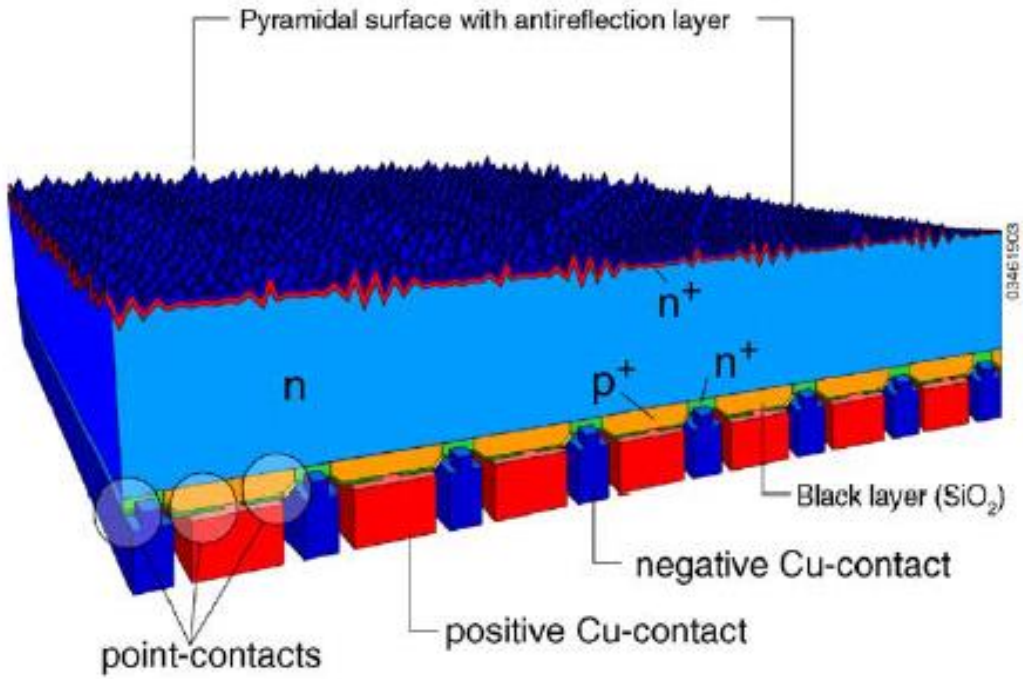
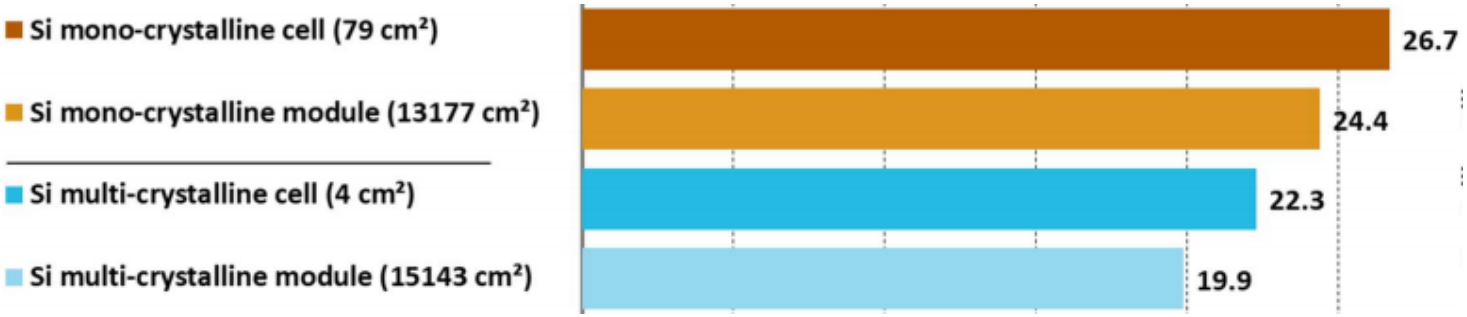
Where are we?

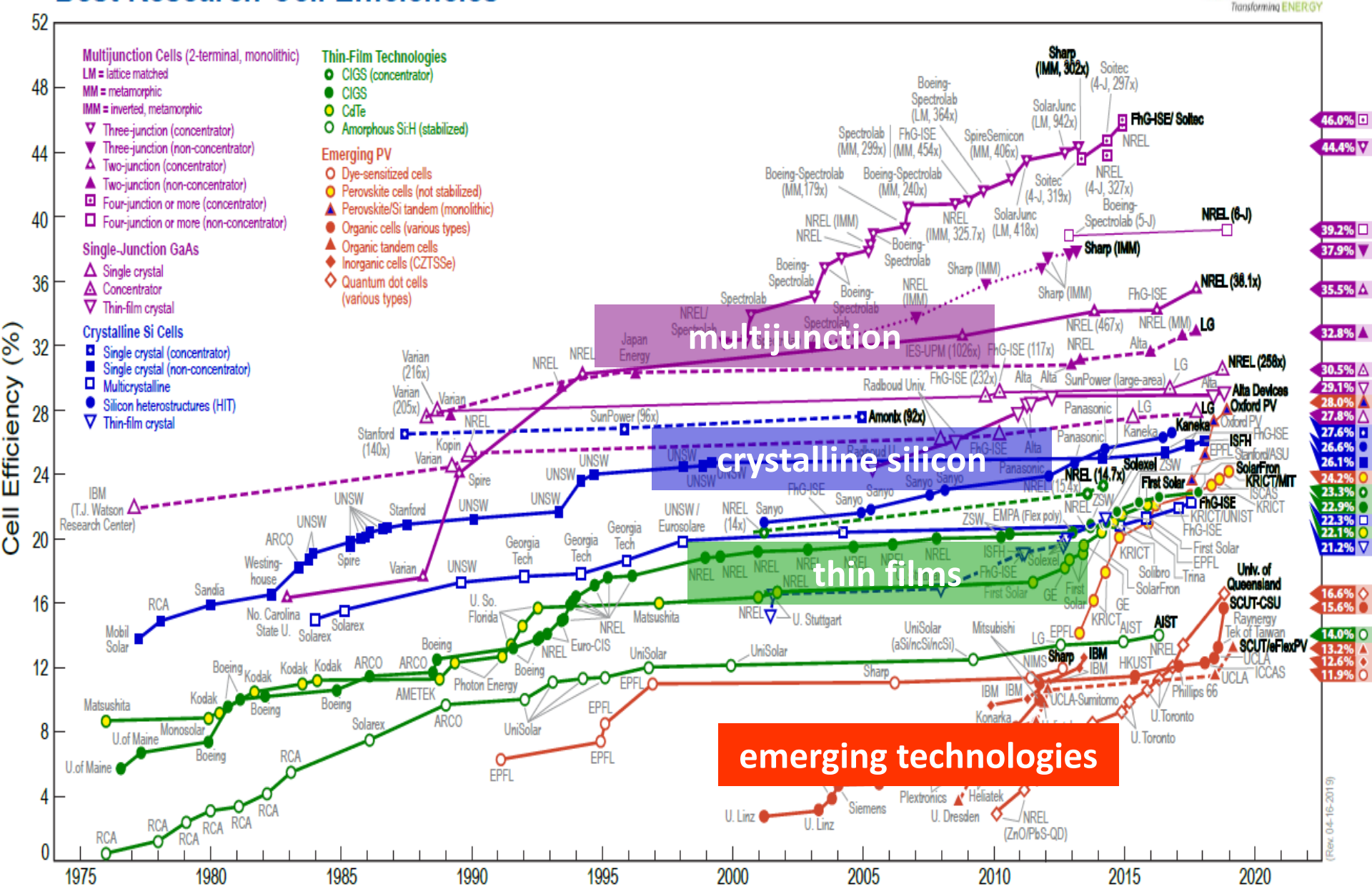




Green et al.: Solar Cell Efficiency Tables (Version 53), Progress in PV: Research and Applications 2018

Best Research-Cell Efficiencies

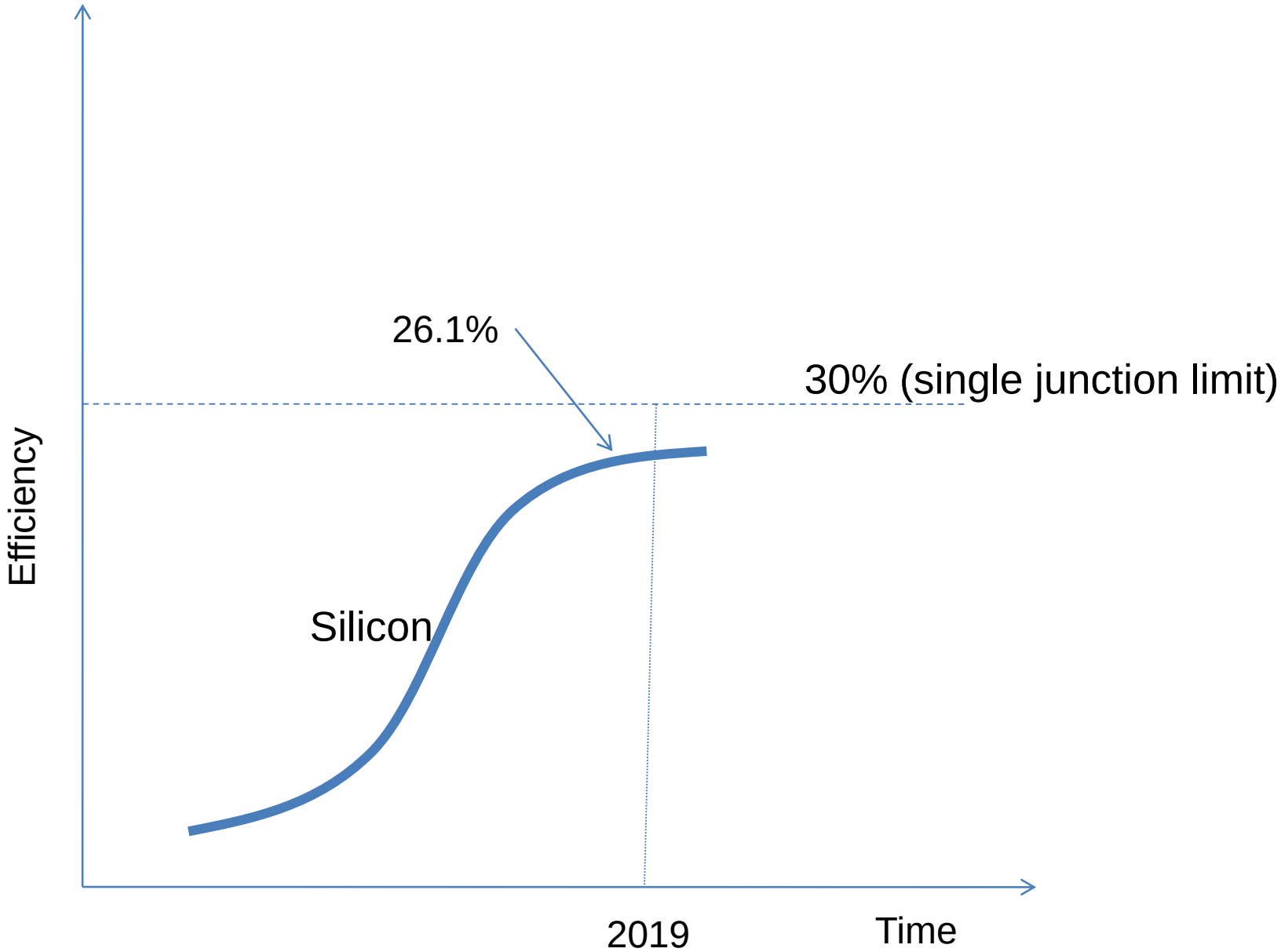
NREL
Transforming ENERGY



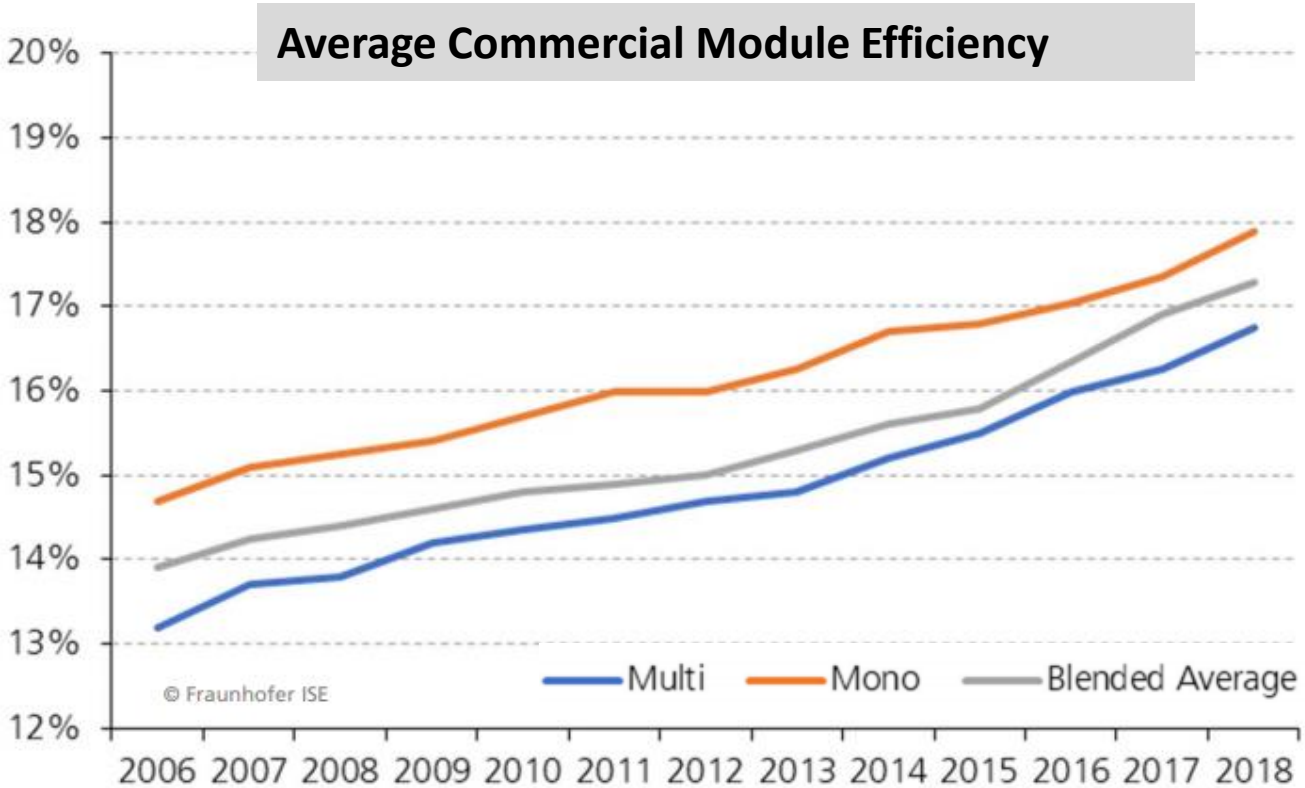
Photovoltaic technologies: state of the art

1. Commercial technologies

Technical evolution and growth potential

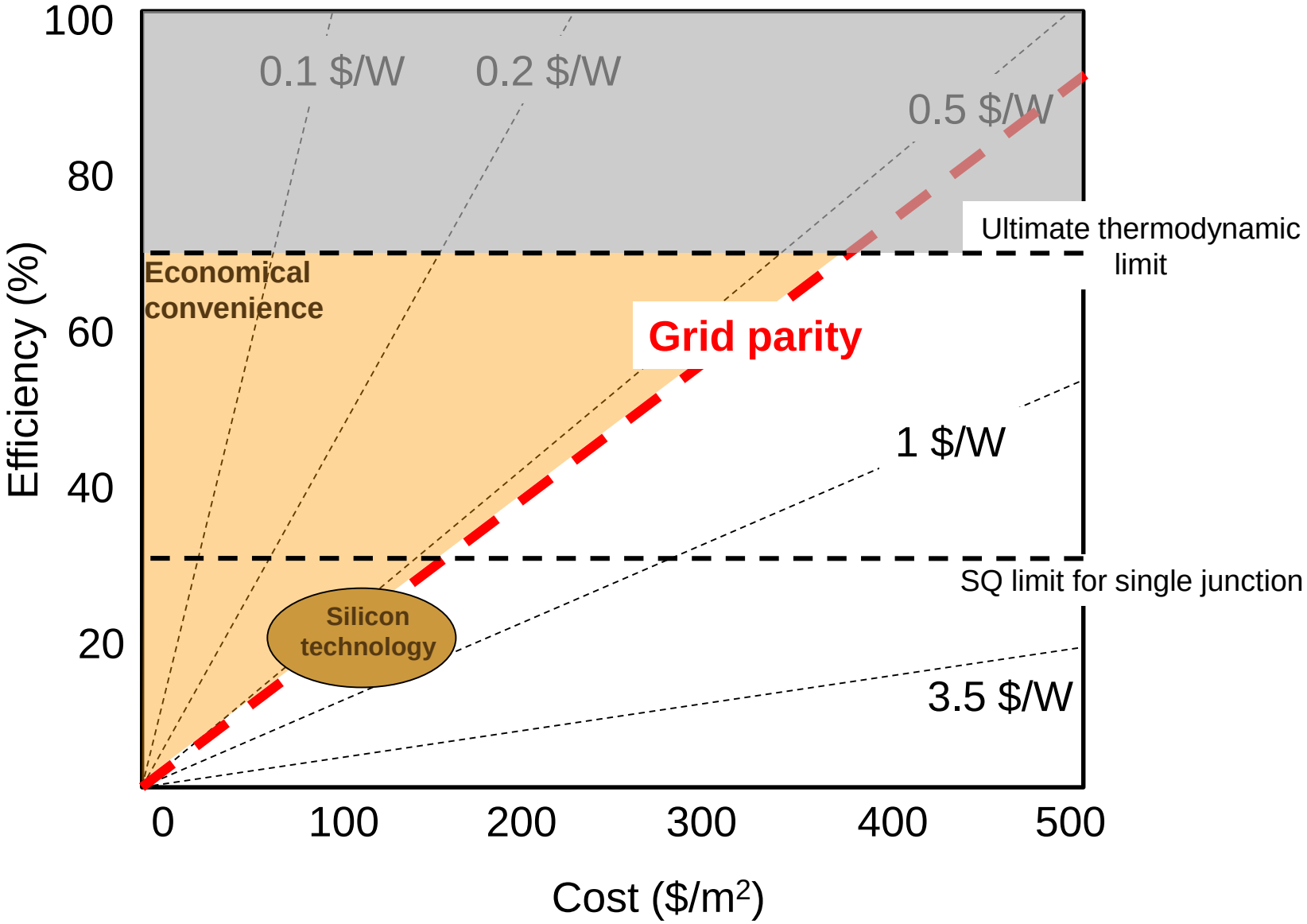


Crystalline silicon modules

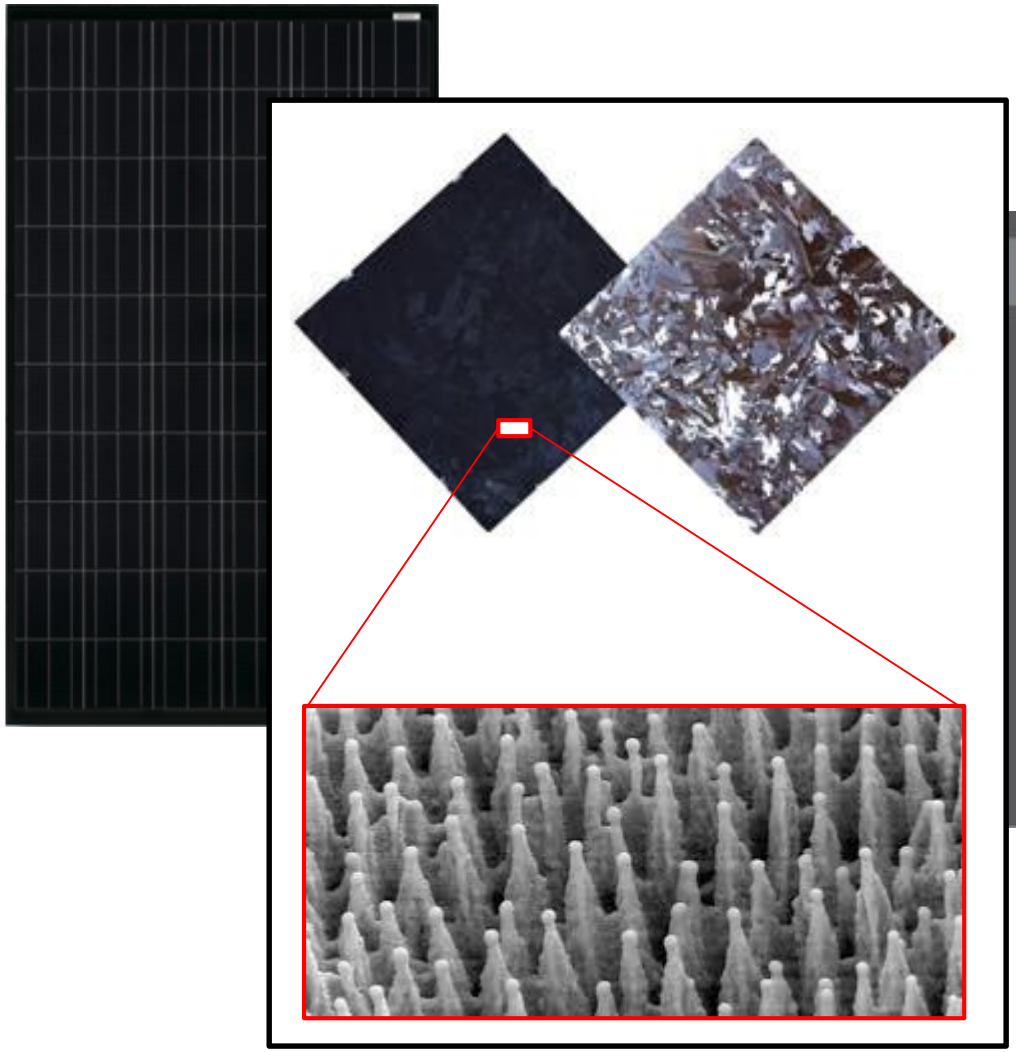


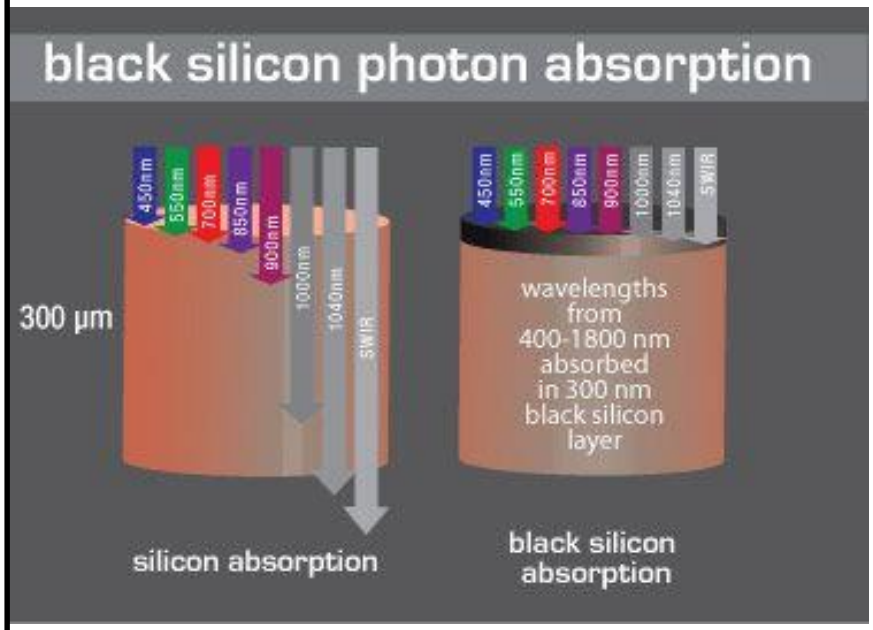
Crystalline silicon modules

- Techno-economic positioning -



New silicon-based commercial technologies: «Black» silicon





€/kWh reduction driver: higher efficiency at constant cost

JA Solar, inc.

New silicon-based commercial technologies:

Bifacial technology

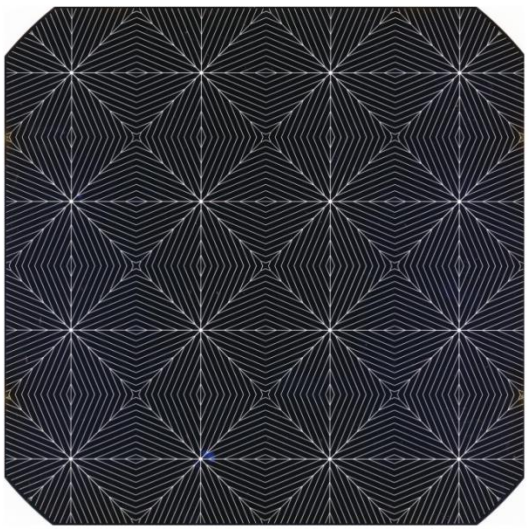
€/kWh reduction driver: higher collection area at constant cost

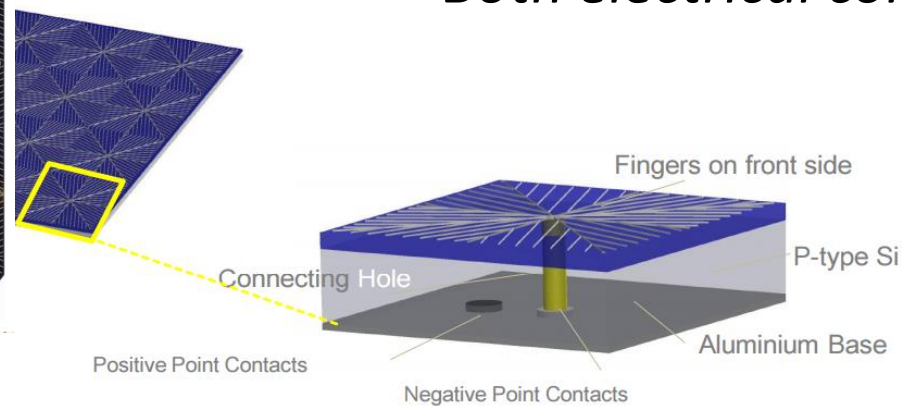
bSolar, inc.

New silicon-based commercial technologies:

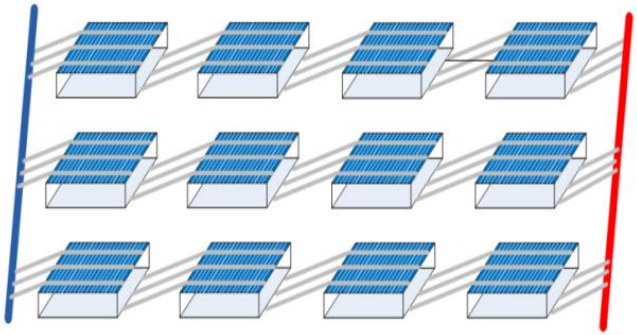
MWT Metal Wrap-Through

Both electrical contacts in the back

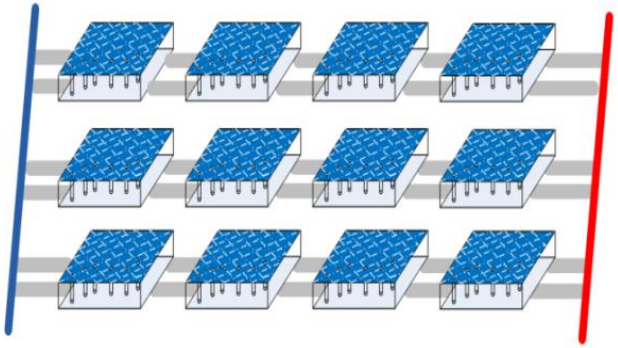




Standard module



Module based on MWT



€/kWh reduction driver: lower manufacturing cost at constant efficiency

Best Research-Cell Efficiencies

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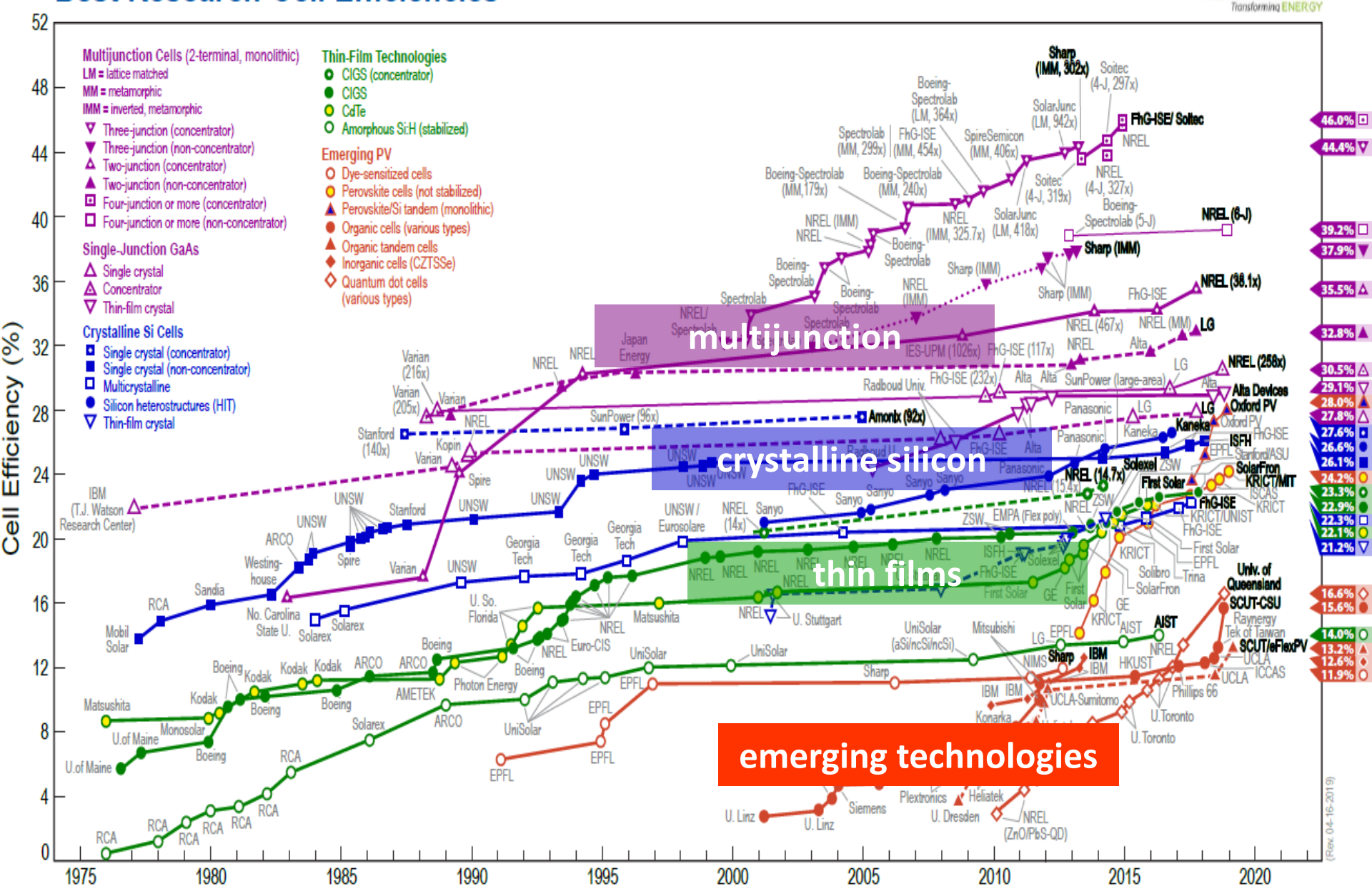
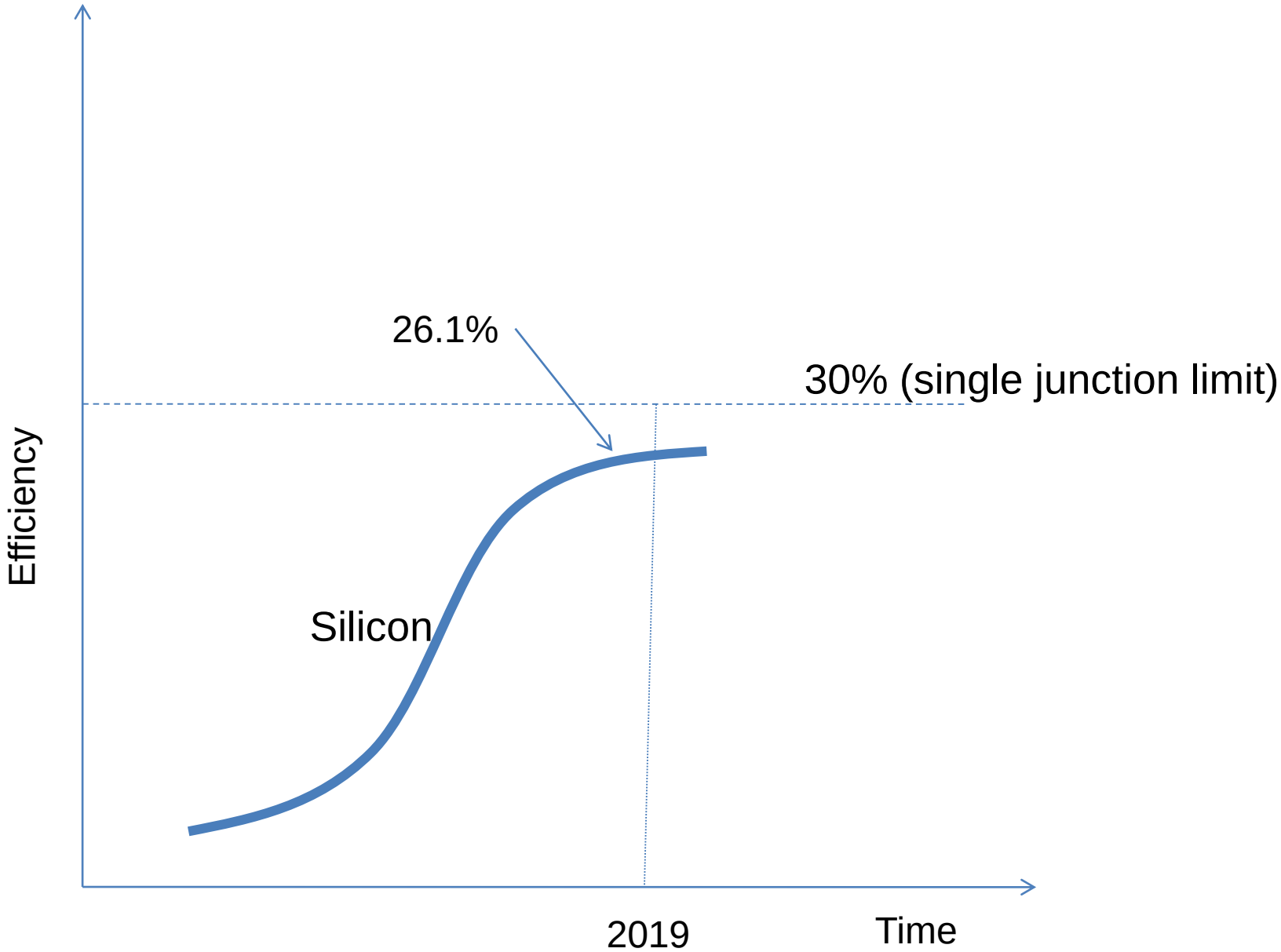
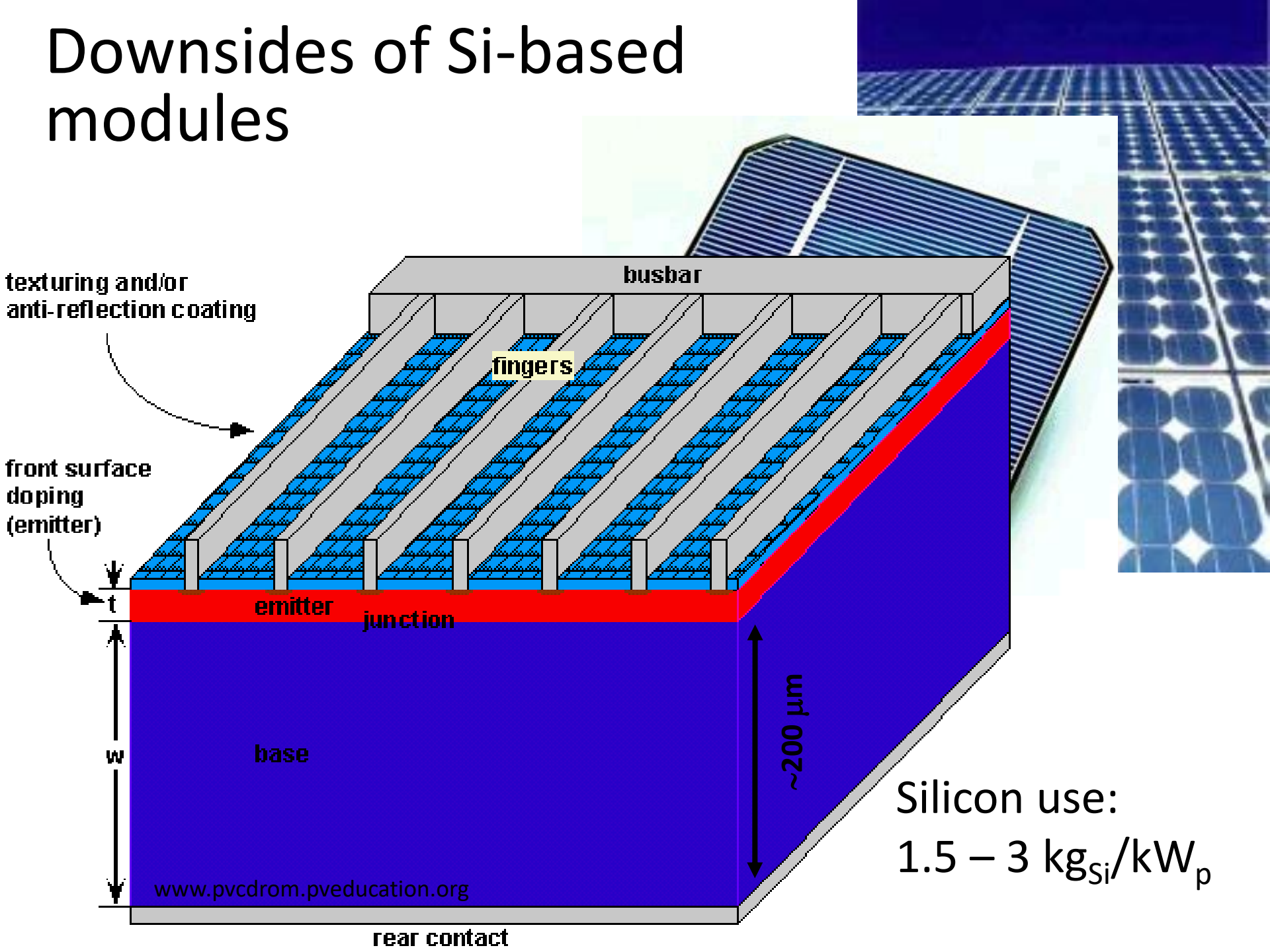


