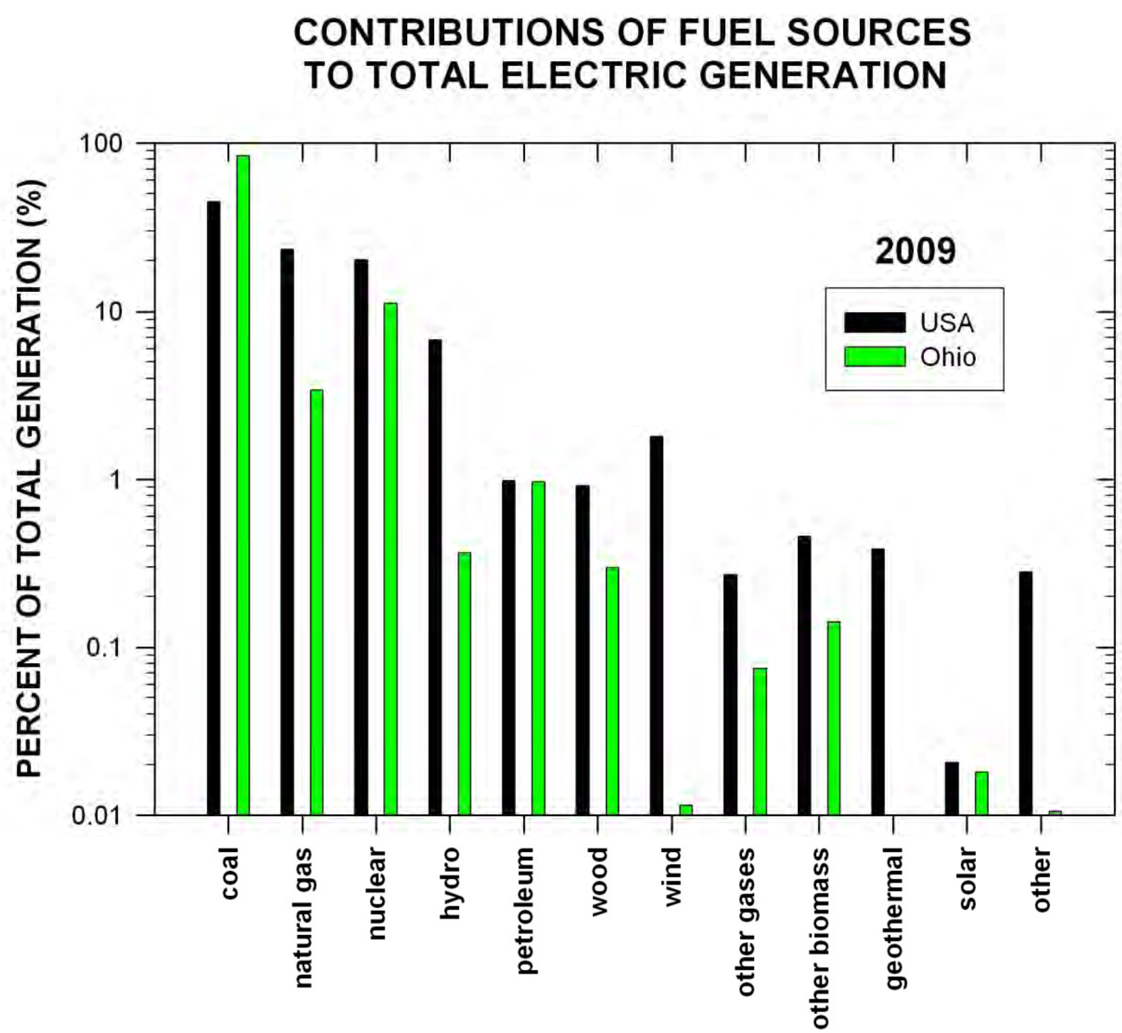
Earth's key natural resources: water and air



Volume of Earth: 1.1 × 10^{12} km^3
Volume of water: 1.4 x 10^9 km^3
Volume of atmosphere: 4.2 x 10^9 km^3

Photo & caption info: ADAM NIEMAN / SCIENCE PHOTO LIBRARY

How does Ohio's electricity generation stack up?



Data Source: Energy Information Administration
U.S. Department.of Energy

Graphs prepared by B. Martner, Lafayette, CO

Happy Birthday (April 11) to Uncle Brooks!

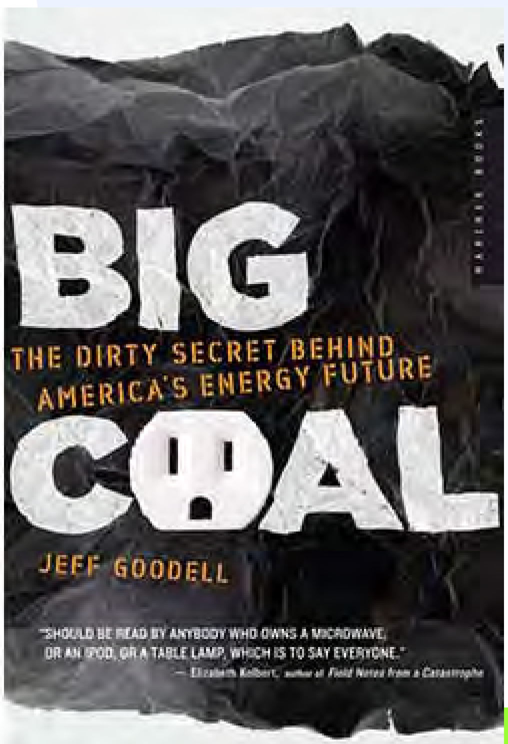
Dirty energy, toxic food, air, and water

Burn a 100 W light bulb for a year:

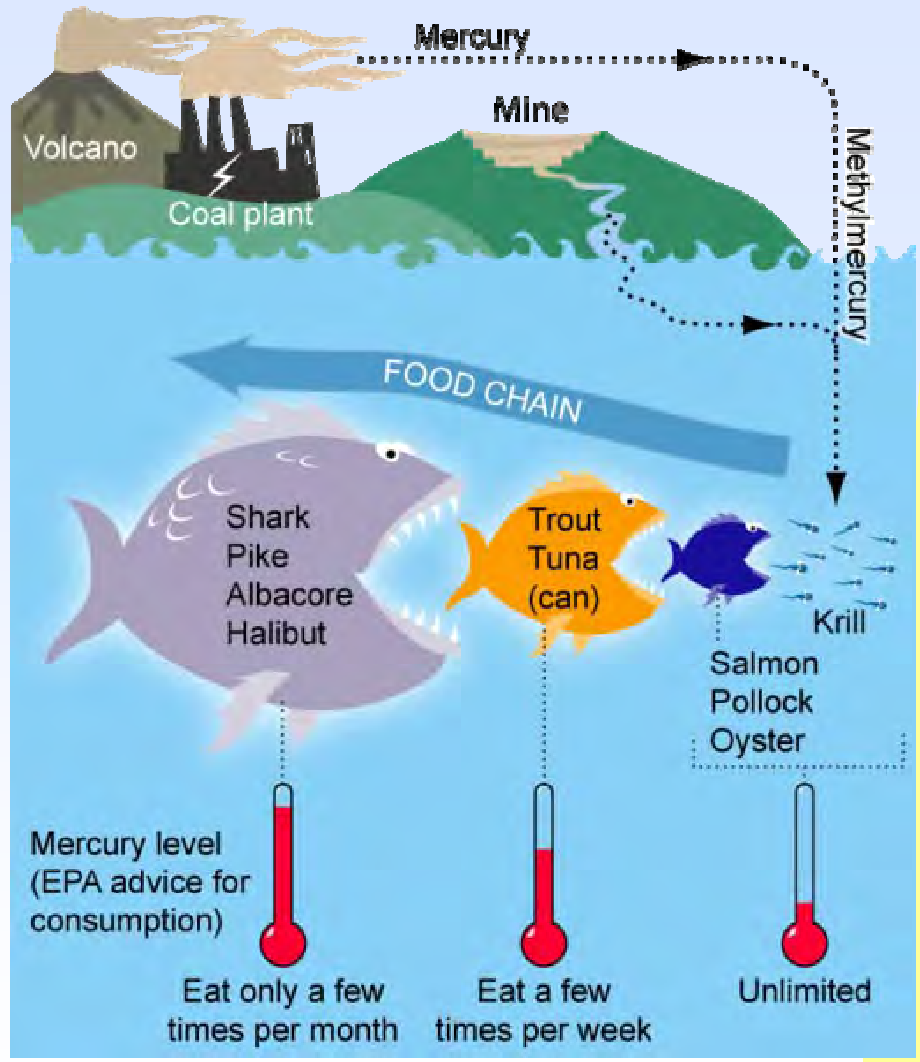
$$\frac{876\ \text{kW}\cdot\text{h}}{2.0\ \text{kW}\cdot\text{h/kg}} = 438\ \text{kg of coal} = 966\ \text{pounds of coal}$$

Ohio only ~85% coal, but also 5-10% transmission losses → ~900 lbs. (~400 kg) coal to light that bulb (or four 25 W CFLs) in Ohio.

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

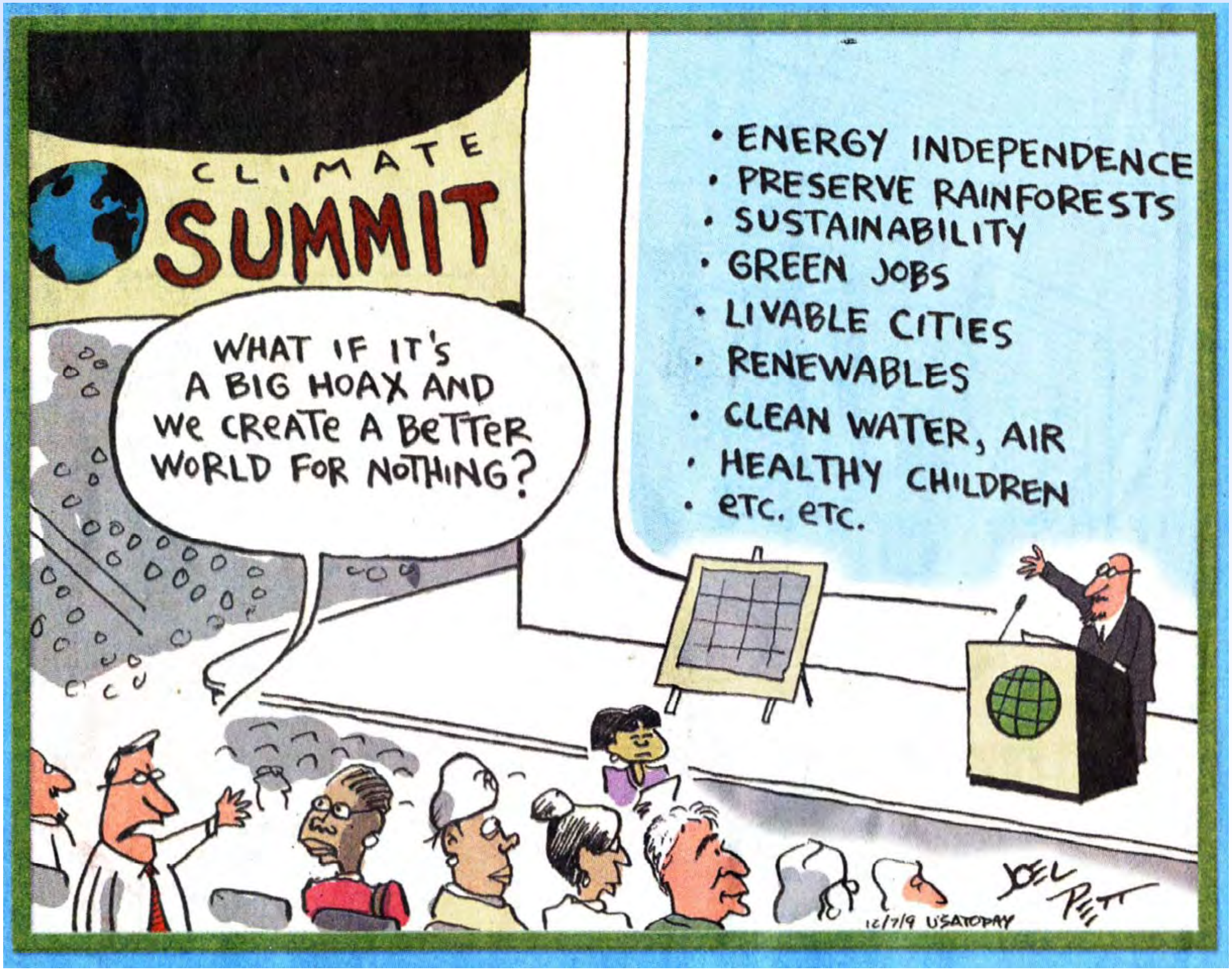


Coal energy density: ~24 MJ/kg

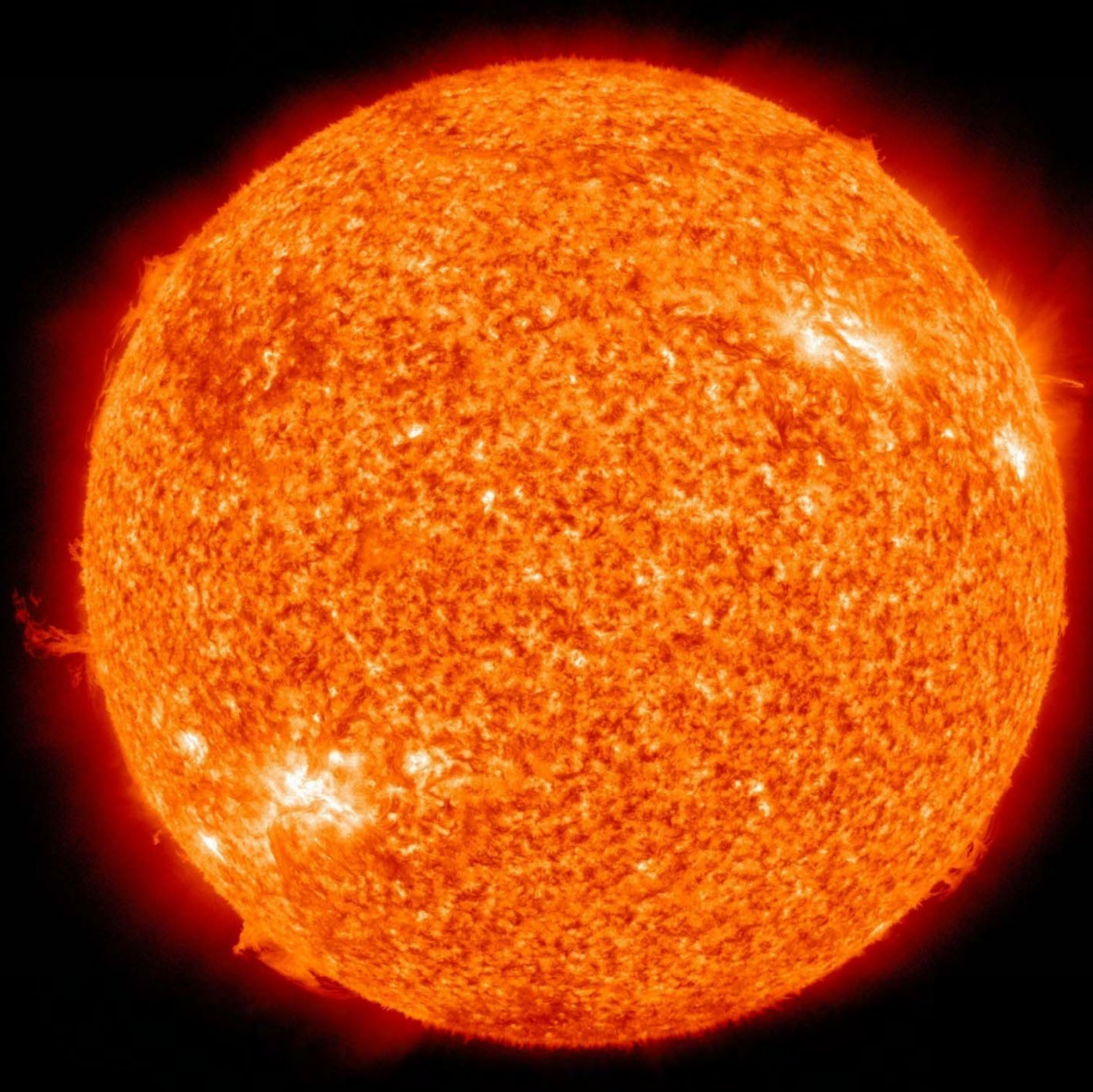


http://en.wikipedia.org/wiki/Mercury_in_fish

The upsides of carbon-free energy



The Sun (worth revering)



“Why Does the Sun Shine?”
by *They Might Be Giants*

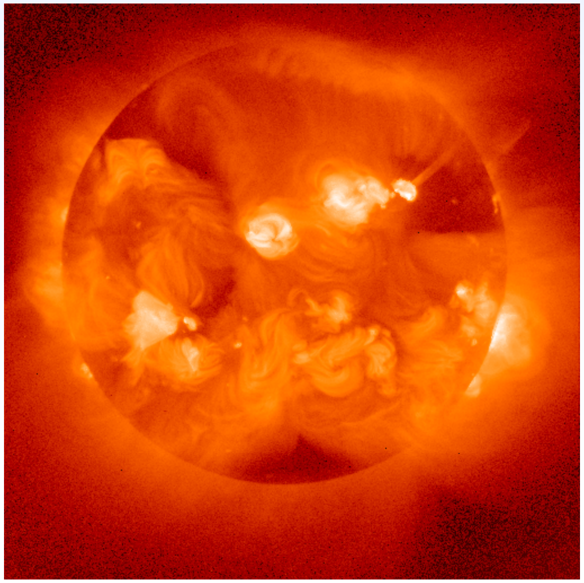
The sun is a mass of
incandescent gas
A gigantic nuclear furnace
Where hydrogen is built into
helium
At a temperature of millions
of degrees

Yo ho, it's hot, the sun is not
A place where we could live
But here on Earth there'd be
no life
Without the light it gives

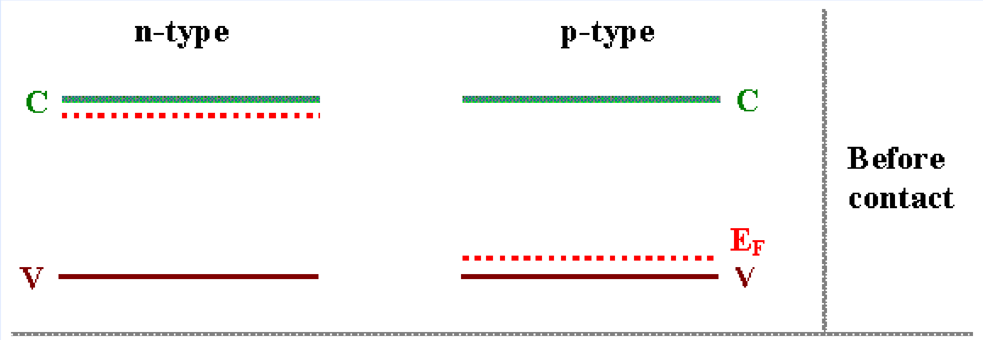
We need its light
We need its heat
We need its energy
Without the sun, without a
doubt
There'd be no you and me

Earth's solar resource

- Theoretical: $1.2x10^5$ TW solar energy potential (1.76 $x10^5$ TW striking Earth; 0.30 Global mean albedo)
- Energy in 1 hr of sunlight ↔ 14 TW for a year
- Practical: > On-shore electricity generation potential of ≈ 600 TW (10% conversion efficiency).
- *Photosynthesis*: 170 TW (90 TW land-based, and 80 TW aquatic)

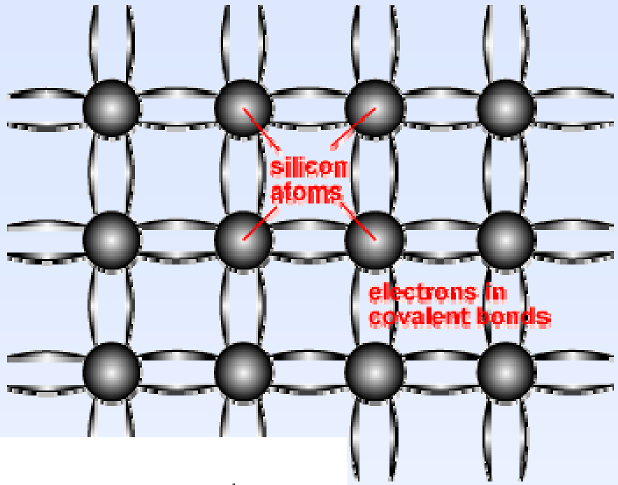


Sunlight to electricity (photovoltaic conversion)

