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What is Photovoltaics ?

with

Pabitra Nayak (Oxford U.)

thanks to

G. Hodes, L. Barnea, R. Milo (WIS),
A. Kahn (PU) + all those mentioned on the slides,**+++++++**

SAERI
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Energy
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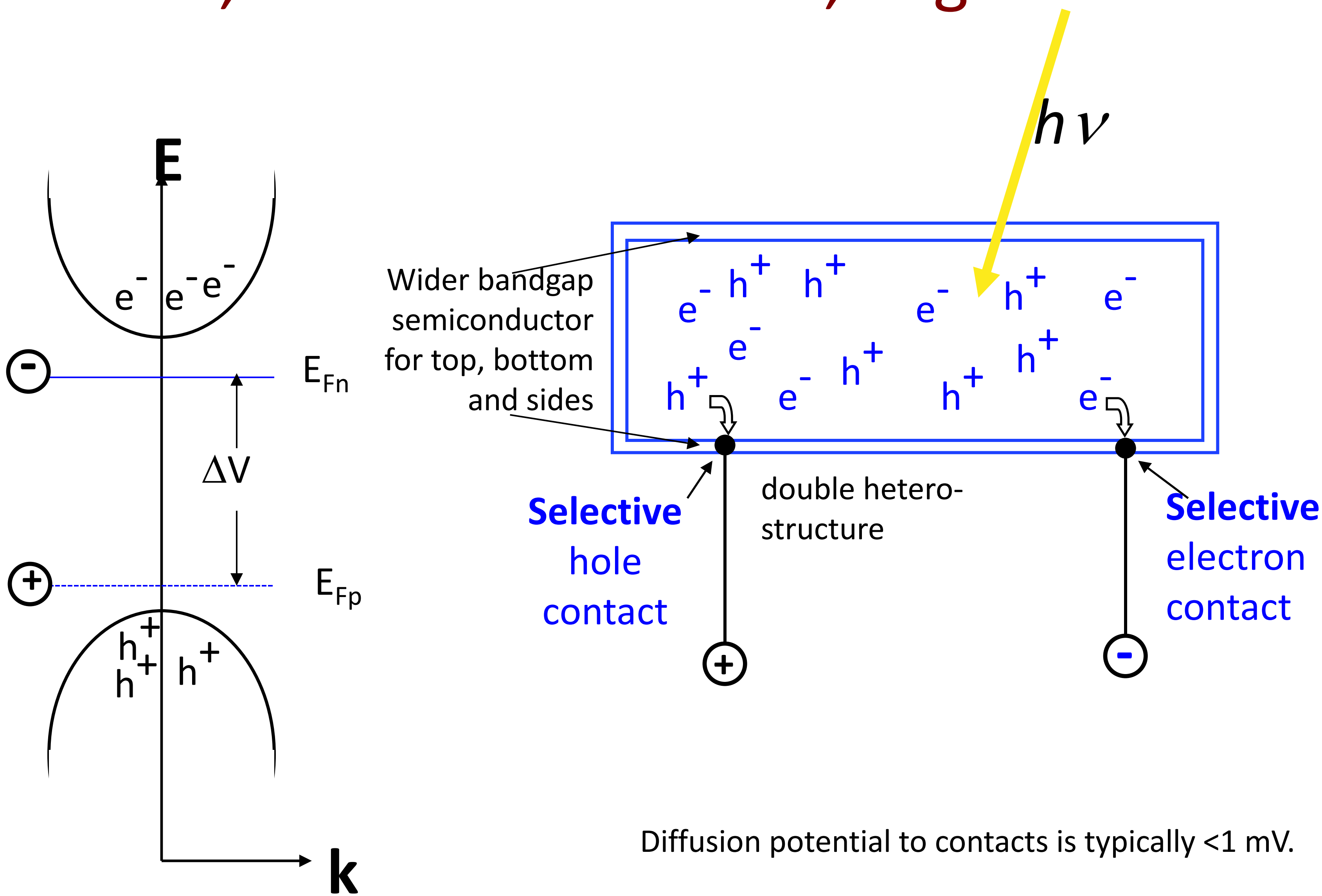
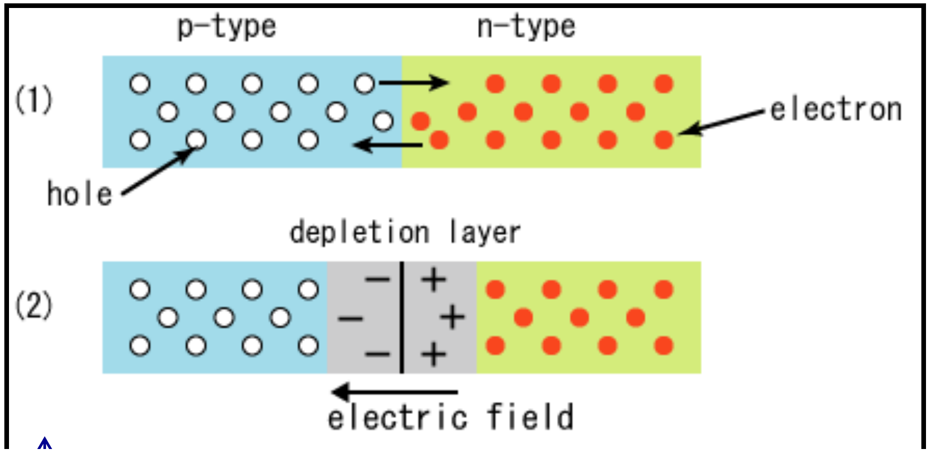
First, what is a Solar Cell, in general?



A Solar Cell does not require a p-n junction!

Conventional p-n Junction Solar Cell



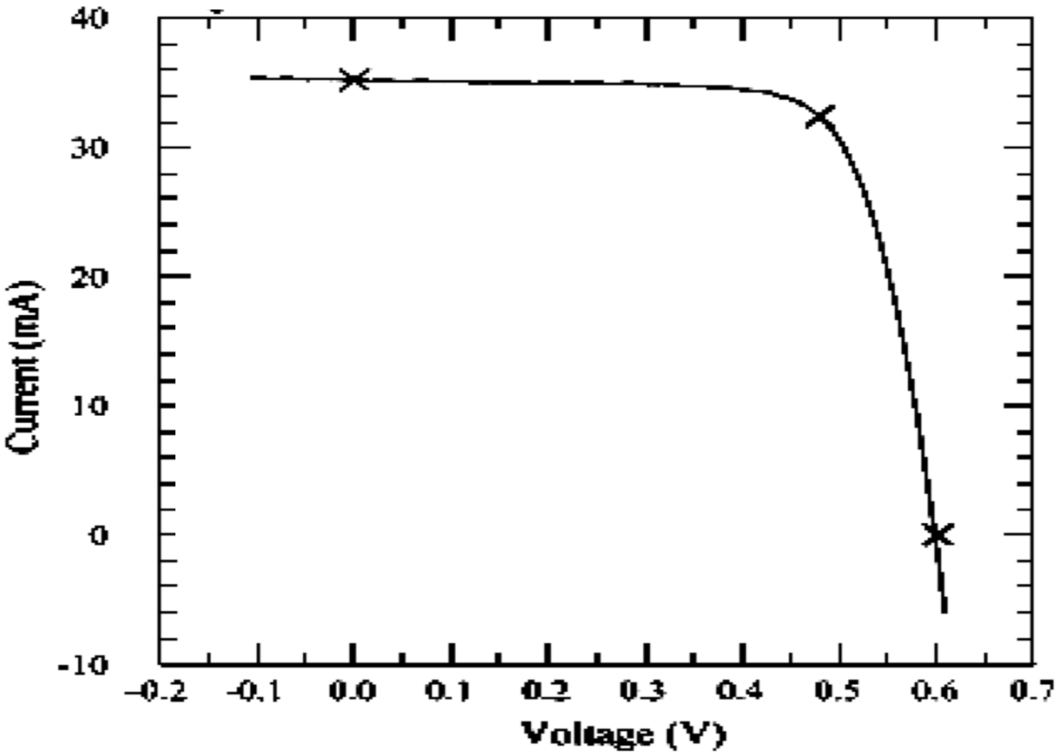
- Absorbs light
- Absorbed light creates carriers
- Carriers collection, by diffusion/ drift

