Basic Limitations to Third generation PV performance

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THANKS to my COLLEAGUES

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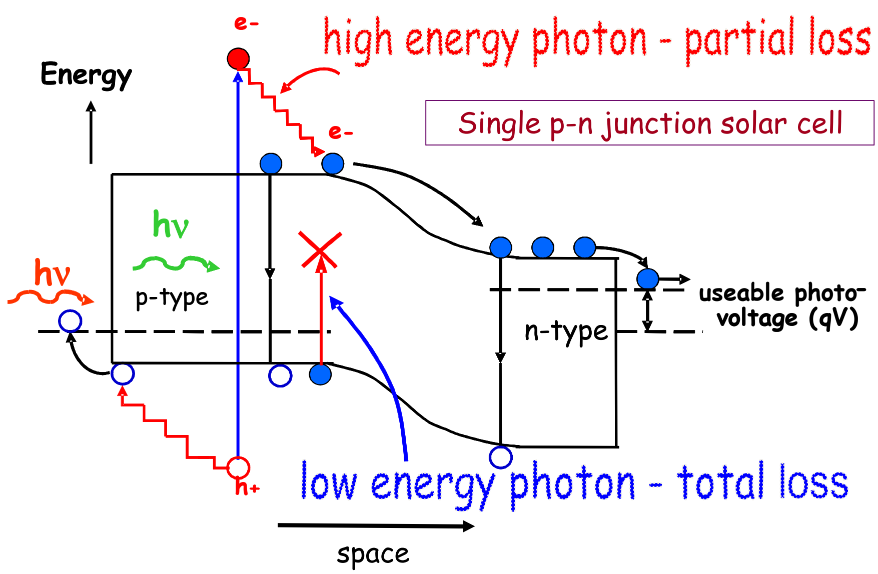
Weizmann Institute of Science

Juan Bisquert, Un. Jaume I, Spain

Antoine Kahn, Princeton University

In Solar Cells Most Solar Energy is "Lost" as Heat



Lowest Loss Laboratory PV cells ($1\text{-}4\ cm^2$):

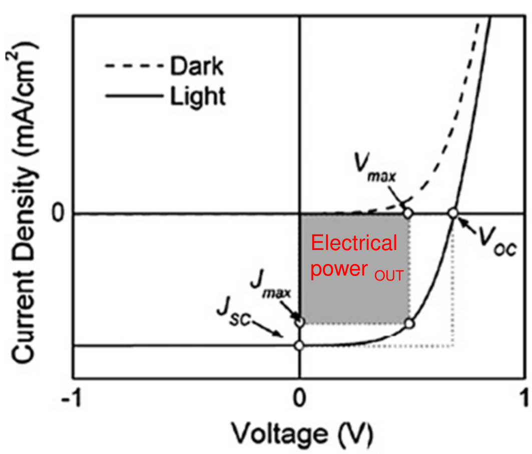
- ~ [75%] 25% **single** crystalline Si
- ~ [80%] 20 % **single** jctn. PX thin films (**CIGS**, Si)
- ~ [90%] 10.4% dye sensitized solar cells (DSSC)
- ~ [92%] 8.3 % organic polymer / molecule

Definition of efficiency:

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

Data from Solar Cell Eff #38, Progr in PV, '11

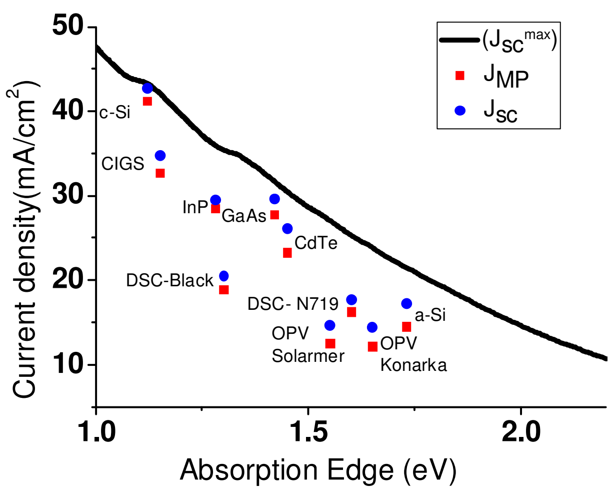
Parameters of efficiency



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

Electrical $Power_{OUT}$
$= V_{MP} \times J_{Mp}$
$= V_{oc} \times J_{sc} \times$ Fill Factor

