Introduction to Photovoltaics

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Outline

- Acknowledgements
- Introduction
- History towards solar cell
- Solar cells industry
- Photovoltaic effect
- Solar cells
- Closing remarks

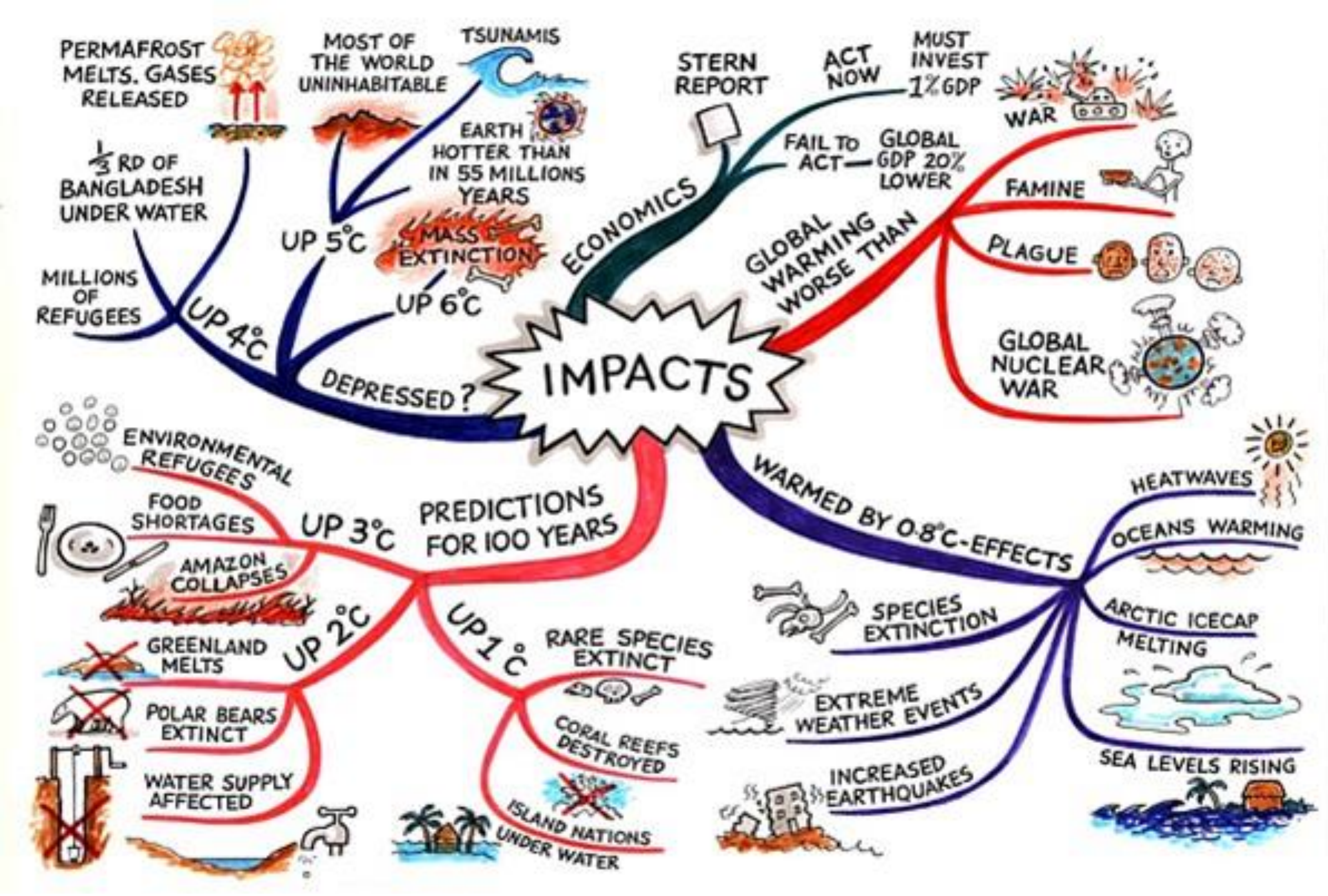