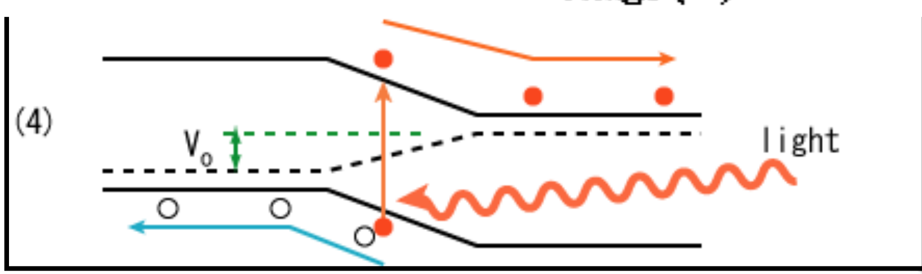
after textbooks & R. Collins, CSM

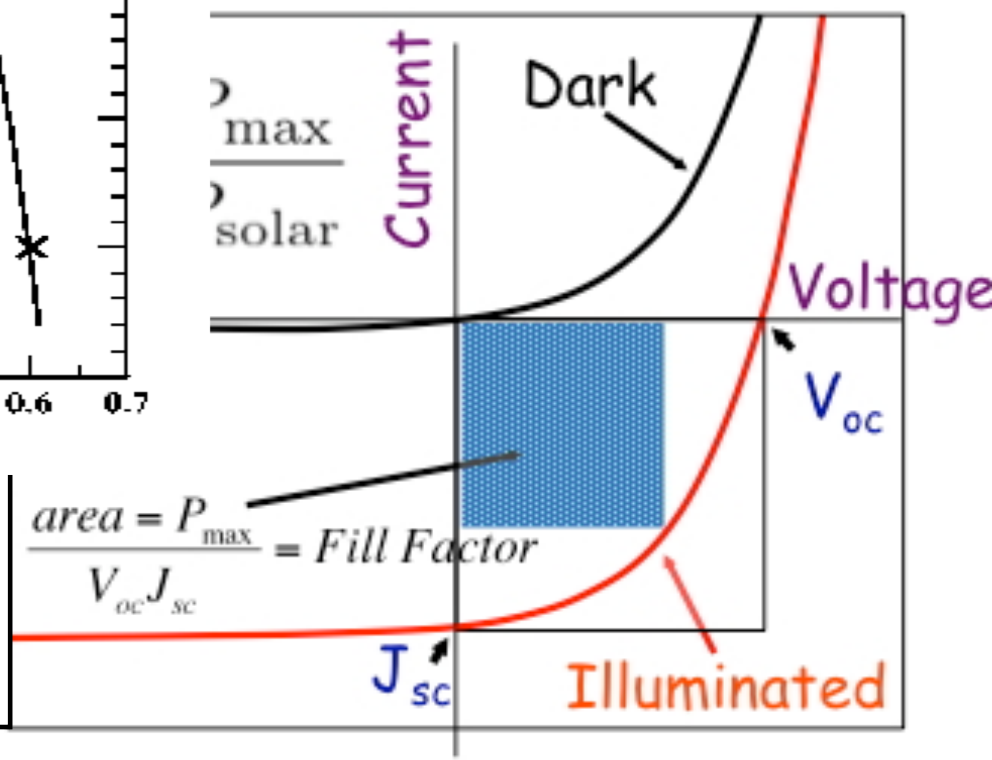
Conventional p-n Junction Solar Cell

+ I-V characteristics

Absorb light
Absorbed light creates carriers
Carrier collection, by diffusion

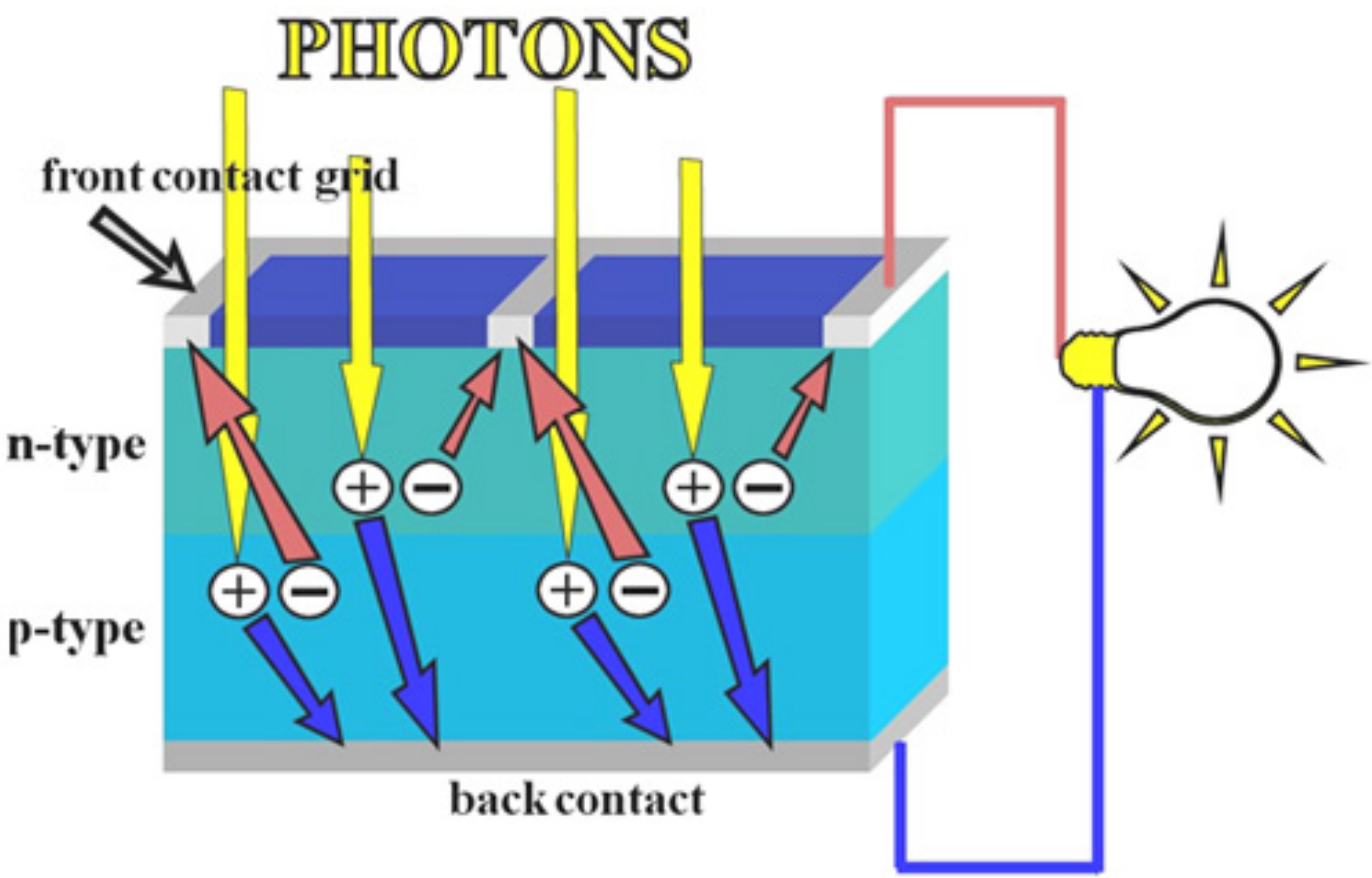




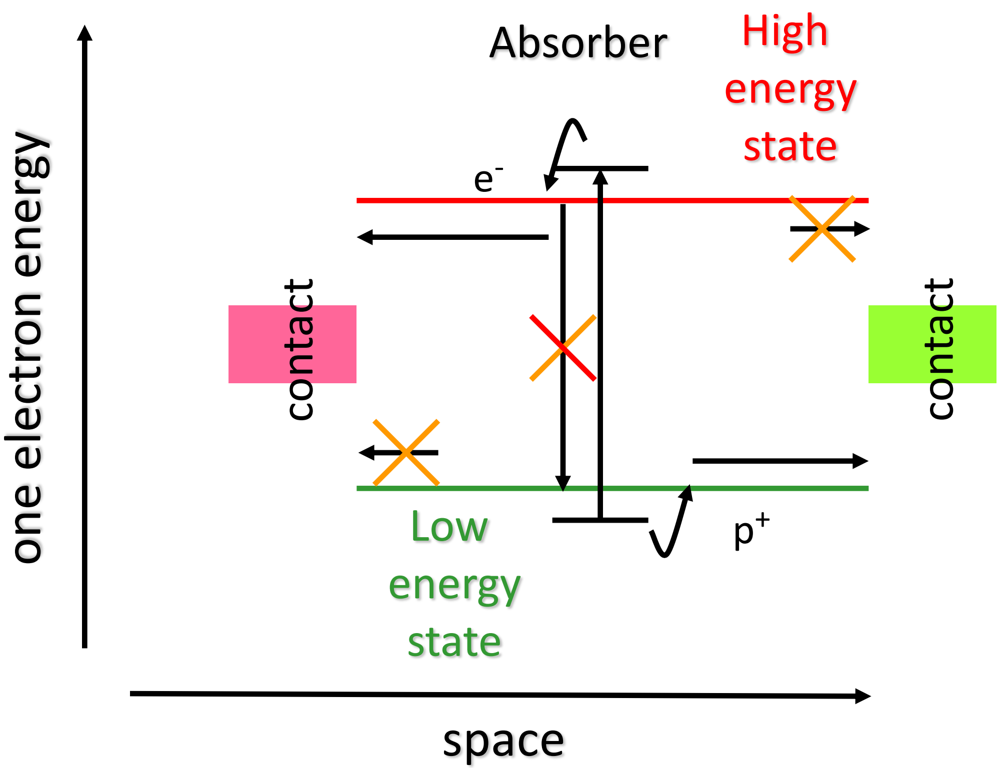


after textbooks & R. Collins, CSM

A schematic of a p-n junction Solar Cell



The Photovoltaic (PV) effect: *Generalized picture*[1]



Metastable high and low energy states

Absorber transfers charges into high and low energy state

Driving force brings charges to contacts

Selective contacts

→ ***high** voltage / current / efficiency,*
requires** to **collect all carriers!

(1) Inspired by RT Ross, JAP (1967);
cf. e.g., MA Green, Physica E (2002)
same principle for photosynthesis

Current Types of PV Cells

Primarily based on solid-state electronic material systems

* self-repair
\# defect-tolerance ?

Elemental Semiconductors

Si,**Ge**

(non) concentrator; single-& multi-junction

homo- junction
hetero-junction

Inorganic Compound Semiconductors

Halide perovskites*,#

(Ga,In)(As,P)
*$Cu(In,Ga)Se_2$**
CdTe

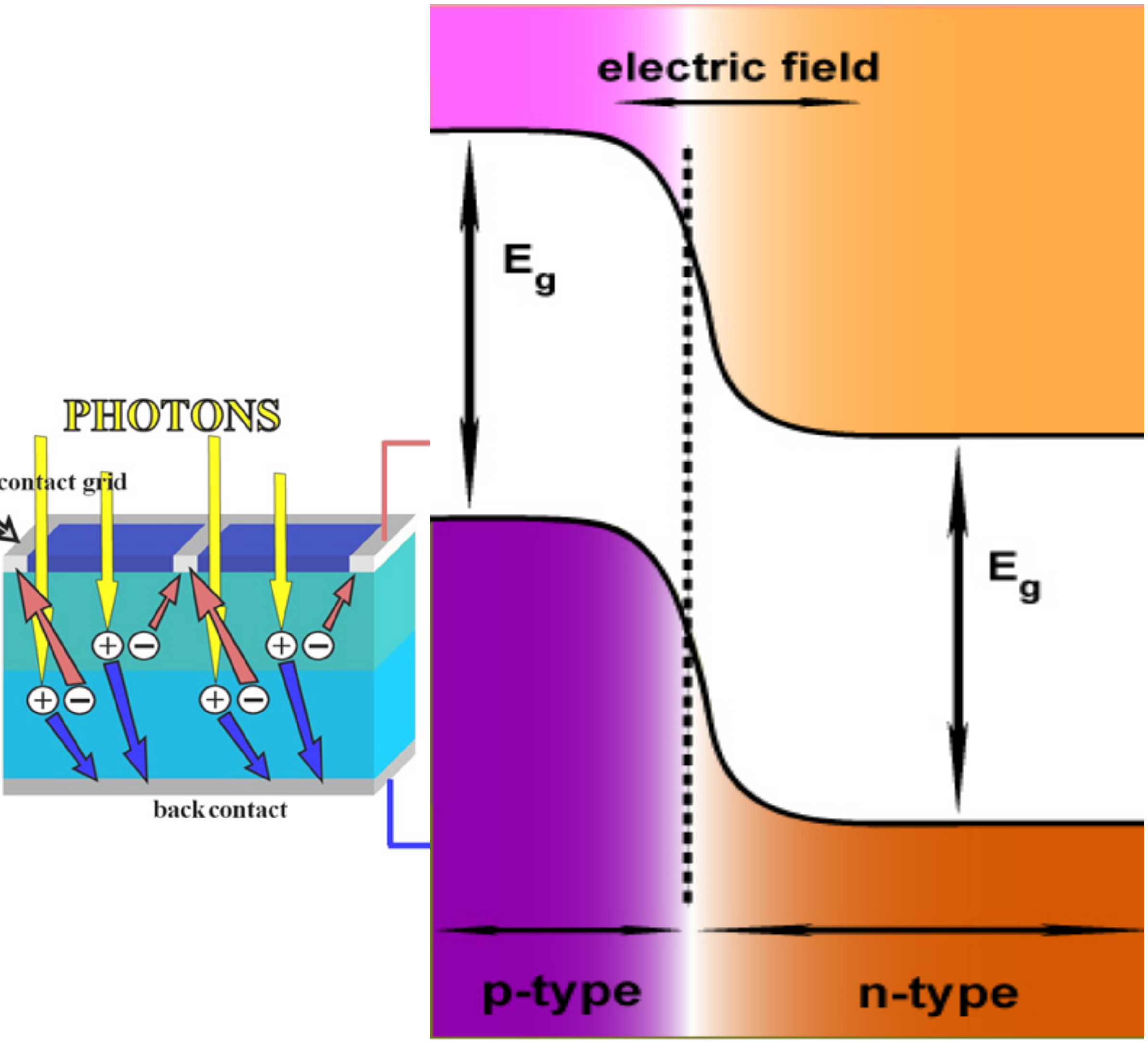
Organic, Excitonic (molecules,polymer)

Interpenetrating network
Mesoporous framework
…………………………………………………………

P3HT-PCBM
Porphyrin
dye+TiO_2

Types of junction for solar cells

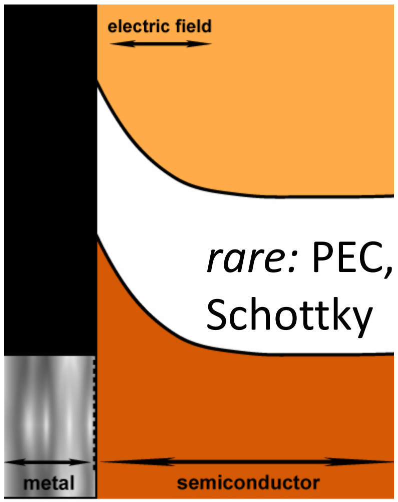
Homojunctions (c-Si, GaAs,



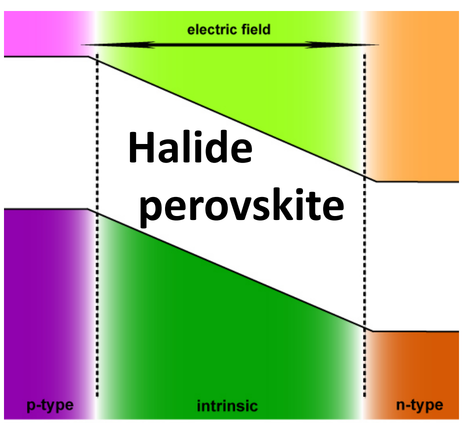
p-n junction

Types of junction for solar cells: **Heterojunctions**

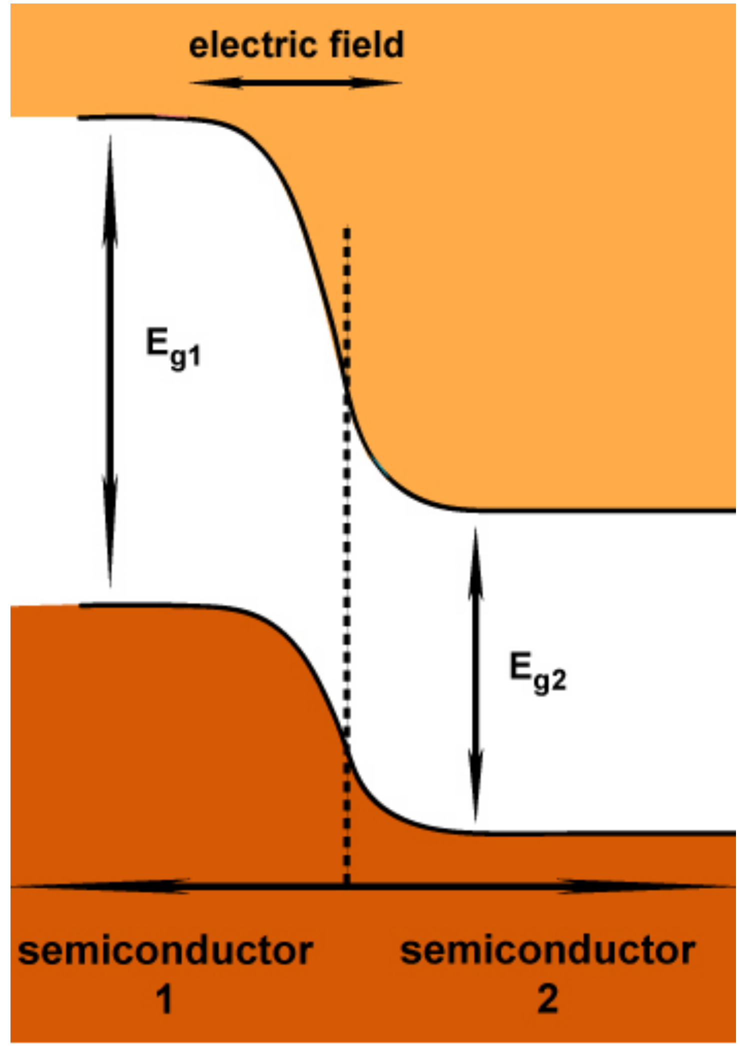
Thin film Cd(Se,Te), Cu(In,Ga)Se_2 = CIGS, Halide Perovskite