Maximal possible vs. experimental photocurrents



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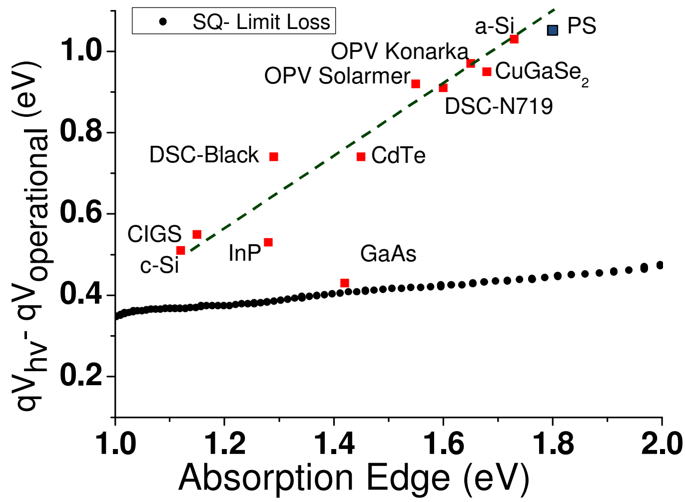
V_{MP} / E_G : Limit or Opportunity?

Cell type (*absorber*)	RT bandgap abs. edge[eV]	qV_{MP}* [eV]	Energy loss	qV_{MP}/E_G [%]
sc-Si	1.12	0.61	0.51	54
GaAs	1.42	0.99	0.43	69
InP	1.28	0.75	0.53	59
CdTe	1.45	0.71	0.74	49
$Cu(In_{\sim0.7}Ga_{\sim0.3})Se$	~1.15[a]	0.60	~0.55	52
a-Si:H	~1.73	0.70	~1.03	~40
DSSC *(black dye)* *(red N719)*	~1.3 ~1.7	0.55 0.69	~0.75 ~1.01	~42 ~41
(OPV) Solarmer *KONARKA*	~1.65 ~1.55	0.68 0.65	~0.97 0.92	~41 ~41

* for best performing cell of given type

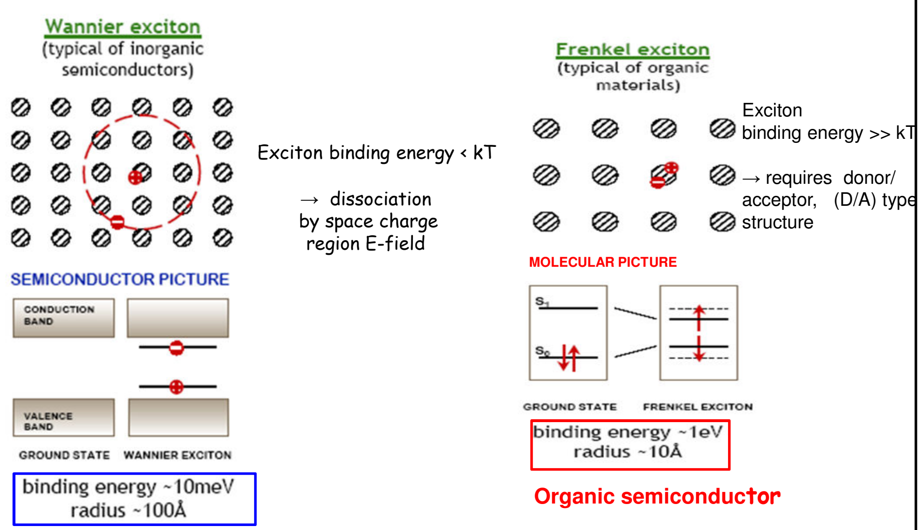
Shockley-Queisser or detailed balance limit *COST* as function of minimal excitation energy



