Quantum Dot and Hybrid Solar Cells

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Part I: Properties and formation of semiconductor Quantum dots

: Introduction
: Basic quantum mechanics applied to quantum dots (QDs)
: Basic properties of quantum wells and dots
: Formation of quantum dots

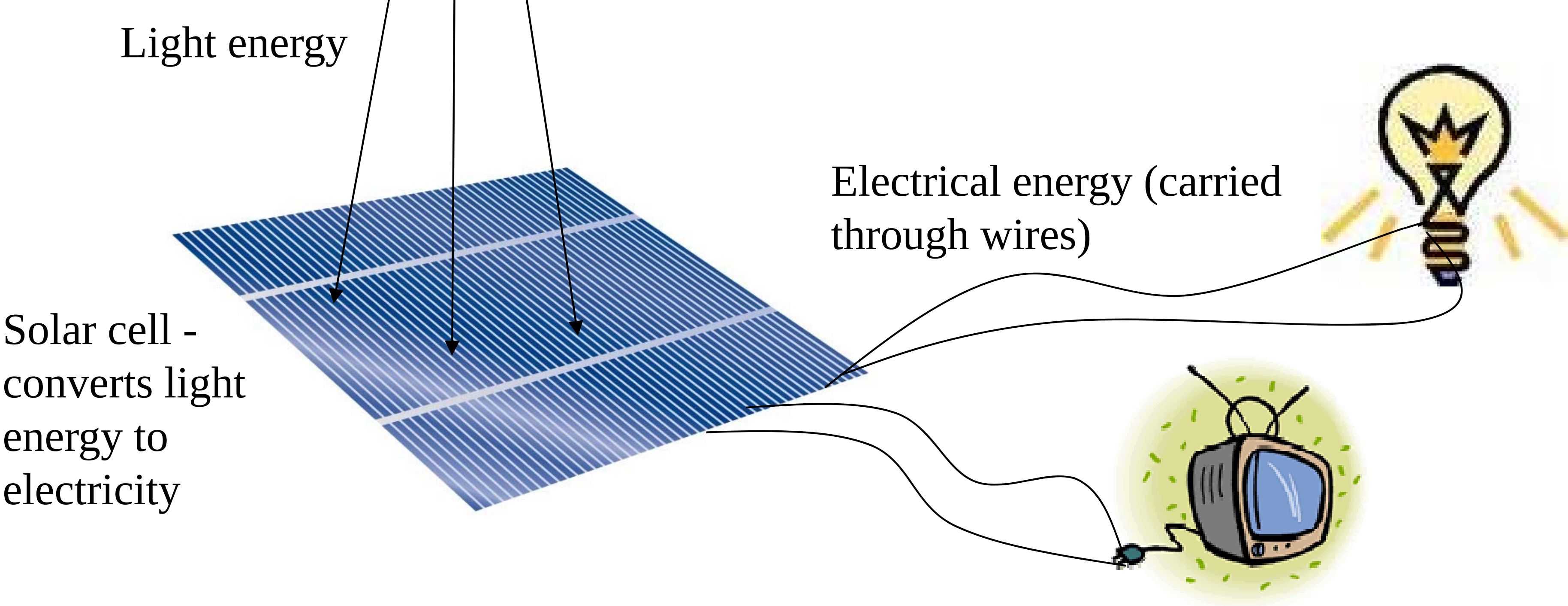
Part II: Colloidal Quantum dot LEDs

: QD-LED device structures and operating mechanism
: History of QD-LED development
: Inverted QD-LEDs
: Polymer–QD hybrid LEDs
: Cd-free QLEDs
: QD patterning

Part III. QD and Hybrid Solar Cells

Solar Cells - Converters of Energy

- Solar cells are devices that take light energy as input and convert it into electrical energy
- Energy produced by the sun
- Clean, renewable source of energy

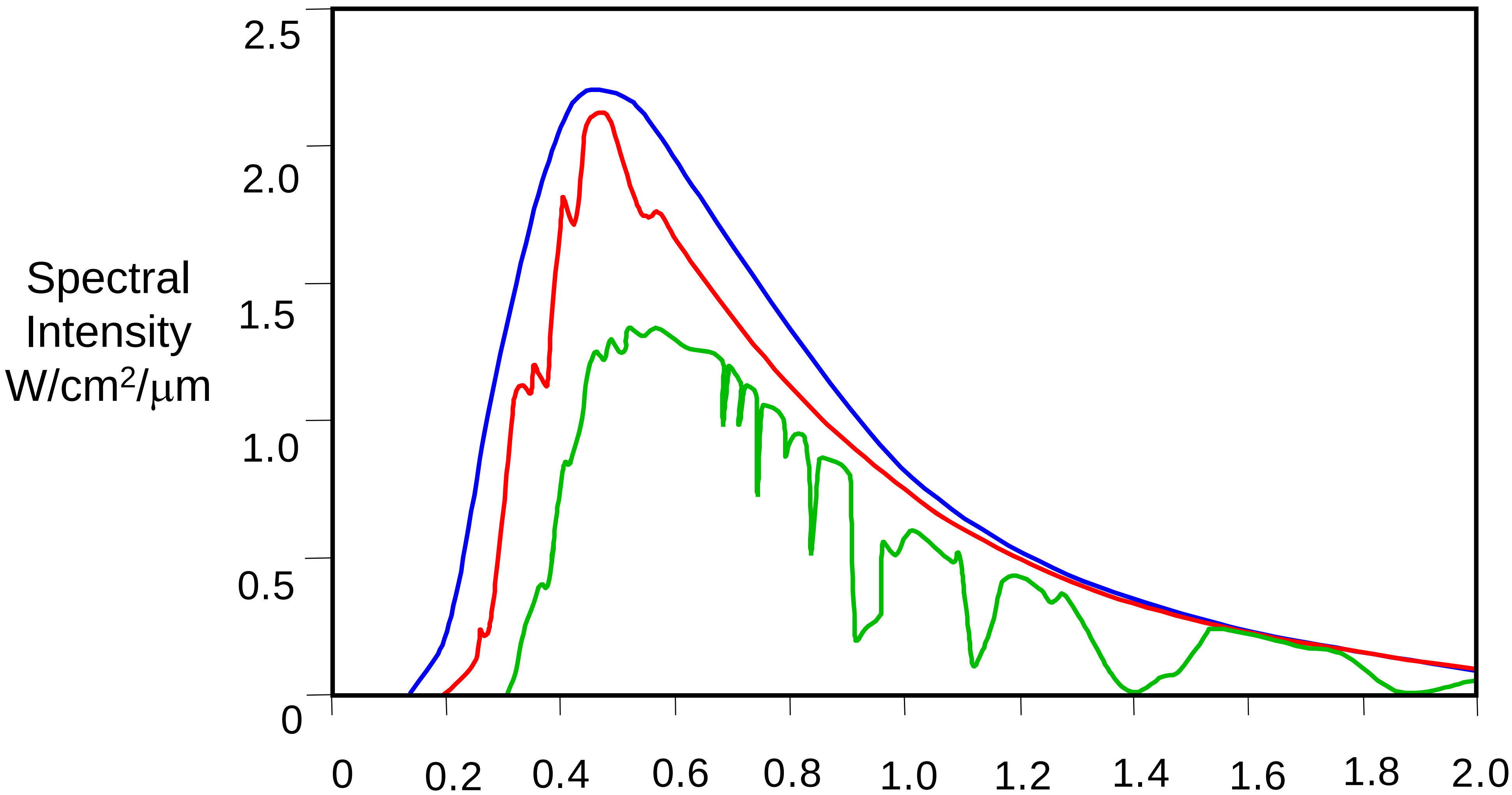


Sources: http://www.econedlink.org/lessons/EM189/images/cartoon_tv.gif
http://emmagoodegg.blogs.com/thebeehive/images/lightbulb.jpg, http://www.torpedowire.com/solar.htm,
http://www.uoregon.edu/~stiedeke/a3/assignment03/a3/assignment_images/cartoon-sun.jpg