Schottky barrier

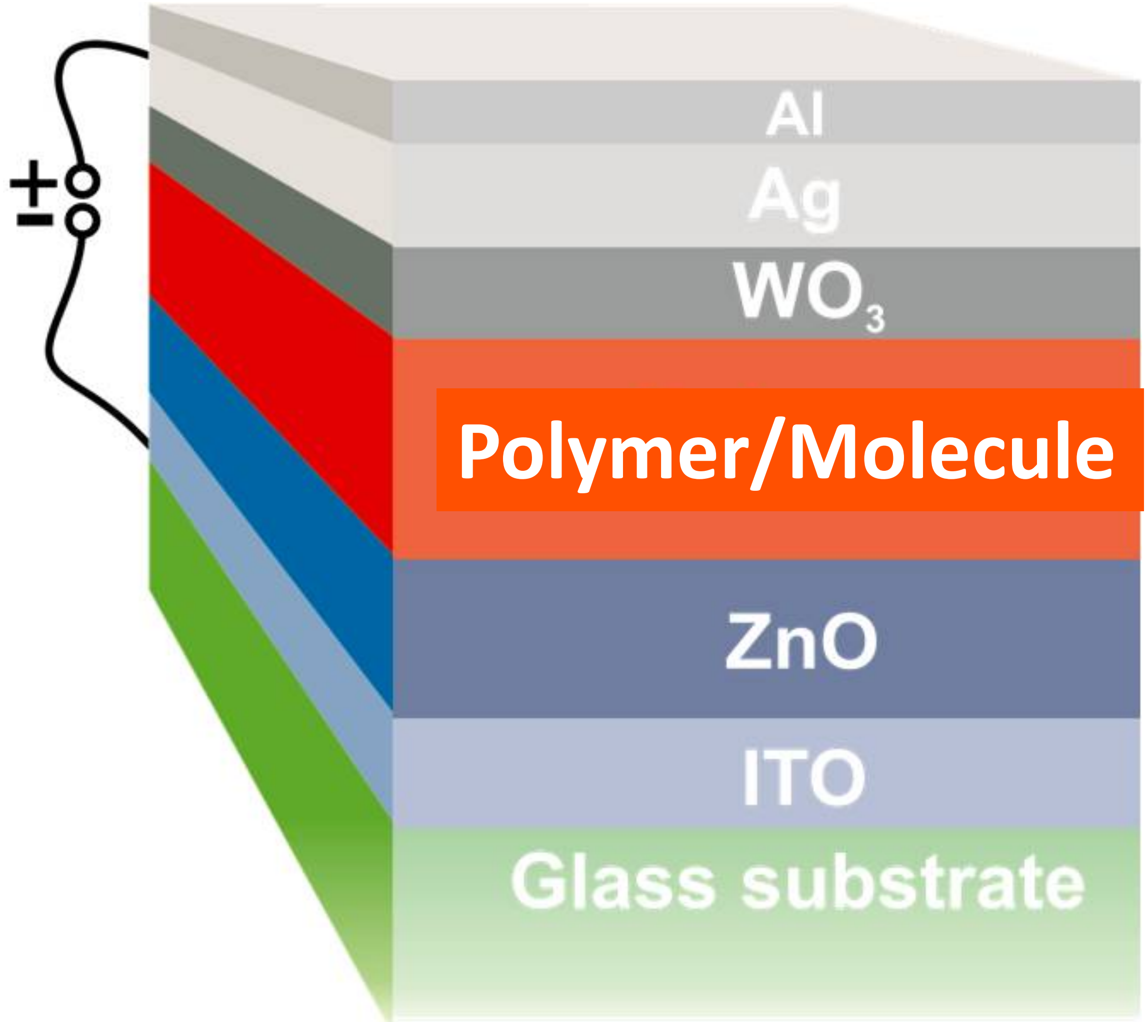


p-i-n junction



heterojunction

One type of Organic Solar Cell Architecture

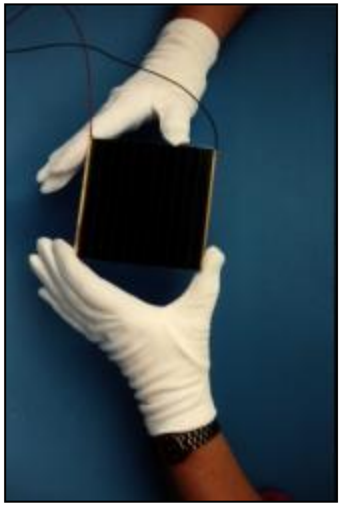


Solar Cell (r)evolutions

1st generation
Si

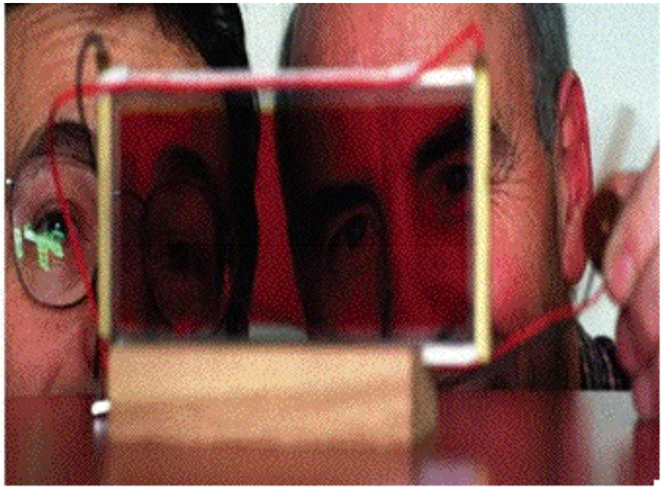
Single- crystalline
cm

2nd generation
CdTe, CIGS

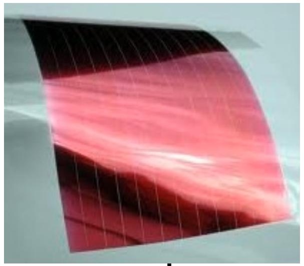


poly-crystalline
μm

3 d generation
TiO_2
Small molecule/
halide perovskite, QDs



nano / *meso* crystalline
~ 20 nm



amorphous
(a-Si:H;
polymers)

In 11/2017 Global *Cumulative* Installed PV Power ~ 0.32 TW_p

PRC goal >2012
≥ 0.01 TW_p/yr

Lowest Loss Single Junction PV lab cells

(1-4 cm^2 ; *most tandems are much smaller;* ***2010 values in blue*****)**

~	[71] 29 % GaAs	*~26 %*
~	[74] 26.7 % **single** crystal Si (79 cm^2)	*~25 %*
~	[79] 21-22 % PX thin films (CIGS, CdTe, Si)	*~17 %*
~	[79] 21 % halide perovskite	*~ 4 %*
~	[88] 12 % dye-sensitized solar cell (DSSC)	*~ 10 %*
~	[89] 11 % organic (molecules; polymers)	*~ 5 %*

\- -

~	[61%] 39 % *tandem* quintuple junction	----------
~	[62%] 38 % “big Mac” *tandem* triple junction	*~ 36 %*
(~	[54%] 46 % bigger Mac” *tandem*, @ 500 x concentration)	*~ 41.5%*

Definition of efficiency:

$$\eta = \frac{Electrical \quad Power_{OUT} \times 100\%}{Solar \quad Radiative \quad Power_{IN}}$$

Data from Solar Cell Eff #50, Progr in PV 2017 and other sources

Possibilities for Technological Progress

2010 values in blue

Efficiency(%)	Manufacturer	Technology (area, if < 600 cm²)	BEST commercial module/cell[1]
24.1	SunPower	Single-crystal Si non-standard jnctn	91 % 78
18.2	Panasonic	Single-crystal Si HIT jnctn	71% ← 74
19.2	Trina Solar	Multi crystal Si standard junction	90% 71
14.3	Evergreen	mc-Si ribbon standard junction	--%
~18.6	First Solar	CdTe	89 %↗ 65
~14.3	Solar Frontier	CIGS (Cd-free)	79 %↗ 58
12.3	Tel Solar	a-Si / nc-Si*	69 % 66
6.7 / 5.7	Uni-Solar	a-Si, triple junction *	54 %
		* stabilized values	
24.8[2,3]	Alta	GaAs thin film (pilot, 860)	~84% --
8.8 [2,3]	Sharp	dye (pilot, 398)	~75% 46
9.1 [2,3]	Toshiba	Organic polymer/molecule (pilot, 25)	~82% 49
12.5 [3,4]	Chose-Rome	Halide Perovskite (pilotissimo, 100)	~60% --

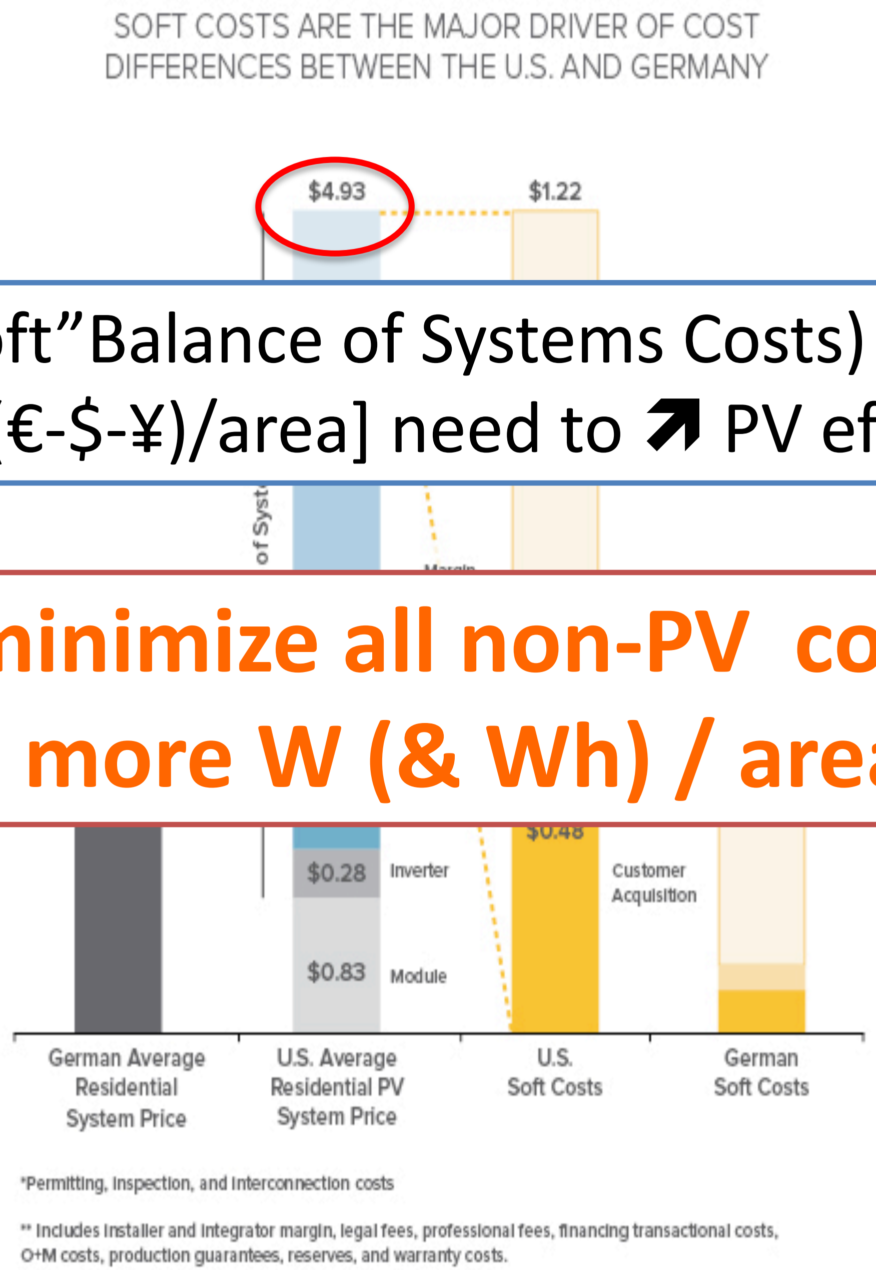
-1- *1 cm² cells;* **-2-** *Pilot modules; few yrs stability;* **-3-** *not yet commercially available;* **4-**; *no stability data as yet*

Nayak et al. *Adv. Mater.*, 5-2011,3-2014; updated 01-2018

Why do we need another Solar Cell, apart from Si ?

Well, what does PV need most?

Solar PV Costs in the USA and Germany (2013)



(Hard & "Soft" Balance of Systems Costs) scale ∝ area

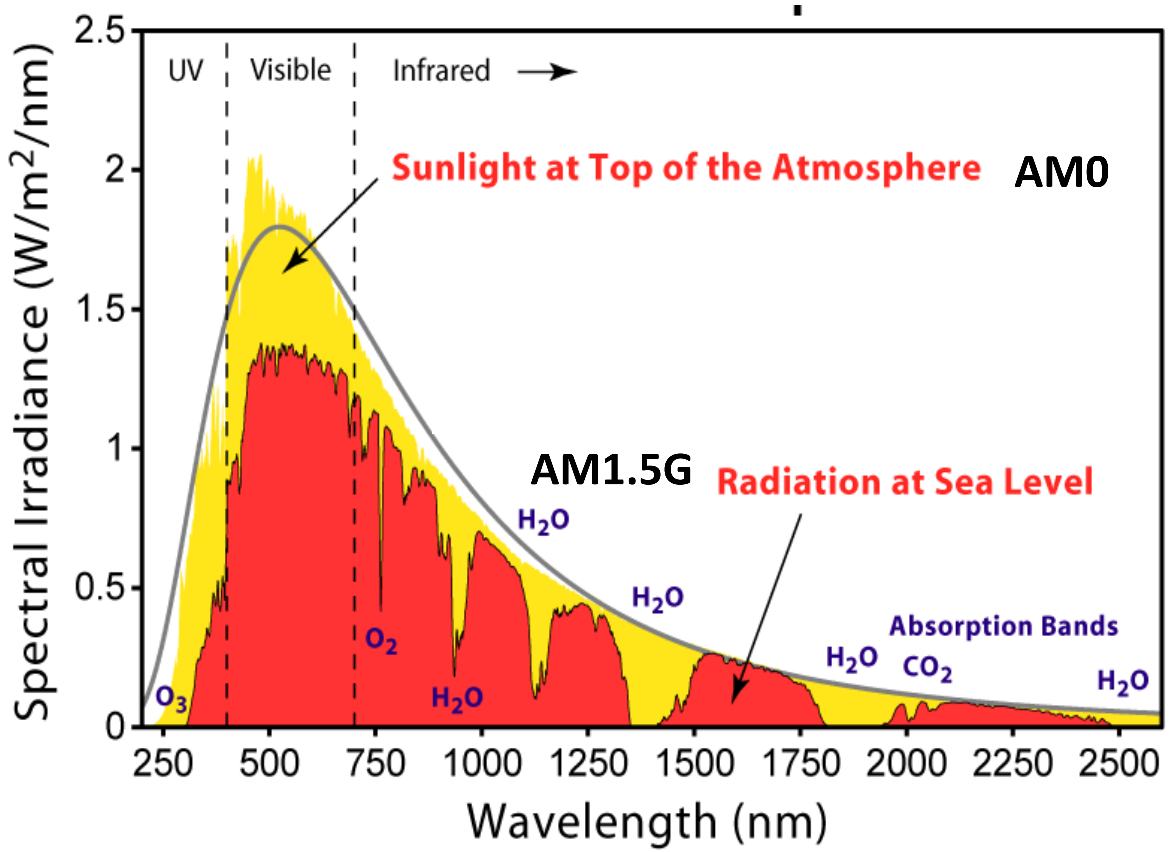
To ➘ [(€-$-¥)/area] need to ➚ PV efficiency

To minimize all non-PV costs,

we need more W (& Wh) / area / €-$-¥

Just Si will go only so far, because a PV cell is not very efficient...

Reminder: Solar Irradiance and power density



Power density at the top atmosphere

$$\varphi_E^{AM0} = 1366.1\ \mathrm{W/m^2}$$

Power density at sea level

$$\varphi_E^{AM1.5G} = 1000\ \mathrm{W/m^2}$$

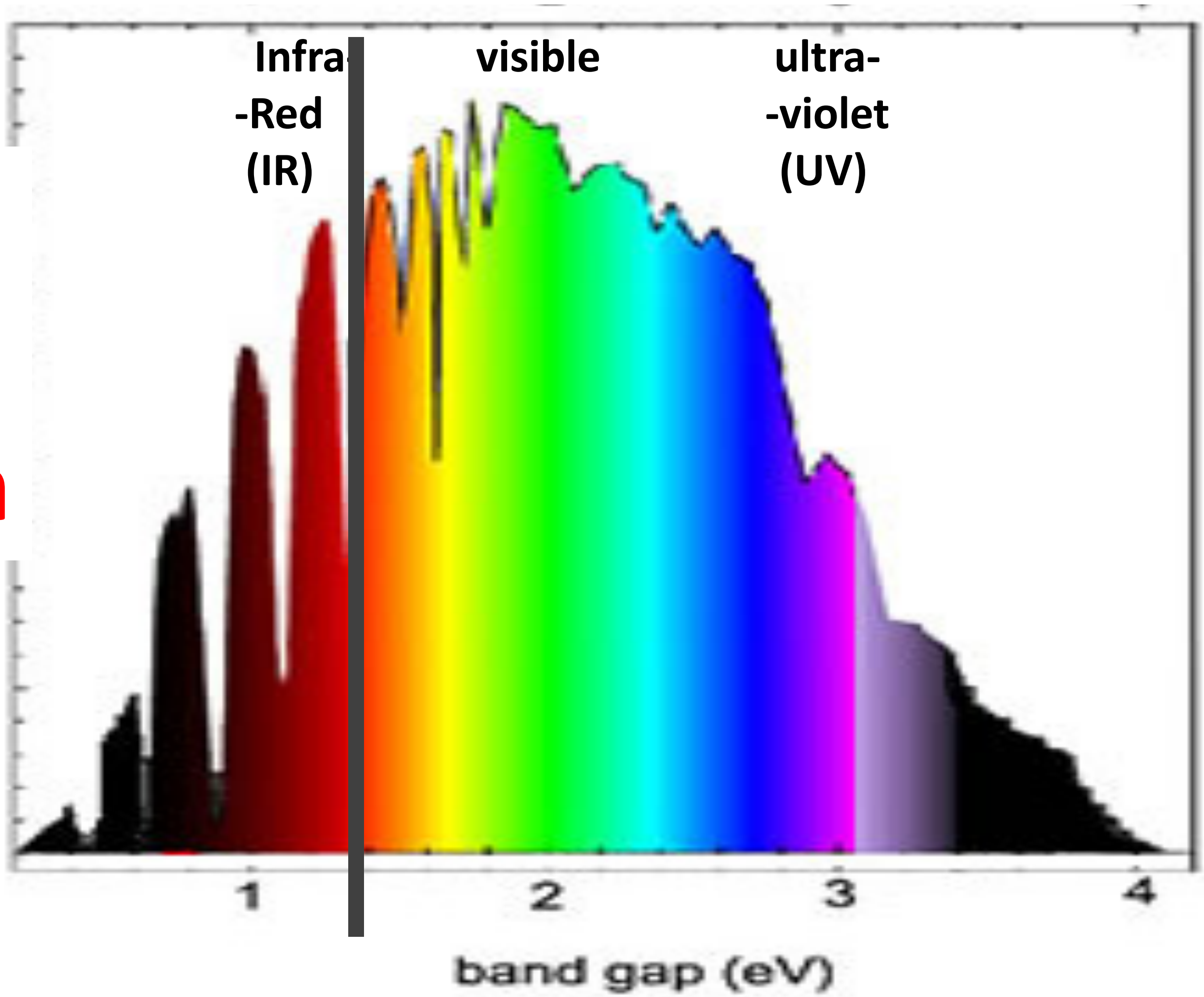
Figure from : http://en.wikipedia.org/wiki/Air_mass_(solar_energy)