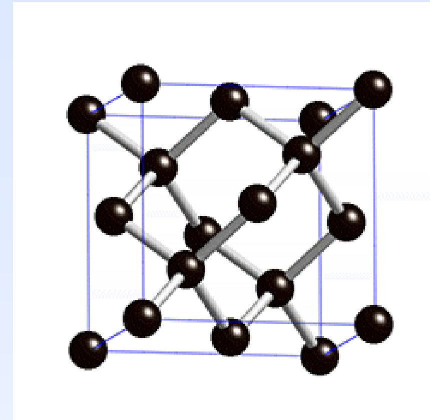


http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/backbone/r2_2_4.html

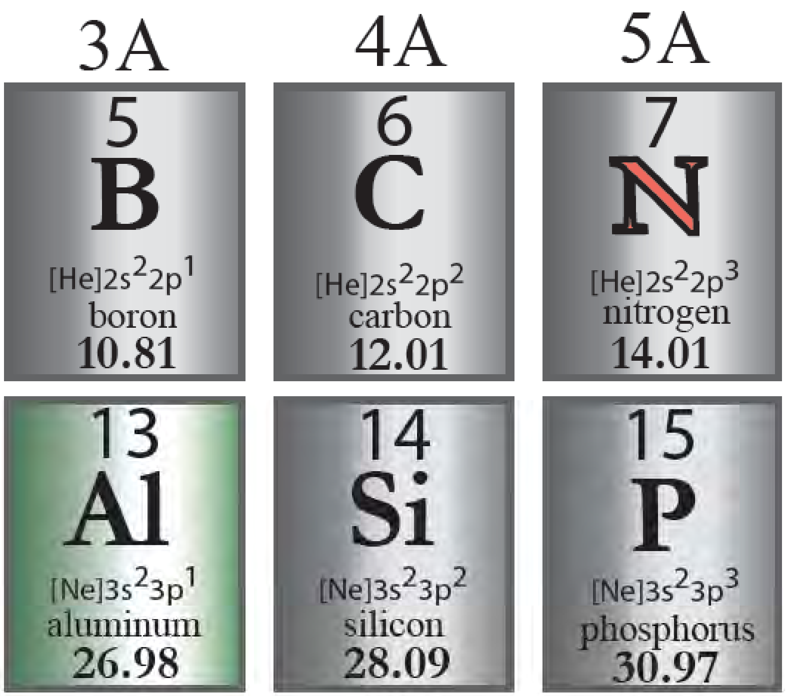
Doping a semiconductor (e.g., Si)

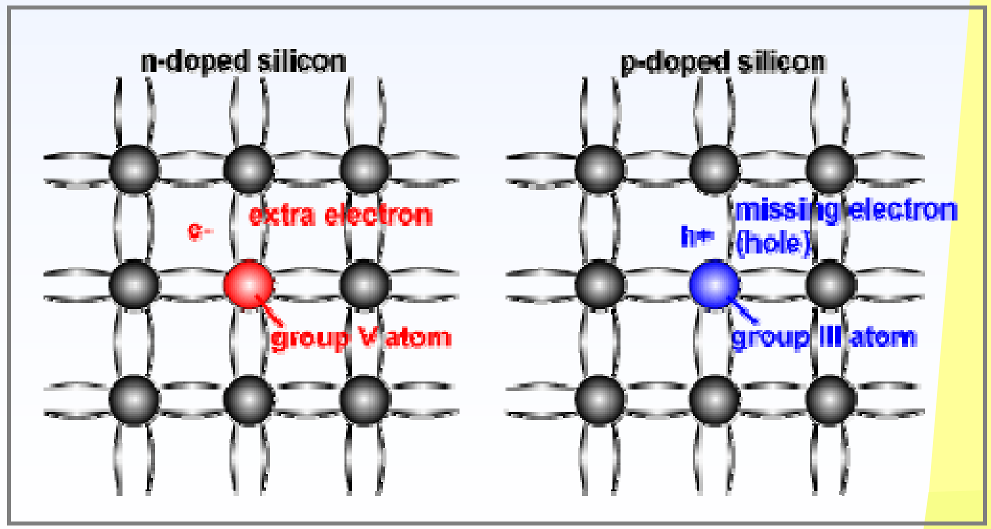


en.wikipedia.org/wiki/File:Diamond_Cubic-F_lattice_animation.gif

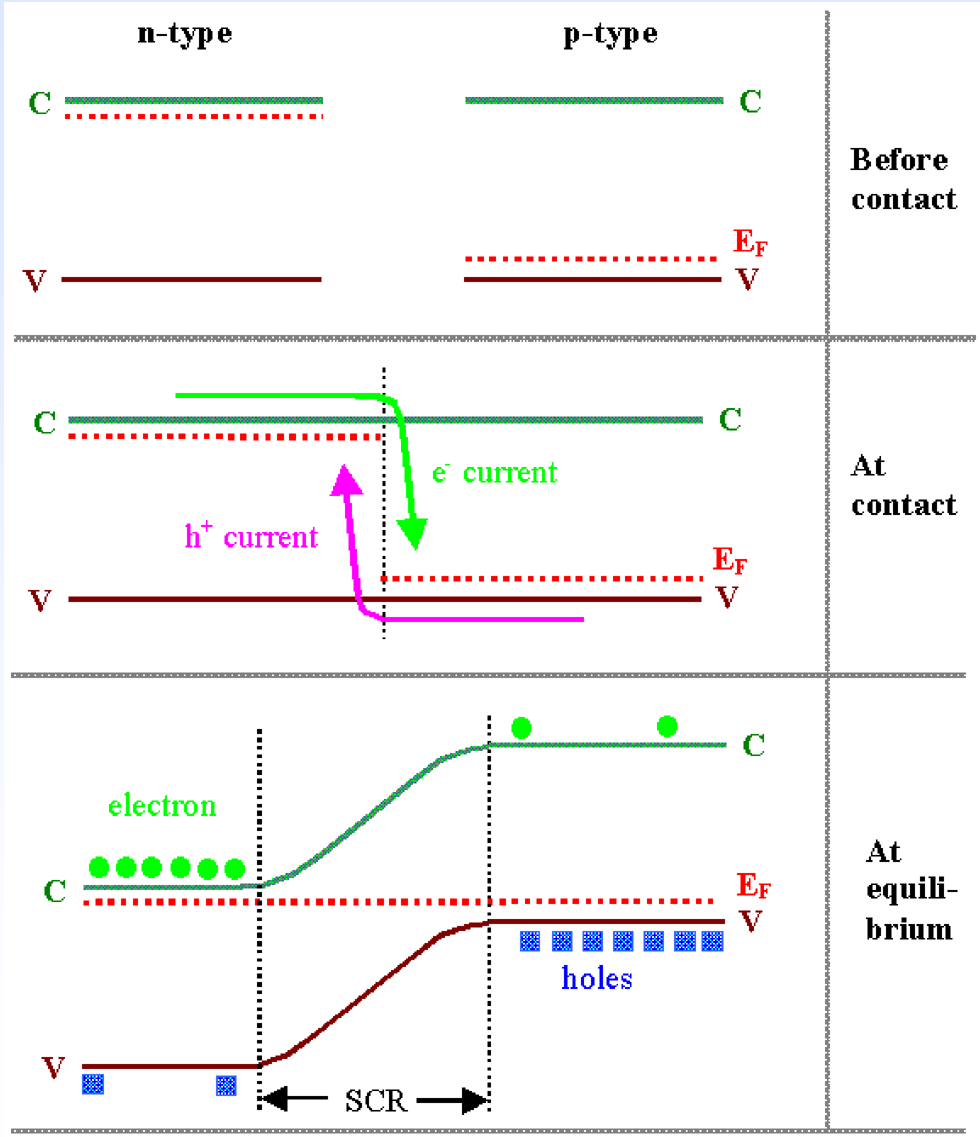


Diamond cubic crystal structure



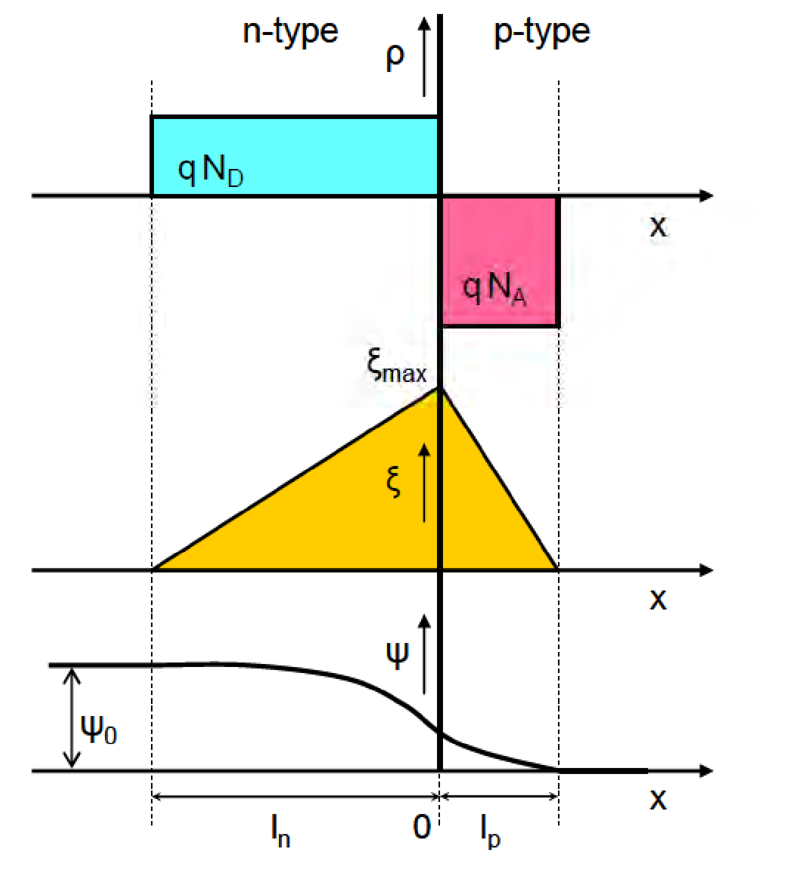


Sunlight to electricity (photovoltaic conversion)



http://www.tf.uni-kiel.de/matwis/amat/semi_en/kap_2/backbone/r2_2_4.html

Depletion width for p-n junction



Transport of free carriers occurs via drift (electric field) and diffusion (concentration gradient)

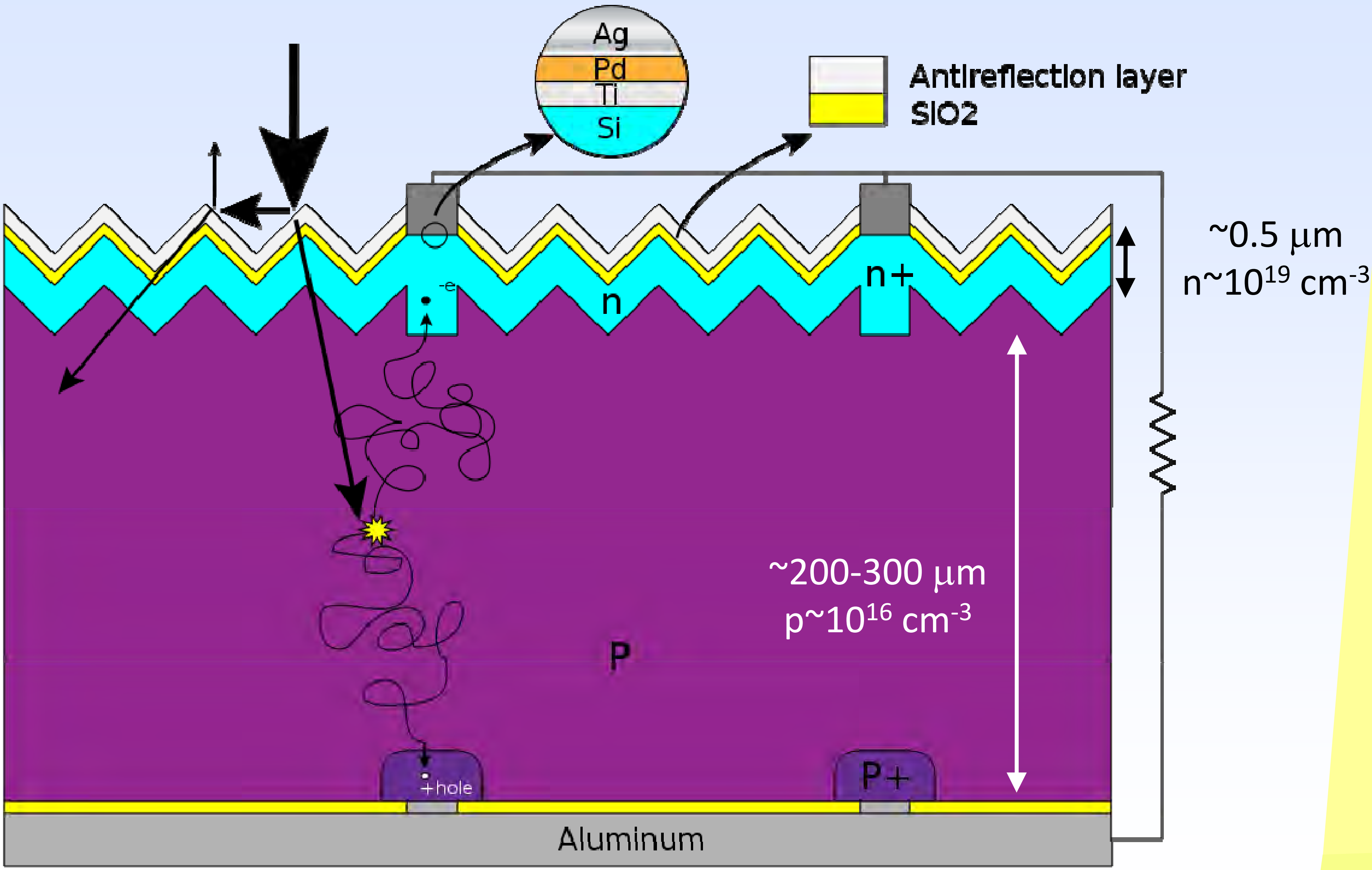
$$J_n = q\mu_n n(x)E + qD_n \frac{dn(x)}{dx}$$

$$J_p = q\mu_p p(x)E + qD_p \frac{dp(x)}{dx}$$

Top: space-charge density (ionized dopants)
Middle: electric field
Bottom: electrostatic potential

http://www.aerostudents.com/files/solarCells/CH4SolarCellOperationalPrinciples.pdf

Typical p-n (homo)junction crystalline silicon (c-Si) PV cell



http://en.wikipedia.org/wiki/File:Silicon_Solar_cell_structure_and_mechanism.svg

Estimating depletion width for c-Si

$$W = \left[\frac{2K_s\varepsilon_0}{q} \left(\frac{N_A + N_D}{N_A N_D} \right) (V_{bi} - V) \right]^{1/2}$$

$$K_s \approx 11.9$$

$$\varepsilon_0 = 8.85x10^{-12}\,\mathrm{C\,V^{-1}\,m^{-1}}$$

$$\frac{10^{16}cm^{-3} + 10^{19}cm^{-3}}{10^{35}cm^{-6}} \approx 10^{-16}cm^3$$

$$W \approx \left[1.3x10^{-13}V^{-1}m^2 (V_{bi} - V)\right]^{1/2}$$

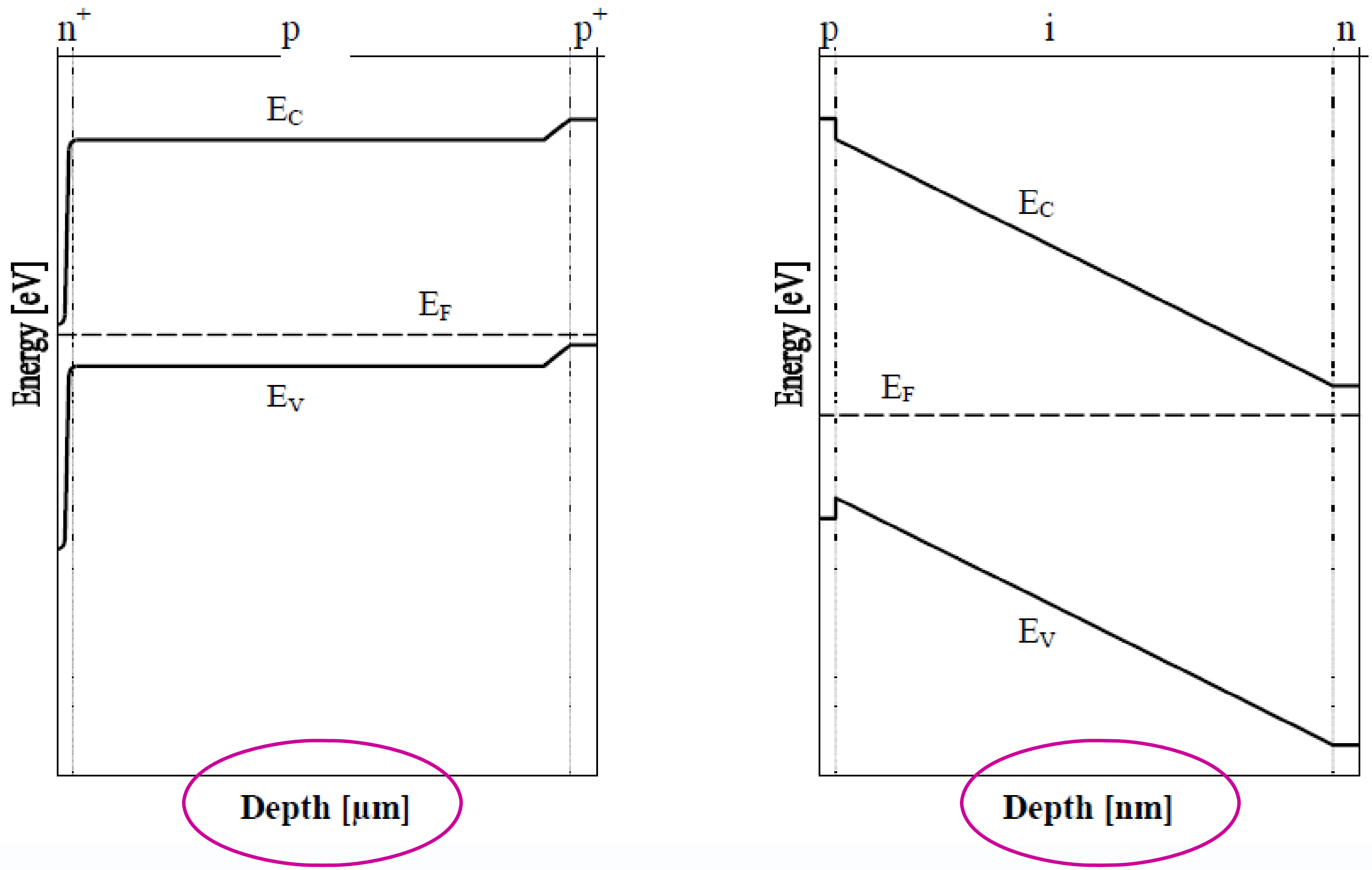
$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_A N_D}{n_i^2} \right)$$

$$n_i(\text{c-Si}) \approx 1.5x10^{10}cm^{-3}$$

$$V_{bi} \approx \frac{kT}{q} \ln\left(\frac{10^{16}cm^{-3}10^{19}cm^{-3}}{2.2x10^{20}cm} \right) \approx 0.84\mathrm{V}$$

W ≈ 330 nm

Example of a p-n (homo)junction crystalline silicon solar cell

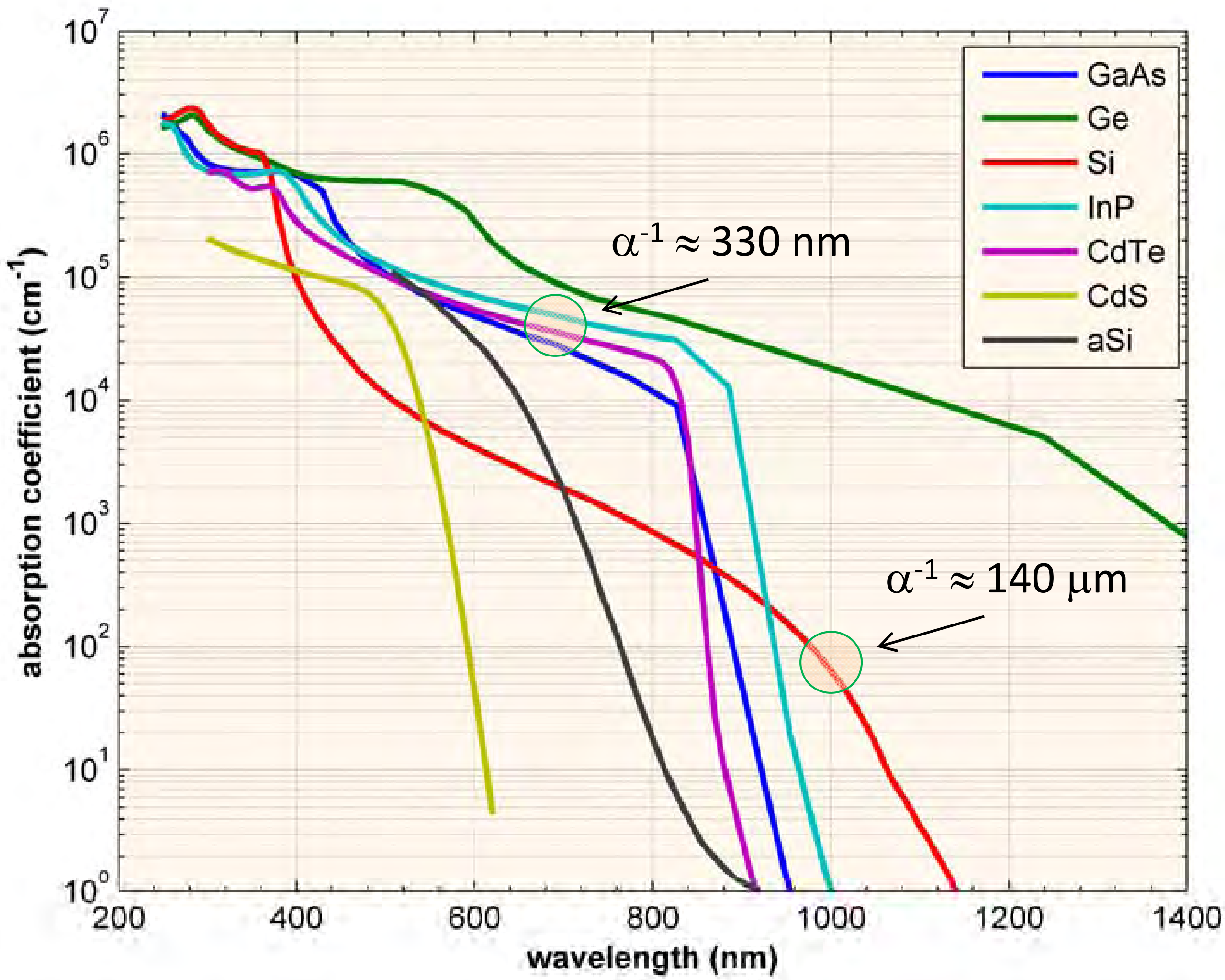


(a) c-Si solar cell (indirect gap), and (b) a-Si solar cell (direct gap)