Solar spectrum

Ref. http://rredc.nrel.gov/solar/standards/am1.5/#Bird

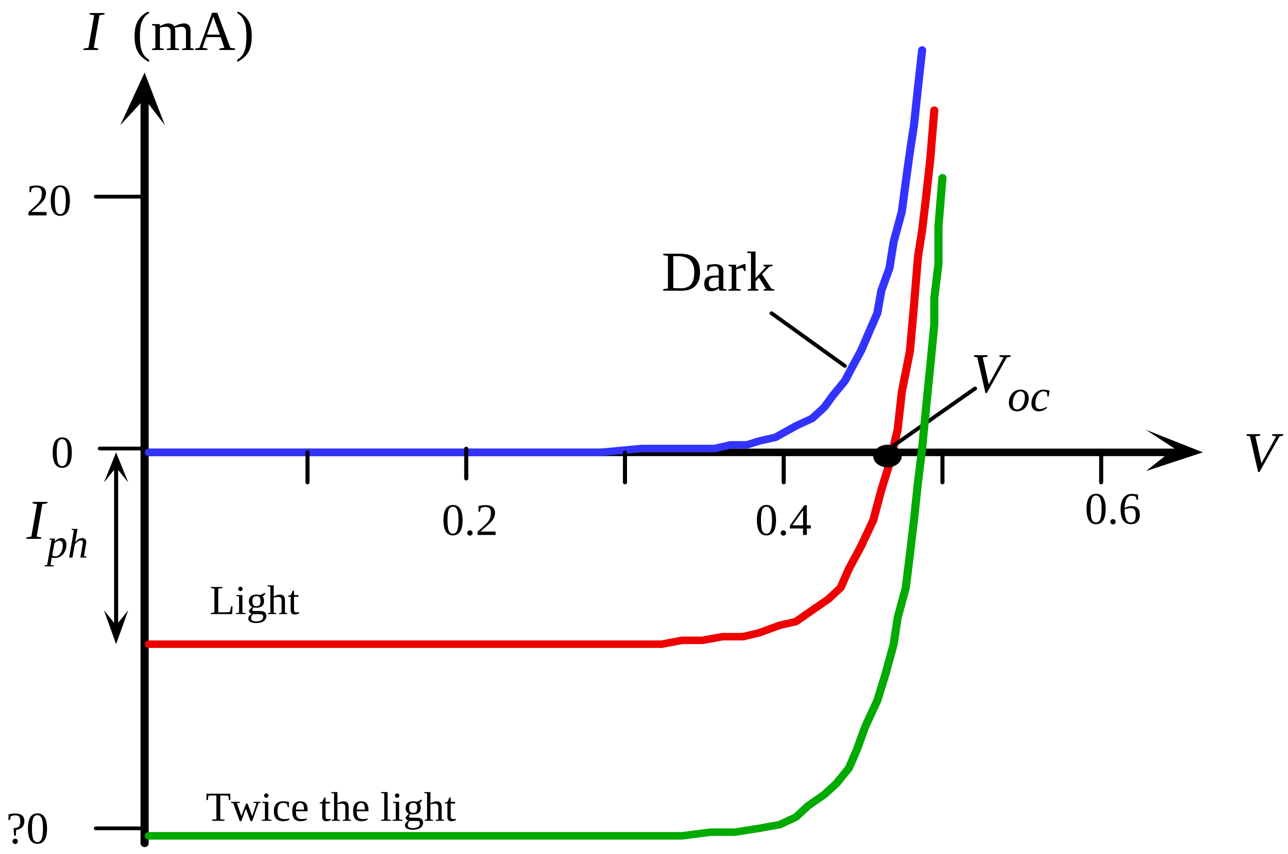
Air Mass 1.5 (solar zenith angle 48.19°)



Power level in outer space (AM0): 1.353 kW/m^2

Power level on earth at sea level, with the sun at zenith (AM1): 100 mW/cm^2

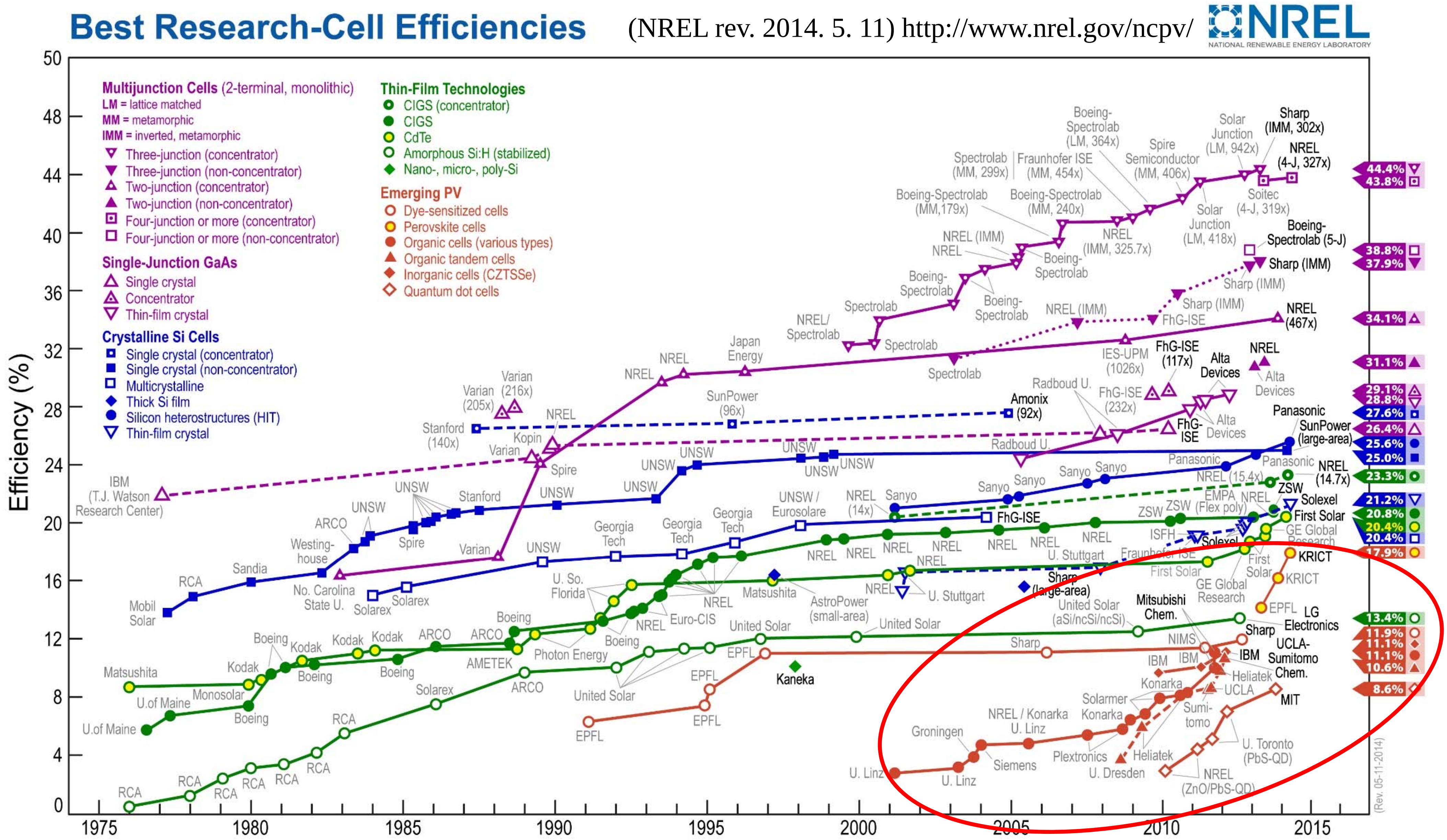
I-V Characteristics of solar cells



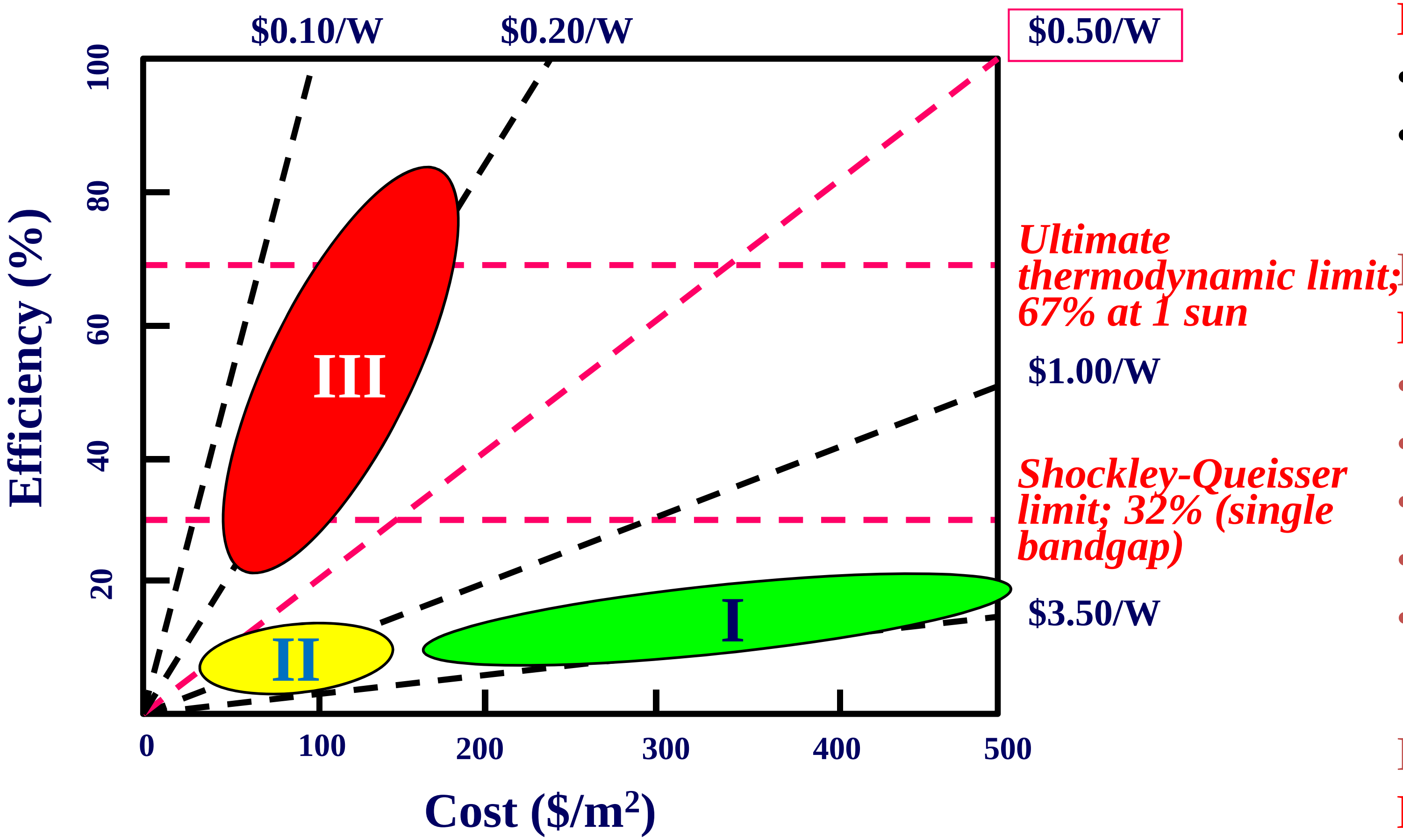
Typical *I*-*V* characteristics of a Si solar cell. The short circuit current is I_{ph} and the open circuit voltage is V_{oc}. The *I*-*V* curves for positive current requires an external bias voltage. Photovoltaic operation is always in the negative current region.