PK NAYAK, OXFORD U

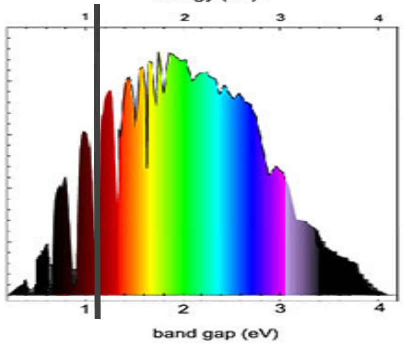
because in Solar Cells Most Energy is "Lost" as Heat

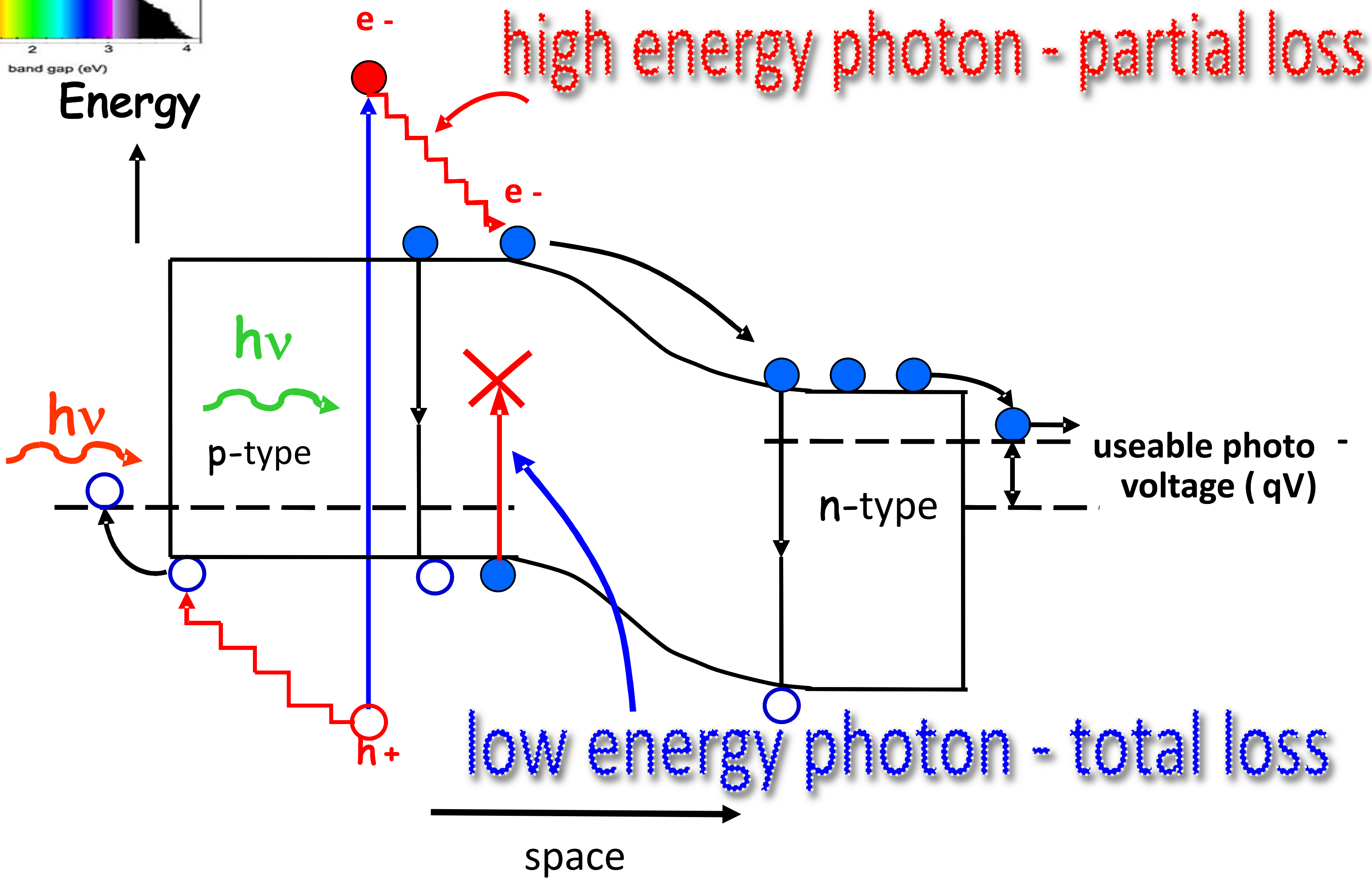
Quantum (**threshold**) Conversion Process

Solar Energy Spectrum



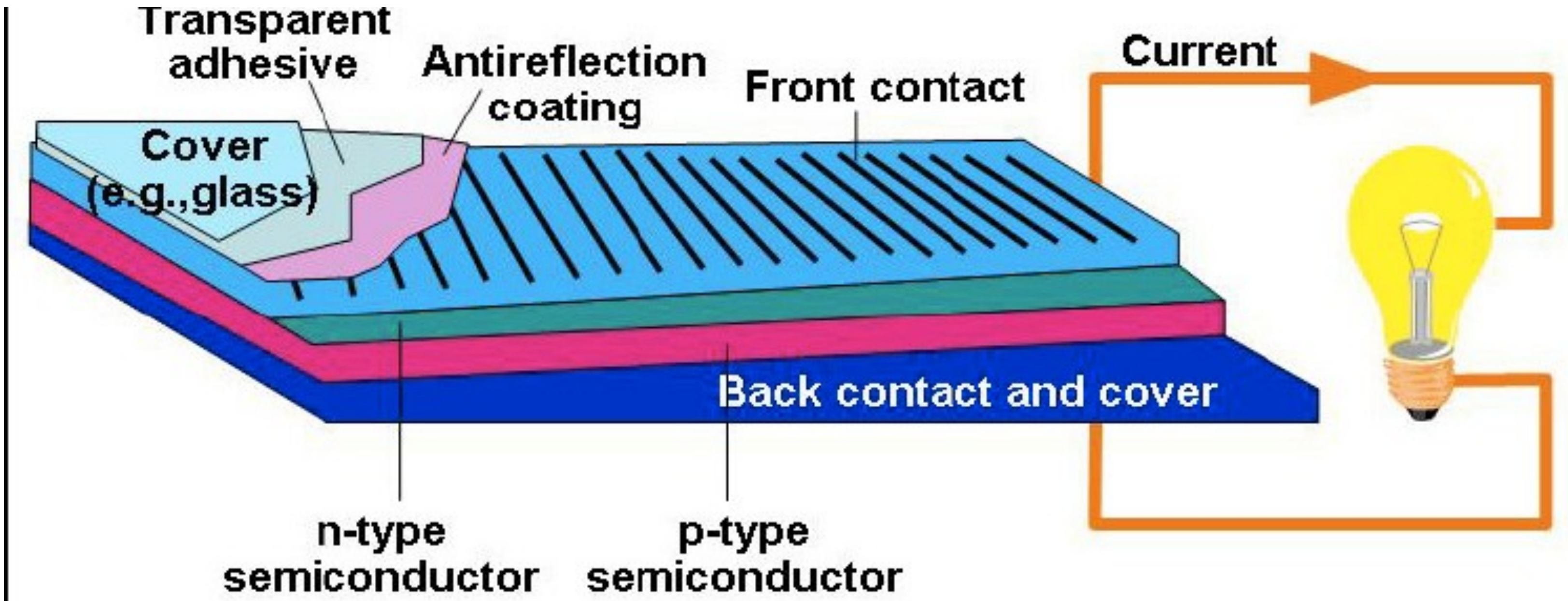
Single p-n junction solar cell





O. Niitsoo

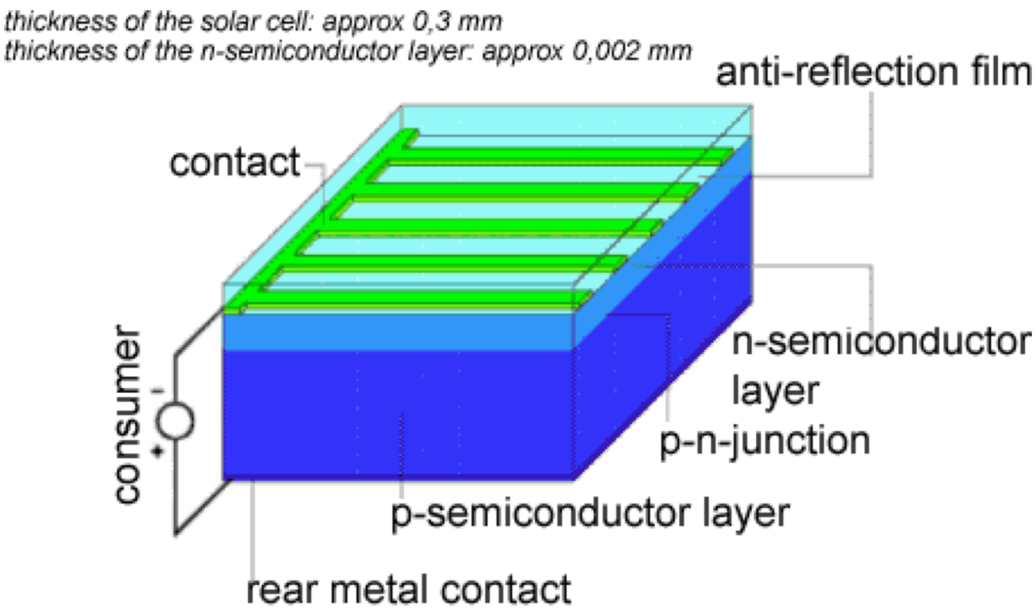
Inside a p/n junction Solar Cell

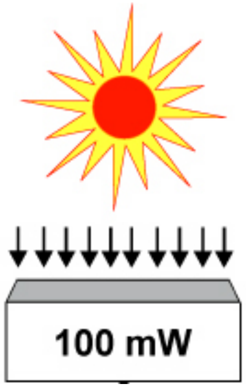


$$\text{Solar cell efficiency (\%)} = \frac{\text{Power out (W)} \times 100\%}{\text{Area (m}^2\text{)} \times 1000\ \text{W/m}^2}$$