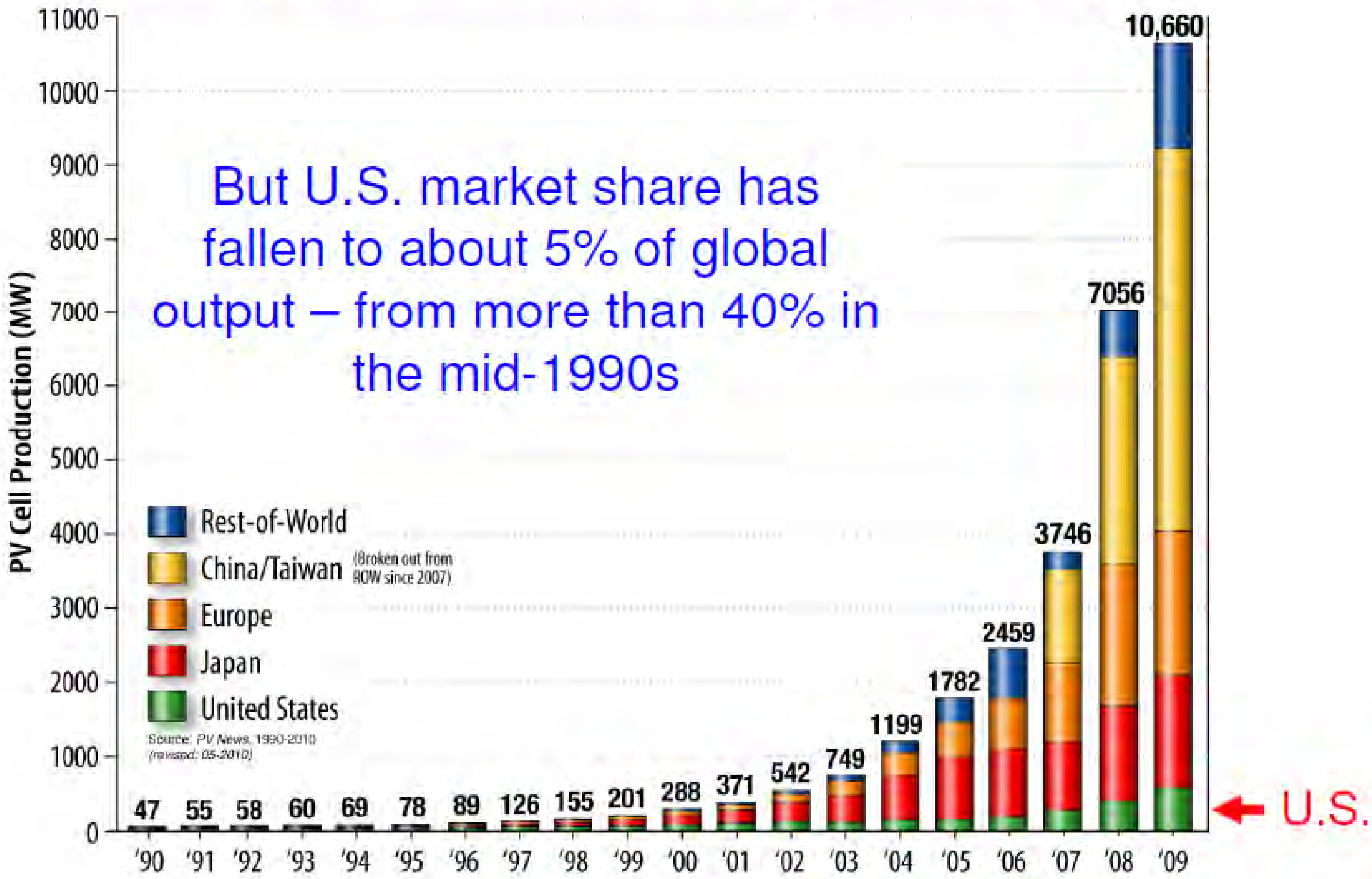
http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/res00030/CH7_Thin_film_Si_solar_cells.pdf

Semiconductor absorption coefficients

$$I(\lambda, x) = I_0 e^{-\alpha(\lambda)x}$$

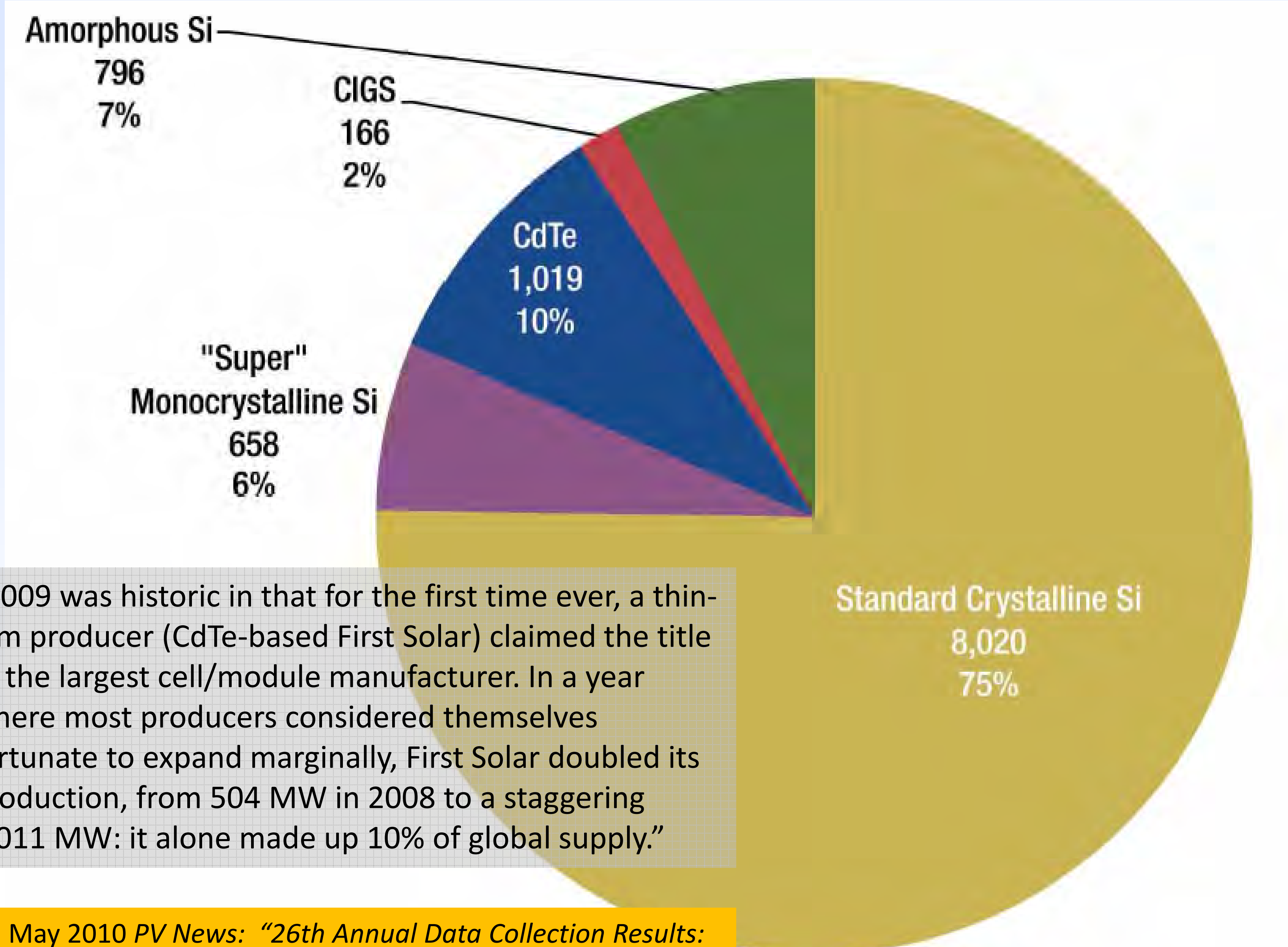


Solar PV is a booming global industry



Worldwide production of solar photovoltaics – in Megawatts

Commercial Photovoltaics as of 2010



"2009 was historic in that for the first time ever, a thin-film producer (CdTe-based First Solar) claimed the title of the largest cell/module manufacturer. In a year where most producers considered themselves fortunate to expand marginally, First Solar doubled its production, from 504 MW in 2008 to a staggering 1,011 MW: it alone made up 10% of global supply."

from May 2010 *PV News: "26th Annual Data Collection Results: Another Bumper Year for Manufacturing Masks Turmoil"*

Attained vs. attainable efficiencies

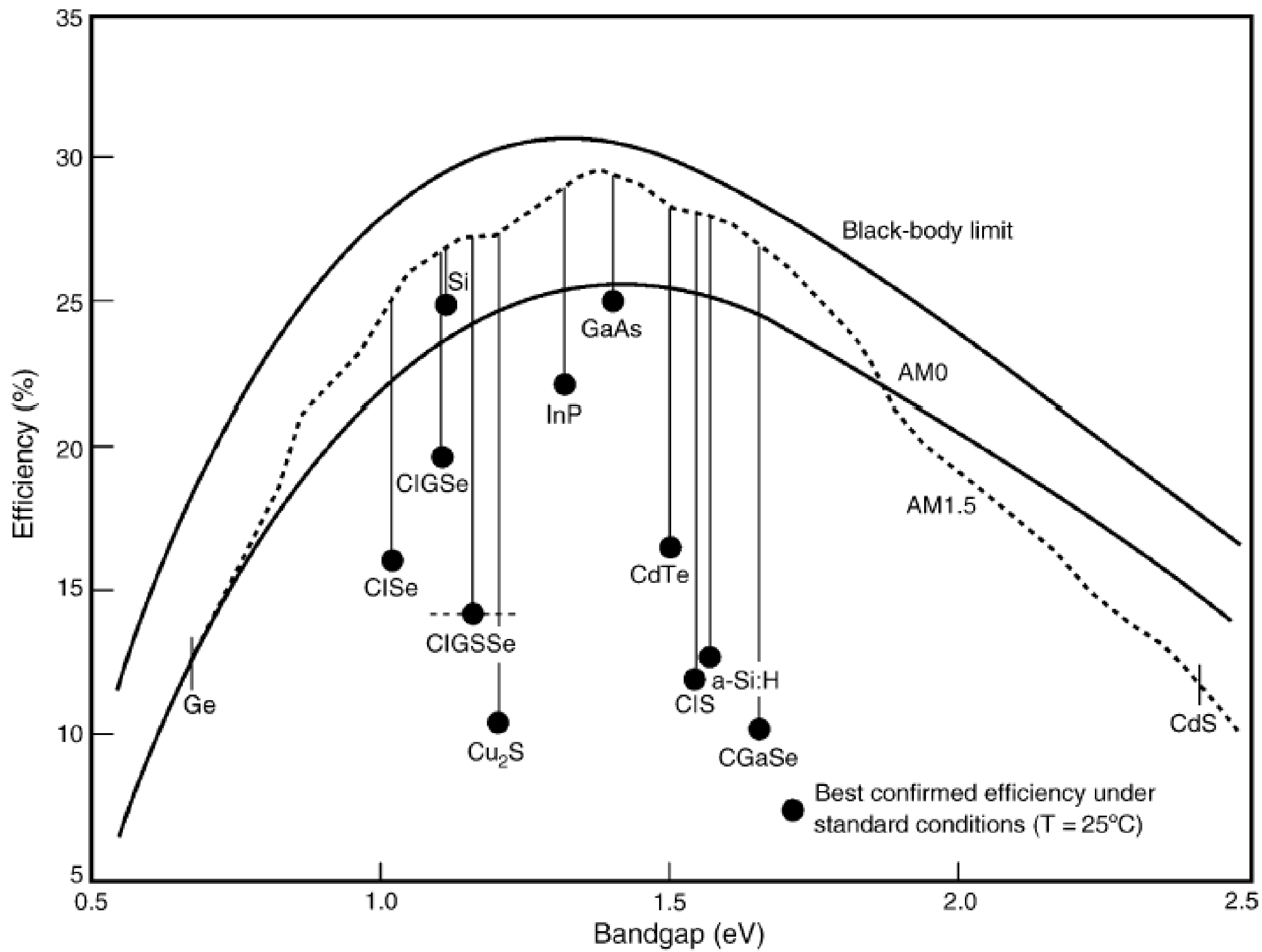


Fig. 3. Performance gaps between best device efficiencies in the laboratory and attainable efficiencies for several solar cell technologies.

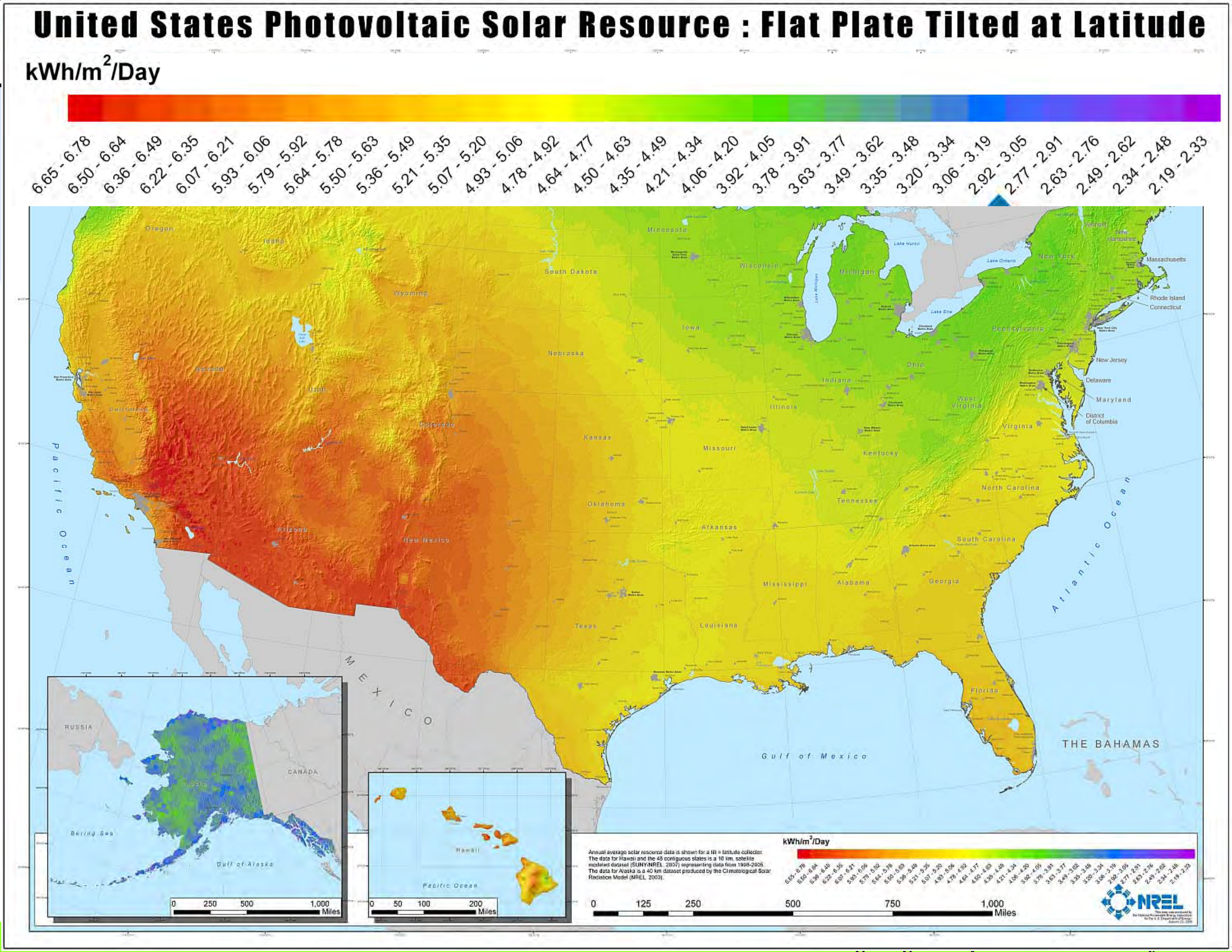
L.L. Kazmerski / Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

Attained vs. attainable **open circuit photovoltage**

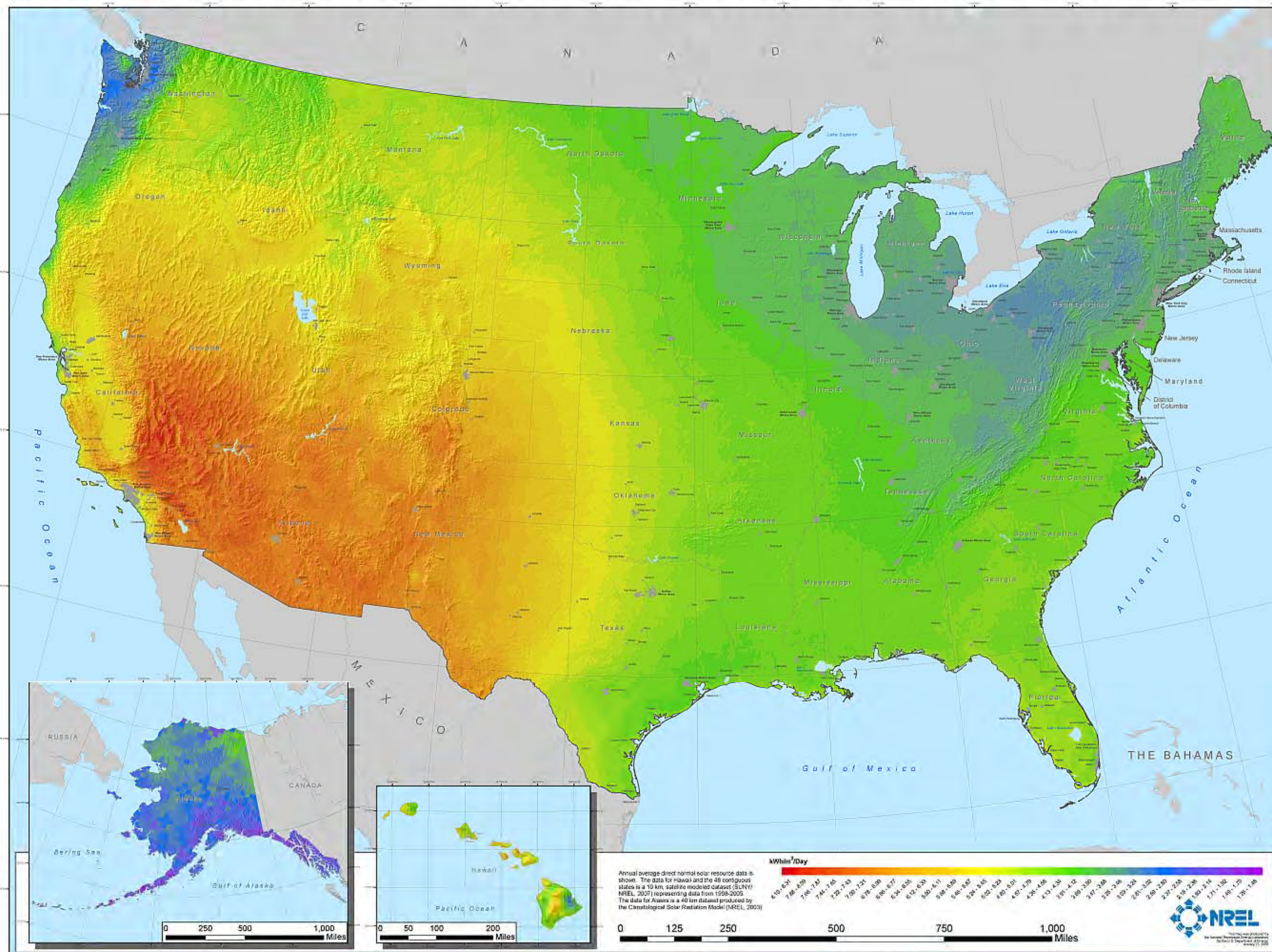
Cell Type	E_g at RT (eV)	V_{OC}^{MAX} (V)	V_{OC} (V)	V_{OC} loss (V)	V_{OC}/V_{OC}^{MAX} (%)
SC-Si	1.12	0.84	0.71	0.13	85
GaAs	1.42	1.14	1.02	0.12	90
InP	1.28	1.00	0.88	0.12	88
CdTe	1.45	1.17	0.84	0.33	72
CIGS	1.14	0.86	0.72	0.14	84
a-Si	1.7	1.42	0.86	0.56	61
DSS					
(black dye)	1.4	1.12	0.72	0.40	64
(Red N719)	1.6	1.32	0.85	0.47	64
(Red N3)	2.0	1.72	0.80	0.92	47
OPV	1.55	1.27	0.75	0.52	59

Attained vs. attainable **short-circuit photocurrent**

Cell Type	E_g at RT (eV)	J_{SC}^{MAX} (mA/cm^2)	J_{SC} (mA/cm^2)	J_{SC}/J_{SC}^{MAX} (%)
SC-Si	1.12	43.8	42.7	98
GaAs	1.42	32.0	28.5	89
InP	1.28	36.3	29.5	81
CdTe	1.45	30.8	25.9	84
CIGS	1.15	42	33.5	80
a-Si	1.7	22.4	17.5	78
DSS				
(black dye)	1.4	33.3	20.5	62
(Red N719)	1.6	25.5	17.7	70
(Red N3)	2.0	14.4	9.2	64
OPV	1.55	26.9	14.7	55