Technical evolution and growth potential



Downsides of Si-based modules

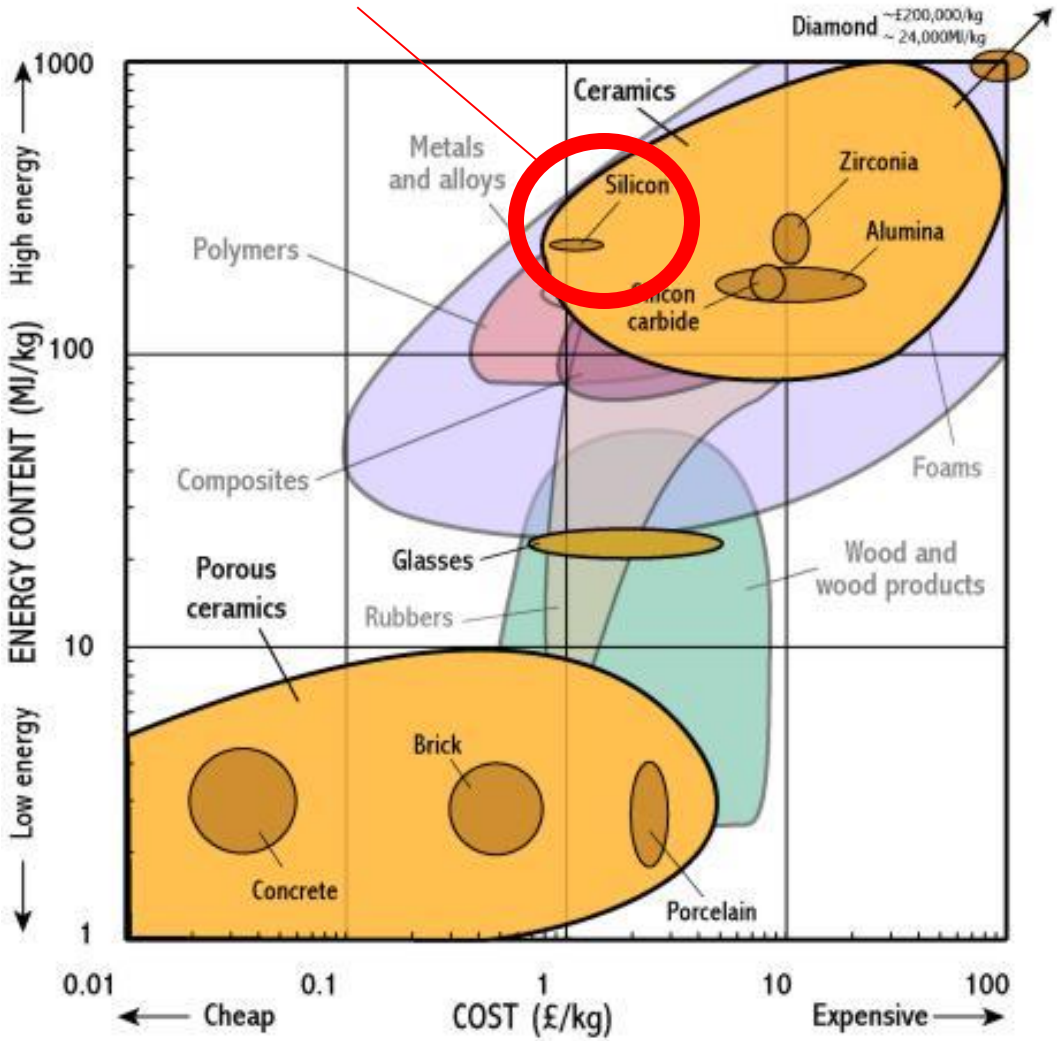


Silicon use:

1.5 – 3 kg_{Si}/kW_p

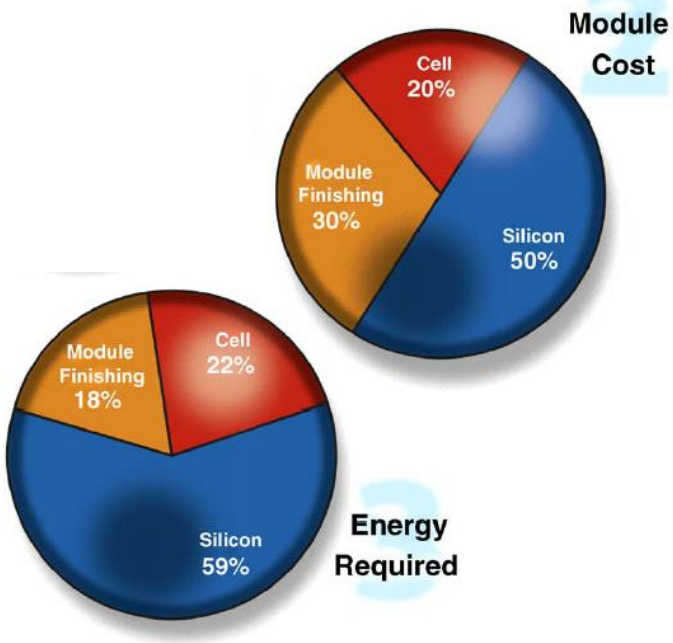
Silicon costs money and energy

Energy cost is high!



Incidence of silicon cost on the module energy and monetary cost:

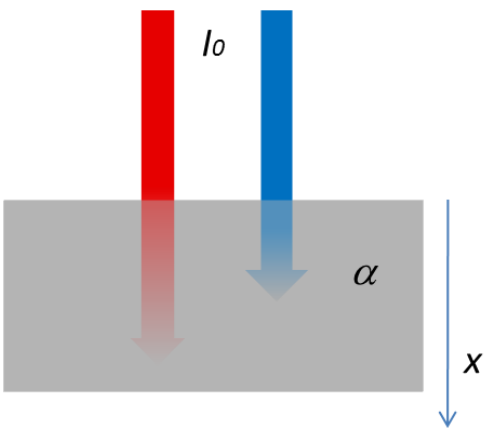
> 50%

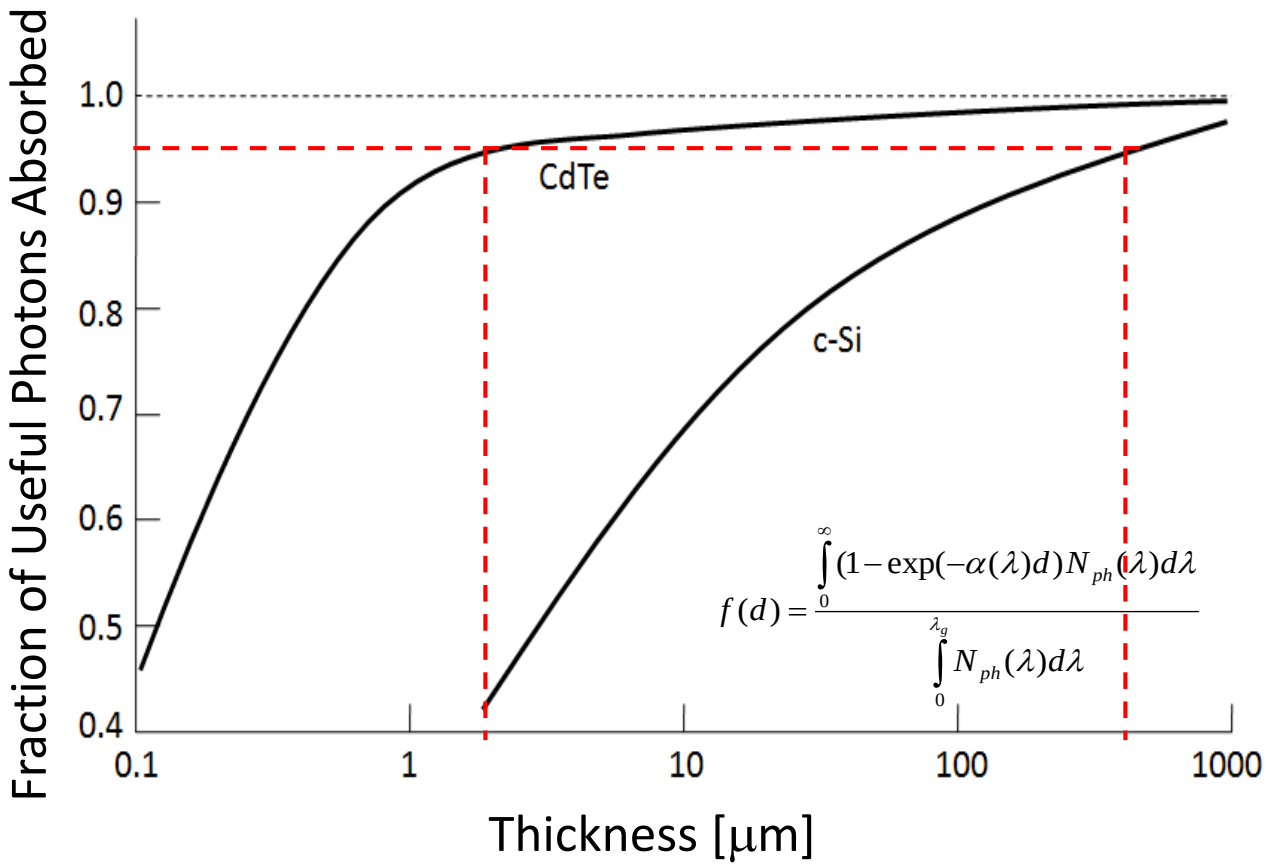


Thin film technology

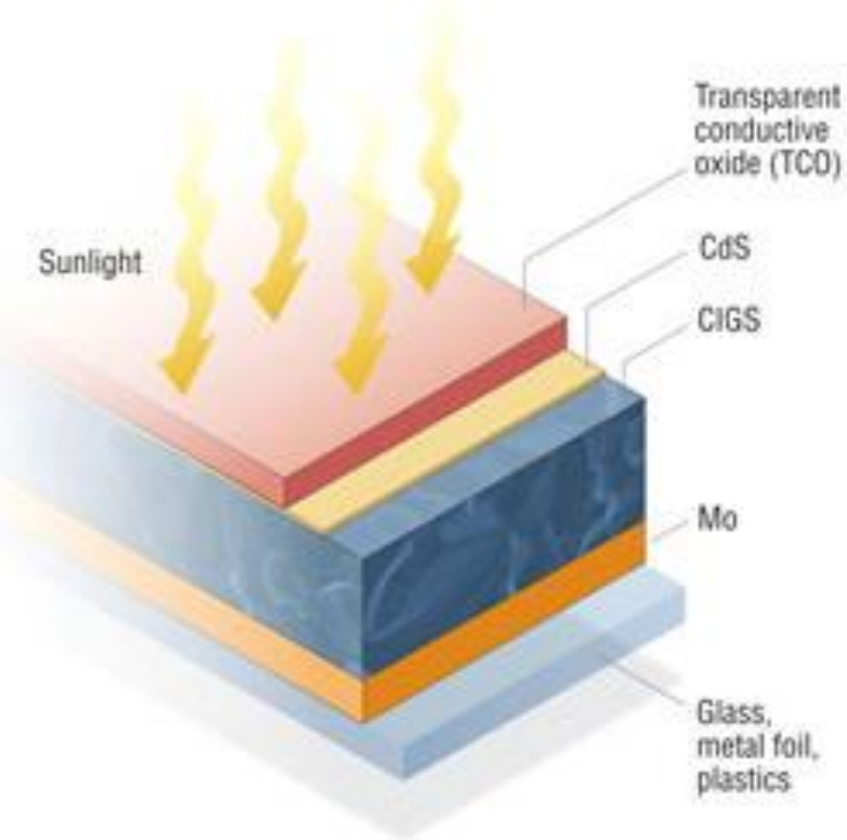
- Based on materials with better light absorption properties-

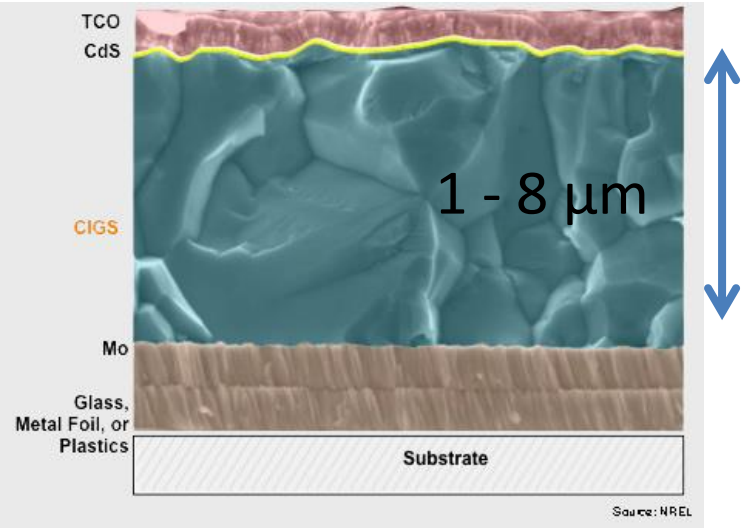
$I = I_0 \exp(-\alpha x)$





Thin film technology: CIGS, a-SI, CdTe

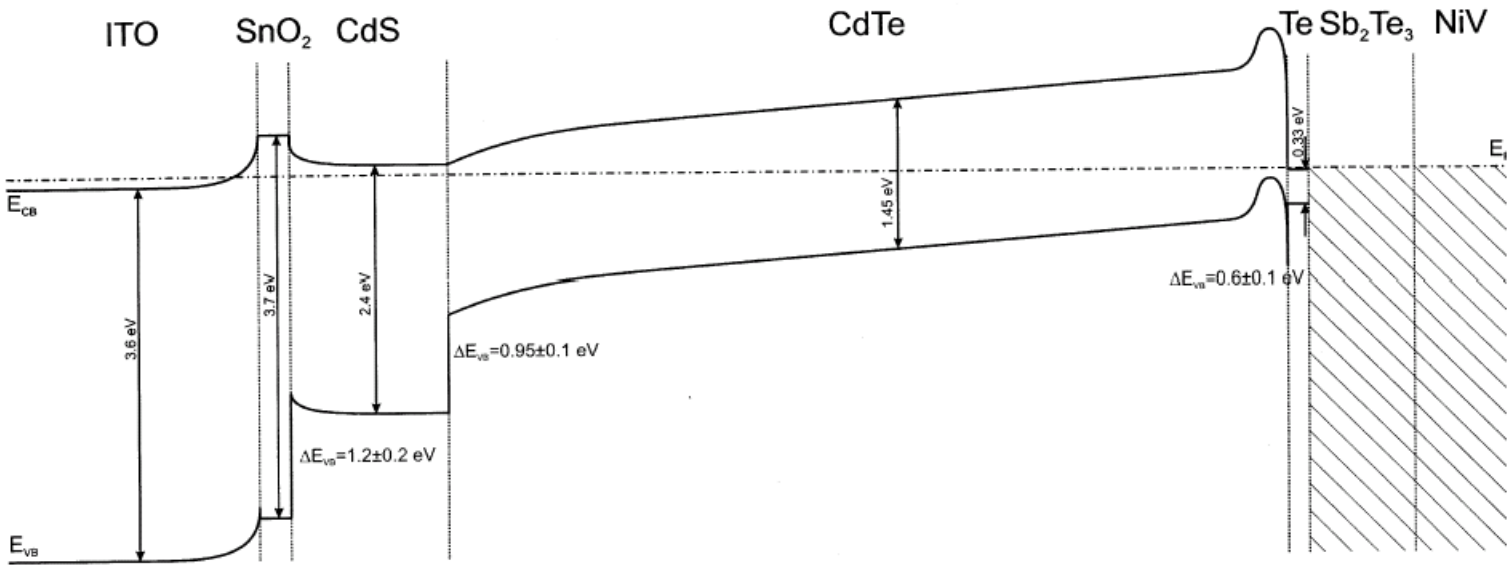




CIGS:
- Solar Frontier, inc.
- Solibro, GmbH
- Miasolé, ltd.
- ... (several global companies)...

CdTe:
- First Solar, inc.

a-Si
- Sharp, inc.
- Sunerg, srl


ITO
SnO2
CdS
CdTe
Te
Sb2Te3
NiV
ECB
EVB
3.6 eV
3.7 eV
2.4 eV
1.45 eV
0.33 eV
ΔEvb=1.2±0.2 eV
ΔEvb=0.95±0.1 eV
ΔEvb=0.6±0.1 eV

Thin film technology:

aesthetics, building integration, reduction of installation cost

Thin film technology: CIGS, a-SI, CdTe

- cost comparison with silicon-based modules -

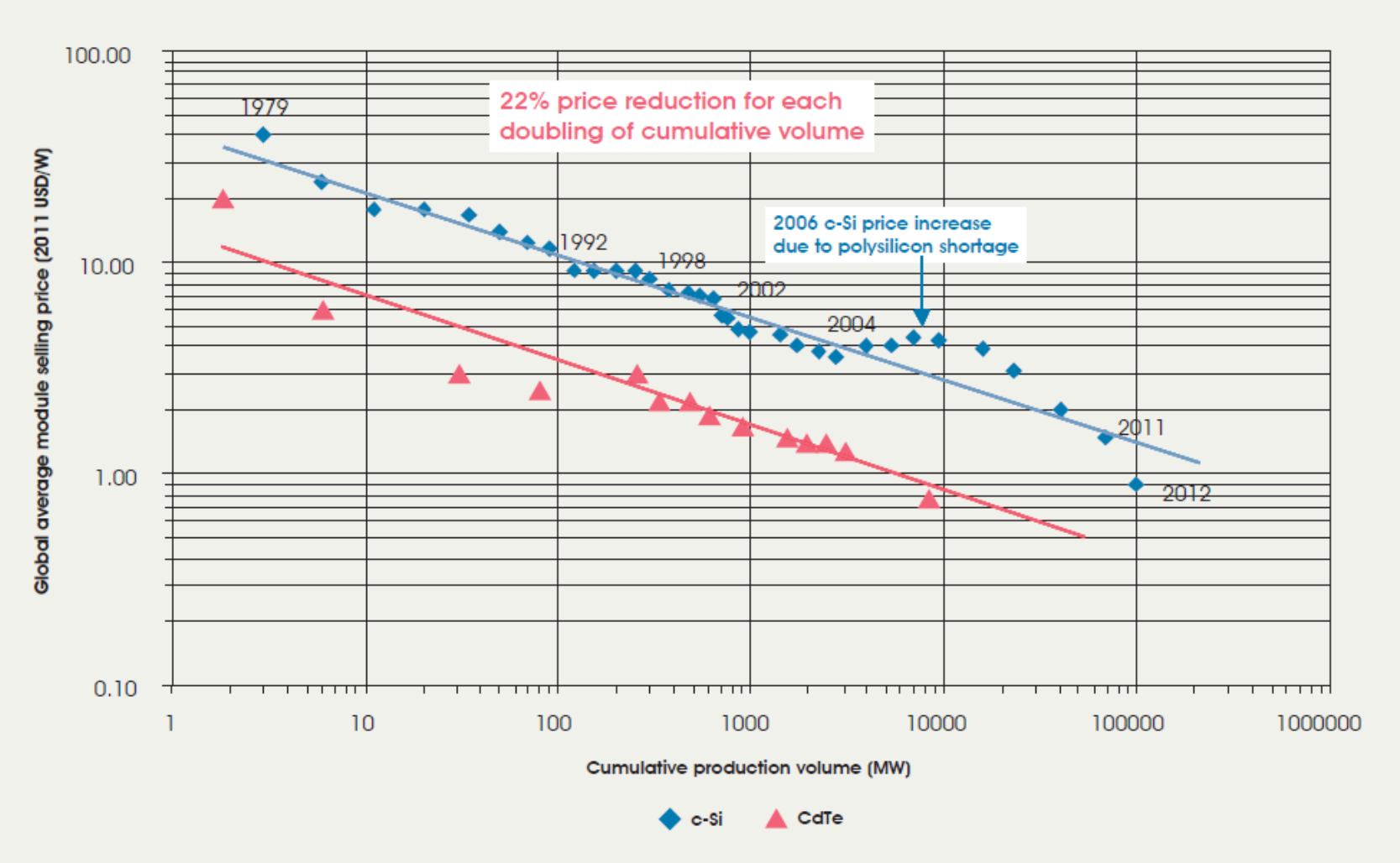


FIGURE 6.2: SOLAR PV MODULE COST LEARNING CURVE FOR CRYSTALLINE SILICON AND THIN-FILM

SOURCE: BASED ON DATA FROM EPIA AND PHOTOVOLTAIC TECHNOLOGY PLATFORM, 2011; LIEBREICH, 2011; SOLOGICO, 2012 AND IRENA ANALYSIS.

Best Research-Cell Efficiencies

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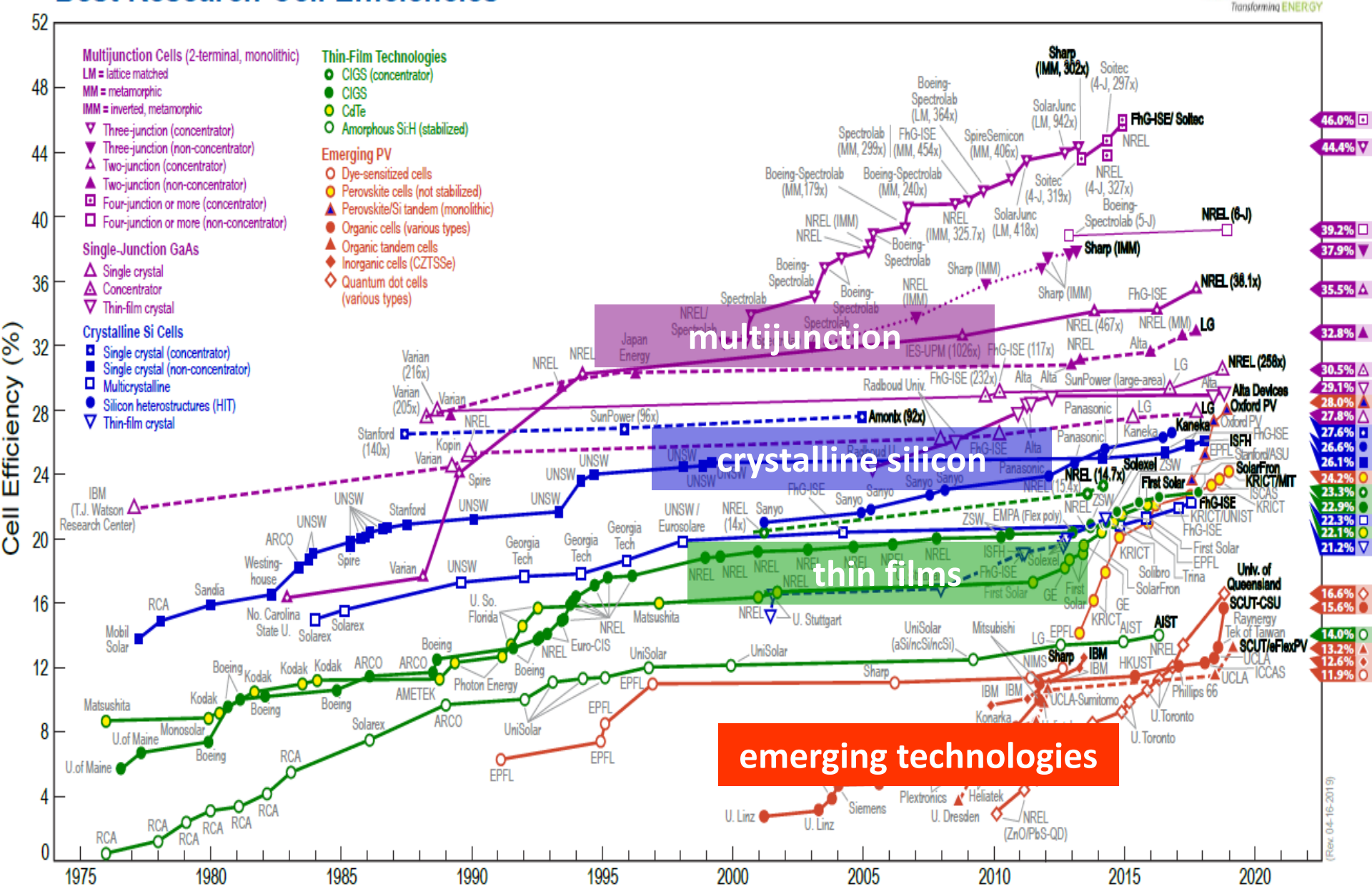
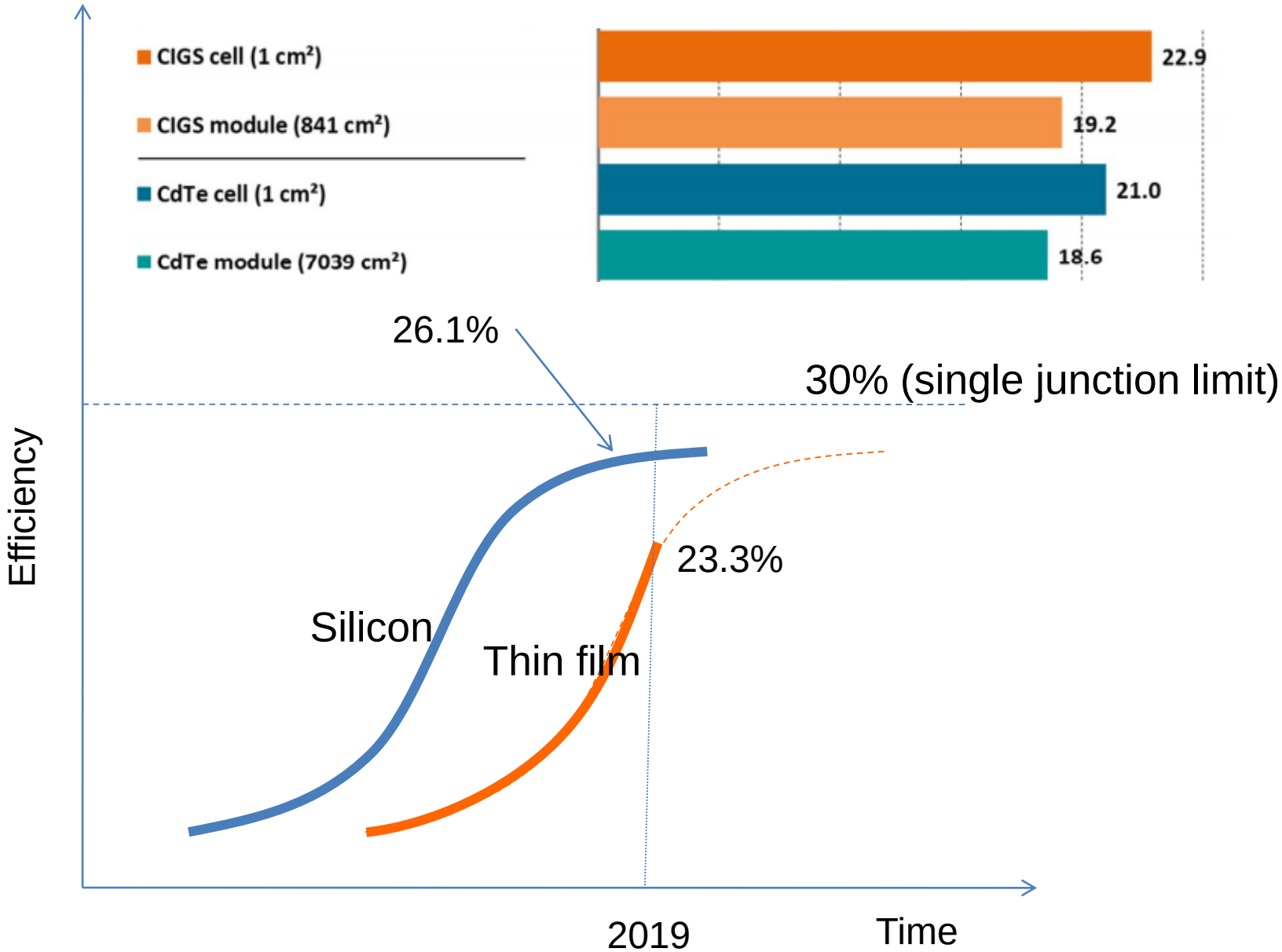
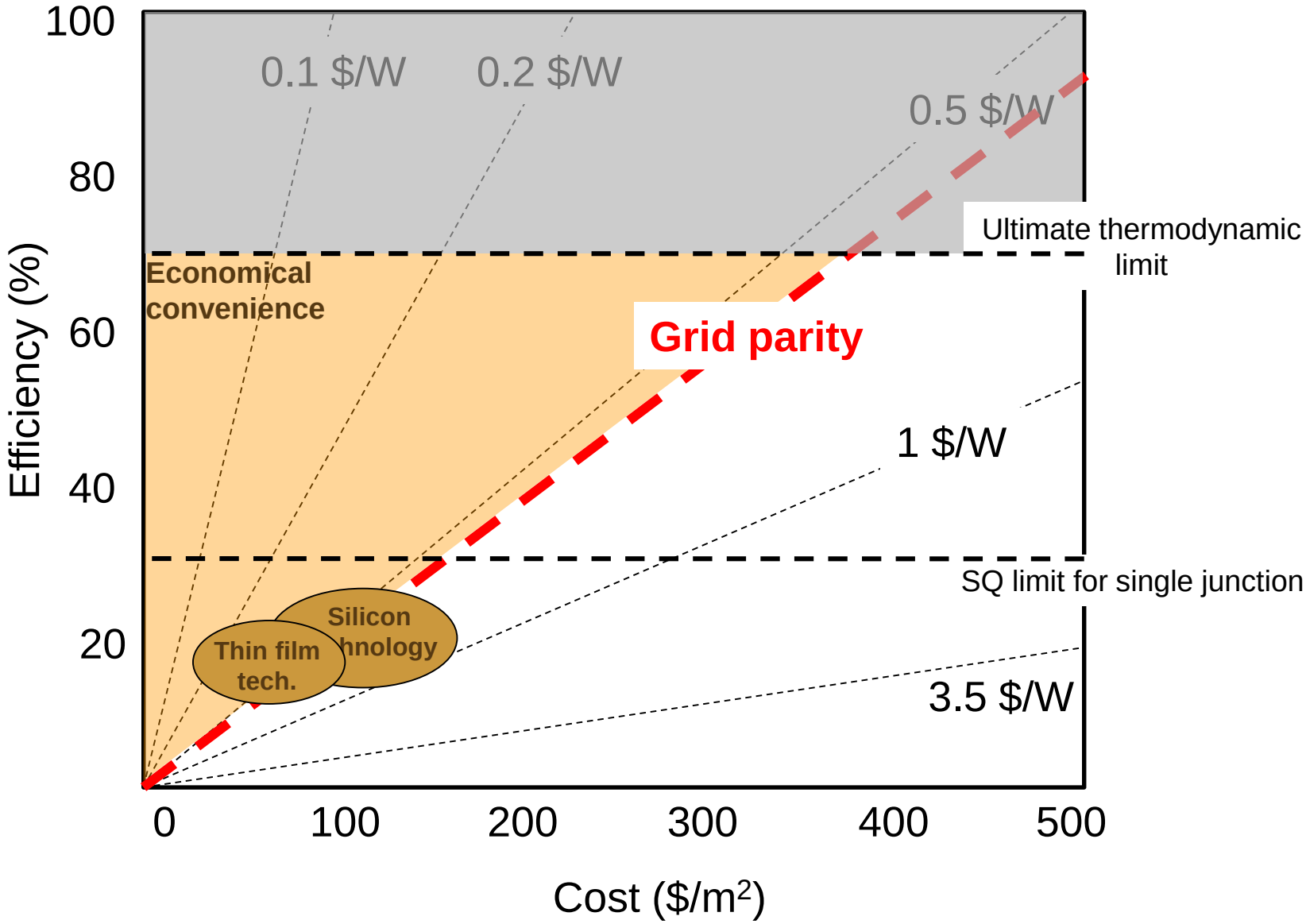