Introduction

- Climate change
- Renewable energy
- Solar energy
- Progress in Solar cells

Climate change

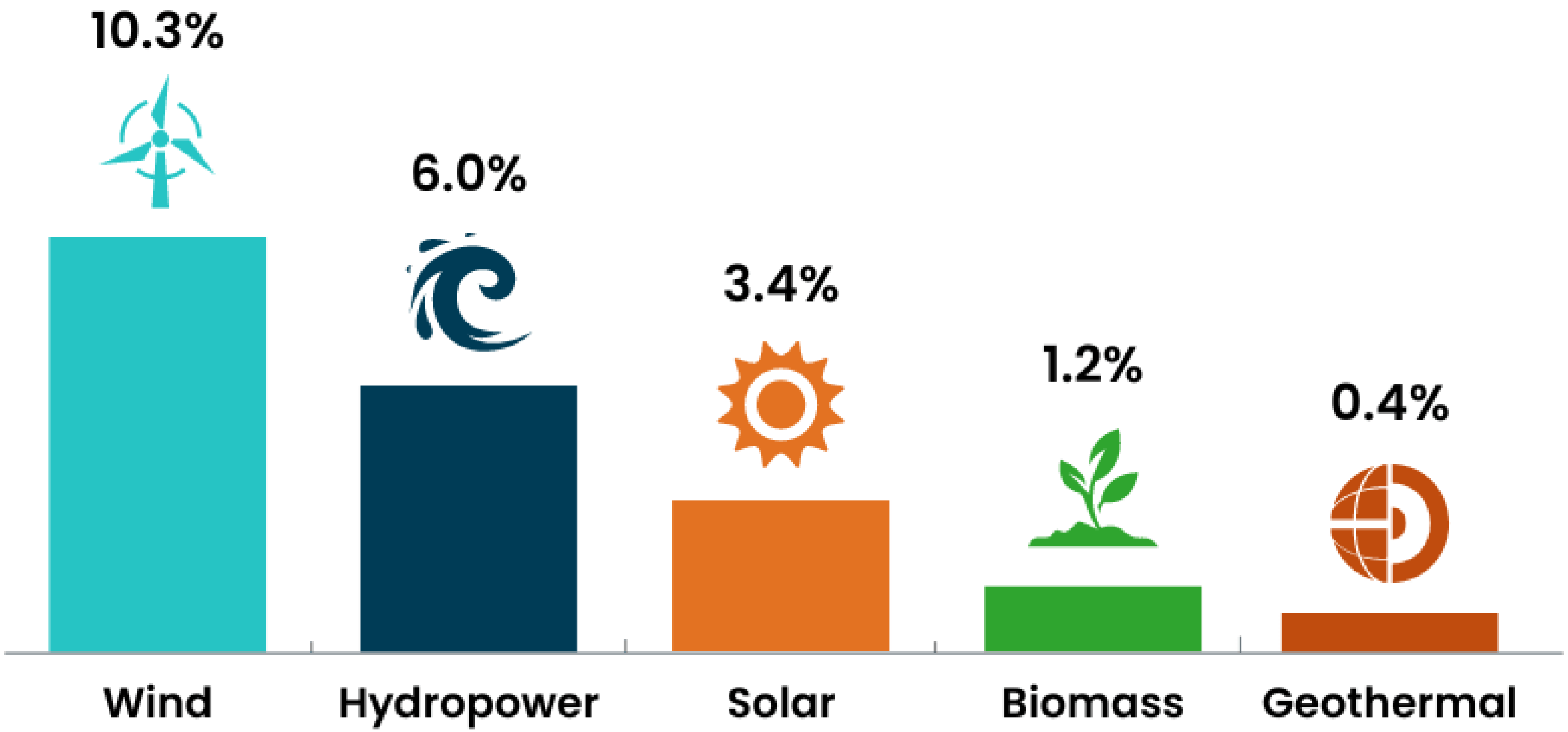
Climate is the reason why we want to reduce the use of fossil fuels and gradually introduce renewable energy