United States Photovoltaic Solar Resource : Flat Plate Tilted at Latitude
kWh/m²/Day
6.65 - 6.78
6.50 - 6.64
6.36 - 6.49
6.22 - 6.35
6.07 - 6.21
5.93 - 6.06
5.79 - 5.92
5.64 - 5.78
5.50 - 5.63
5.36 - 5.49
5.21 - 5.35
5.07 - 5.20
4.93 - 5.06
4.78 - 4.92
4.64 - 4.77
4.50 - 4.63
4.35 - 4.49
4.21 - 4.34
4.06 - 4.20
3.92 - 4.05
3.78 - 3.91
3.63 - 3.77
3.49 - 3.62
3.35 - 3.48
3.20 - 3.34
3.06 - 3.19
2.92 - 3.05
2.77 - 2.91
2.63 - 2.76
2.49 - 2.62
2.34 - 2.48
2.19 - 2.33
Pacific Ocean
Atlantic Ocean
Gulf of Mexico
MEXICO
THE BAHAMAS
RUSSIA
CANADA
Bering Sea
Gulf of Alaska
Hawaii
Pacific Ocean
Annual average solar resource data is shown for a tilt = latitude collector. The data for Hawaii and the 48 contiguous states is a 10 km, satellite modeled dataset (SUNY/NREL, 2007) representing data from 1998-2005. The data for Alaska is a 40 km dataset produced by the Climatological Solar Radiation Model (NREL, 2003).
0 125 250 500 750 1,000 Miles
0 250 500 1,000 Miles
0 50 100 200 Miles
NREL

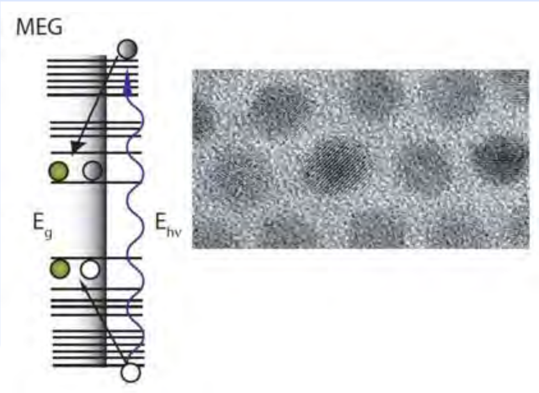
United States Concentrating Solar Power Resource : Direct Normal



Nanomaterials for solar energy conversion

- High surface area devices →
  - strong light absorption (dye-sensitized nanostructured TiO_2)
  - fast charge separation (proximity of photoexcited carriers to charge-separating interface)
- Customizable properties →
  - Size-dependent optical properties
  - Controlled geometries – e.g., efficient transport in oriented quantum rods, nanotubes
  - Controlled chemical functionalization for directed charge separation (surface chemistry)
- Novel effects? (multiple exciton generation, excitonic behavior)

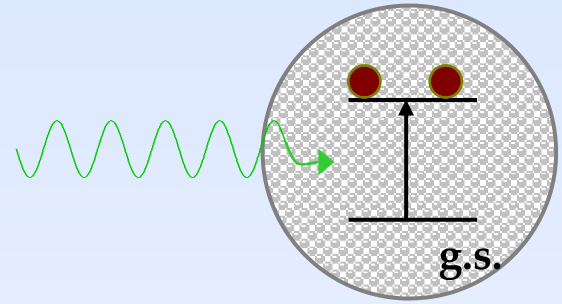
Early history on Multiple Exciton Generation (MEG) in NCs



NCs of: IV-VI, II-VI, III-V, IV (e.g., PbSe, PbS, PbTe, CdSe, Si, InP), and **SWNTs** as well…

Spectroscopic Techniques: TA (interband, intraband), TRPL*, TRTS (THz), and quasi-cw PL*

(* shows red-shifted biexciton PL)



A. J. Nozik, *Physica E* **14**, 115 (2002).

R. Schaller and V. Klimov, *PRL* **92**, 186601 (2004).
(PbSe QDs → QY 2.2)

Ellingson, Beard, Efros, Nozik, *et al.*, *Nano Lett.* **5**, 865 (2005).
(PbSe, PbS QDs → QY 3.0)

R. Schaller *et al.*, *App. Phys. Lett.* **87**, 253102 (2005).
(CdSe → QY 1.6 at $3.1E_g$)

J. Murphy *et al.*, *JACS* **128**, 3241 (2006).
(PbTe → QY 3.0 at $4E_g$)

R. Schaller *et al.*, *Nano Lett.* **6,** 424-429 (2006).
(PbSe → QY of 7.0 at $8E_g$)

J. Pijpers *et al.*, *J. Phys. Chem. C* **111**, 4146 (2007).
(InAs/CdSe/ZnSe QDs → QY 1.6 at $2.7E_g$)

M. C. Beard *et al.*, *Nano Lett.* **7**, 2506 (2007).
(Si QDs → QY 2.6 at $3.4E_g$)

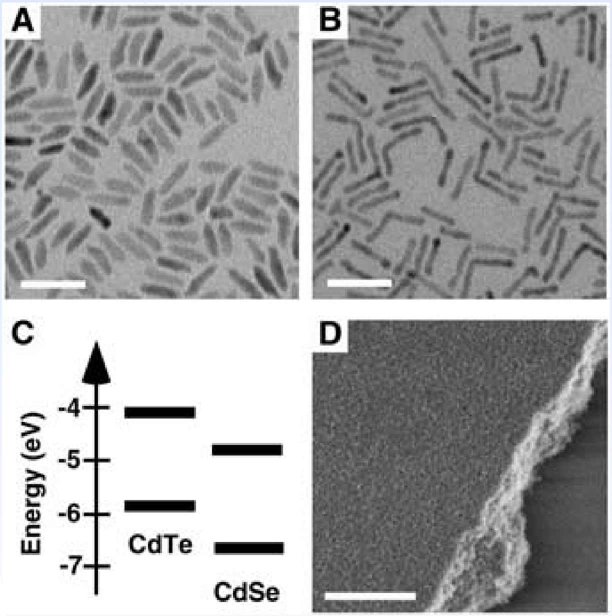
R. Schaller *et al.*, *Nano Lett.* **7,** 3469 (2007).
(InAs/CdSe core/shell QDs → QY of 1.95 at ~$4.8E_g$)

J. Luther *et al.*, *Nano Lett.* **7**, 1779 (2007).
(Efficient MEG in PbSe QD films)

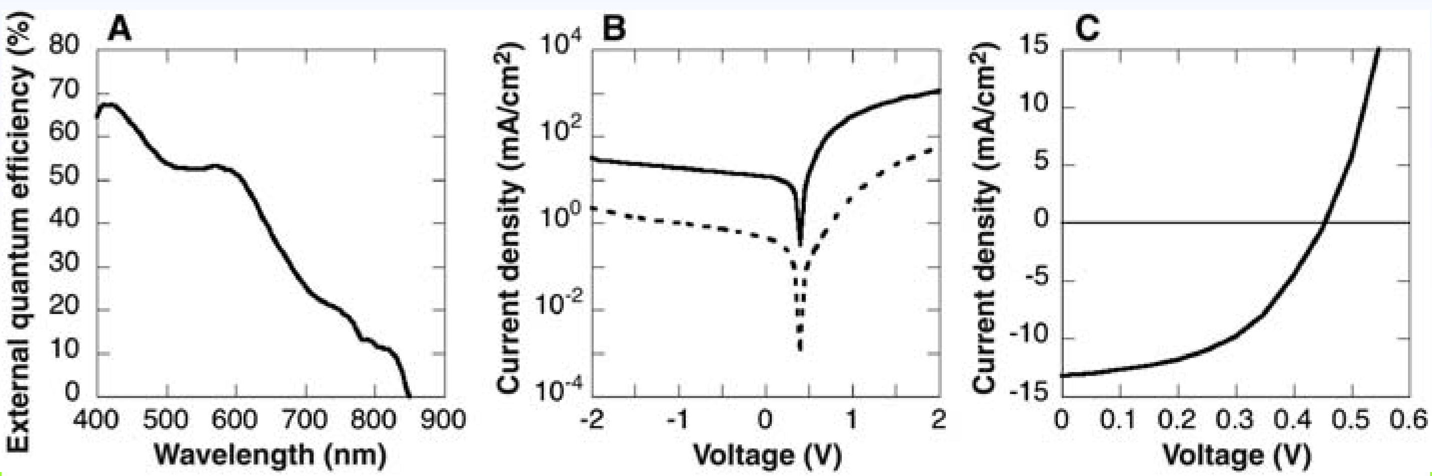
M. Tuan Trinh *et al.*, *Nano Lett.* **8**, 1713 (2008).
(PbSe QDs → QY 1.7 at 4.8 $8E_g$)

Annealed NC-based solar cell

Air-Stable All-Inorganic Nanocrystal Solar Cells Processed from Solution
Ilan Gur, Neil A. Fromer, Michael L. Geier, A. Paul Alivisatos
21 OCTOBER 2005 VOL 310 SCIENCE



TEM images of (A) CdSe and (B) CdTe NCs. Scale bar, 40 nm. (C) An energy diagram of valence and conduction band levels for CdTe and CdSe illustrates the type II charge-transfer junction formed between the two materials…



Roll-to-roll processing from solution source (e.g., Nanosolar CIGS)

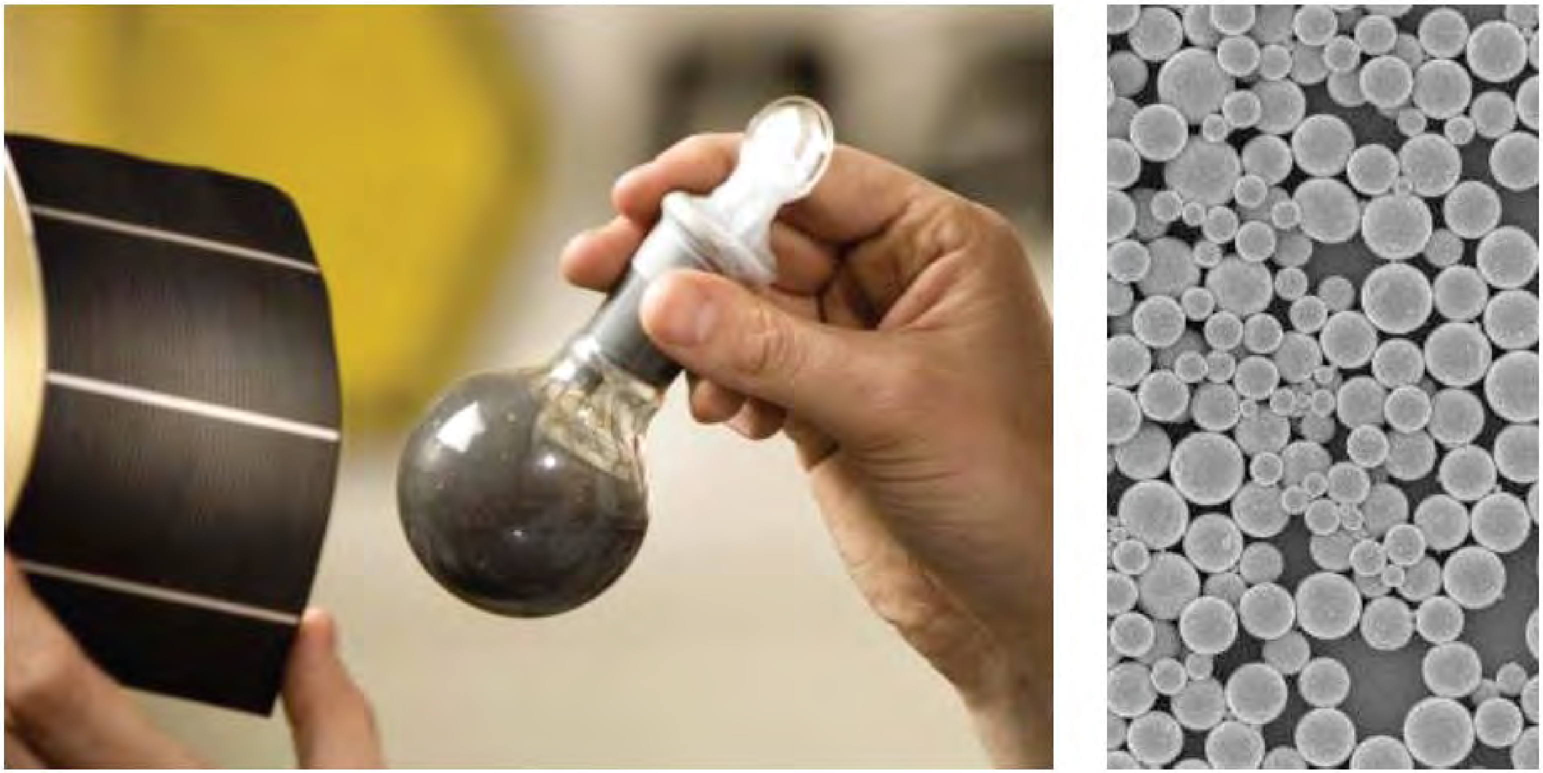
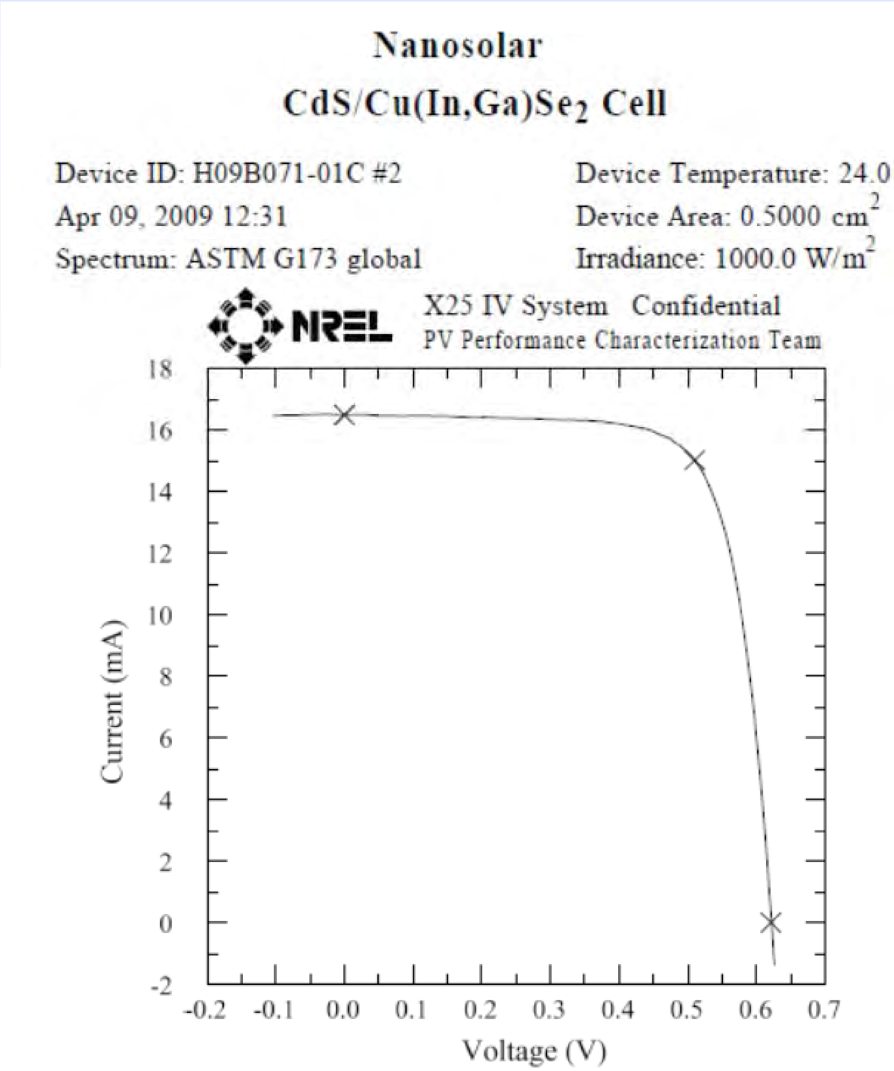


Figure 6 and 7: A laboratory sample of our nanoparticle ink. Nanoparticles shown to the right are an average of 20nm in diameter.

from NanoSolar white paper

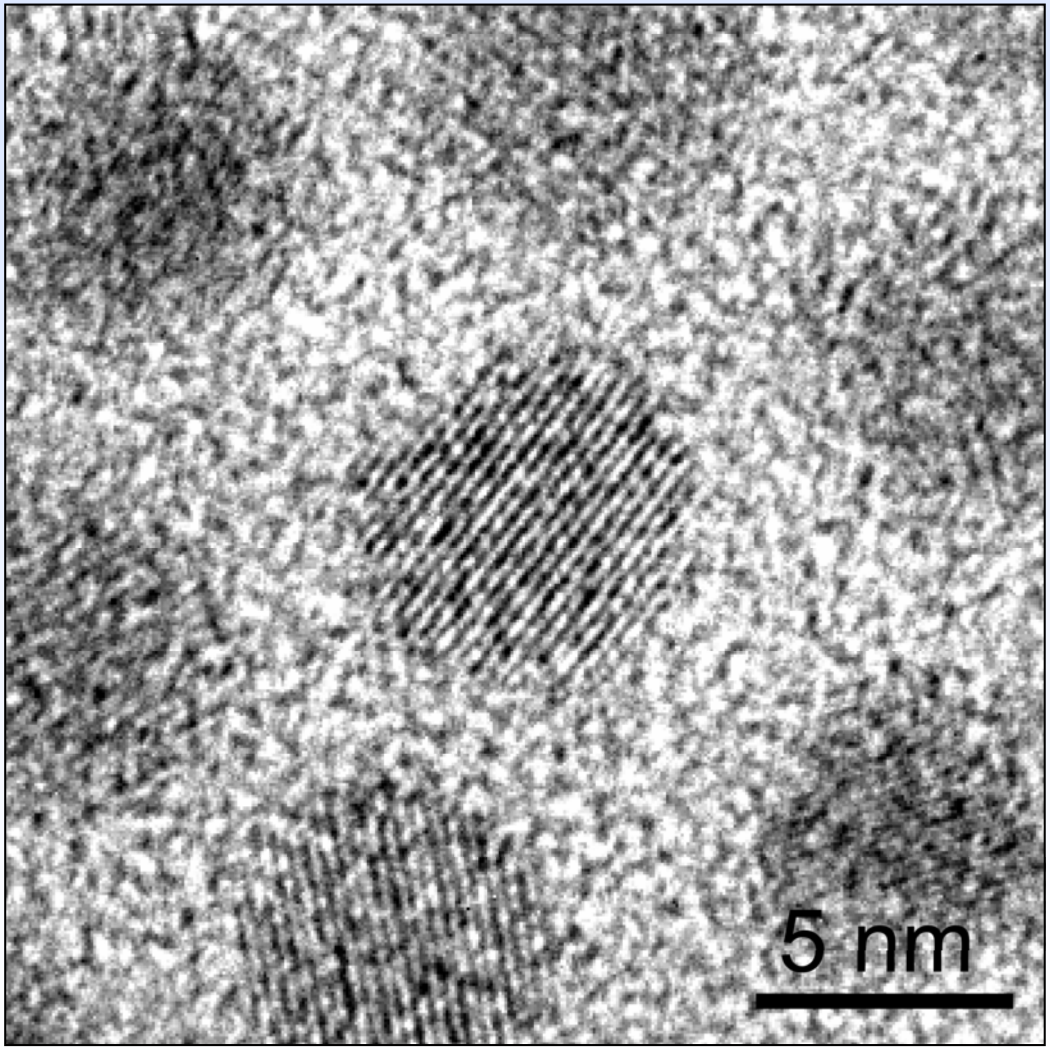
Good solar cells from nanoparticle inks (CIGS)



V_{oc} = 0.6214 V	I_{max} = 15.010 mA
I_{sc} = 16.490 mA	V_{max} = 0.5101 V
J_{sc} = 32.980 mA/cm^2	P_{max} = 7.6540 mW
Fill Factor = 74.70 %	Efficiency = 15.31 %

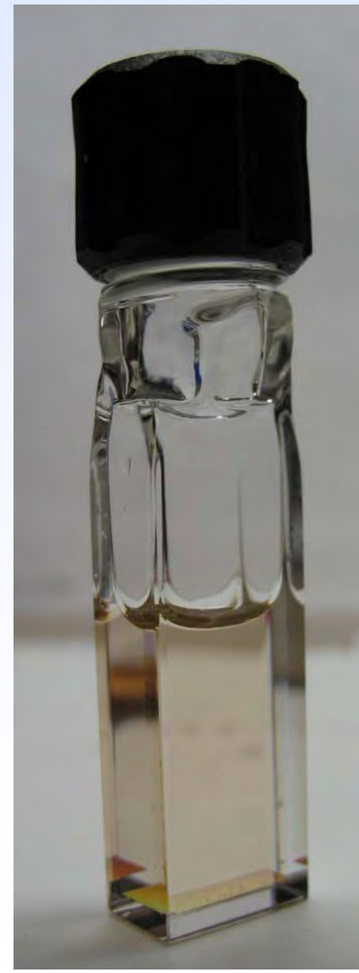
from NanoSolar white paper

TEM of colloidal lead selenide QDs



PbSe exciton Bohr radius ~ 46 nm

PbSe QDs



Synthesis of Colloidal PbS NCs

Hines, M. A.; Scholes, G. D. *Adv. Mater.* ***2003, 15, 1844***

Sample synthesis recipe (**Krauss et al.**, adapted from **Hines and Scholes**)