Technical evolution and growth potential

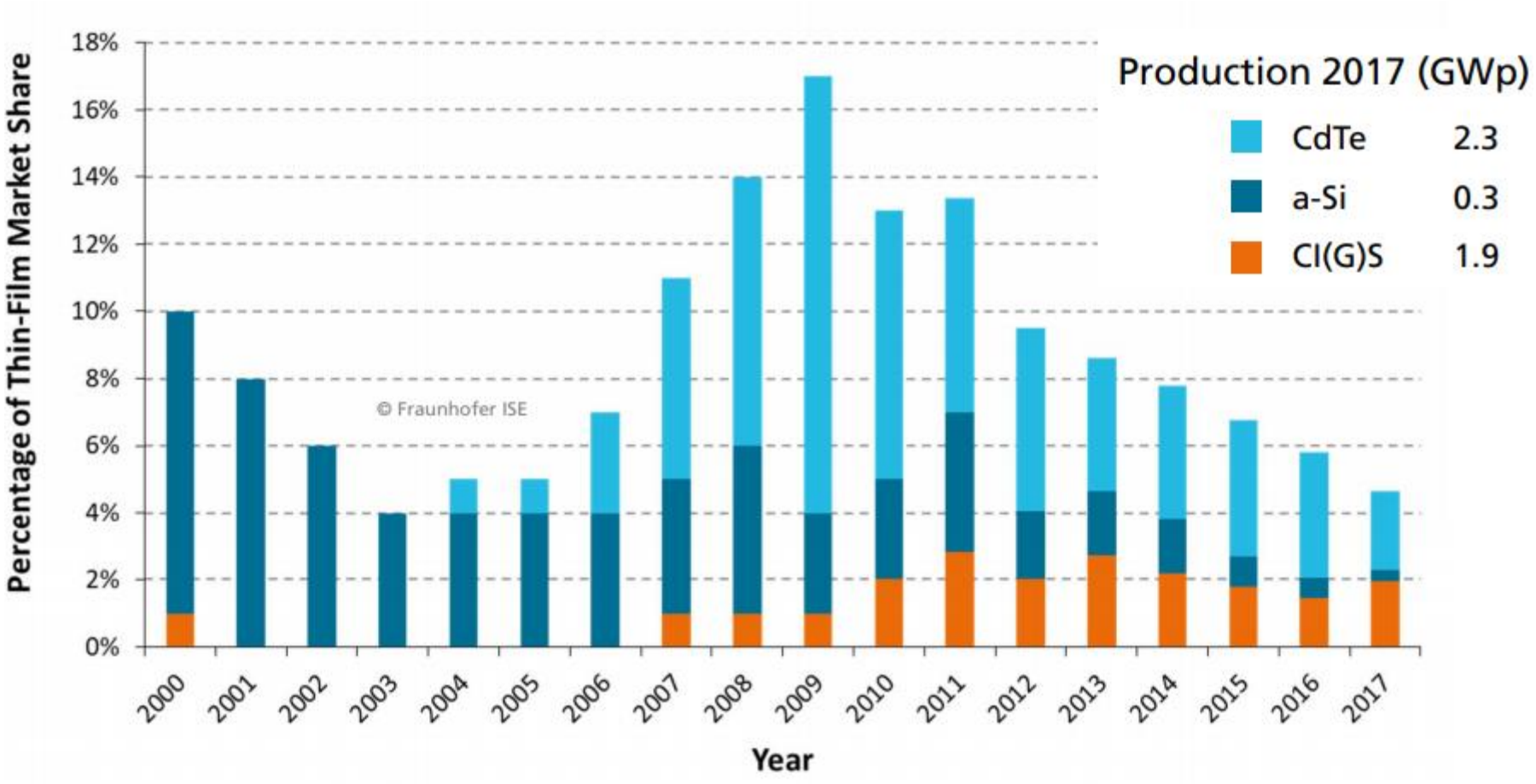


Thin film PV modules

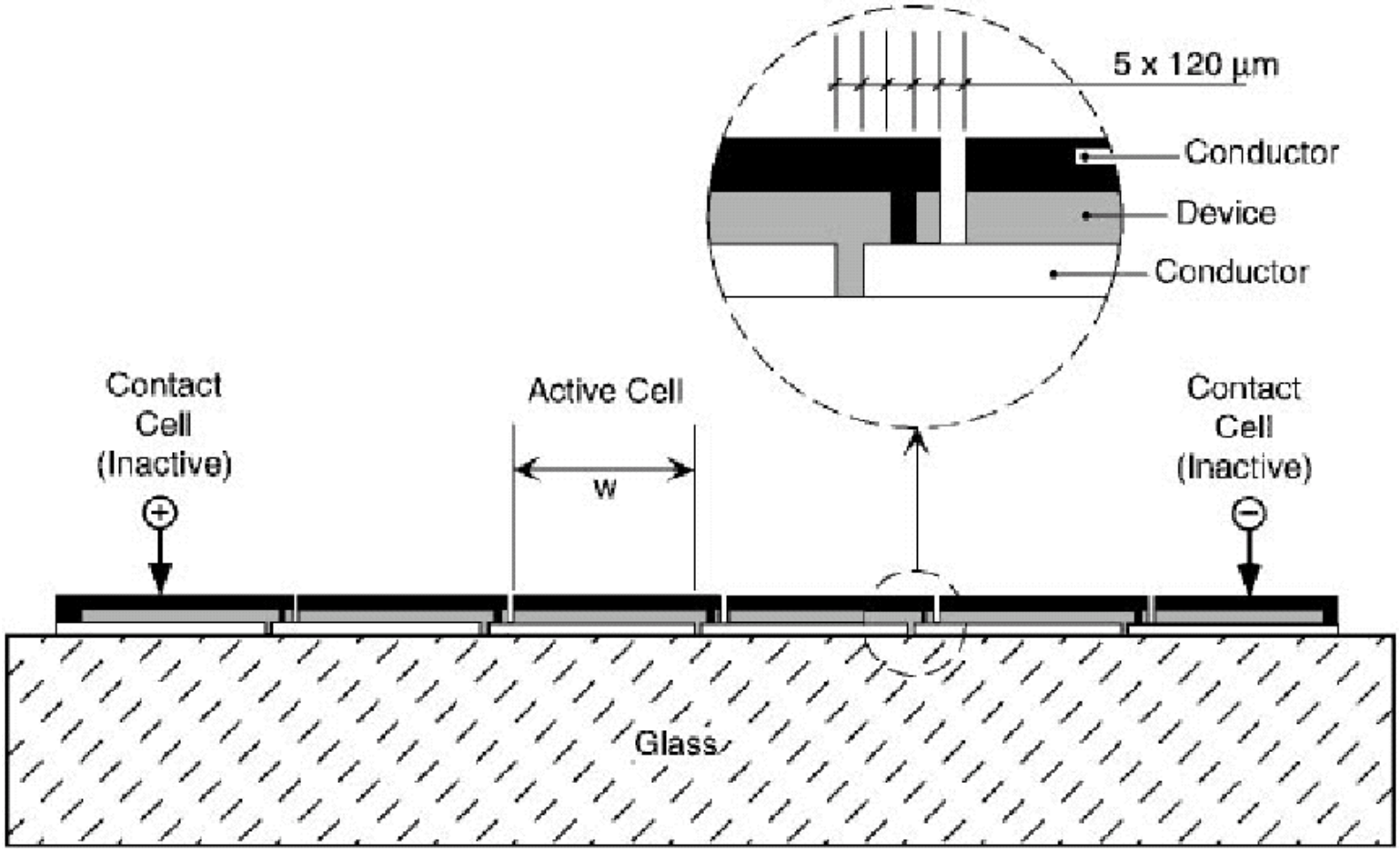
- Techno-economic positioning -



Impact of Thin Film Technology is Dropping



Data: from 2000 to 2010: Navigant; from 2011: IHS. Graph: PSE GmbH 2018


5 x 120 µm
Conductor
Device
Conductor
Contact
Cell
(Inactive)
Active Cell
w
Contact
Cell
(Inactive)
Glass

Basic working principle of a PV cell

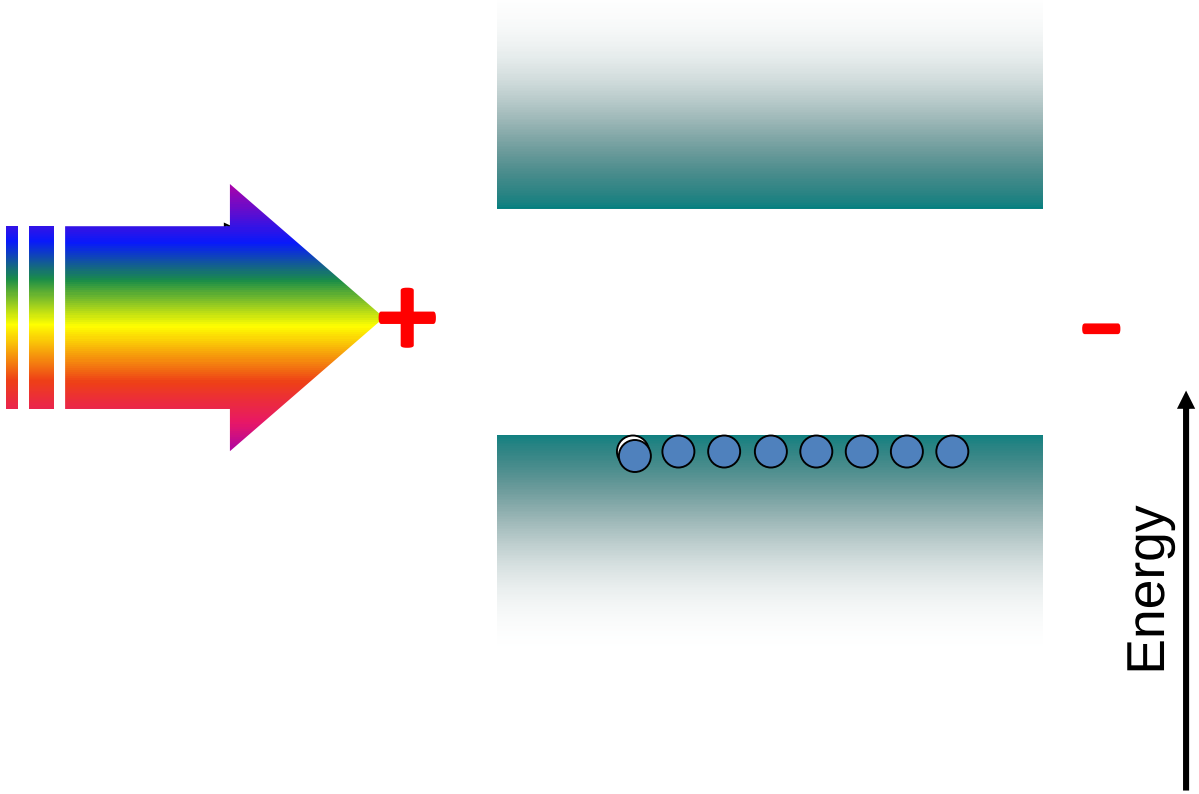
- an electron's perspective -

1.
Absorption
of solar radiation

Generation
of electrical charges

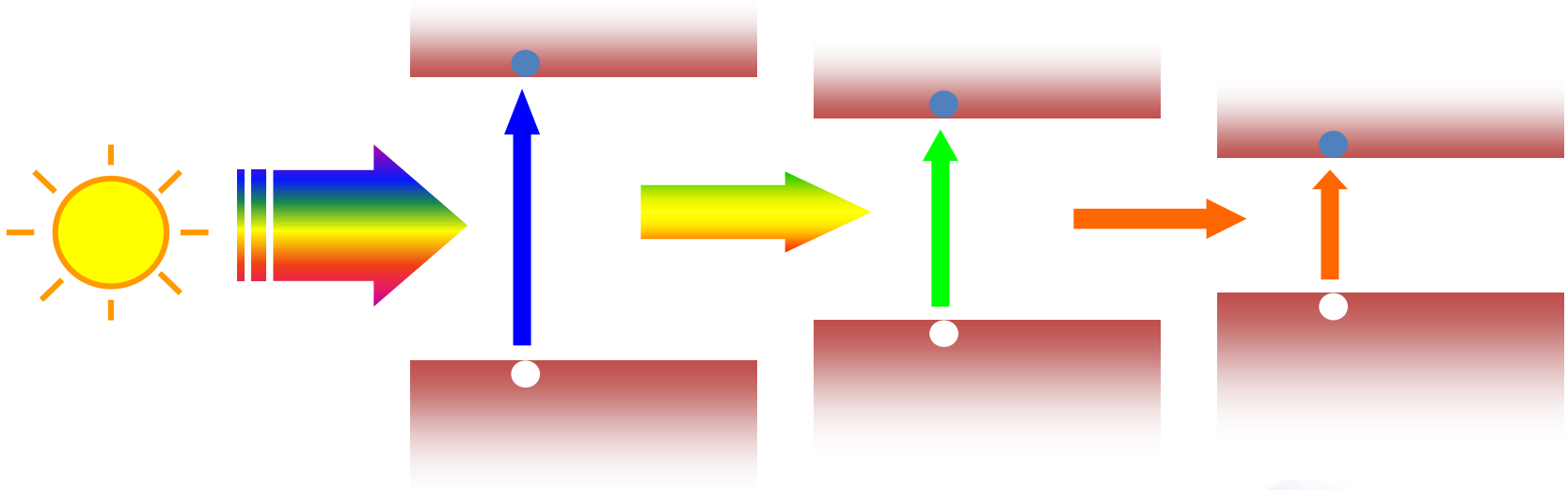
2.
Extraction
of electrical charges

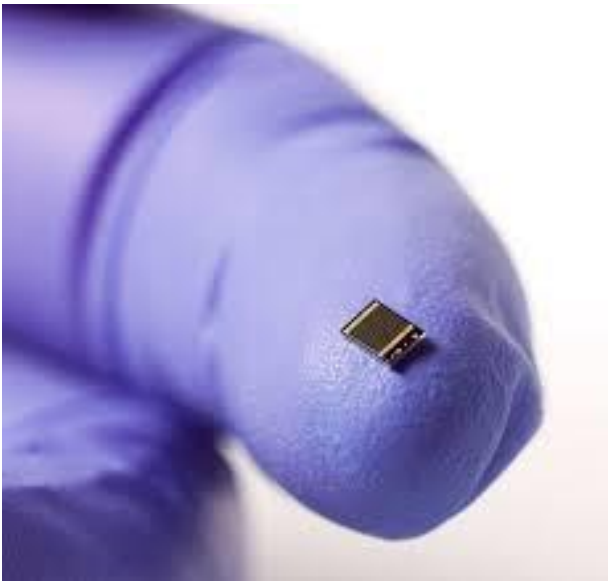
Electrical energy

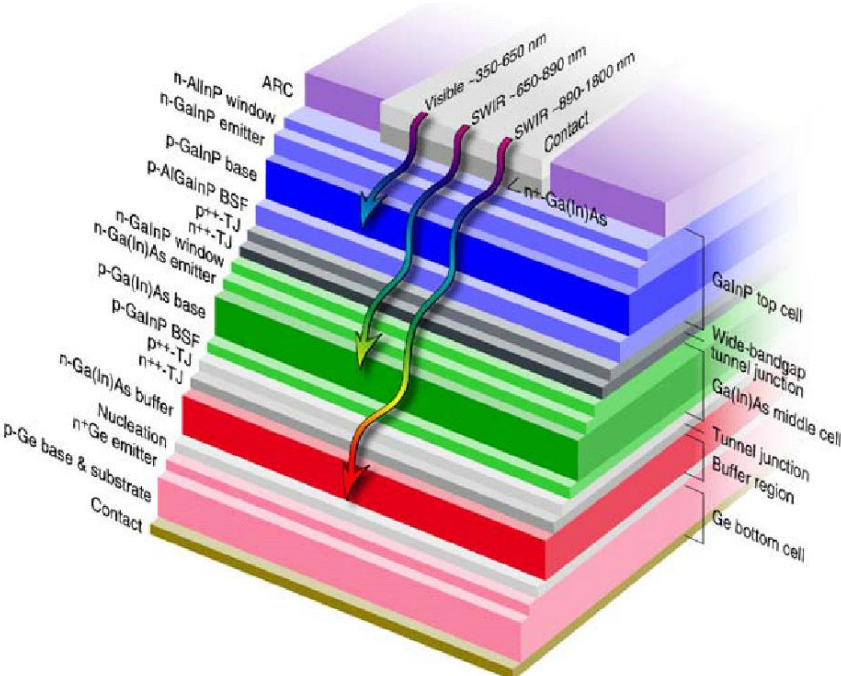


Multijunction («tandem») cells

- A more efficient use of the solar radiation -







Best Research-Cell Efficiencies

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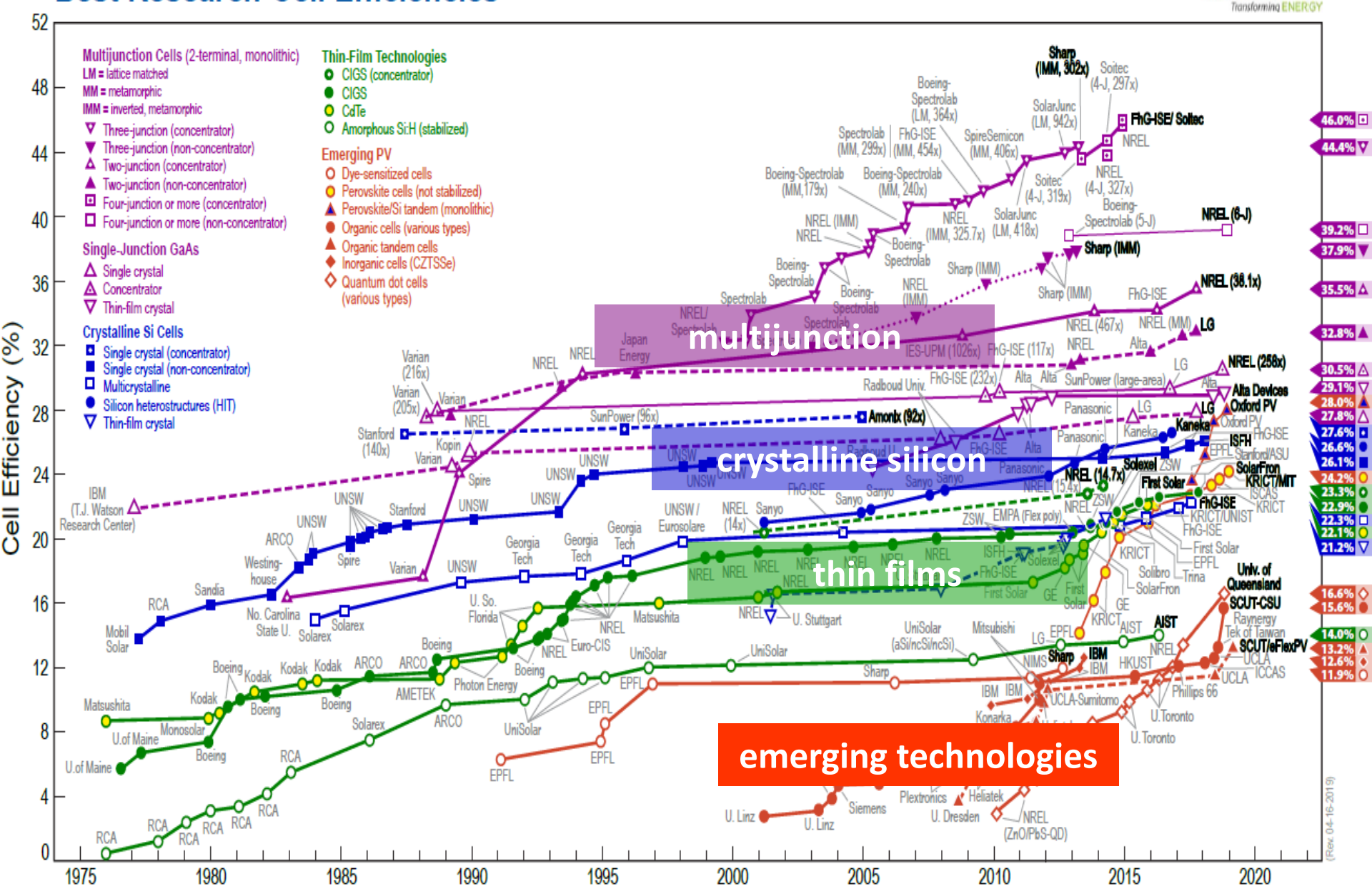
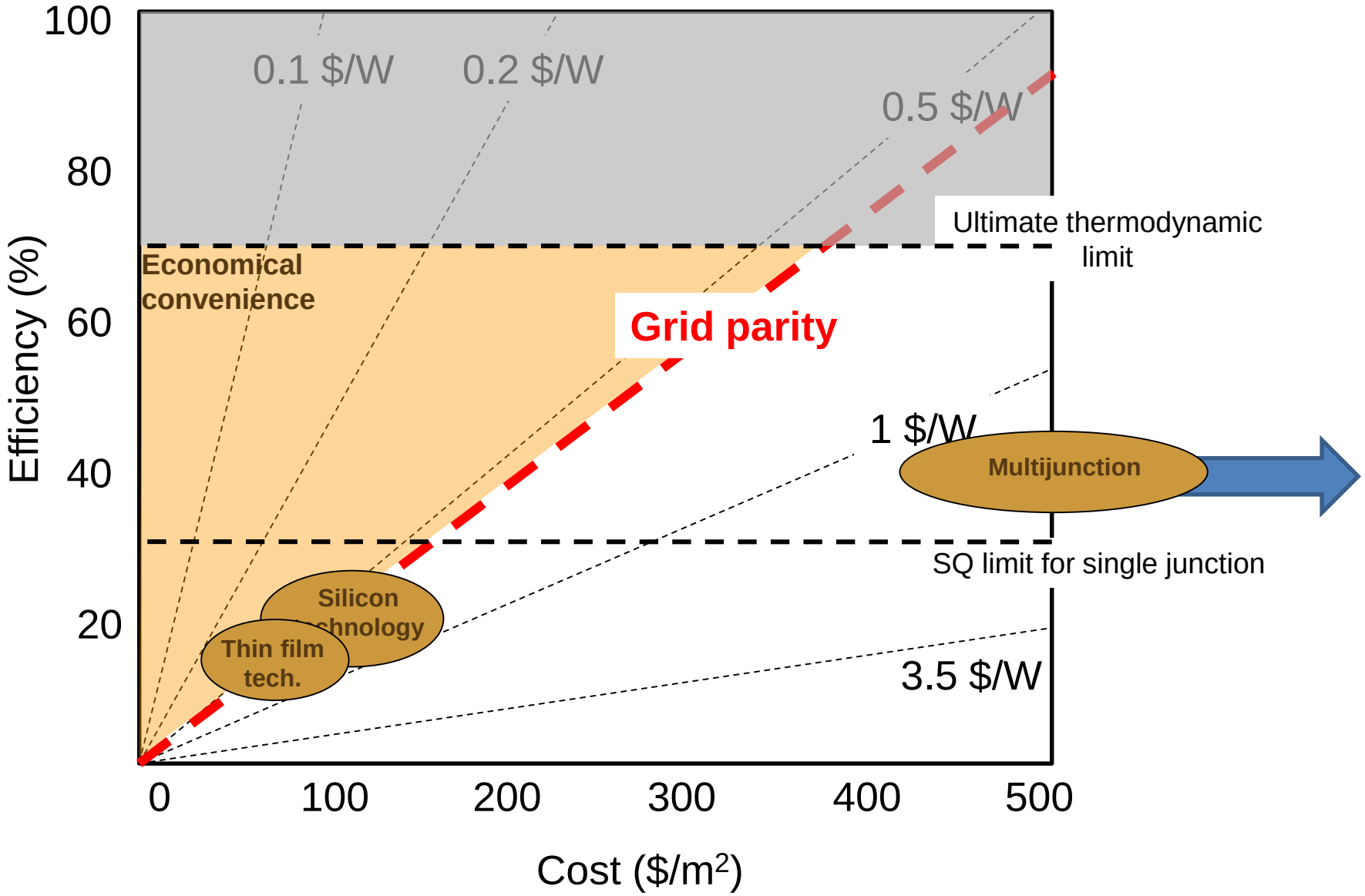


Multijunction cells

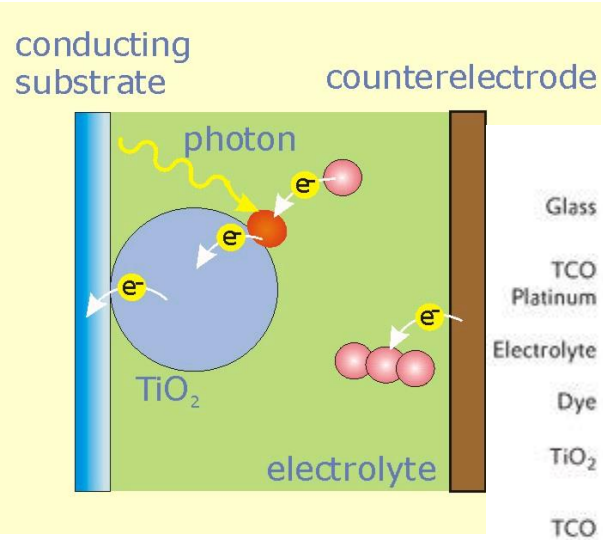
- Techno-economic positioning -

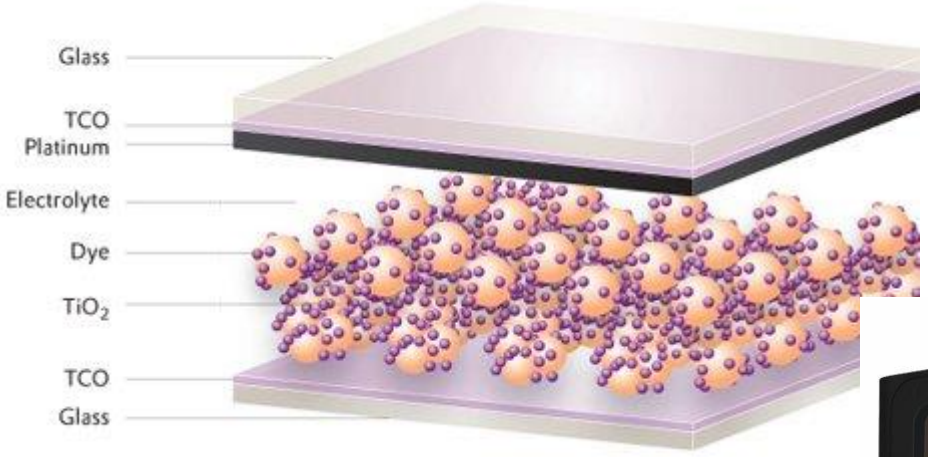


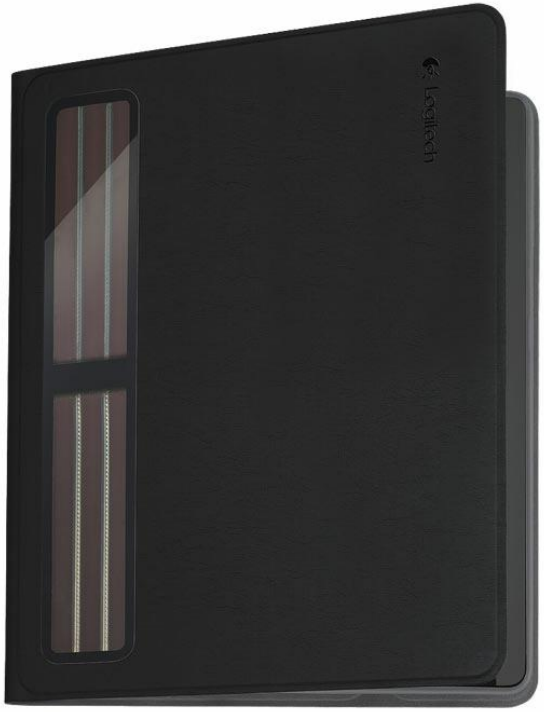
Photovoltaic technologies: state of the art