P. K. Nayak , J. Bisquert and D. Cahen; Adv. Mater. 2011

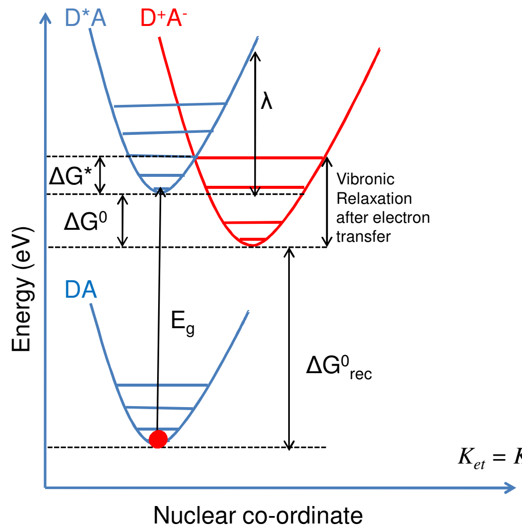
S-Q based on R.Milo,WIS

Electron-hole pair: Organic *vs.* Inorganic PV cells



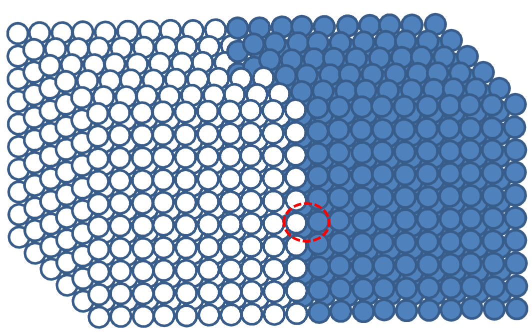
Inorganic semiconductor from A. Kahn, Princeton U