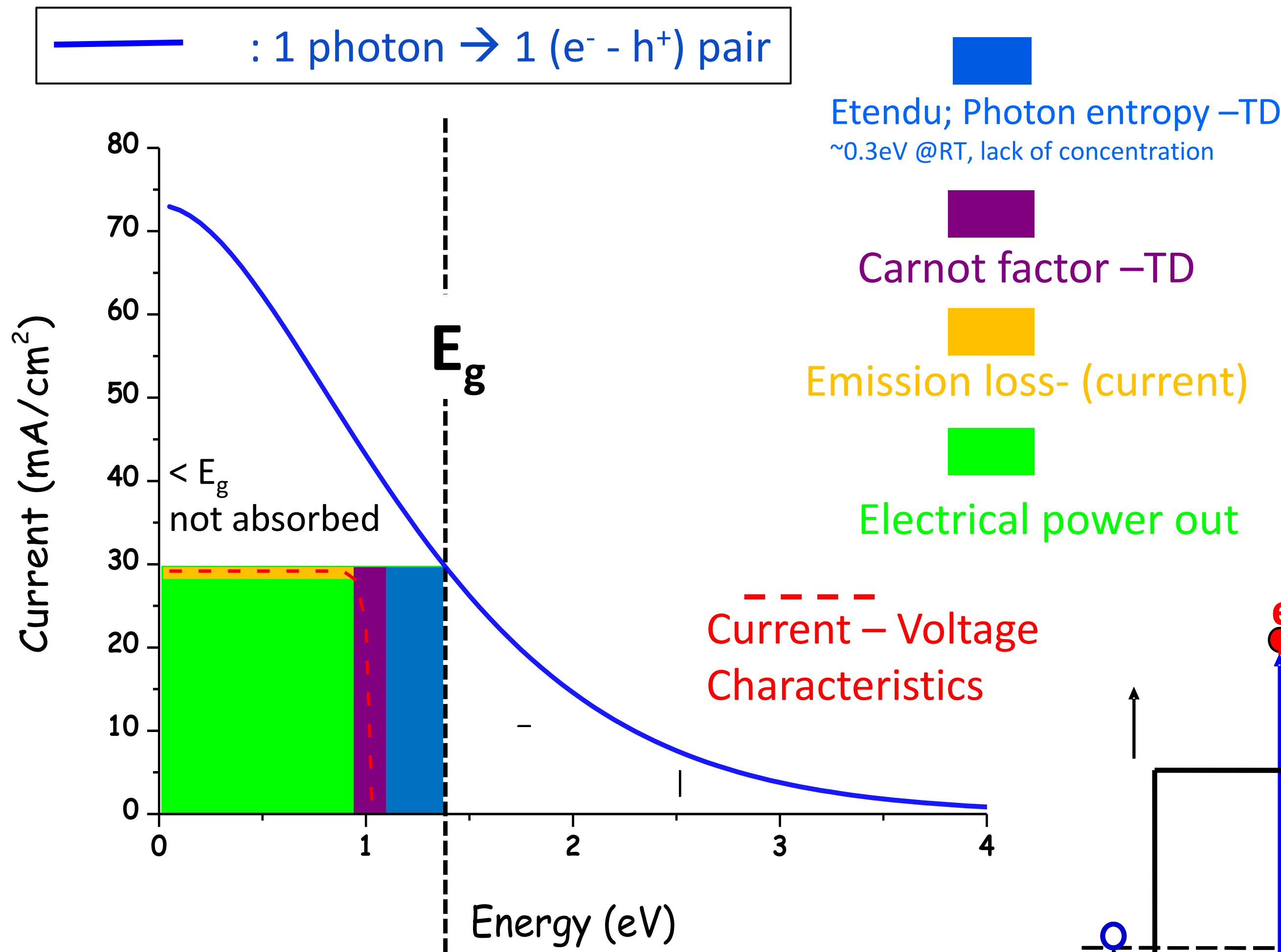
10% efficiency = 100 W/m^2 or 10 W/ft^2

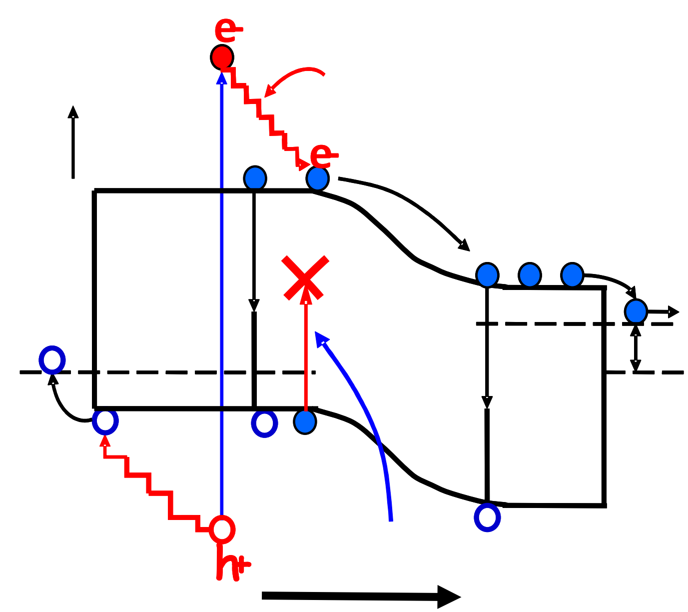
Power Losses in Solar Cells





Losses in PV cell

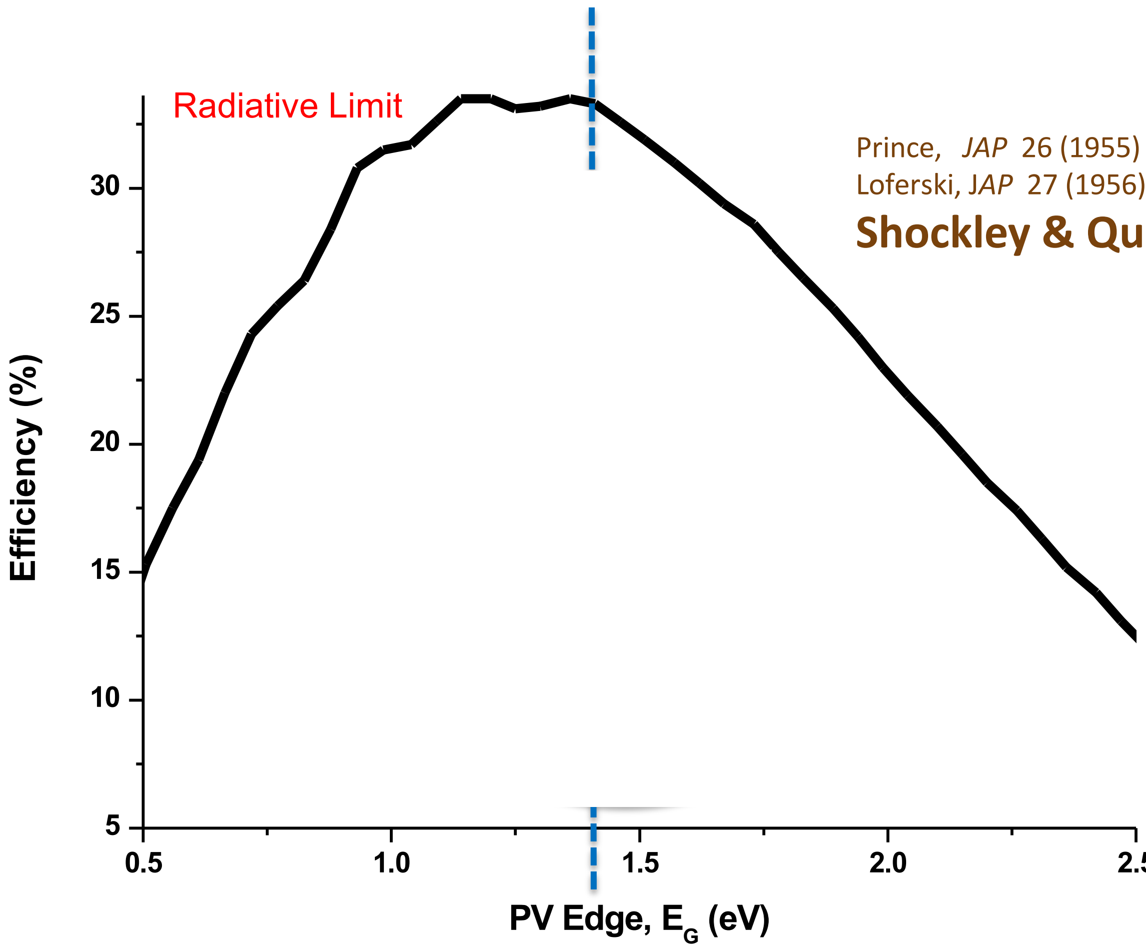




After Hirst & Ekins-Daukes
Prog.Photovolt:Res:Appl. (2010)

Shockley-Queisser* (SQ) Limit

* **detailed balance**, photons-in = electrons-out + photons out;
on earth, @ RT, for single absorber / junction;



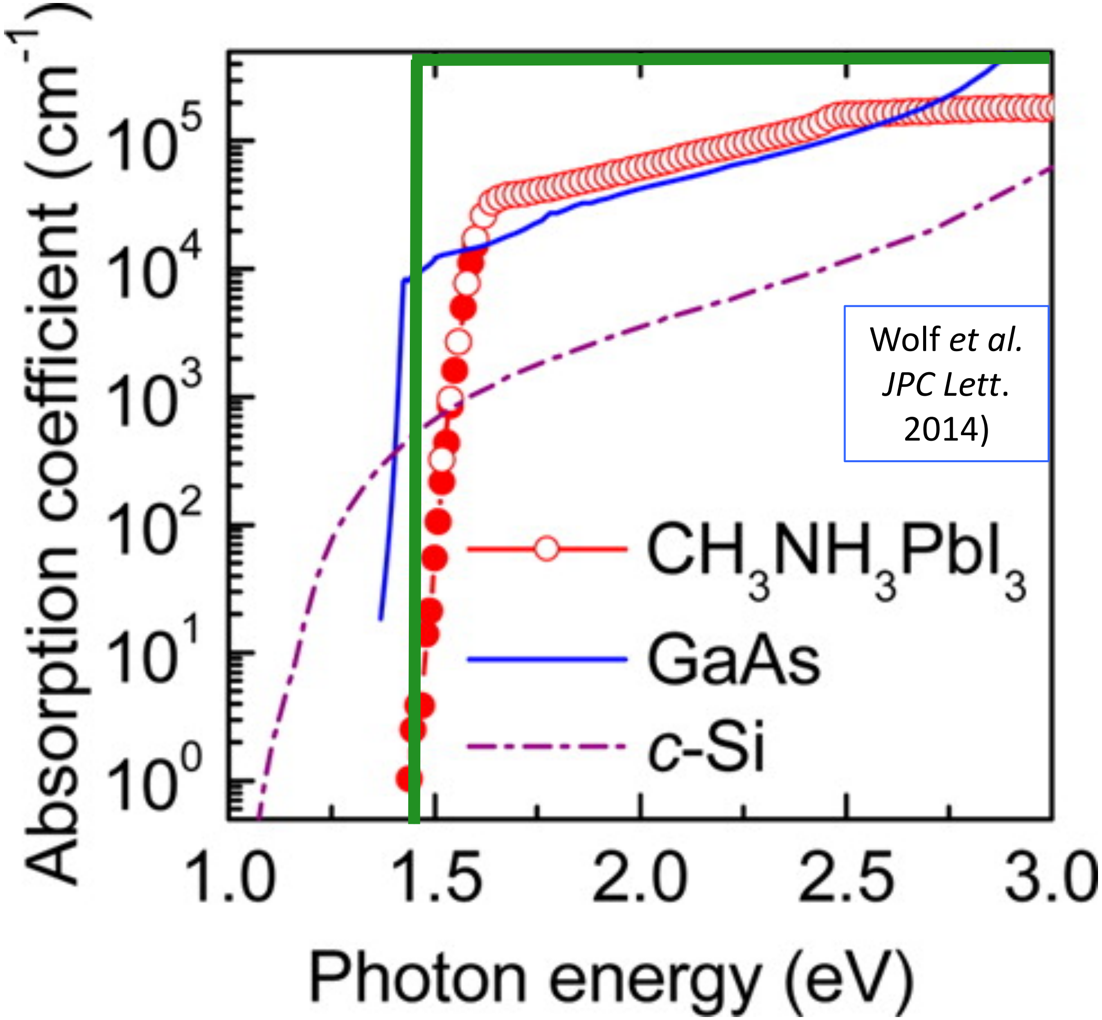
Prince, *JAP* 26 (1955) 534
Loferski, *JAP* 27 (1956) 777

Shockley & Queisser *JAP* (1961)*

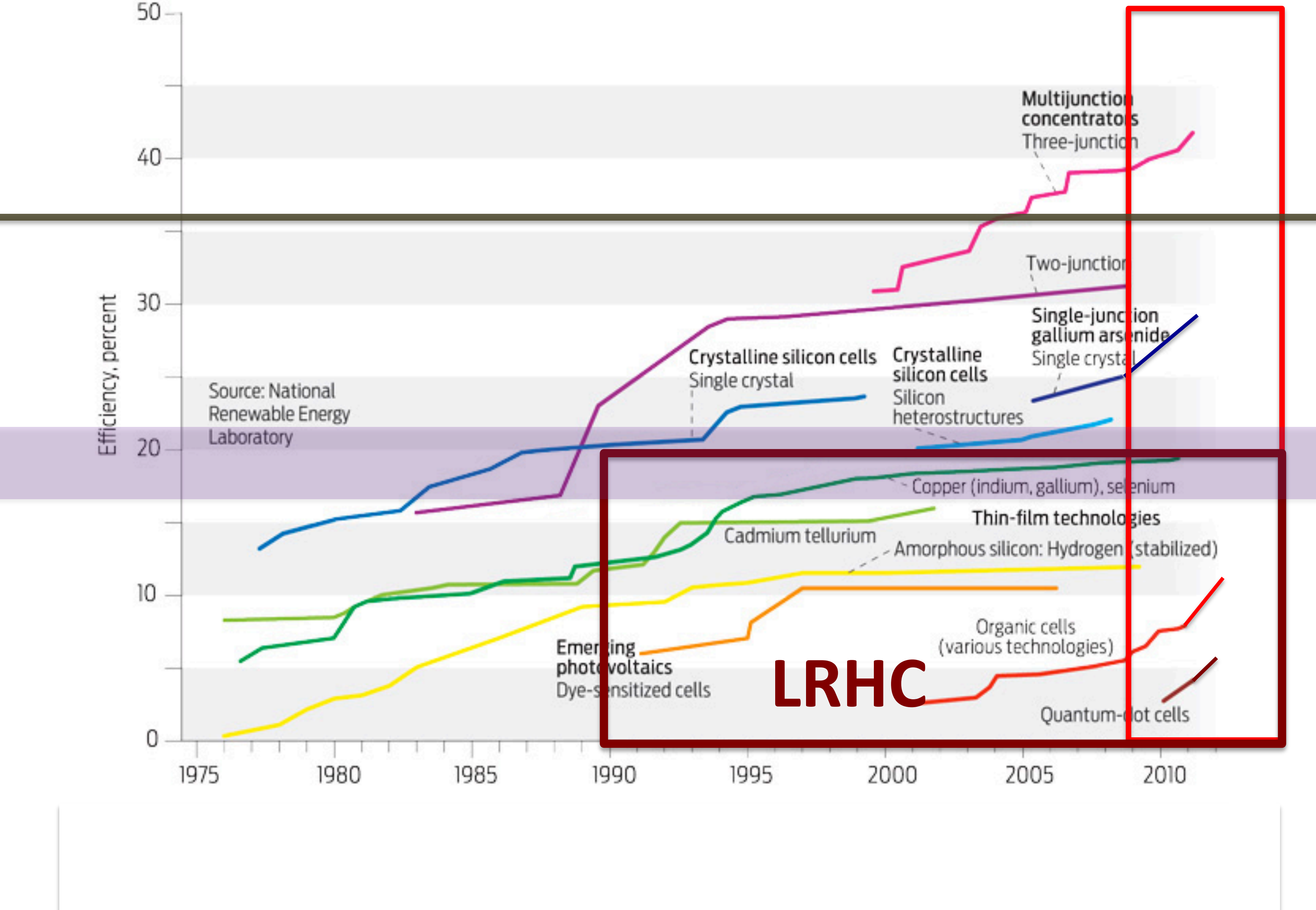
Cell area < 1 cm^2

updated 01-2018

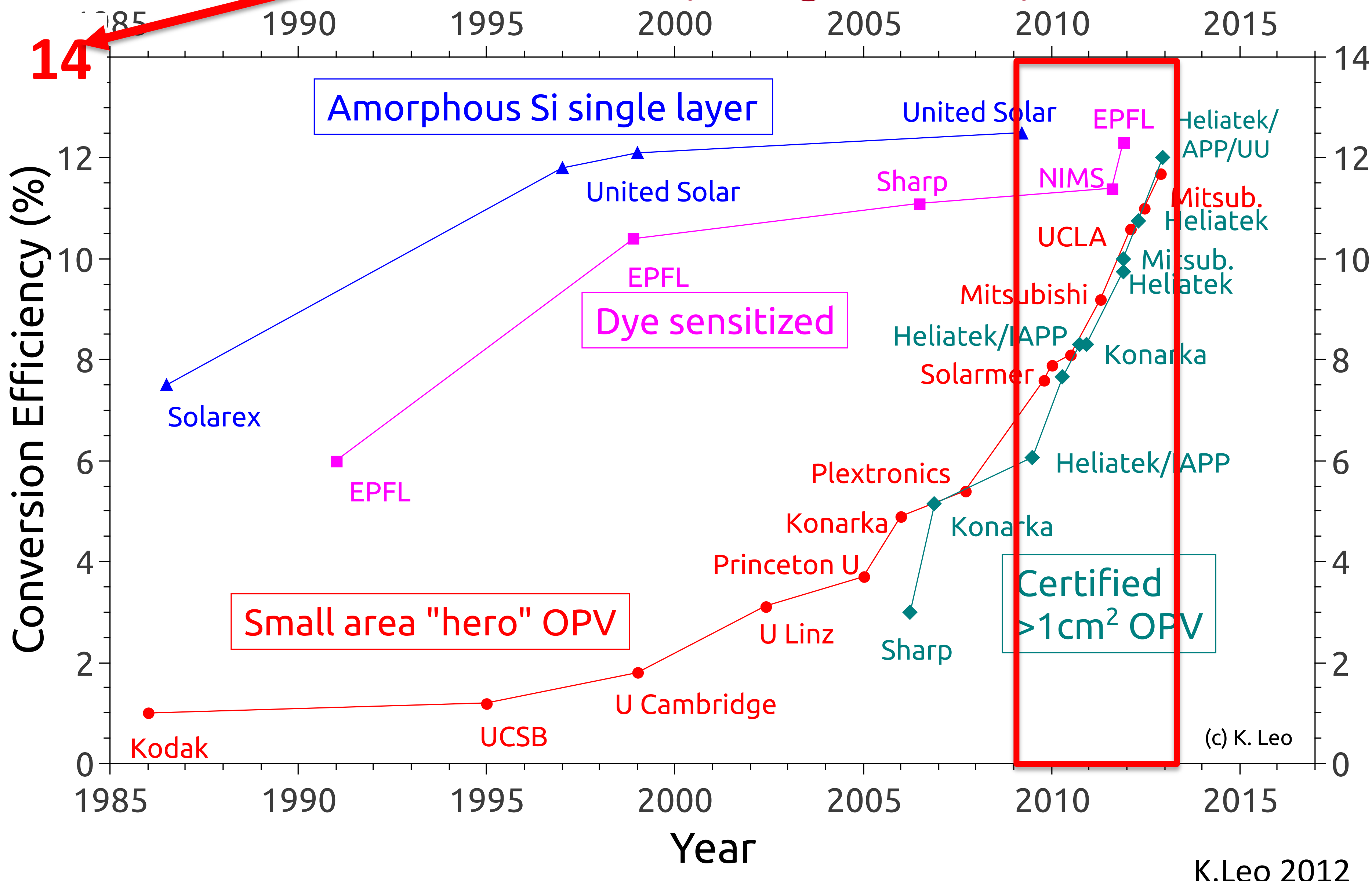
Shockley-Queisser **model** assumes step function optical absorption (and EQE)