2. Frontier technologies

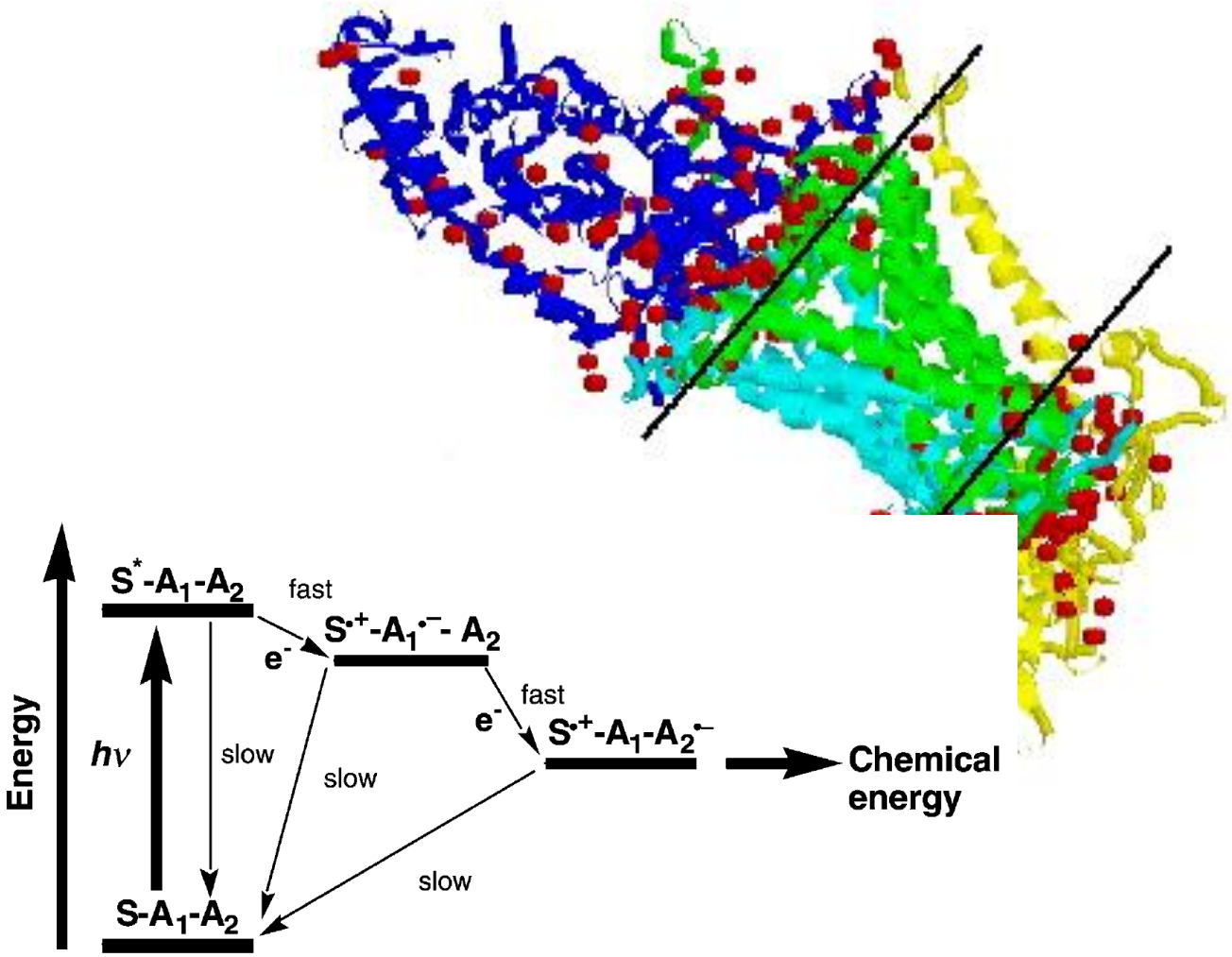
Dye Sensitized Solar Cell - DSSC



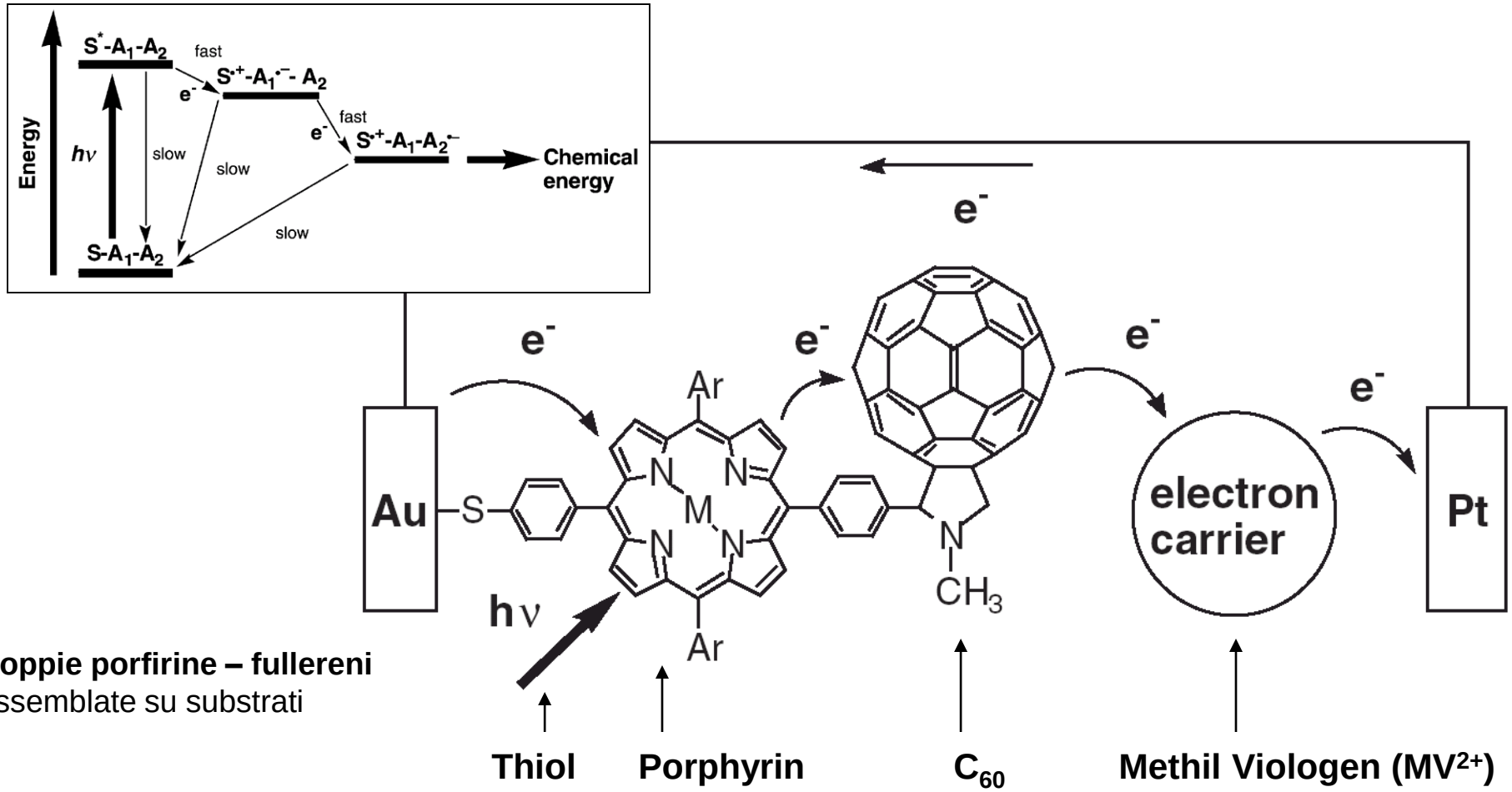




Fotosintesi



Fotosintesi artificiale

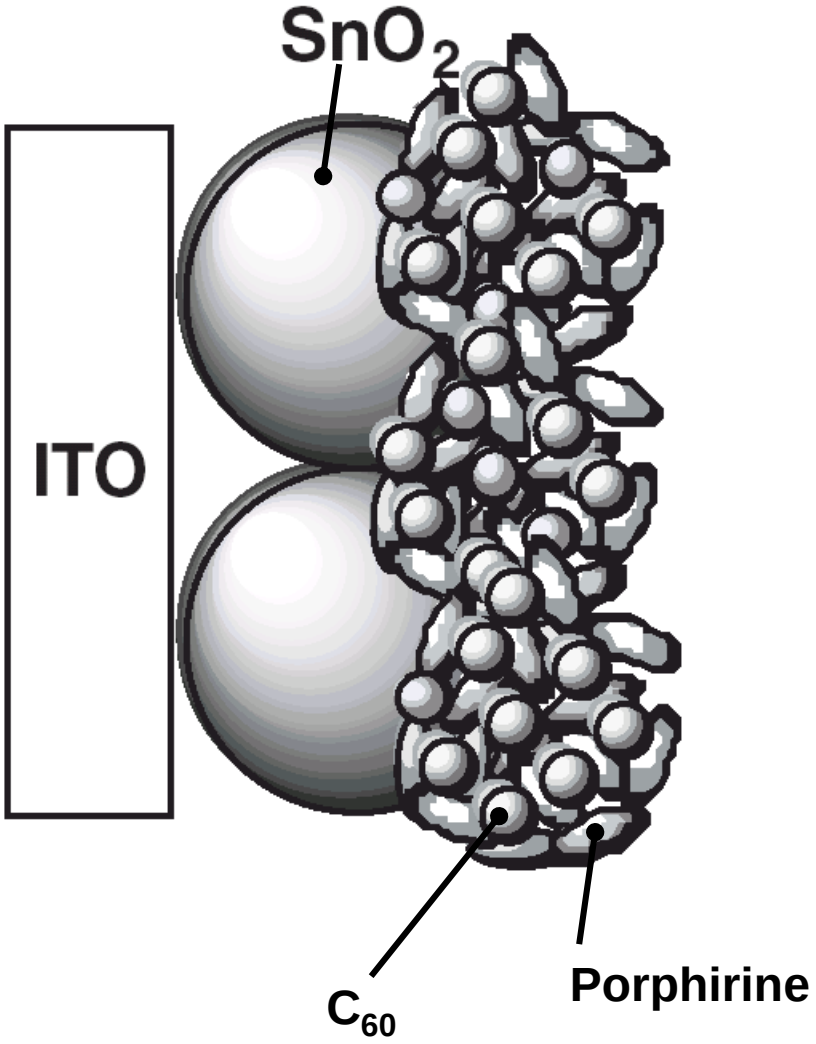


- **Coppie porfirine – fullereni** assemblate su substrati

- **Quantum yield: 0.5%**
- **Lifetime 0.77 μs**
- **Loose packaging on the surface**

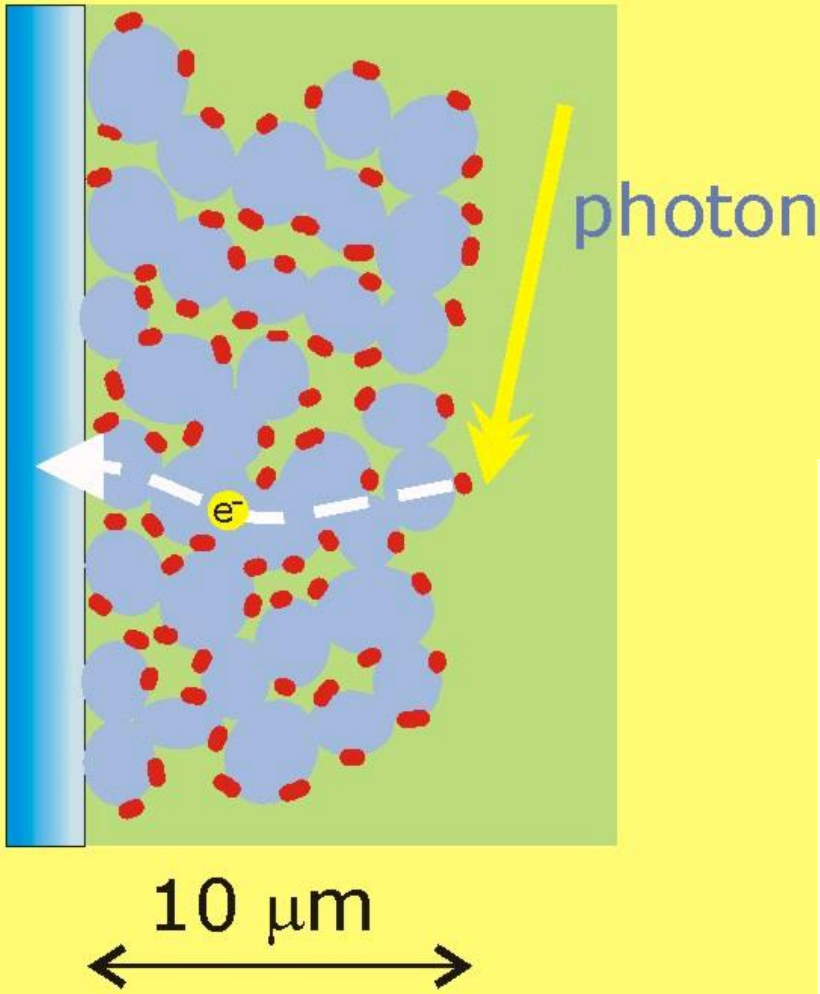
Fotosintesi artificiale

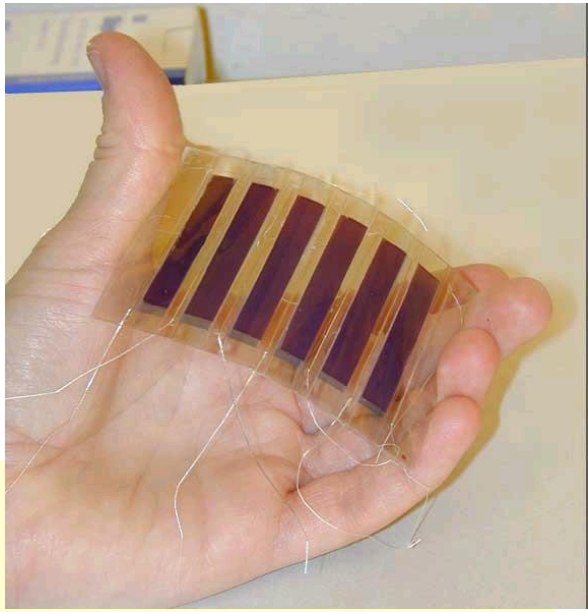
Assemblaggio gerarchico per un migliore assorbimento

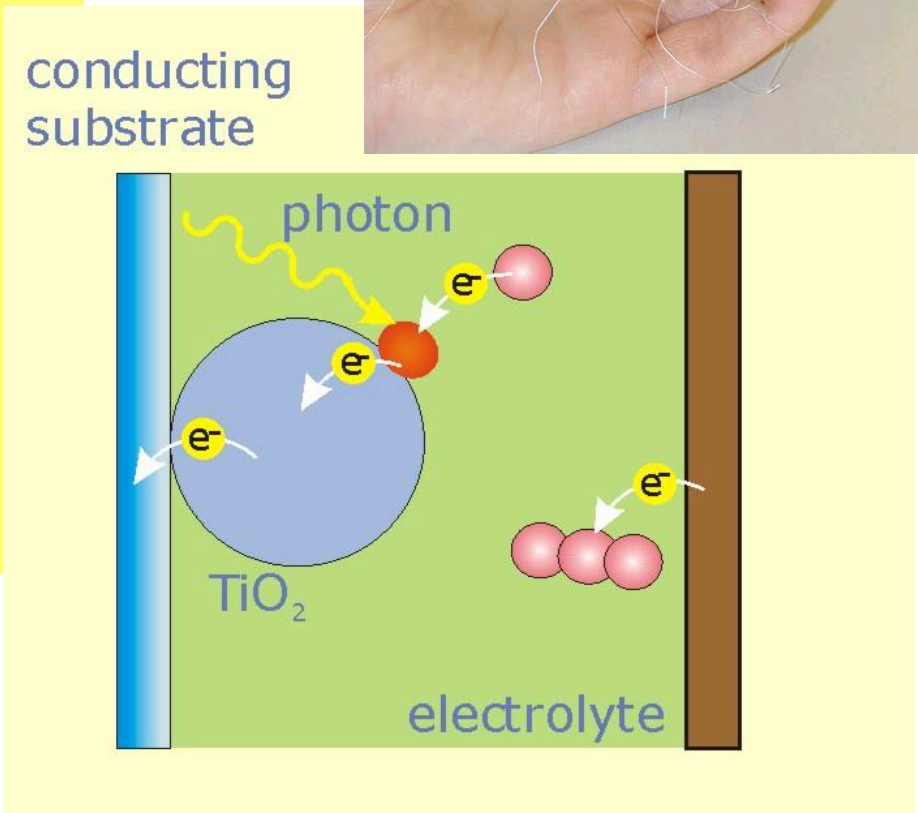


H. Imahori et al., Adv. Func. Materials 14, 525 (2004)

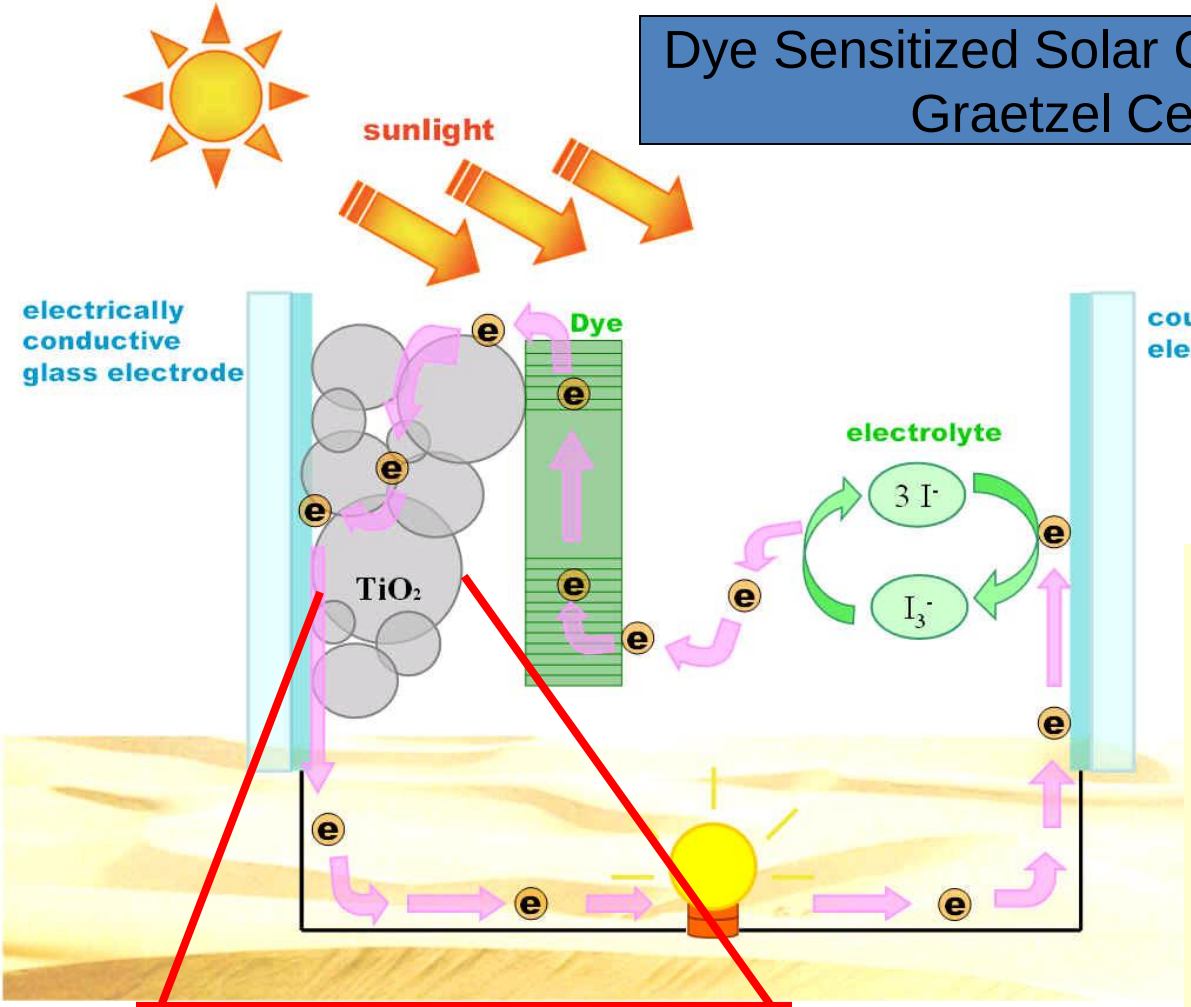
Dye Sensitized Solar Cell (DSSC)
Graetzel Cell

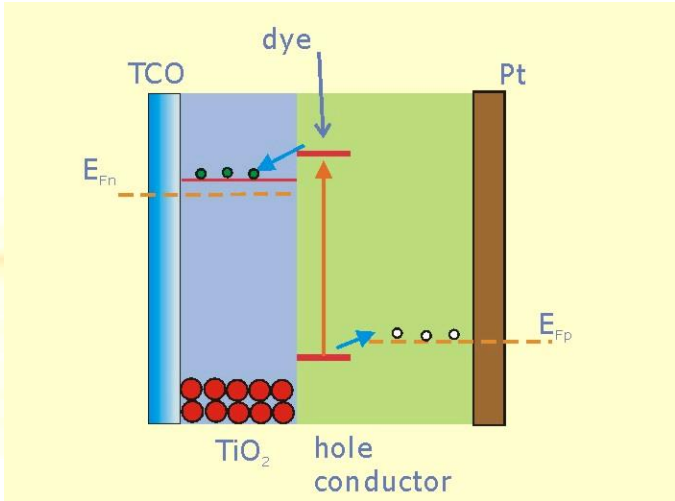


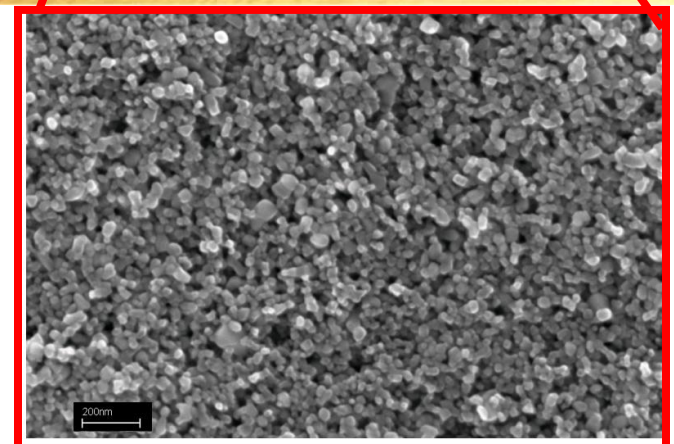




Dye Sensitized Solar Cell (DSSC)
Graetzel Cell







Best Research-Cell Efficiencies

NREL
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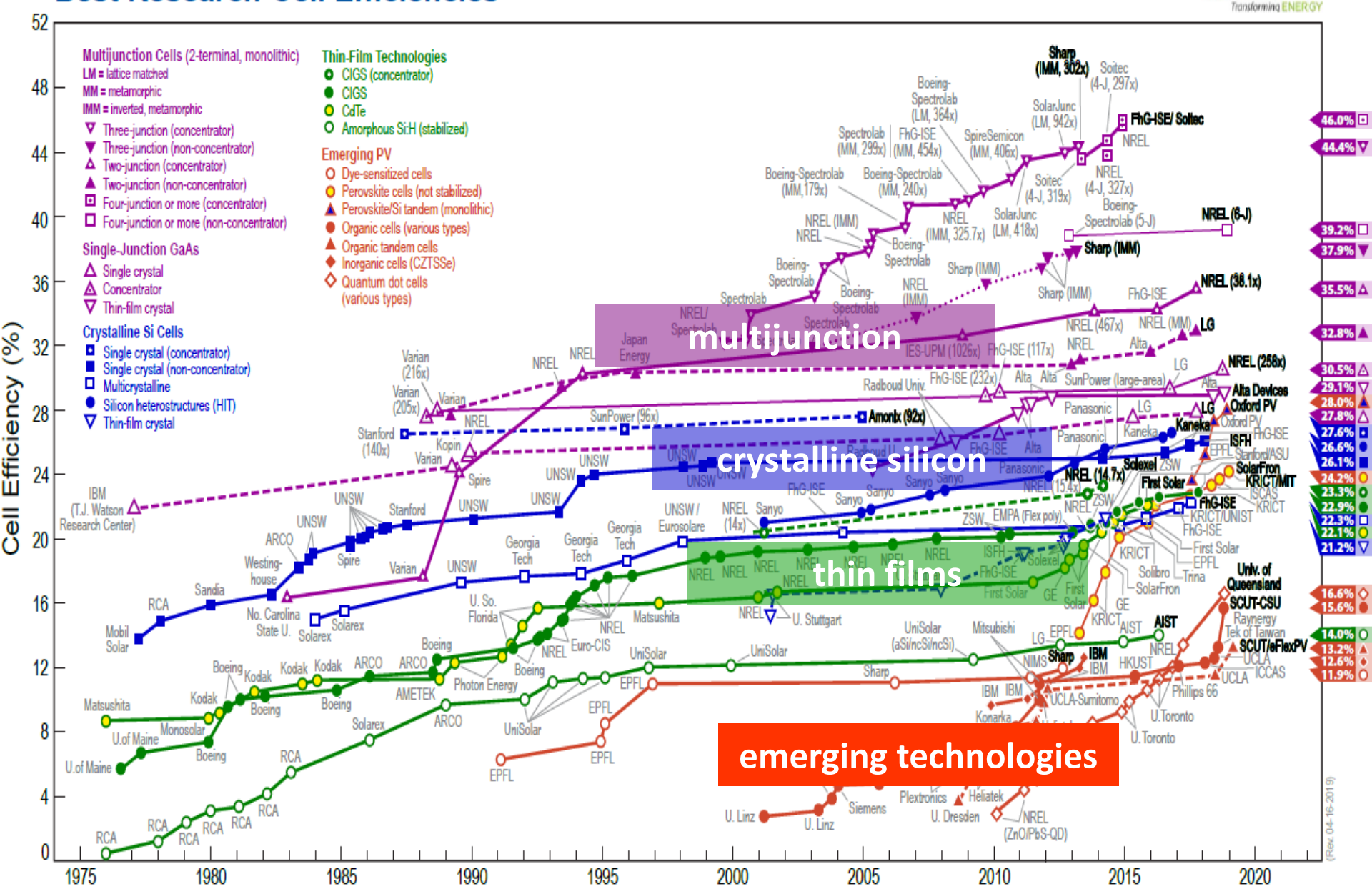
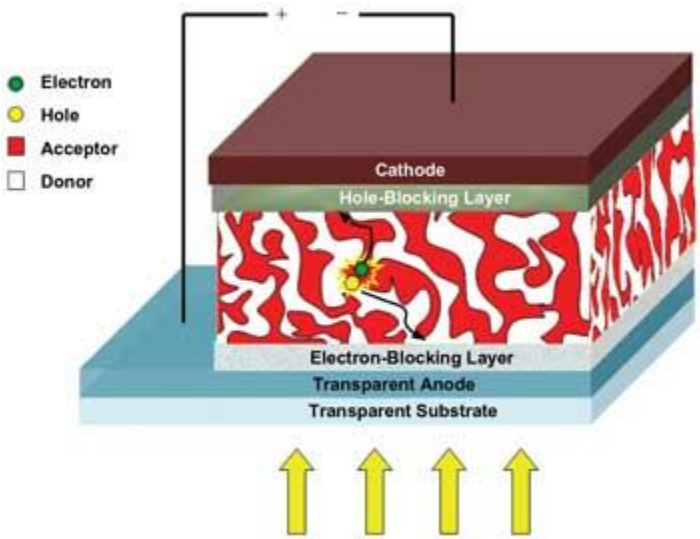
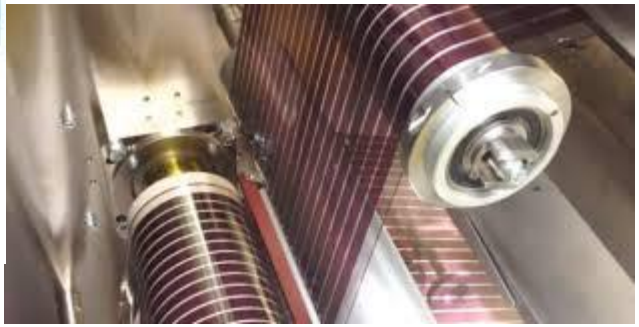
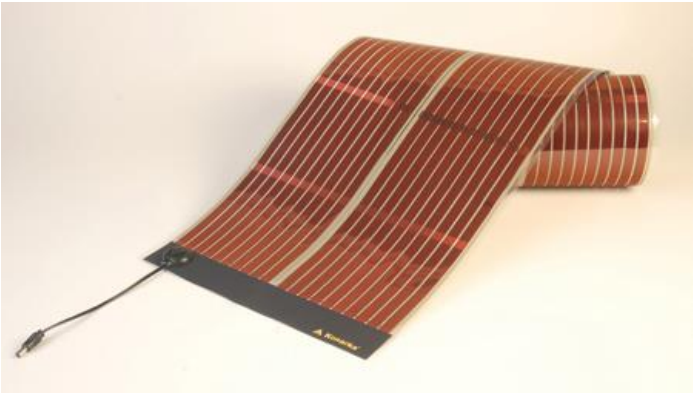


Organic photovoltaics - OPV

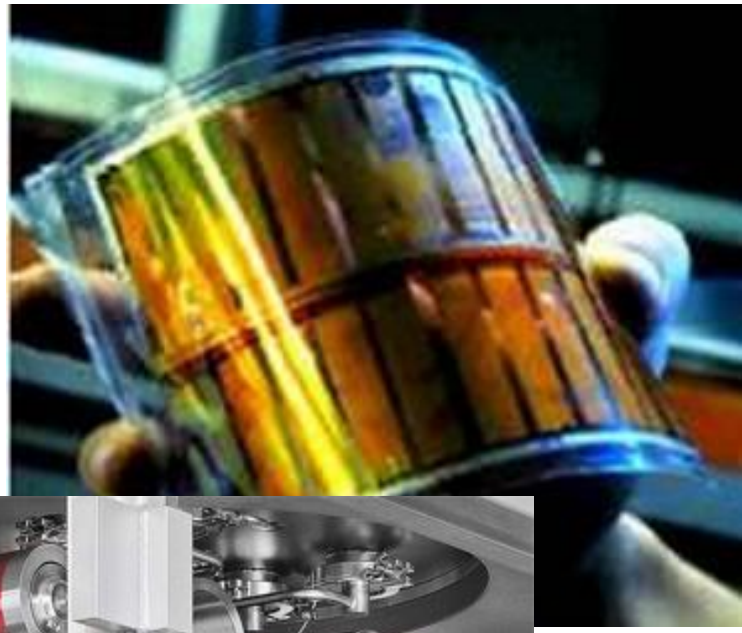




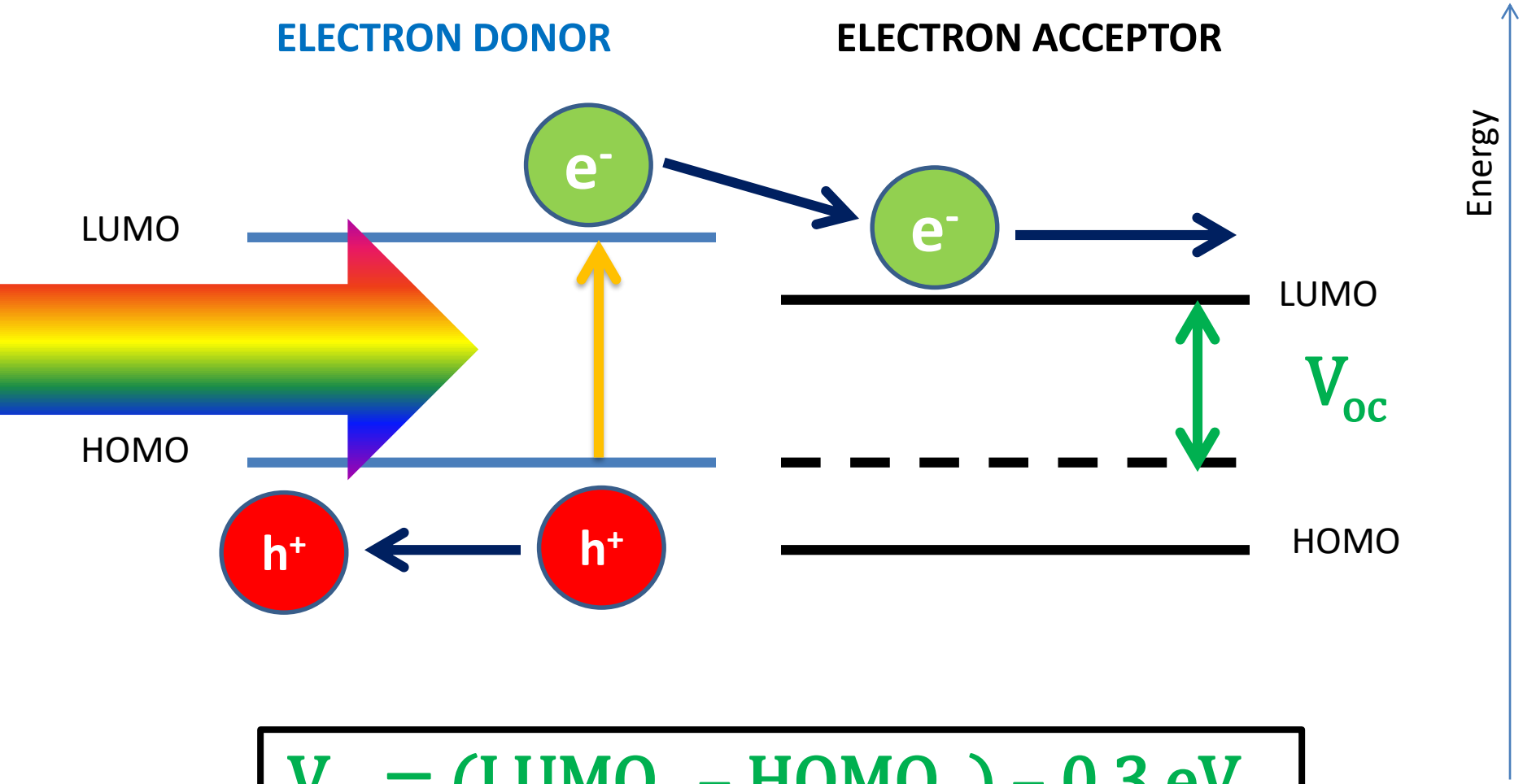


Why Organic Cells?

