Organic Electronic Devices

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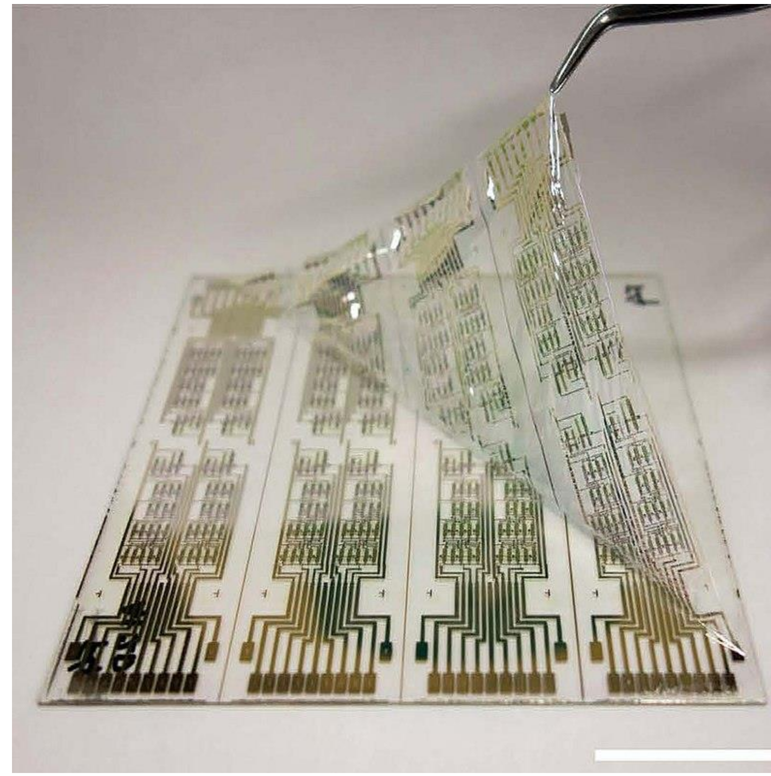
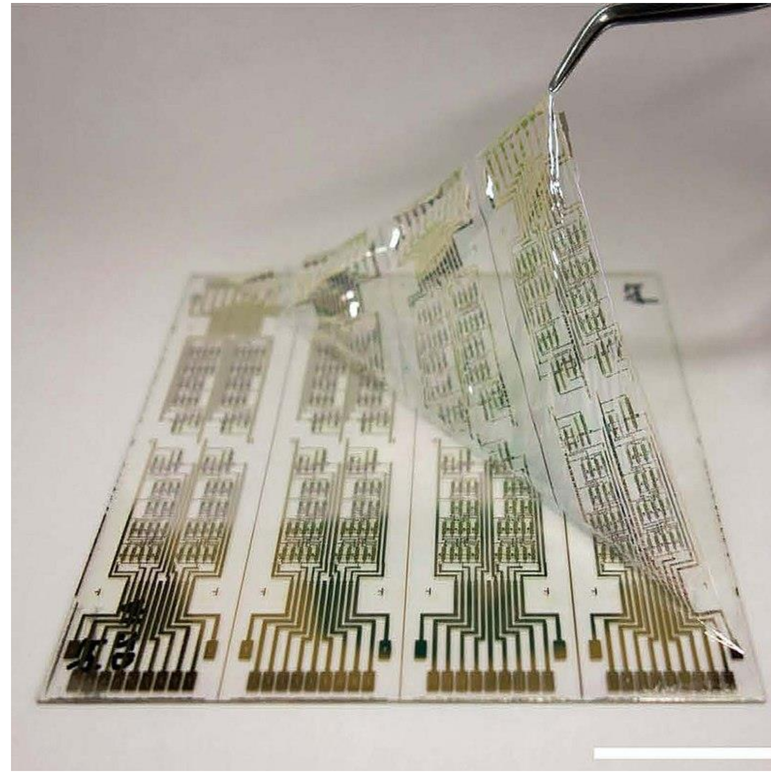
Organic Electronics

- ✓ Organic electronics is a field of materials science concerning the design, synthesis, characterization, and application of organic molecules or polymers that show desirable electronic properties such as conductivity.
- ✓ Unlike conventional inorganic conductors and semiconductors, organic electronic materials are constructed from organic (carbon-based) molecules or polymers using synthetic strategies developed in the context of organic chemistry and polymer chemistry.

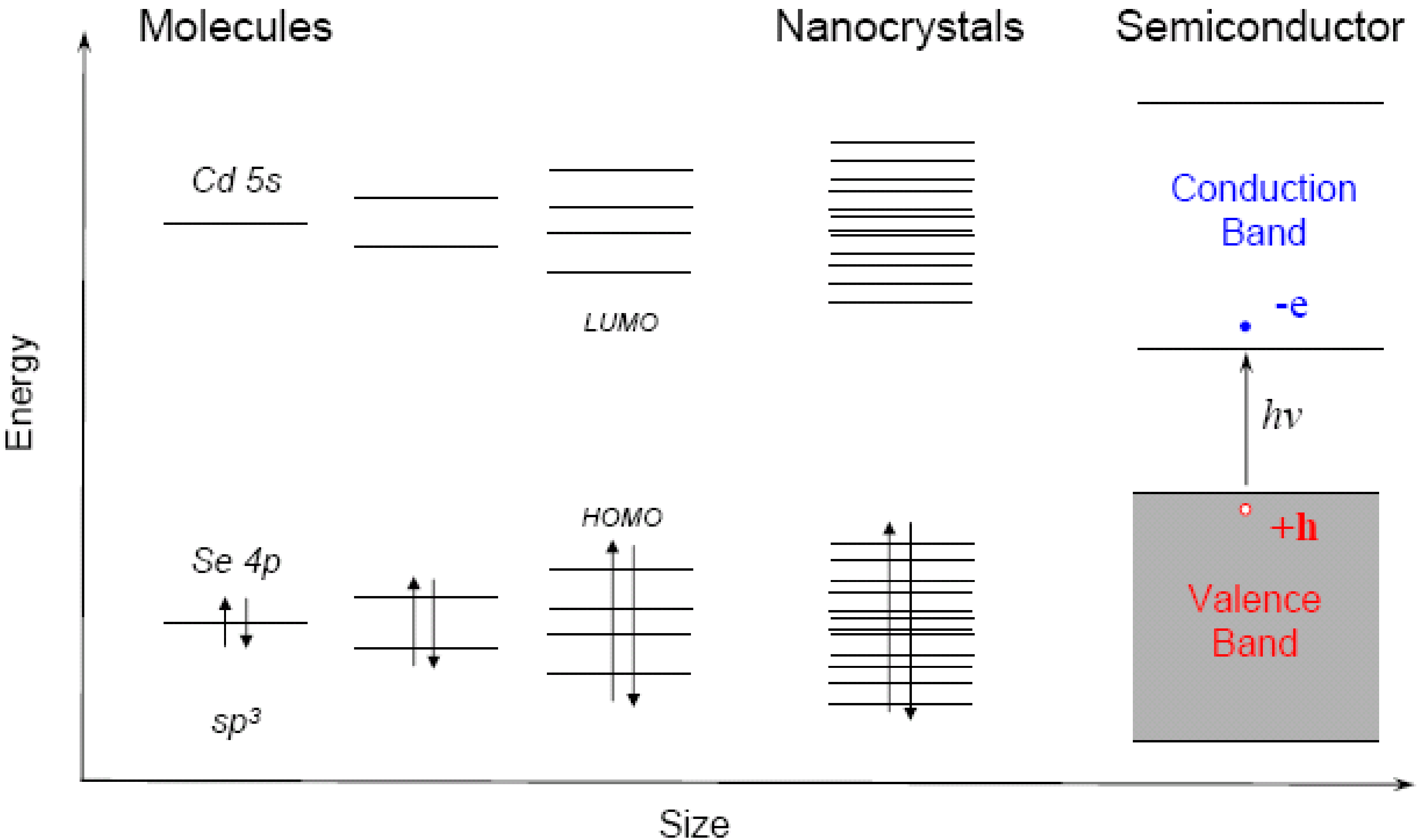


Organic Electronics

- ✓ One of the promised benefits of organic electronics is their potential low cost compared to traditional electronics
- ✓ Attractive properties of polymeric conductors include their electrical conductivity (which can be varied by the concentrations of dopants) and comparatively high mechanical flexibility.
- ✓ Challenges to the implementation of organic electronic materials are their inferior thermal stability, and diverse fabrication issues.

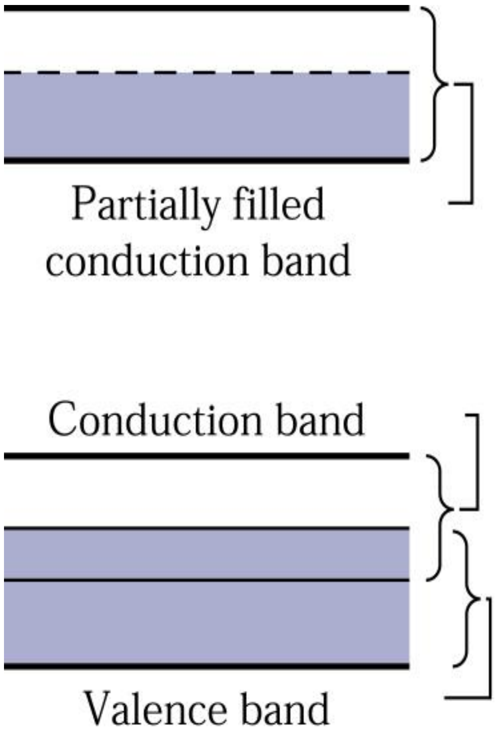


Energy Band Formation in Solid

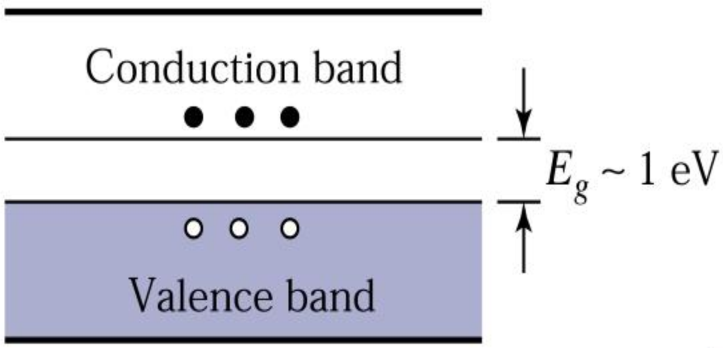


- Each isolated atom has discrete energy level, with two electrons of opposite spin occupying a state.
- When atoms are brought into close contact, these energy levels split.
- If there are a large number of atoms, the discrete energy levels form a “continuous” band.

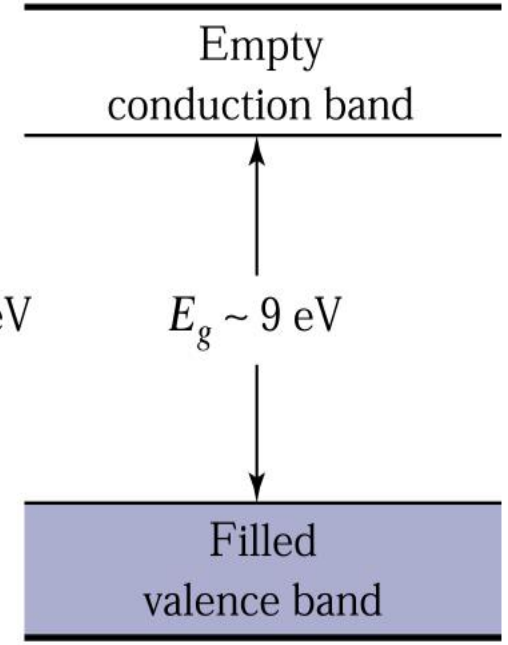
Energy Band Diagram of a Conductor, Semiconductor, and Insulator



a conductor



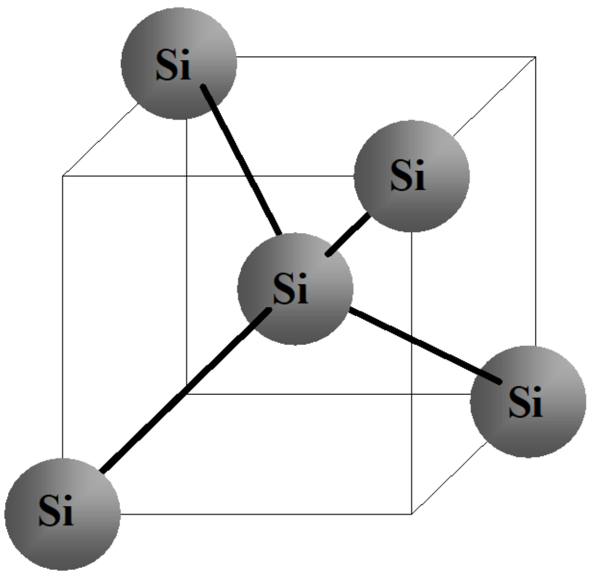
a semiconductor

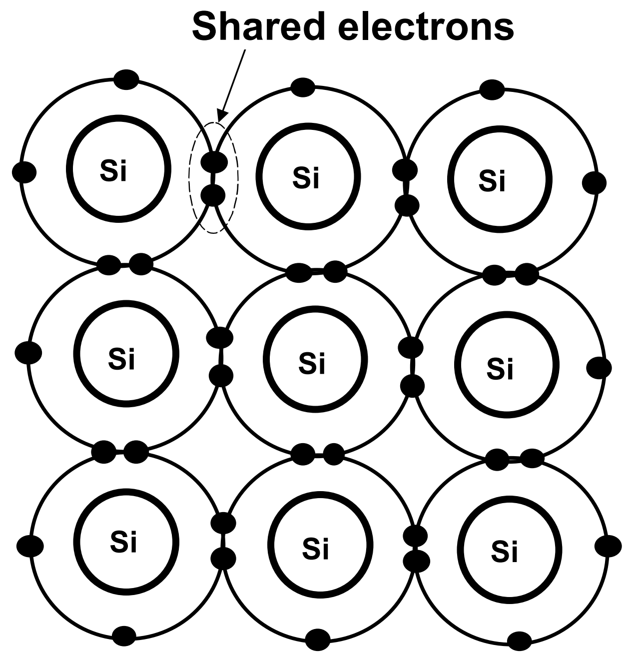


an insulator

- Semiconductor is interest because their conductivity can be readily modulated (by impurity doping or electrical potential), offering a pathway to control electronic circuits.

Silicon





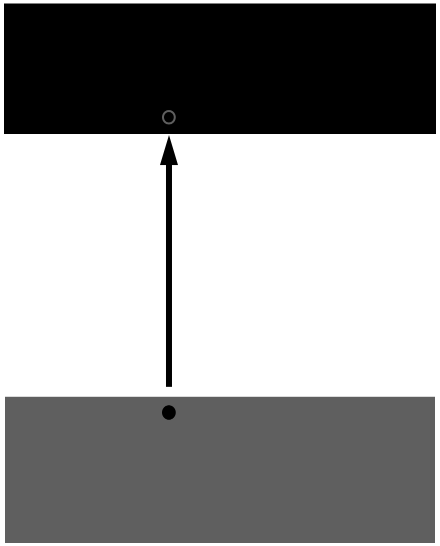
- Silicon is group IV element – with 4 electrons in their valence shell.
- When silicon atoms are brought together, each atom forms covalent bond with 4 silicon atoms in a tetrahedron geometry.

Intrinsic Semiconductor

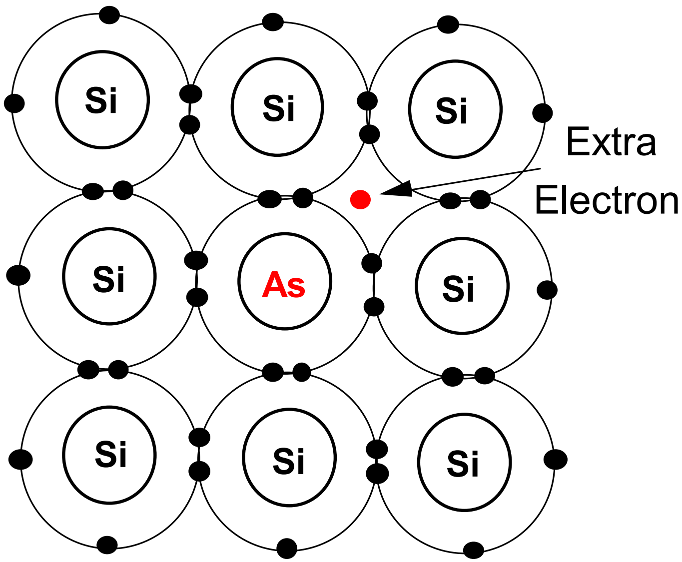
- At 0 ºK, each electron is in its lowest energy state so each covalent bond position is filled. If a small electric field is applied to the material, no electrons will move because they are bound to their individual atoms.

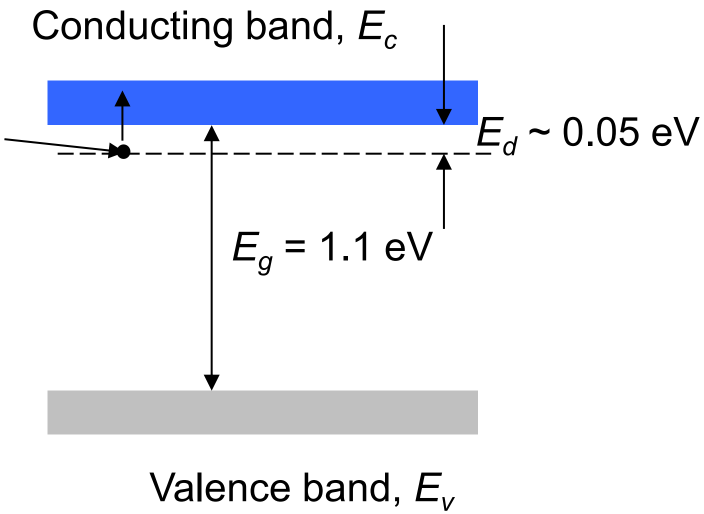
  => At 0 ºK, silicon is an insulator.

- As temperature increases, the valence electrons gain thermal energy. If a valence electron gains enough energy (Eg), it may break its covalent bond and move away from its original position. This electron is free to move within the crystal.
- Conductor Eg <0.1eV, many electrons can be thermally excited at room temperature.
- Semiconductor Eg ~1eV, a few electrons can be excited (e.g. 1/billion)
- Insulator, Eg >3-5eV, essentially no electron can be thermally excited at room temperature.



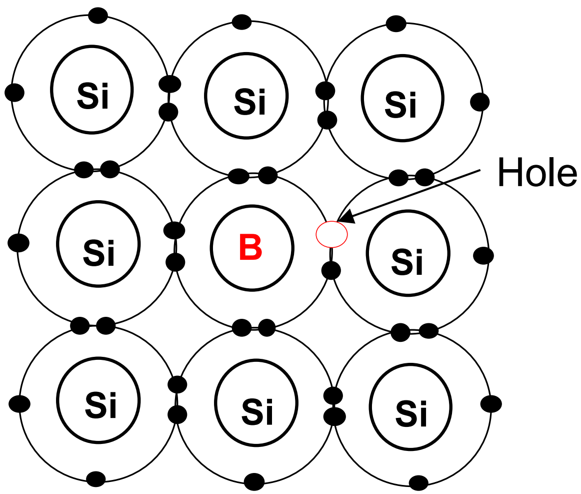
Extrinsic Semiconductor, n-type Doping

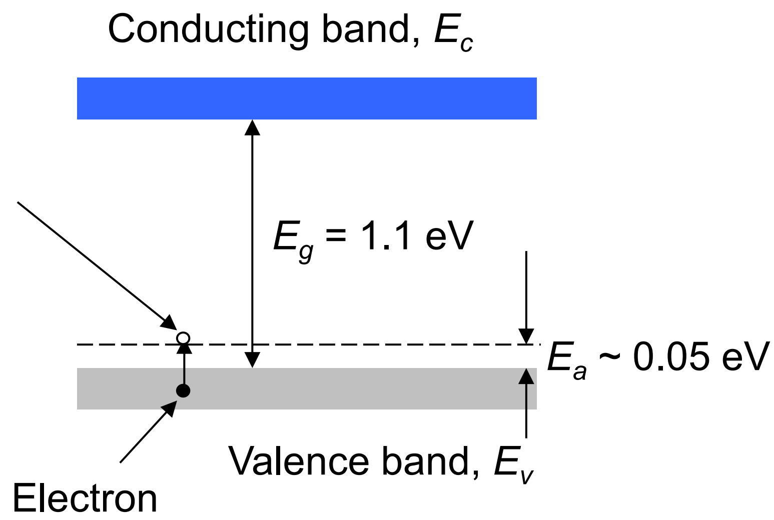




- **Doping silicon lattice with group V elements can creates extra electrons in the conduction band — negative charge carriers (n-type), As- donor.**
- **Doping concentration #/cm^3 (10^{16}/cm^3 ~ 1/million).**

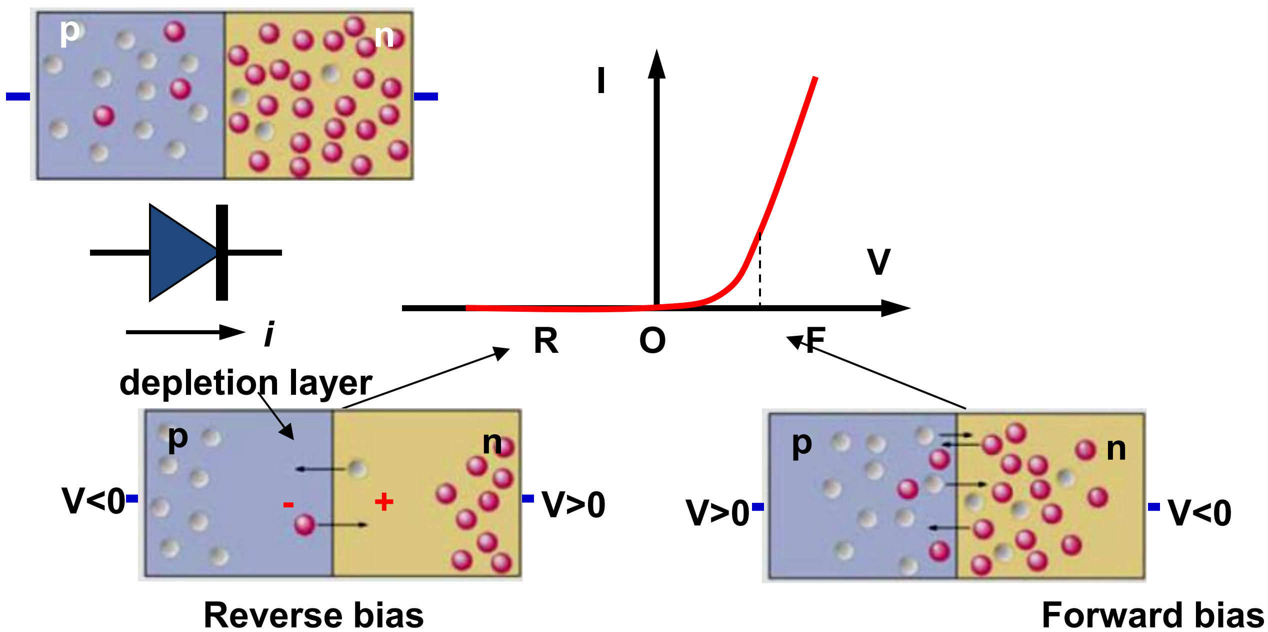
Extrinsic Semiconductor, p-type doping





➢ Doping silicon with group III elements can creates empty holes in the conduction band — **positive charge carriers (p-type), B-(acceptor).**

p-n Junction (p-n diode)



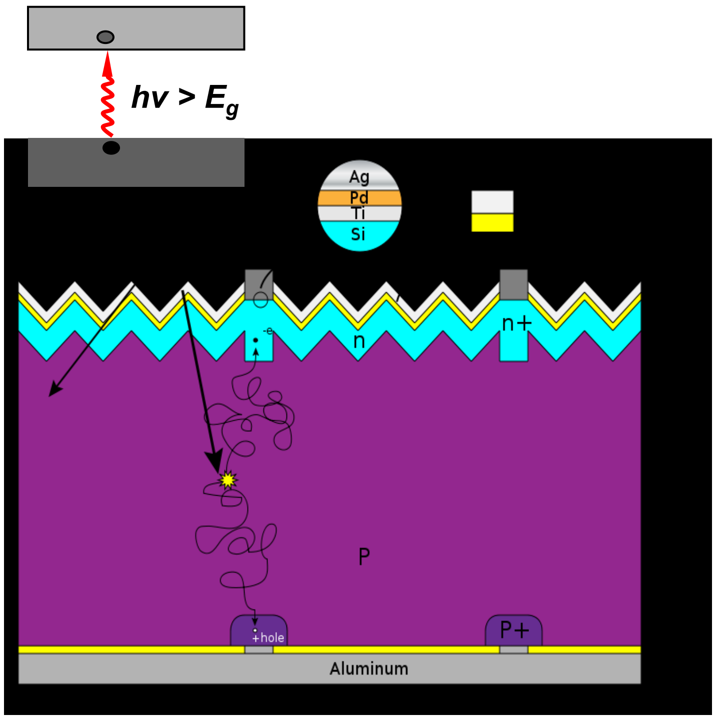
- A p-n junction is a junction formed by combining p-type and n-type semiconductors together in very close contact.
- In p-n junction, the current is only allowed to flow along one direction from p-type to n-type materials.