Photovoltaic Solar cell Efficiencies (≦ 2012)



PV - LRHC (Lower Right Hand Corner): 2013 Status ("large" cells)



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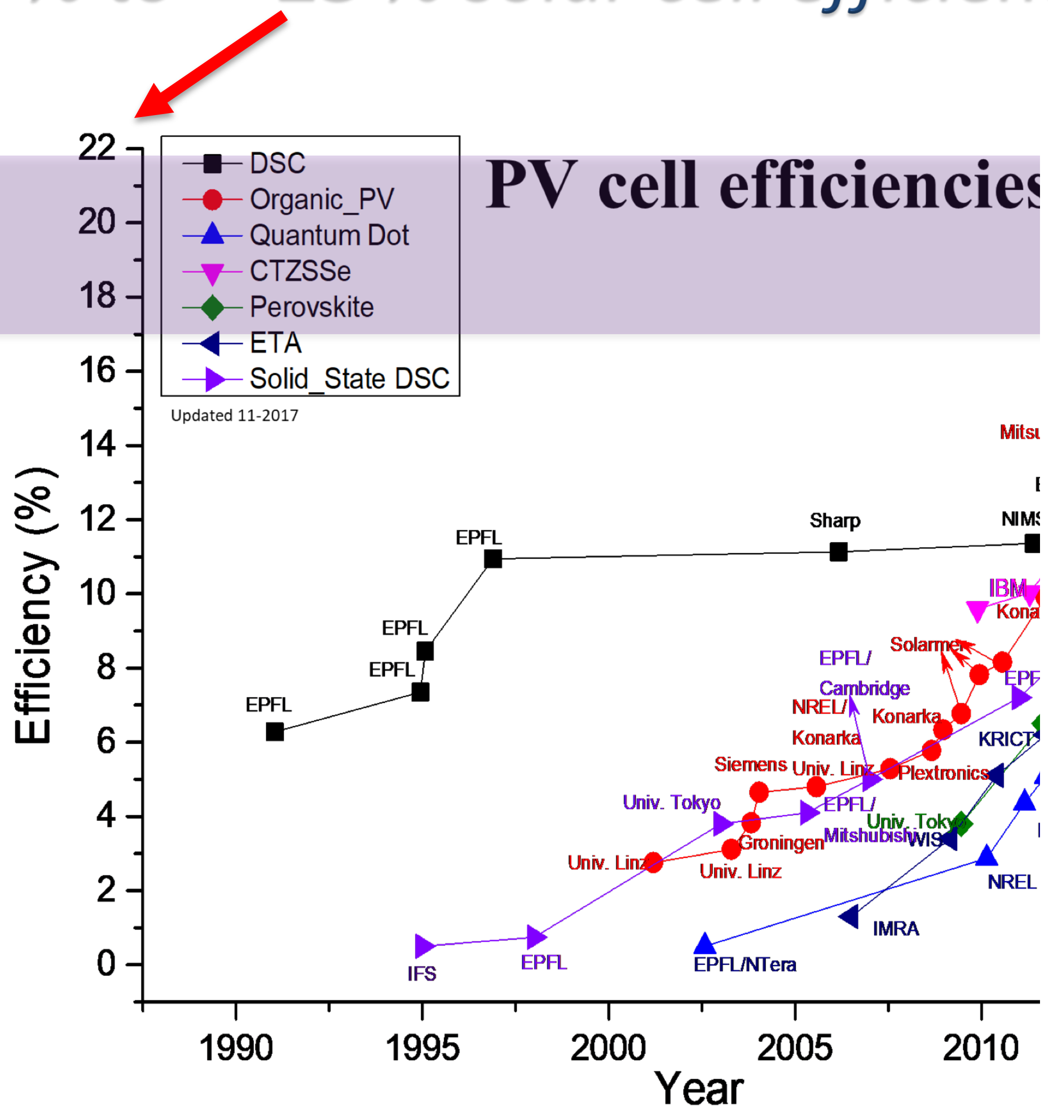
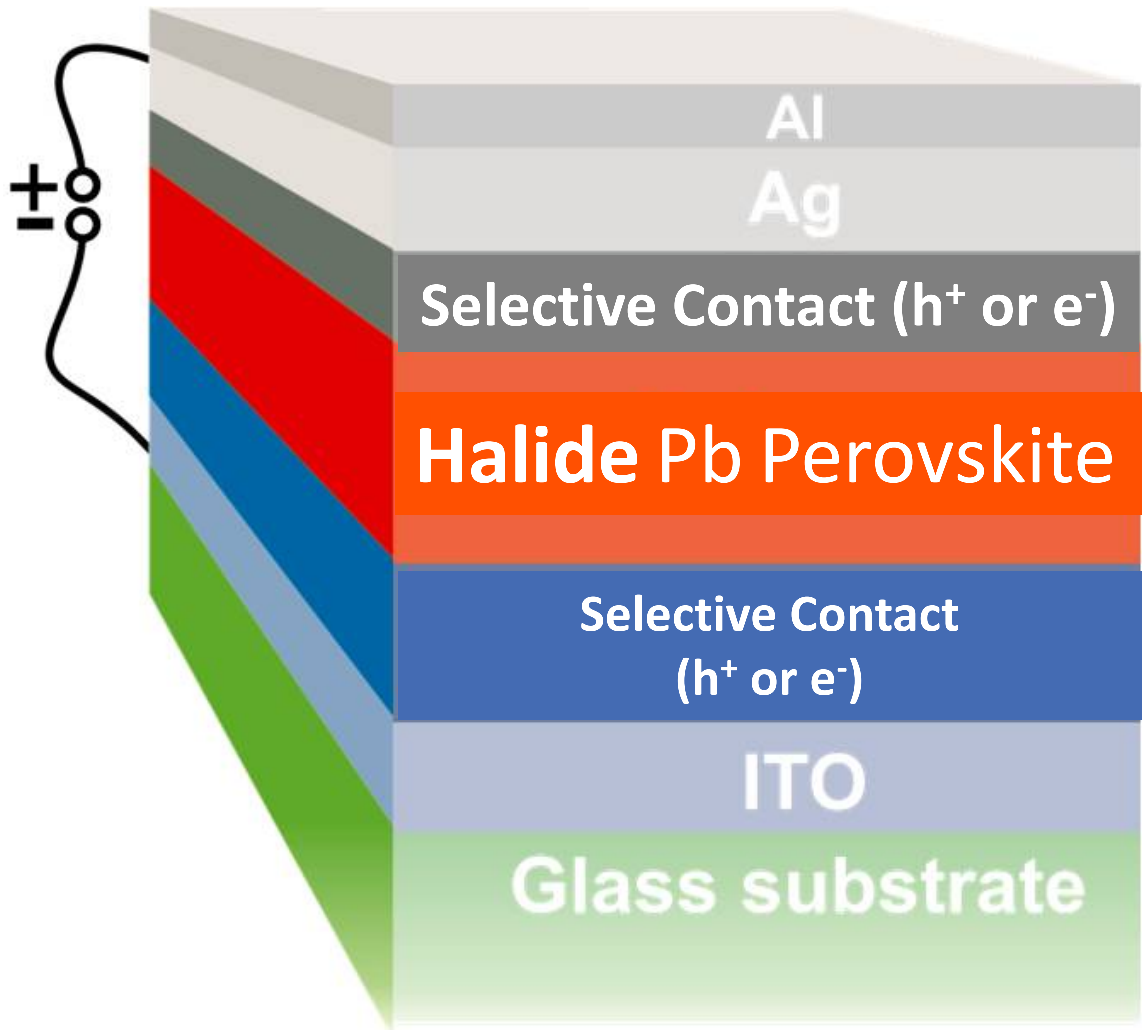
From 2013 till now

*From 4 % to > **23** % solar cell efficiency in 7 years!*

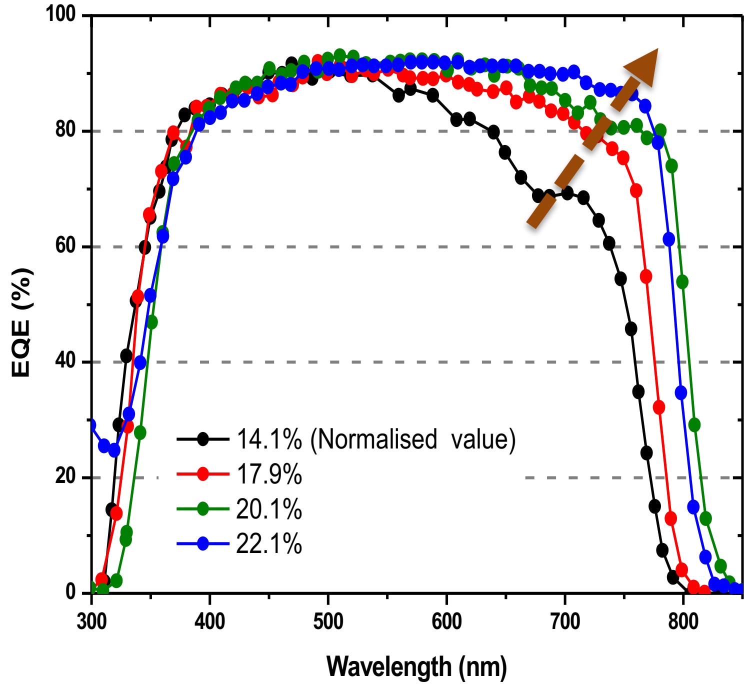


David Cahen Weizmann Inst. 2018

Halide Perovskite Solar Cell Architecture (~ OPV)



Evolution of EQE in halide perovskite cells



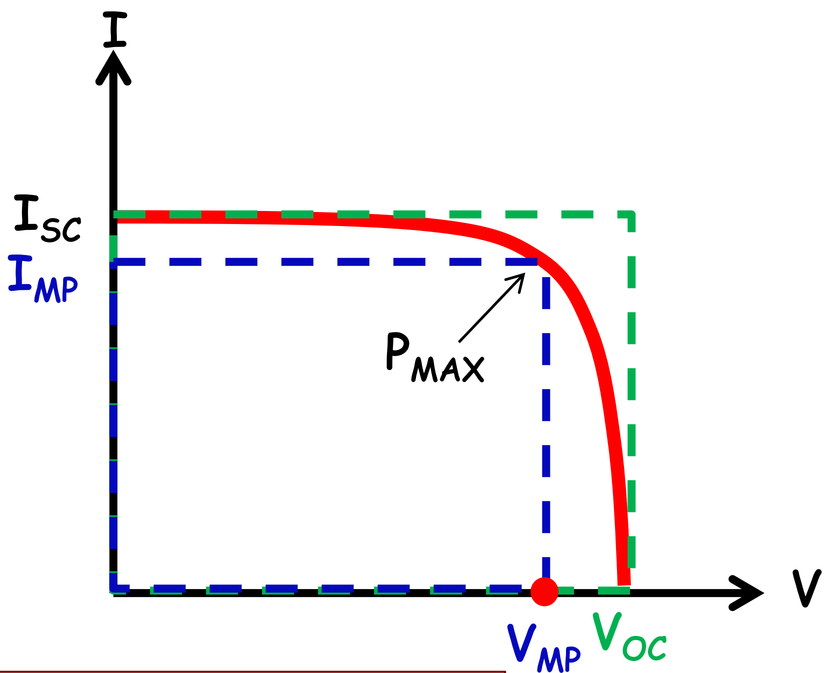
Improvements
of low energy
quantum efficiencies