- **Low cost**
- **High thoughput production**
- **Flexibility**

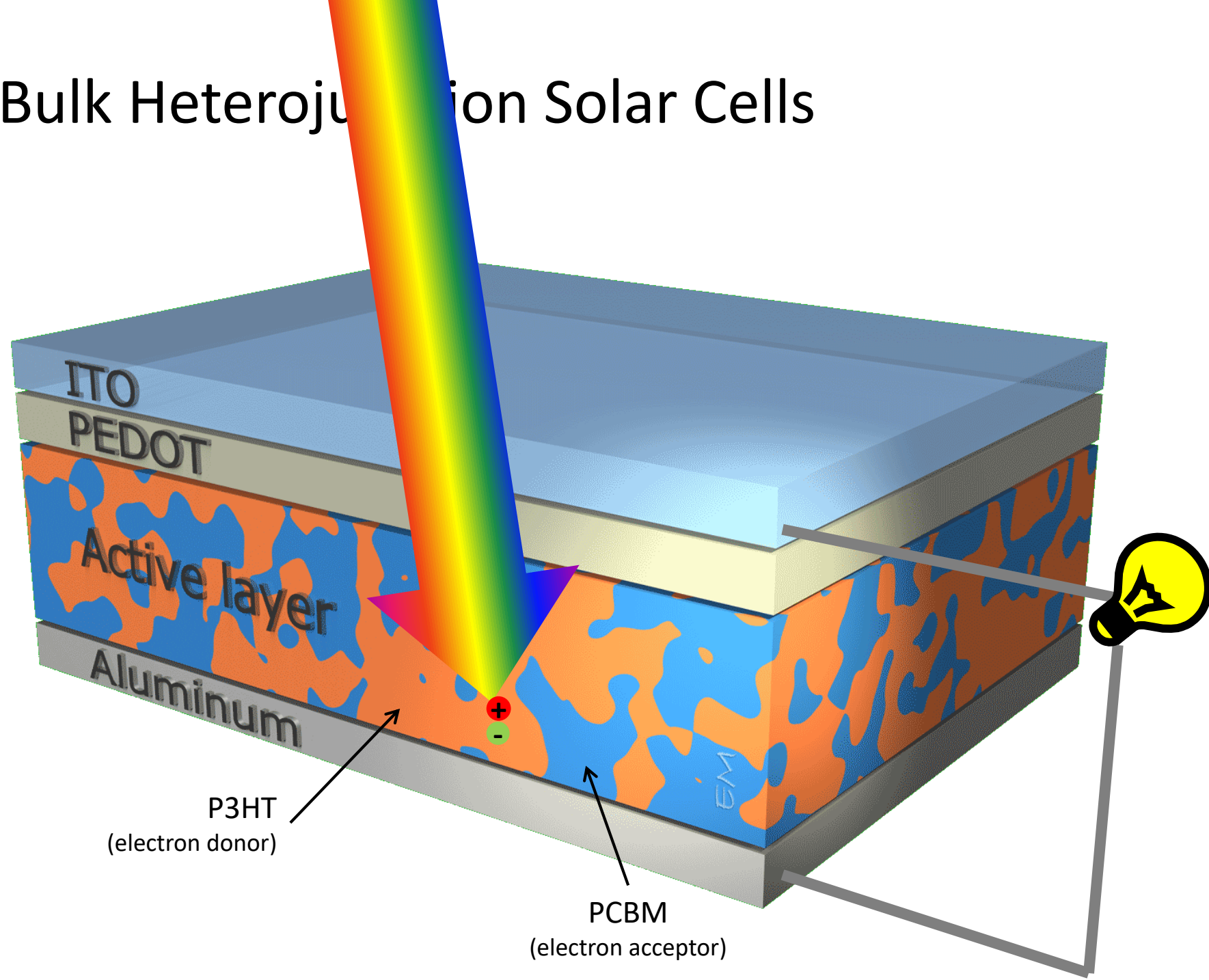


Physics of Organic Solar Cells



$$V_{oc} = (LUMO_A - HOMO_D) - 0.3\ eV$$

Bulk Heterojunction Solar Cells



Best Research-Cell Efficiencies

NREL
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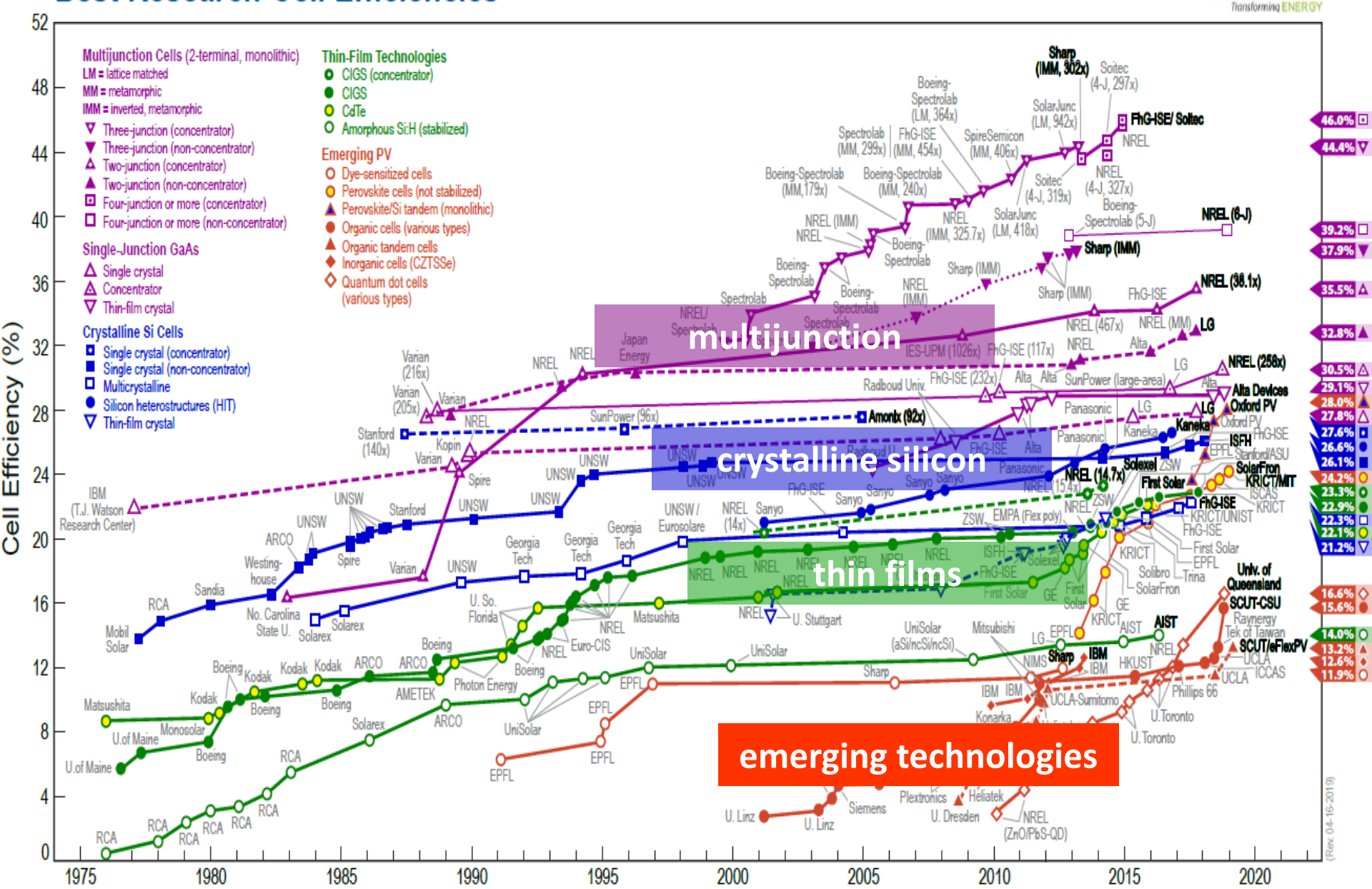
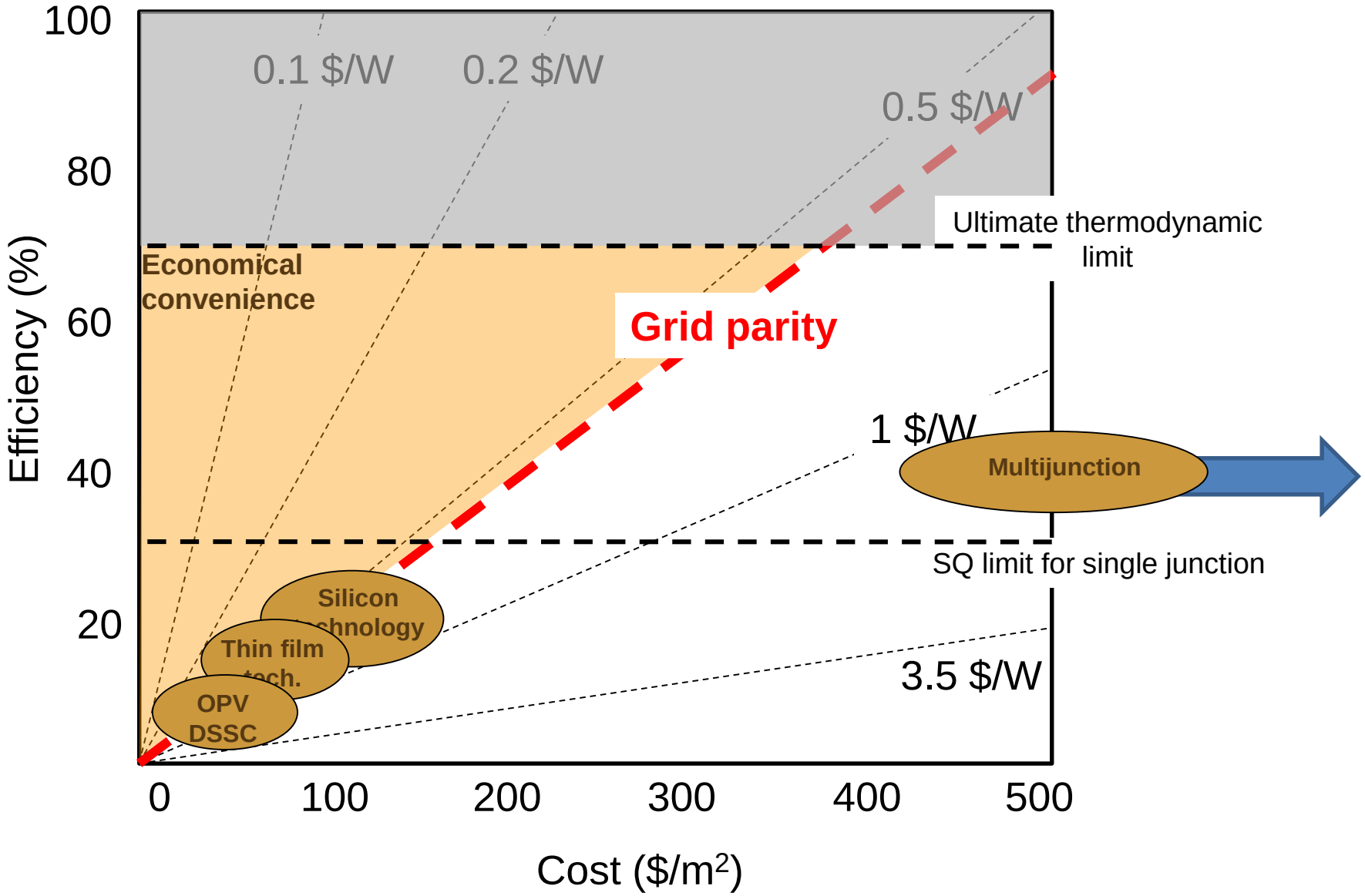


DSSC e OPV

- Techno-economic positioning -

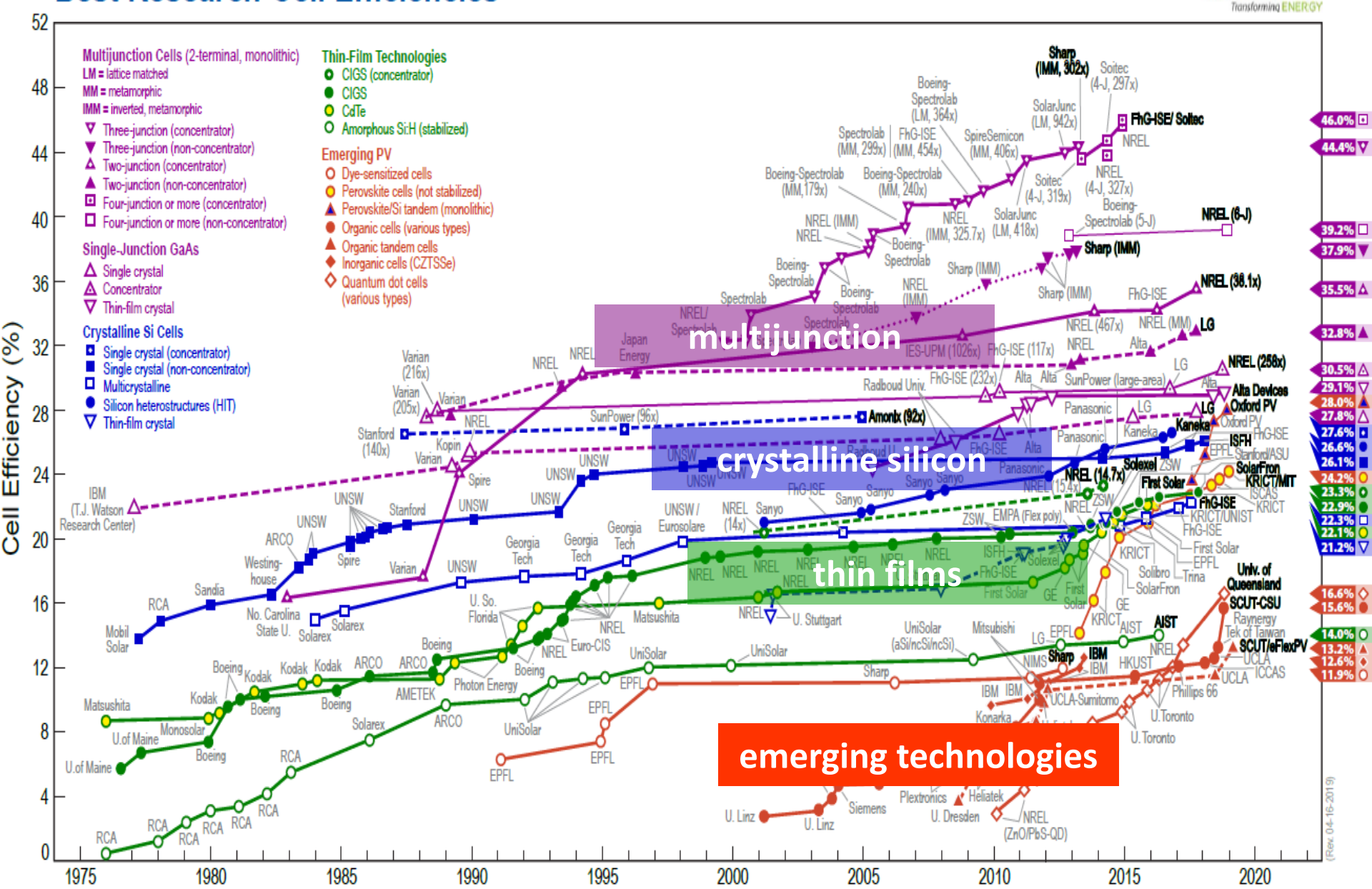


Photovoltaic technologies: state of the art

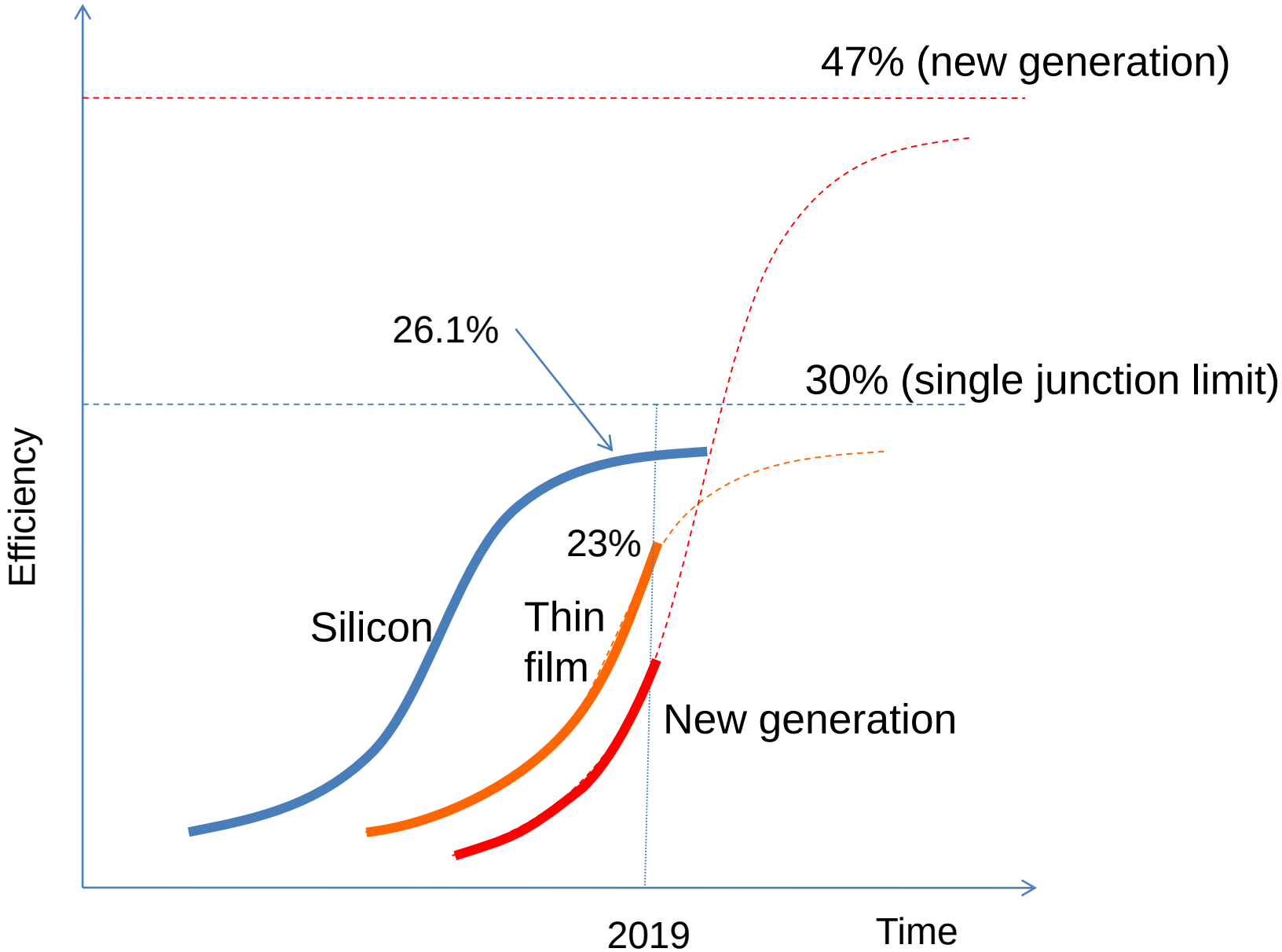
3. Beyond the frontier - nanotechnology

Best Research-Cell Efficiencies

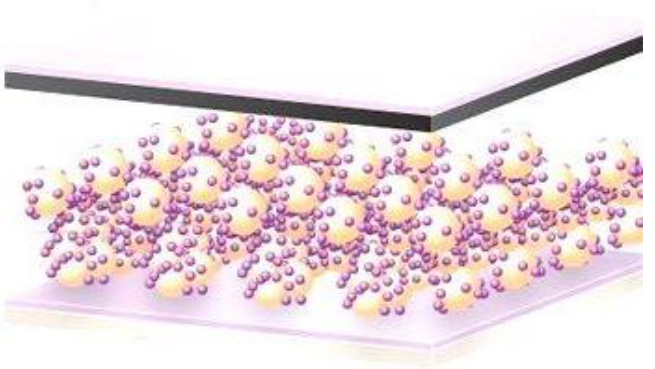
NREL
Transforming ENERGY



Enhancement potential



Nanotechnology and PV: Why?

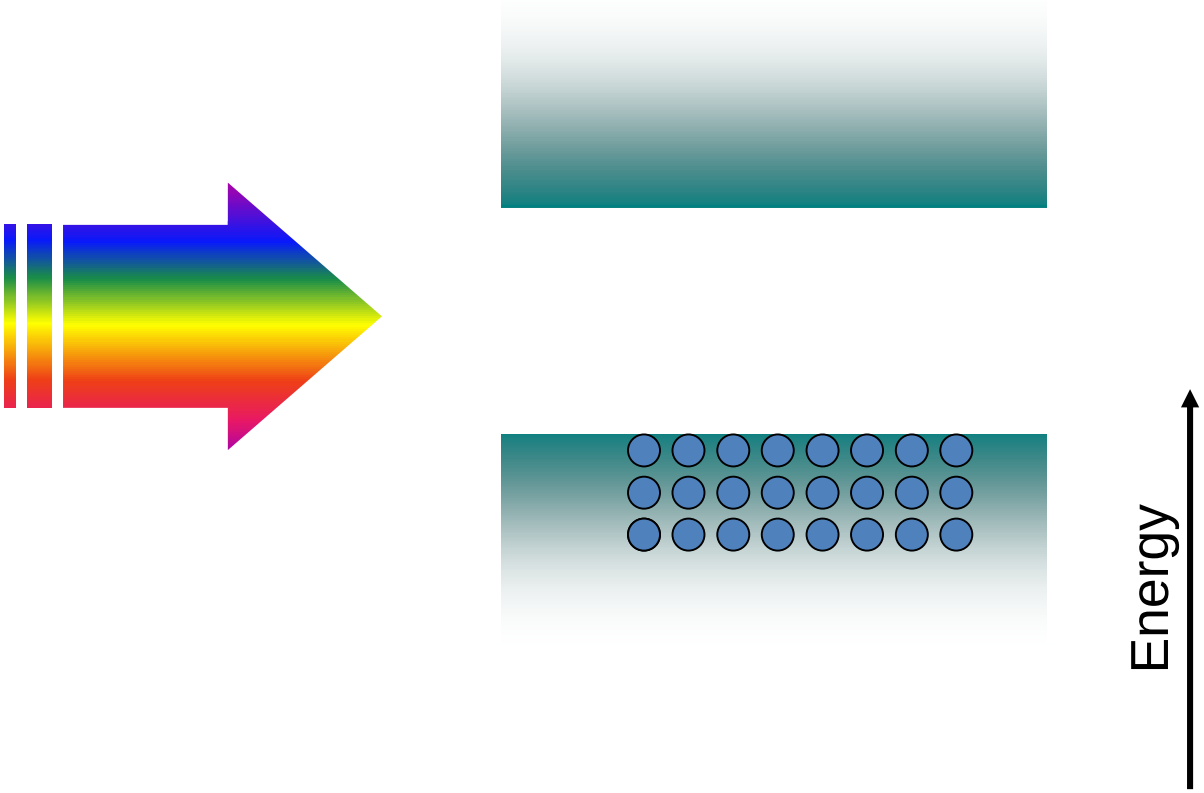


- Morphologic advantages: nanometric structures have a lot of surface area (*e.g. DSSC*)

- The optoelectronic properties of materials are dominated by phenomena occurring at the nanoscale → we need to engineer the nanostructure of materials

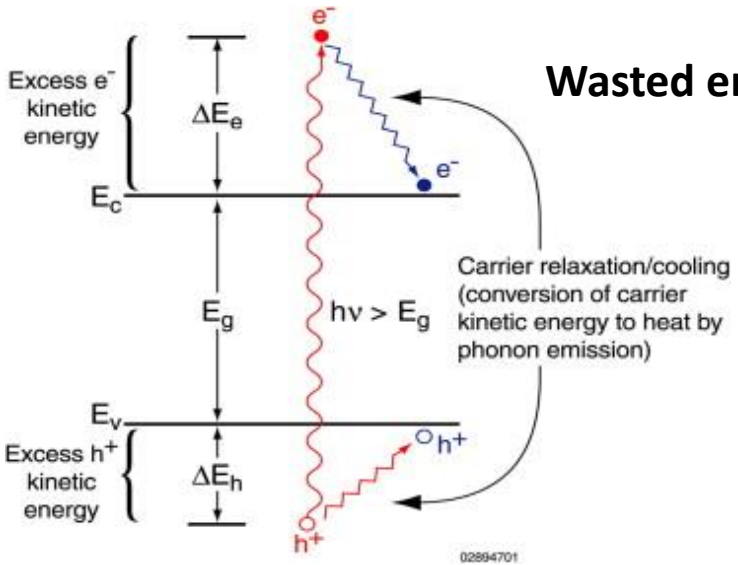
- Nanoscale phenomena are governed by quantum mechanics → nanomaterials can exploit untapped physics at the macroscale (*e.g. intermediate band*)

Thermalization of electrons: wasted energy!



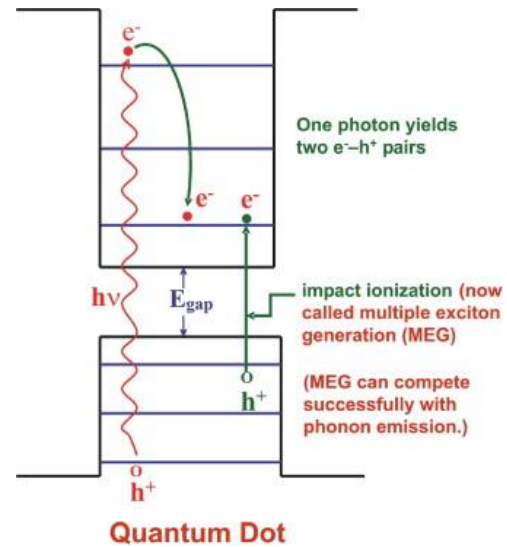
Nanotech and Photovoltaics:

- Better use of high-energy photons: MEG (Multiple Exciton Generation) -

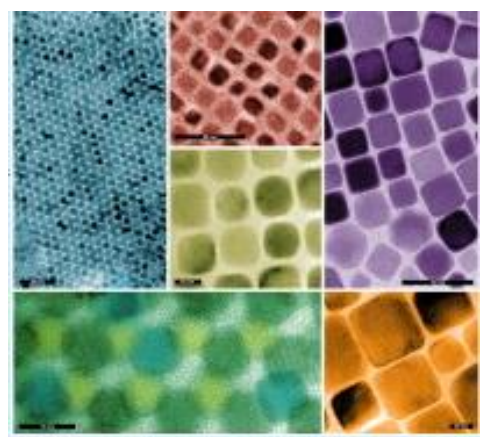


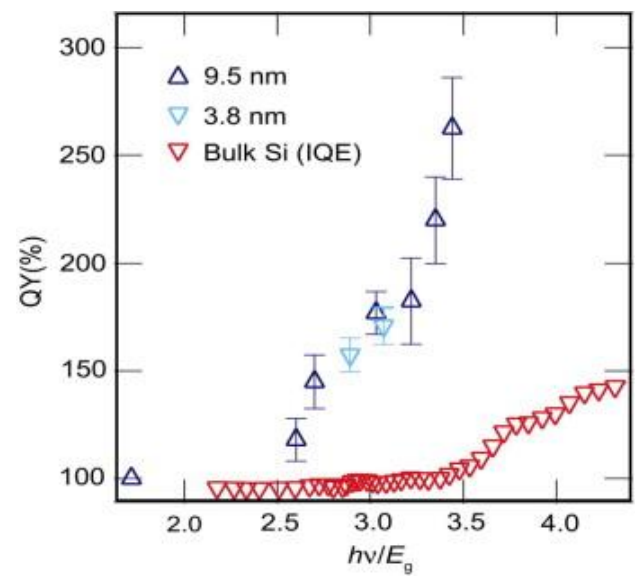
Wasted energy!

Exploiting high-energy photons



Limiting efficiency: 45%
(86.6% under concentration)

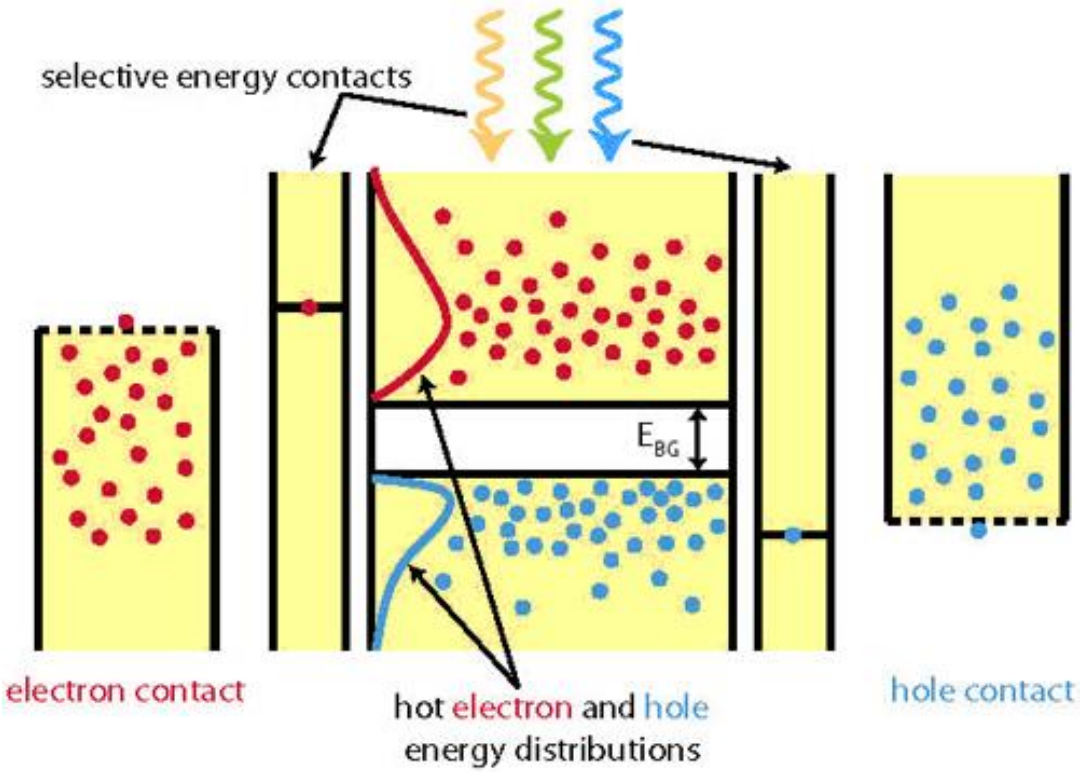




Special nanoparticles (quantum dots) favor the **generation of more than one electron per photon**

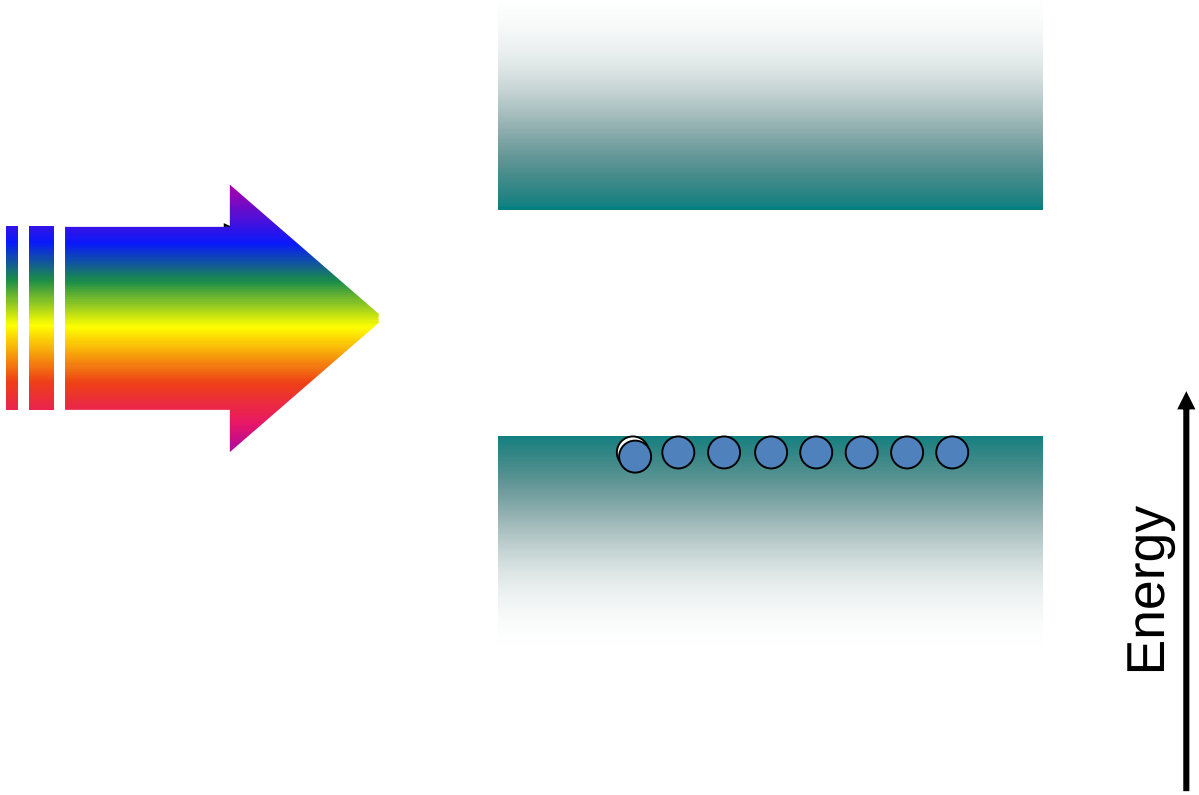
A. Nozik, M. Beard, NREL

Using High Energy Photons: Hot Electron Extraction



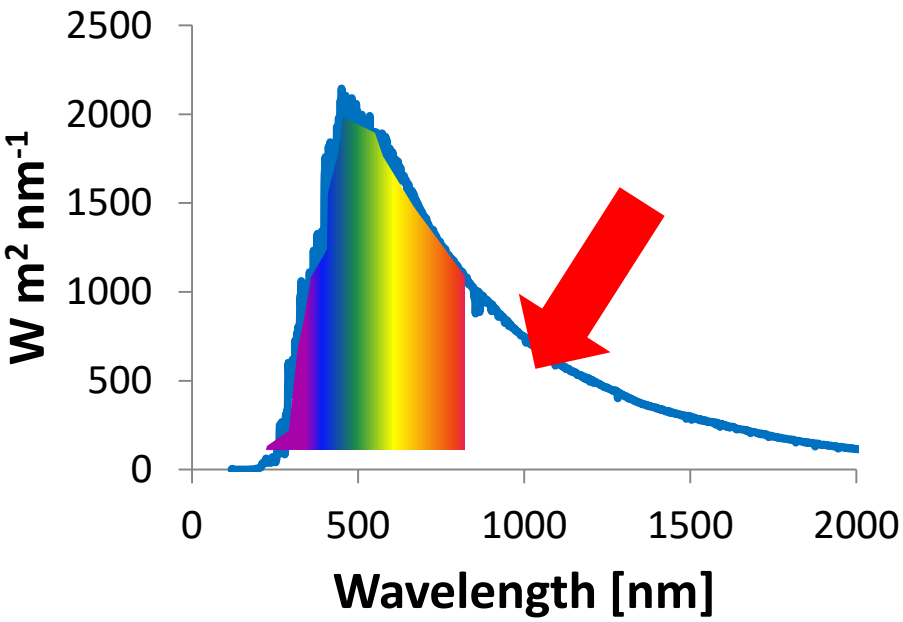
PV Kamat, Nature Chemistry 2 p809 (2010)
A. Pandey, P. Guyot-Sionnest*,J. Phys. Chem. Lett. 1 p45–47 (2010)
JA McGuire et al., ACS Nano 4, p6087 (2010)