Impact of climate change



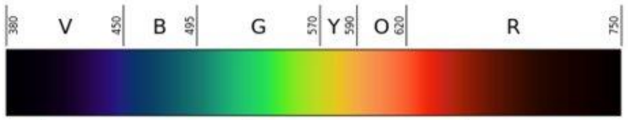
Renewable energy

Renewable energy in USA

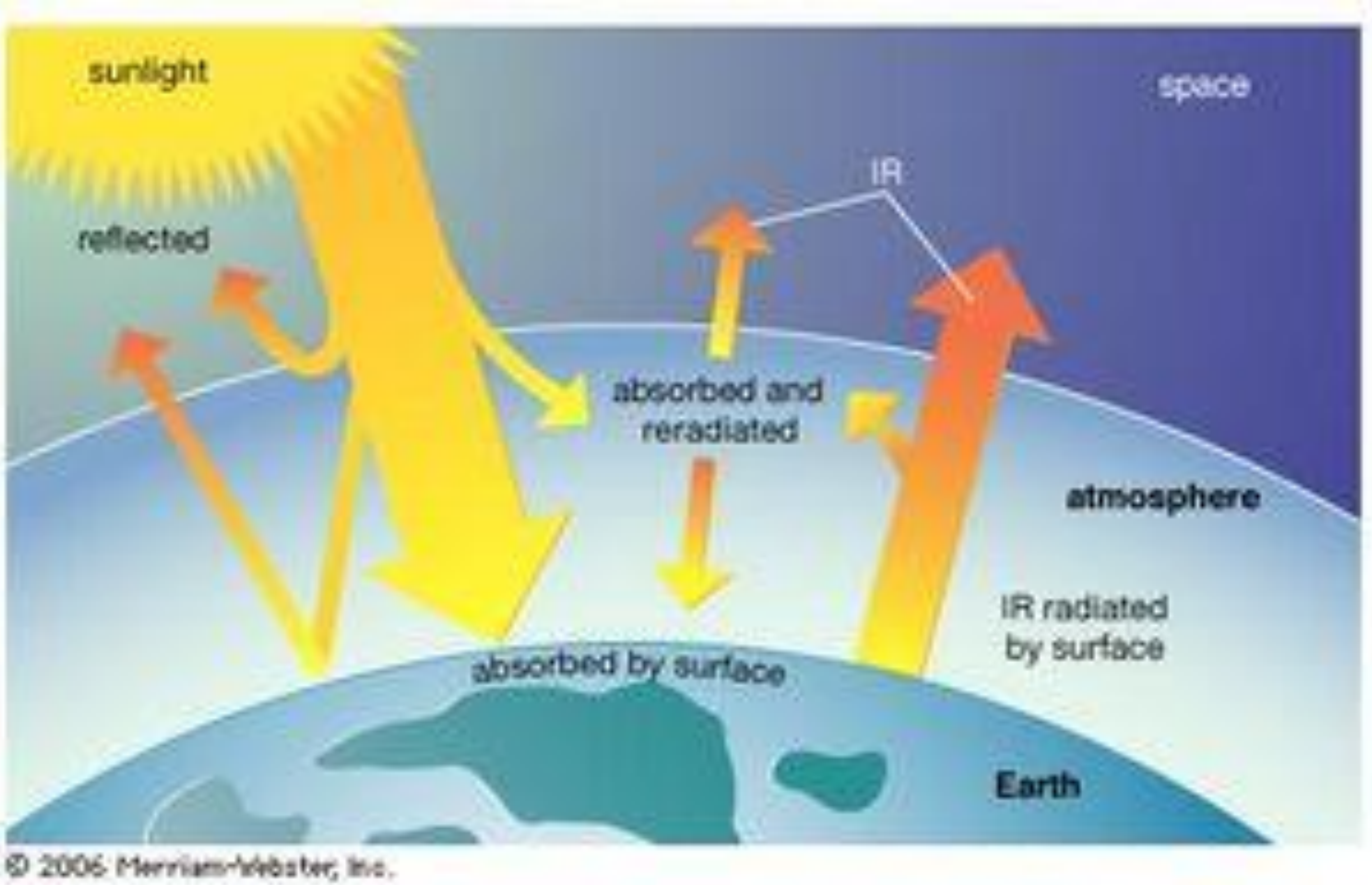


Renewable Energy in SGDs

Solar energy



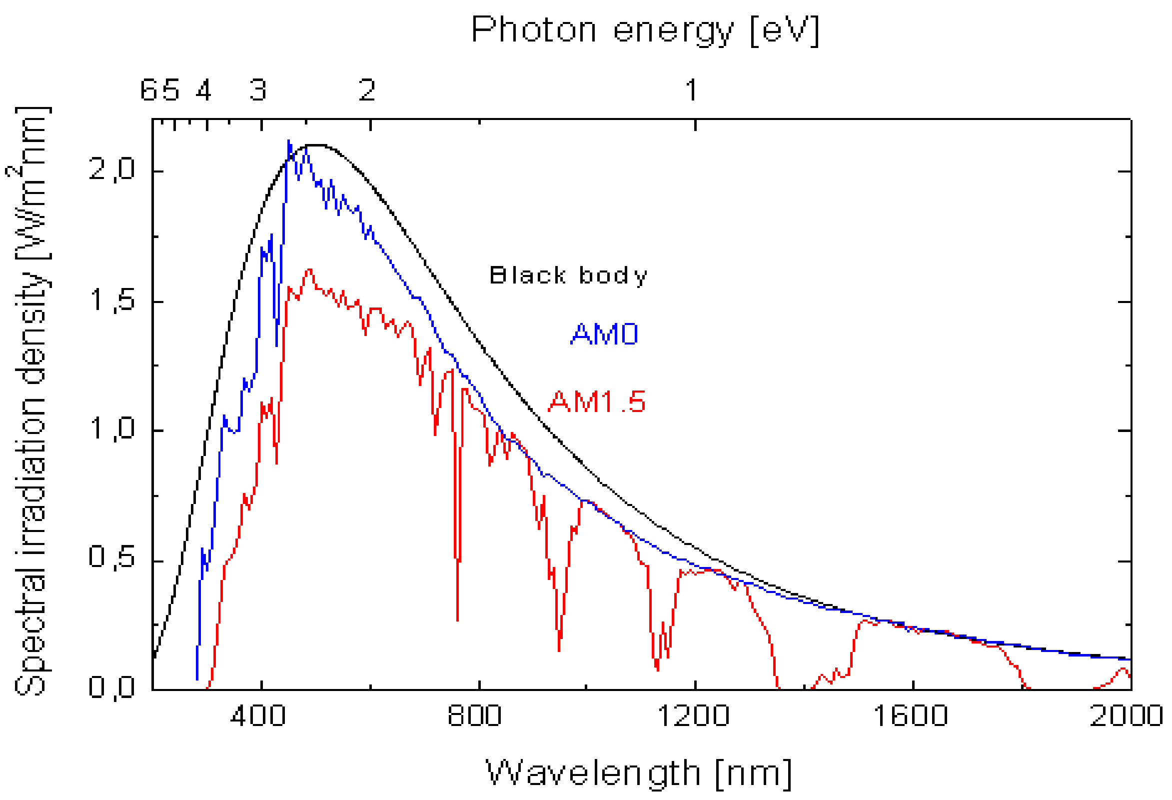
Color	Wavelength	Frequency	Photon energy
violet	380–450 nm	668–789 THz	2.75–3.26 eV
blue	450–495 nm	606–668 THz	2.50–2.75 eV
green	495–570 nm	526–606 THz	2.17–2.50 eV
yellow	570–590 nm	508–526 THz	2.10–2.17 eV
orange	590–620 nm	484–508 THz	2.00–2.10 eV
red	620–750 nm	400–484 THz	1.65–2.00 eV