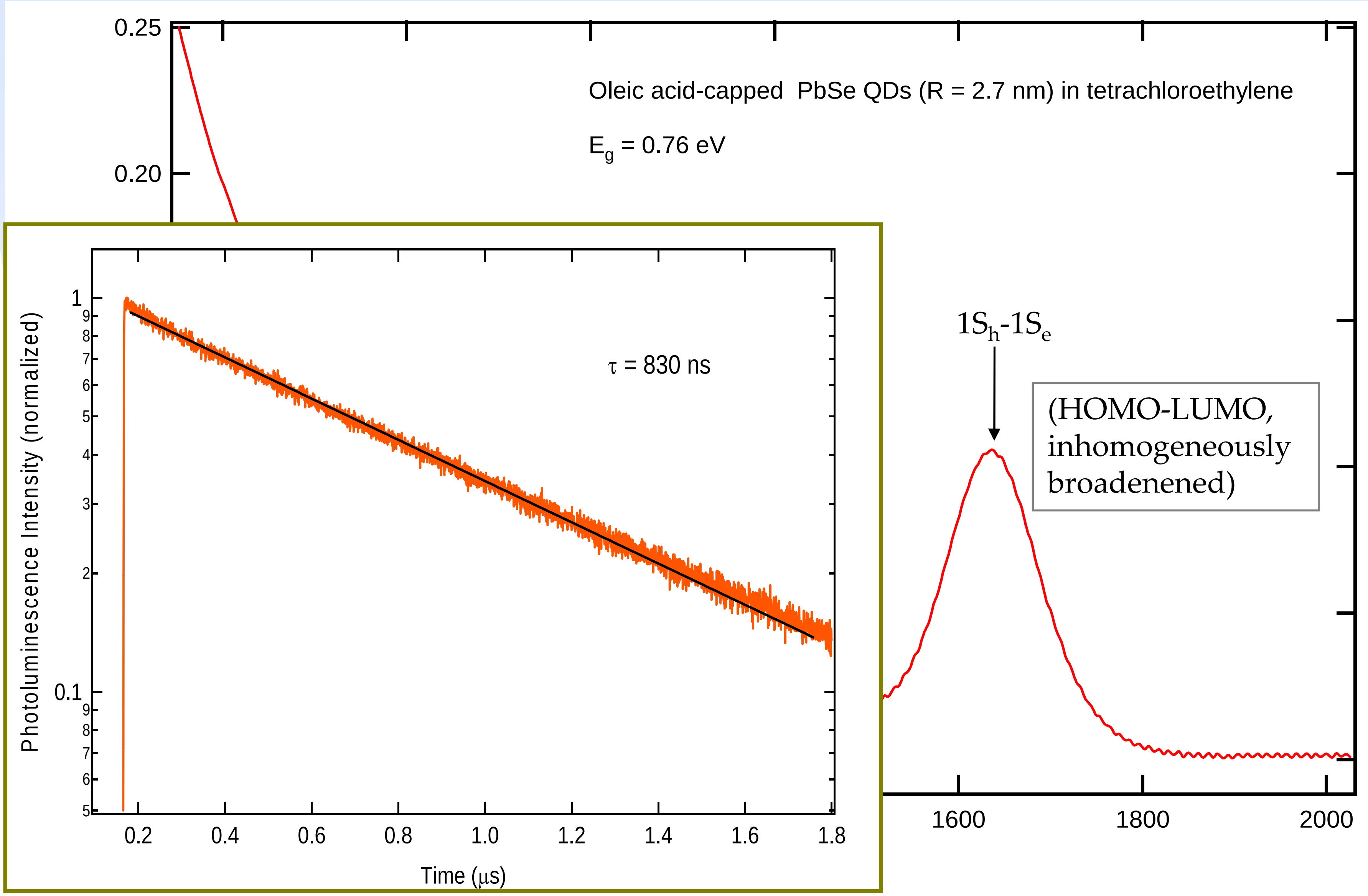
- heat together in a flask at 150 °C for 1 hr under N_2 flow (to make lead oleate):
  - 220 mg lead(II) oxide
  - 0.25 ml oleic acid (tech grade)
  - 9.75 ml 1-octadecene (ODE, tech grade)
- after cooling to 90-100 °C, quickly inject into the reaction flask 5 ml of 0.1 M hexamethyldisilathiane (0.5 mmol) dissolved in ODE
- immediately cool with an ice bath
- precipitate (methanol/butanol mixture), centrifuge and resuspend in non-polar solvent (e.g., toluene, tetrachloroethylene, or hexanes).

$$PbO + 2\ C_{18}H_{34}O_2 \xrightarrow[< 122C]{N_2,\ ODE} Pb(oleate)_2 + H_2O$$

$$Pb(Oleate)_2 + ((CH_3)_3Si)_2S \xrightarrow[< 122C]{N_2,\ ODE} \text{PbS NC capped with OA}$$

http://pubs.acs.org/doi/suppl/10.1021/nl0525756/suppl_file/nl0525756si20060213_112831.pdf

Colloidal PbSe QDs in tetrachloroethylene (TCE)

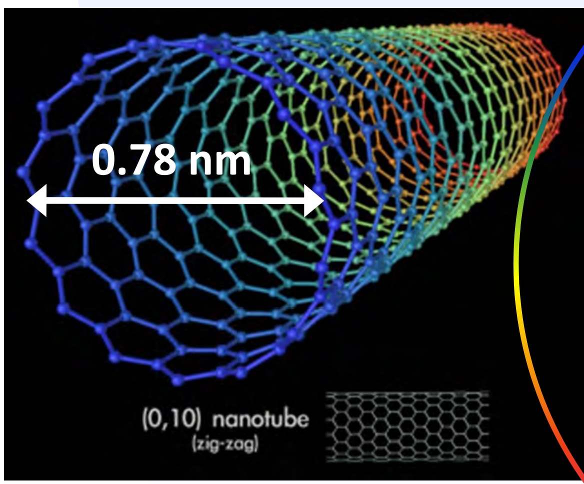


Colloidal semiconductor nanocrystals

- Solution synthesis, typically at elevated temperature
- Inorganic crystalline core surrounded by organic capping molecules
- Most frequently suspended in organic solvents
- Can be stored stably either in powder or solution form

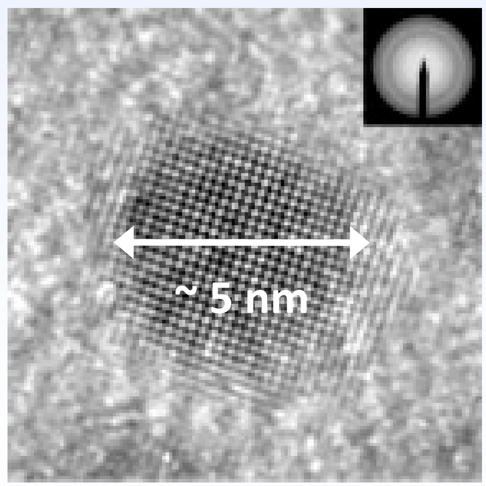
Colloidal semiconductor NCs have typical diameters of 1 nm to 10 nm

SWNT (10,0)



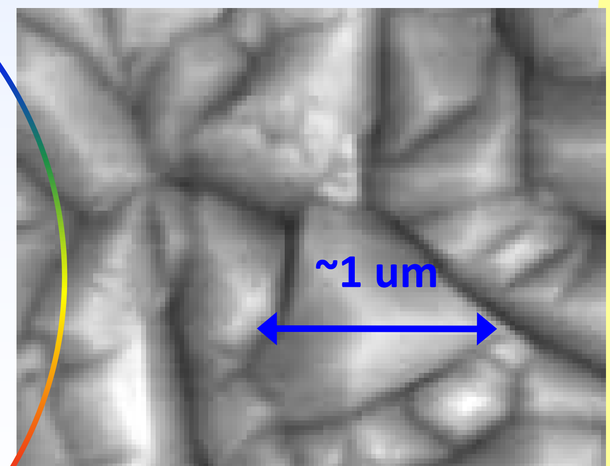
http://commons.wikimedia.org/wiki/Main_Page

PbS NC



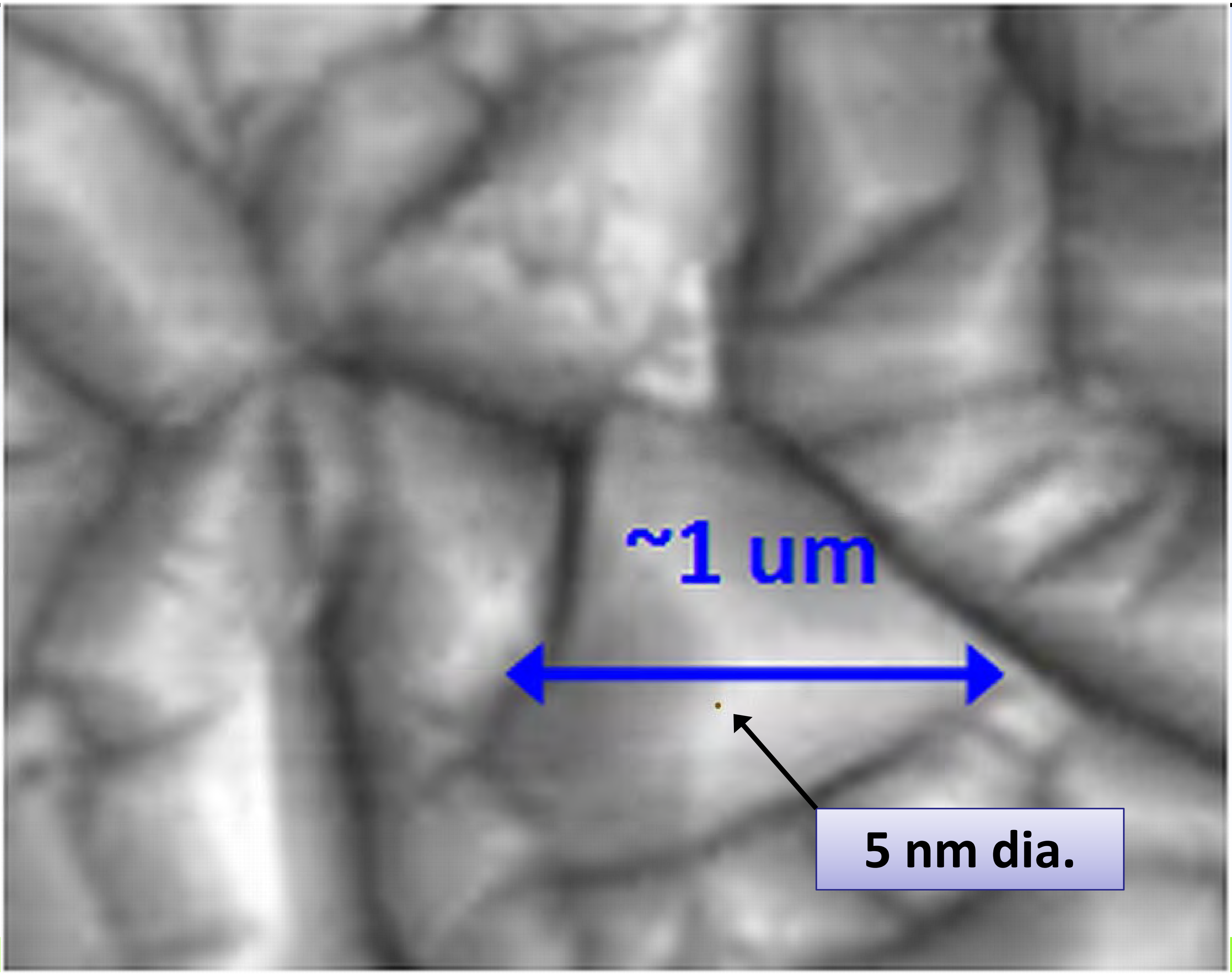
Sargent, Adv. Mat. (2005), 515-522.

CdTe grain size (CSS)



Quiñones et al., J. Mater. Sci: Mat. Electron (2007), 1085–1091

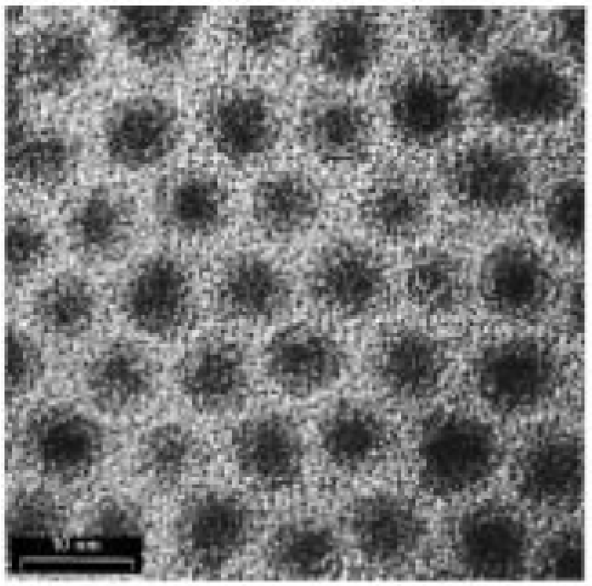
Colloidal quantum dot – scale



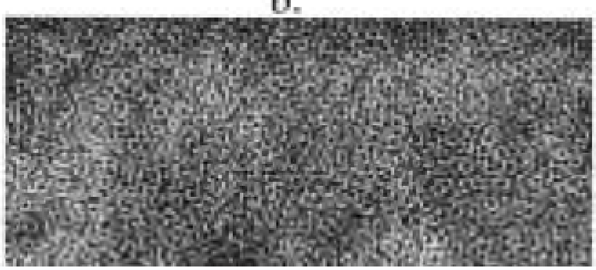
Coupling QDs within a film (or array)

9794 *J. Phys. Chem. B, Vol. 102, No. 49, 1998* Micic et al.

a.



b.



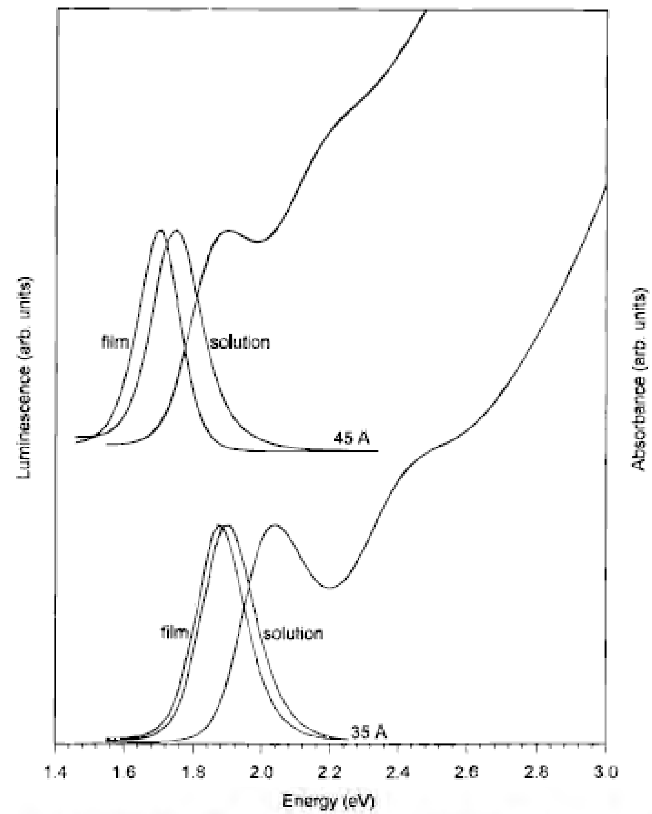


Figure 6. Absorption and luminescence spectra (λ_{exc} = 500 nm) of InP QDs in dilute colloidal solution and in close-packed films for 45- and 35-Å diameter QDs.

Optical, Electronic, and Structural Properties of Uncoupled and Close-Packed Arrays of InP Quantum Dots
Olga I. Mic´ic´ et al., 1998.

Coupling mechanisms

What could cause a decrease in QD-QD spacing to red-shift the exciton transition?

"This can cause (i) an increase in the average dielectric constant of the film, (ii) an increase in the inter-QD radiative coupling, and (iii) an increase in the inter-QD electronic coupling."

Strong Electronic Coupling in Two-Dimensional Assemblies of Colloidal PbSe Quantum Dots, Williams et al., ACS Nano (2009)

i) Increased wavefunction extension

ii) Increased FRET

iii) Reduced barrier width for tunneling/hopping transport

$$a_B^* = \frac{4\pi\varepsilon\hbar^2}{m^* e^2}$$

Energy/charge transport mechanisms

Energy transfer (FRET):

$$E = \frac{1}{1+\left(\frac{r}{R_0}\right)^6}$$

$\Rightarrow R_0 \approx$ 8-9 nm for ~3 nm InP QDs

J. Phys. Chem. B ***1998, 102, 9791-9796***

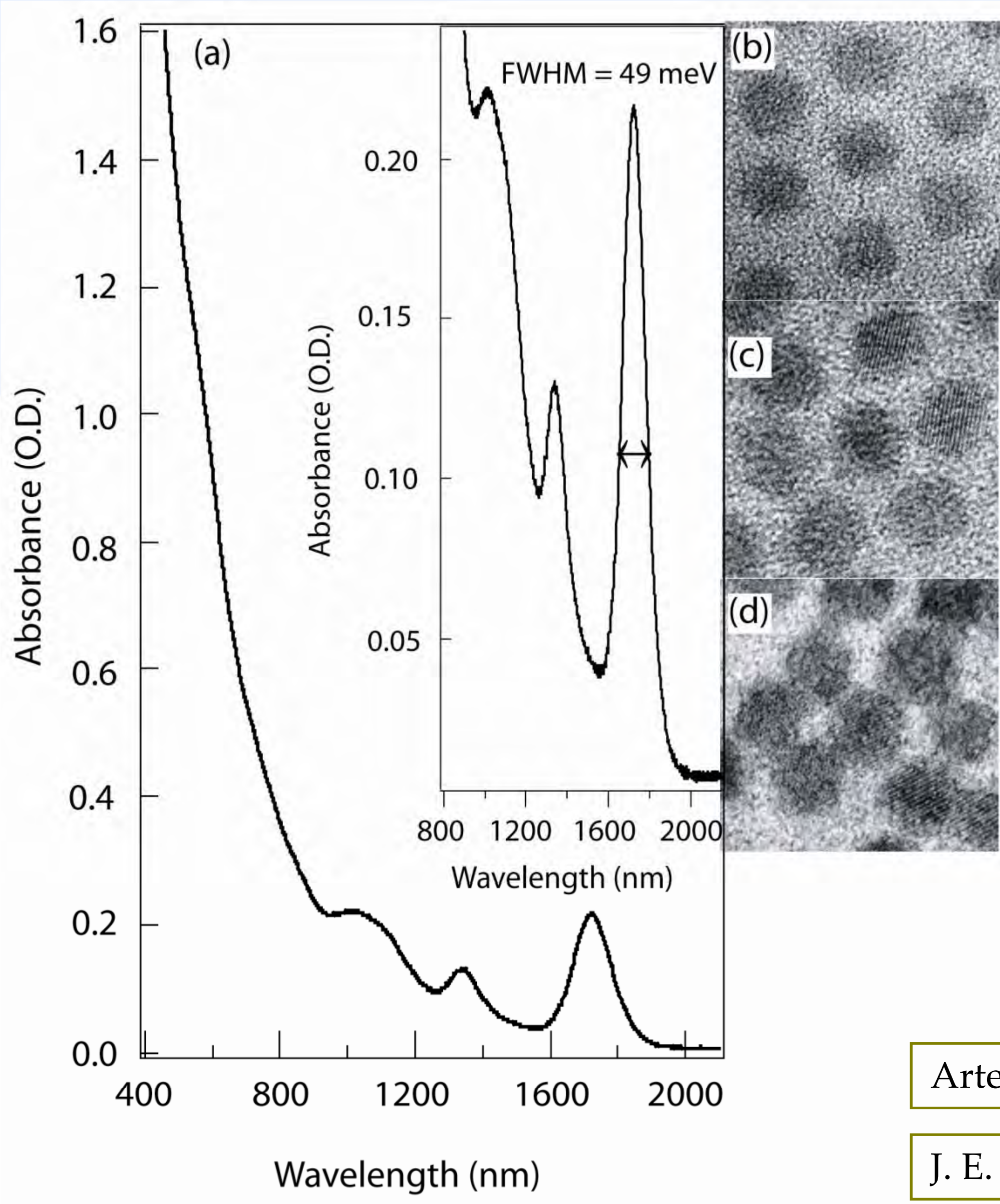
Hopping/tunneling transport:

$$\Gamma_{ij} = \Gamma_0 \exp(-\beta d)\begin{cases}\exp\left[-\frac{E_j - E_i}{kT}\right] & E_j > E_i \\ 1 & E_i > E_j\end{cases}$$

Miller, Abrahams, Phys. Rev. 120, 745–755 (1960)

Liu, Hillhouse, Law, Nano Lett. (2010), 10, 1960.