?1999 S.O. Kasap, *Optoelectronics* (Prentice Hall)

Solar cell efficiencies (NREL rev. 2014. 5. 11)



Efficiency-cost of organic solar cells



I. 1st Generation:

High efficiency but high cost

- Single crystal Si, 24.7%
- Polycrystalline Si, 20.3%

II. 2nd Generation:

Low cost but low efficiency

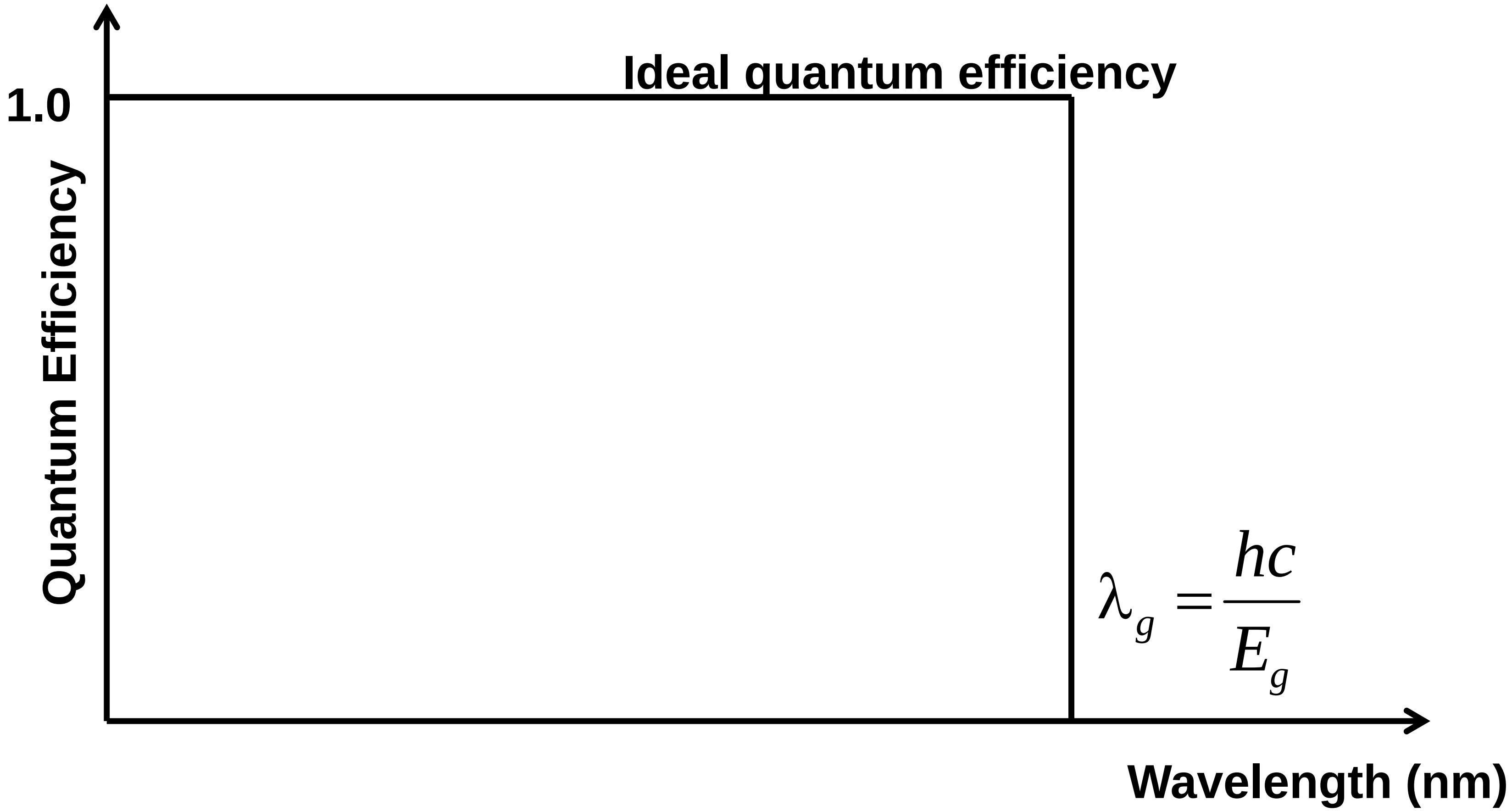
- Amorphous Si, 11.7%
- CuInSe2, 19.9%
- CdTe, 16.5%
- DSSC, 11.1%
- OPV, 8.3% (small cell)

III. 3rd Generation:

High efficiency (h>Q-S limit) & low cost (<$0.50/W)