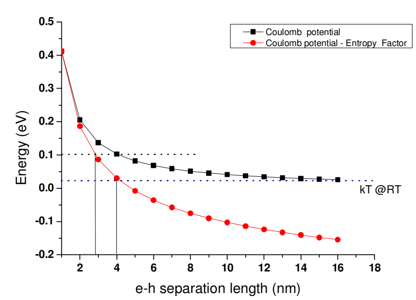
Electron transfer & Vibronic relaxation



$$K_{et} = K_o exp\ -[(\Delta G^0+\lambda)^2/4\lambda k_B T]$$

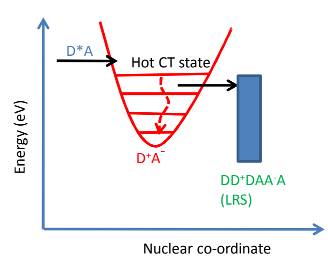
Entropy factor on dissociation



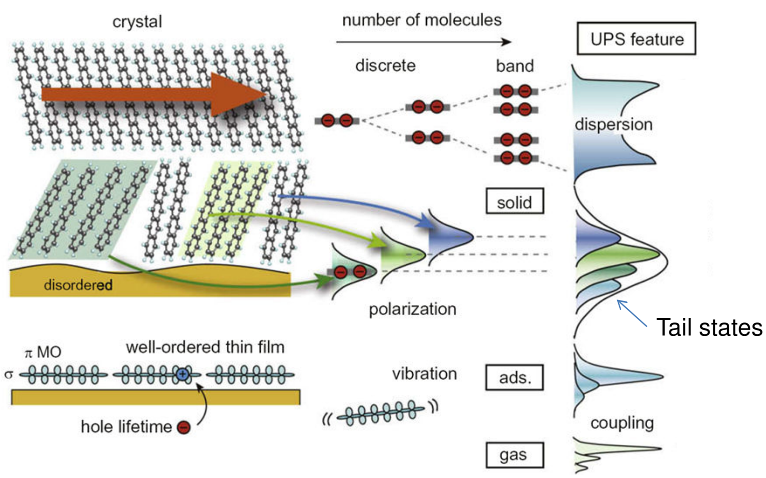


Entropy contribution = $k_B T\ln(\Omega)$

where Ω corresponds to number of available molecular pairs

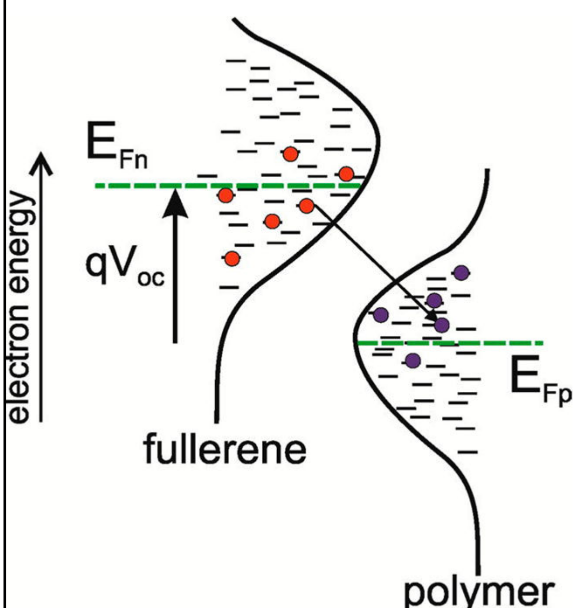


Static and Dynamic disorder



Kera, Yamane and N. Ueno ,
Progress in Surface Science, 2009

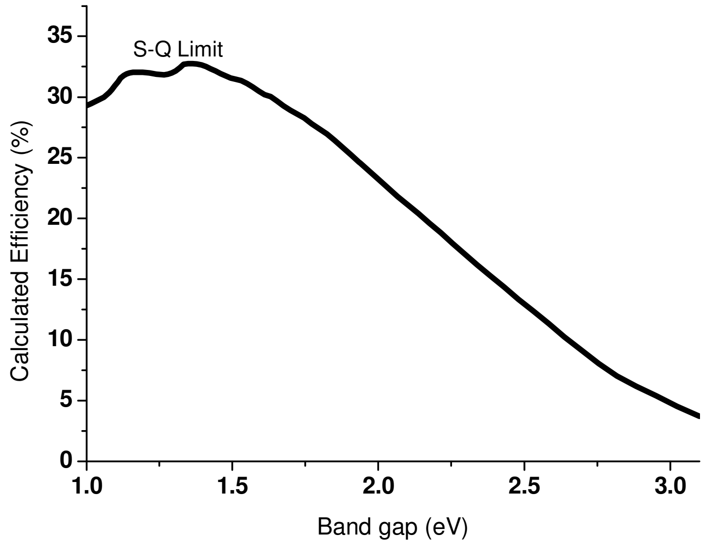
Do Tail States Matter???