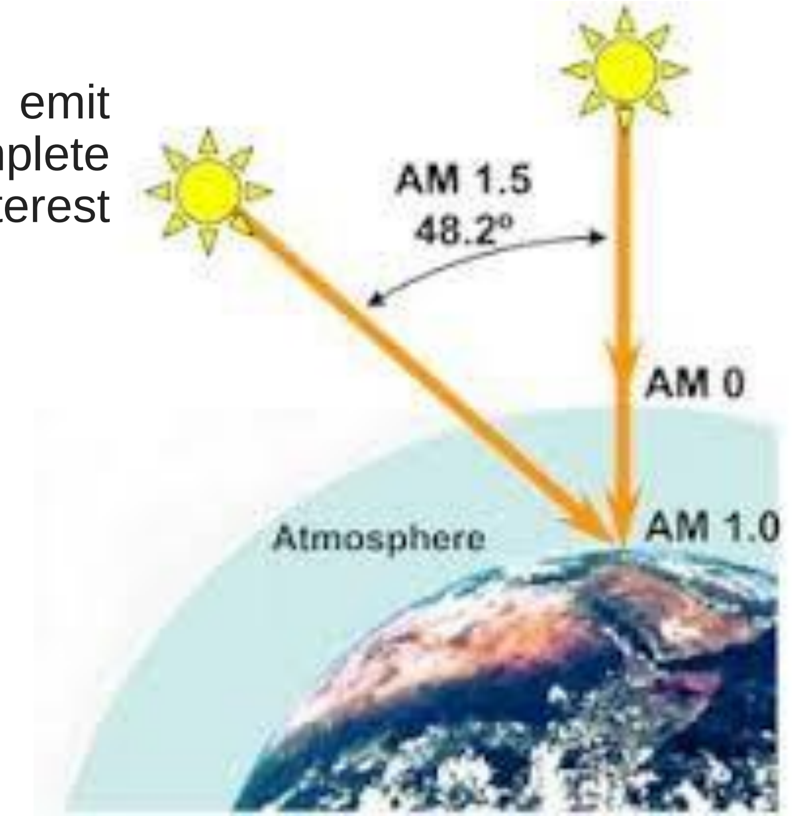


Solar energy in one form or another is the source of nearly all energy on the earth. Humans, animals and plants, rely on the sun for warmth and food.

Measurement of solar energy

Blackbodies derive their name from the fact that, if they do not emit radiation in the visible range, they appear black due to the complete absorption of all wavelengths. The blackbody sources which are of interest to photovoltaics, emit light in the visible region





The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust.
Air Mass is defined as:

$$\eta_{\text{Air Mass}} = \frac{\text{Optical path length at angle } \gamma}{\text{Optical path length at } \gamma=0}$$

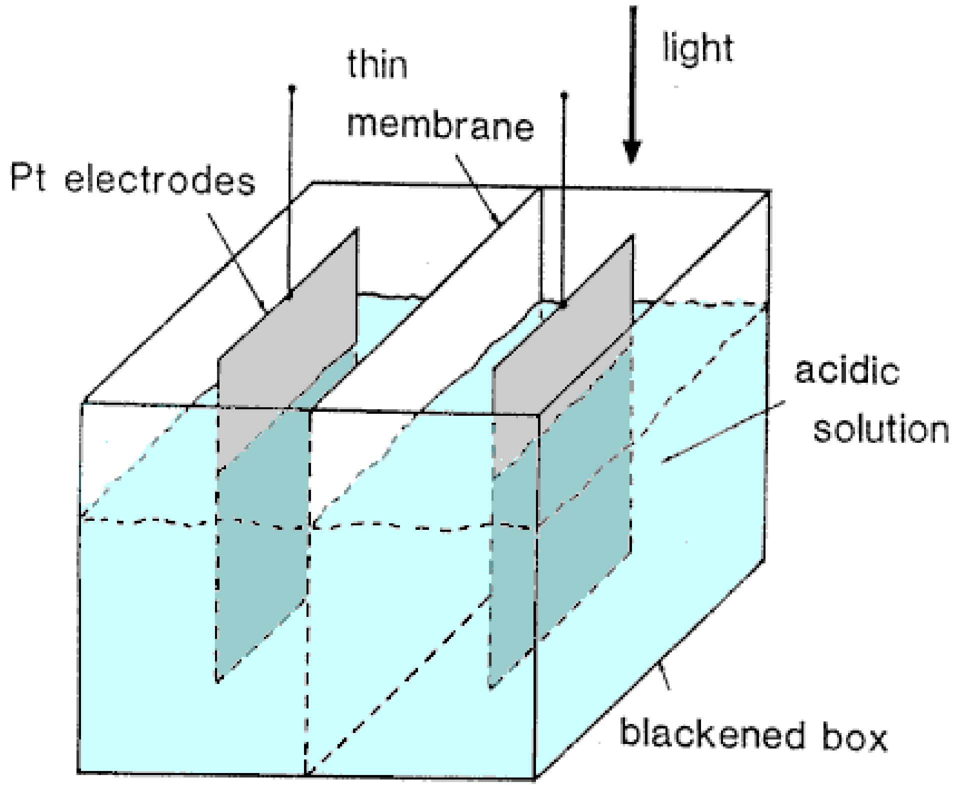
$$\eta_{\text{Air mass}} = \text{cosec}\,\gamma = \frac{1}{\sin\gamma}$$

History towards solar cell

- Physics discoveries
- Photovoltaic effect
- Schottky
- Bardeen

Physics discoveries

- 1839 – Edmund Becquerel: discovery of PV effect in electrolytic cell
  - The **photovoltaic effect** is the generation of voltage and electric current in a material upon exposure to light.
  - In his experiment he produced electricity (voltage or electric current) using two plates of platinum or gold immersed in an acid, neutral, or alkaline solution are exposed in an uneven way to solar radiation.