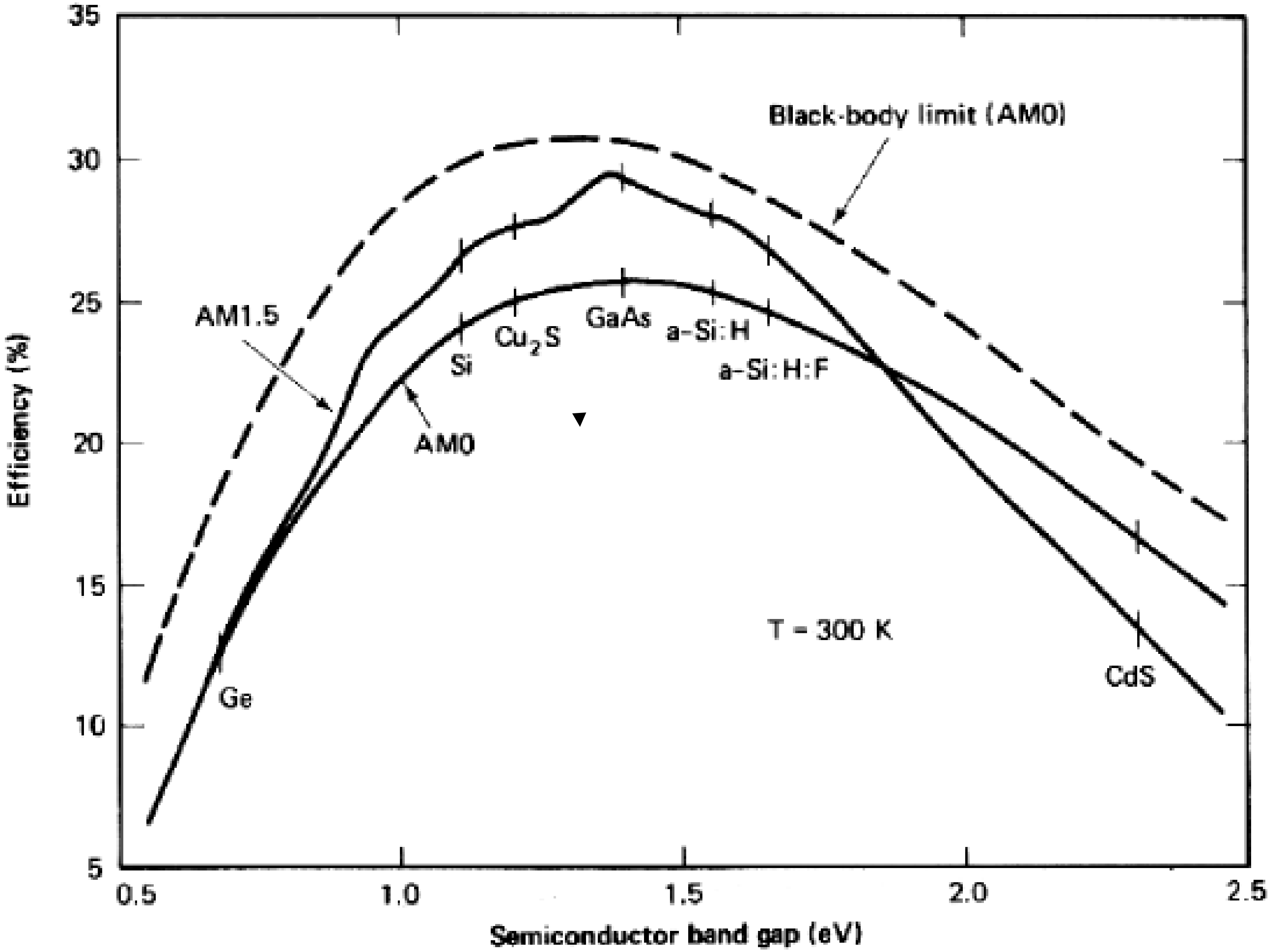
Quantum Efficiency

$$Eff. = \frac{P_{out}}{P_{in}} = \frac{V_{OC} J_{SC} FF}{P_{in}}$$



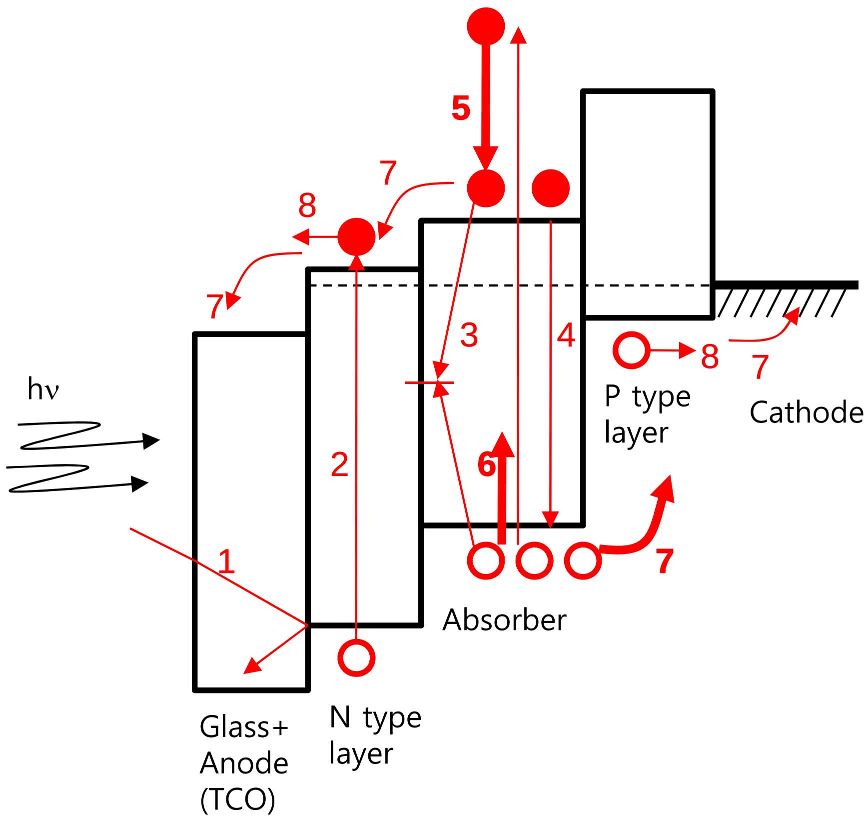
$$\lambda_g = \frac{hc}{E_g}$$

Thermodynamic cell efficiency



M. A. Green, "Third generation photovoltaics"

Principles of efficiency losses

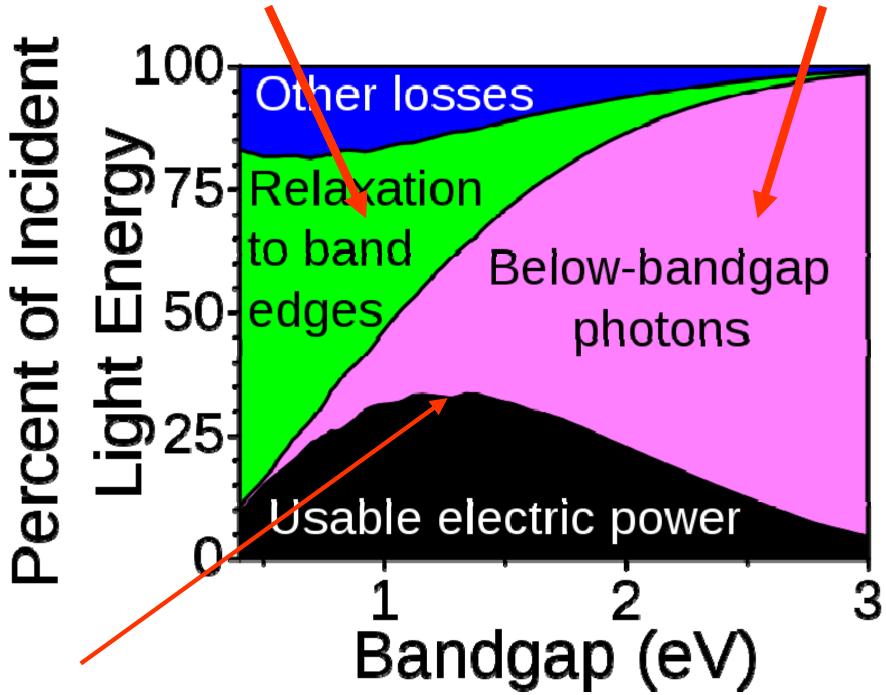


	Loss mechanism	Idea	Experiment
1	Reflection	Textured surface	In production (c-Si, TCO)
2	Absorption	High Eg window	a-p-SiC of a-Si solar cell
3	Interface recombination	Graded interface	p/i buffer of a-Si solar cell
4	Bulk recombination	High quality, Nanostructure	Clean process, DSSC, polymer-acceptor
5	Thermalization	Carrier multiplication, Energy selective contact (ESC)	PbSe 300% quantum yield, QD ESC
6	Color limit	Multijunction, intermediate band, Up/Down converter, Thermo-photovoltaic	III-V triple junction 34.1%, QD/impurity band, Er converter
7	Contact loss	Energy selective contact	QD ESC
8	Series resistance	High mobility	Amorphous Si vs. Poly Si

자료: 백승재박사 (KAIST)