Post-deposition treatment of drop-cast films of 5.7 nm dia. PbSe QDs



oleic acid (1.8 nm)

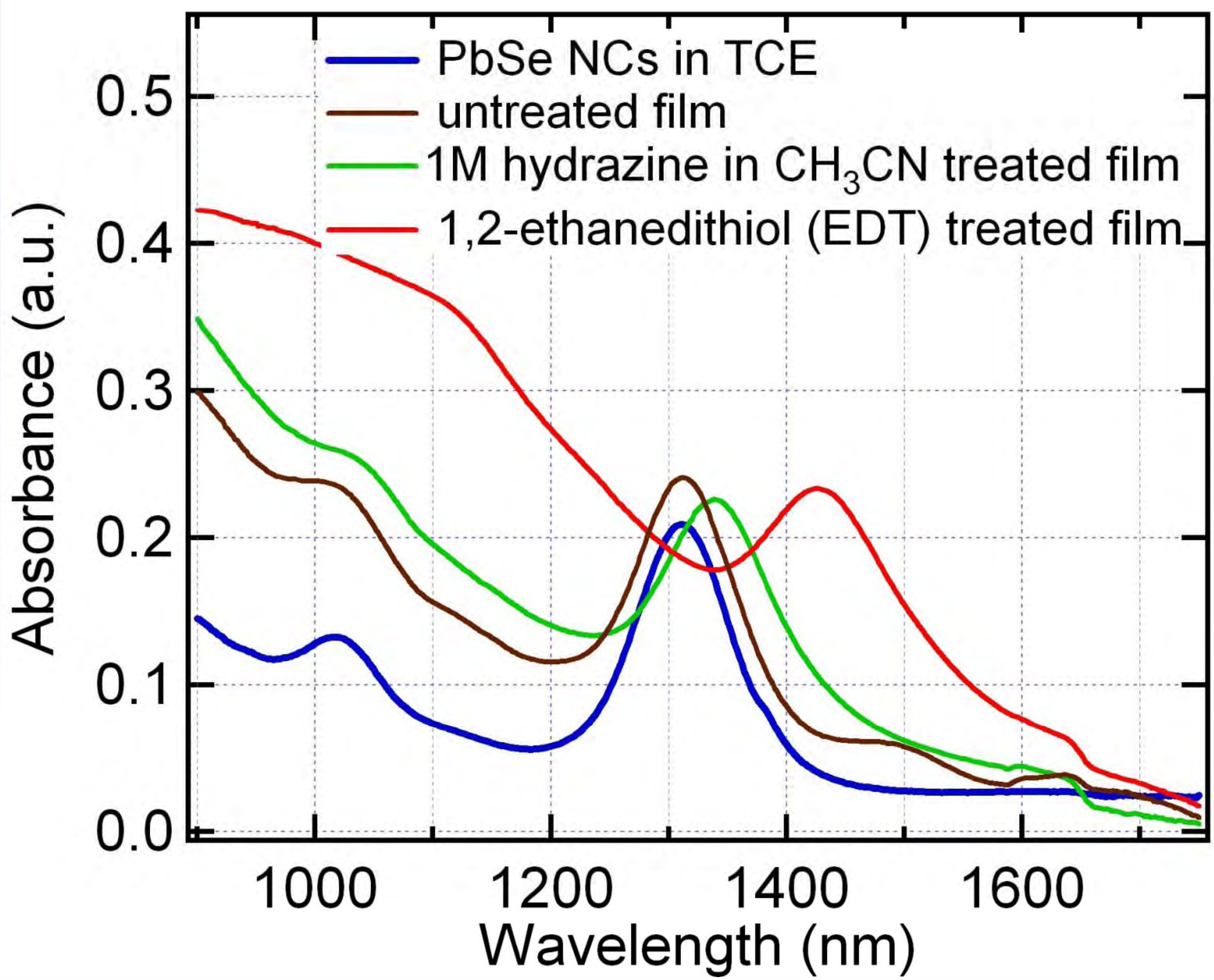
aniline (0.8 nm)

ethylenediamine (0.4 nm)

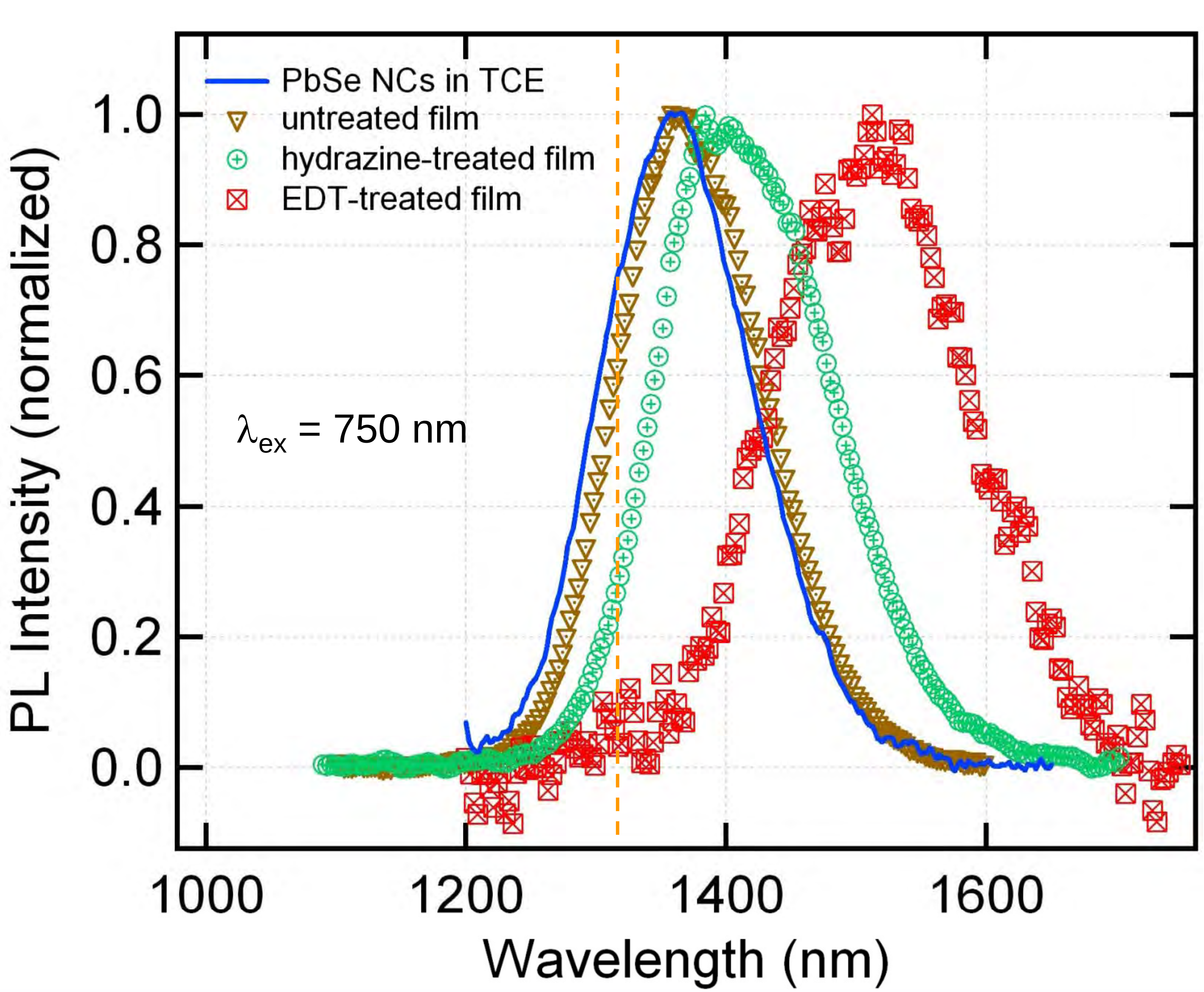
Artemyev *et al*., J. Phys. Chem. B 2000, 11617.

J. E. Murphy *et al*., J. Phys. Chem. B 2006, 25455.

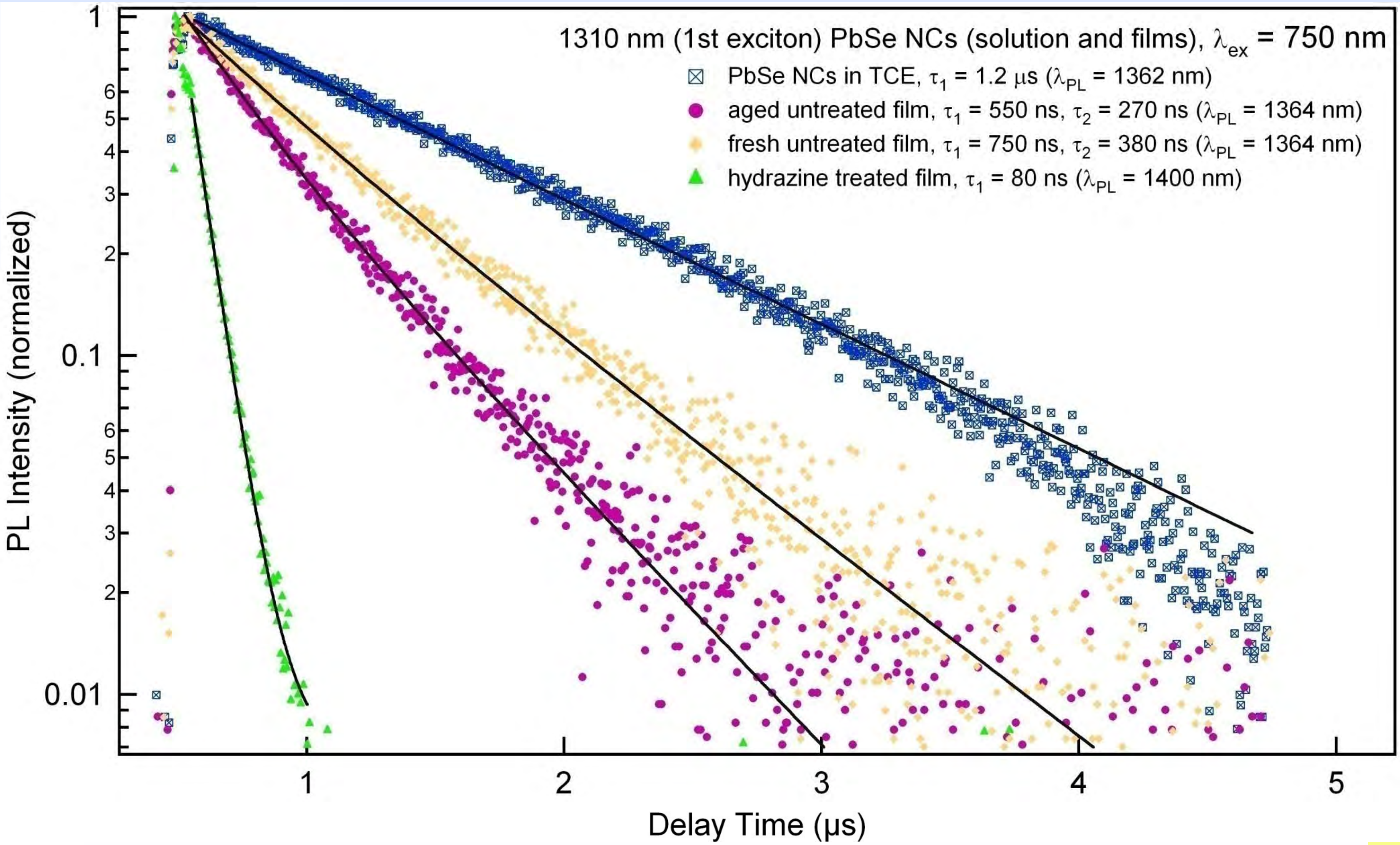
Absorption spectra: spincast films of 1310 nm PbSe NCs



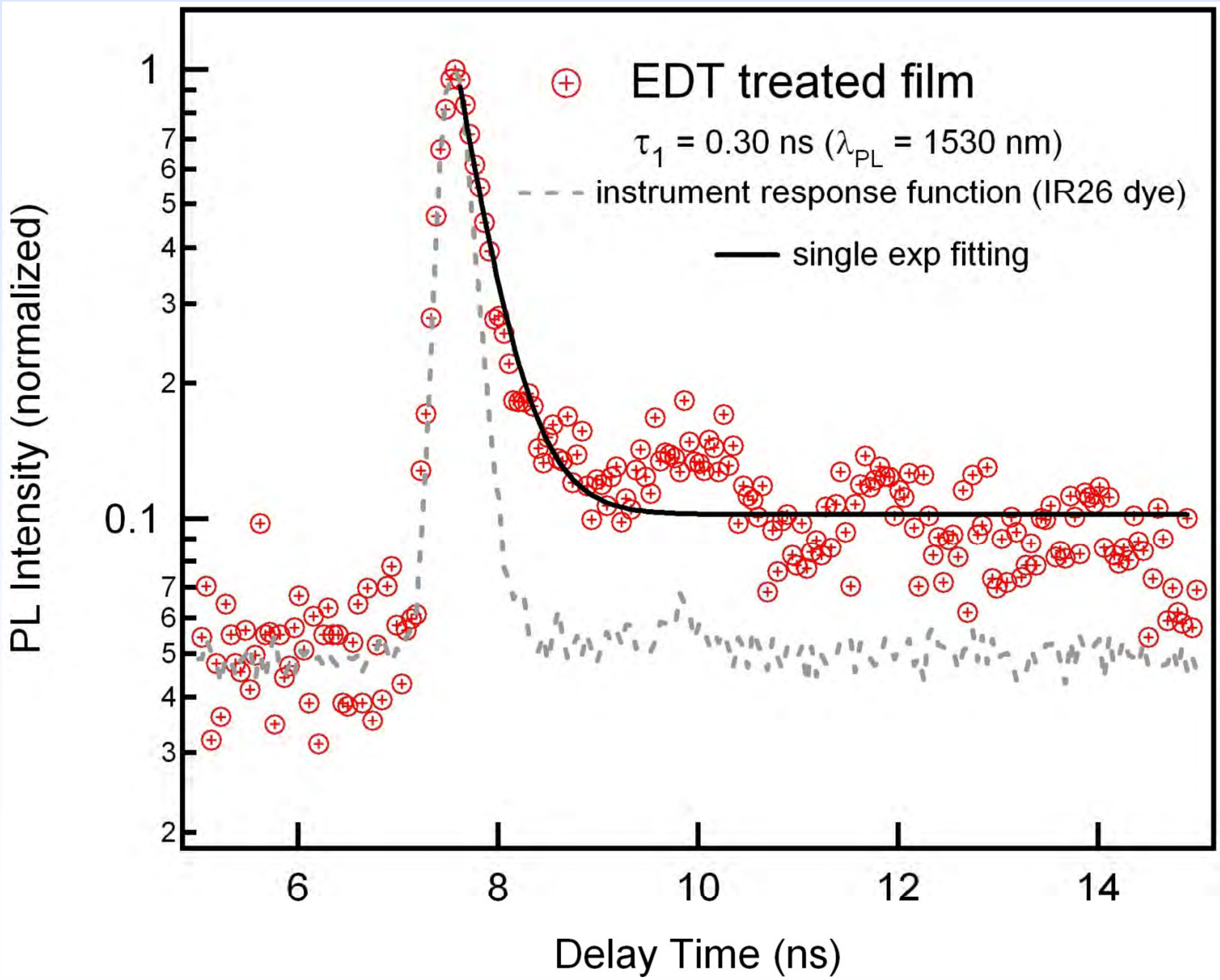
Steady-state photoluminescence (1310 nm NCs)



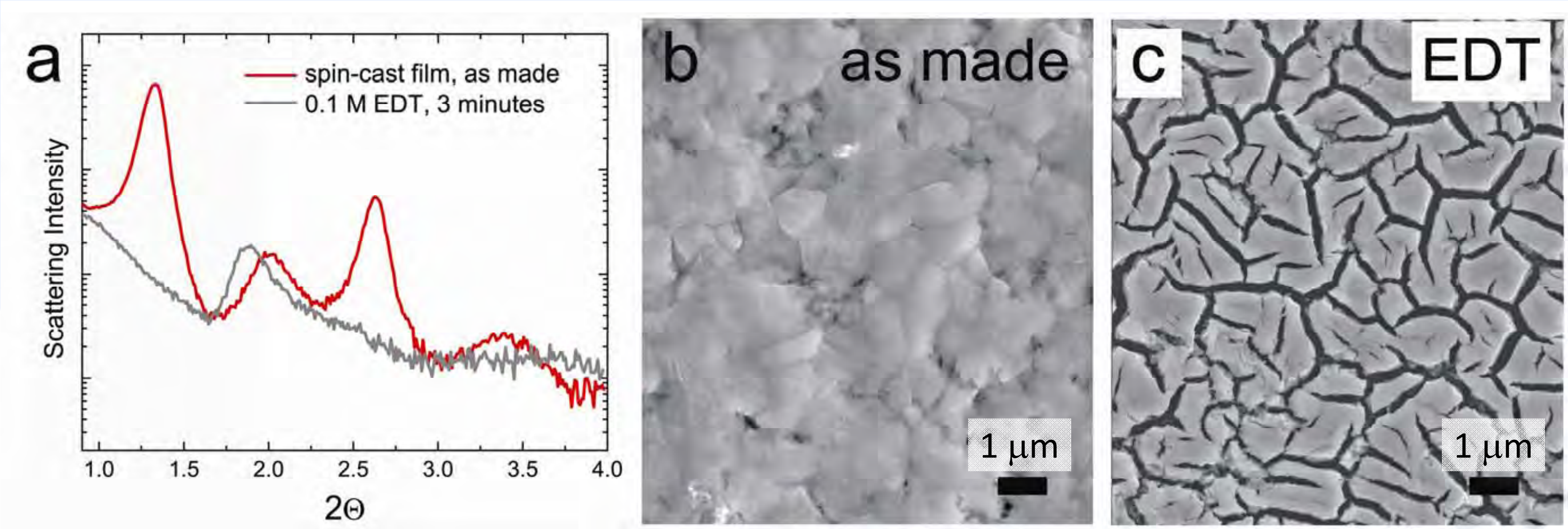
Time-resolved photoluminescence spectra



PL lifetime for EDT-treated PbSe NC film



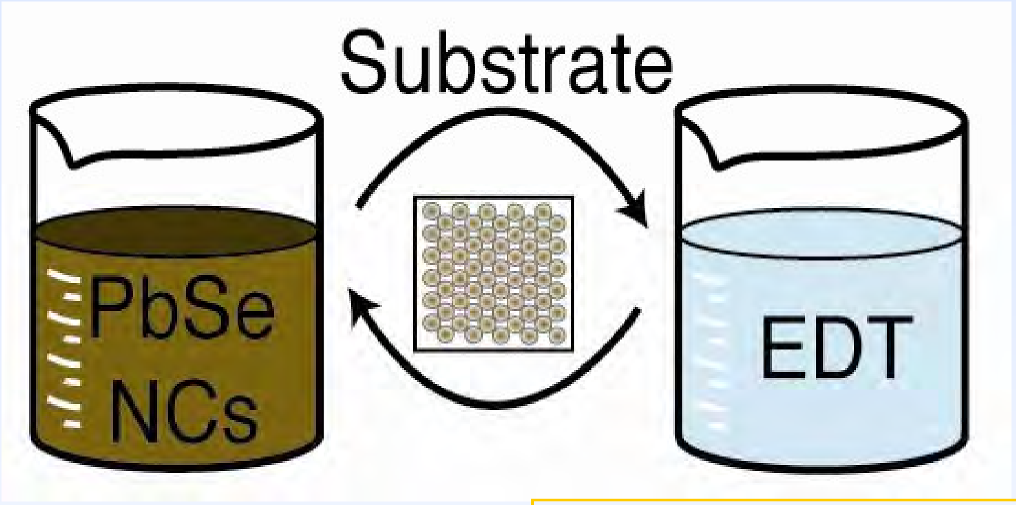
Post-casting treatment of spin-cast films of PbSe NCs



"Microstructure of the spin-cast NC films before and after EDT treatment. (a) SAXS data, showing a ~16 Å decrease in the spacing between the NCs and a dramatic loss of superlattice order upon EDT treatment. Measurements were taken in air. (b, c) Plan-view SEM images of (b) an untreated film and (c) a treated film."

J. Luther, M. Law et al., ACS Nano 2, 271 (2008).

Layer-by-layer fabrication of PbSe NC films

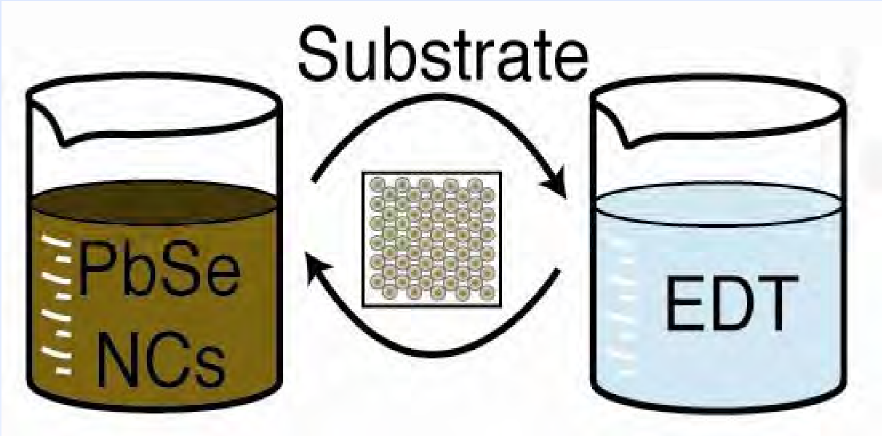


EDT = 1,2-ethanedithiol

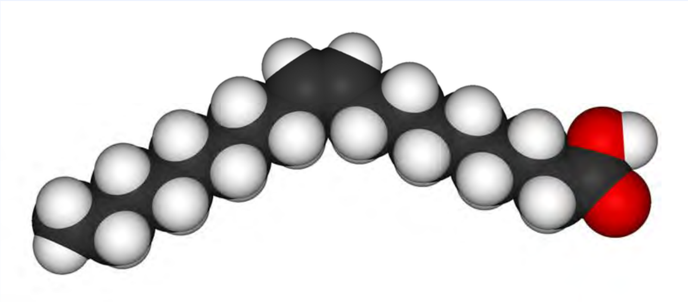
Layer by layer (LbL) fabrication of PbSe nanocrystal (NC) films. Nanocrystal films prepared by dip-coating, alternating between (1) PbSe NCs in hexane and (2) 0.1 M EDT in anhydrous acetonitrile, allowing the film to dry between each layer.

J. M. Luther, M. Law *et al.*, "Structural, Optical, and Electrical Properties of Self-Assembled Films of PbSe Nanocrystals Treated with 1,2-Ethanedithiol", *ACS Nano* **2**, 271 (2008).