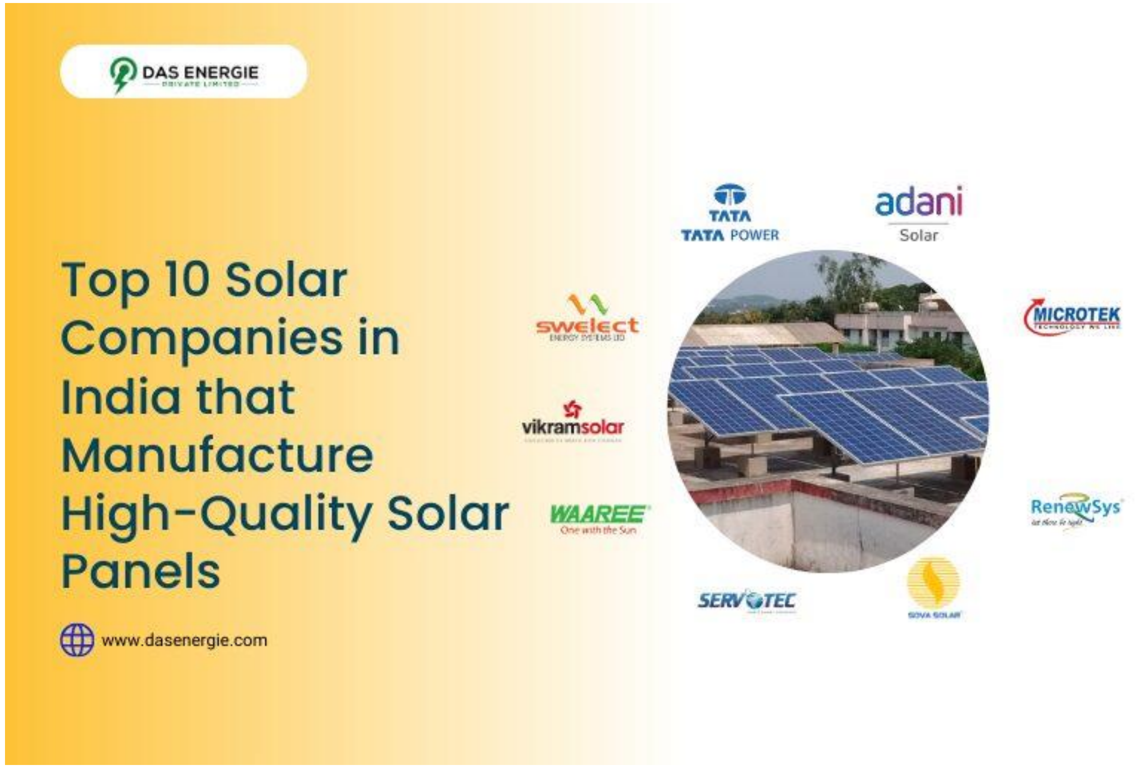
- 1873 – Willoughby Smith: observes photoconductivity in Selenium
- 1884 – Charles Frits: First solar cell using Selenium covered with thin film of Au

Chapin, Pearson, and Fuller,

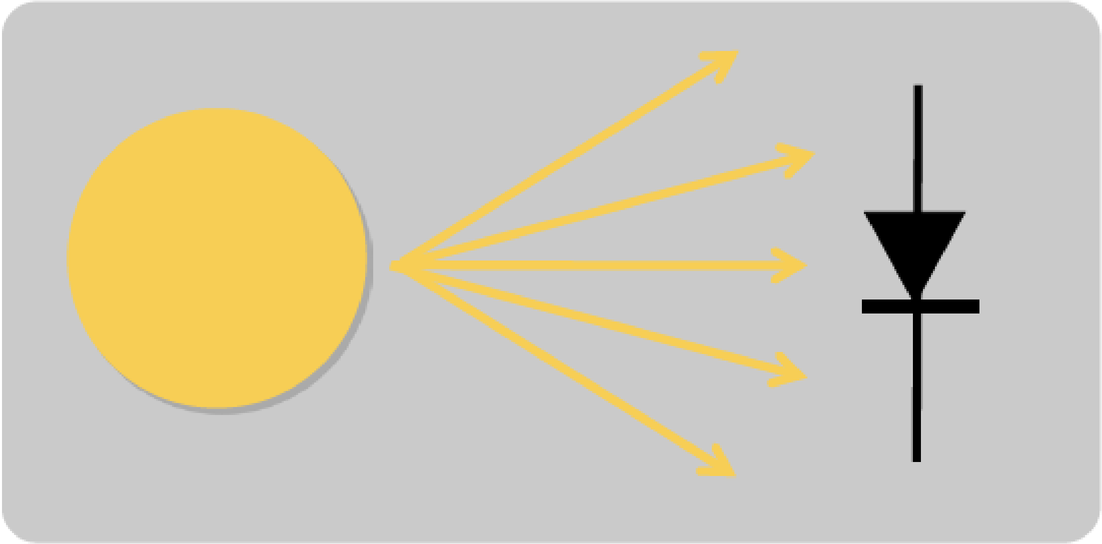
1954 – Bell labs: First PV cell with 4% efficiency