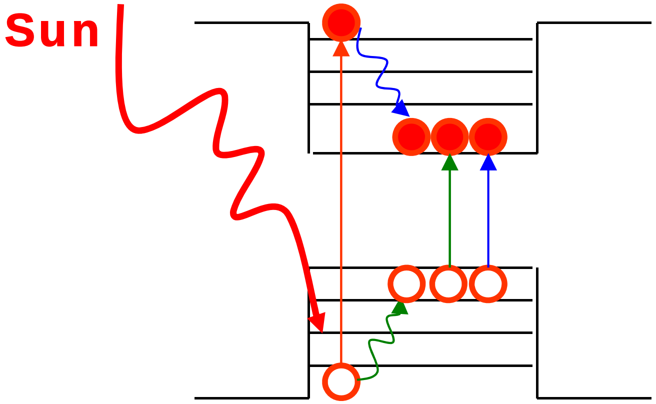
Breaking efficiency limits

3rd generation concept:
MEG, Intermediate band

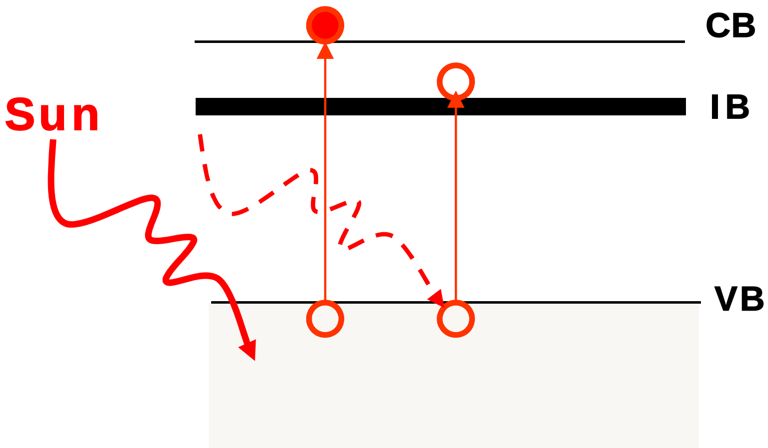


Shockley-Queisser limit

Multi-exciton generation



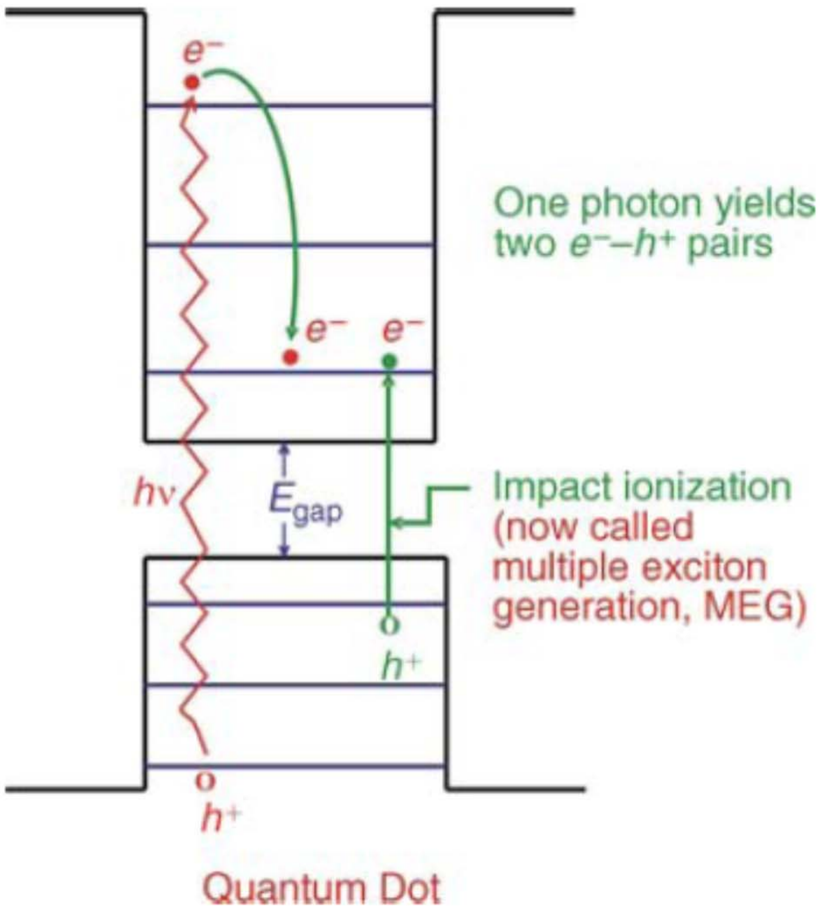
Intermediate band



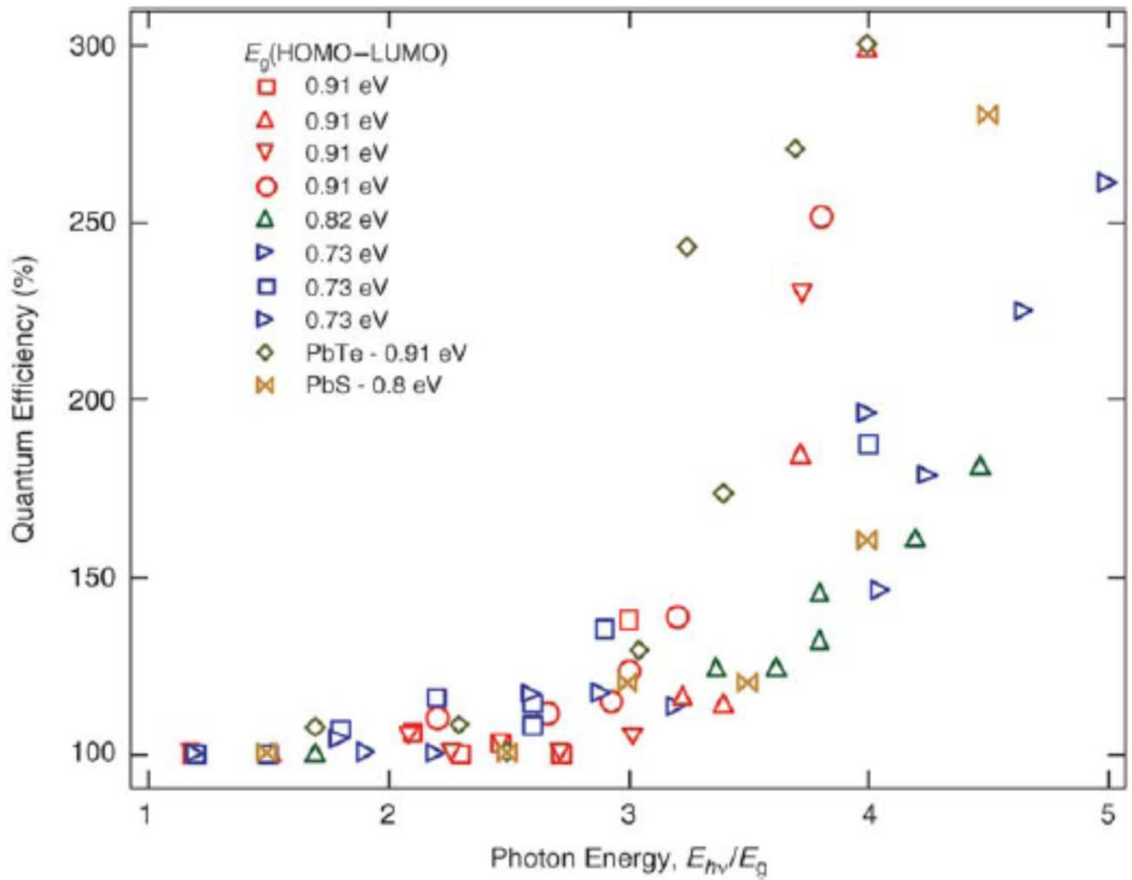
자료: 백승재박사 (KAIST)

Multi-exciton generation (MEG)

Principle of carrier multiplication



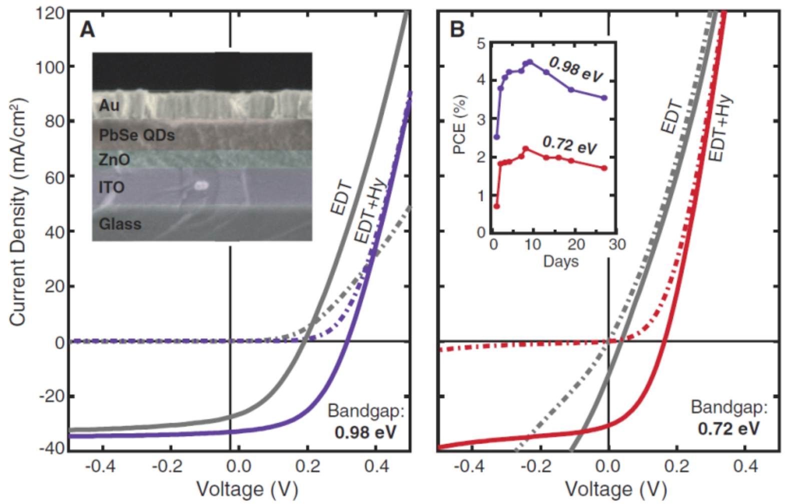
QE of PbSe, PbS, PbTe QD's (3.9-5.5nm)

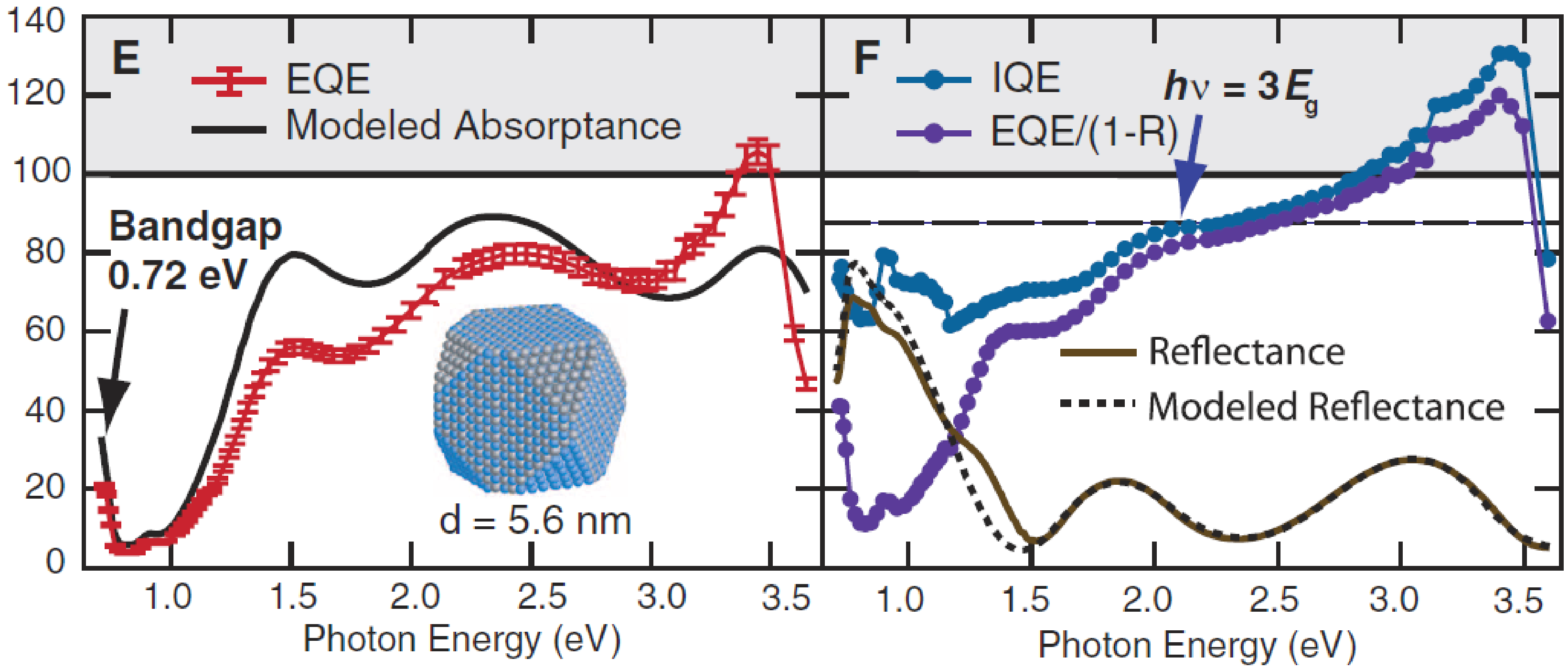


MRS Bulletin V.32 2007

- Efficiency limit ~45% (86% @ full solar)
- QD: much higher QE than bulk
- Problem: how to separate e- & h+'s to electrodes from QD

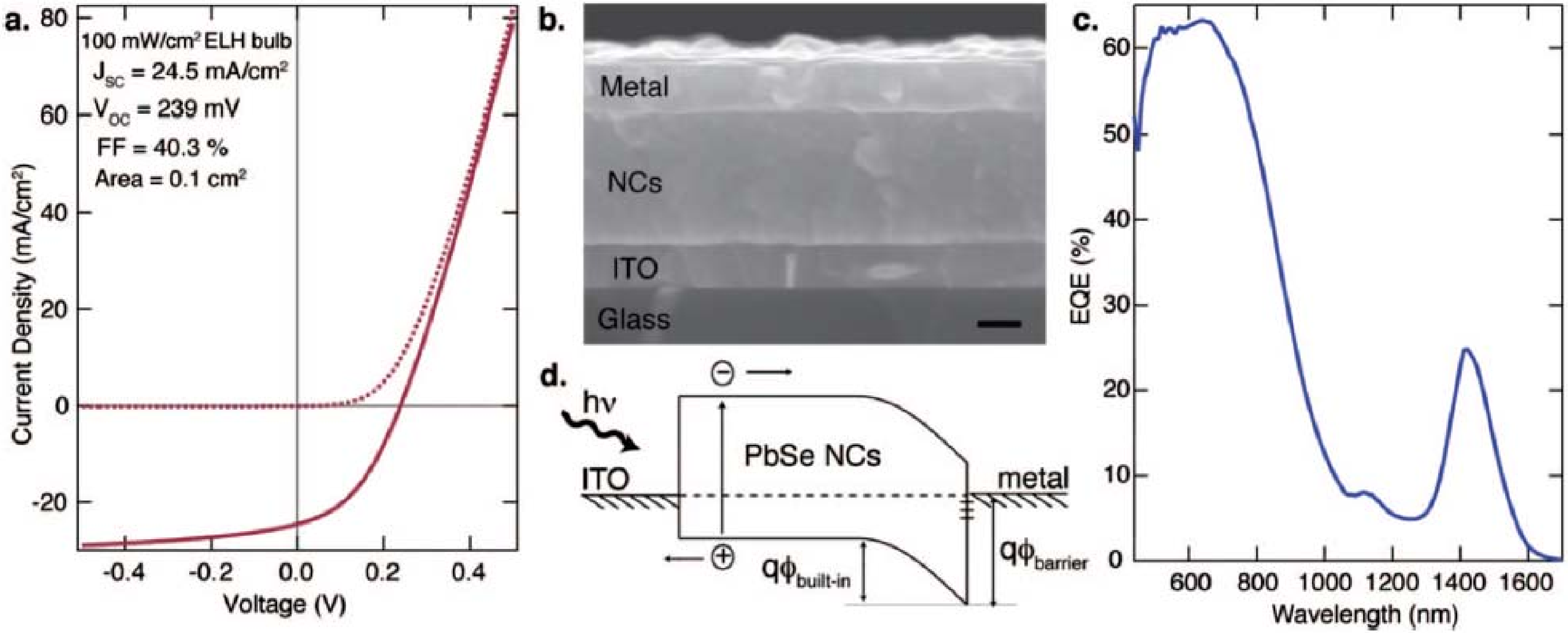
Multi-exciton generation (MEG)