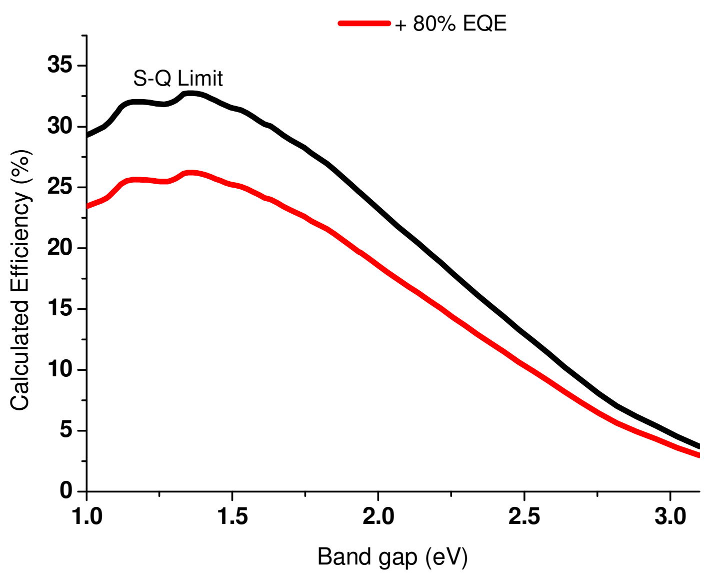
In a- Si, tail states cause a loss of ~ 0.3 V. Organic materials also show presence of tail-states, due to impurities and, esp. structural dis-order.