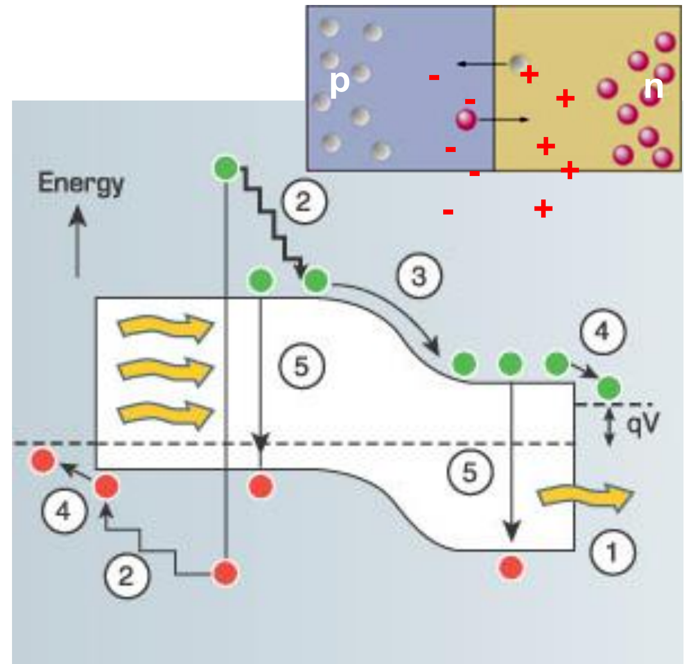
p-n Junction (p-n diode)

- **Solar Cells**
- Light-emitting Diodes
- Diode Lasers
- Photodetectors
- Transistors

➢ A p-n junction is the basic device component for many functional electronic devices listed above.

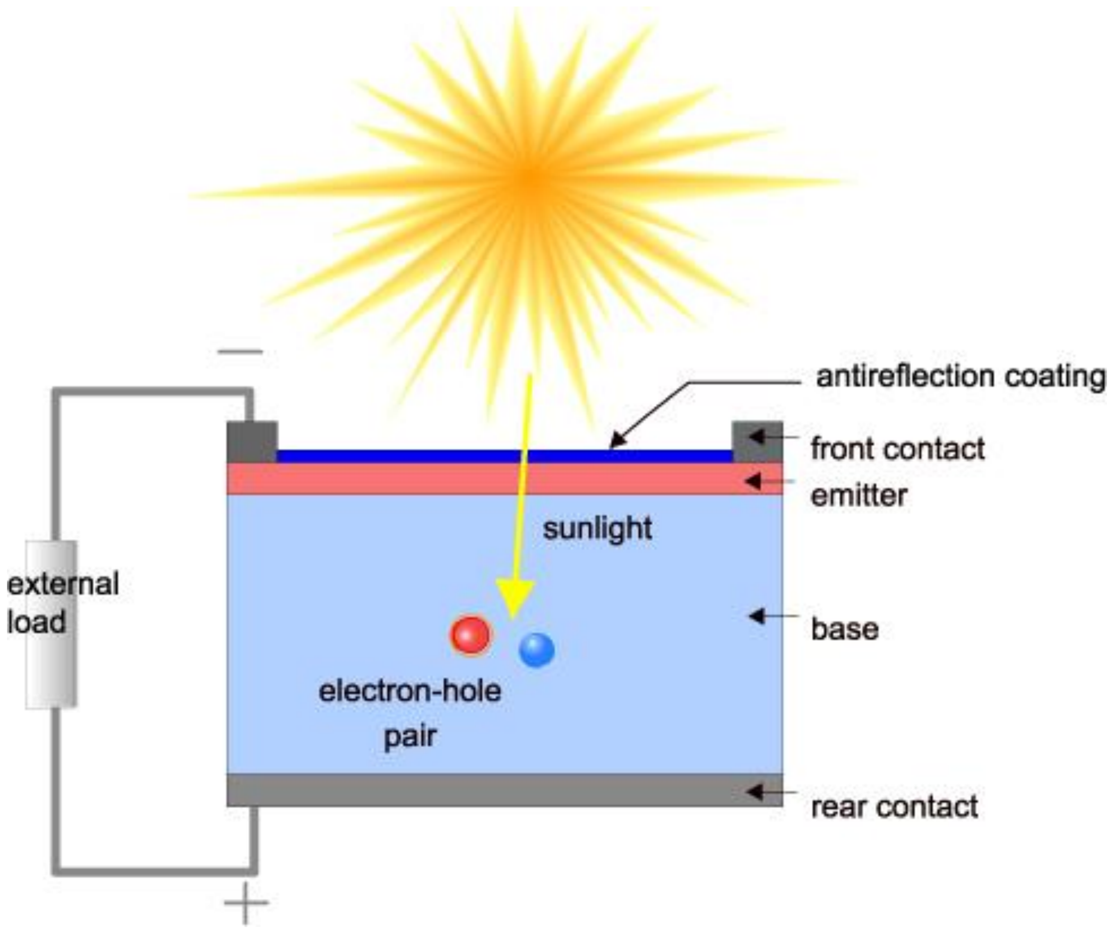
How Solar Cells Work





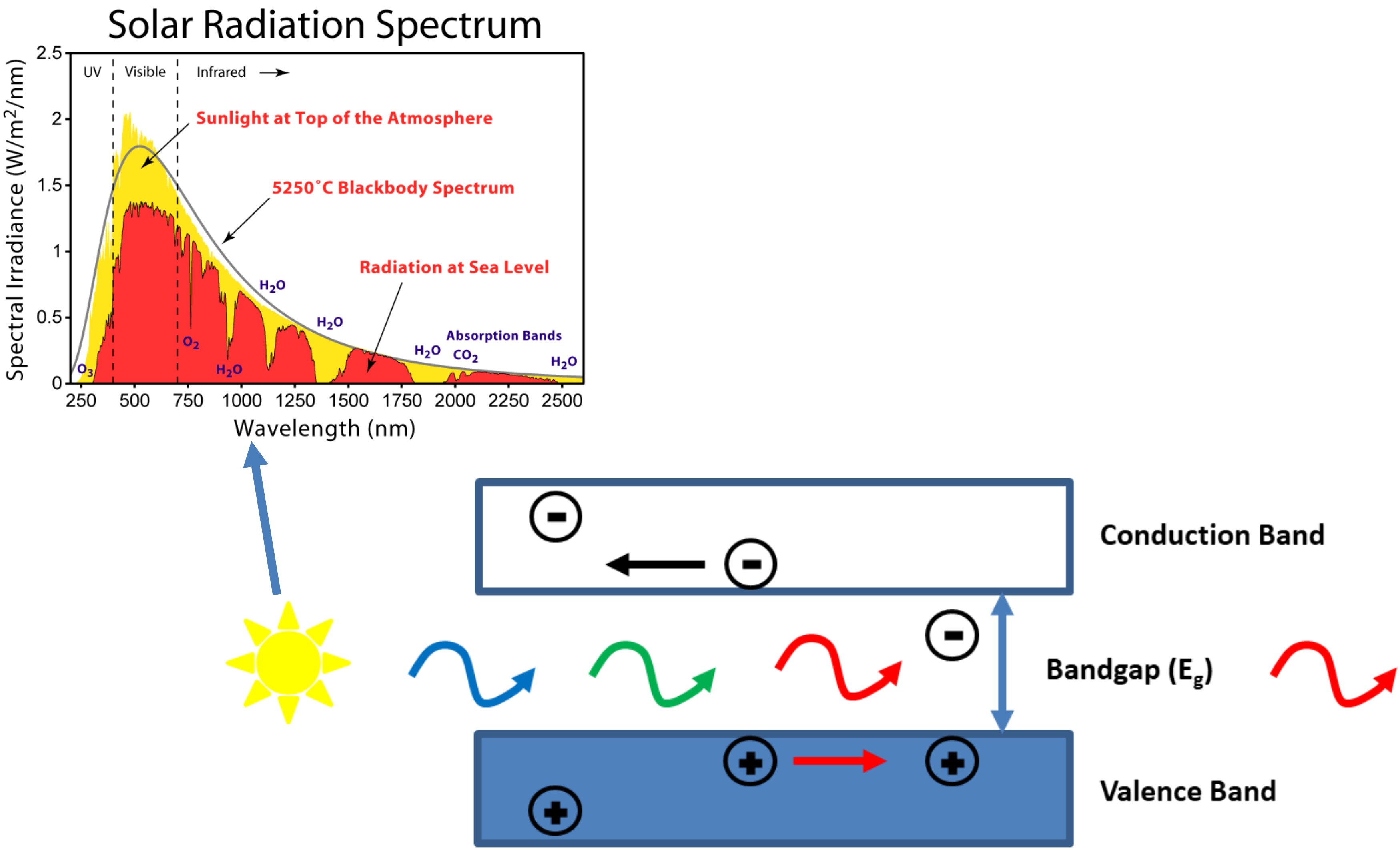
- Photons in sunlight hit the solar panel and are absorbed by semiconducting materials to create electron hole pairs.
- Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity.

Solar (photovoltaic) cells absorb sunlight and generate electricity



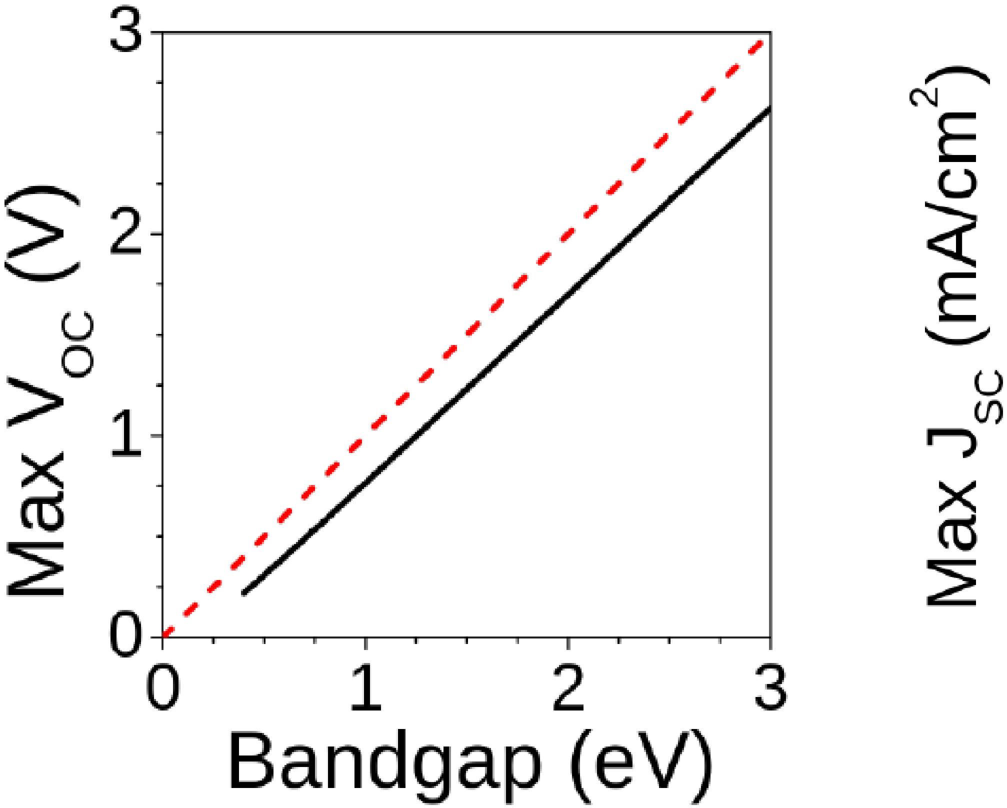
- A Photovoltaic Cell converts light into electrical Energy
- φῶς (*phōs*) meaning "light", and "voltaic", meaning electric, from the name of the Italian physicist Volta.

Energy is stored when light is absorbed



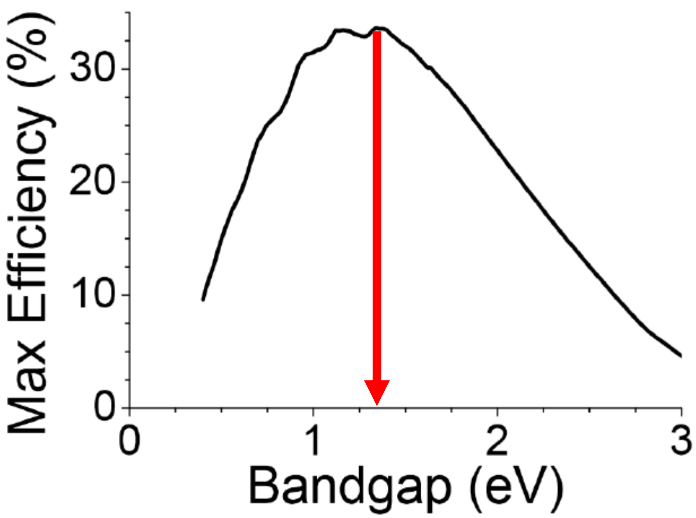
Energy stored in the e^-/h^+ is ~ E_g

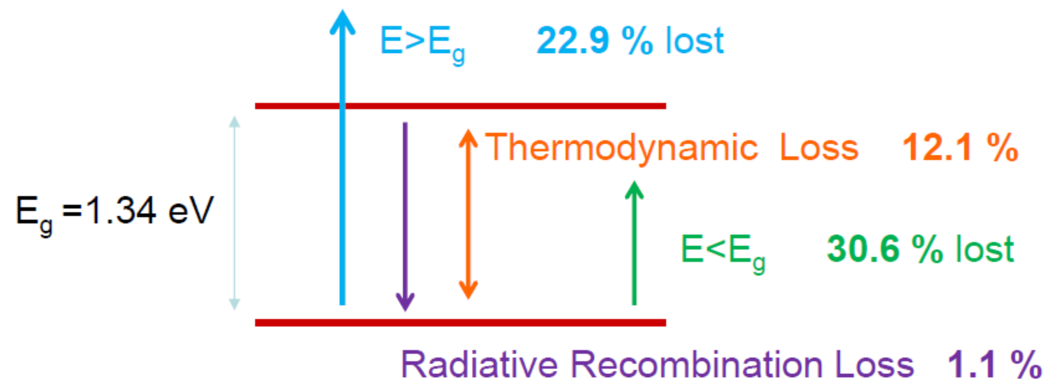
The dependence of the PV parameters with the band gap of the absorber



W. Shockley and H. J. Queisser, Journal of Applied Physics, 1961, 32, 510-519

Detailed balance (S.Q. Limit)





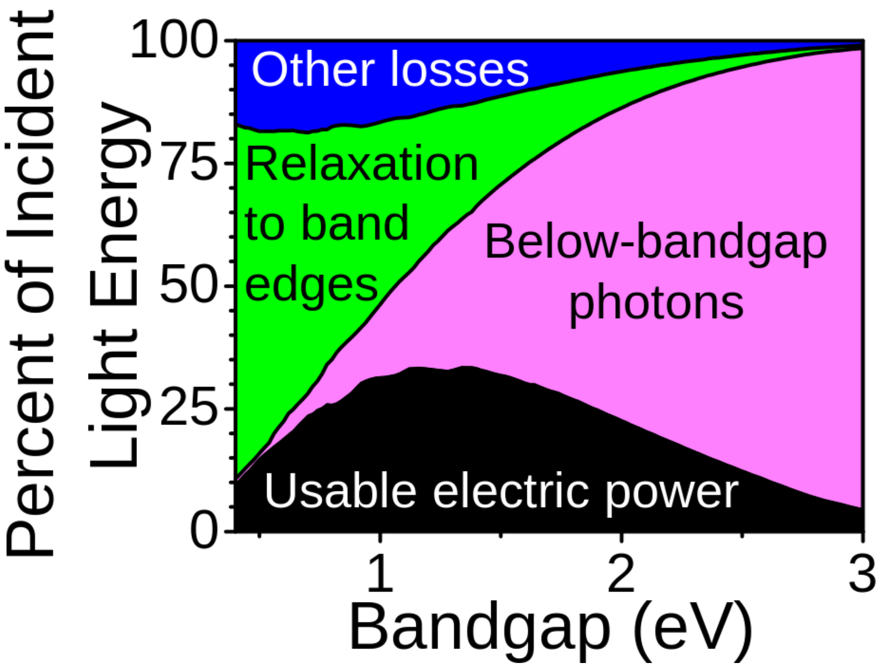
Σ 22.9% + 12.1% + 30.6% + 1.1 % = 66.7 % =>

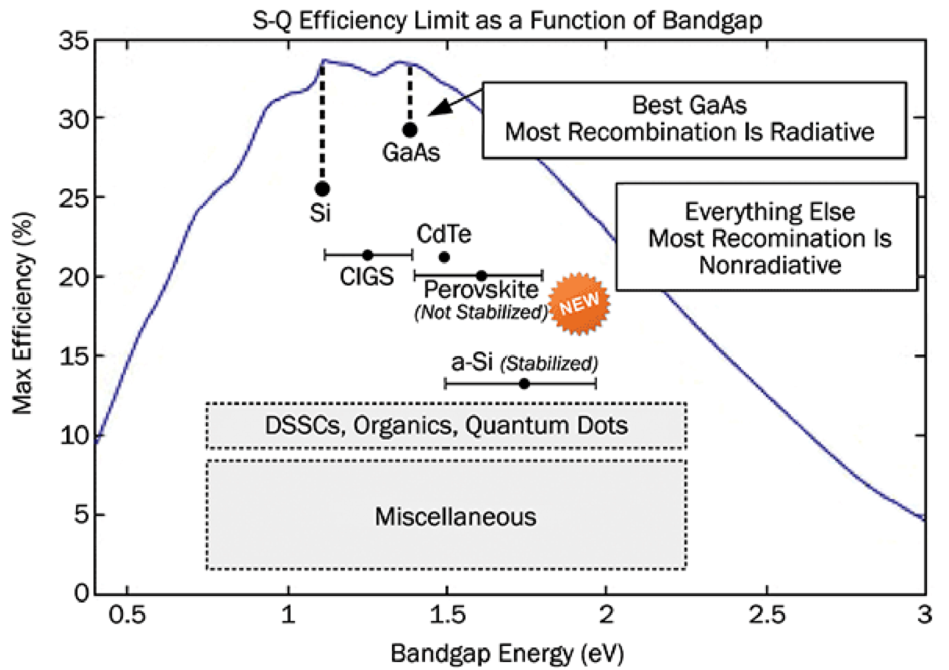
Max. Efficiency is 33.3 %

✓ **A max. PCE of ~33.3% can be achieved for a bandgap of ~1.34 eV**

W. Shockley and H. J. Queisser, Journal of Applied Physics, 1961, 32, 510-519

Power losses and different solar absorbers



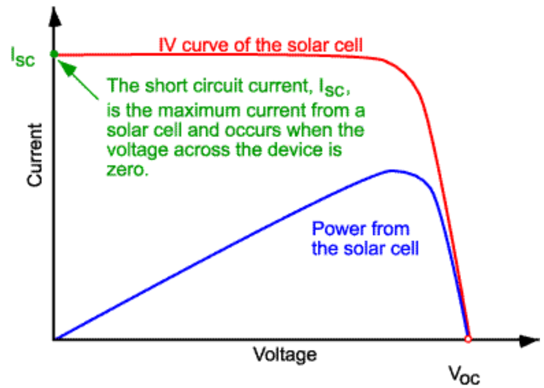


The golden triangle of PVs

- Solar competitiveness measured by the ‘Golden Triangle’ = Cost, Efficiency, Lifetime
- Achieving the Golden Triangle is critical to capture of market share
- High efficiency, low cost and 20 year+ life span will open up the ‘holy grail’ of solar - BIPV

Solar Cells Efficiency

< Power conversion efficiency (η) >



J_{SC} : Short-circuit current Density

→ Current Density value when V = 0

V_{OC} : Open-circuit voltage

→ Voltage value when J = 0

P : Power output of the cell

P = IV

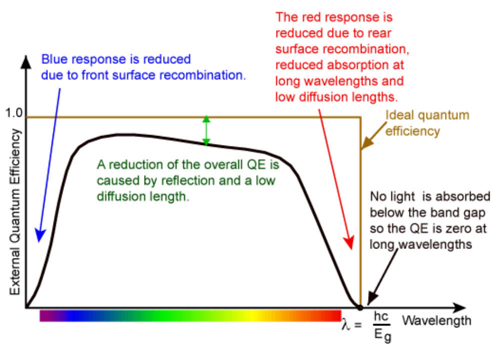
F.F. : Fill factor

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}}$$

$$\eta = \frac{I_{mp}V_{mp}}{P_S} \times 100 \rightarrow \eta = \frac{J_{sc}V_{oc}FF}{P_S} \times 100$$

Under **AM 1.5G** simulated solar illumination

< External quantum

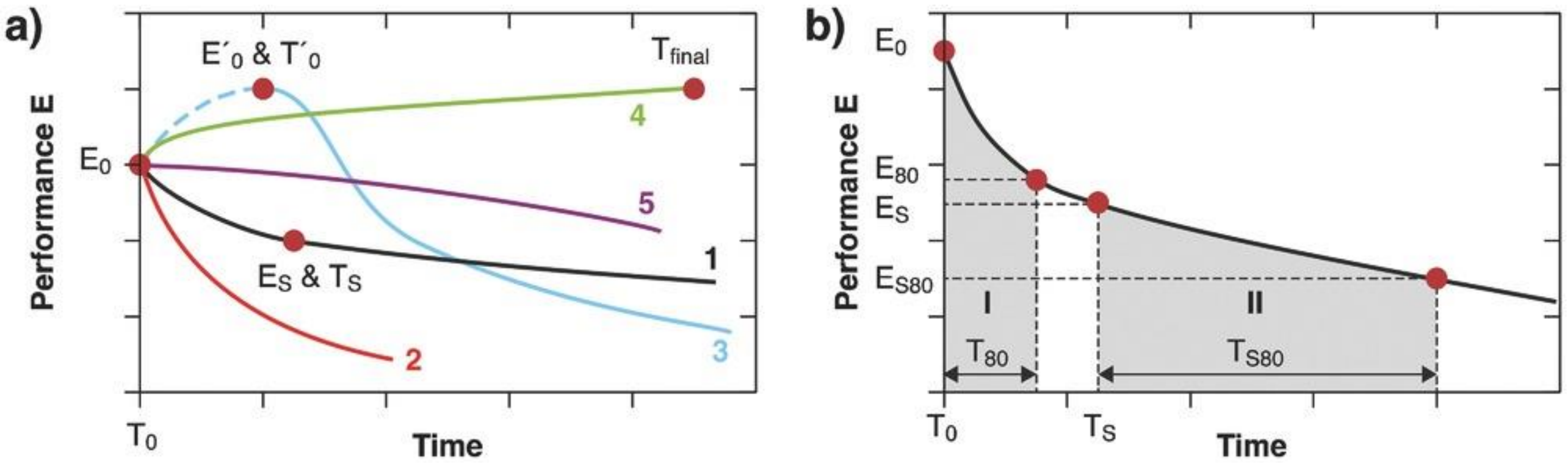


$$IPCE = \frac{\text{no. of electrons through the external circuit}}{\text{no. of photons incident}}$$

$$= \frac{[1240\ eV\ nm][photocurrent\ density\ \ (\mu A\ cm^{-2})]}{[wavelength\ \ (nm)][irradiance\ \ (mW\ cm^{-2})]}$$

$$J_{sc} = q\int_{\lambda_{min}}^{\lambda_{max}} \Phi(\lambda) \cdot EQE(\lambda) \cdot d\lambda$$