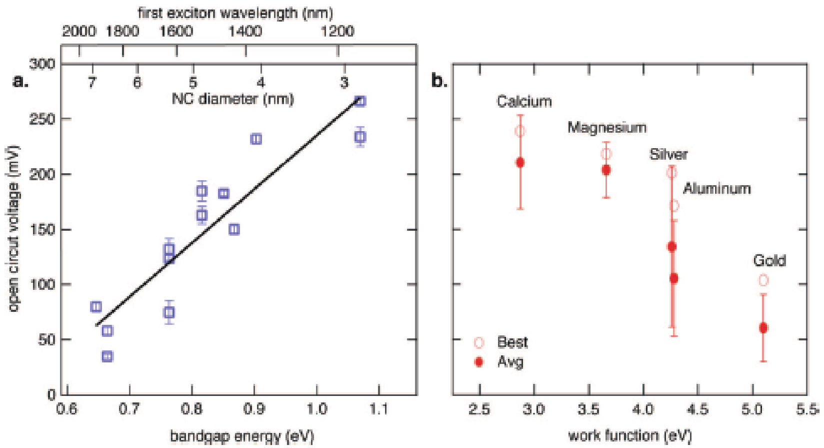




O. E. Semonin, et al., Science, 334, 1530, 2011

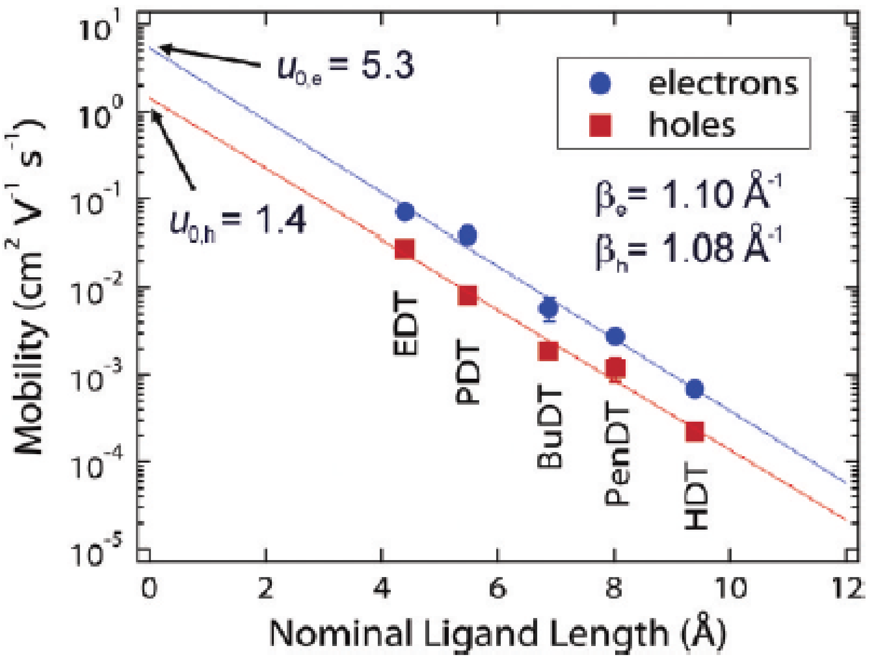
Schottky QD solar cell

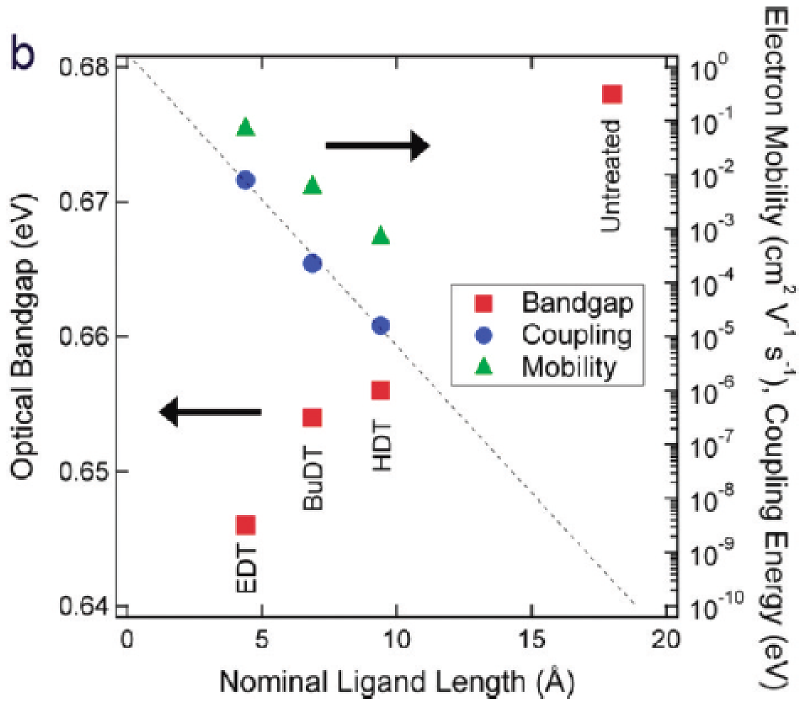


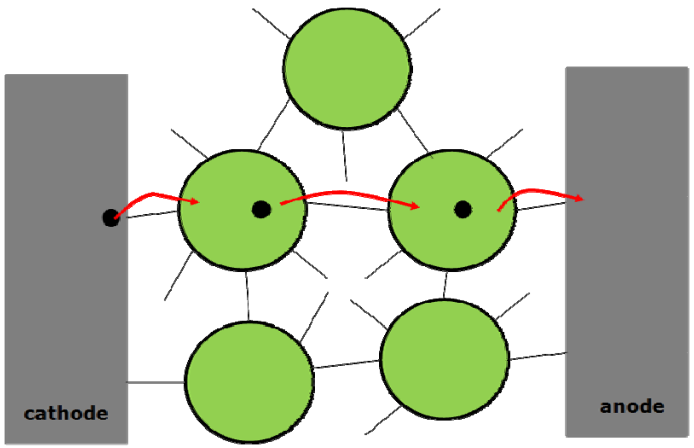


Luther et al., Nano lett, vol.8, no.10, 3488-3492, 2008

Inter-QD distance controls transport



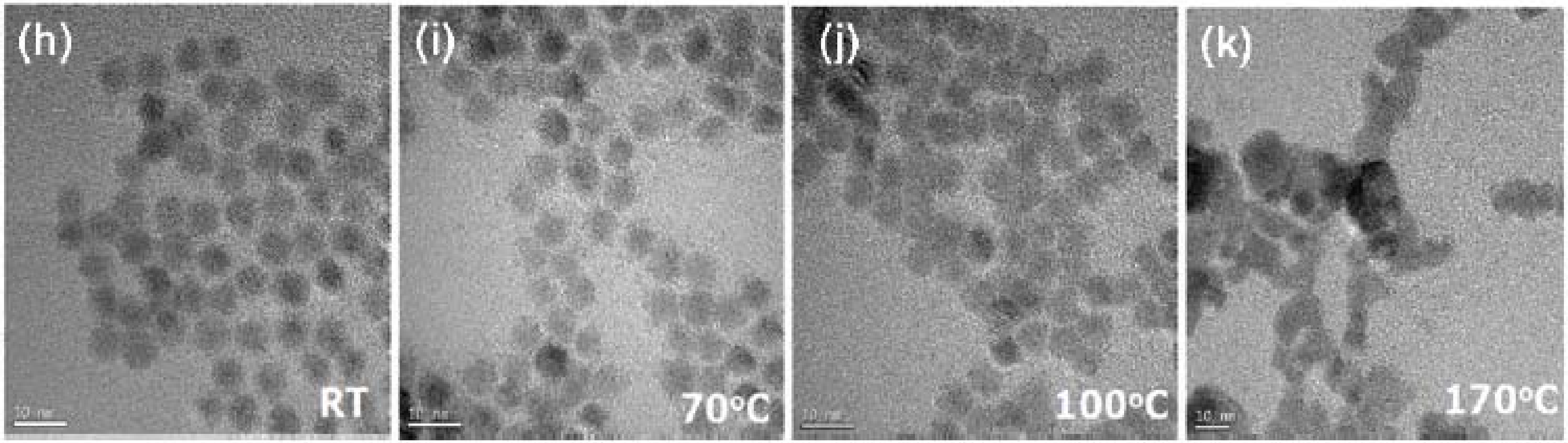


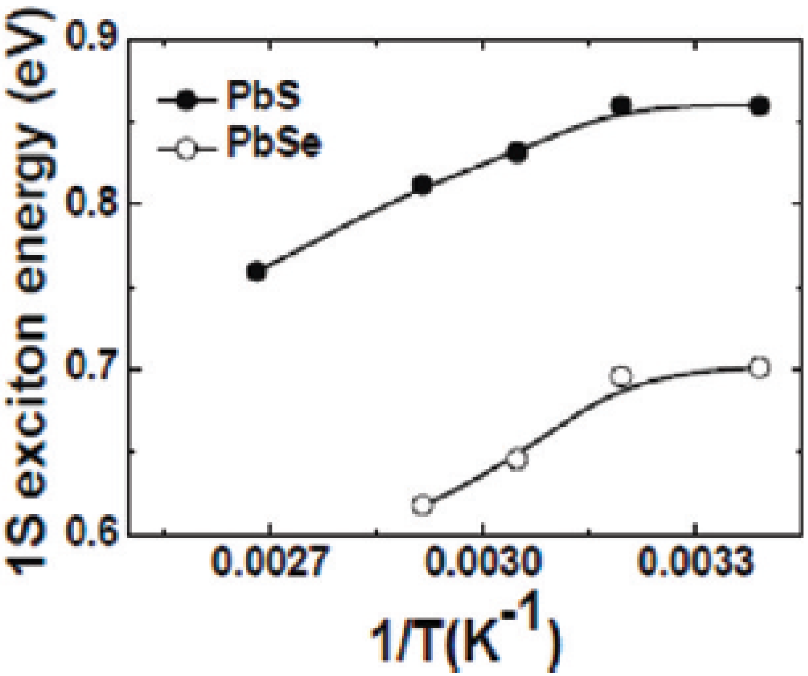


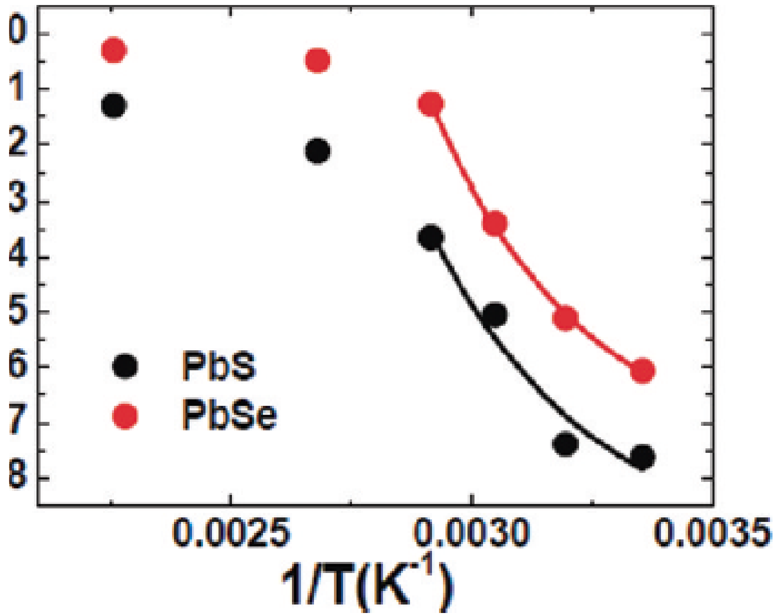
- Electrode interface: Schottky emission with tunneling
- Site to site transport: variable range hopping

Y. Liu et al., Nano Lett., 10, 1960, 2010