From **J. Bisquert, UJ, Spain**

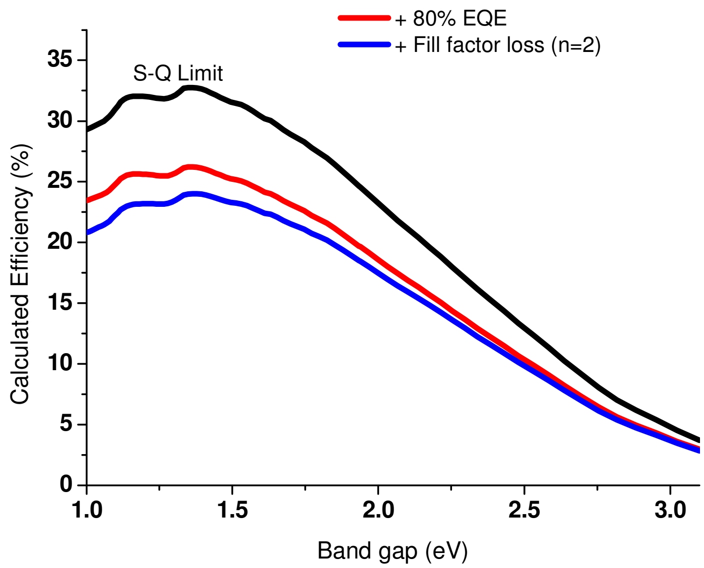
Efficiency of OPV cells



Efficiency of OPV cells



Efficiency of OPV cells



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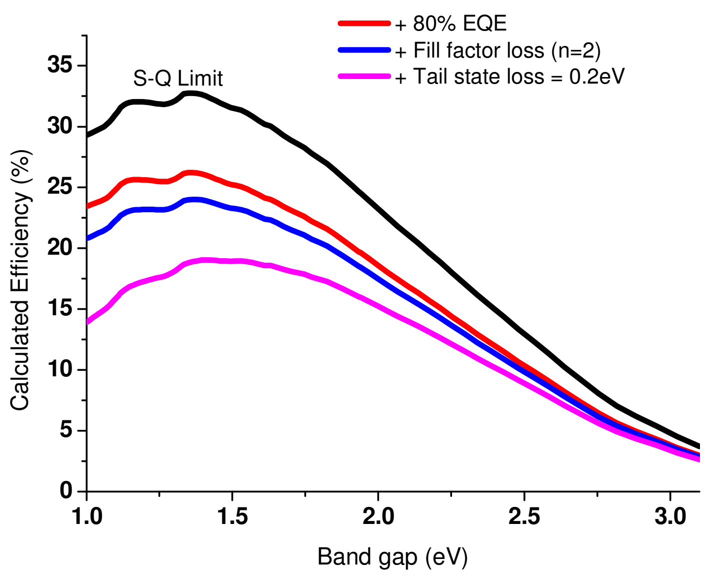
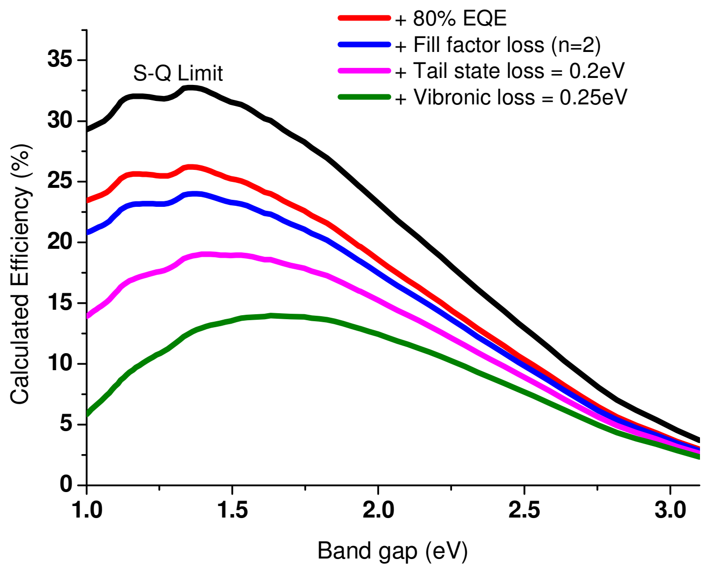
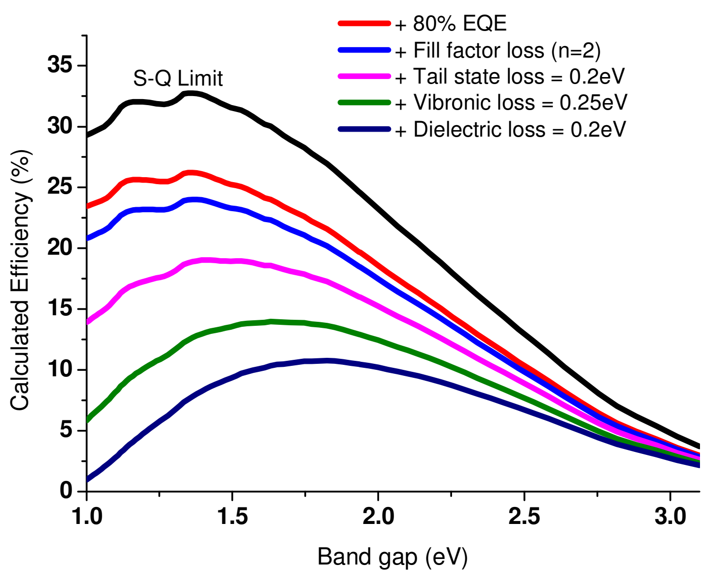


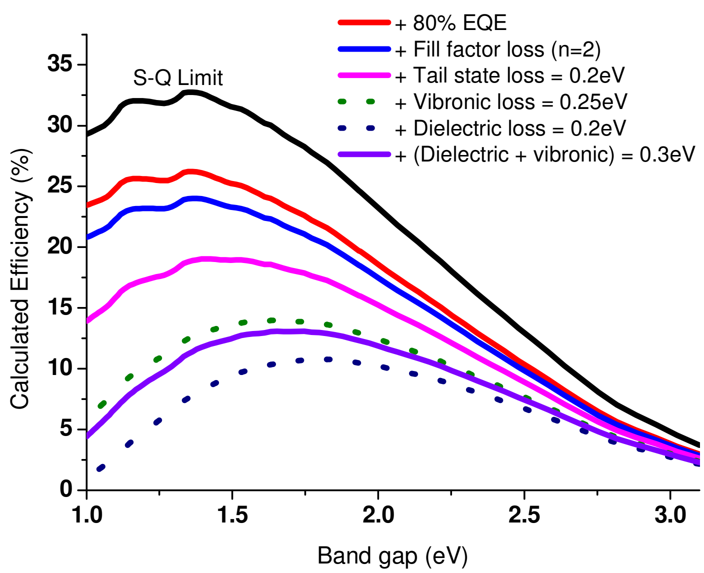
Efficiency of OPV cells



Efficiency of OPV cells



Efficiency of OPV cells



Summary

There are limits, beyond Shockley-Queisser for photo-conversion with organics (OPV, DSSC, PS, AP)

disorder	~ 0.2 eV
vibronic coupling	~ 0.3 eV
low dielectric constant	~ 0.2 eV
	Σ = 0.5 - 0.7 eV