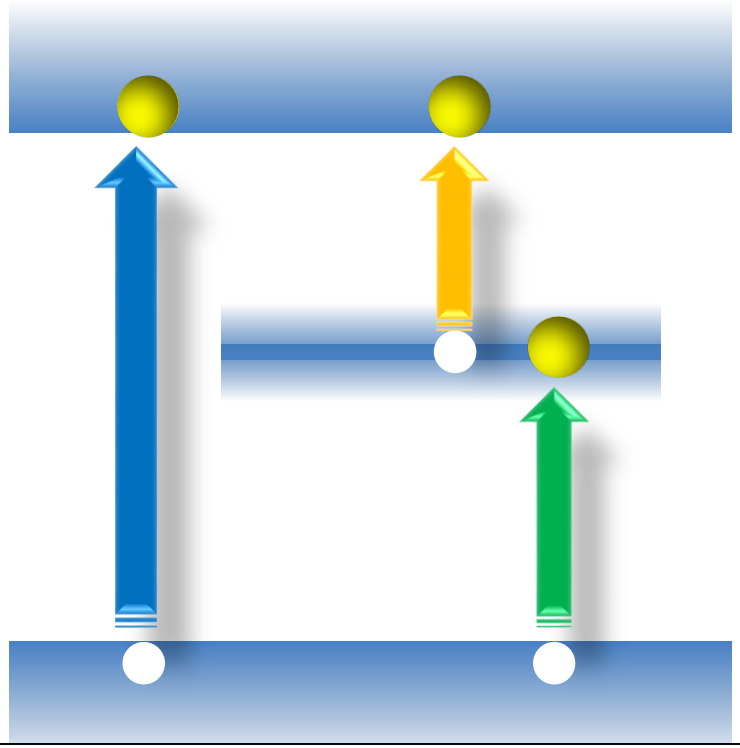
Low energy photons are lost

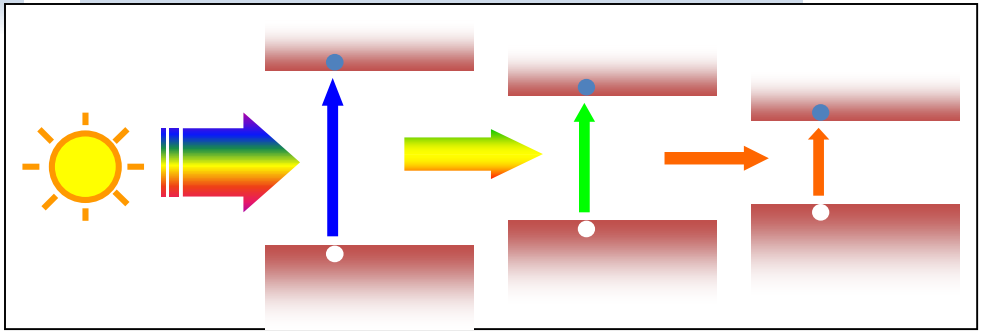


Beyond the single junction limit

- Intermediate Band Materials: Using Low Energy Phonons-

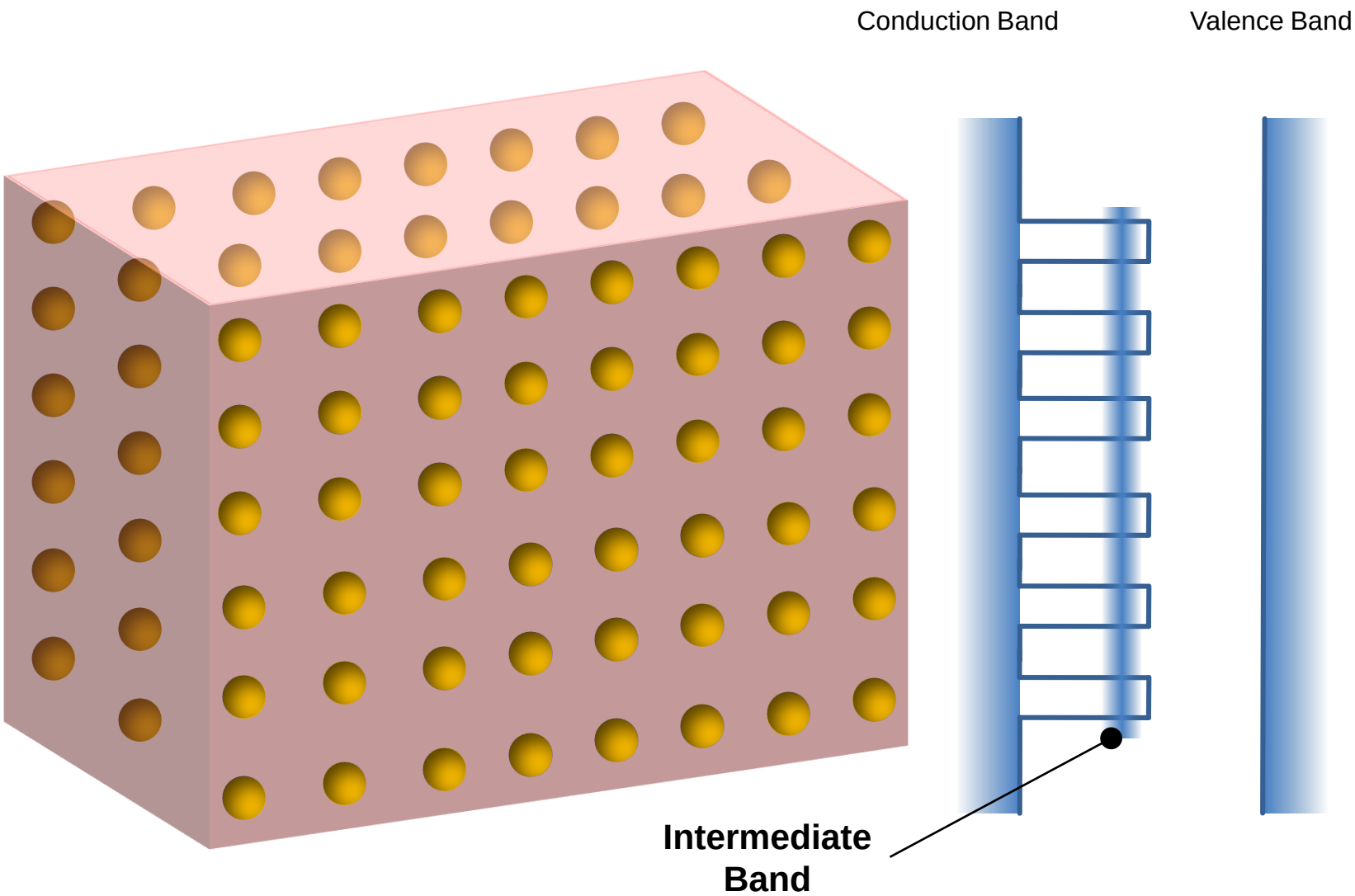




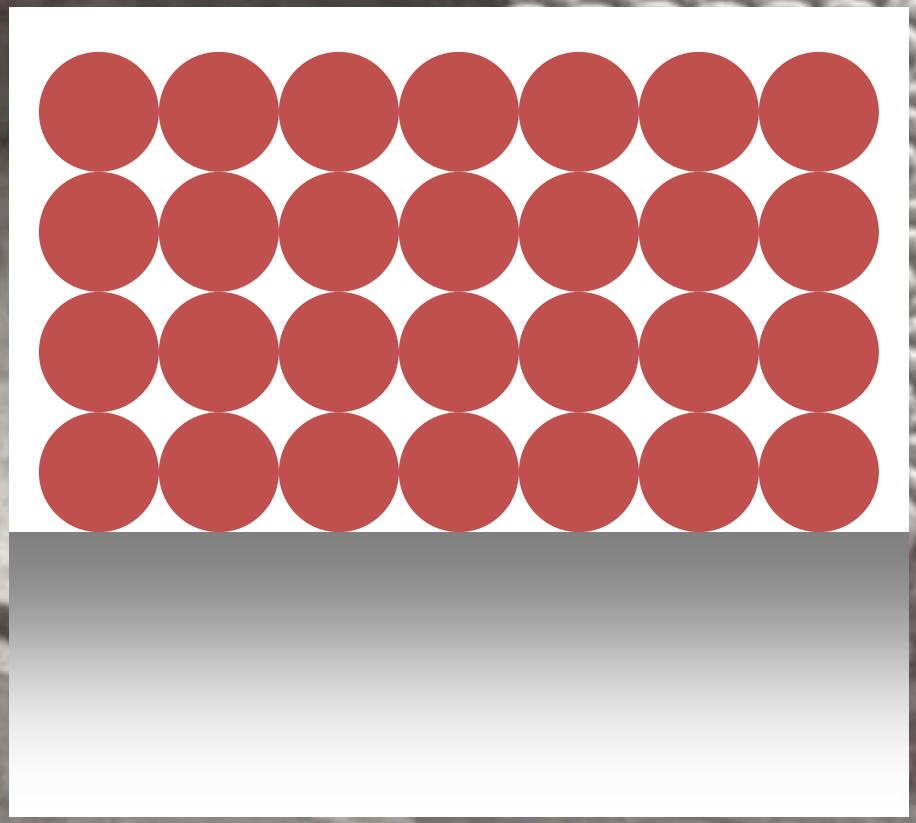


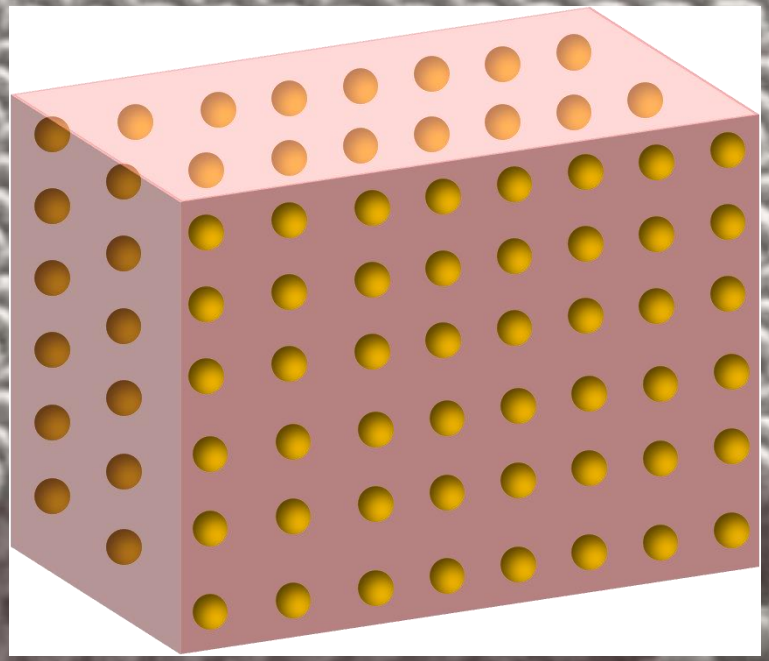
Making an Intermediate Band Material

Quantum dots embedded in a semiconductor



Assemblying Quantum Dots into Colloidal Solid Films

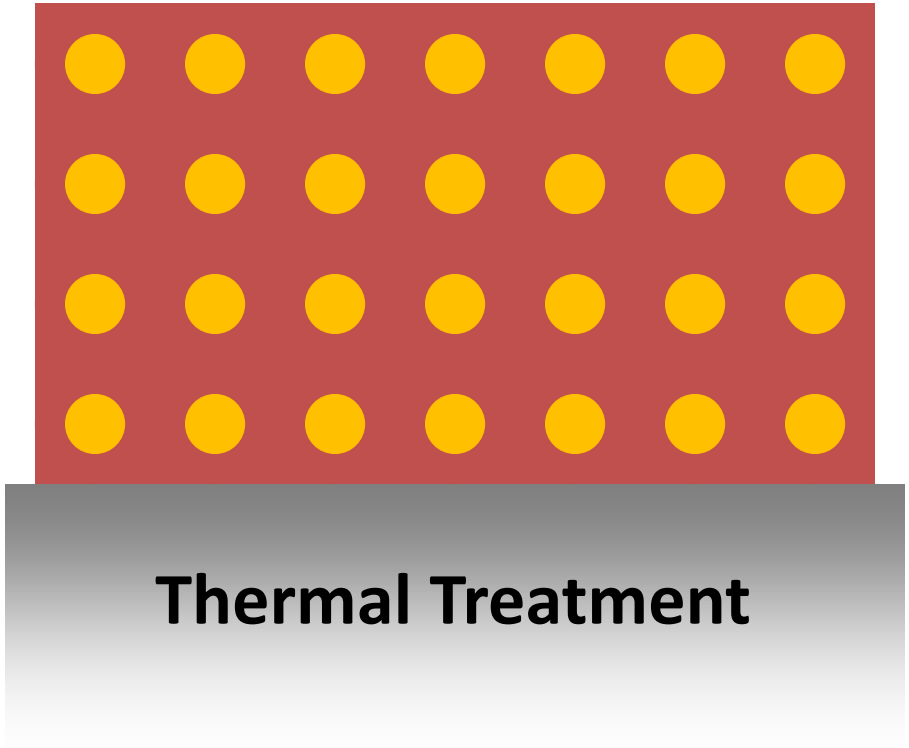


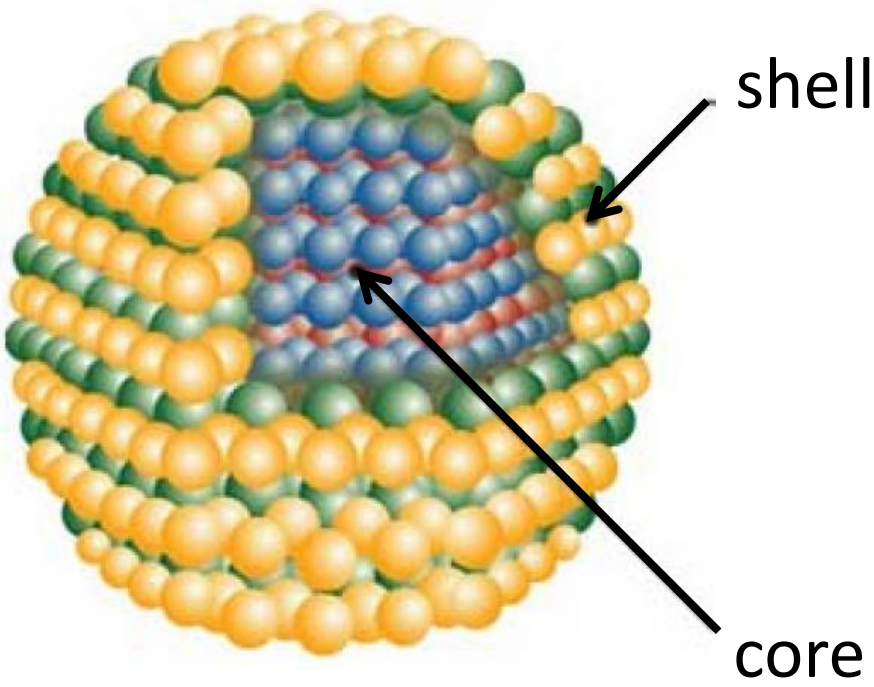


5 µm

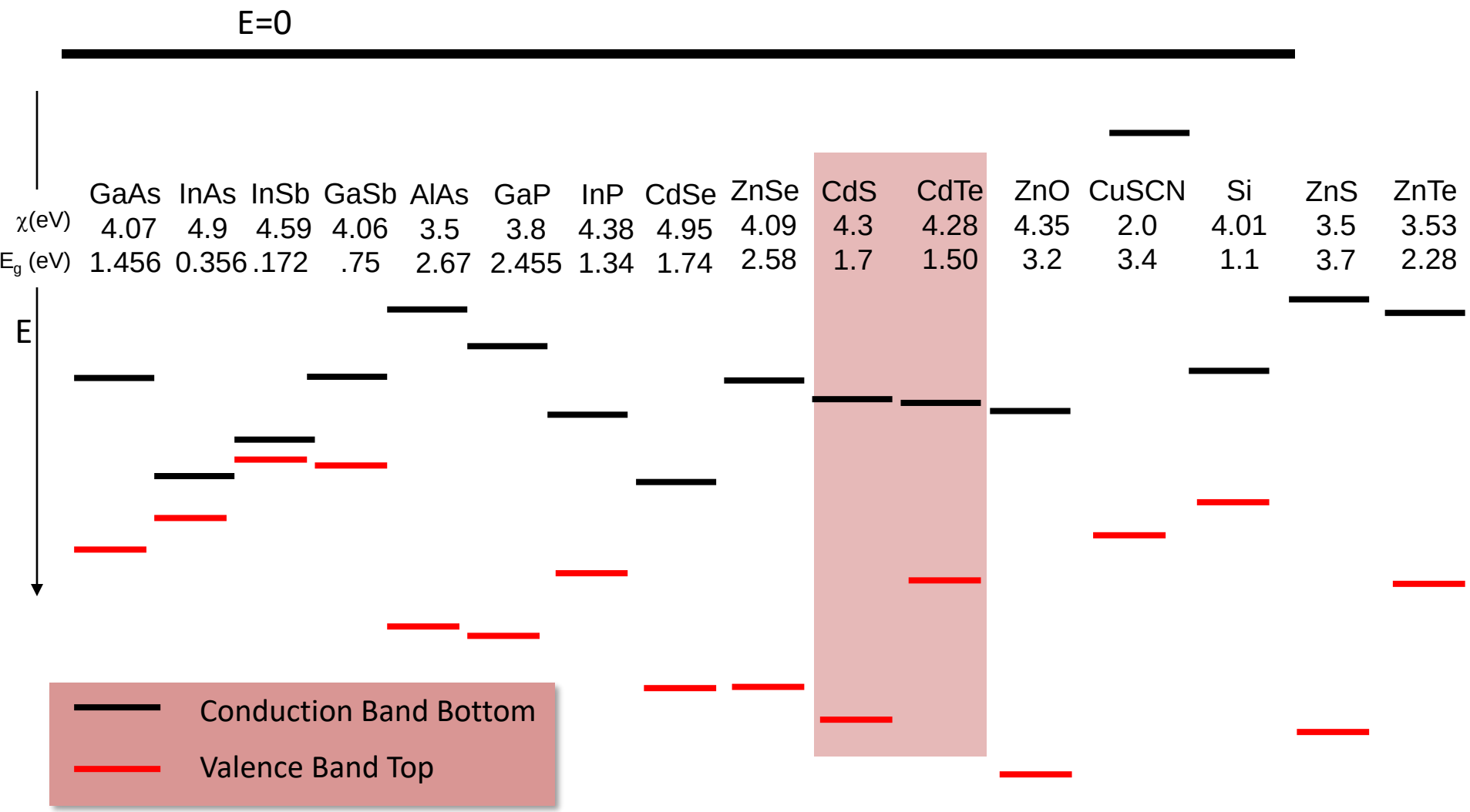
From a Colloidal Solid to a Dense Nanostructured Film

Use Core/Shell Nanocrystals





Materials System Selection



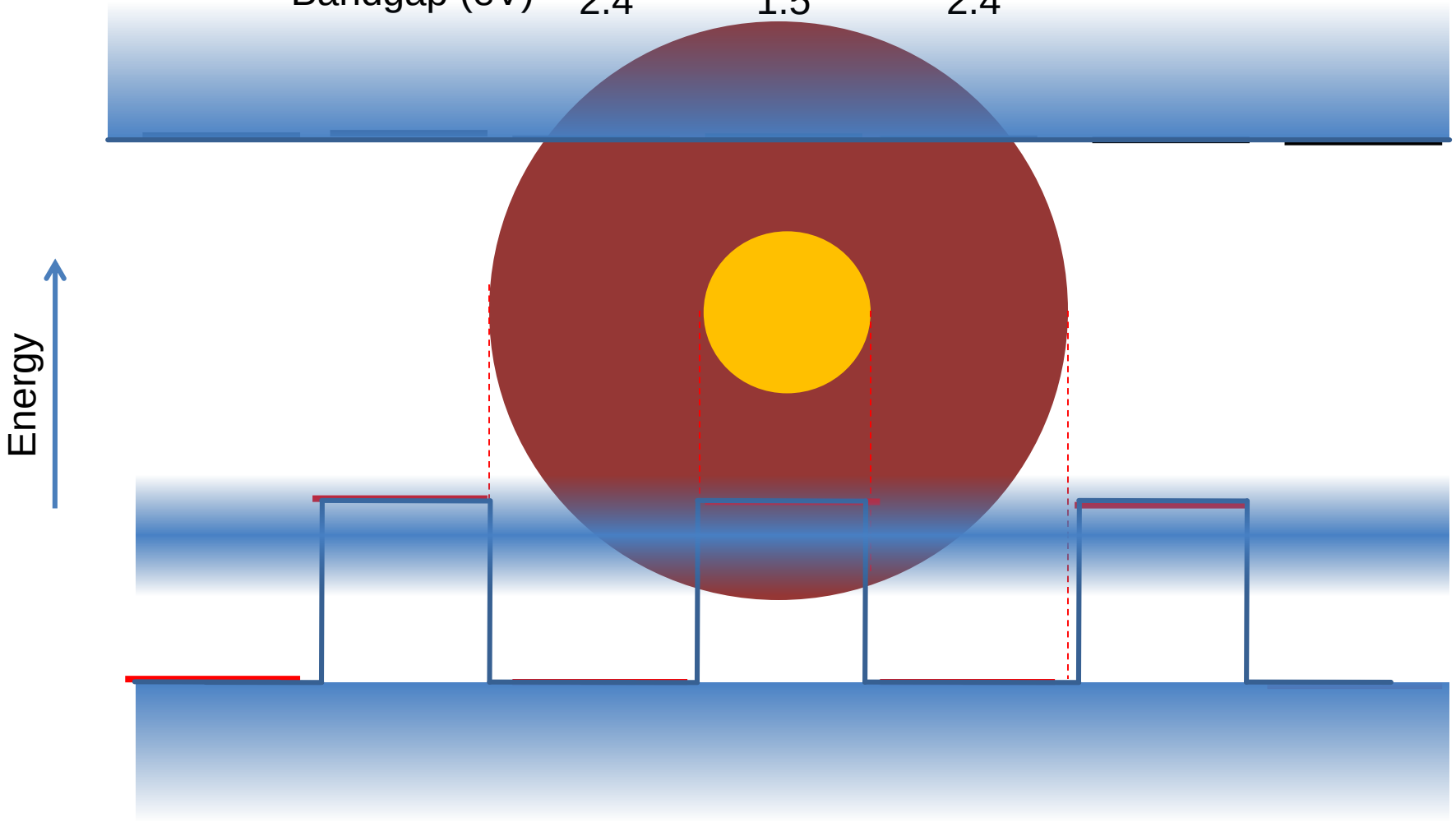
RK Swank, *Phys. Rev.* **153**, 844 (1967)

S. Adachi, *Properties of Grup IV, III-V and II-VI Semiconductors,* Wiley 2005

Goldbery Yu.A. *Handbook Series on Semiconductor Parameters*, vol.1, M. Levinshtein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1996.

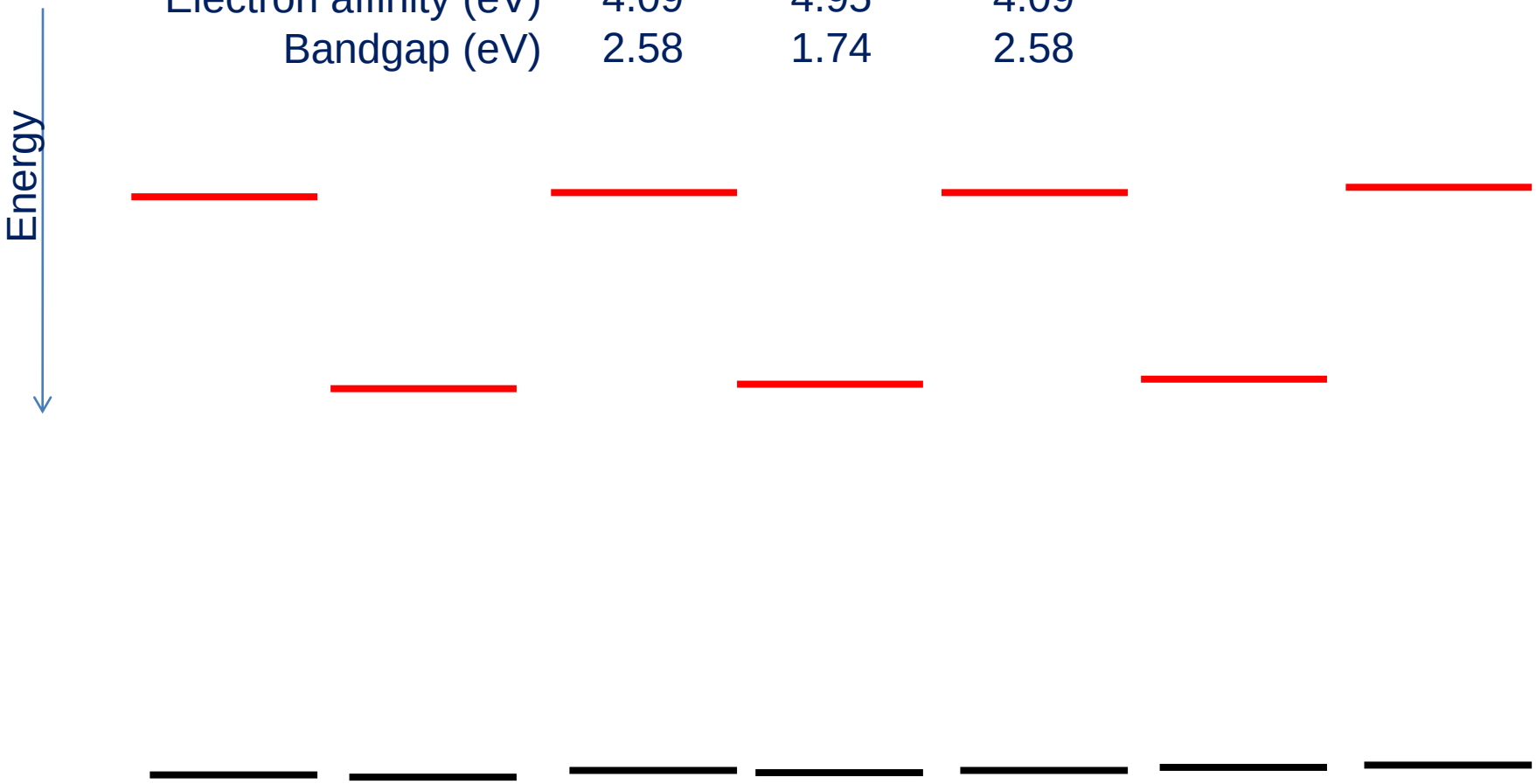
Materials System Selection: Energy Level Alignment

	CdS	CdTe	CdS
Electron affinity (eV)	4.5	4.5	4.5
Bandgap (eV)	2.4	1.5	2.4

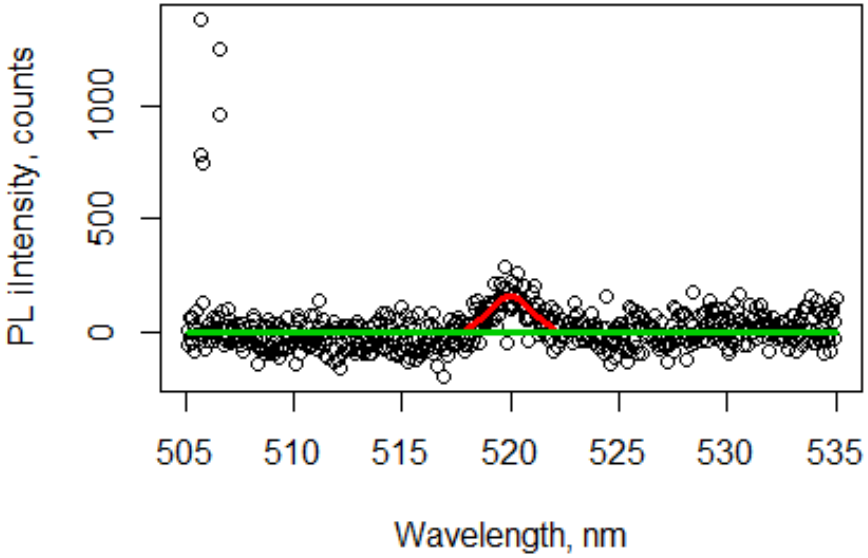


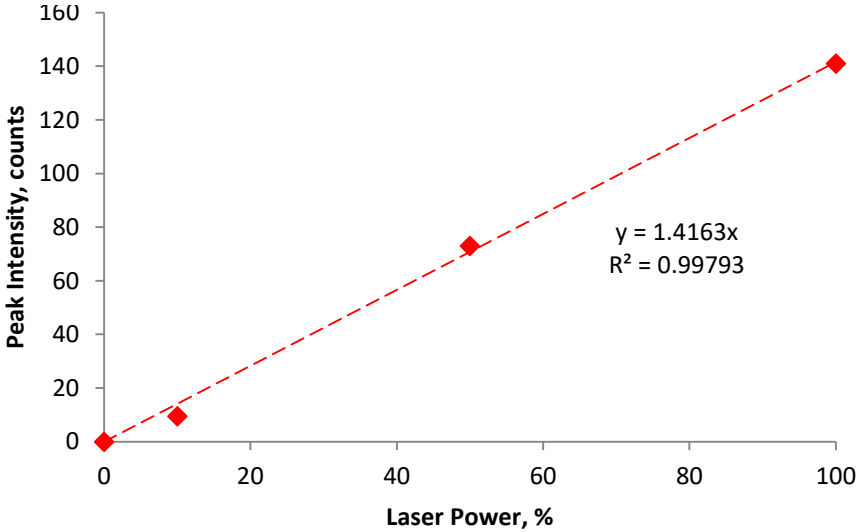
Materials System Selection: Energy Level Alignment

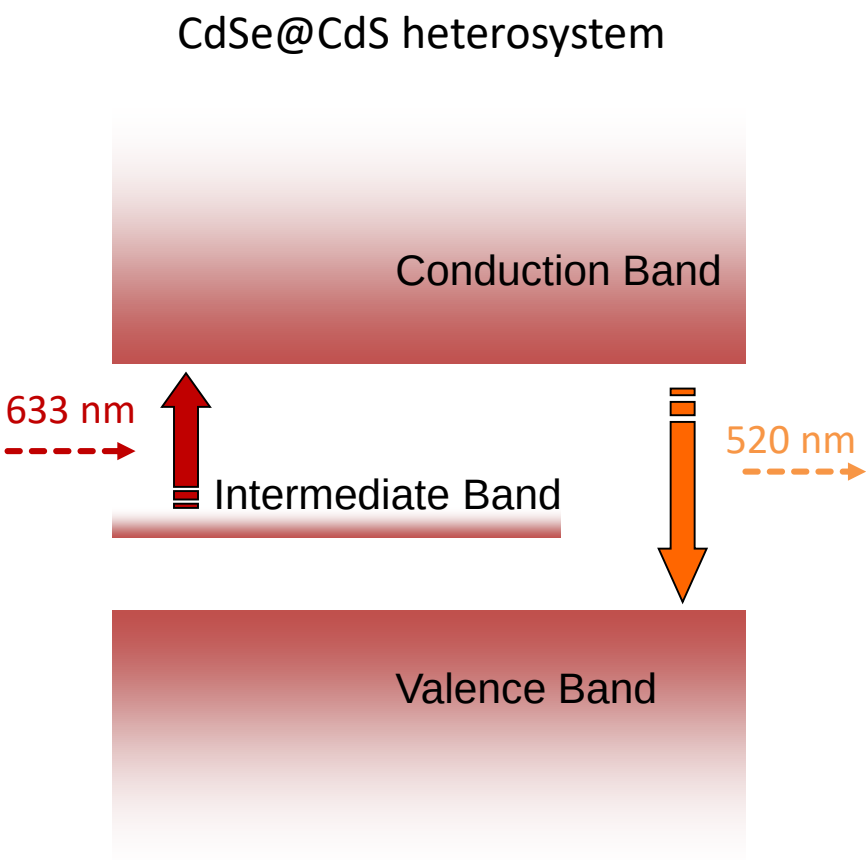
	ZnSe	CdSe	ZnSe
Electron affinity (eV)	4.09	4.95	4.09
Bandgap (eV)	2.58	1.74	2.58



Intermediate Band Materials: Evidence of Upconversion



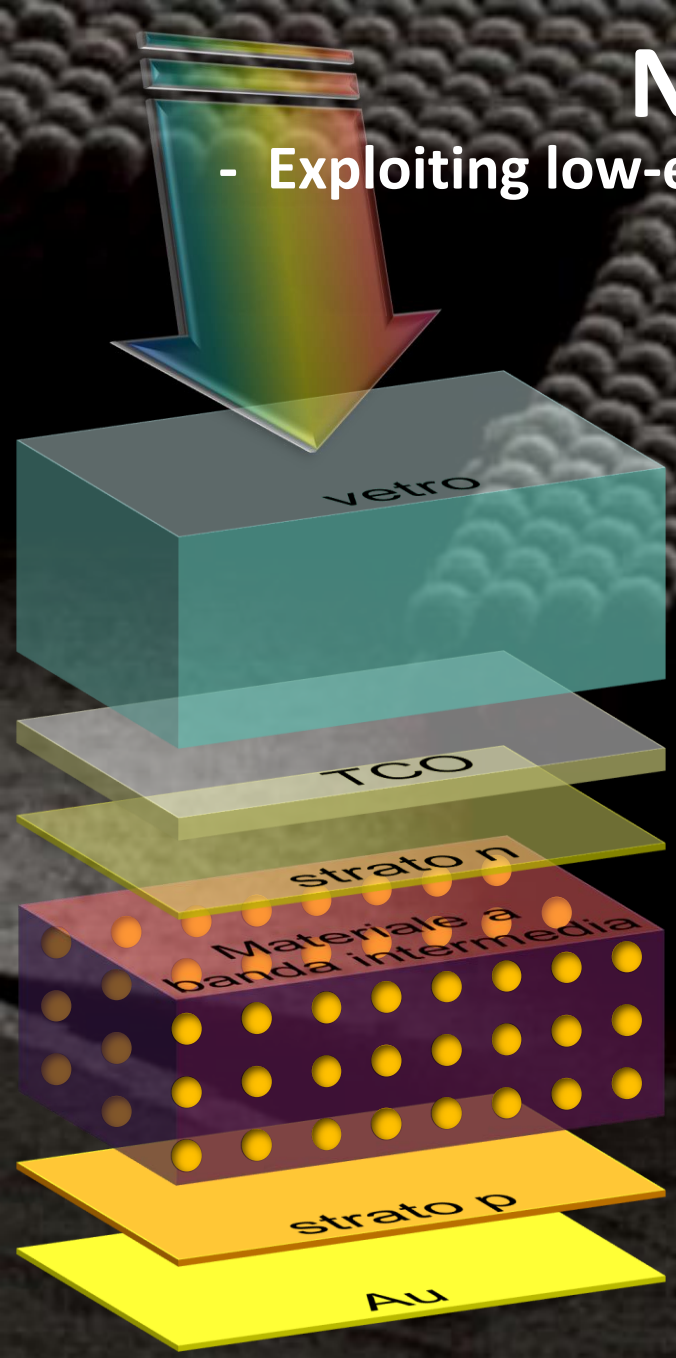


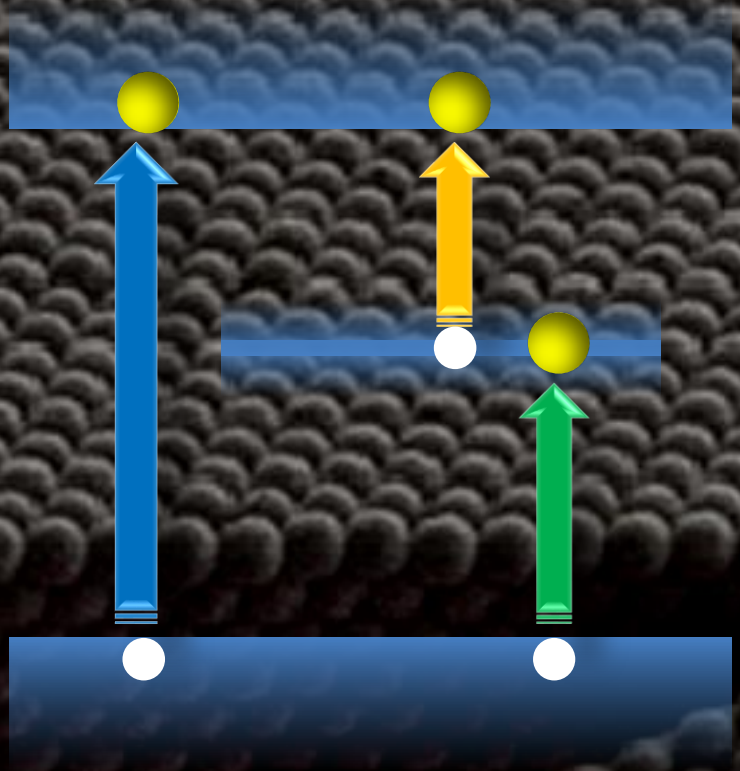


Slejko, PhD Thesis
Slejko, Lughi et al., in prep.