Current efficiencies

$$J_{SC}/q\int \phi(\nu)d\nu = (J_{SC}/J_{SC}^{\max})$$

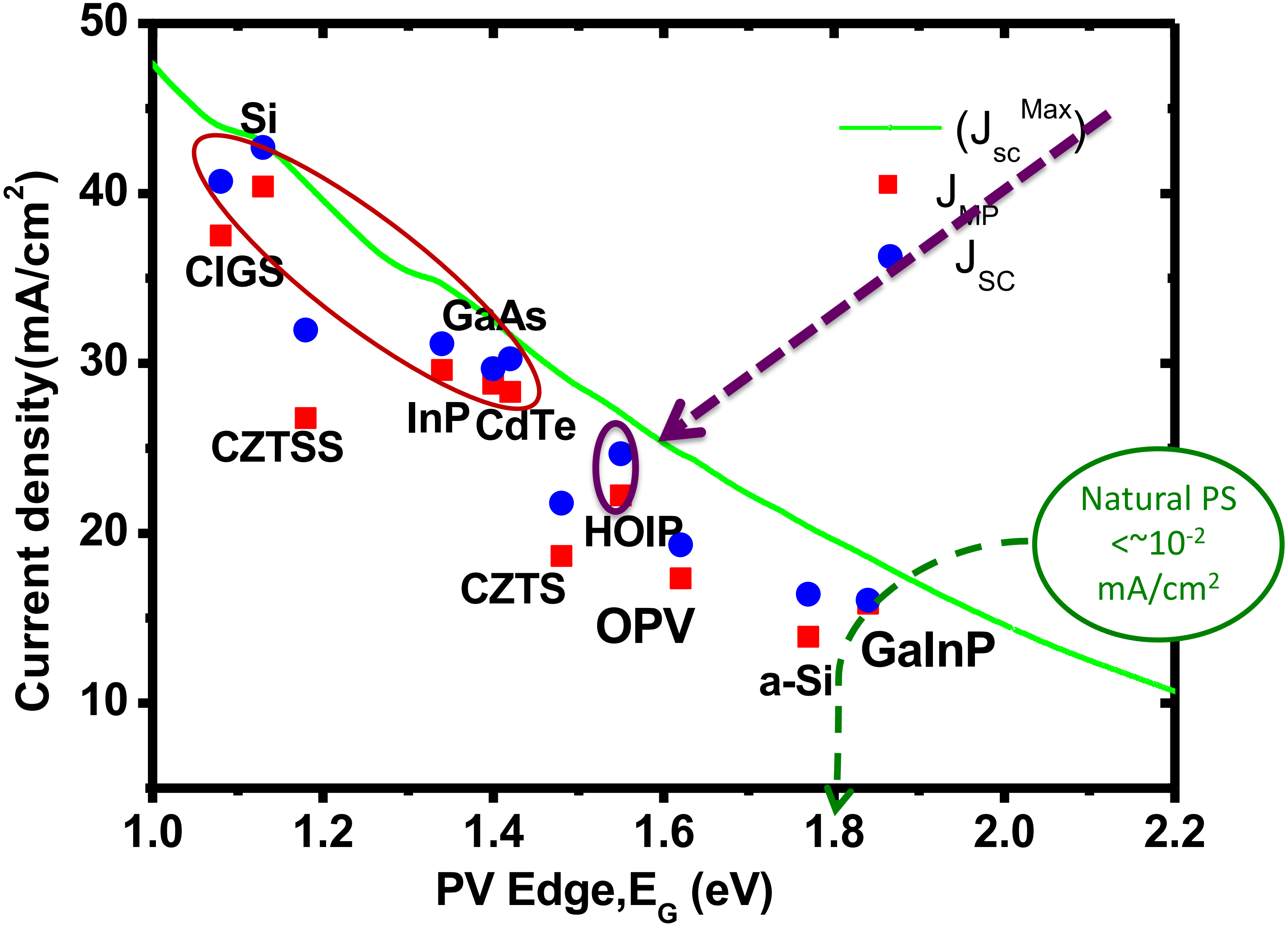
Cell type (*absorber*)	RT bandgap abs. edge [eV]	J_{sc}^{max} [mA/cm²]	**J_{sc}^{*} [mA/cm²]**	J_{sc}/J_{sc}^{max} [%]
sc-Si	1.12	43.3	**42.6**	**98** ***98***
GaAs	1.42	31.7	**29.7**	**94** ***89***
InP	1.28	36.0	**31.1**	**86** ***81***

2010 values in blue



Nayak et al. *Adv. Mater.*, 5-2011,3-2014; updated 01-2018

Maximum possible vs. experimental photocurrents



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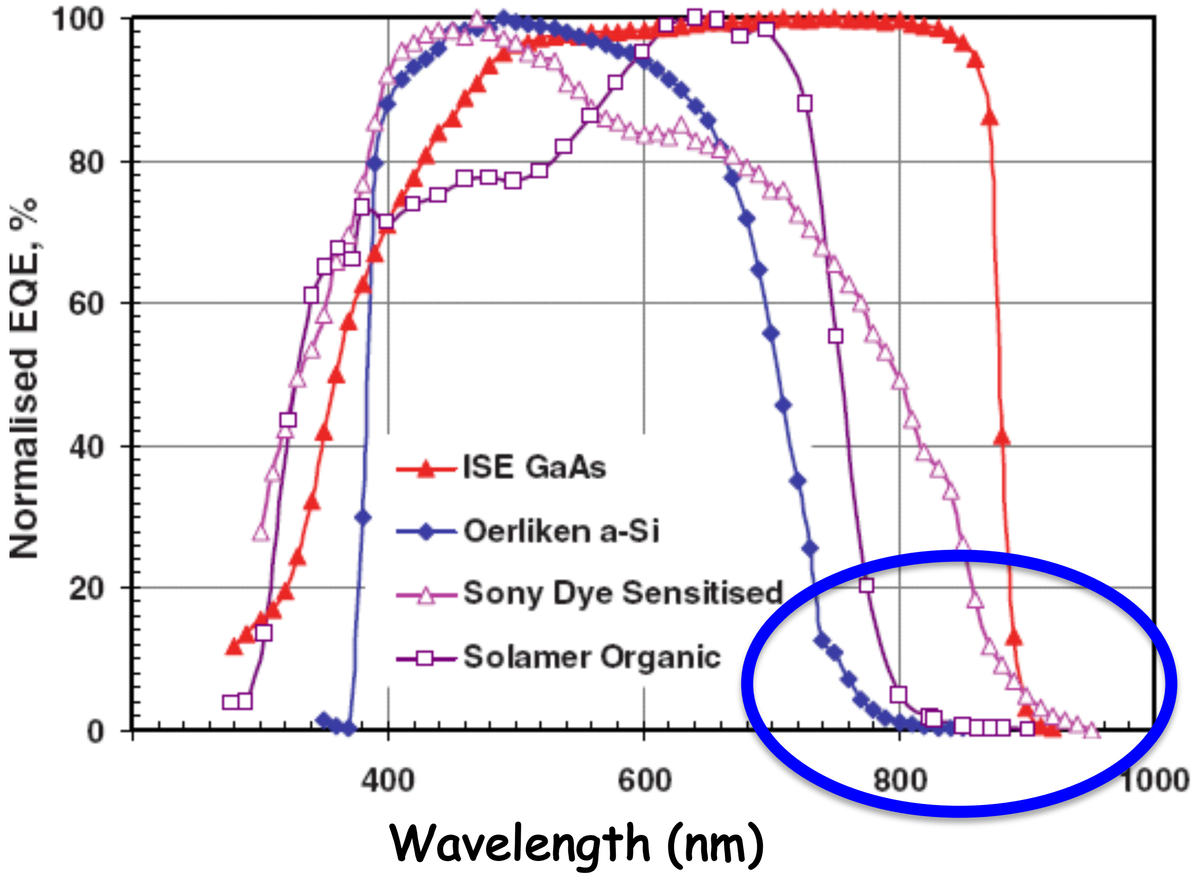
External quantum efficiency of several types of cells



In organic based solar cells EQE does not have sharp edge.
This limits current efficiency.

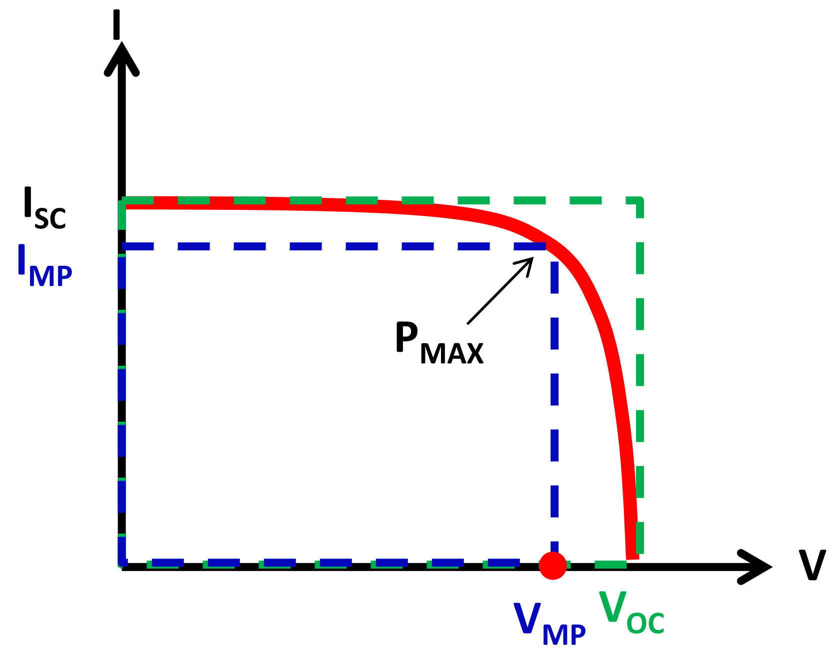
Solar Cell Eff #35, Progr. in PV, 2010

Voltage efficiency:
V_{OC}/E_G

qV_{oc} / E_G : voltage efficiency

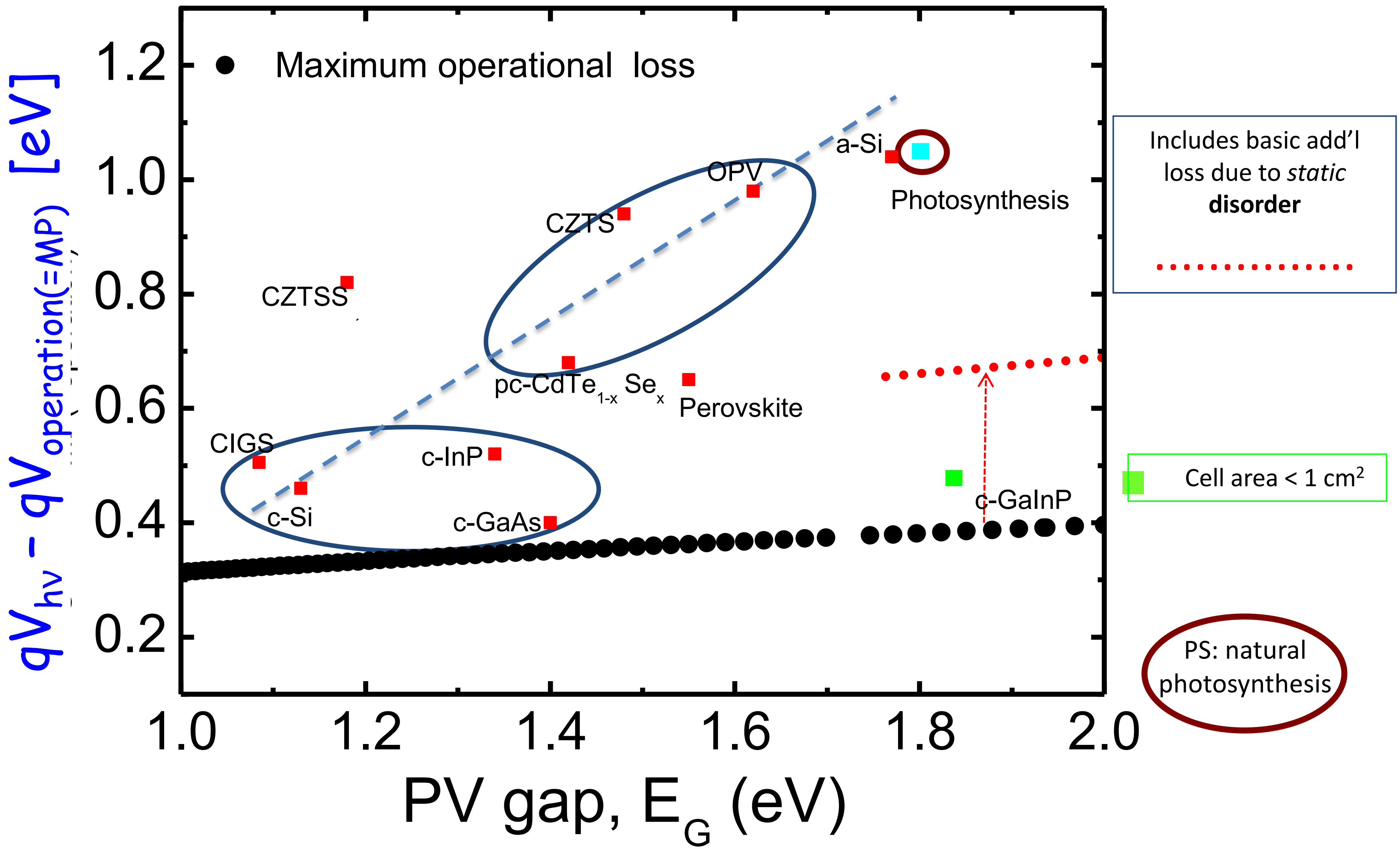
Cell type (*absorber*)	RT bandgap abs. edge[eV] [a]	V_{oc} * [V]	Voltage loss [V]	qV_{oc}/E_G [%]
sc-Si	1.12	0.74	0.39	65 ***63***
GaAs	1.42	**1.12**	**0.30**	78 ***72***
InP	1.28	0.88	0.40	69 --
[b]GaInP	1.81	1.45	0.36	80

2010 values in blue



Nayak et al. *Adv. Mater.*, 5-2011,3-2014; updated 01-2018 & TBP

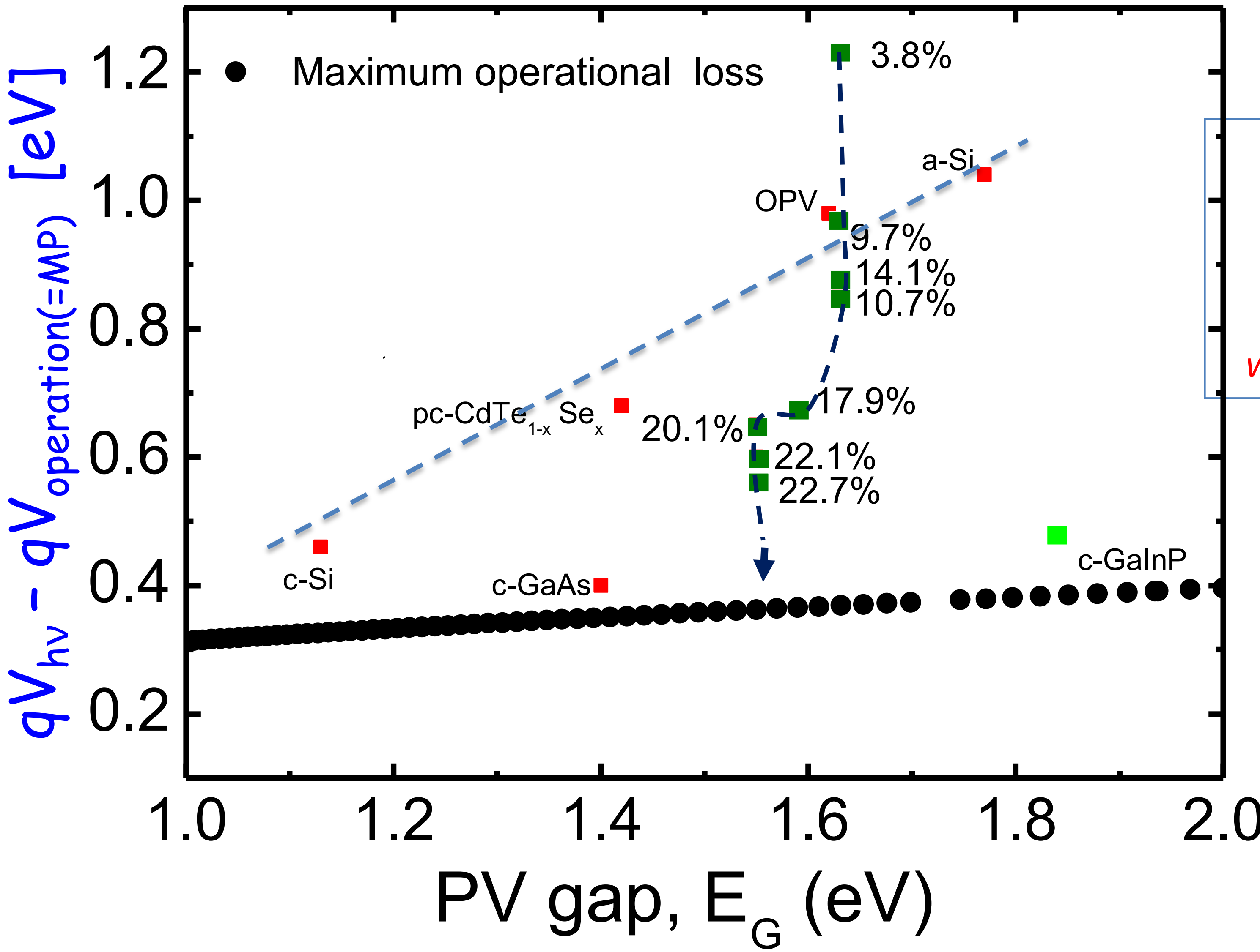
Shockley-Queisser (•) and experimental (■■) *LOSS* as function of minimal excitation energy