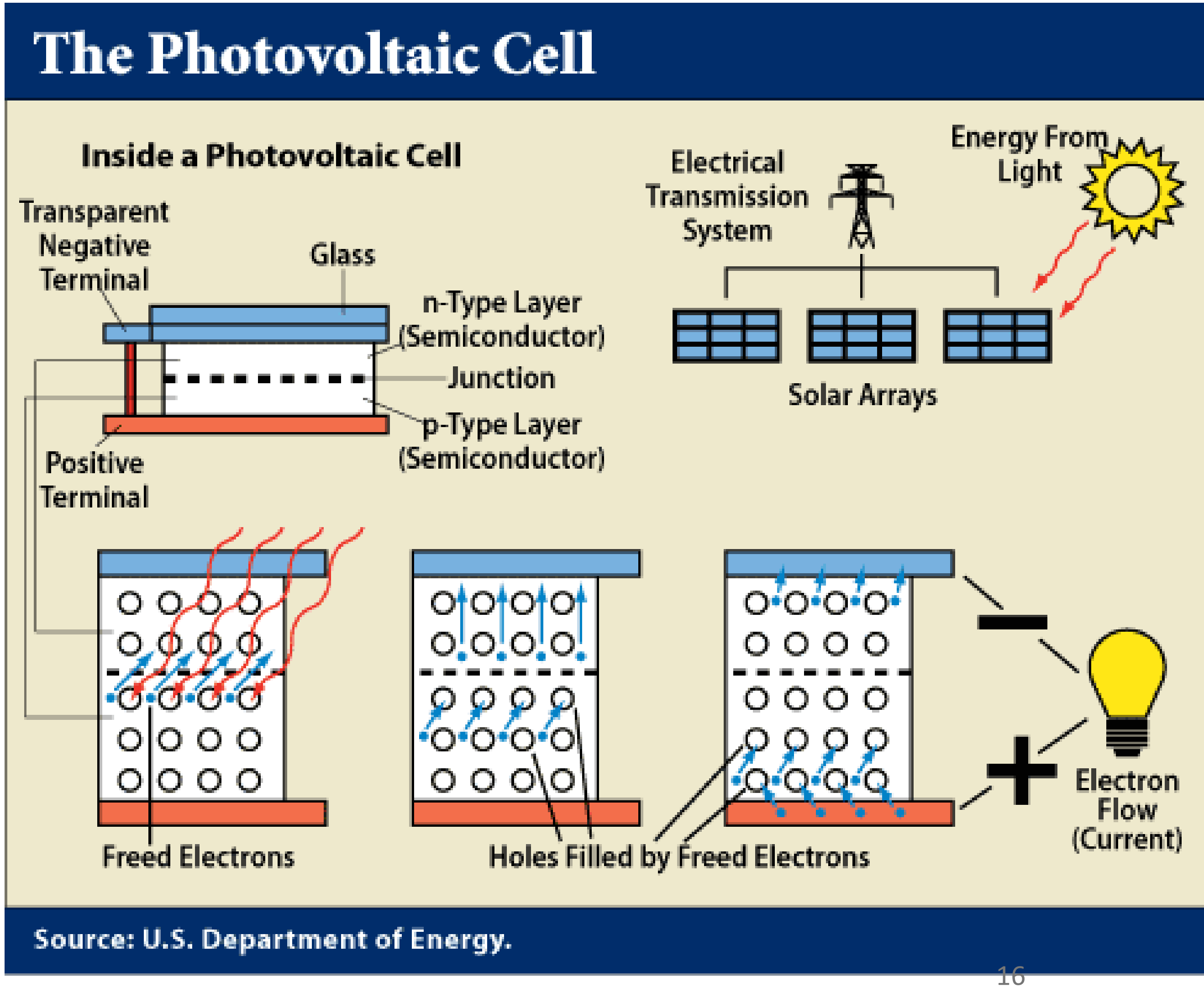
http://www.belllabs.com/org/physicalsciences/timeline/span10.html#