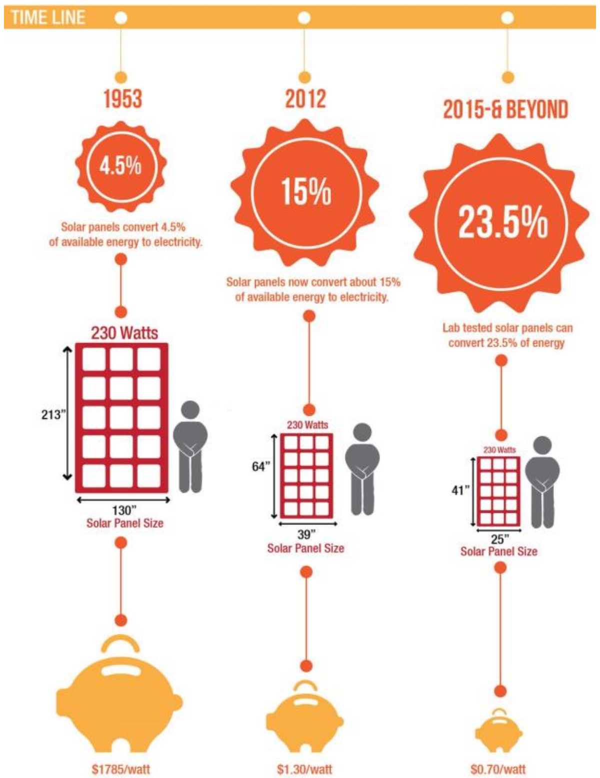
Lifetime of PV devices

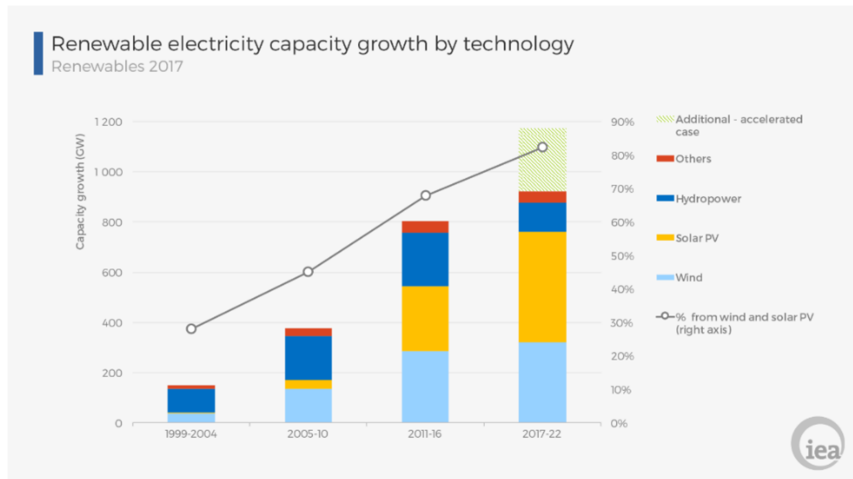


- ✓ The accelerated damp heat test is performed by applying 85°C ± 2°C with a relative humidity of 85% for for an uninterrupted cycle of 1000 hours, which is well over 1 month (annual sunshine in central Europe ~1500 hours).
- ✓ The performance of the devices should be constantly recorded (MPPT)
- ✓ T_{80} lifetime should well exceed 1000 hours
- ✓ Passing this test ensures reliable operation for ~25 years of a normally operated panel

S.A. Gevorgyan, et al., Adv. Energy Mater. 2016, 6, 1501208

The rise of solar panels efficiency led to significant cost reduction

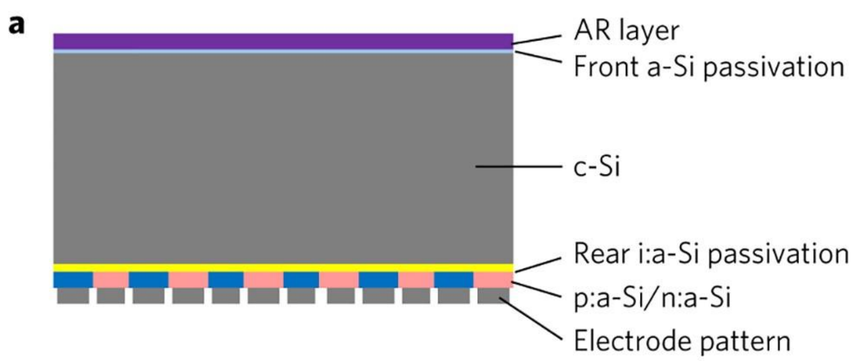


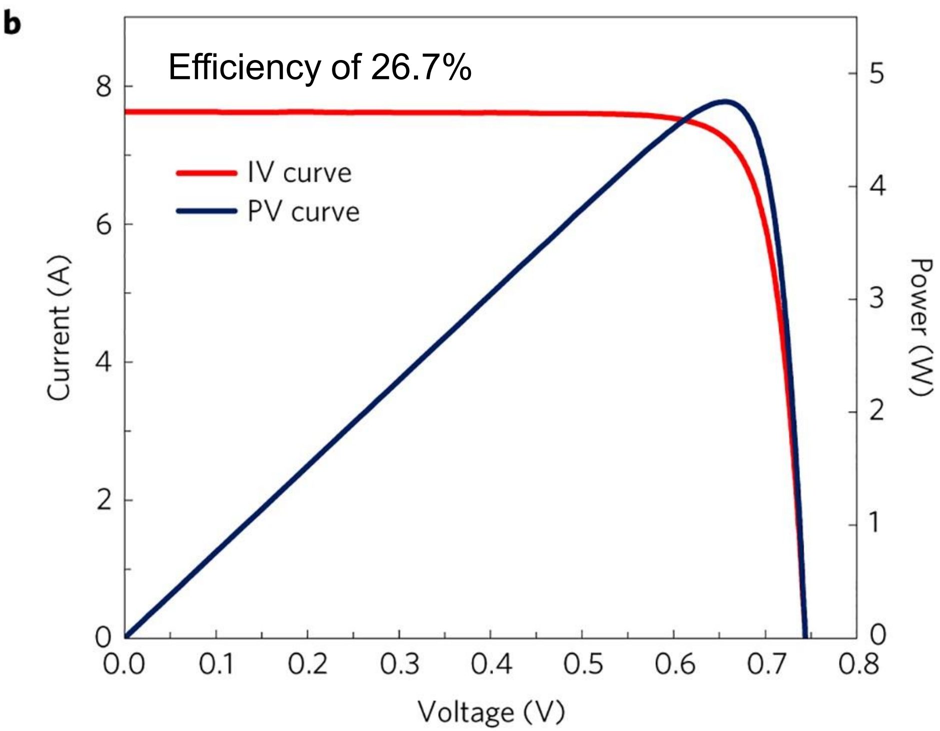


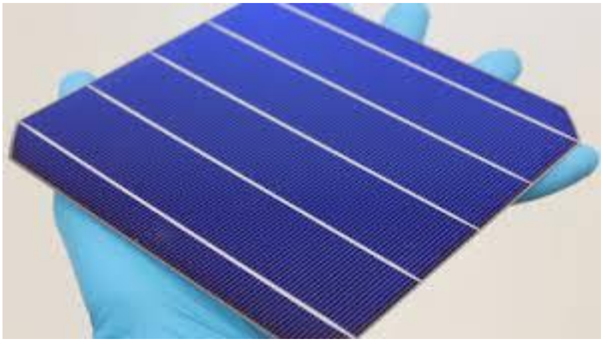
RENEWABLES 2016 GLOBAL STATUS REPORT

Imagine what it will happens in the PV market if we achieve to further reduce the cost of the raw materials (i.e. replace Si, use simple device architectures, etc.)

Silicon Solar Cells Dominate the Market of PVs

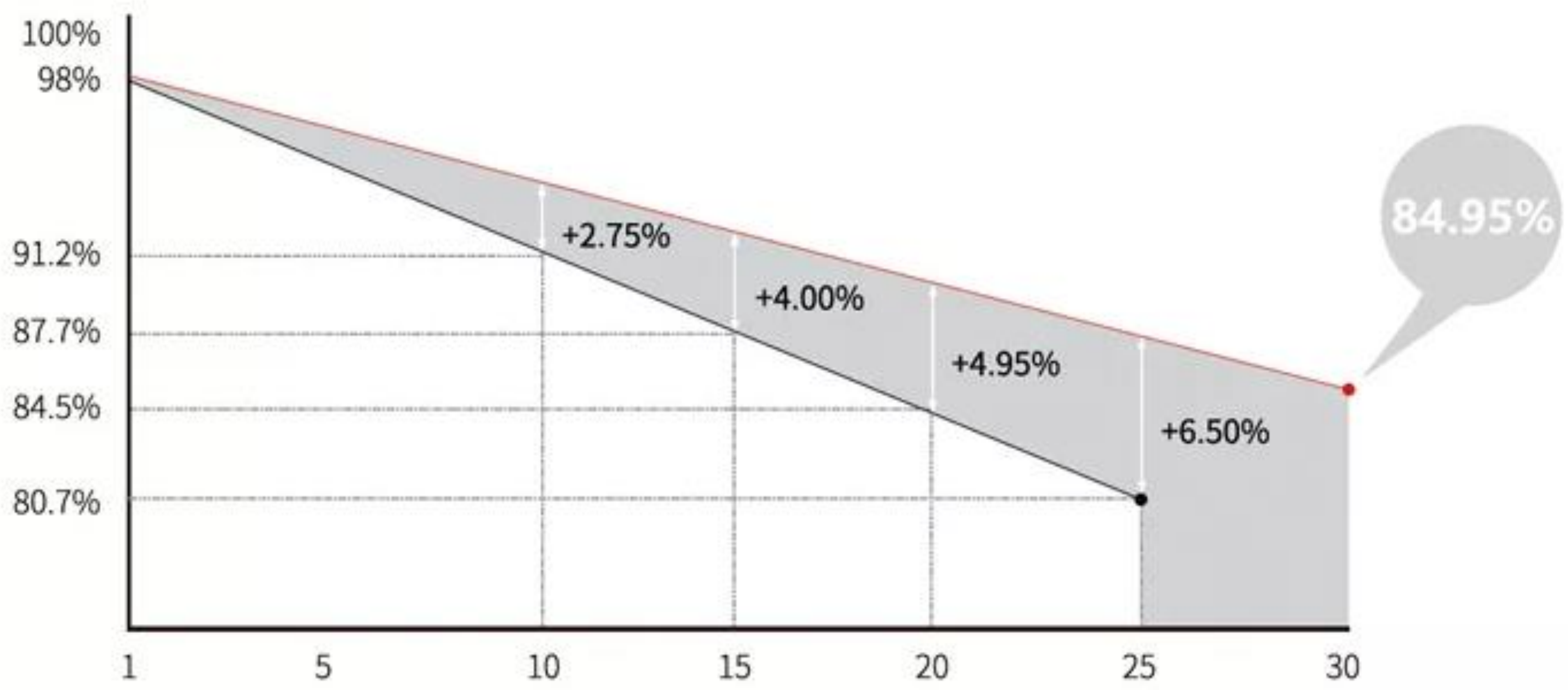




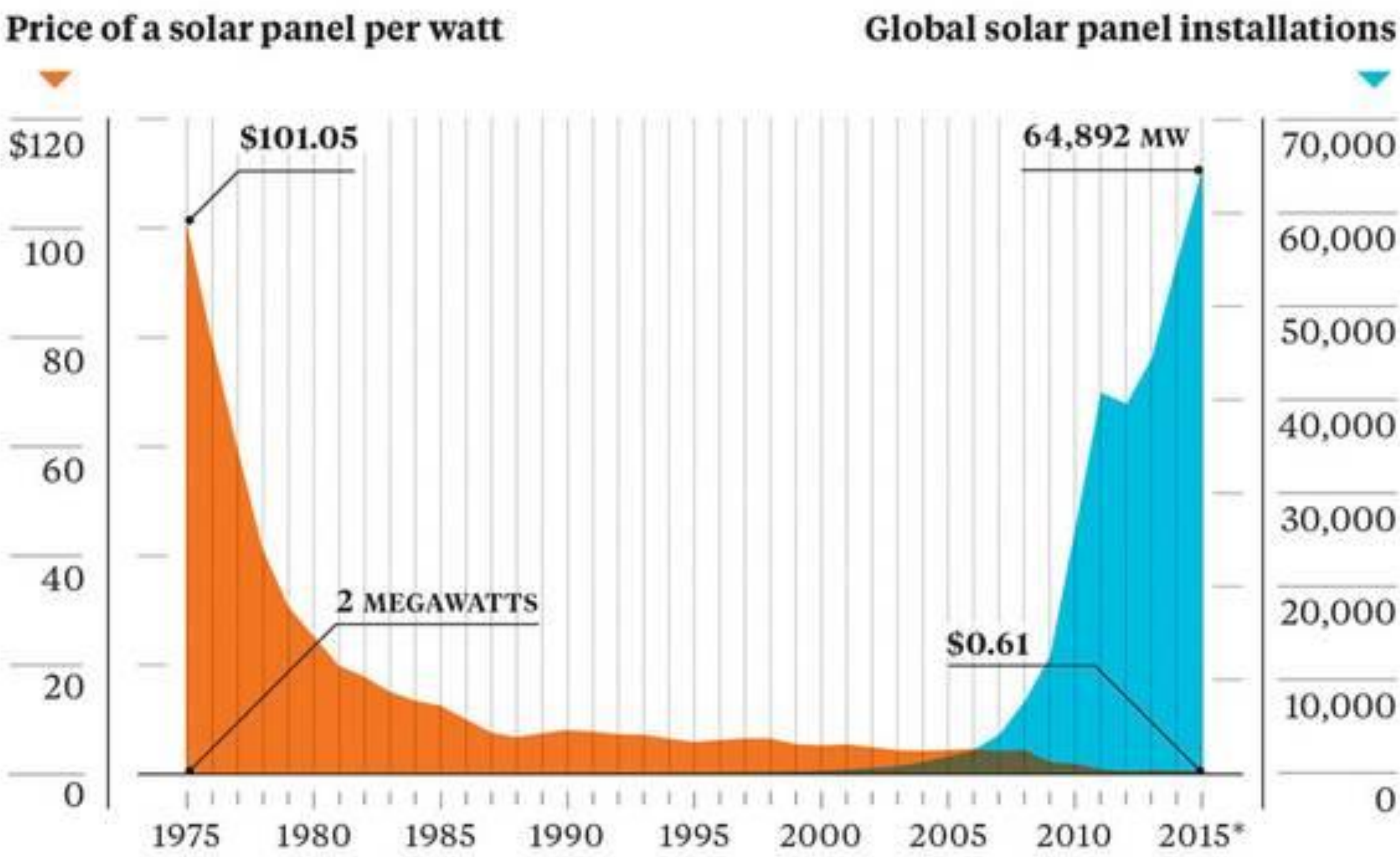


K. Yoshikawa et al., Nat. Energy, 2017, 2, 17032.

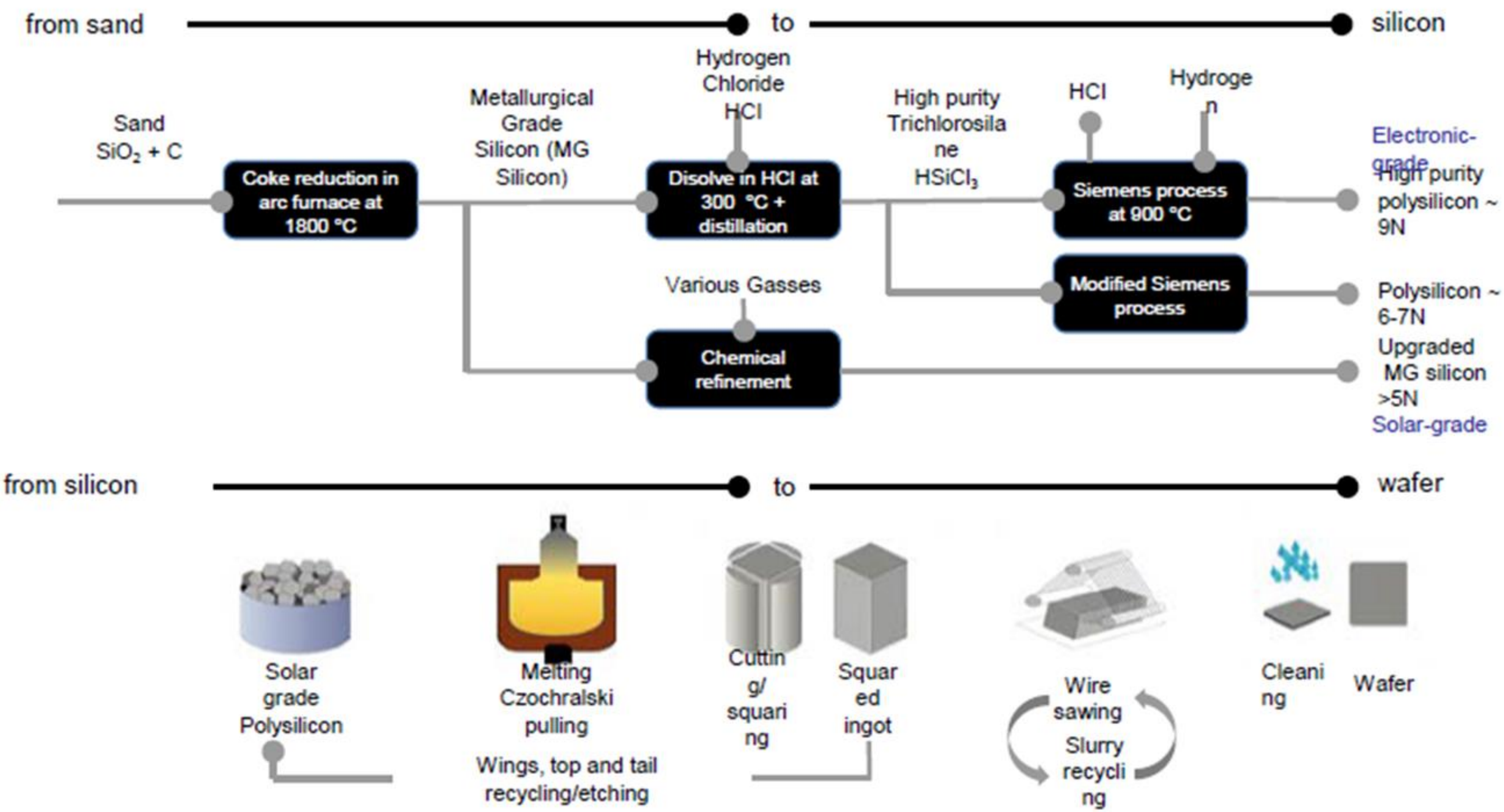
Lifetime of silicon solar panels



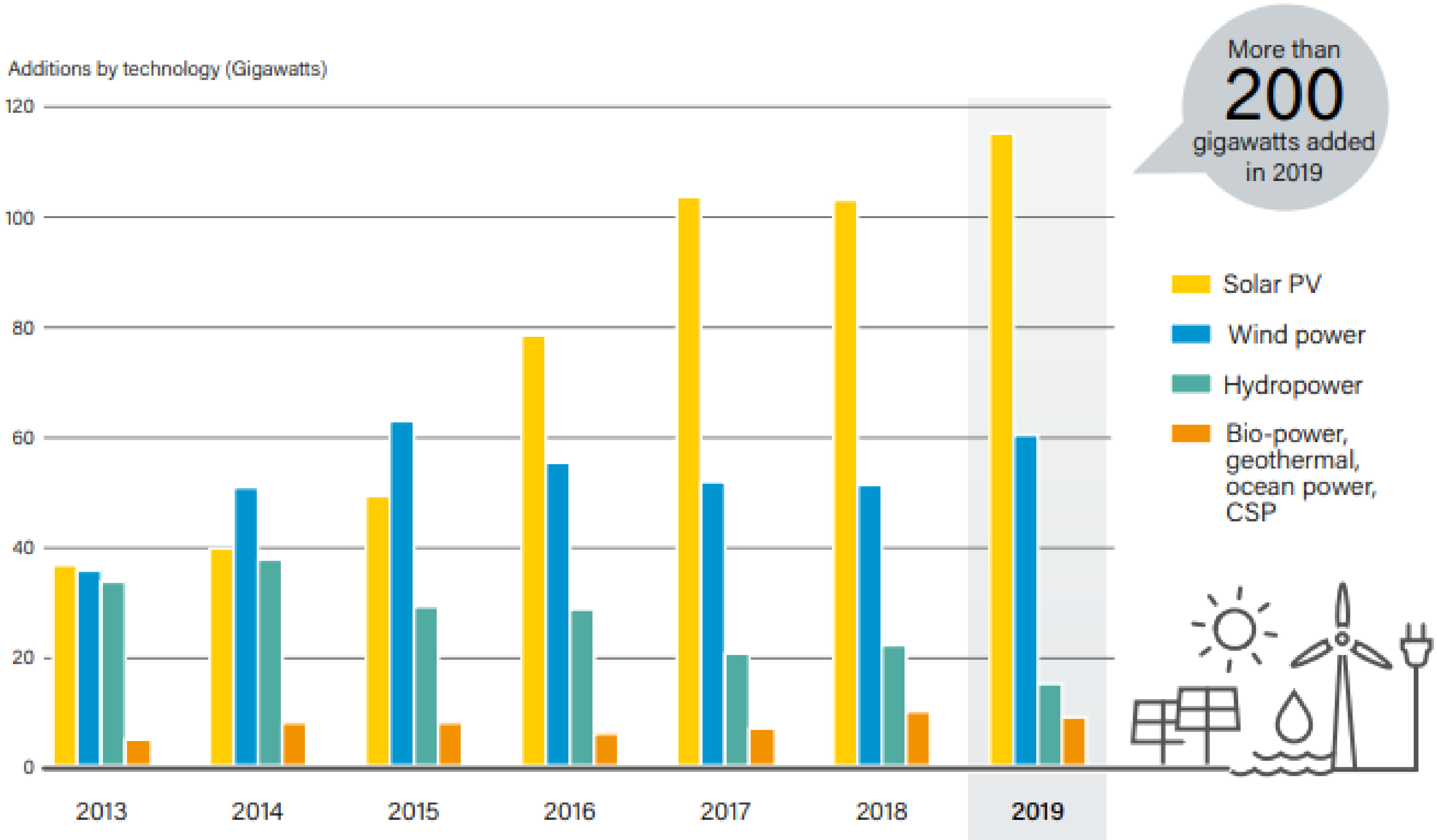
The price drop of solar cells led to rise in global installations