Nanotech and Photovoltaics:

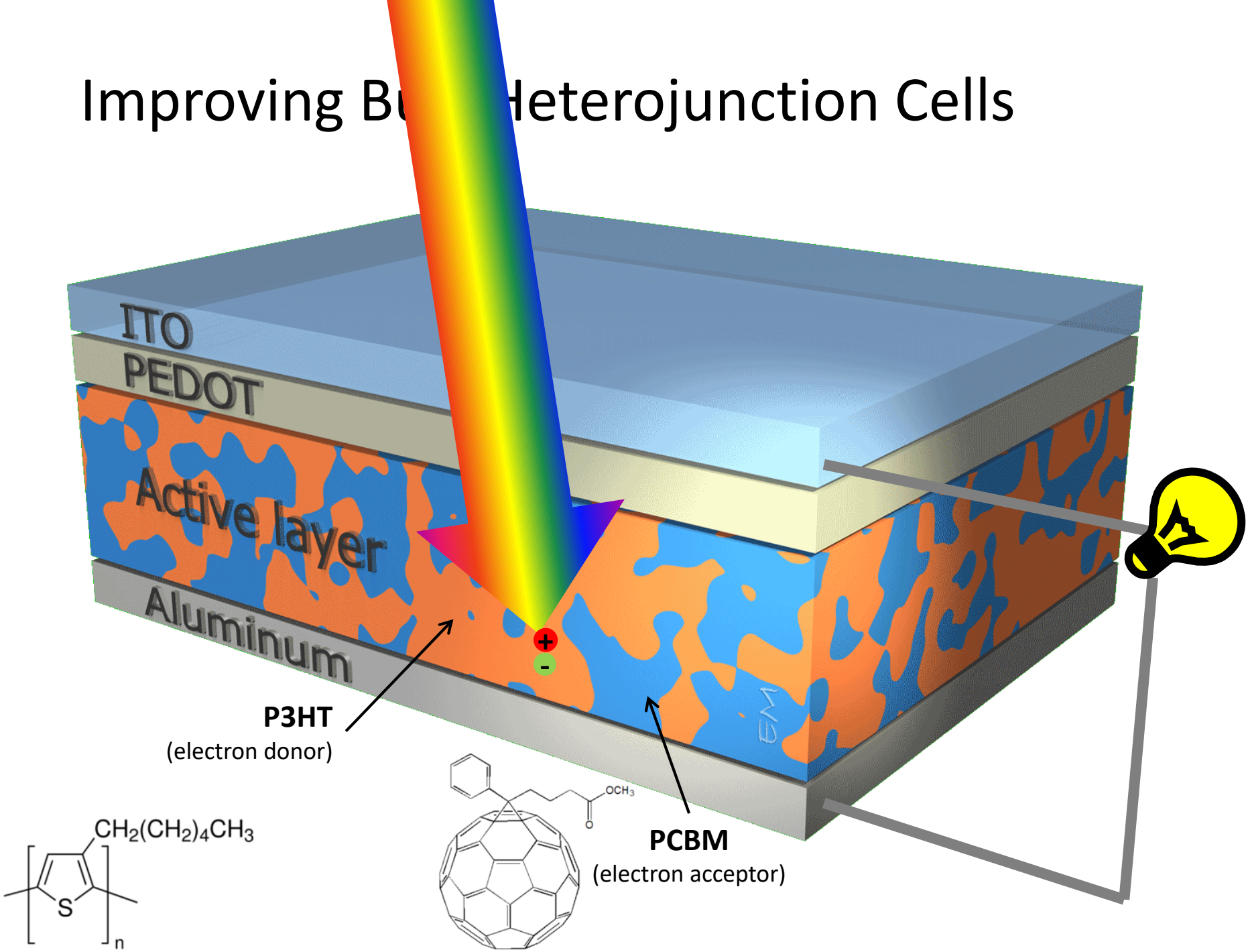
- Exploiting low-energy photons: Intermediate Electronic Band-



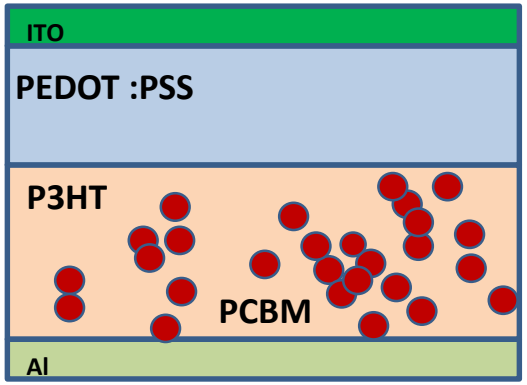


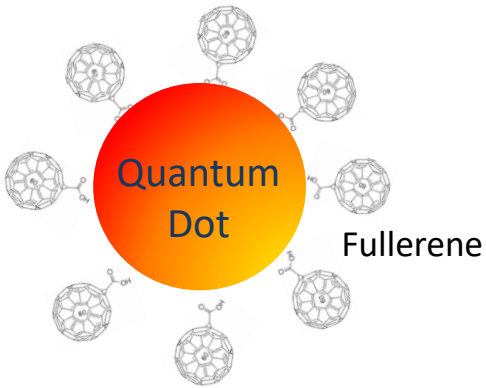
5 µm

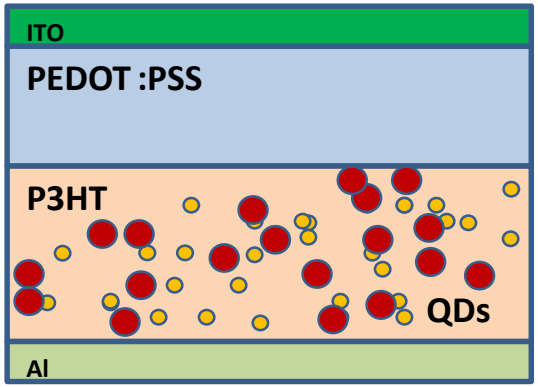
Improving Bu Heterojunction Cells



State of the Art and Founding Idea

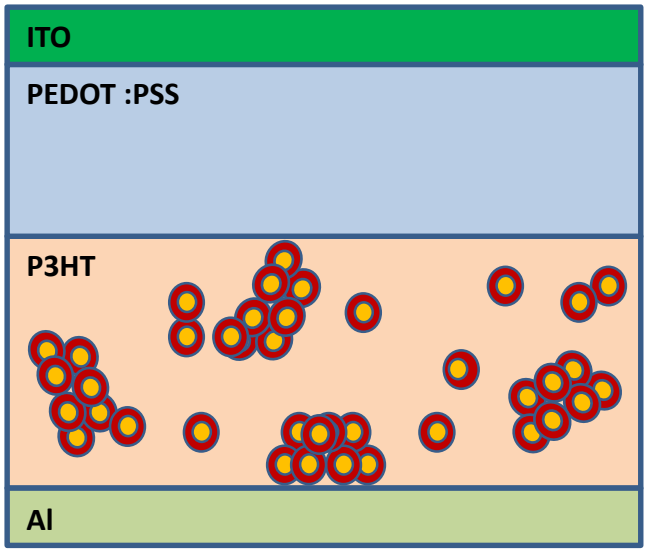




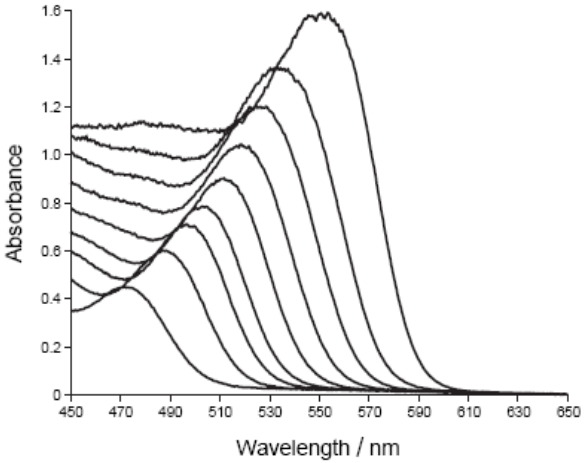


Fullerenes

(e.g. PCBM)



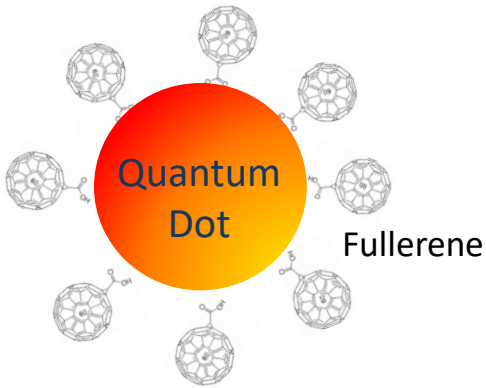
Quantum dots



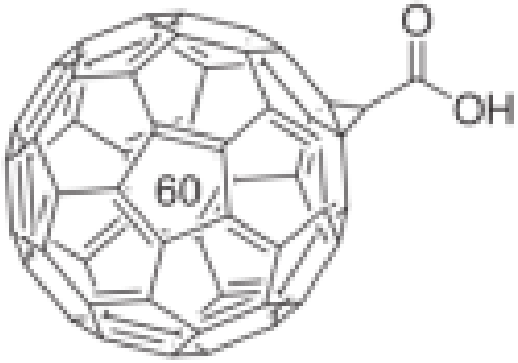
TRANSPORT

ENHANCED ABSORBTION

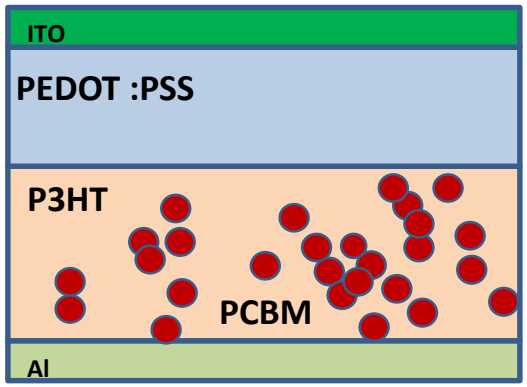
Quantum dot + Fullerene Hybrid: **CdSe@C61**

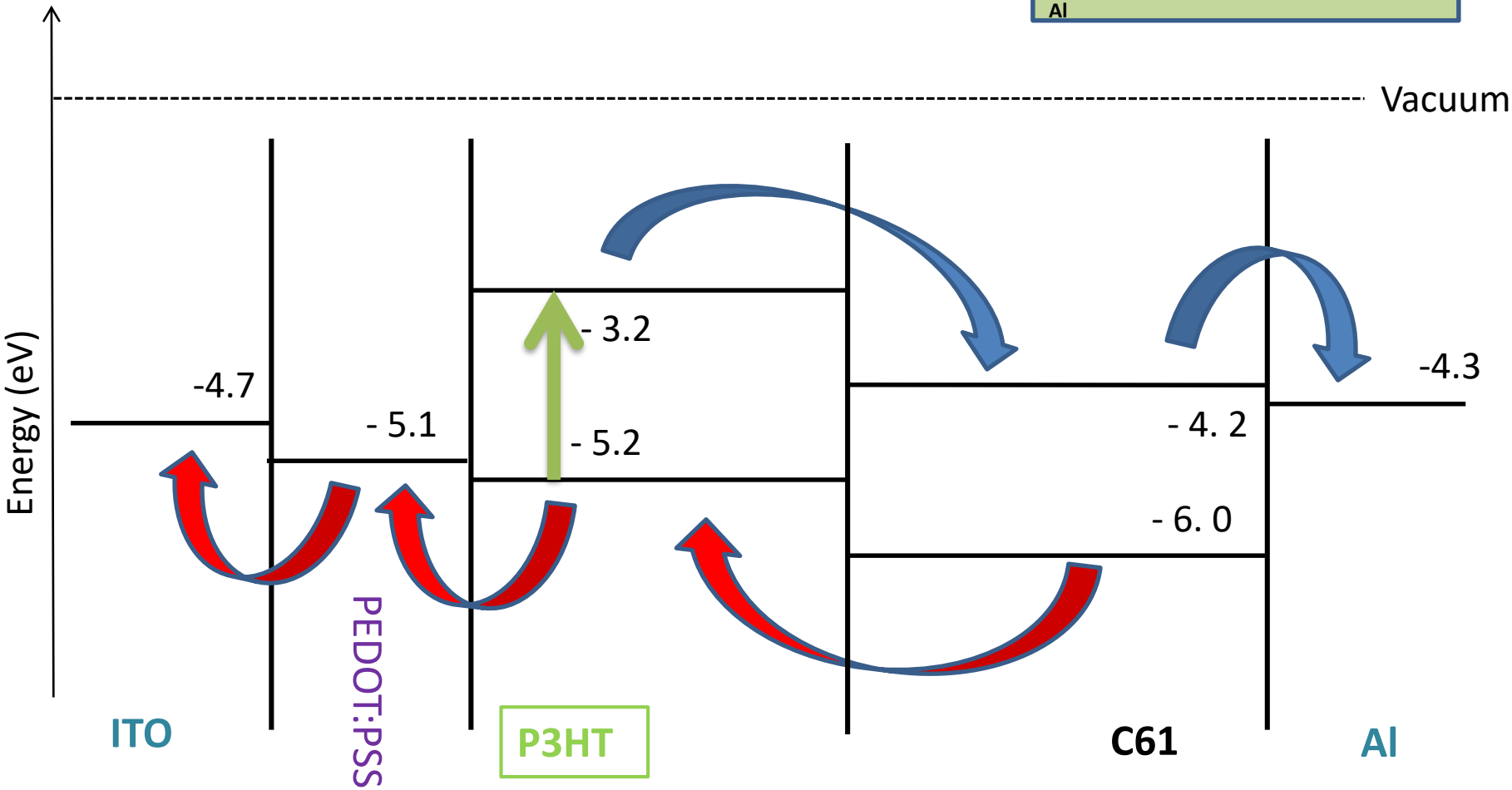


CdSe Quantum Dots + **(1,2-Methanofullerene C60)-61-carboxylic acid**

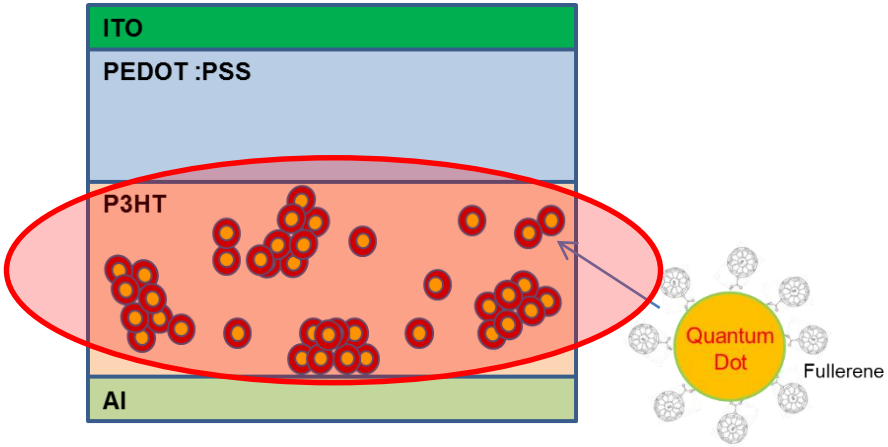


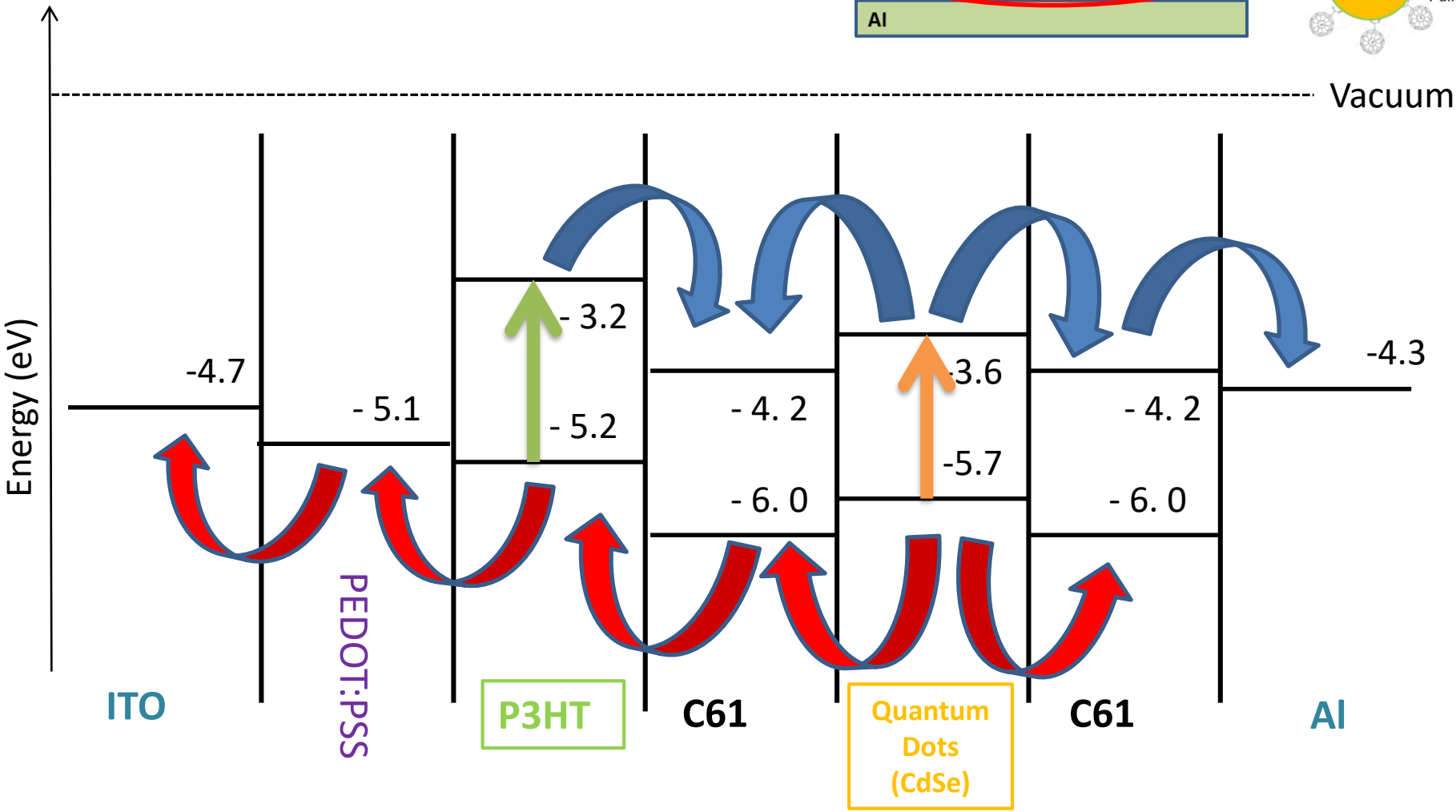
Working principle: standard OPV cell



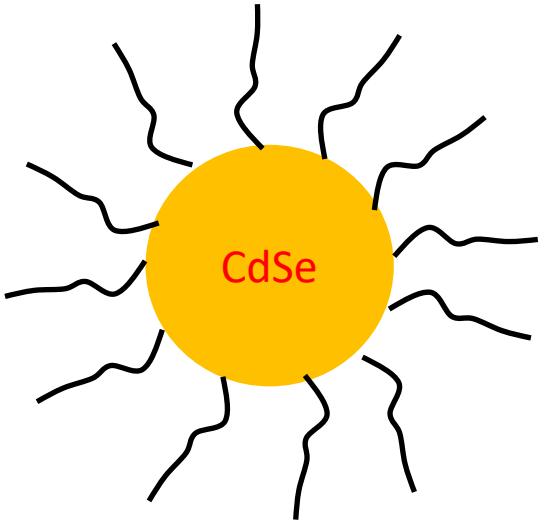


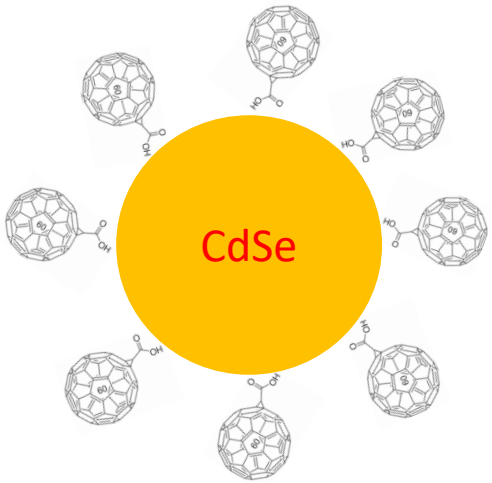
Working principle:
OPV cell with CdSe@C60