Annealing controls inter-QD distance



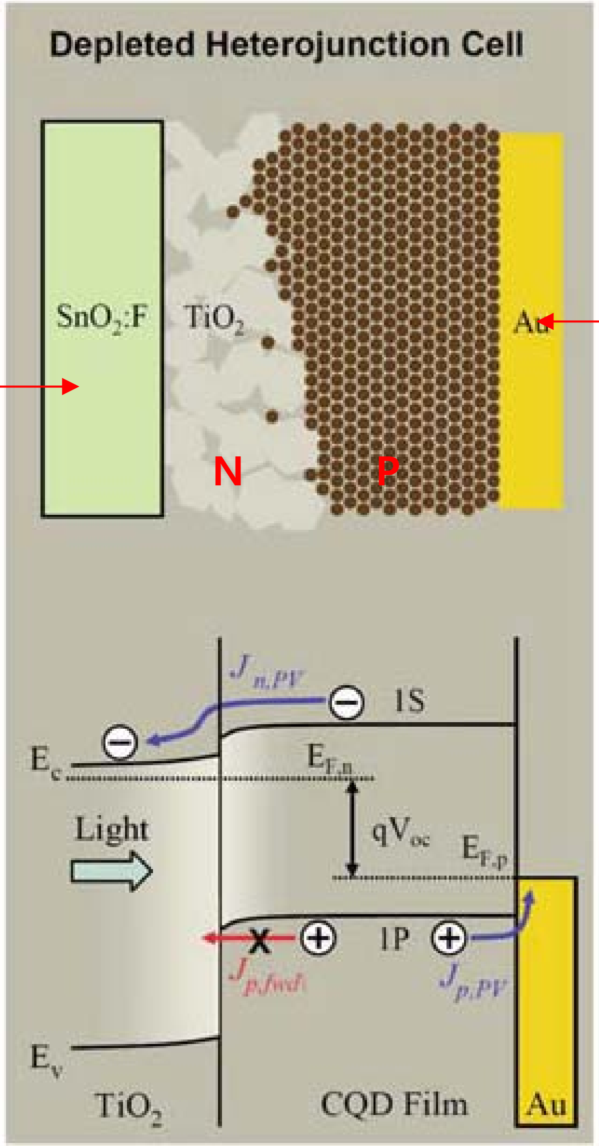




S. J. Baik et al., JPCC, 115, 607, 2011

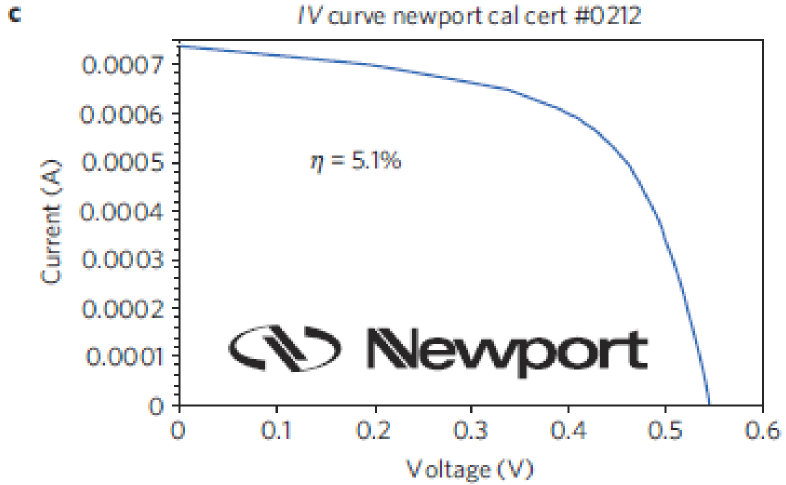
Heterojunction QD solar cells

Front transparent electrode



Back metal electrode

R. Debnath et al., Energy and Environmental Sciences, 2011

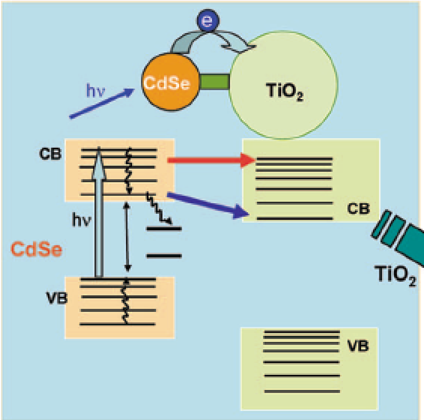


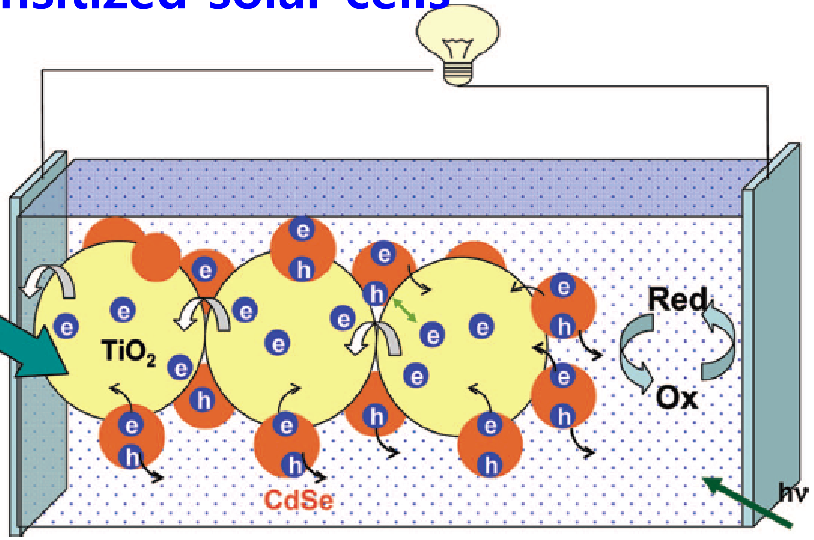
J. Tang et al., Nat. Mat., 2011

- **Similar to conventional thin film solar cells**
- **N layer with colloidal nanocrystals**
  - **Voc ~ Φ_p-Φ_n**
- **More efficient: front junction**
- **Rear ohmic design**