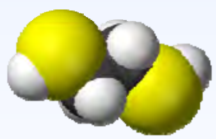
Ligand exchange in PbX NC films



EDT = 1,2-ethanedithiol

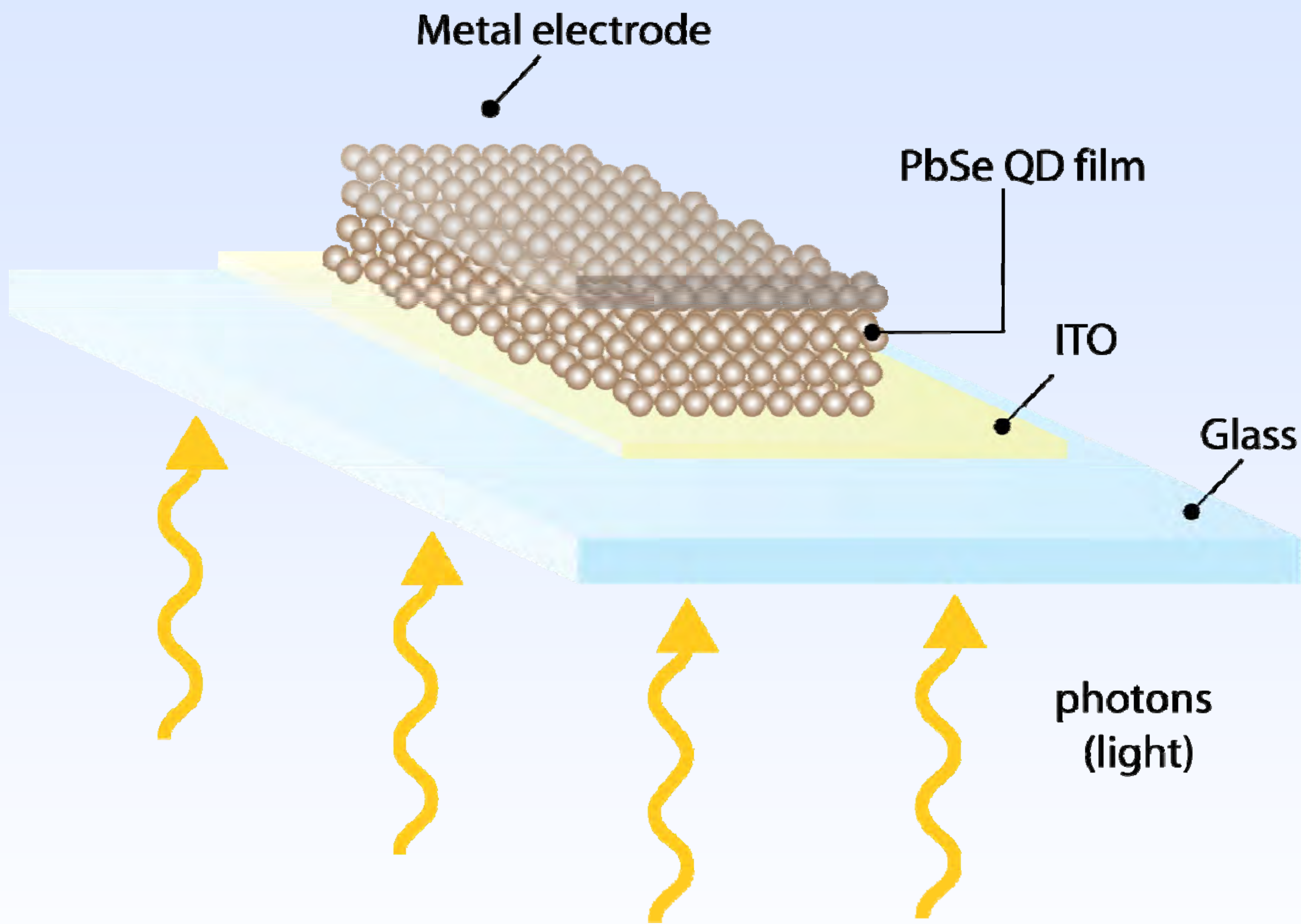


Oleic acid, $C_{18}H_{34}O_2$
$L \approx 20$ Å



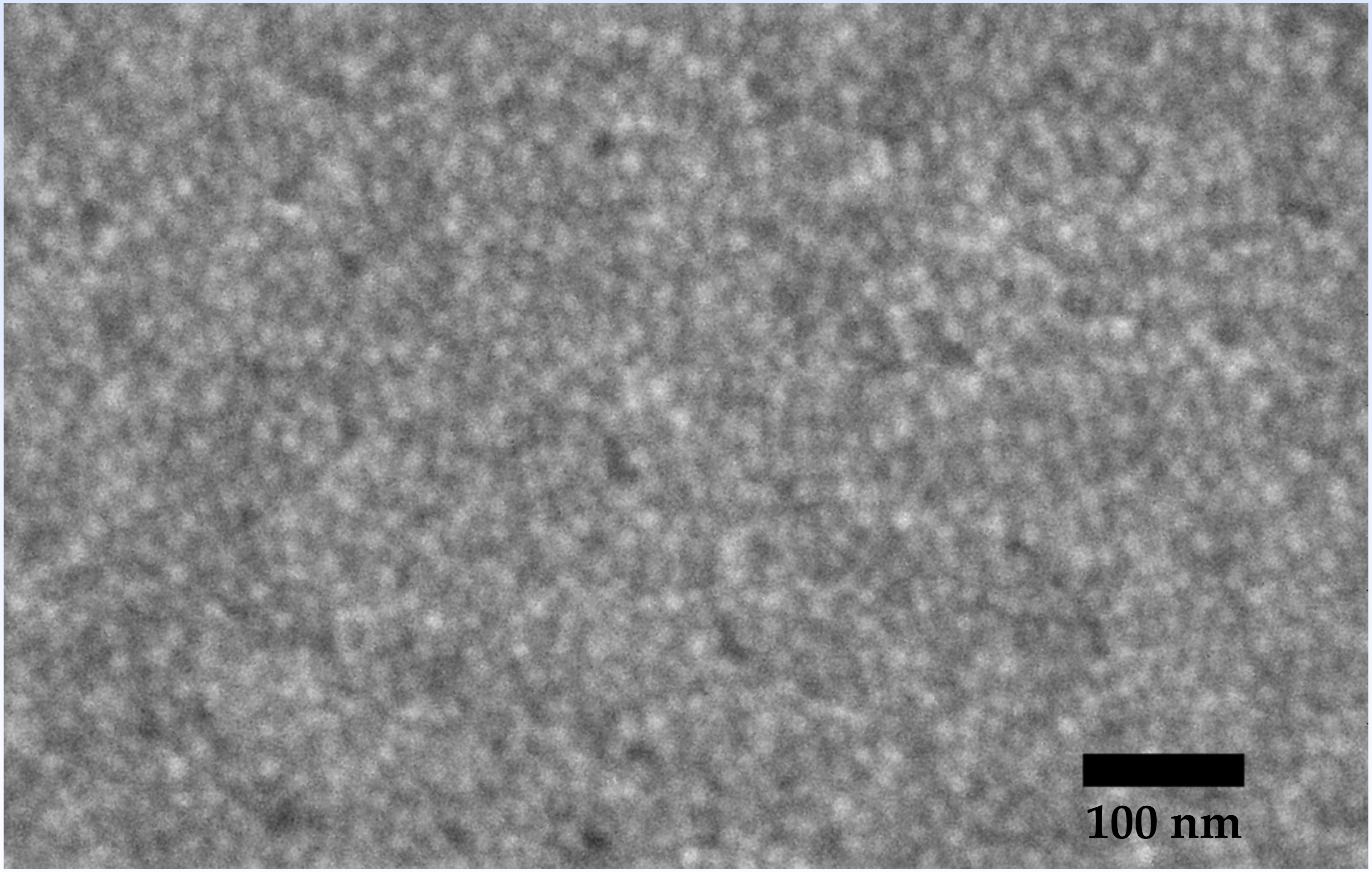
1,2-ethanedithiol
$C_2H_6S_2$
$L \approx 6$ Å

Schottky barrier nanocrystal-based solar cell



- Auger recombination typically occurs on ≲ 100 ps timescale (need fast exciton dissociation and/or diffusion to low density)
- High long-range mobility desired
- EQE > 100% would provide MEG process/concept confirmation

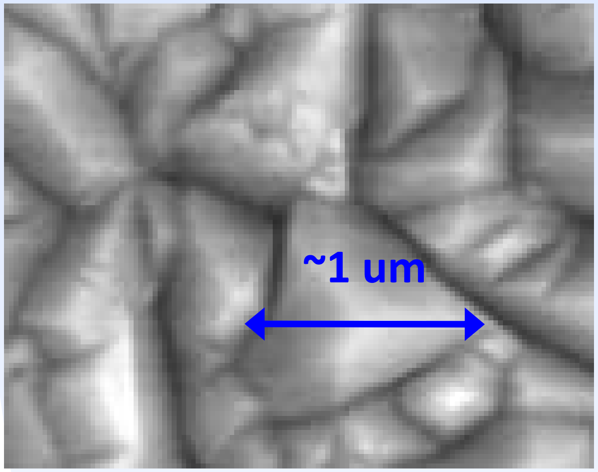
Layer-by-layer dip-coated PbSe films



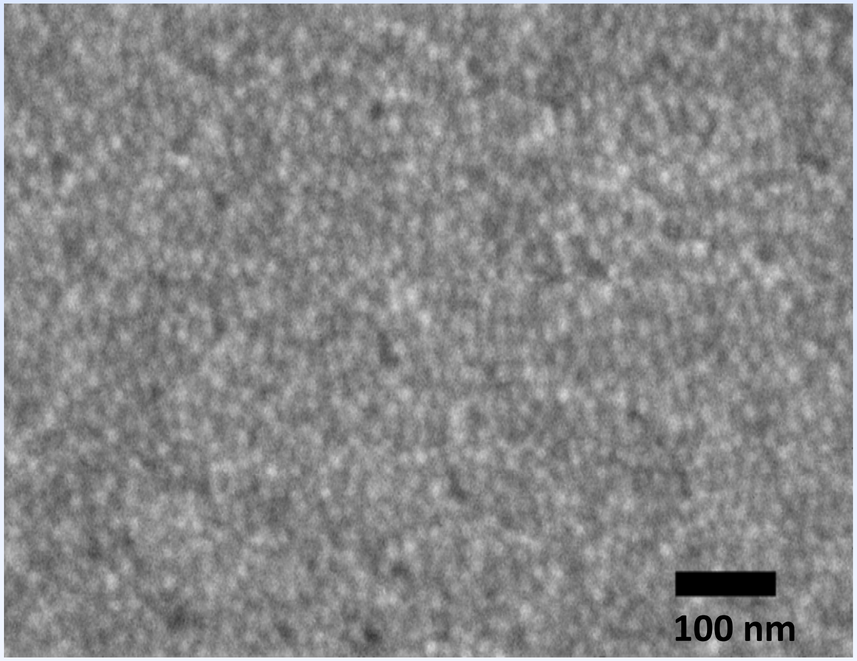
Plan view SEM image of PbSe NC films prepared by layer-by-layer dip coating onto ITO substrate. LbL film shown was produced using 10-20 dip coating cycles.

J. Luther, M. Law *et al.*, *ACS Nano* **2**, 271 (2008).

Grain boundary density considerations



e.g. CdTe



Rough estimates of grain boundary densities (boundary area / layer area)

CdTe: ~1 μm grain size (assumed cubic grains, ~ 1 μm thick layer):

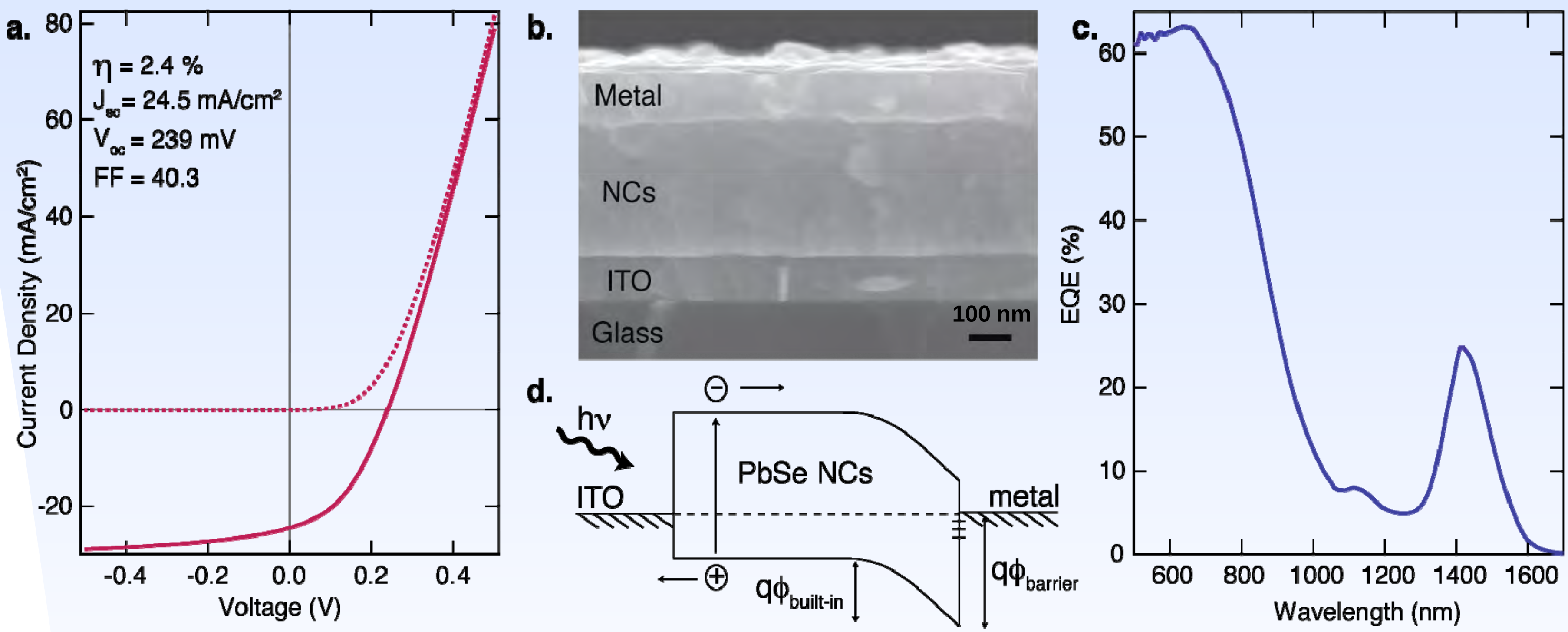
3 (μm^2/ μm^2)

PbSe QD film: ~5 nm "grain size" (assumed cubic grains 5 nm on a side, 1 μm thick film):

600 (μm^2/ μm^2)

$S/V \propto 1/r$

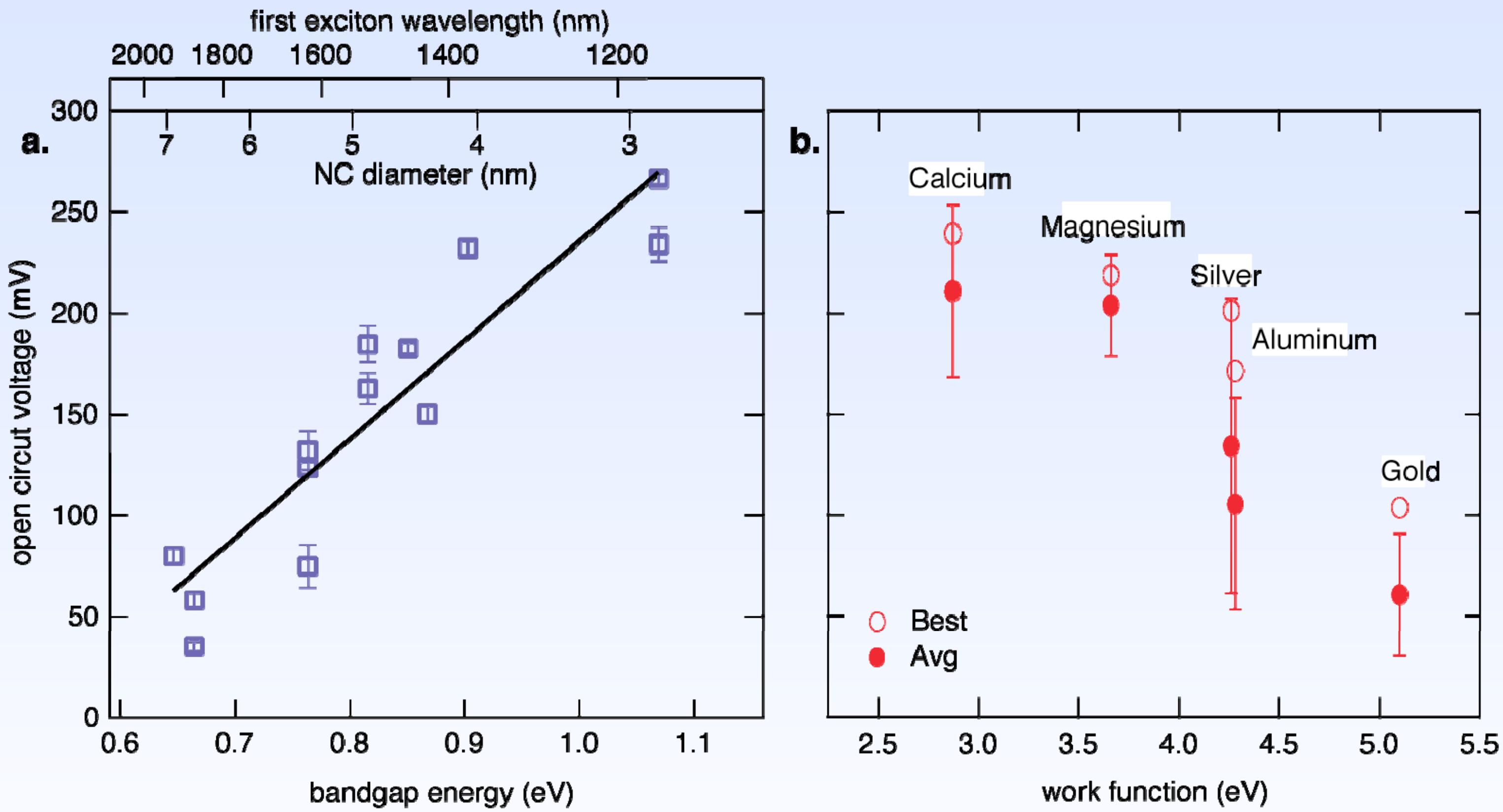
Nanocrystal-based solar cell



(a) J-V in dark and under 100 mW cm^{-2} AM 1.5G (E_g = 0.9 eV). **(b)** SEM cross-section of the stack (metal is 20 nm Ca / 100 nm Al). **(c)** EQE of a device with 140 nm-thick NC film and an efficiency of ~2.2% (E_g = 0.95 eV). **(d)** Proposed equilibrium band diagram; band bending occurs at interface between the NCs and metal electrode. Schottky barrier height ($q\varphi_{barrier}$) for p-type material is the difference between the valence band max. and the metal Fermi level.

J. M. Luther, M. Law, *et al.*, *Nano Lett.* **8**, 3488-3492 (2008).

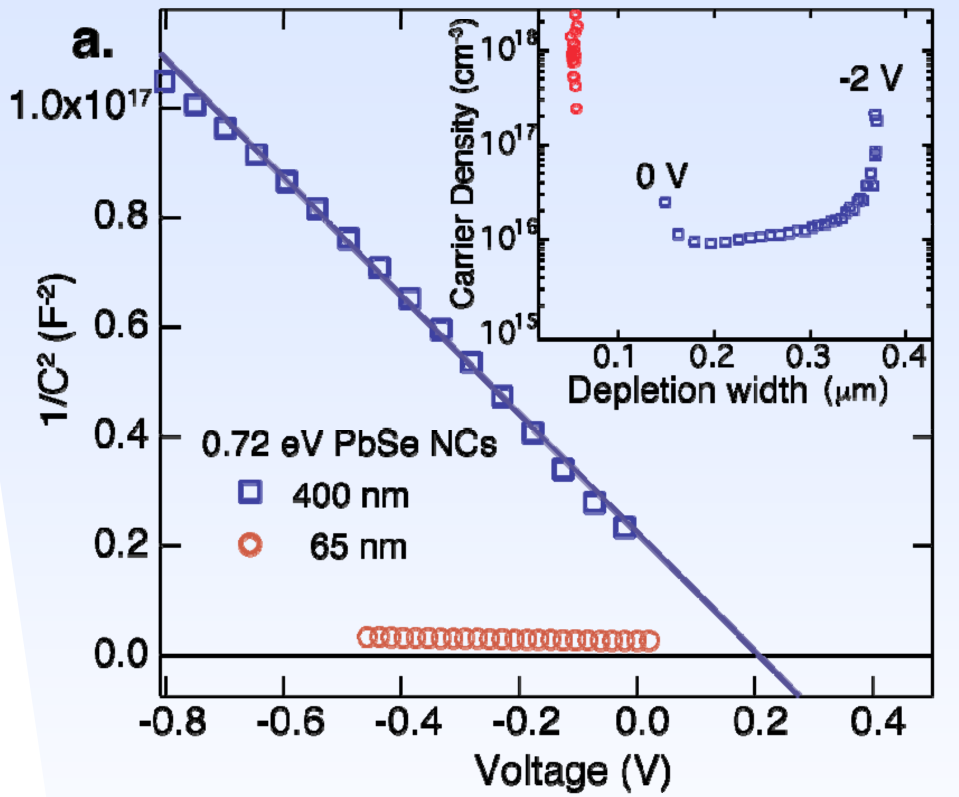
Trends in V_{oc} with NC size and metal work function



(a) Dependence on NC size. Each point is the average of six devices from a single substrate. The line is a least-squares fit to the data. **(b)** Dependence on metal work function (E_g = 0.82 eV). The best and average V_{oc} for each metal are shown, along with the standard deviation of six devices.

J. M. Luther, M. Law, *et al.*, *Nano Lett.* **8**, 3488-3492 (2008).

Depletion width and doping density



"Mott-Schottky plots at 1 kHz for devices with a thin (65 nm, red) and thick (400 nm, blue) NC layer. The thick device has an equilibrium depletion width of ~150 nm, while the thin device is fully depleted."