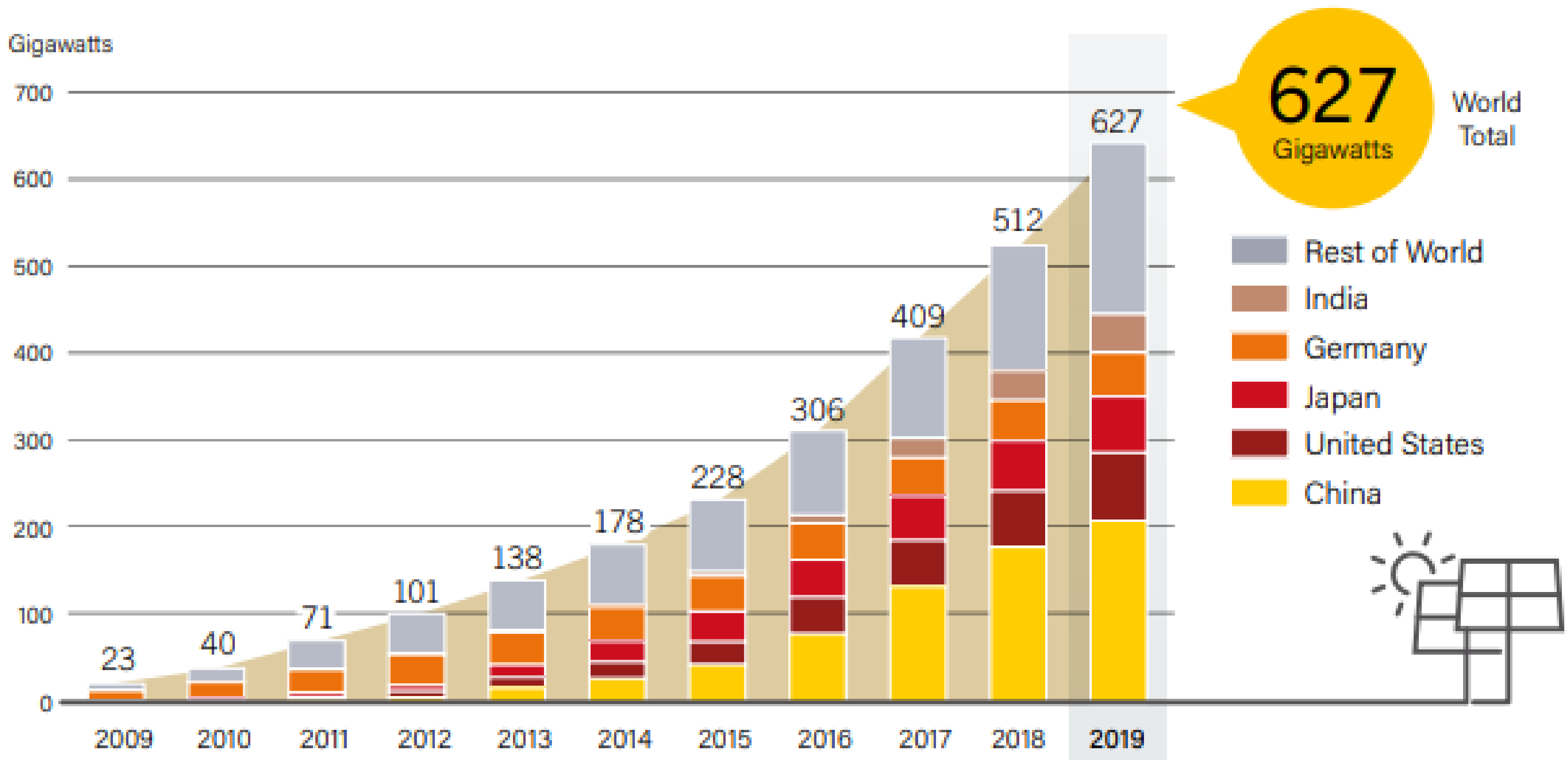
Si PVs have complicated and expensive production processes



Annual Additions of Renewable Power Capacity, by Technology and Total, 2013-2019

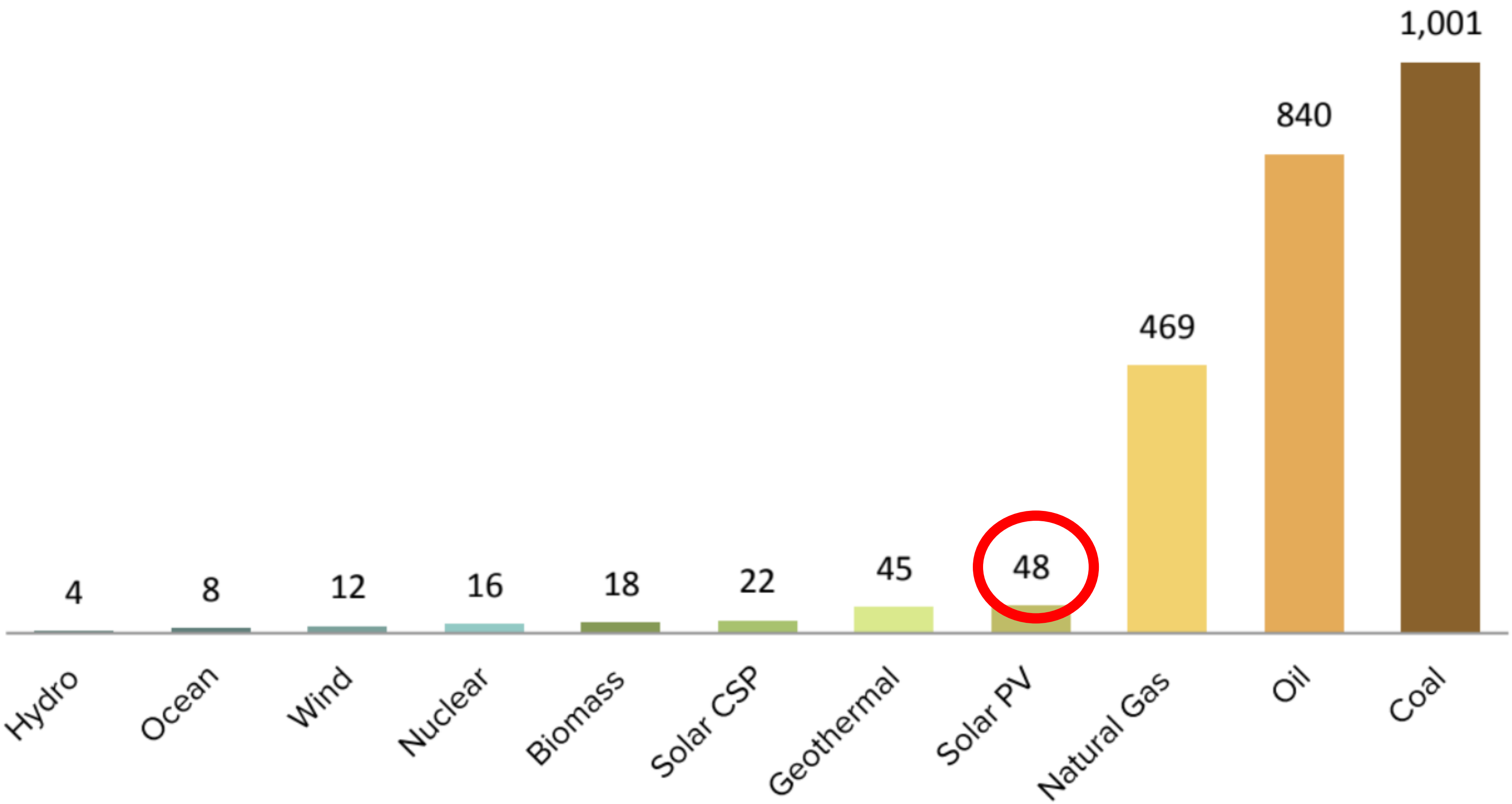


Solar PV Global Capacity, by Country and Region, 2009-2019



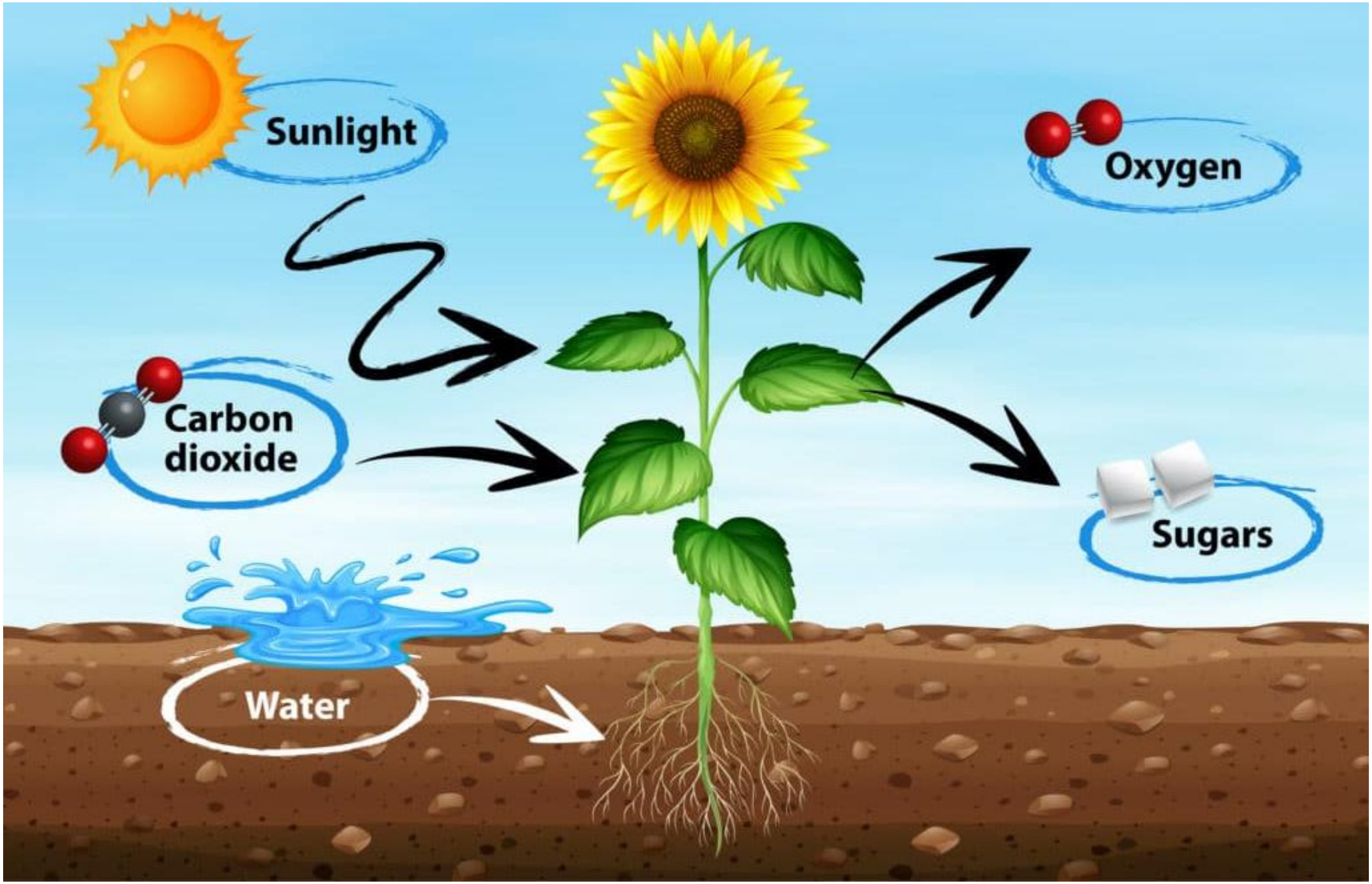
Global Electricity Consumption: 20 TW/year
Annual additions: 100GWp/5 (average) = 20 GW/year
It would take approximately 1000 years to cover the global energy consumption with the current rate of production

Carbon Footprint by source (g CO_2/kWh)

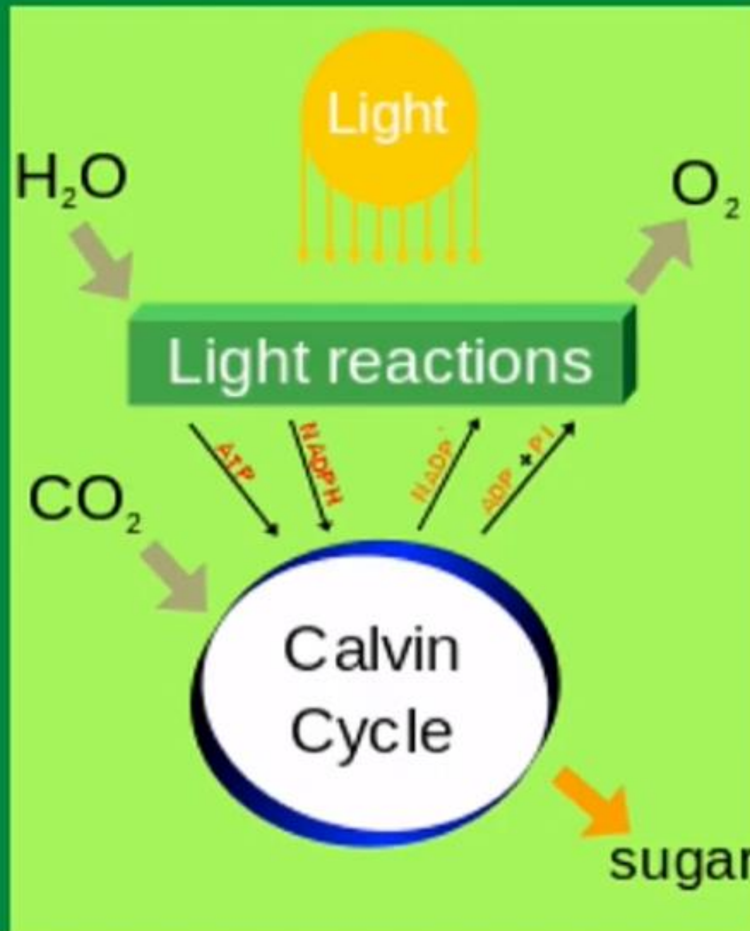


✓ **Is there a more sustainable and of high throughput method to capture the sunlight?**

Inspiration: Photosynthesis



The potential of photosynthesis

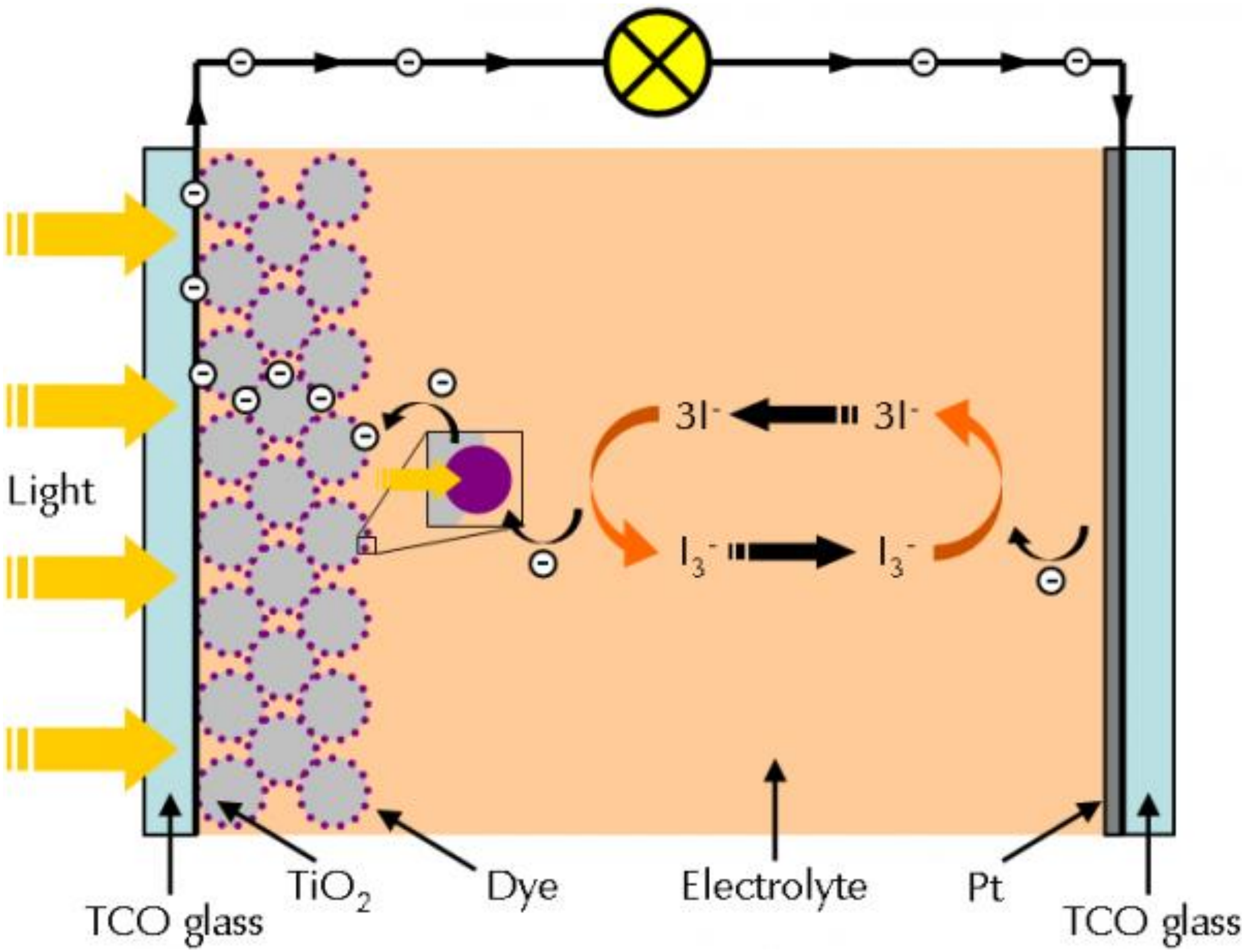


Total solar power Incident on earth is 178’000 TW

$CO_2 + 2\ H_2O + 8$ photons $\rightarrow [CH_2O] + O_2$ $\Delta G^* = 477$ KJ/mole

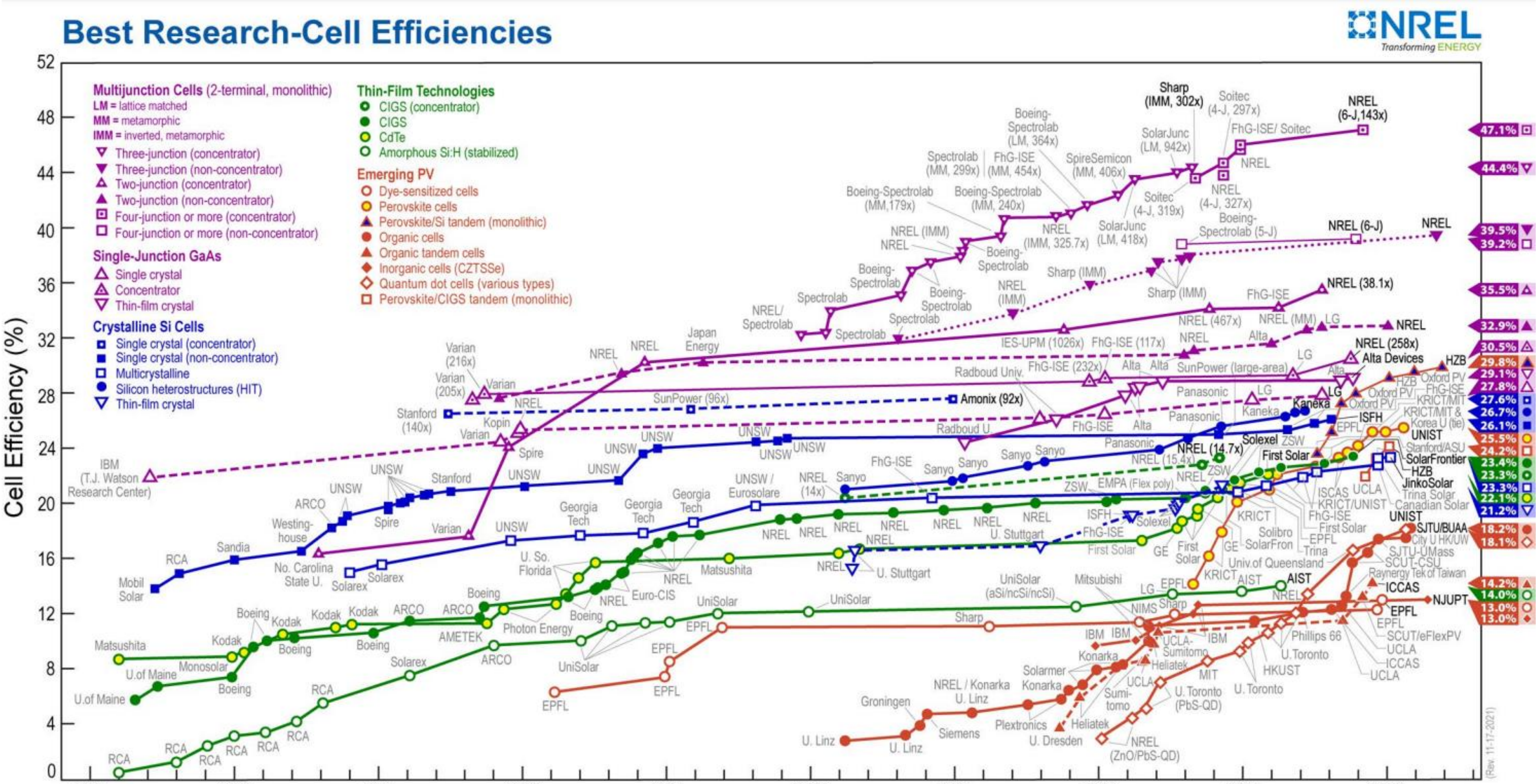
solar power converted to chemical energy stored in biomass is 95 TW

DSSCs: The first solution processed PV cells based on mesostructured electrodes



M. Graetzel et al. 1992

Photovoltaic Technologies: Crystalline, Thin film and Emerging

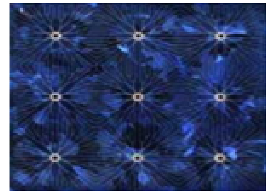


PV Technologies

First Generation

crystalline silicon (mono & multi)

This will be the PV-backbone technology and leader of the BIPV sector.



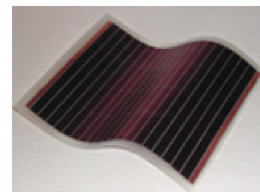
module efficiency:

13% ········→ **20%**

Second Generation

thin film: a-Si, CdTe, CIGS

Viable competitor in BIPV and roll-to-roll process for flexible substrates.



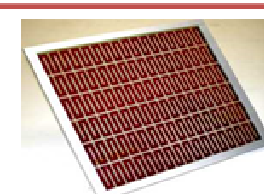
module efficiency:

9% ········→ **15%**

Disruptive/ New Generation

Organic and Perovskite Solar Cells

Initially niche market oriented, but breakthroughs could push field towards mass power generation.



module efficiency:

5% ········→ **20+%**

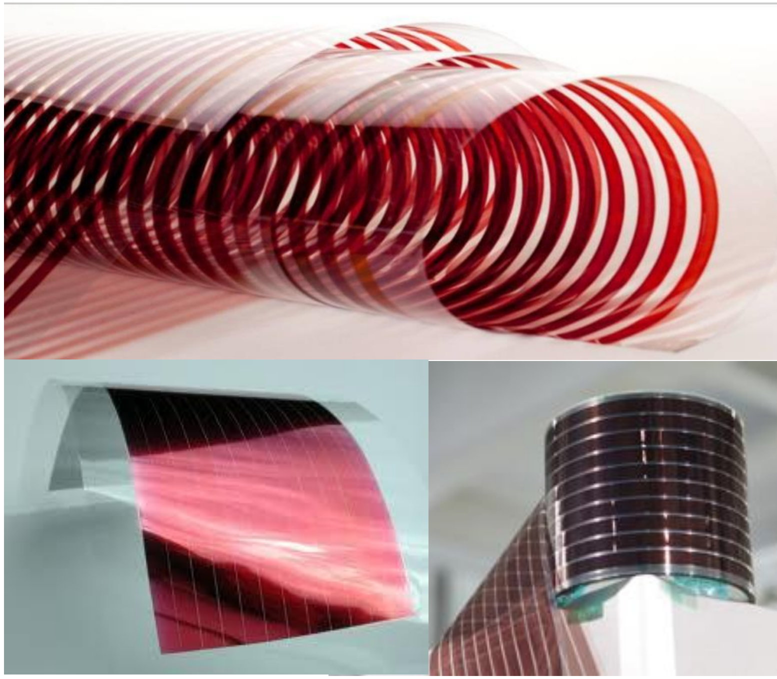
Target: Hybrid Tandem Solar Cells

2000 **2010** **2020** **2030**

\$0.30/kWh → \$0.05/kWh

Why OPVs ?