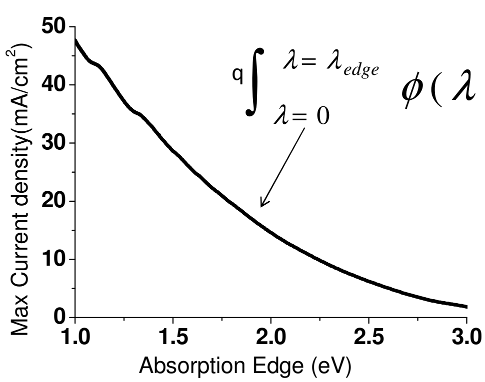
→1.35eV optimum band gap is not required for Organic systems. High(er) optical absorption edge systems should be considered.

Ways to beat those limits

- Filling the tail states with permanent dopants ?
- Smart design of materials with low vibronic loss

Thank you

Maximum current from solar cell



$$q\int_{\lambda=0}^{\lambda=\lambda_{edge}} \phi(\lambda)\,d\lambda$$

q is the elementary charge, λ is the wavelength, and Φ is photon flux (AM 1.5)

V_{oc} / E_G : Limit or Opportunity ?

Cell type (*absorber*)	RT bandgap abs. edge[eV]	V_{oc} [V]	Voltage loss [V]	qV_{oc}/E_G [%]
sc-Si	1.12	0.71	0.41	63
GaAs	1.42	1.03	0.40	72
InP	1.28	0.88	0.40	69
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a-Si:H	~1.73	0.88	~0.85	~51
DSSC *(black dye)* (*red N719*)	~1.3 ~1.7	0.72 0.85	0.58 0.85	~55 ~50
Org.polymer Konraka solarmar	 ~1.65 ~1.55	 0.81 0.76	 0.84 0.79	 ~49 ~49

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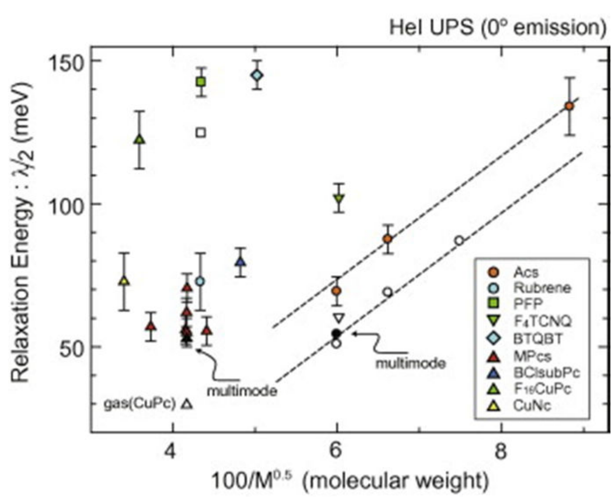

Current Types of PV Devices

Primarily based on solid-state electronic material systems

(non) concentrator; single-& multi-junction

homo- & hetero-junction; MIS

- Elemental Semiconductors
  - Single or multi-crystal
  - Polycrystalline
  - Amorphous thin film

Si, Ge

- Inorganic Compound Semiconductors
  - Single crystal
  - Polycrystalline thin film

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

- Organic, Excitonic (molecules, polymer)
  - Polycrystalline
  - Interpenetrating network
  - Nanocrystalline; dye-sensitized

P3HT-PCBM
Ru-dye+TiO_2

Solar Cell (r)evolutions