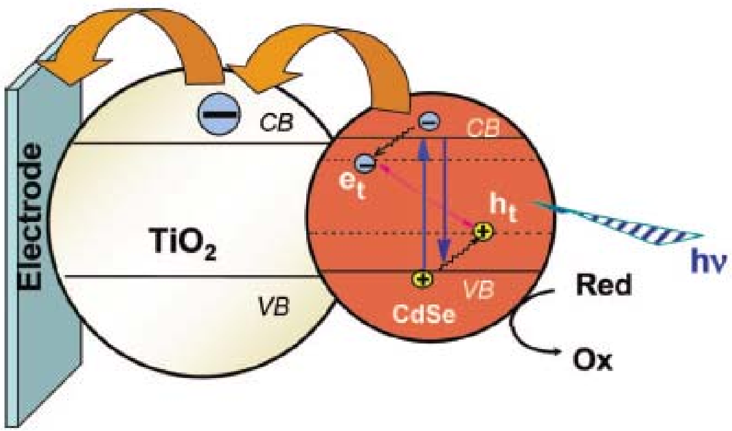
QD sensitized solar cells

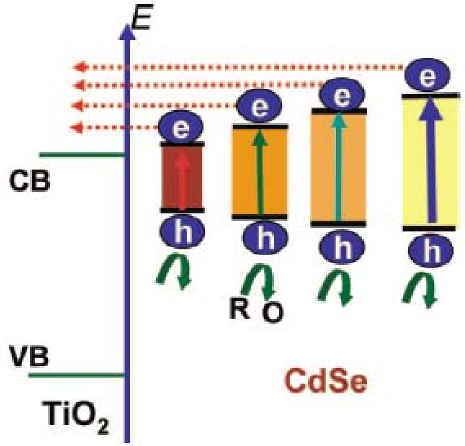
Mimicking Dye sensitized solar cells





Absorber QD size tuning

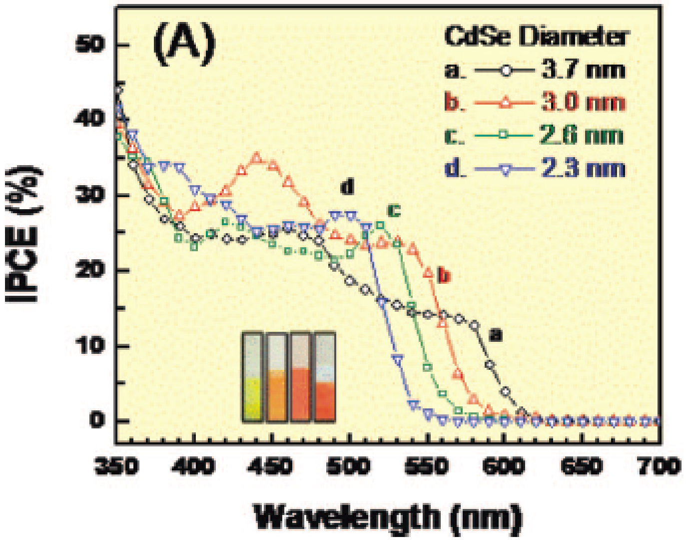


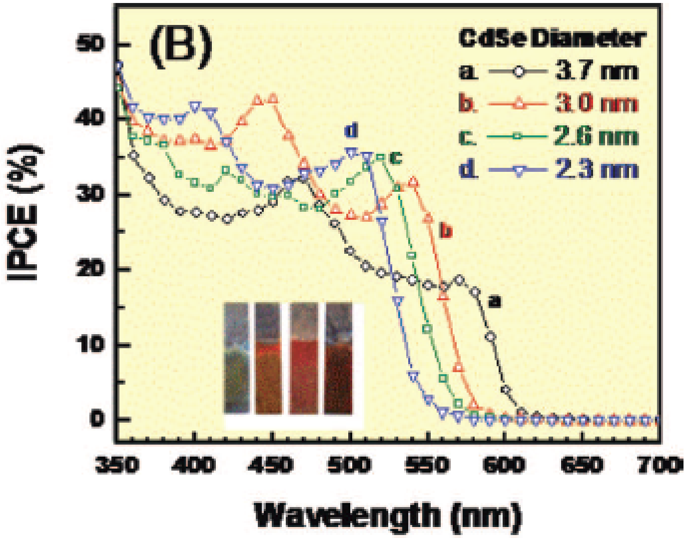


Kamat, JPCC, 112, 18737 (2008)

QD sensitized solar cells

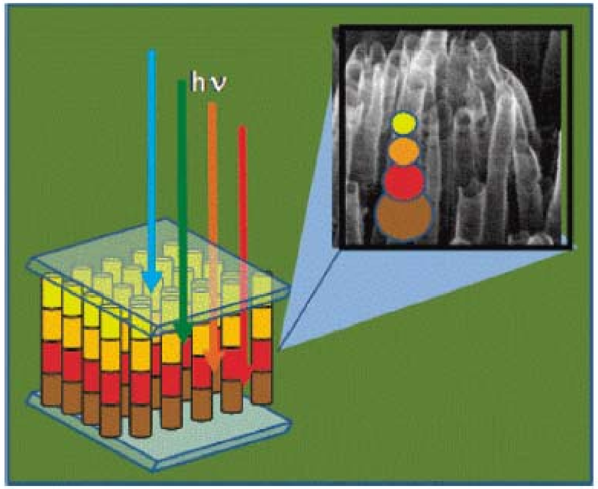
Absorber QD size tuning





Full band solar cell

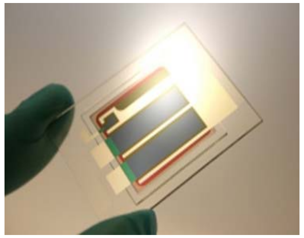
Kamat, JPCC, 112, 18737 (2008)



- Similar to DSSC
- Potential high Voc
- Potentially most efficient
- Surface chemistry
- Hole transport materials

Recent reports of thin film solar cells

Organic PVs

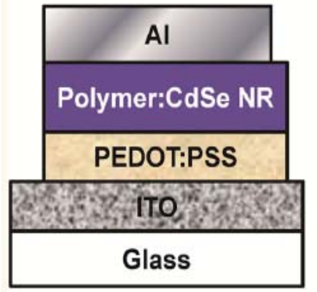


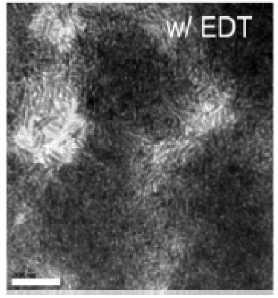
Heliatek
PCE=12.0%

Kolon
PCE=11.3%

Mitsubishi Chemical
PCE=11.1%

Organic-Inorganic Blend PVs

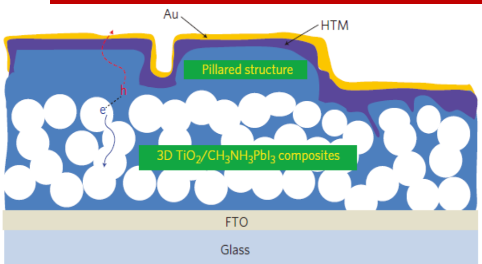


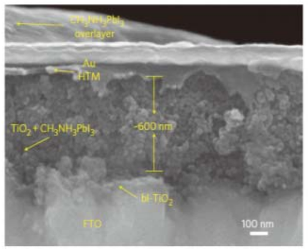


ACS Nano (2013)

University of Florida (Jiangeng Xue)
PCE=4.7%, V_{OC}=0.74 V, J_{SC}=12.8 mA/cm^2, FF=0.50

Perovskite Solar Cells

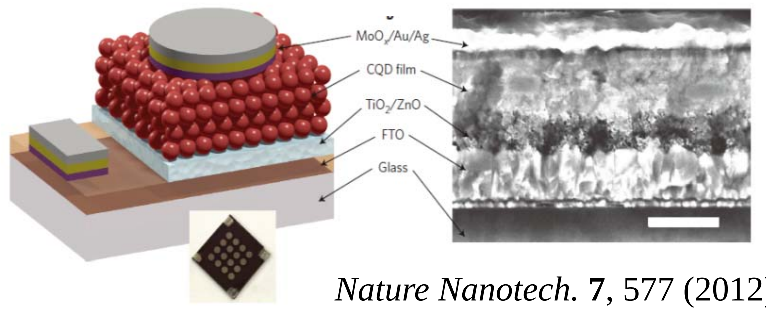




Nature Photon. (2013)

KRICT (Sang Il Seok) & EPFL (Michael Grätzel)
PCE=12%, V_{OC}=1.0 V, J_{SC}=16.5 mA/cm^2, FF=0.73

QD PVs



Nature Nanotech. **7**, 577 (2012)

University of Toronto (Edward H. Sargent)
PCE=7.4%, V_{OC}=0.6 V, J_{SC}=21.8 mA/cm^2, FF=0.58

- Best efficiency of perovskite solar cells : 19.3% (Yang Yang, UCLA)
- lead-free (Sn) perovskite solar cells: ~ 6.4% (Henry Snaith, Energy & Environmental Science, 2014)

http://news.sciencemag.org/chemistry/2014/05/perovskite-solar-cells-get-lead-out

BIPV - DSSC

R.F. Service Science 2014;344:458