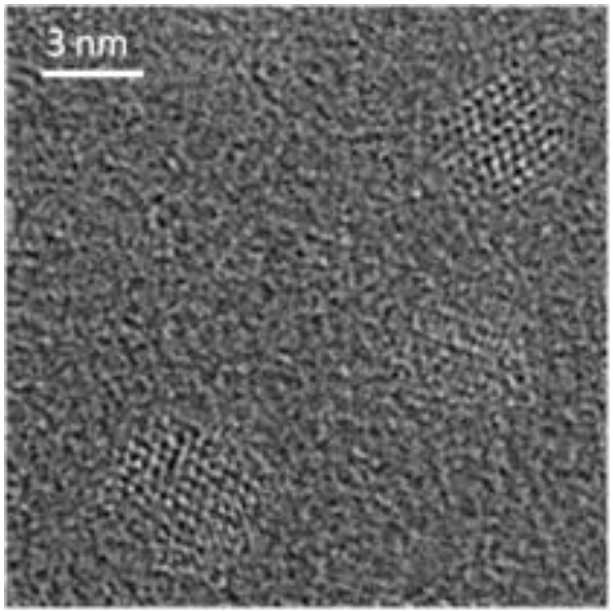


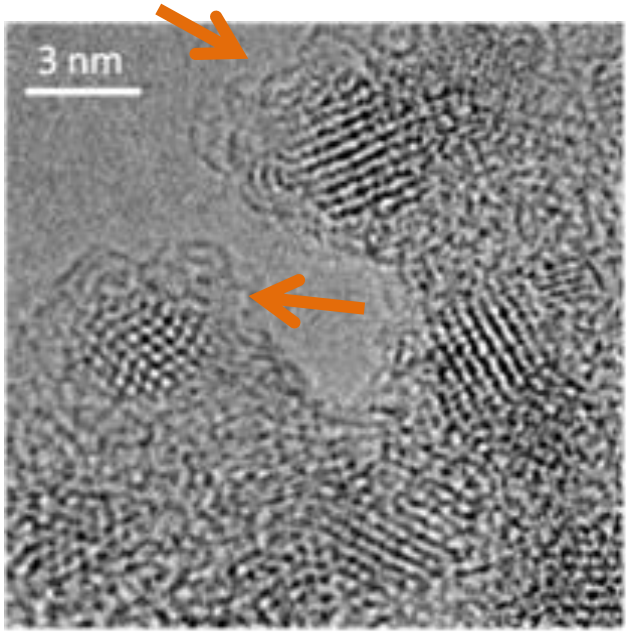


CdSe@C6: Synthesis via Capping Exchange



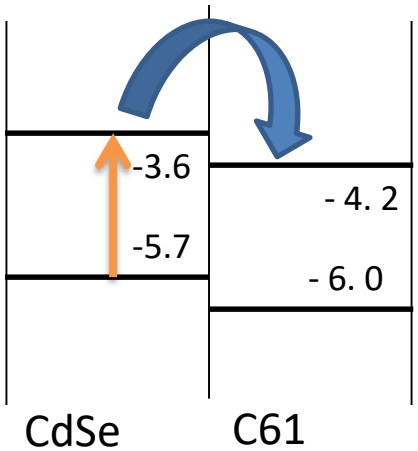


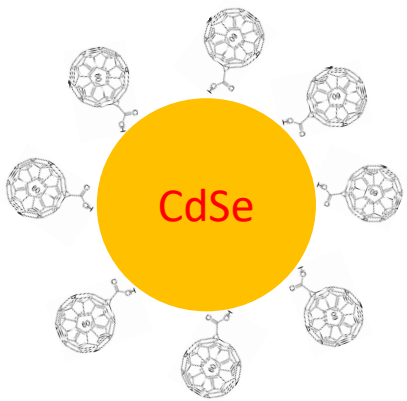


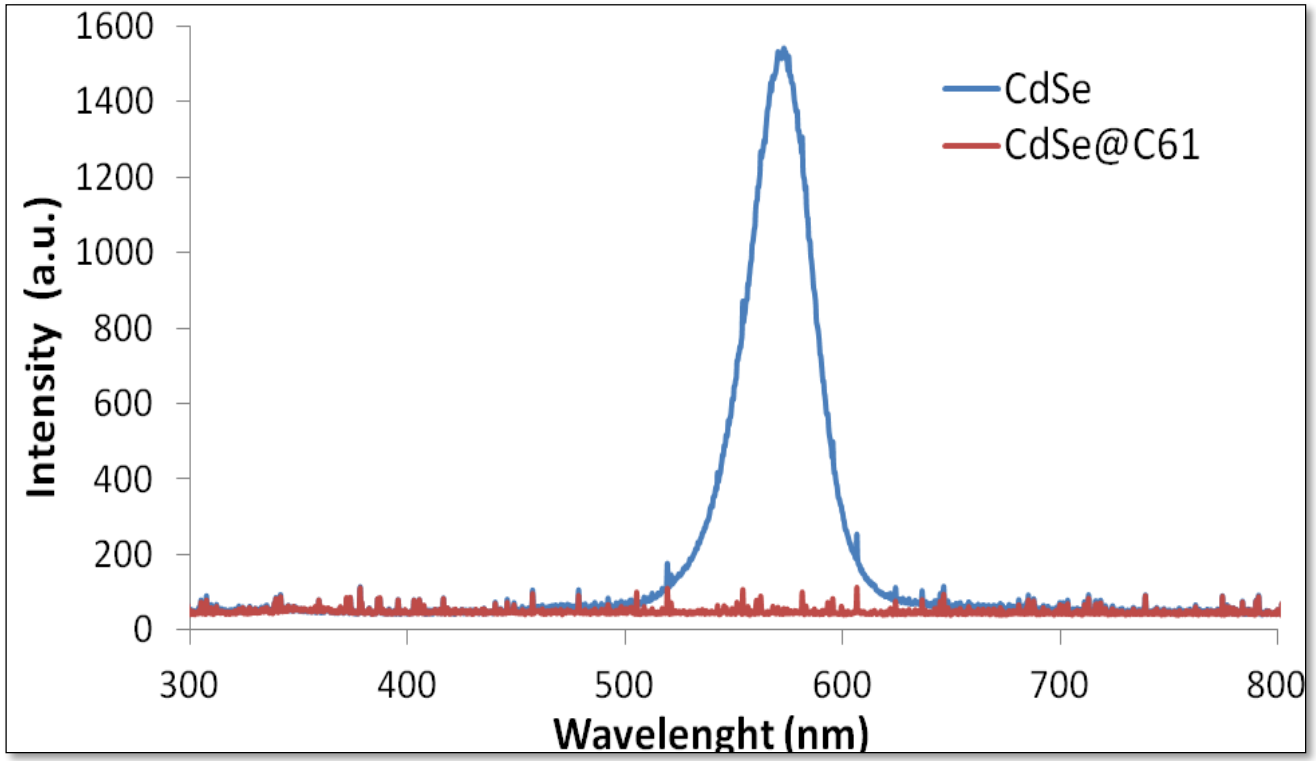


Cacovich, Lughi et al., J. Phys 622, 2014

Photoluminescence Quenching in CdSe@C61

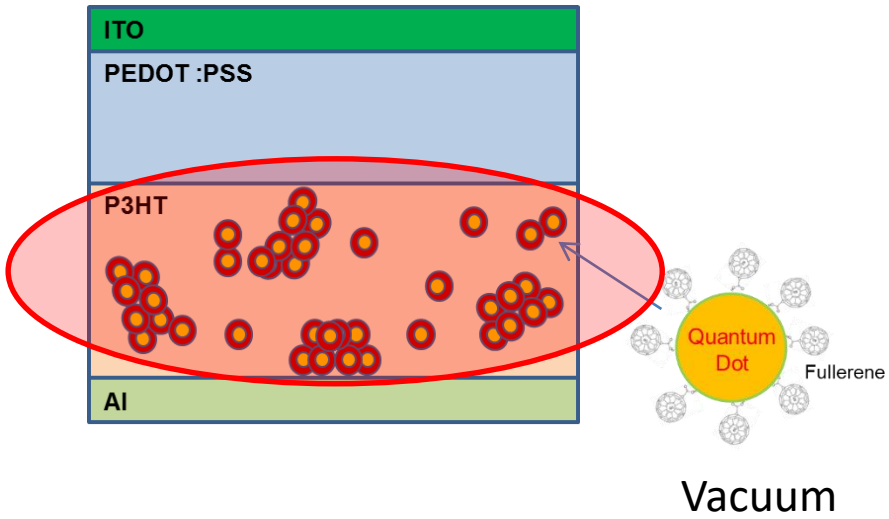


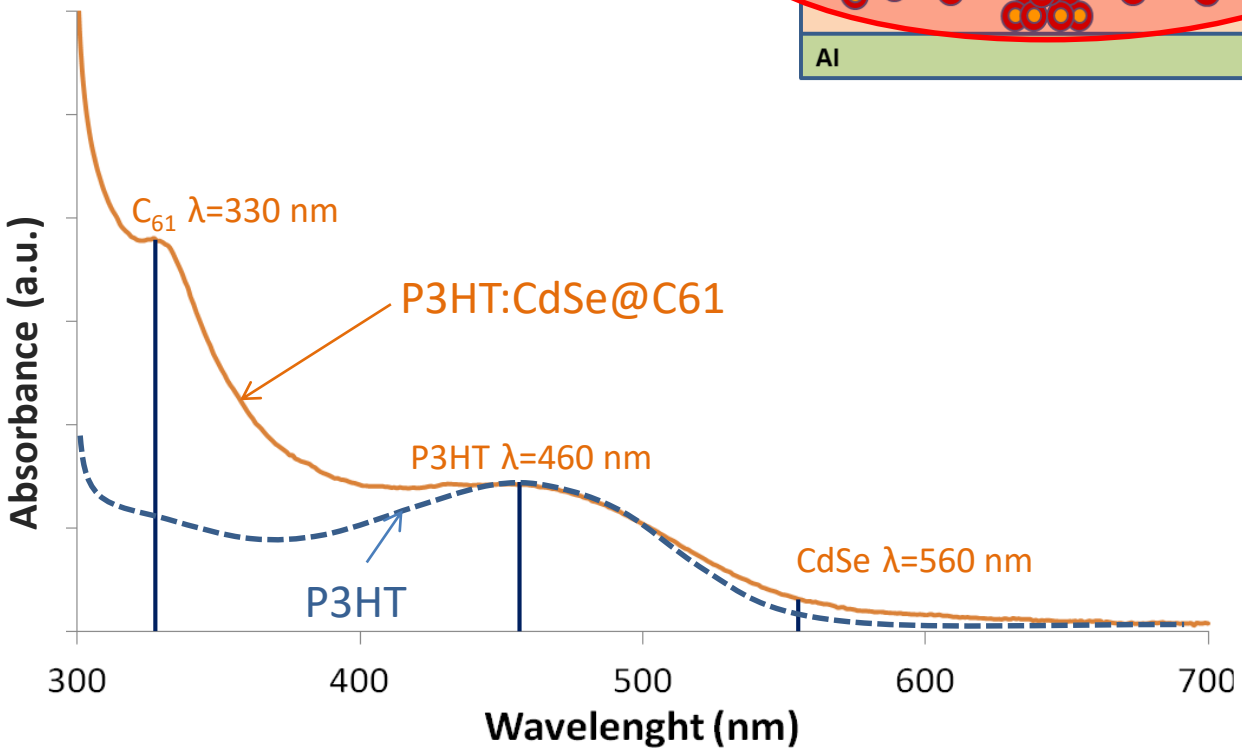




Cacovich, Lughi et al., J. Phys 622, 2014

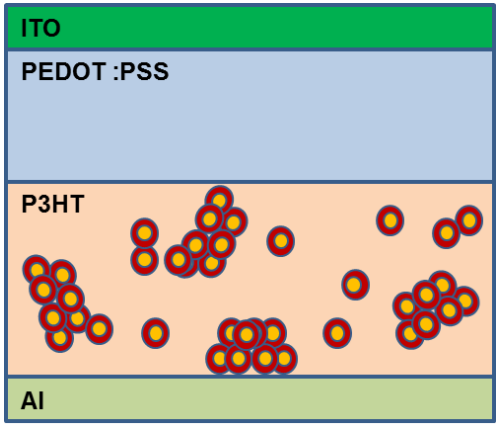
Absorption of P3HT:CdSe@C61 blend

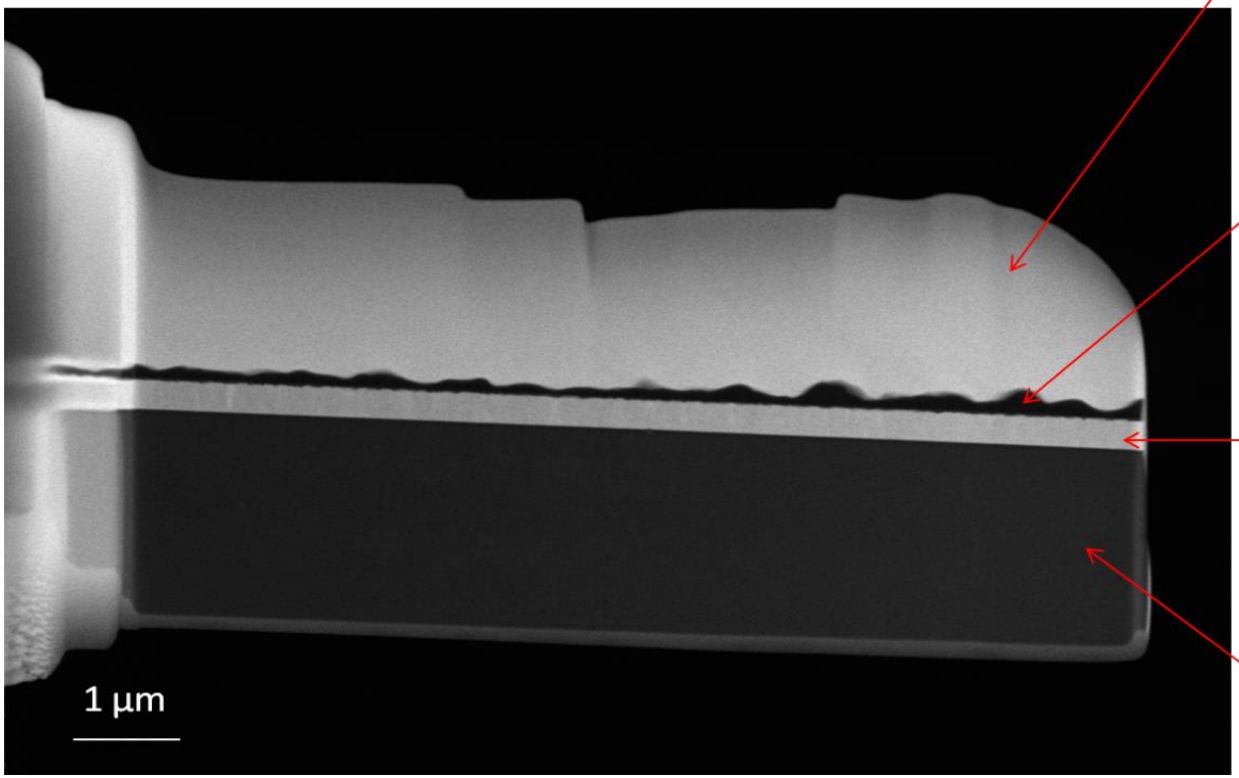




Cacovich, Lughi et al., J. Phys 622, 2014

Photovoltaic device

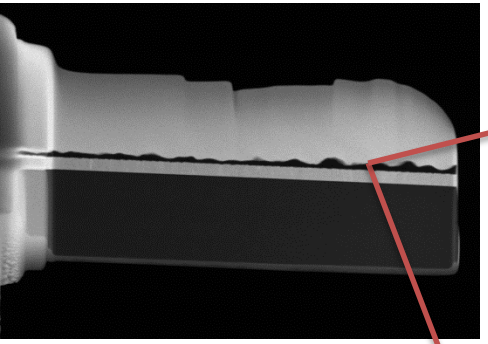


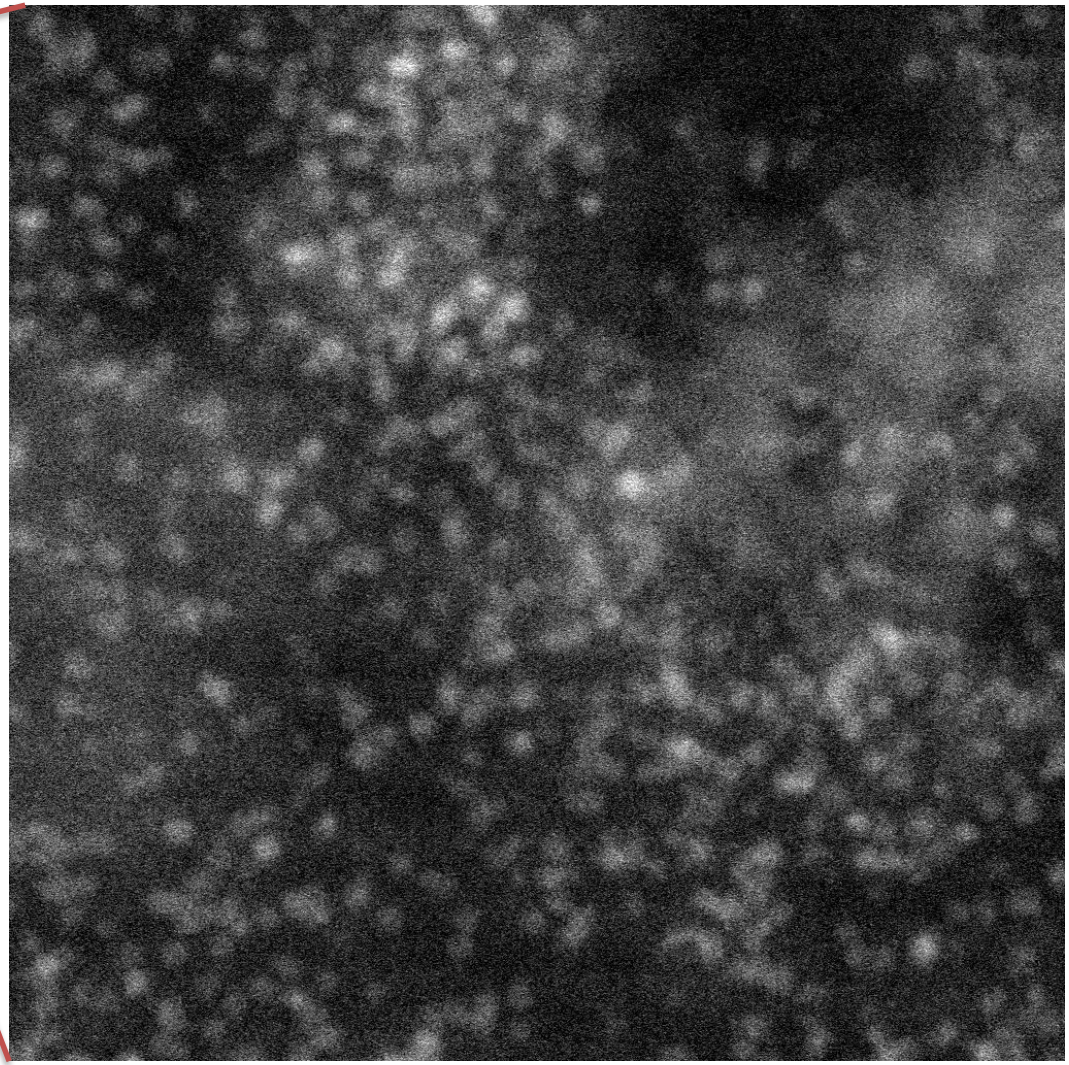


ITO	300 nm +- 3nm
TiO_2	20 nm +- 2nm
Blend	140 nm +- 44 nm

Cacovich, Lughi et al., J. Phys 622, 2014

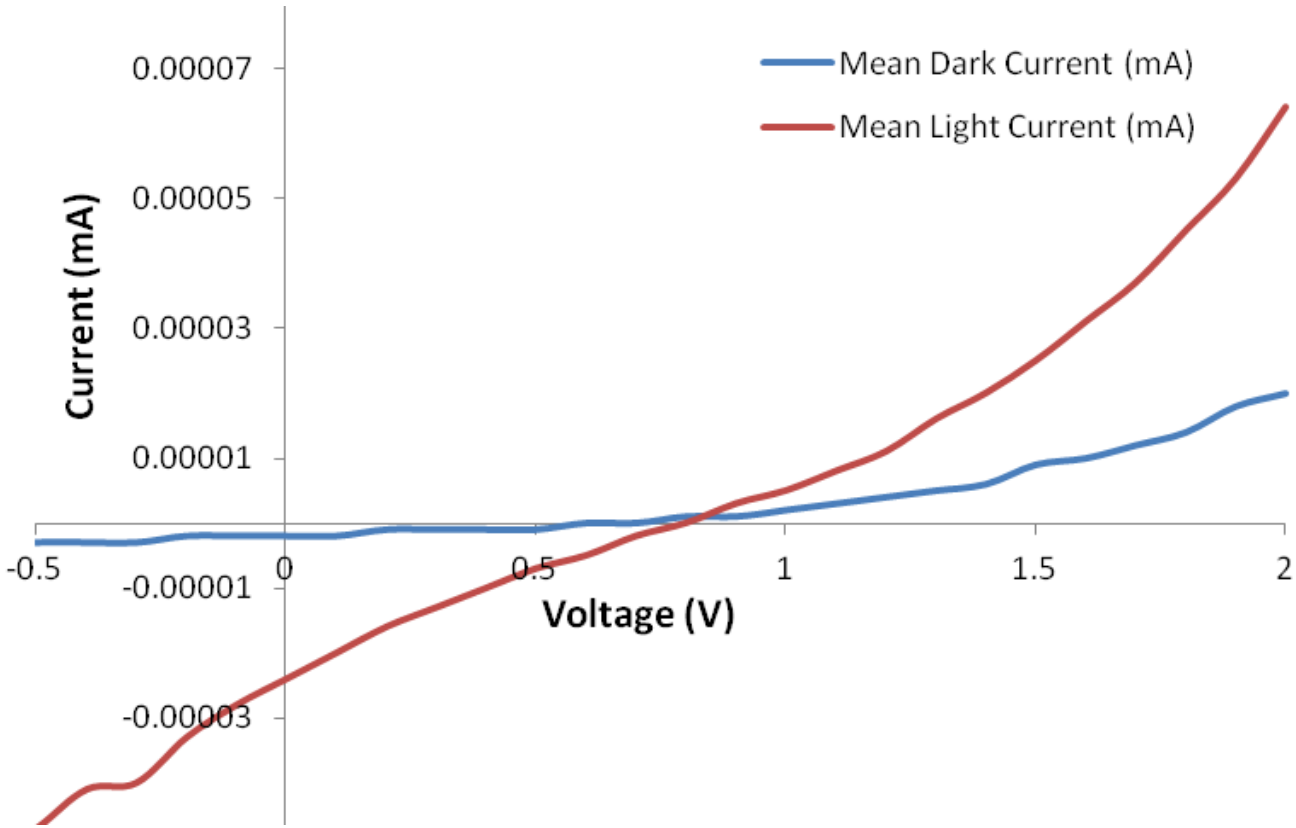
P3HT:CdSe@C61 blend





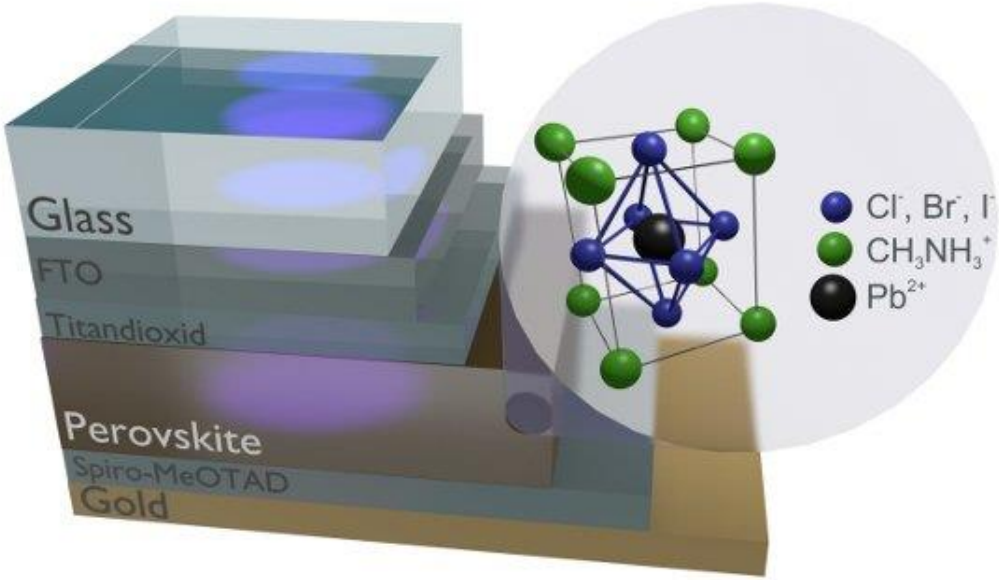
GOOD DISPERSION !!!

I-V Characteristic

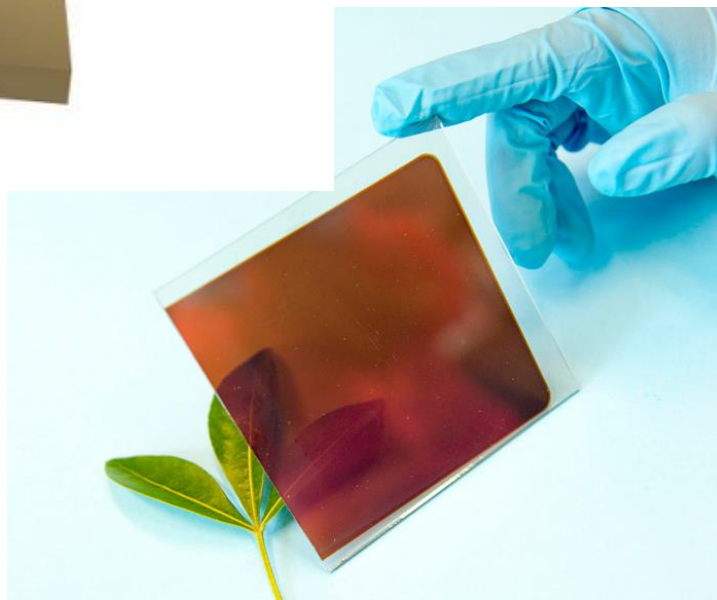


Voc ~ 0.8 V

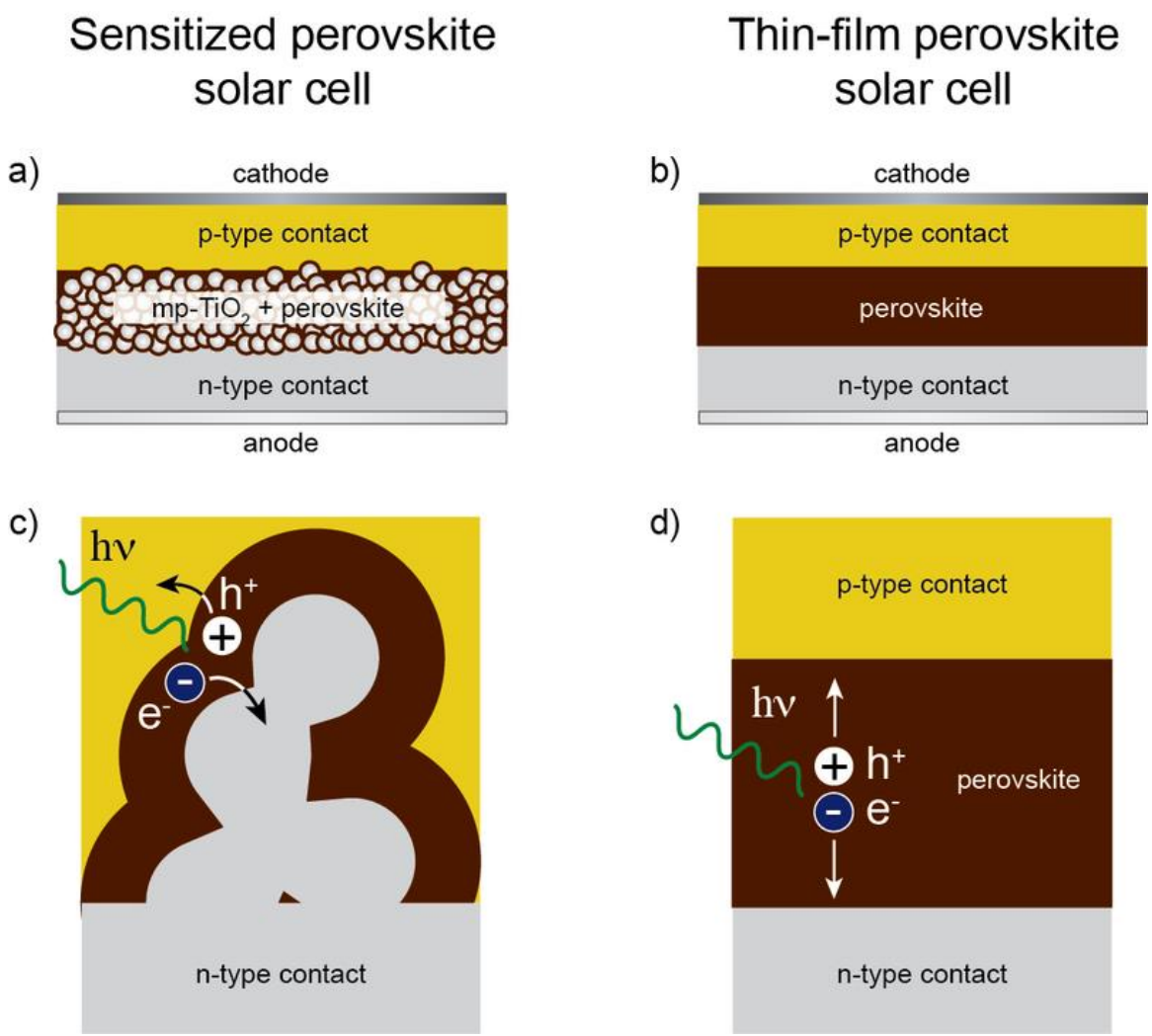
The latest frontier
Perovskite-based solar cells



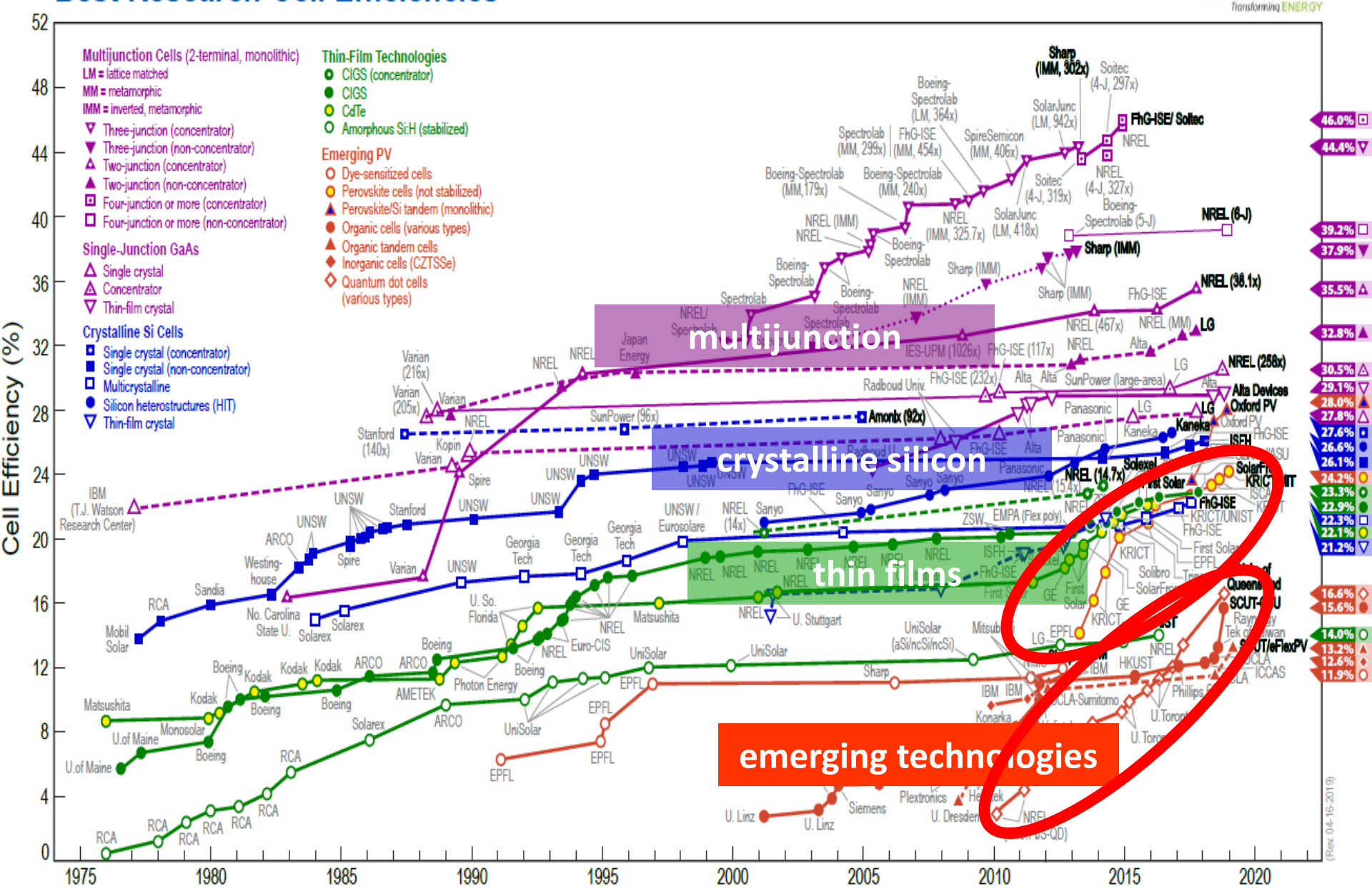
- Most promising thin film technology (high efficiency)
- Cheap, high-throughput manufacturing



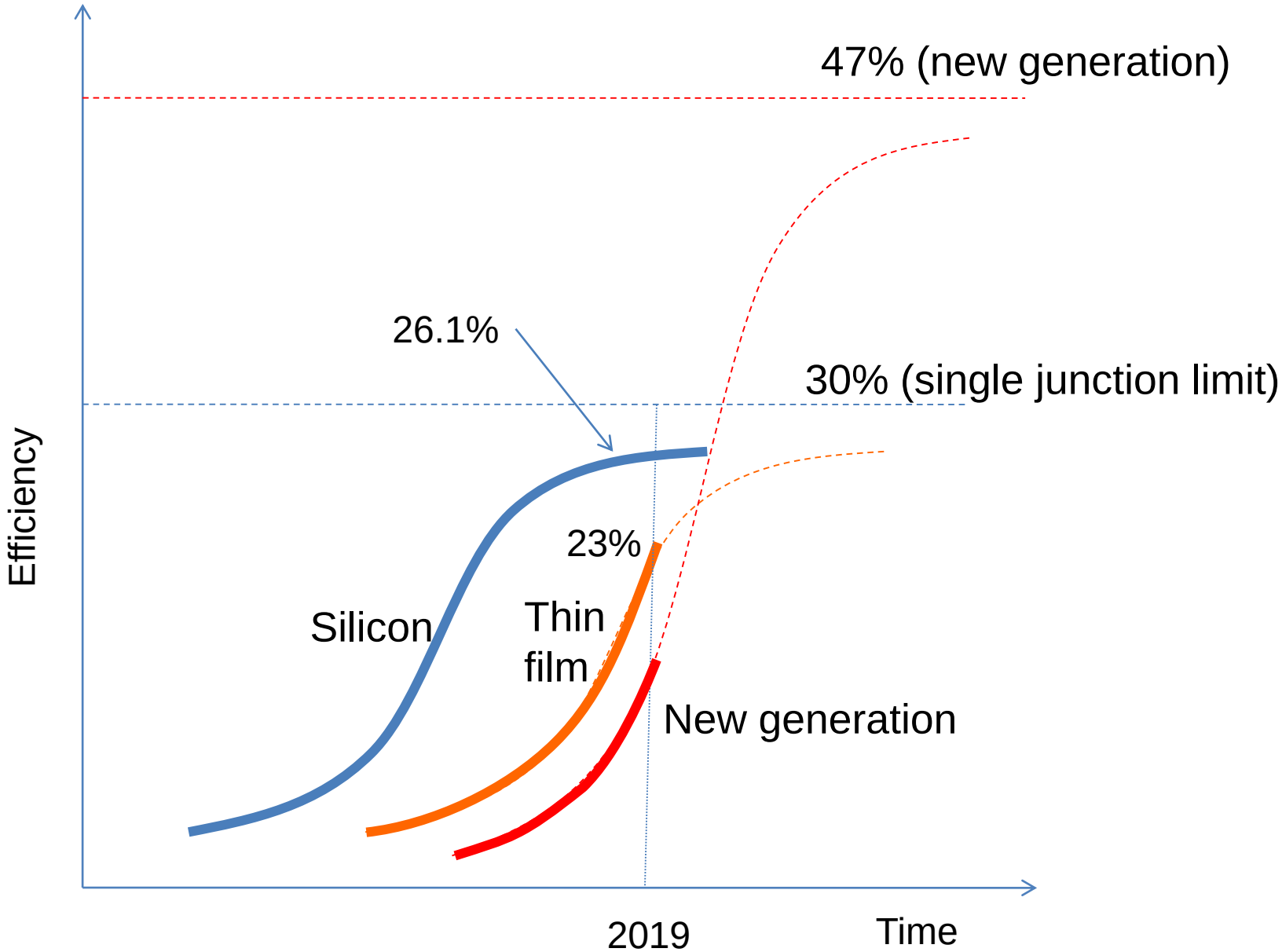
The latest frontier
Perovskite-based solar cells



Best Research-Cell Efficiencies

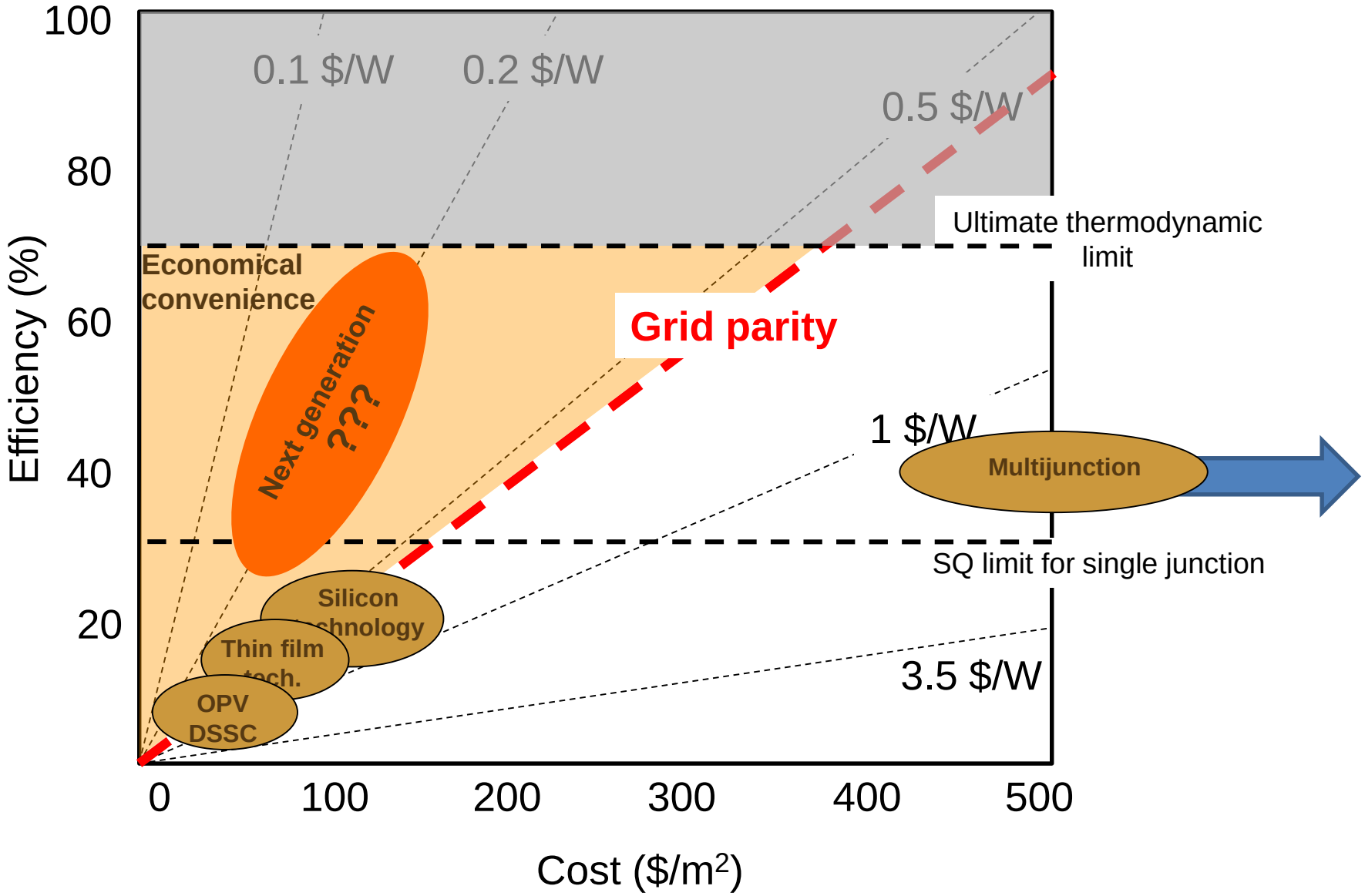


Enhancement potential



Next-generation solar cells

- Techno-economic positioning -



Concluding Remarks

- The cost reduction of the PV-kWh enabled attainment of grid parity in many Countries
- Most of the cost reduction has been driven by the economies of scale
- Nevertheless, technological innovation and breakthroughs are still important
- Current technologies have shown incremental, marginal improvements
- «Emerging» technologies such as Organic PV and DSSC need to prove robustness. They will hardly play a role in power generation
- The newest technologies (perovskites, quantum dot-based) have the chance to be a real breakthrough by combining high efficiency and extremely low cost