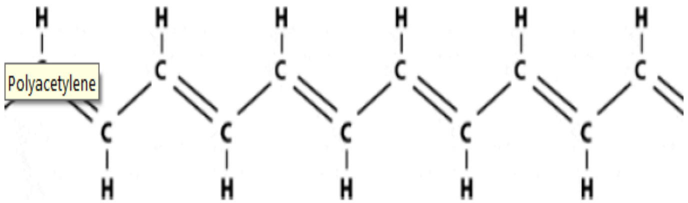
- ✓ Processed easily over large area
  - -spin-coating
  - -doctor blade techniques (wet-processing)
  - -evaporation through a mask (dry processing)
  - -printing
- ✓ Low cost of fabrication
  - ✓ Poly and TF-Si costs around 500-1000 $\$/m^2$
  - ✓ Plastic-PV expected below 50 $\$/m^2$
- ✓ Light weight technology
- ✓ Mechanical flexibility and transparency
- ✓ Band gap of organic materials can be easily tuned chemically by incorporating different functional groups



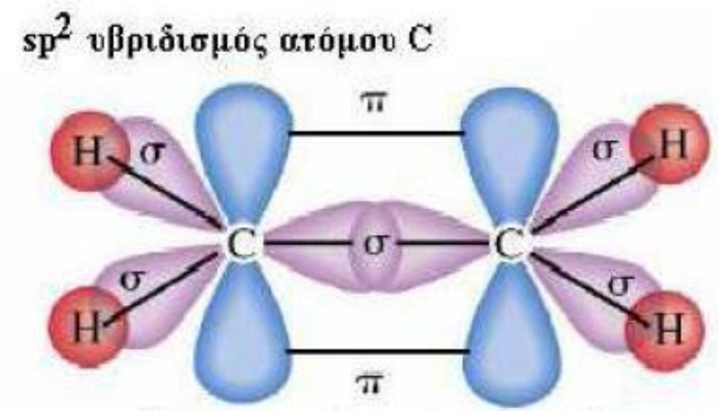
- ➤ OPVs shows a promising technological development
  - efficiencies at 20% level.
- ➤ The usage of roll to roll printing technologies guarantees a favorable cost structure
- ➤ The PV market demands low cost flexible solutions

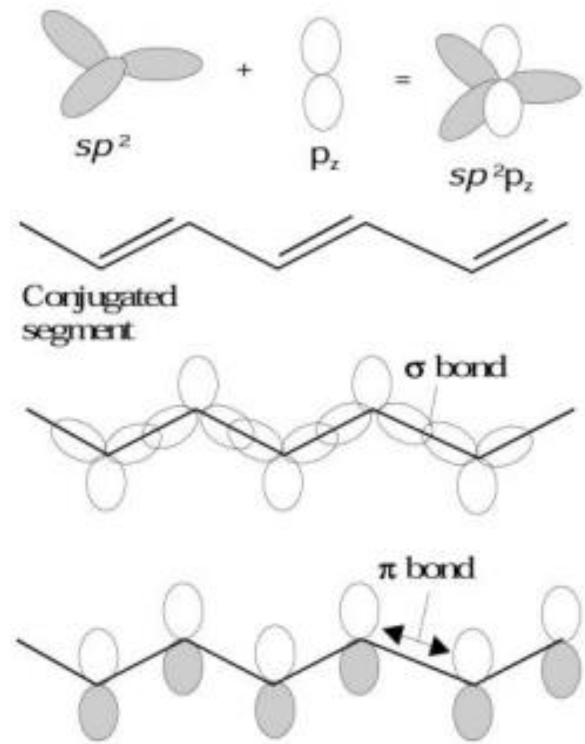
Organic materials – Origin of Semiconducting Behavior

- **Organic Macromolecules with alternating single and double bonds**
- **sp^2 hybridization**

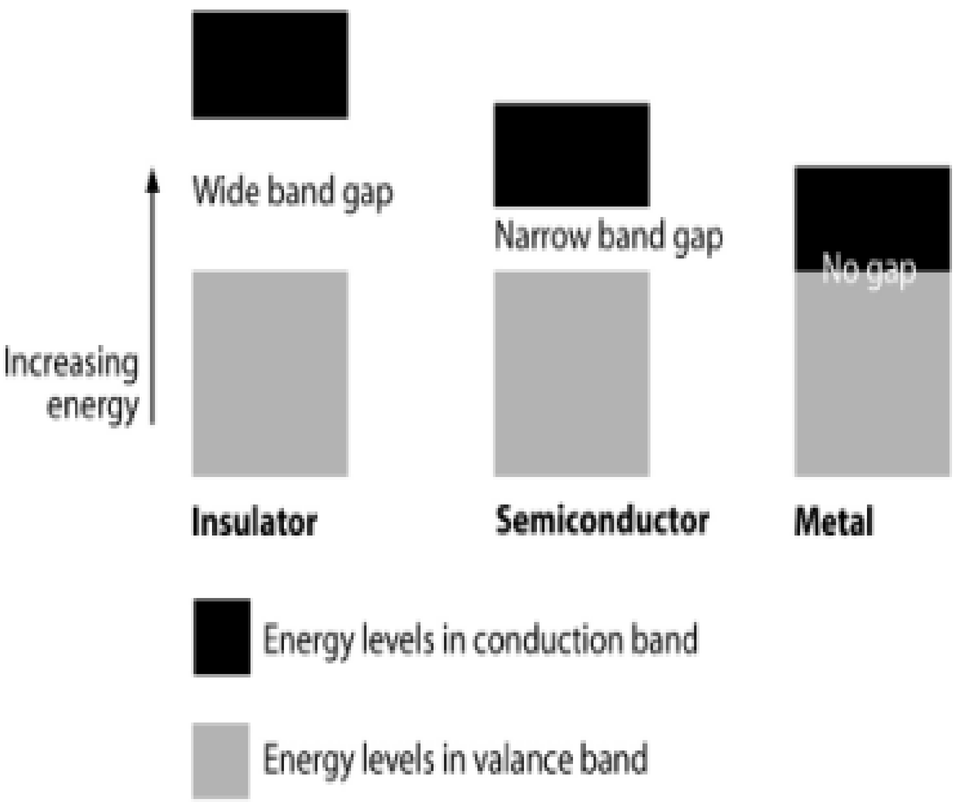


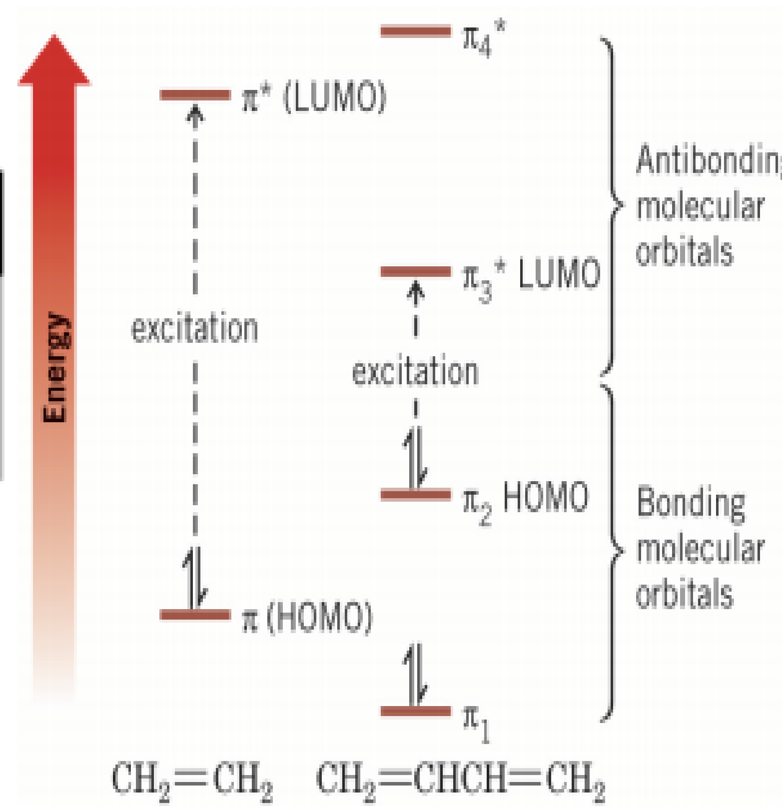
Polyacetylene





HOMO & LUMO LEVELS

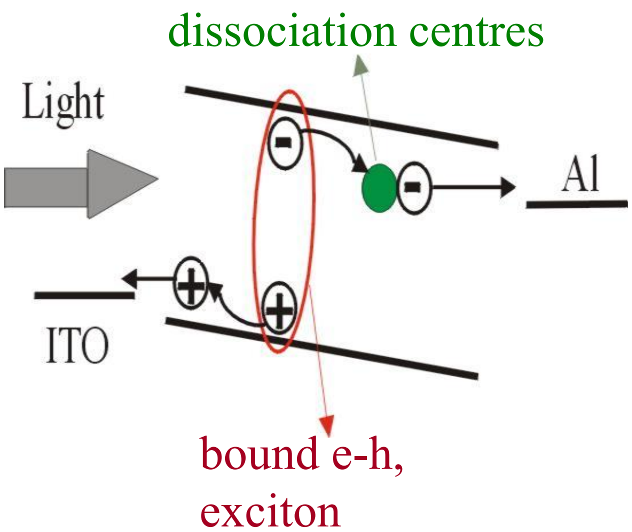




Theory of Organic Semiconductors

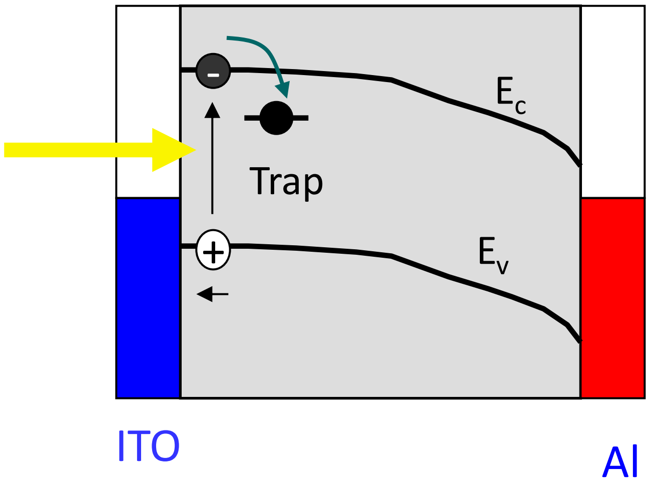
Conjugated Polymers:

- Light creates bound e-h pairs, excitons (0.4eV)
- Mobility of charges is relatively low
- Low exciton diffusion lengths

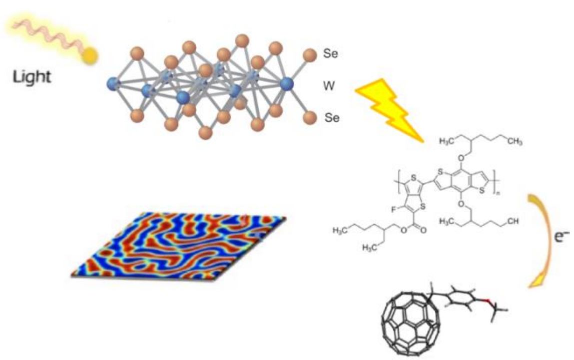


In a single-layer polymer photovoltaic device, excitons may be dissociated at:

- *strong internal electric fields found at polymer/metal interfaces.*
- *<u>dissociation centres</u>, such as oxygen acting as e^- traps.*

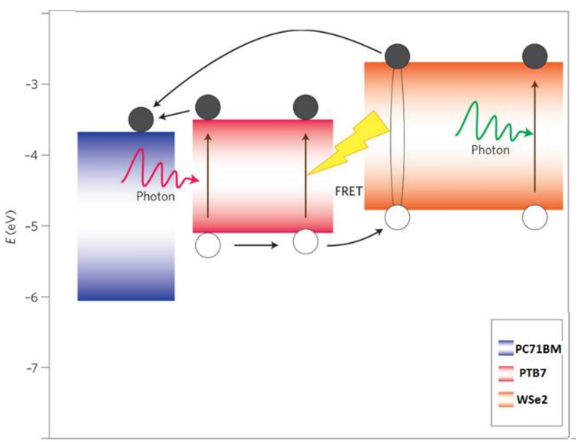


Light Absorption by Semiconductors – Light Induced charge generation



$$E_{binding} = \frac{q^2}{4\pi \varepsilon_0 \varepsilon_r r}, \Rightarrow$$

Silicon≈ 0.06eV
Organic ≈0.5eV
2D Mater. ≈ 0.9eV
Perovskite ≈ 0.1meV



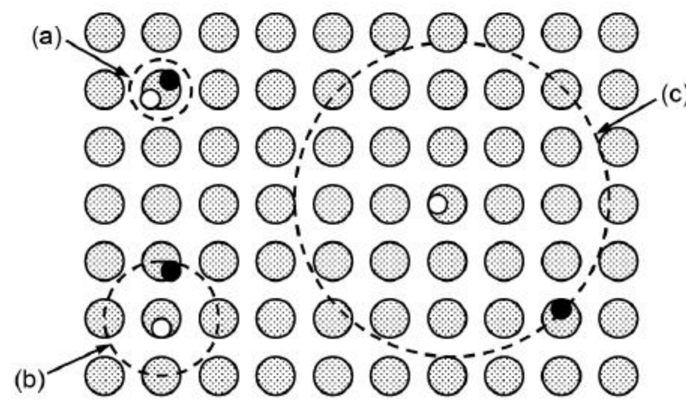
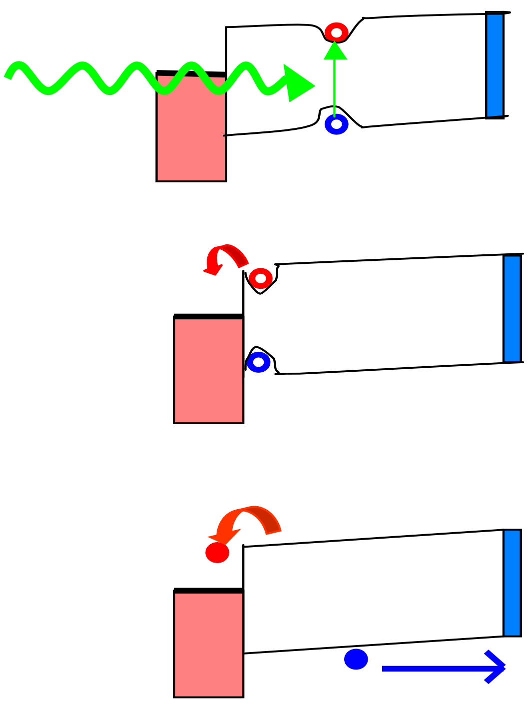


Figure 2.5 A schematic representation of the three types of excitons: (a) Frenkel, (b) charge transfer, and (c) Wannier-Mott. From Ref. 21.

Single layer organic devices

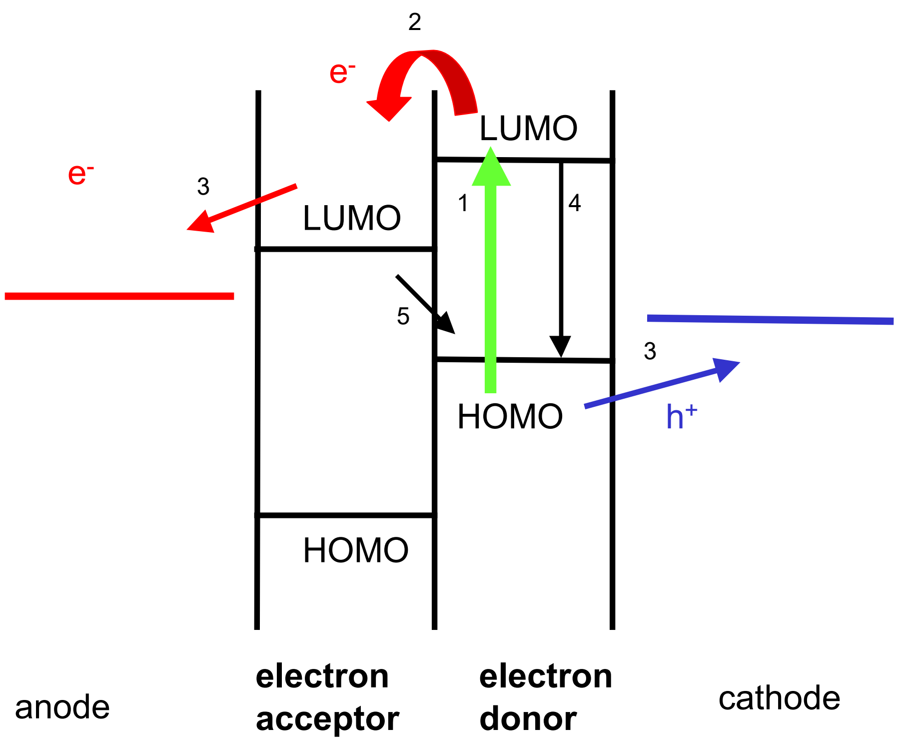
- Organic films between asymmetric contacts
- Light generates excitons, charge separation by exciton dissociation at interfaces
- Exciton diffusion length 1-10 nm, absorption depth >100 nm
- Photocurrent limited by exciton diffusion length
- *Recombination of exciton at metal interface*
- *Recombination of free electron/hole*

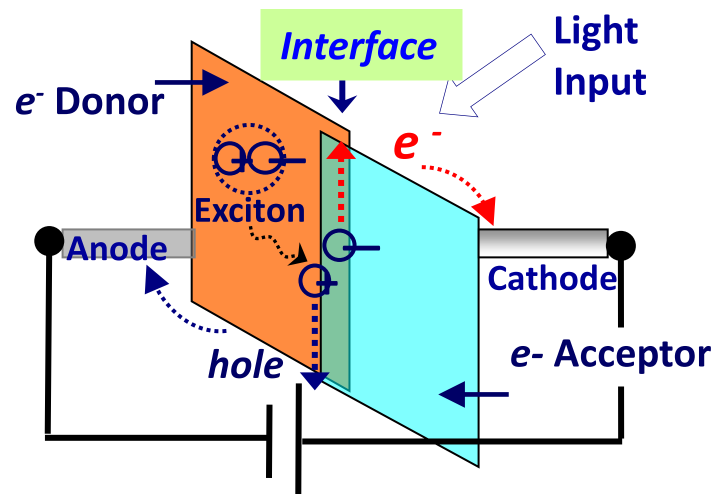


Single layer devices efficiencies very low!

II. Organic bilayer structures

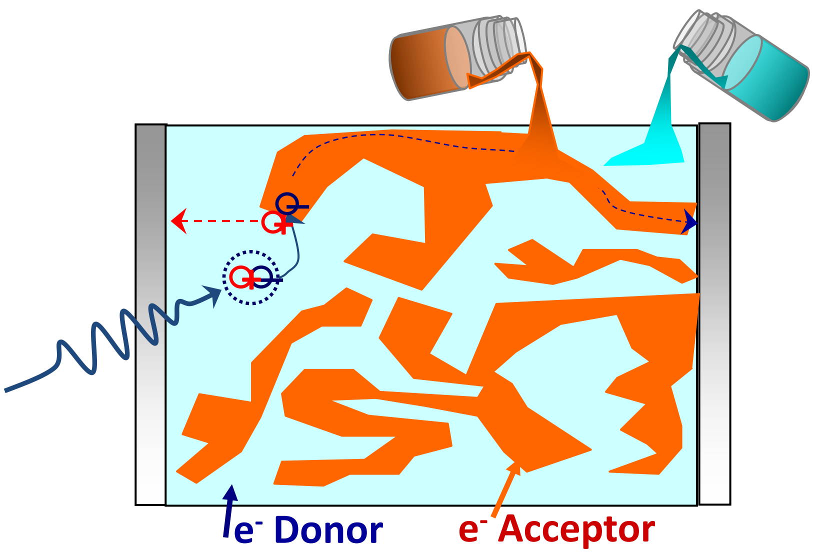
- Exciton diffusion & dissociation at D-A interface
- Current output ~ absorber band-gap
- Voltage (potential energy) output ~ $LUMO_{acceptor} - HOMO_{donor}$
- Bilayer device: Low efficiency due to insufficient light absorption

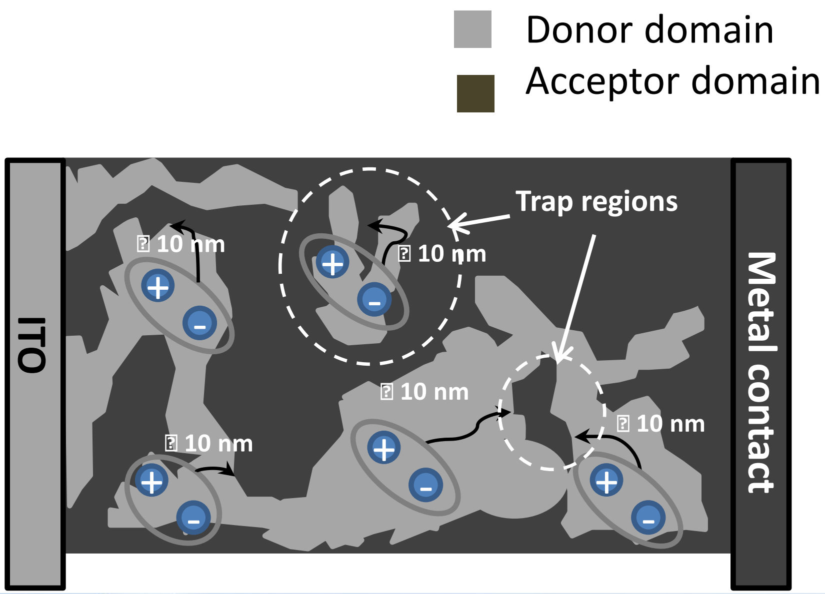




III. Blended Devices - Bulk Heterojunction Concept

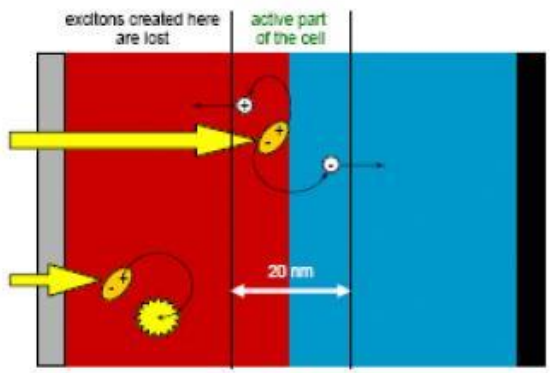
- Mix hole and electron acceptor materials with offset energy levels together → bicontinuous nanoscale mixture of D-A materials
- Both D and A materials must be very soluble in the same solvent
- Length scale of blend ~ exciton diffusion length (10-20nm)
- Exciton dissociation at interfaces; Electrons transferred to e^- acceptor, while h^+ to the polymer
- Percolation limit for both materials has to be reached.
- The blend morphology has to enable charge-carrier transport in the two different phases in order to minimize acceptor recombination





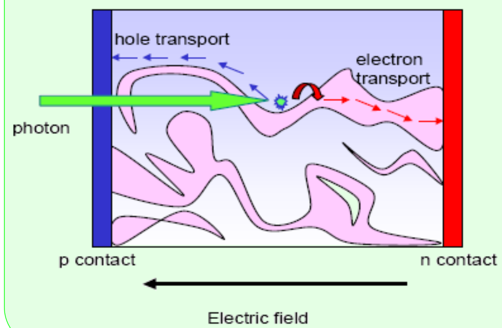
Road to BHJ concept in OPVs

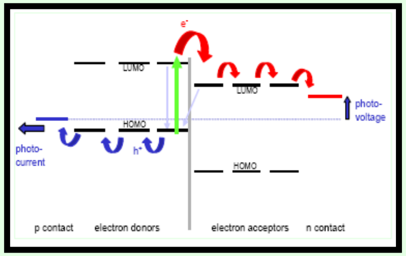
- *Exciton binding Energy(Eg)~200-500meV(Frenkel Excitons)*
- *Exciton diffusion length L_D ~ 1-20 nm*
- *L_D << layer thickness*



Solution

Bulk heterojunction concept in OPVs



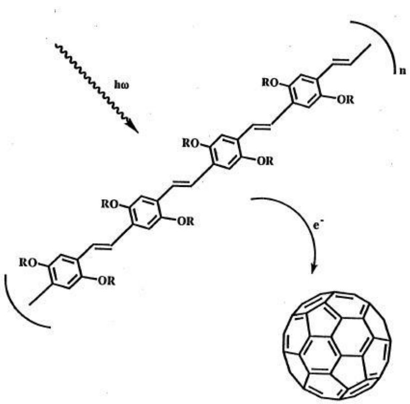


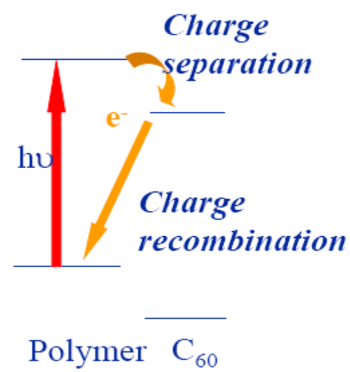
Problem: How can we absorb enough light in 20nm thick layer?