J. M. Luther, M. Law, *et al.*, *Nano Lett.* **8**, 3488-3492 (2008).

Relation between doping density and QD density? QD size ~ 6 nm dia., add 1 ligand ~0.5 nm, so V(QD) = $(4\pi/3)(3.2\ \text{nm})^3 = 1.3 \times 10^{-19}\ \text{cm}^3$

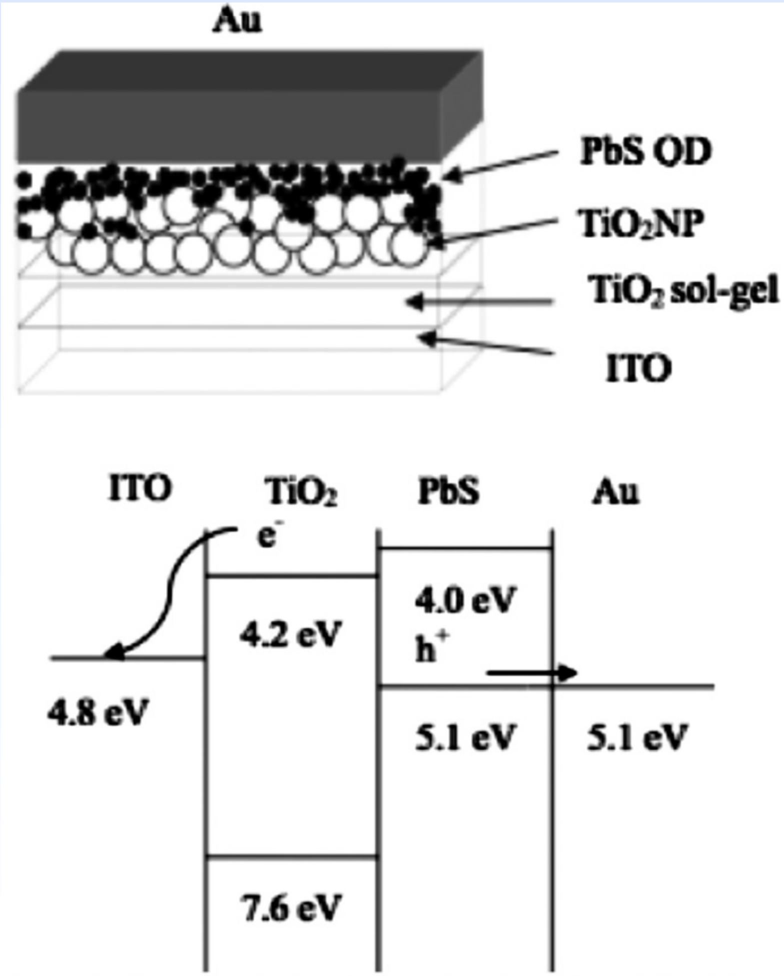
Random packing of spheres → ~ 0.64

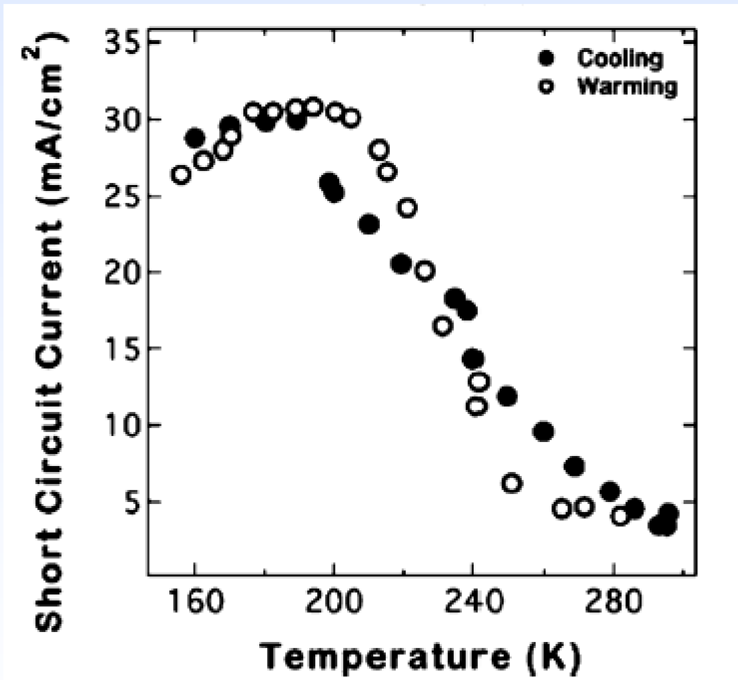
→ Vol. density of QDs ~ $5 \times 10^{18}\ \text{cm}^{-3}$

→ **~1 free carrier per 500 QDs**

How/why?

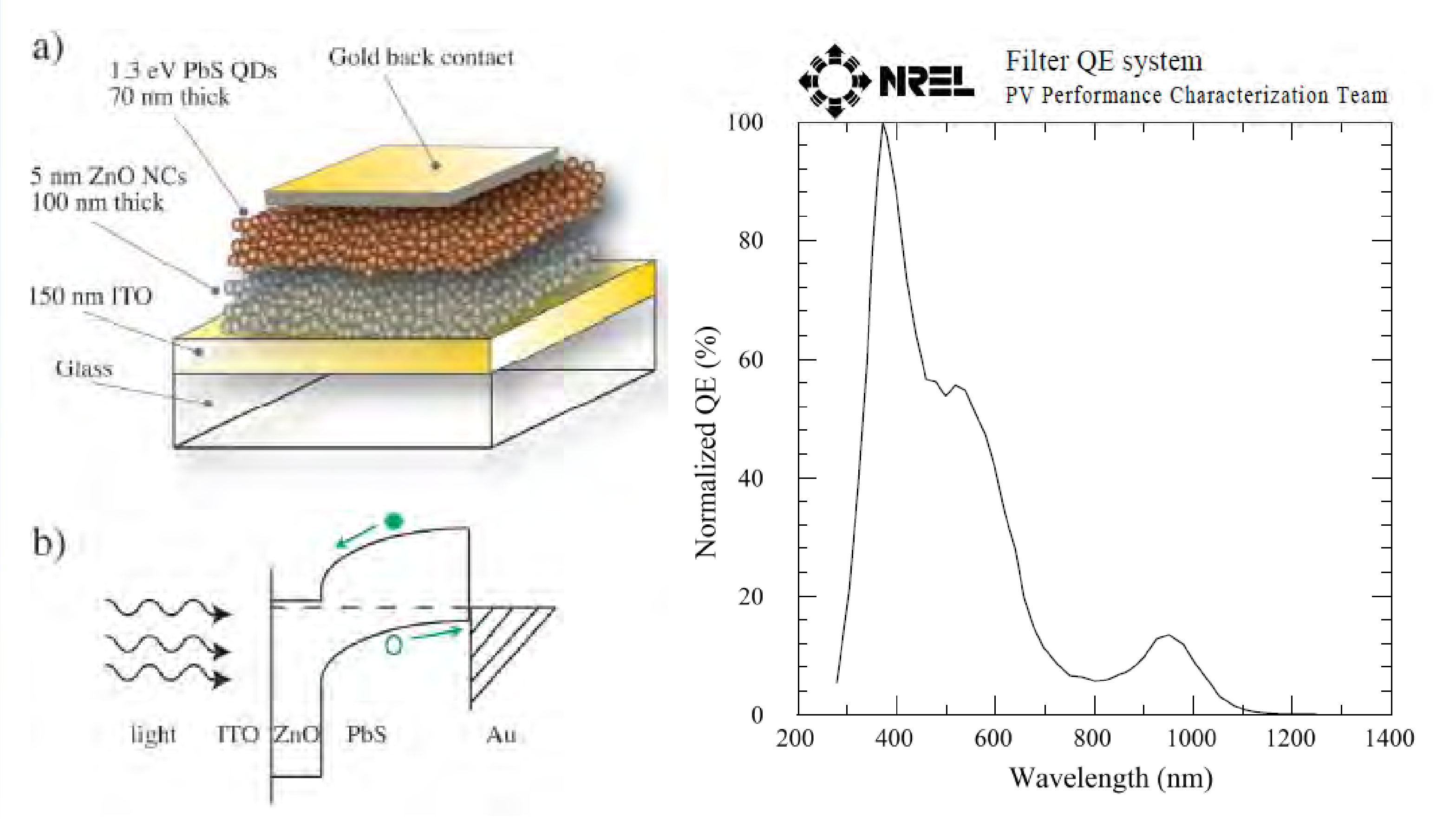
T-dependent performance in PbS QD device





T. Ju et al., *APL* 97, 043106 2010

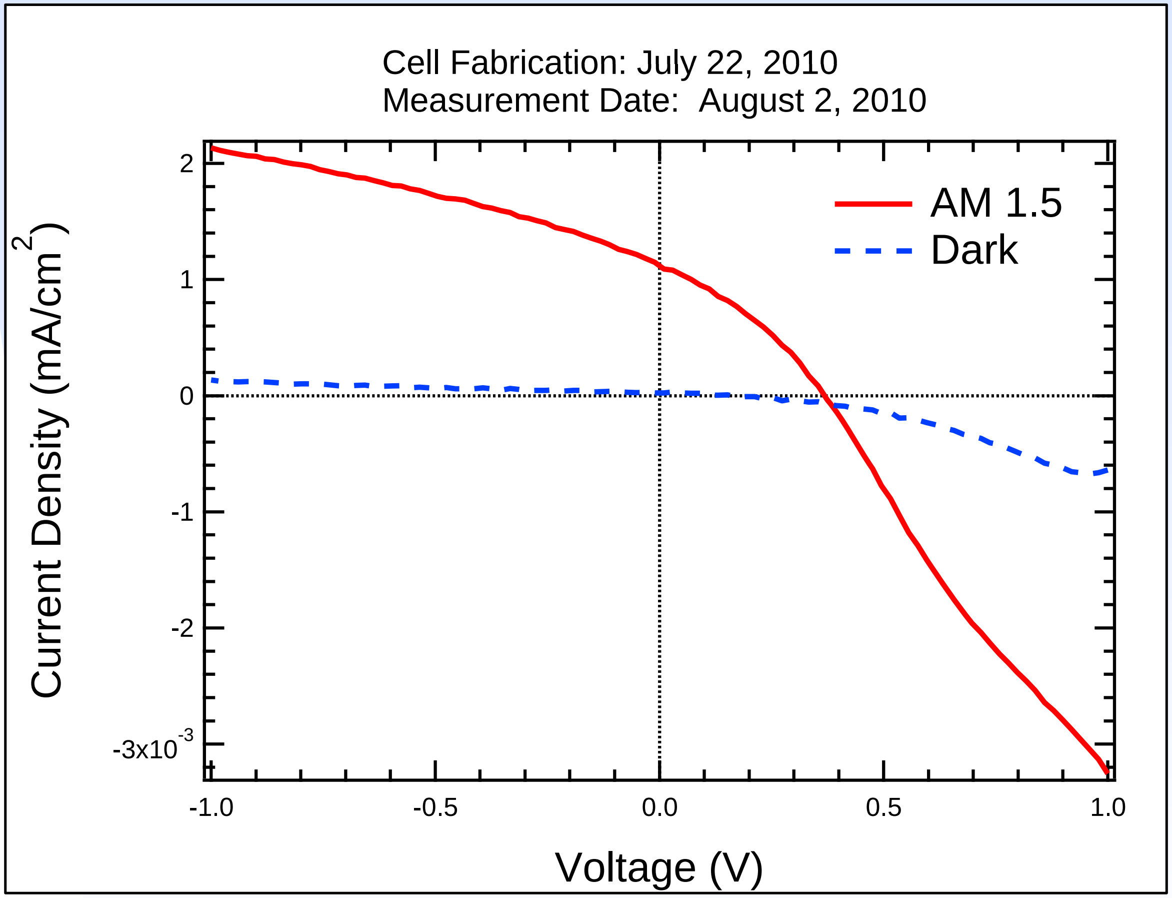
PbS/ZnO heterojunction solar cell

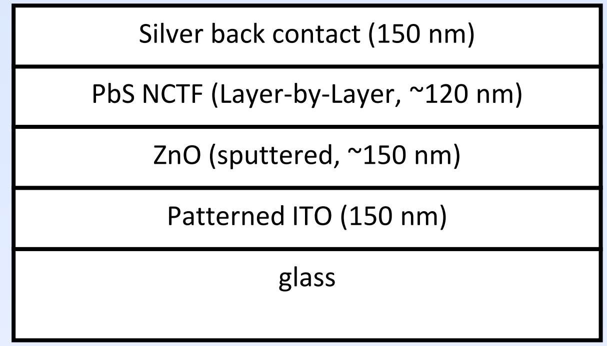


Layers of ZnO and PbS fabricated in air. Device shows good air stability over ~1,000 hrs.

Luther et al., *Adv. Mater.* ***2010, 22, 3704–3707***

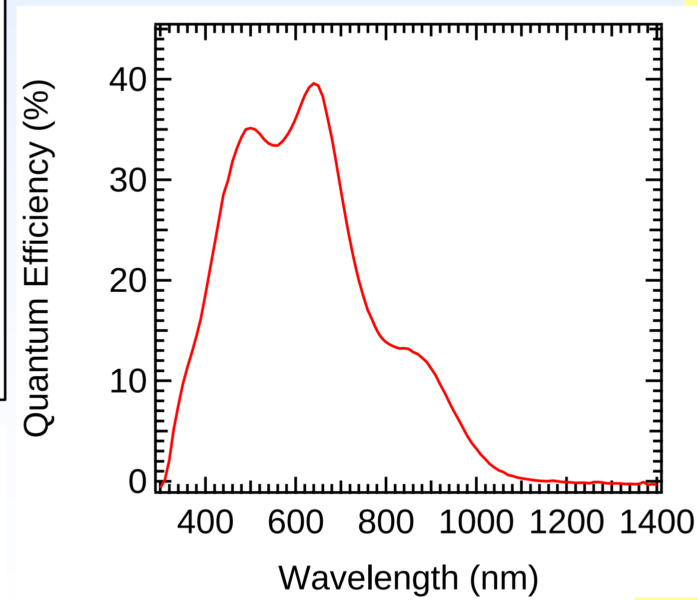
PbS/ZnO heterojunction solar cell (UT)



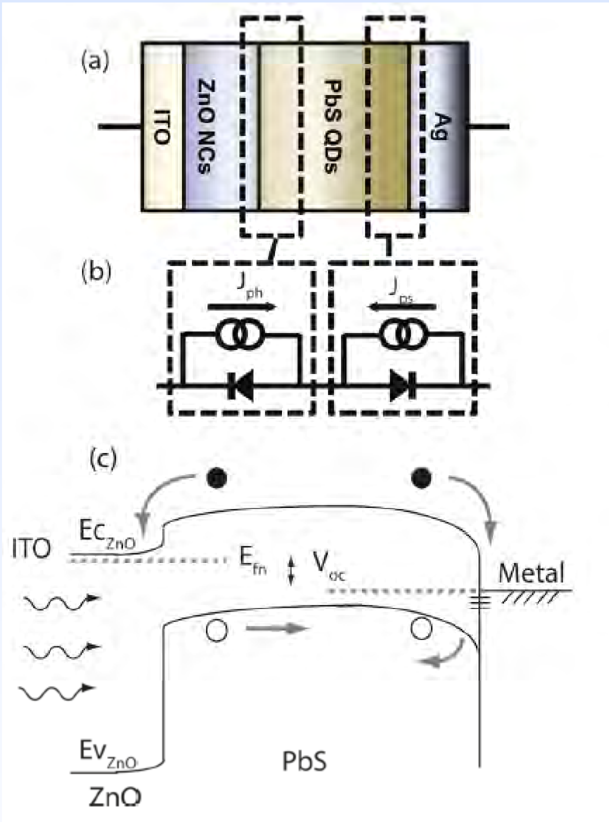


4.1 mg/mL concentration of PbS 820nm NC in hexanes;
1 mM solution of 1,2-ethanedithiol in acetonitrile
Layer-by-Layer deposition for 20 cycles (~ 120nm PbS film thickness)

V_{OC} = 368 mV J_{SC} = 12.44 mA/cm^2 FF = 0.33
Efficiency = 1.53% R_{sh} = 613 Ohms R_s = 191 Ohms



Two-diode model for PbS/ZnO heterojunction device



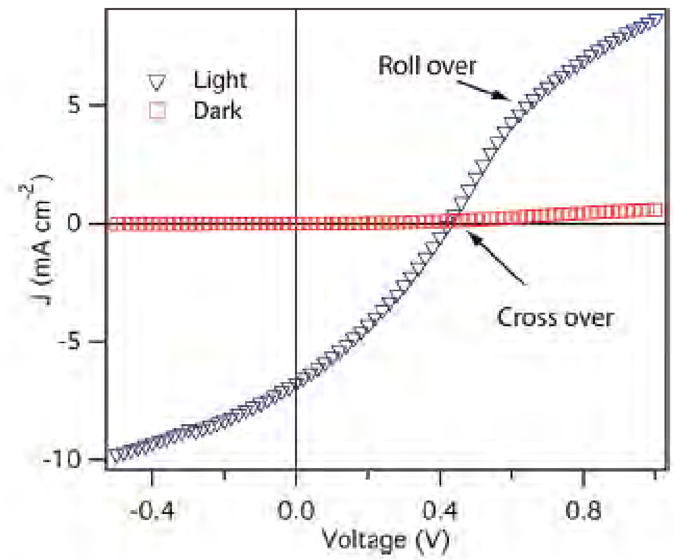


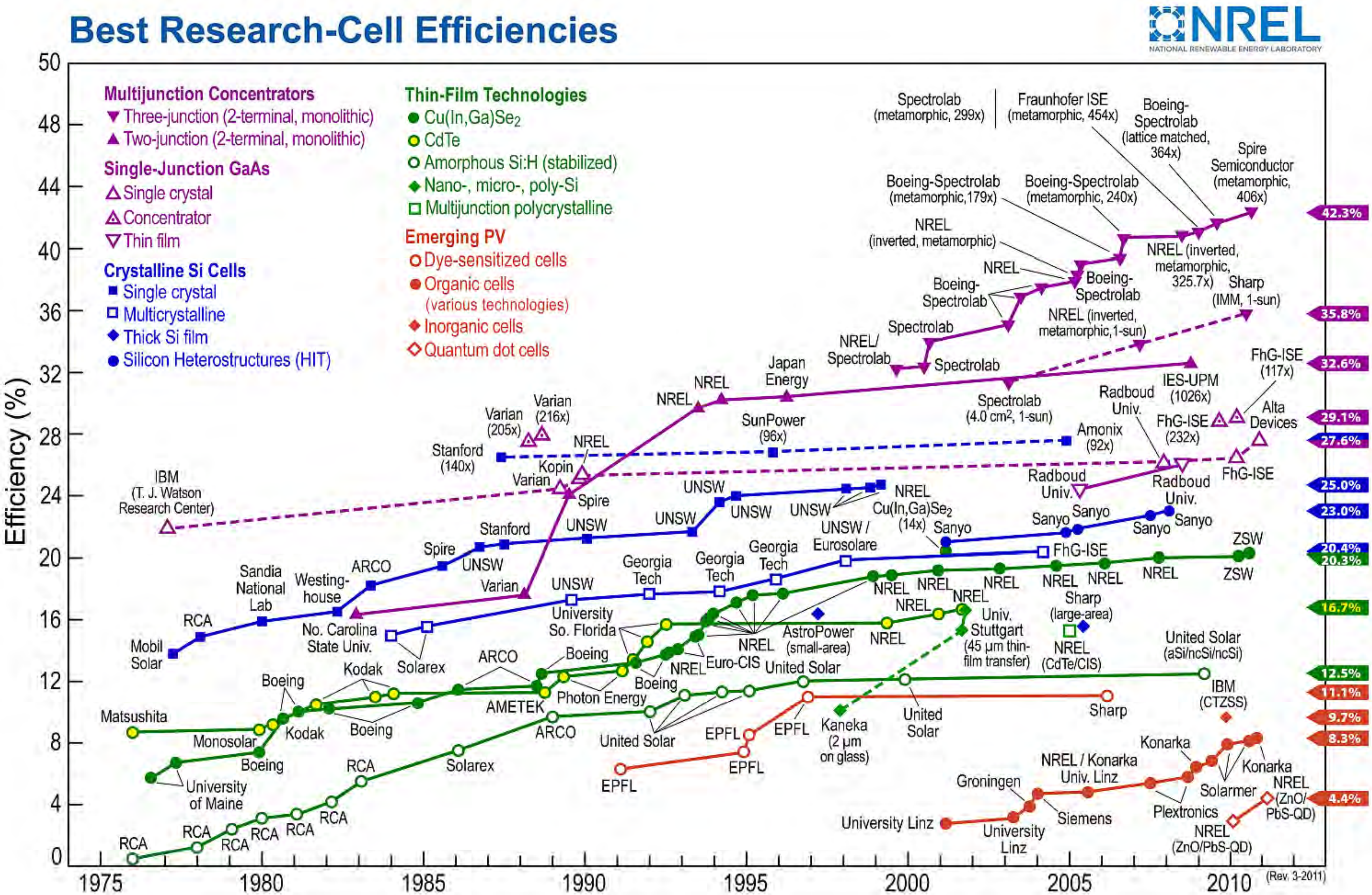
Figure 1. Typical characteristics of $J-V$ in the dark and under 1 sun illumination, which shows the crossover and roll-over effects. The device structure is ITO/ZnO NC/PbS QD/Ag with PbS layer thickness of ~550 nm.

Two-diode model equivalent circuit including a main diode between ZnO QD film with PbS QD film, and a Schottky-diode between PbS QD film with top contact Au or Ag.

1. **Roll-over effect**, a fact of current limiting at positive voltage, is due to a hole transport barrier at Schottky-junction formed by PbS QD film with metal contact .
2. **Cross-over effect:** low forward current due to Schottky barrier at metal contact (hole transfer barrier).

"Quantum Dot Size Dependent J-V Characteristics in Heterojunction ZnO/PbS Quantum Dot Solar Cells", J. Gao et al, Nano Lett. 2011.

Best Research-Cell Efficiencies



Issues of interest for QD-based thin film PV

- Energy intensity of materials and deposition
- Doping control within films
- Air/moisture tolerance (deposition and operation)

Thank you to Funny Times (Cleveland Heights, OH)!

Contributors/Collaborators

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Neale Haugen, laser spectroscopy
Paul Roland, device characterization and spectroscopic ellipsometry
Ryan Zeller, laser scribing
Tyler Kinner (undergraduate), Earth-abundant NC synthesis

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- UT-PVIC startup funds
- National Renewable Energy Lab/DOE-EERE
- AFRL

Left to right: Julia Deitz, Ryan Zeller, Neale 'Ole' Haugen, Khagendra Bhandari, Paul Roland, Tieneke Dykstra, and Randy Ellingson