S-Q from R.Milo,WIS

Nayak et al. *Adv. Mater.*, 5-2011,3-2014; updated 11-2017 & TBP

Evolution of energy loss in metal halide perovskites

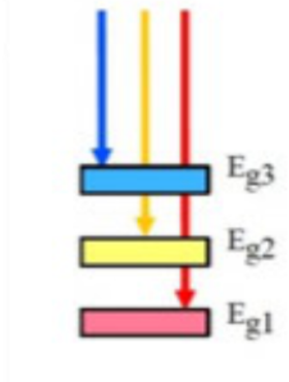


GREAT,

but, I'd say

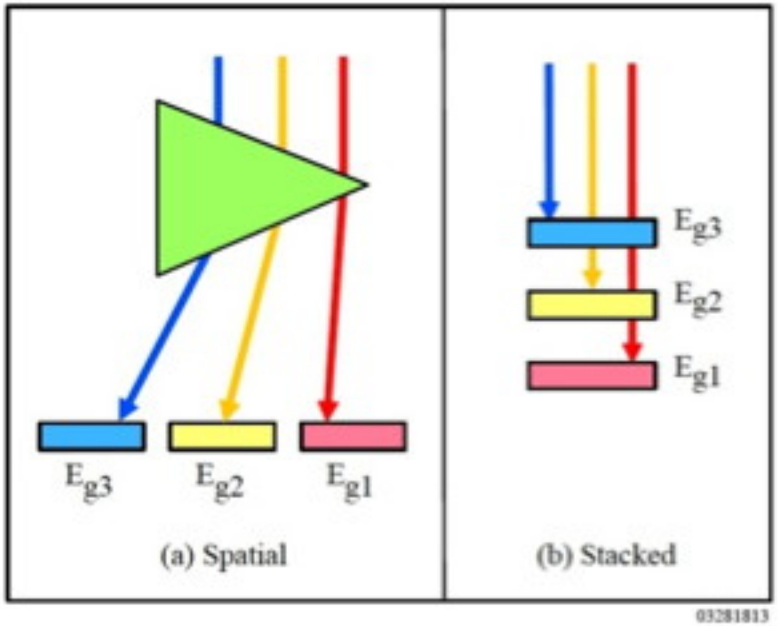
in the

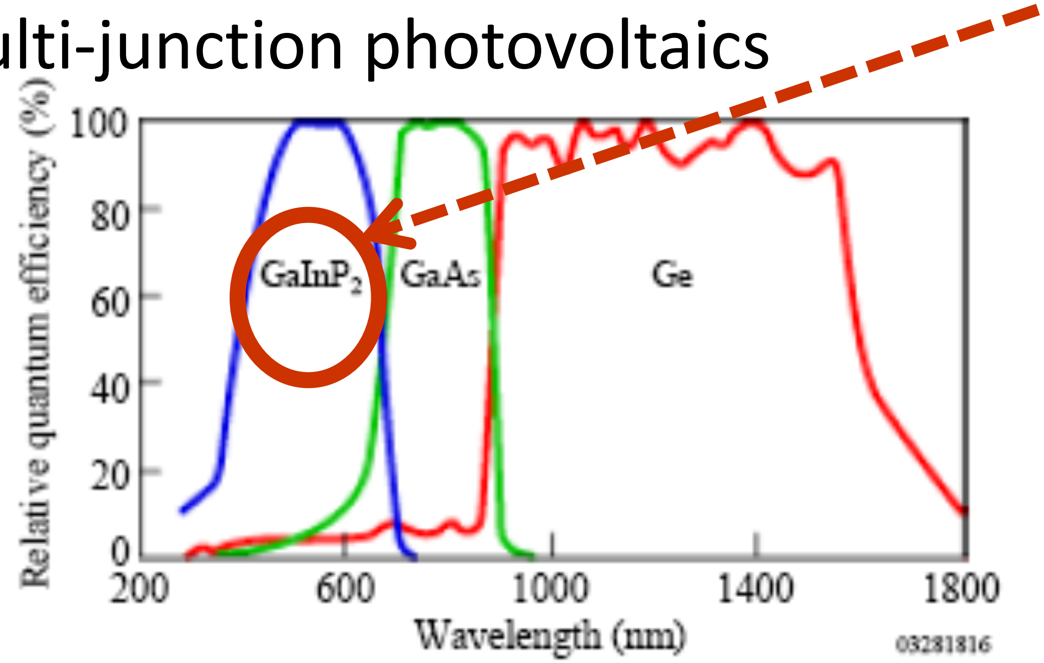
wrong direction !



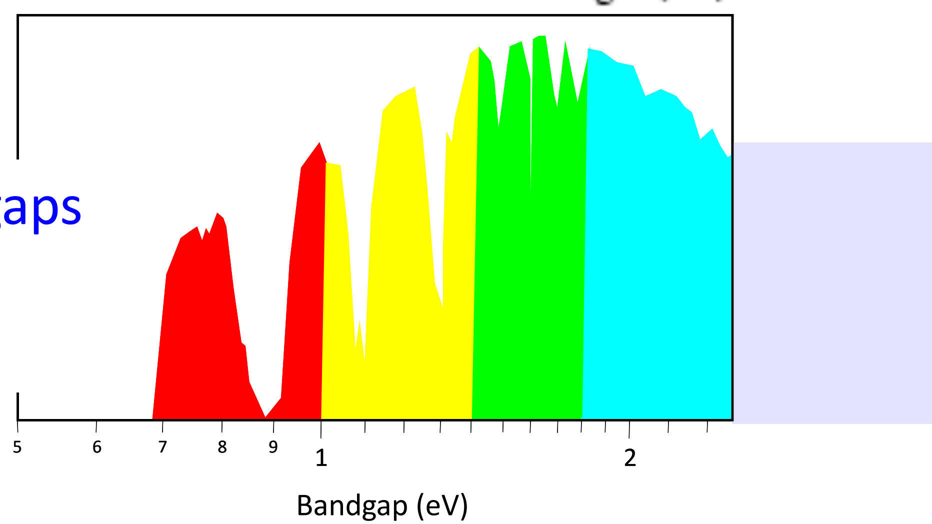
What can we do about this?

Better utilization of sunlight: Photon management: Multi-bandgap, multi-junction photovoltaics



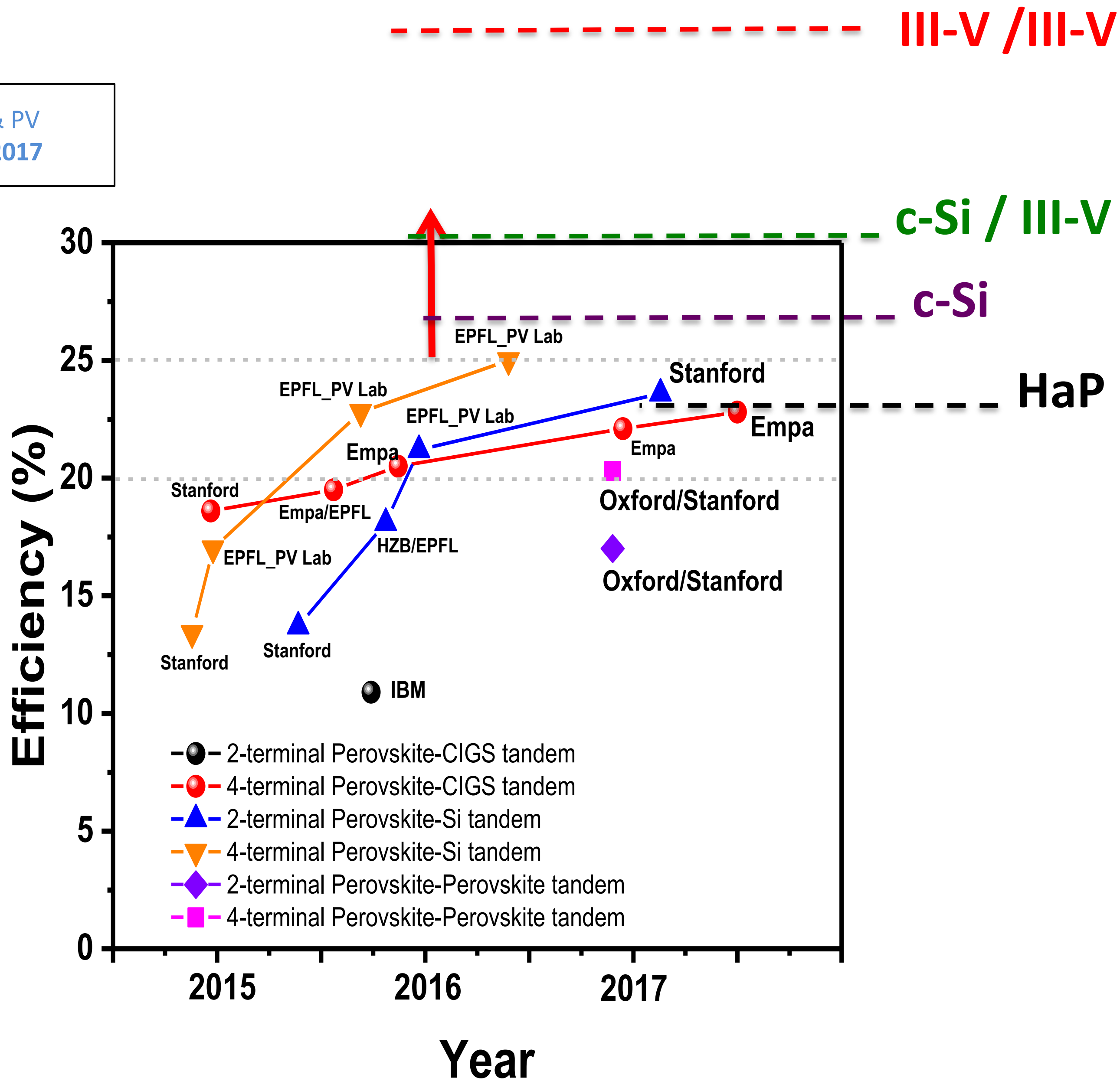


Four-junction device with bandgaps
1.8 eV/1.4 eV/1.0 eV/0.7 eV
Theoretical efficiency > 52%

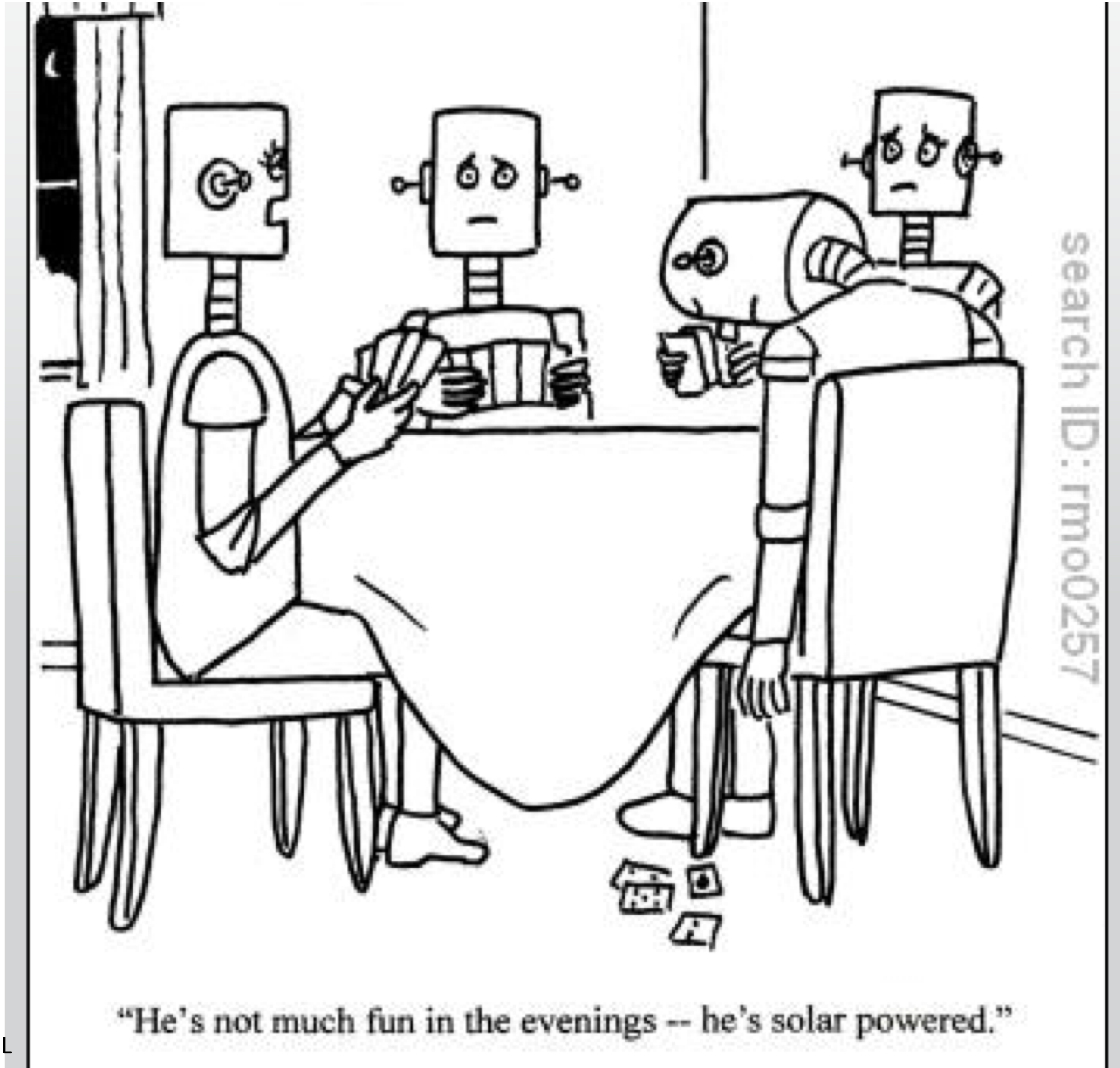


HaP-based TANDEM solar cells

EMPA Lab. for Thin Films & PV
Dr.Stephan Buecheler, 3-2017



remember…,there's more than PV



ourtesy David Ginley, NREL