Thickness of act.layer ~ 200nm
L_D ~ length scales within BHJ

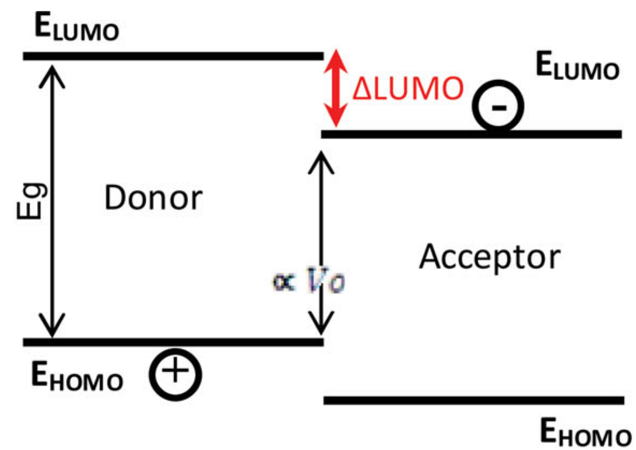
Road to BHJ concept in OPVs

Conjugated Polymer and Fullerenes

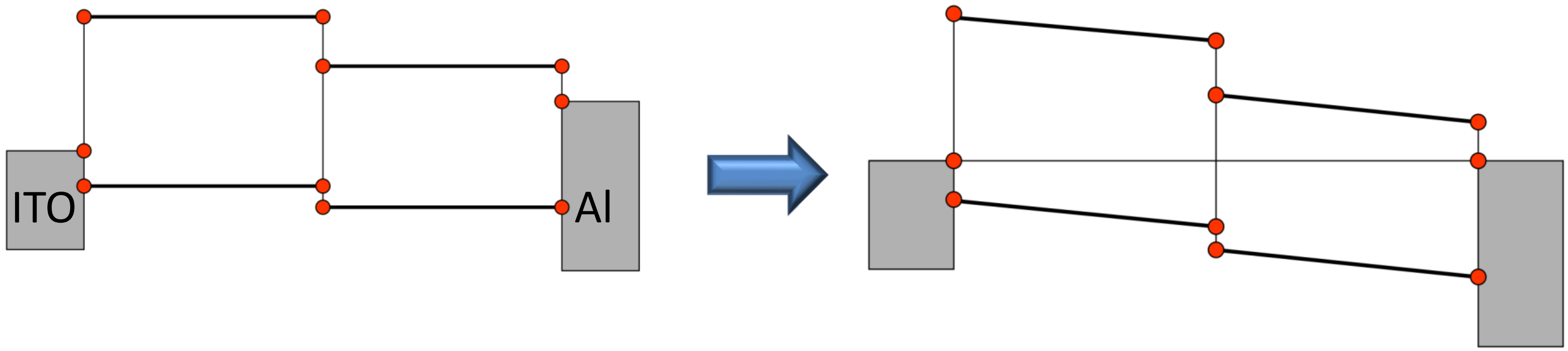




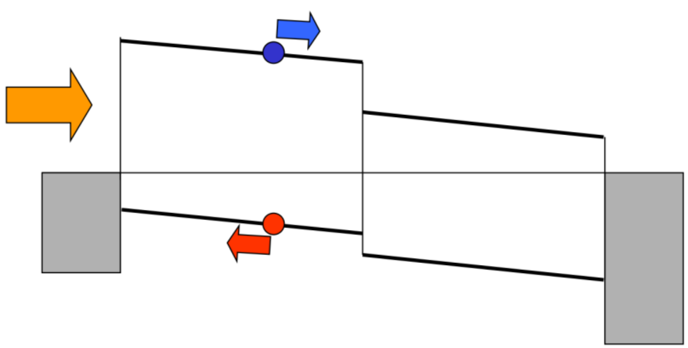
Ultrafast Photoinduced Charge Separation (fs) in the interface
Slow Charge Recombination (μs)



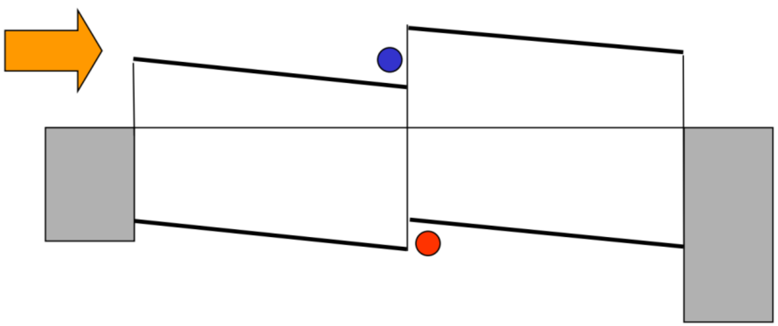
Bulk heterojunction concept and operating principles



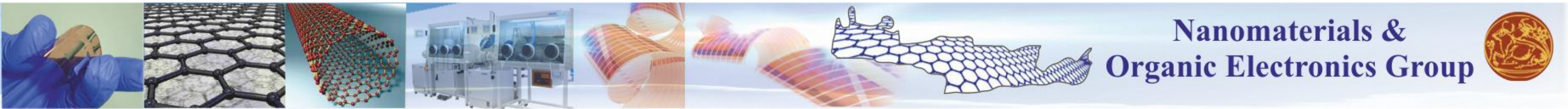
Fermi levels of anode and cathode aligned



Exciton dissociates at interface before it has a chance to recombine

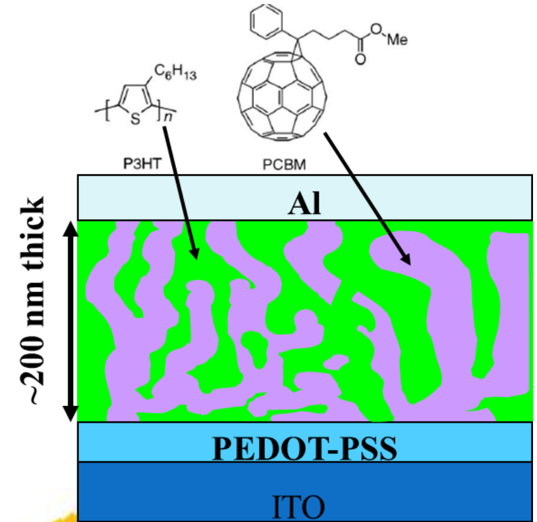


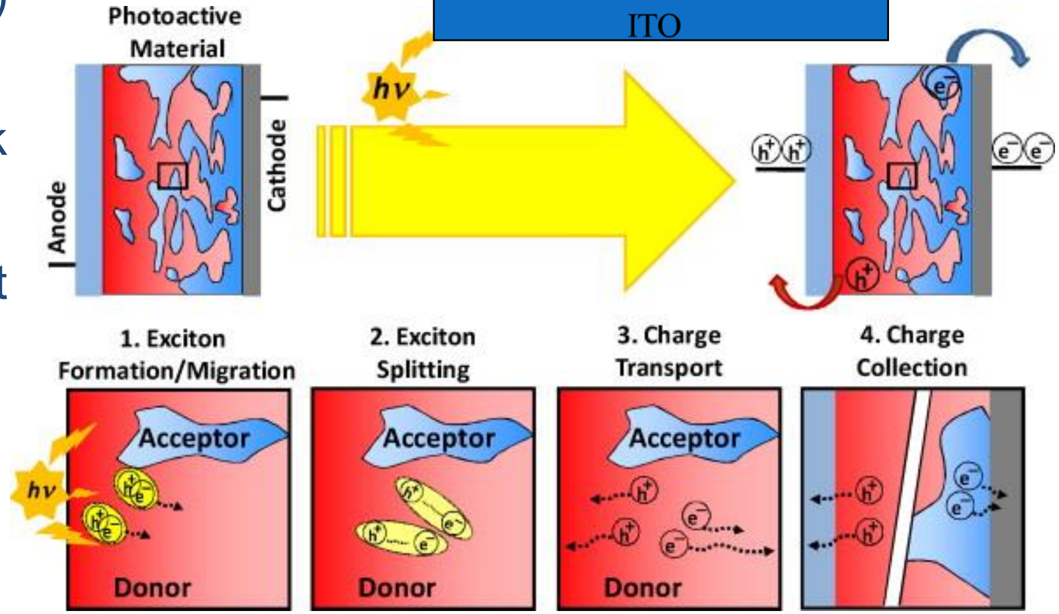
If the acceptor layer is deposited on the low work function electrode, charges get trapped at the interface

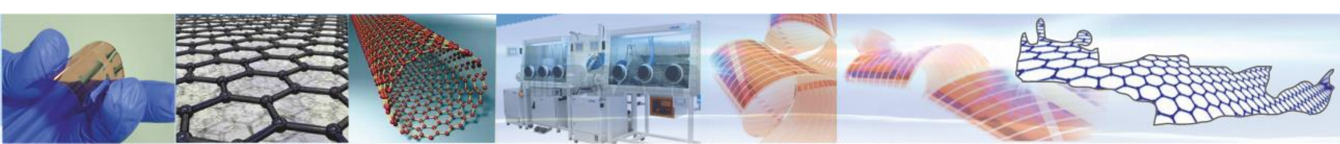


Working principle of bulk heterojunction

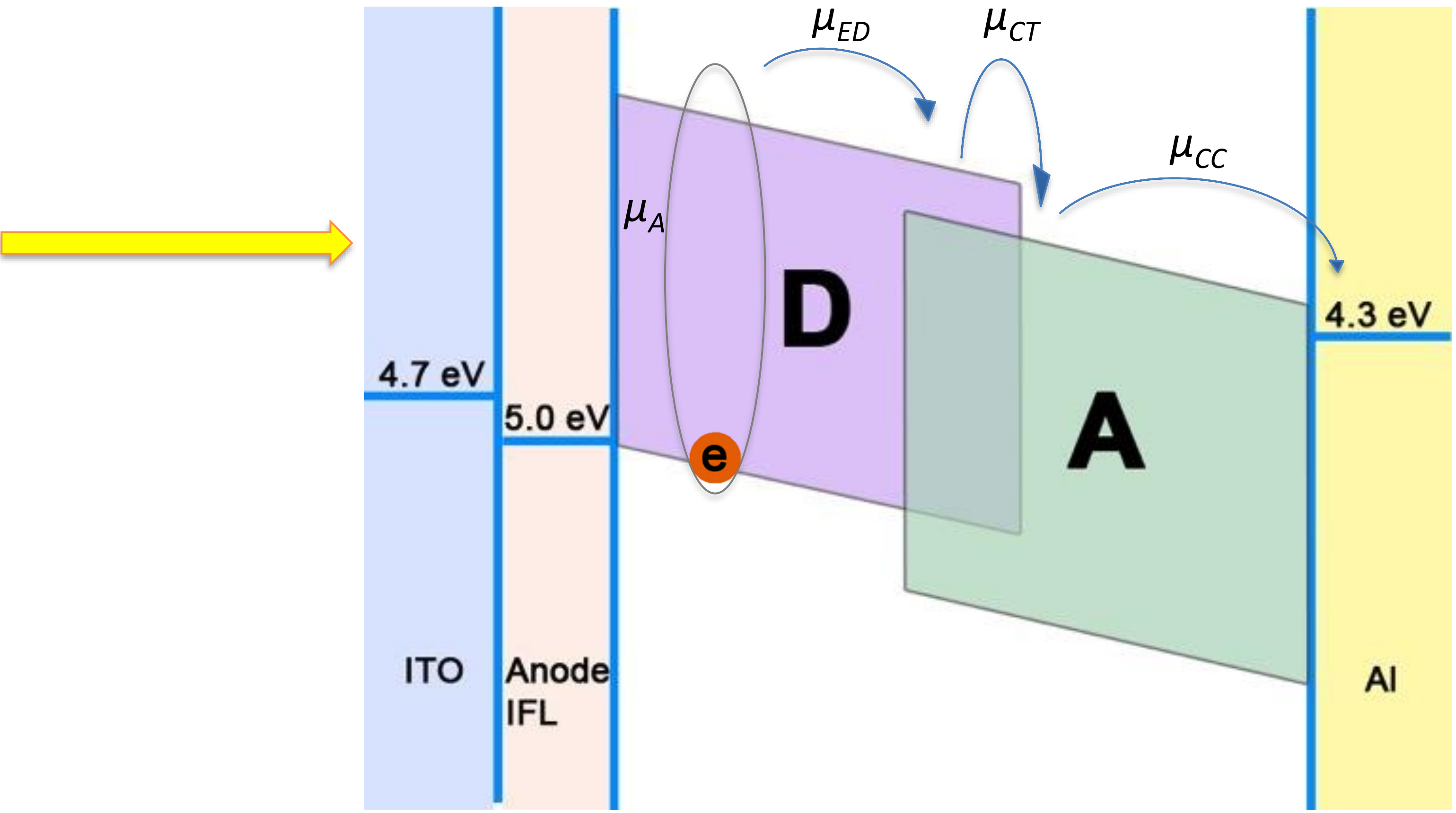
- Donor polymer (i.e. P3HT) absorbs light generating an exciton (i.e. bound electron hole pair)
- Exciton must diffuse to the Donor/Acceptor (e.g. PCBM) interface to split
- Electrons travel to the back electrode
- Holes travel to the front electrode





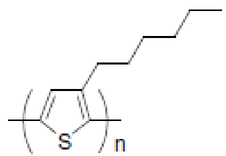


OPV Device Operation Principle

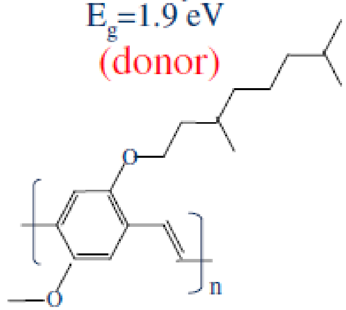


Efficiency ~$\mu_A x \mu_{ED} x \mu_{ct} x \mu_{cc}$

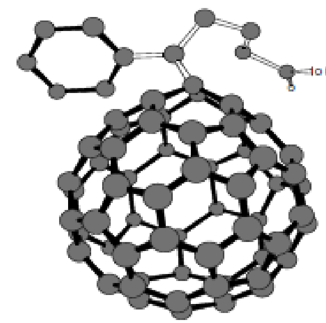
Conjugated Polymers and Fullerenes: An ideal Comporiste for exction generation and charge separation



RR-P3HT
E_α=3.0 eV, I_p=4.9 eV
E_g=1.9 eV
(donor)



MDMO-PPV
E_α=2.9 eV, I_p=5.0 eV
E_g=2.1` eV
(donor)



PCBM:
E_α=3.7 eV, I_p=6.1 eV
(acceptor)

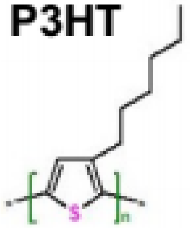
Why PCBM?

- Ultrafast electron transfer from polymer to fullerene.
- High solubility
- Excellent transport properties

What kind of materials do we use?

"Classic" wide band gap Polymers

P3HT

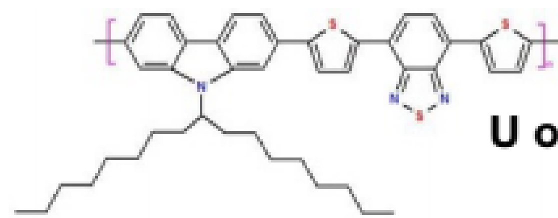


PPV

Burroughes, J. H. et al. *Nature* **(1990)**
Chen & Rieke *JACS* **(1992)**

Low band gap Copolymers

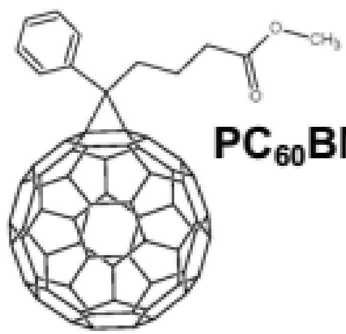
PCDTBT



U of Laval

Blouin, et al. *Advanced Materials* **(2007)**
Blouin et al. *JACS* **(2008)**

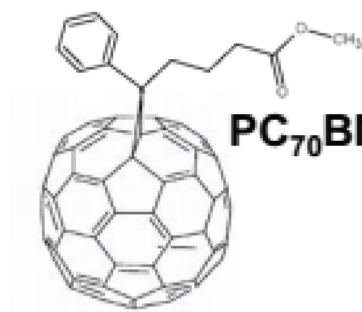
"Classic" Fullerene



$PC_{60}BM$

Hummelen et al. *J. Org. Chem.* **(1995)**

"Absorbing" Fullerene

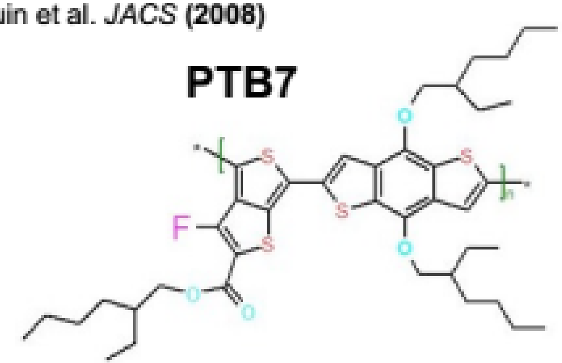


$PC_{70}BM$

Wienk et al. *Angew. Chem. Int. Ed.* **(2003)**

"Exotic" Fullerene $Lu_3N@C_{80}$

PTB7

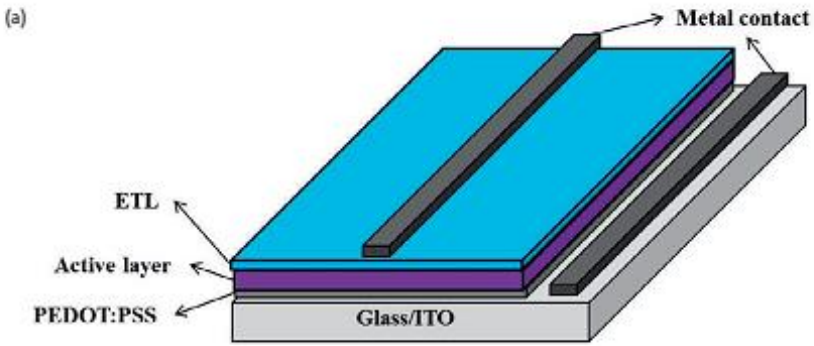


U of Chicago

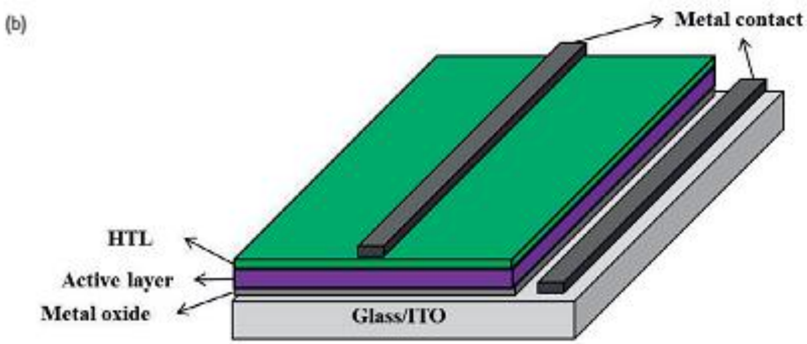
Liang et al. *JACS* **(2009)**
Liang, et al. *Advanced Materials* **(2010)**

Device structures

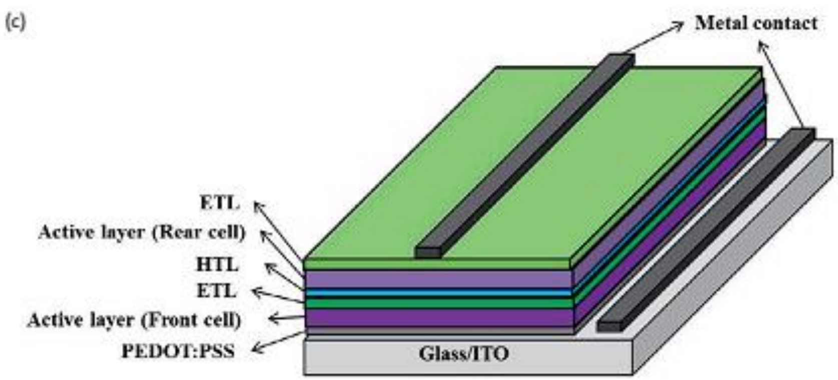
(a) conventional single-junction cell,



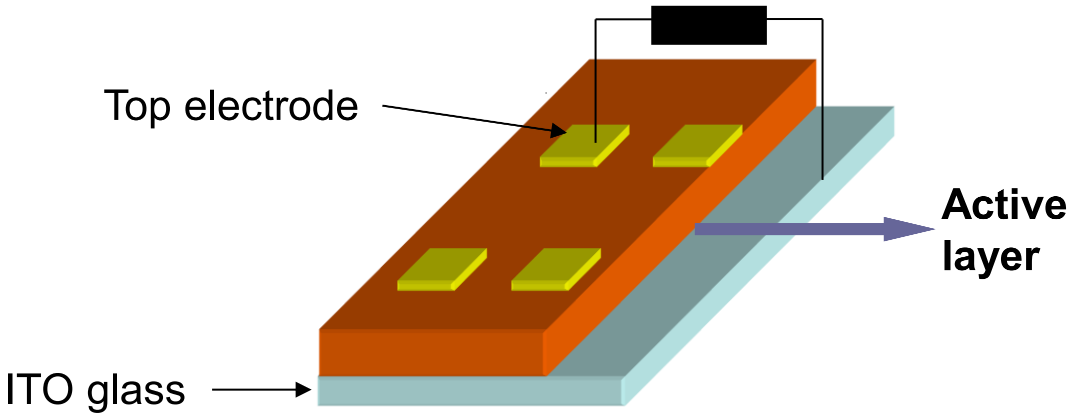
(b) inverted single-junction cell, and



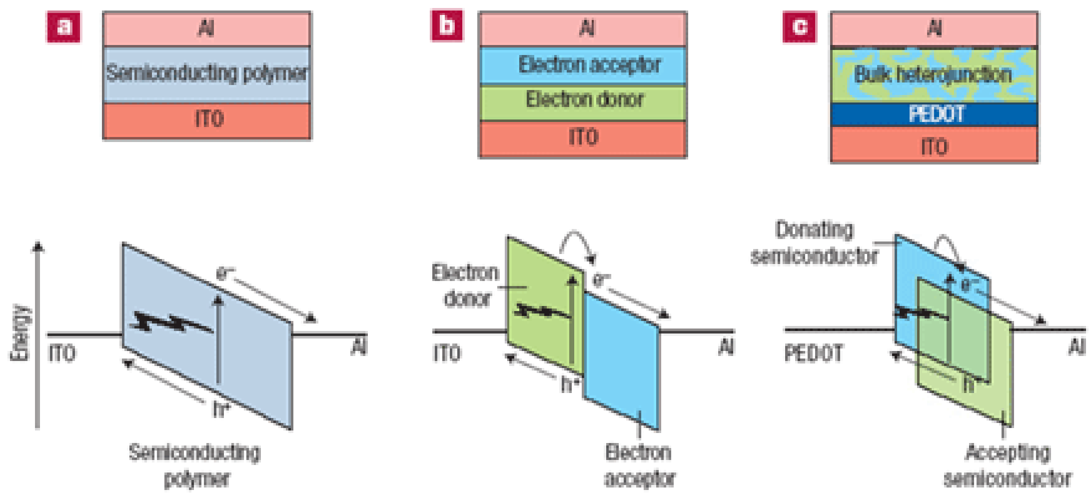
(c) conventional multi-junction tandem cells.



Possible Device architectures



- ✓ Single-layer
- ✓ Bilayer
- ✓ Bulk heterojunction



Single-layer PV cell　　Bilayer PV cell　　Bulk heterojunction PV cell

Factors Limiting Device Performance

Fill factor limited by:

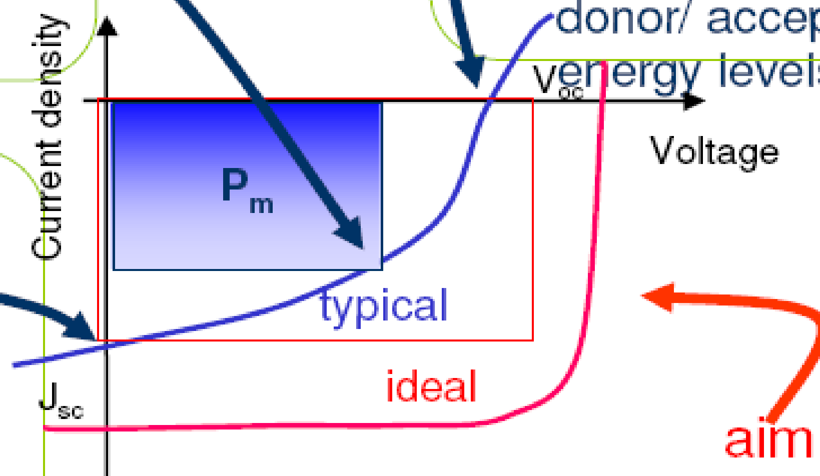
- charge transport
- recombination

Open circuit voltage limited by:

- recombination
- donor/ acceptor energy levels.

Short circuit current density limited by:

- light harvesting
- charge separation and transport



$PCE = FF \times J_{sc} \times V_{oc} / P_{inc}$ (100 mW/cm^2)

$FF = P_m / Jsc \times Voc$

Optimization for high efficiency

1. Conjugated polymer with low band gap

Maximum photon flux of sun = 700 nm

E_g= 1.24 / 0.7= 1.77 [eV]

Maximum absorption of photon of sun

2. Bulk heterojunction morphology

exciton diffusion length of conjugated polymer

= below 20 nm

3. High carrier mobility

electron and hole mobility of conjugated polymer

I_{sc}: tuning of the **transport property** (mobility); Optimization of cell geometry in dependence of the cell thickness

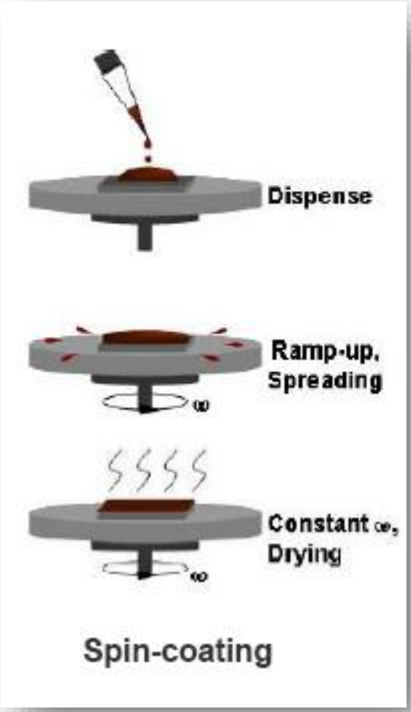
V_{oc}: tuning of the **electronic energy level** of the donor-acceptor system; V_{oc} of ~2 V observed in polymeric donor- acceptor system

F.F: tuning of the contacts and **morphology**: lowering of serial resistance

$$\eta = \frac{I_{sc} V_{oc} FF}{P_S} \times 100$$

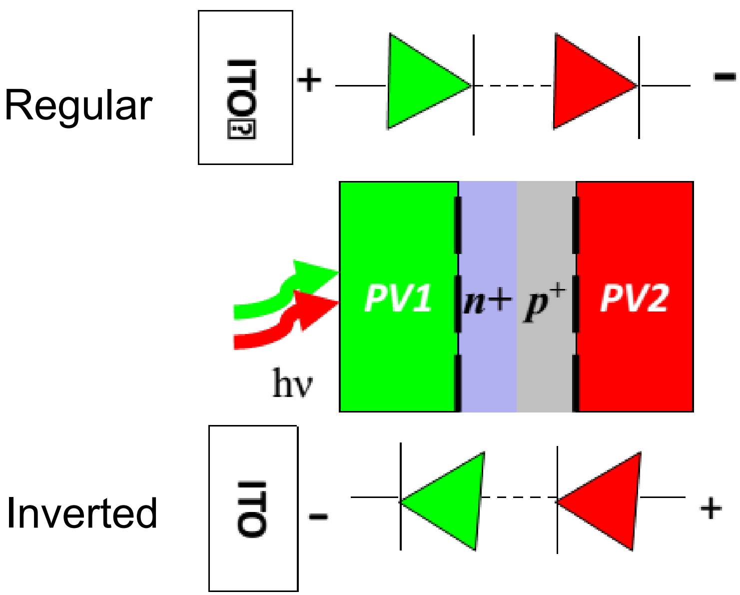
Organic PVs Fabrication & Film preparation

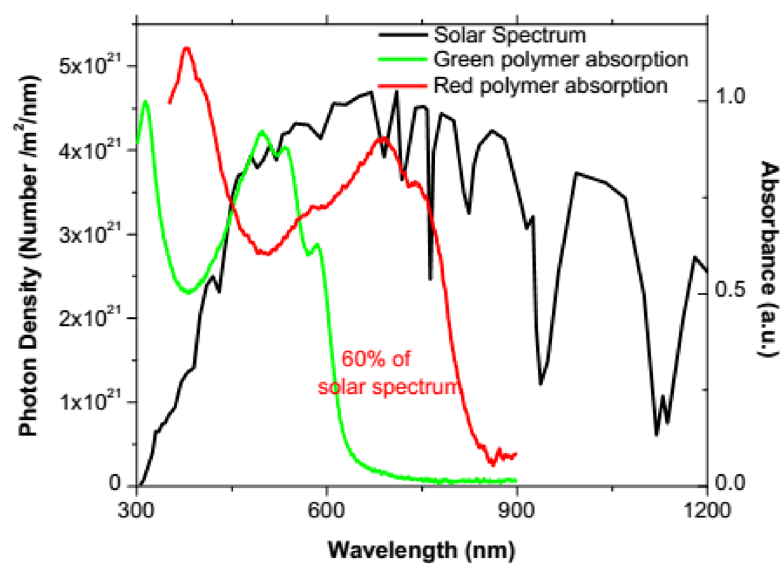
- ✓ To increase life time and efficiency of organic electronics fabrication processes should be realized in controlled atmosphere where the device is never in contact with oxygen, moisture and white light at the same time. Glove Boxes are directly connected to deposition chambers



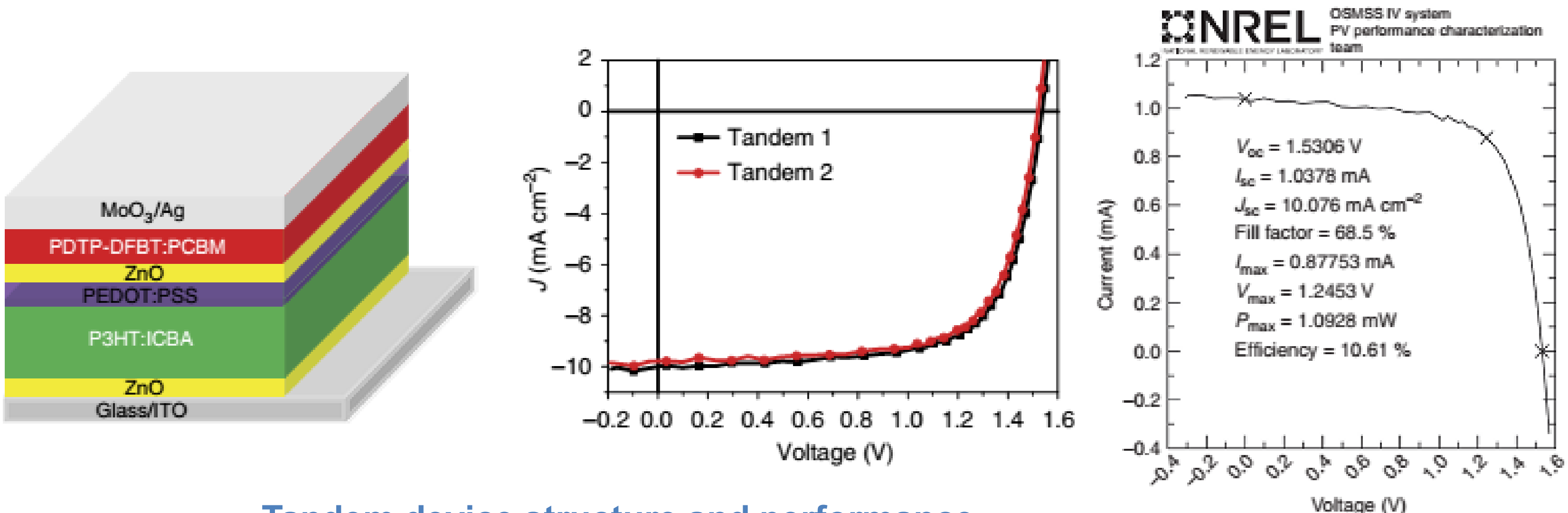
Tandem Polymer Solar Cells

- Two solar cells with complementary absorption range
- Reduce the “Quantum/Energy Loss” of high energy photons
- Transparent/conductive/robust interconnection layer (ICL)
- Multijunction solar cell compatible with **Low-Cost ➔Solution process**





World record of 10.6% PCE of a polymer tandem solar cell



Tandem device structure and performance

Table | P3HT and PDTP-DFBT single junction cell and tandem solar cell performance.

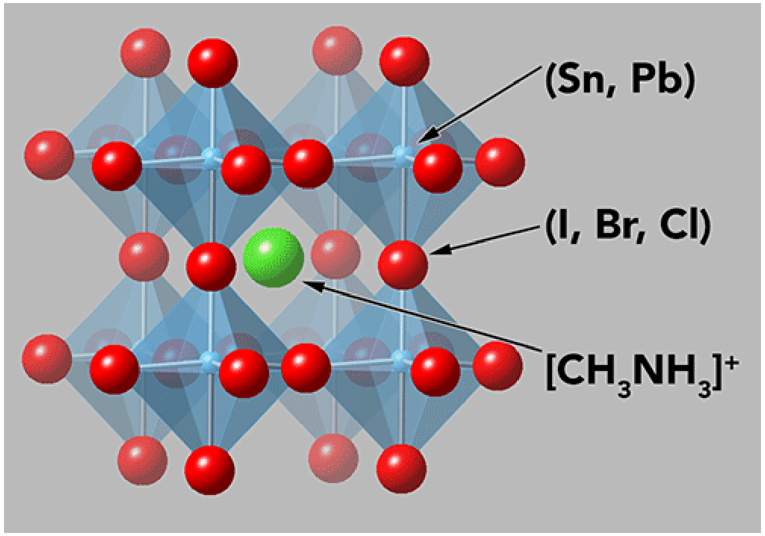
Devices	V_{OC} (V)	J_{SC} (mA cm^{-2})	FF (%)	PCE (%)
P3HT:ICBA	0.84	10.3	71.1	6.1
PDTP-DFBT:$PC_{61}BM$	0.70	15.4	66.2	7.1
PDTP-DFBT:$PC_{71}BM$	0.68	17.8	65.0	7.9
P3HT:ICBA/PDTP-DFBT:$PC_{61}BM$ (Tandem 1)	1.53	10.1	68.5	**10.6***
P3HT:ICBA/PDTP-DFBT:$PC_{71}BM$ (Tandem 2)	1.51	9.8	69.2	10.2

The devices have a potential but with such a low efficiency it is difficult to be commercialized

Hybrid Perovskite Semiconductors

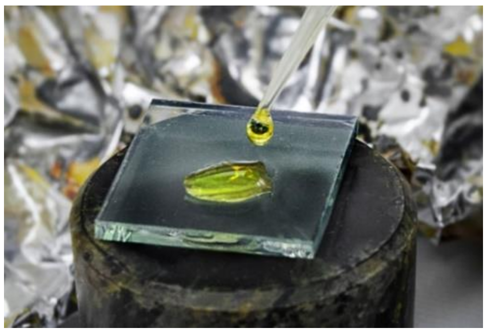
- The low efficiencies in organic solar cells turned the research community to search for now more efficient materials to capture sunlight
- A promising material using similar device fabrication and configuration is metal halide perovskites

The name 'perovskite solar cell' is derived from the ABX_3 crystal structure of the absorber materials, which is referred to as perovskite structure. The most commonly studied perovskite absorber is methylammonium lead trihalide ($CH_3NH_3PbX_3$, where X is a halogen ion such as I−, Br−, Cl−), with an optical bandgap between 3 eV and 1.6 eV depending on halide content.

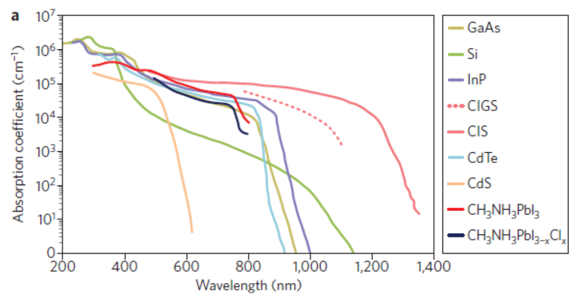


Organometal Halide Perovskites: Why so special Semiconductor materials?

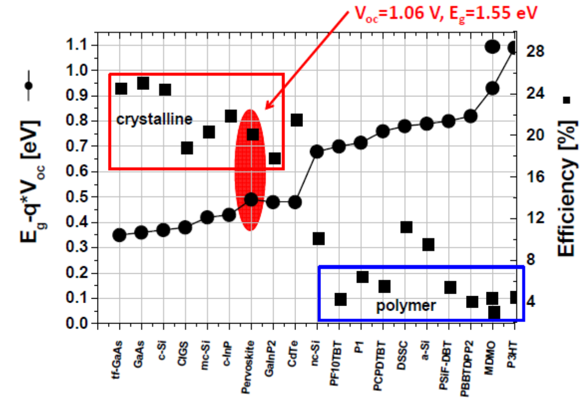
Solution and RT Processed



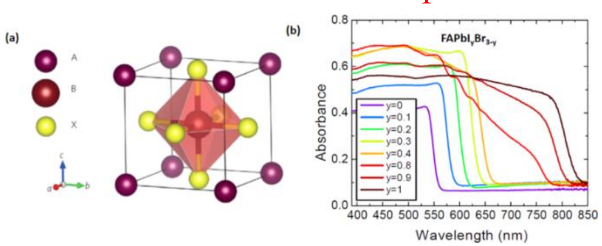
Strong Absorption Coefficient



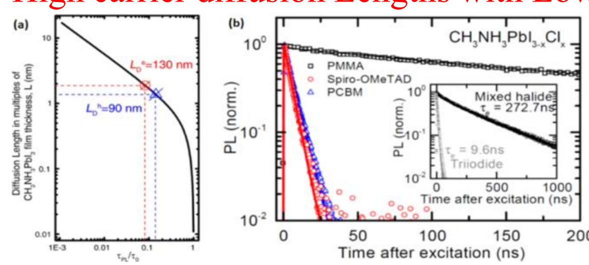
Low energetic lossses



Tunable Band Gap

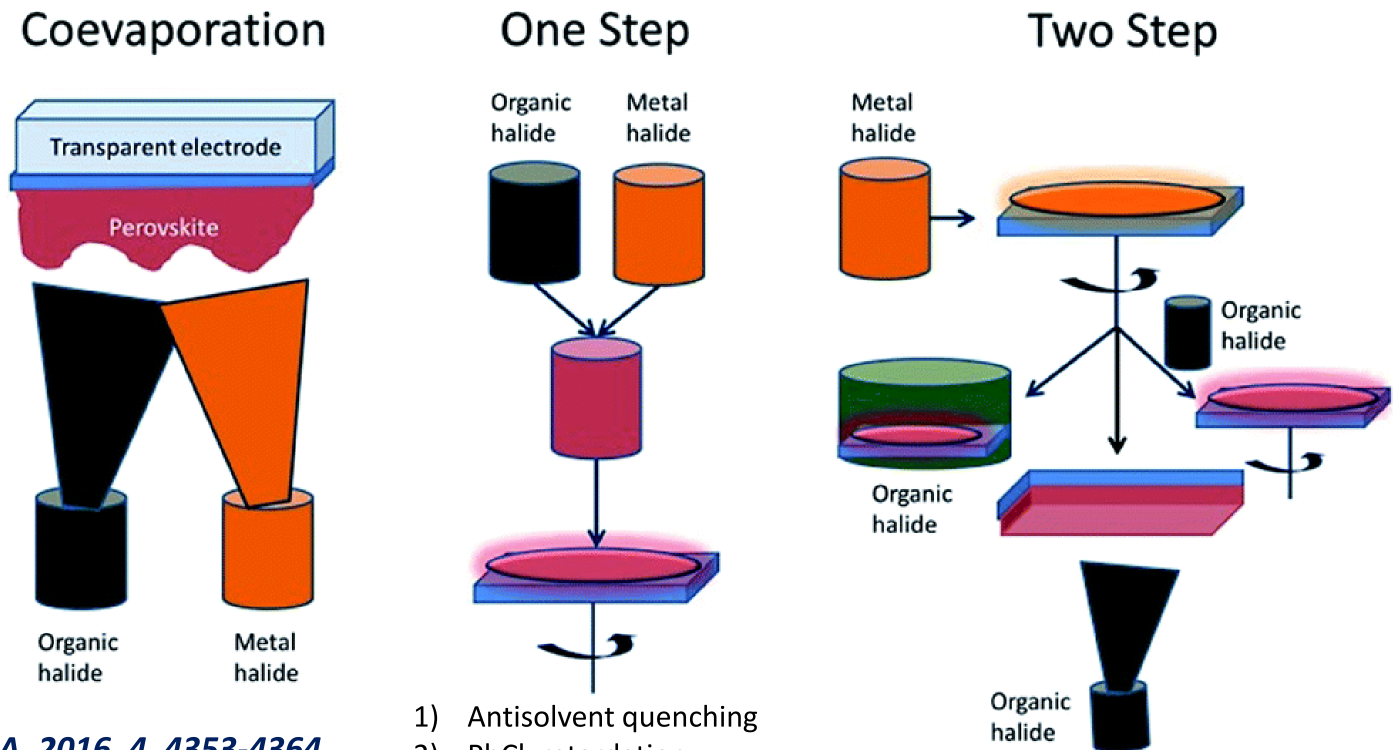


High carrier diffusion Lengths with Low E_b



Nature Nanotechnology (2015) **10**, 391–402

How to grow a perovskite thin film?

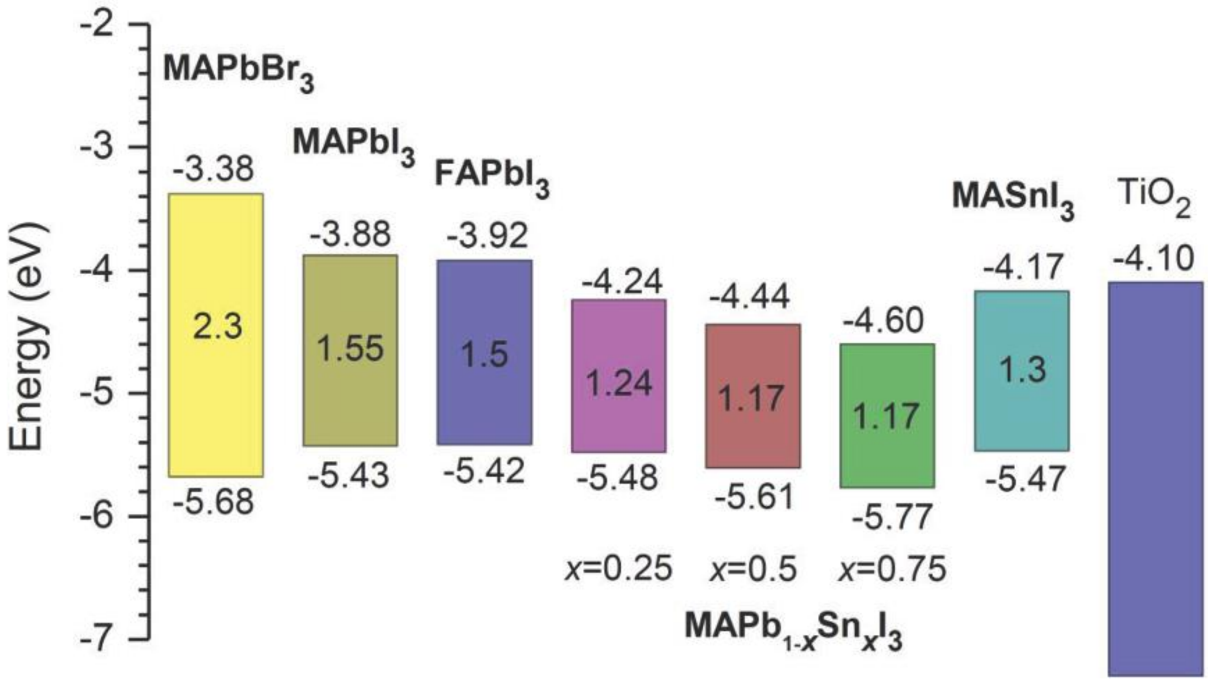


J. Mater. Chem. A, 2016, 4, 4353-4364

1) Antisolvent quenching
2) $PbCl_2$ retardation

Band Gap Tuning

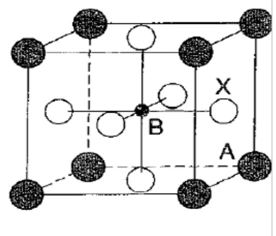
- Bandgap tuning is required to extend the absorption to longer wavelengths without sacrificing the absorption coefficient.
- Changing in any of A, M and X in ABX_3 changes the bandgap
- The bandgap also can be tuned in between 1.55 eV and 1.17 eV by varying the ratio of lead to tin



Conditions for the formation of 3D Perovskite

- When will a 3D perovskite form?

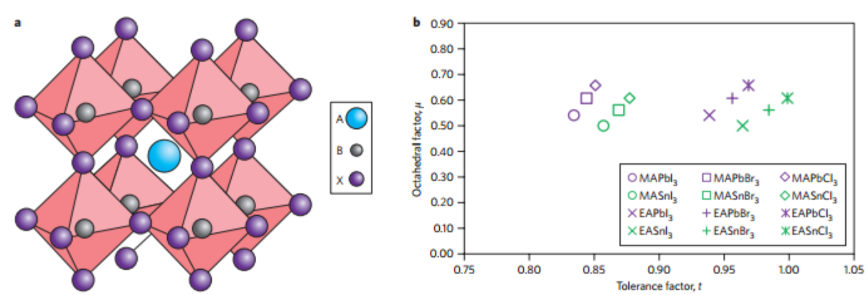
- When the A, B and X components fit together neatly in the crystal lattice.
- Assuming ionic radii of R_A etc, For a close packed cubic perovskite the structure is possible, provided:



ABX_3

$$(R_A + R_X) = t\sqrt{2}(R_B + R_X)$$

Where t is a non defined tolerance factor, typically $0.8 < t < 1$, which relates to how much strain the lattice can tolerate before it will no longer form.

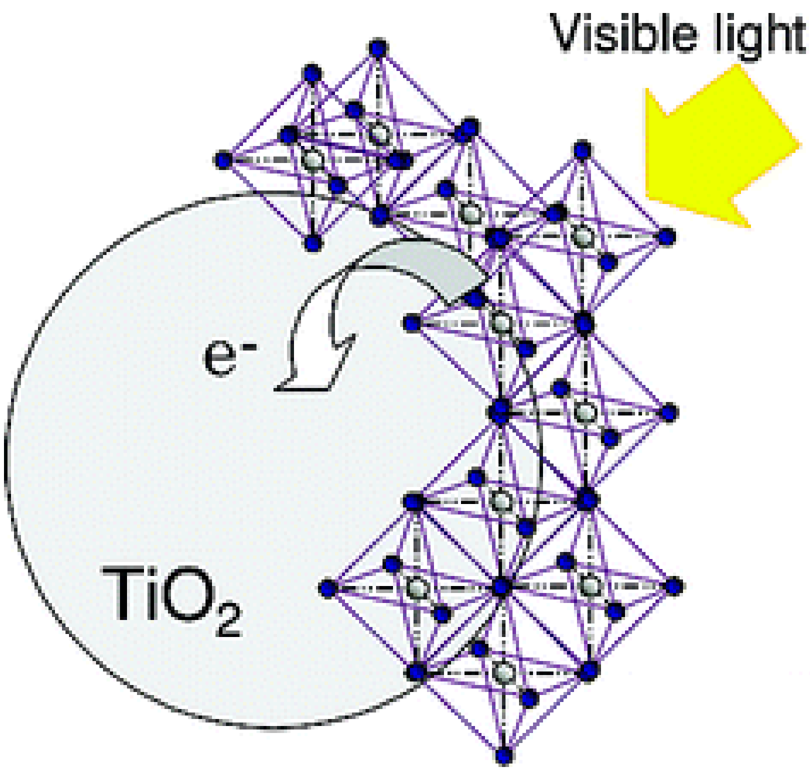


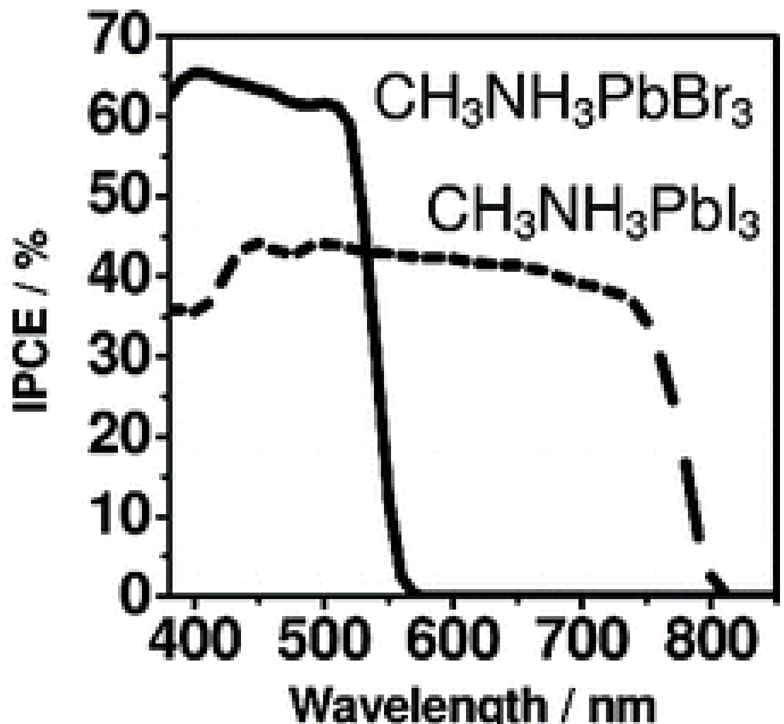
The first demonstration of metal halide perovskite as solar absorbers

Organometal Halide Perovskites as Visible-Light Sensitizers for Photovoltaic Cells

Akihiro Kojima,† Kenjiro Teshima,‡ Yasuo Shirai,§ and Tsutomu Miyasaka*,†,‡,∥

J. AM. CHEM. SOC. 2009, *131*, 6050–6051

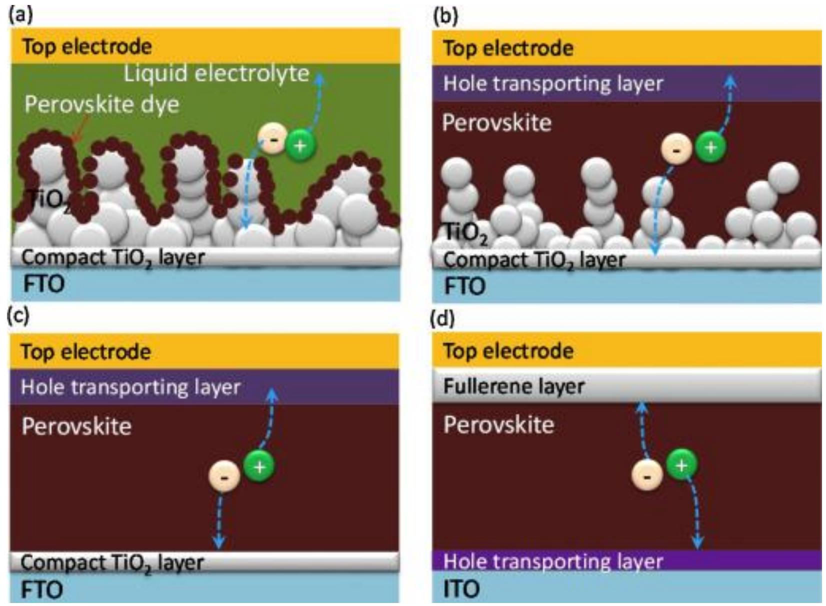




Device Structures and operating principles

ETA PSCs
3.9%

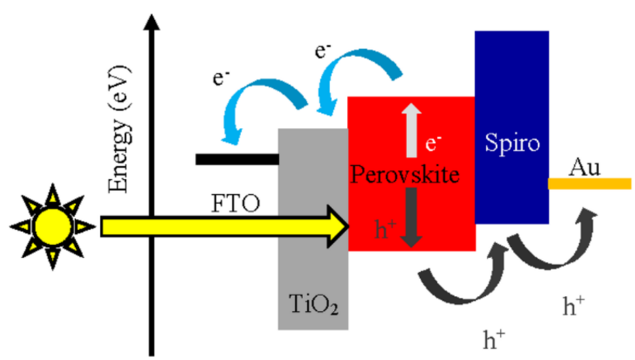
Planar Normal PSCs
26%



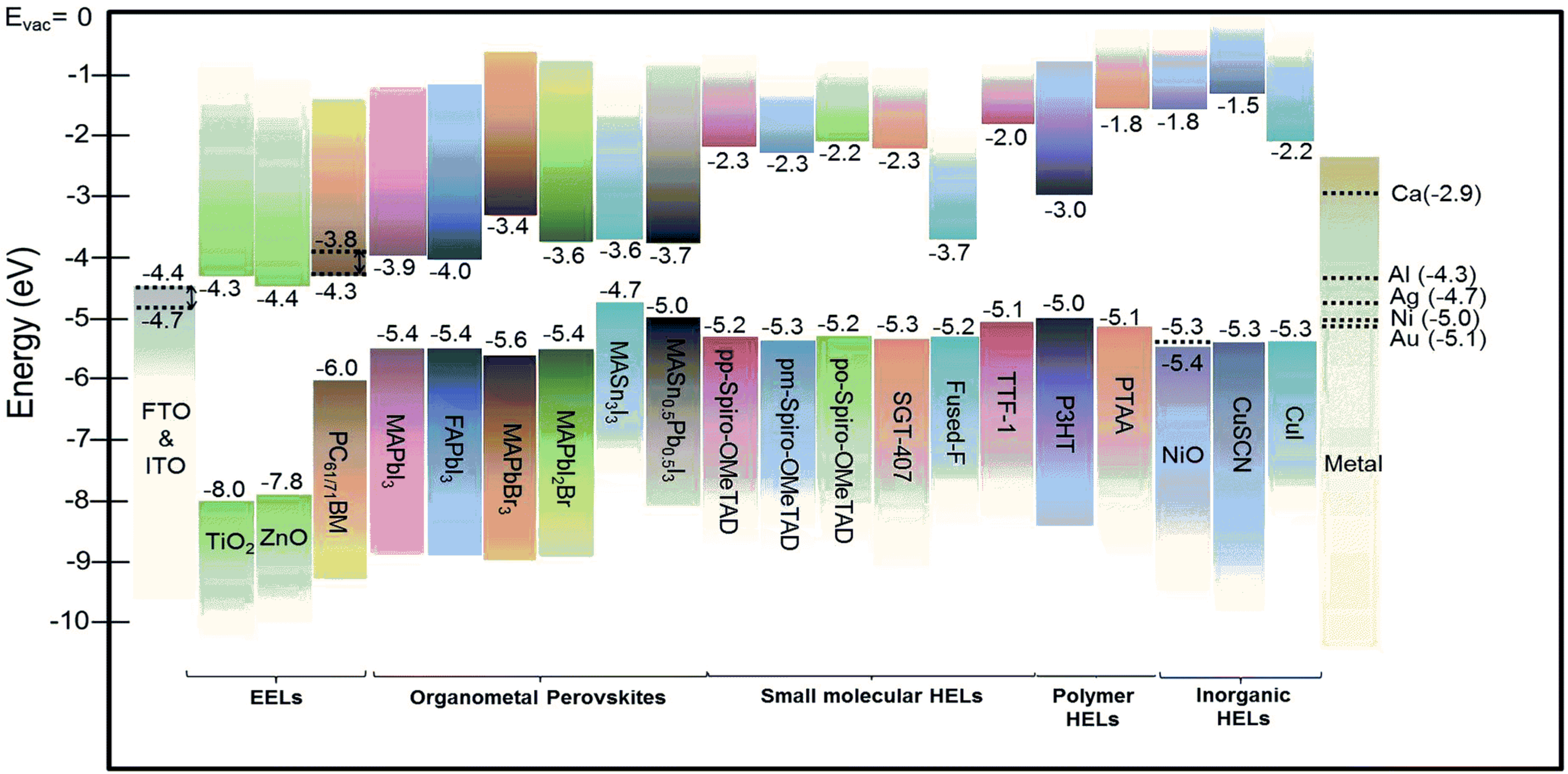
Mesoscopic PSCs
25%

Planar Inverted
26%

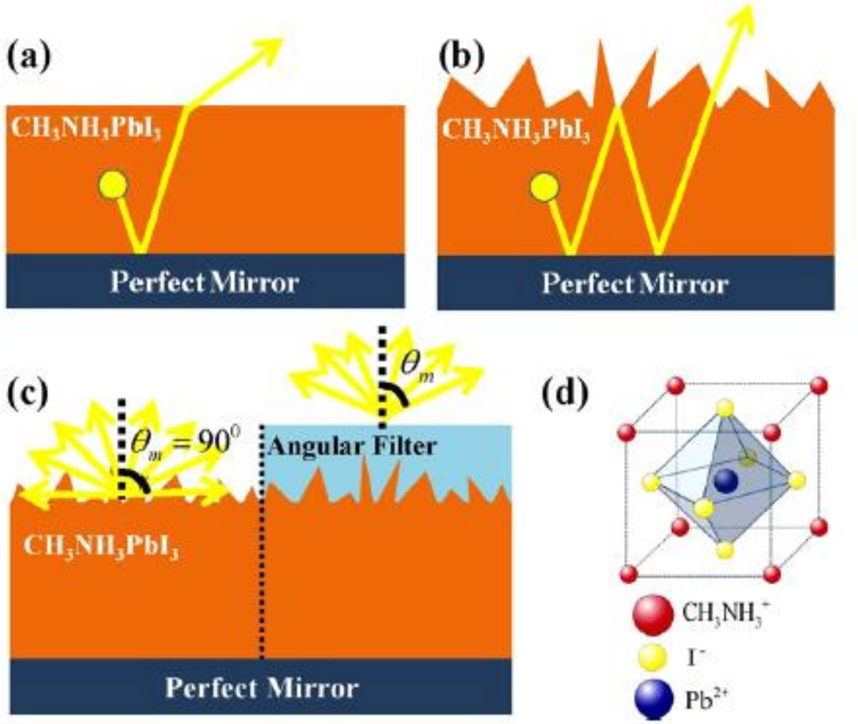
- ✓ **High carrier diffusion lengths (>1 µm)**
- ✓ **Low exciton binding energy (~k_BT)**
- ✓ **Direct Bandgap Semiconductor with high Abs. Coefficient**

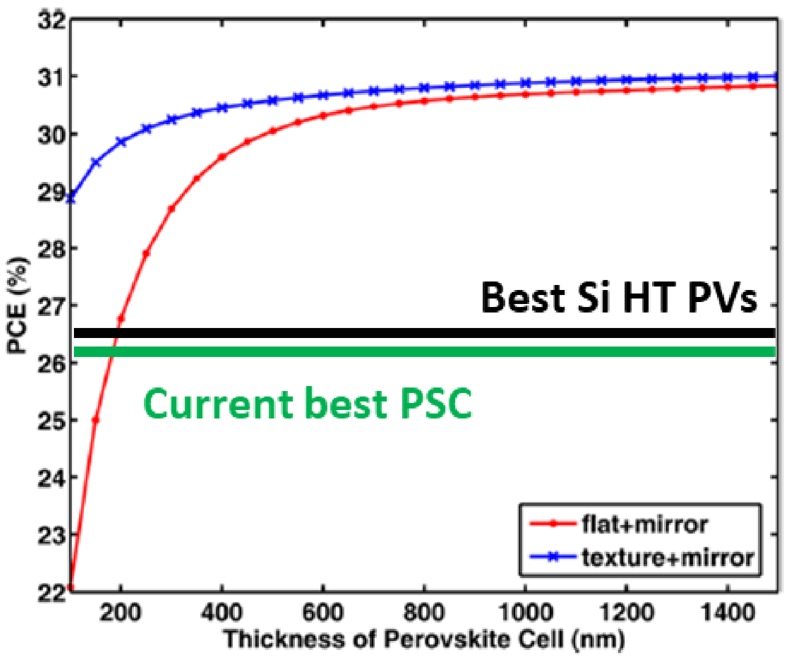


Device building blocks: a plethora of interfacial materials



The great potential of Perovskite Solar Cells





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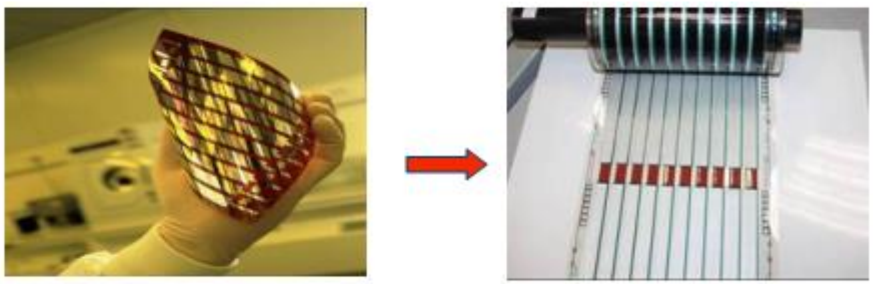
	Flat and perfect mirror			Textured and perfect mirror		
Thickness (nm)	200	500	1000	200	500	1000
V_{oc} (V)	1.325	1.315	1.305	1.300	1.295	1.290
J_{sc} (mA/cm^2)	22.27	25.27	25.97	25.38	26.13	26.46
FF	0.91	0.91	0.91	0.91	0.91	0.91
PCE (%)	26.77	30.06	30.69	29.86	30.59	30.88

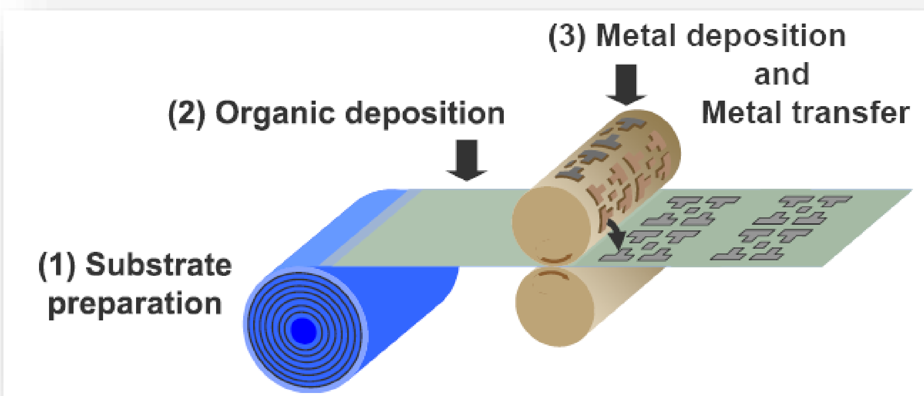
Open challenges towards commercially available perovskite solar cells

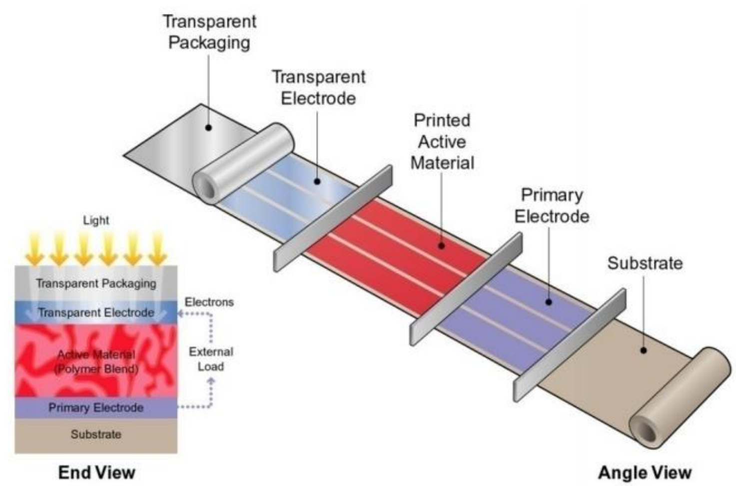
- ✓ **Push the efficiency of PSCs to their limits (surpass that of Si-HT PVs)**
- ✓ **Pass the damp heat stability protocol (85 ^{o}C, 85% RH, MPPT)**
- ✓ **Use low cost raw materials to further reduce the cost/watt figure of merit**
- ✓ **Scalability of perovskite solar cells to modules and panels**
- ✓ **Flexible and still highly efficient solar cells**

From lab-cells to mass production

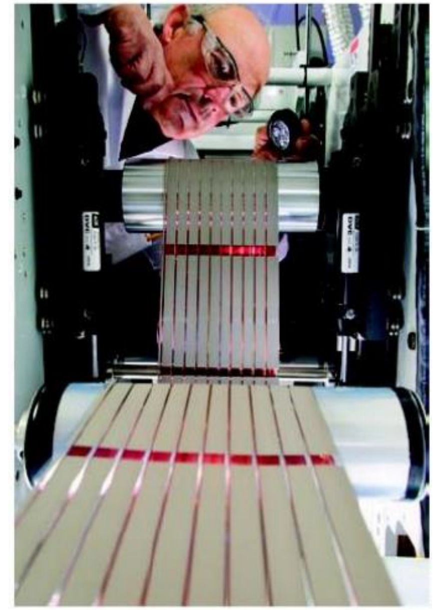
- A proposed means to lower the cost of producing flexible displays in a high-volume manufacturing environment by taking advantage of a unique attribute of flexible substrates relative to the traditional glass substrate



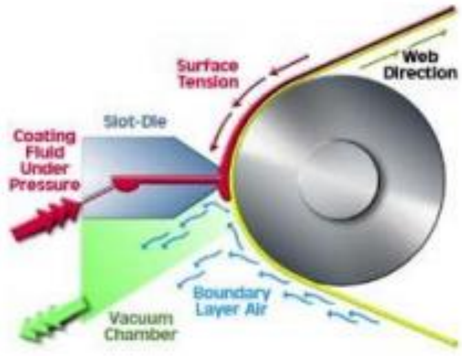


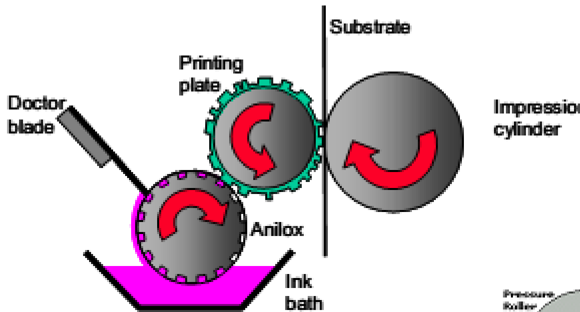


Large Scale Printing of Semiconductors

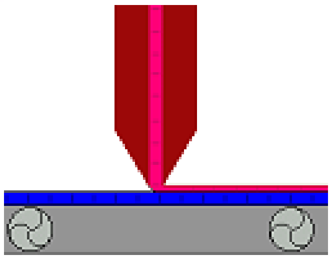


Deposition Technology

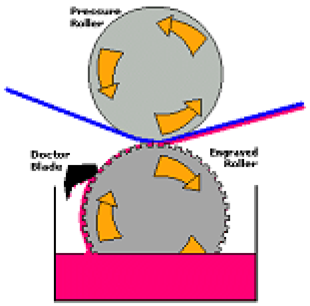


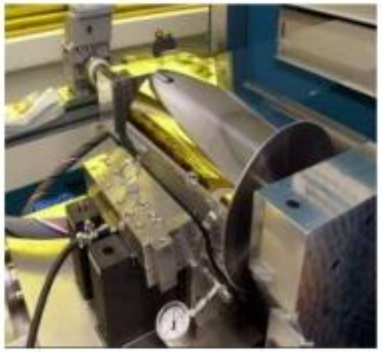


Slot die coating



Gravure / flexo printing

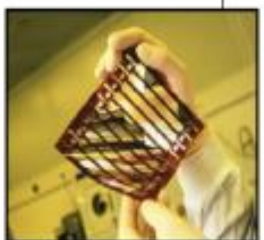




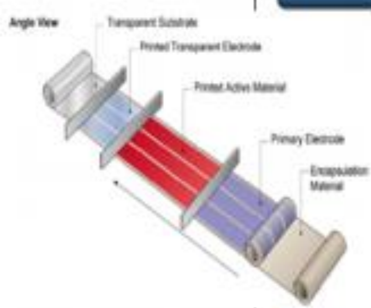
Key Technology and Requirement for Flexible OPVs Commercialization

Flexible OPVCs Technology

- **Power Conversion Efficiency** — ~10%
  - **Low-bandgap** Donors — ~1.4 eV
  - **High LUMO** Acceptors — ΔE > 0.3 eV
  - D-A Nanomolpology control — Bulk Heterojunction
  - Organic Multijunction — Tandem, Stack
  - **Buffer Layer**



- **Device Stability** — >5 years
  - Opti-/Thermally **Stable** Materials
  - **Nanomorphology** Stabilization — Self-Organizable Mater.
  - High Barrier Flexible Substrate — OLED Tech.
  - Encapsulation/Passivation — OLED Tech.



- **Manufacturing Technology** — <0.5$/Wp
  - **Printing Technology** — Gravure, Inkjet, Aerosol-Jet
  - **R2R** Processibility — Flexible substrate

Thank you for your attention!!!

Any Questions?

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