Solar cell industry



Solar cell

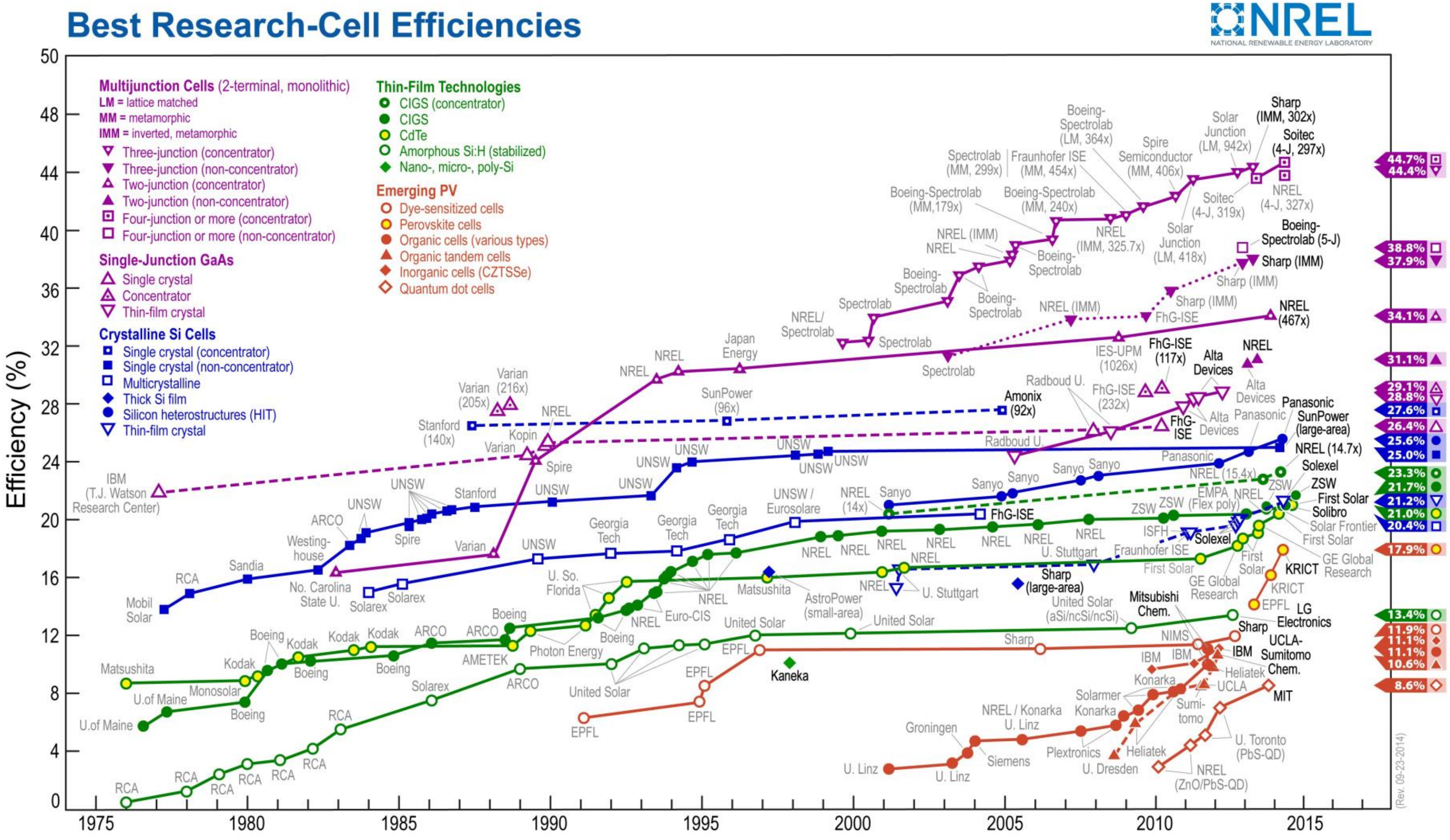




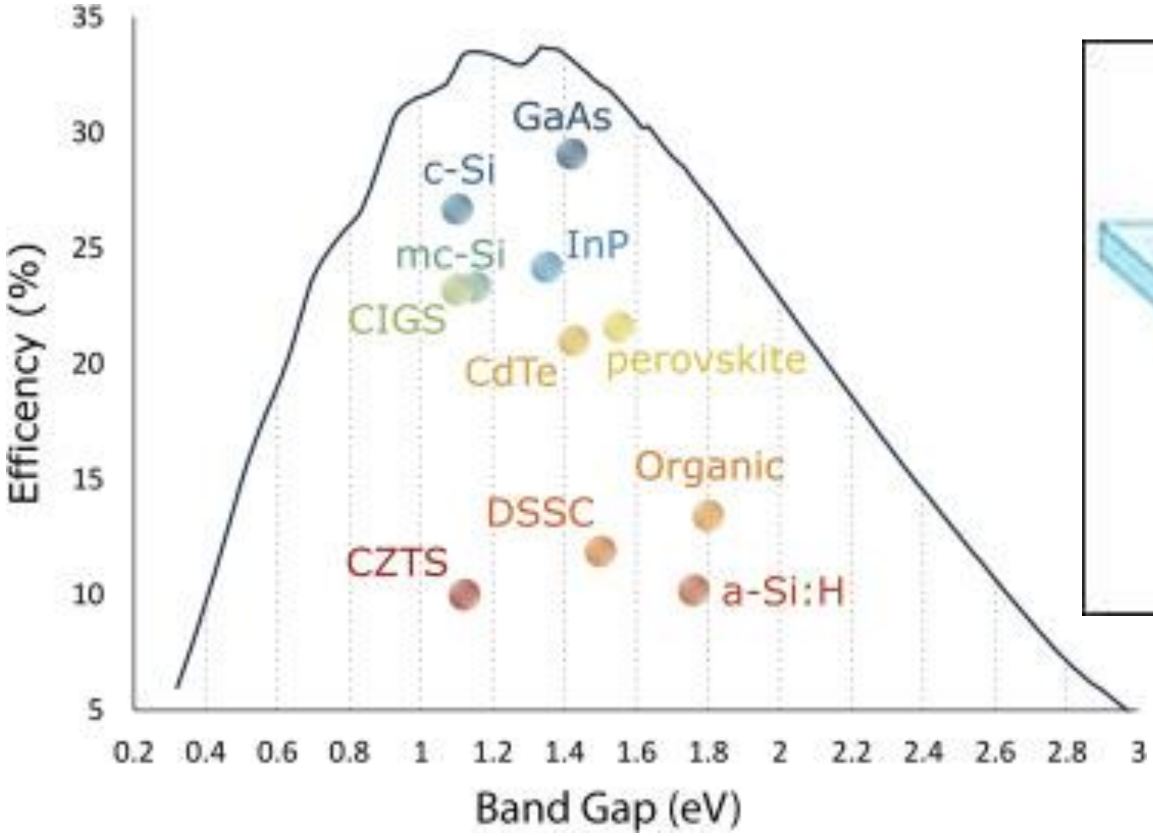
To understand how a solar cell works, we need to understand:

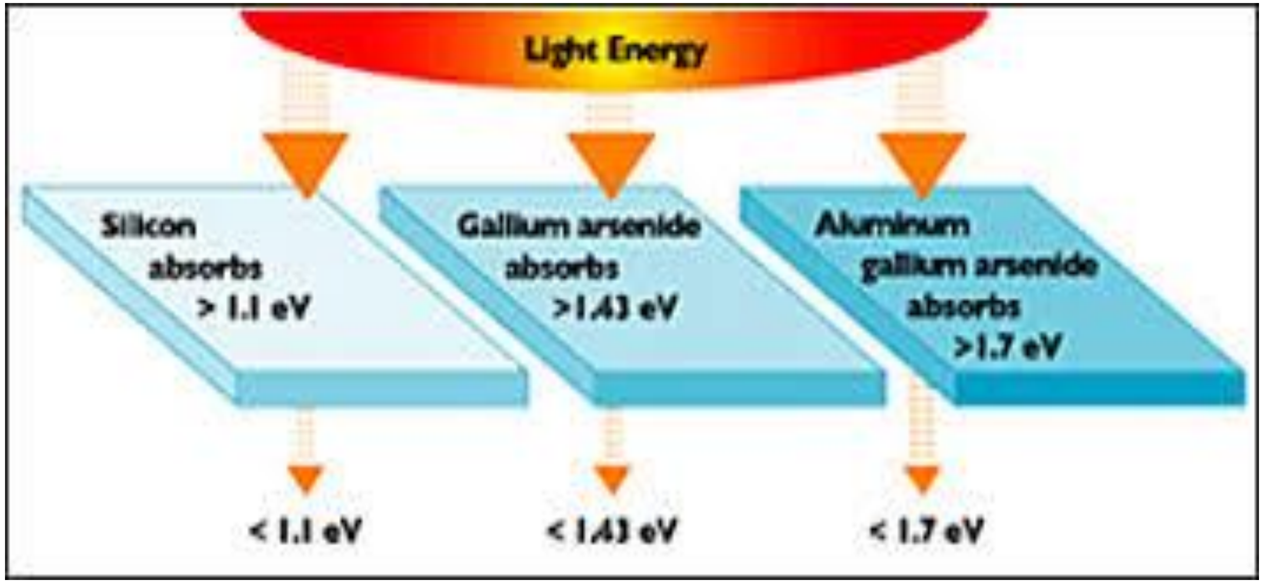
1. Semiconductors
2. p-n Junction

Progress in solar cells



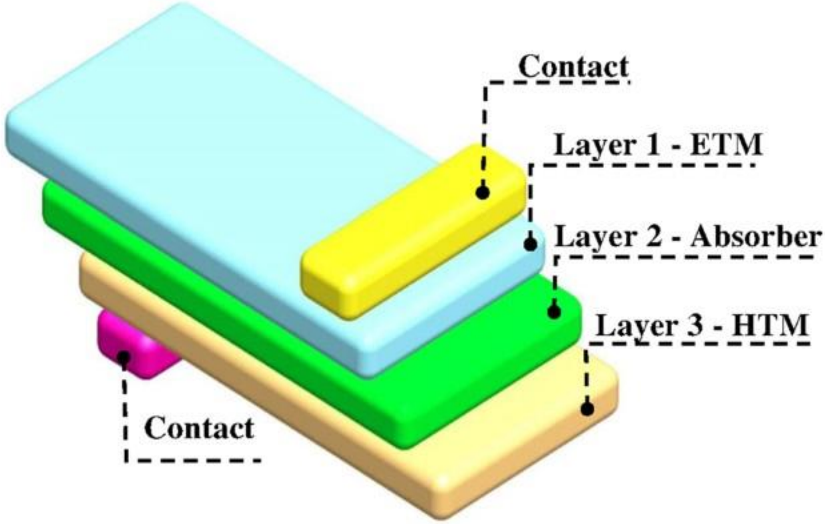
Semiconductors for solar cells

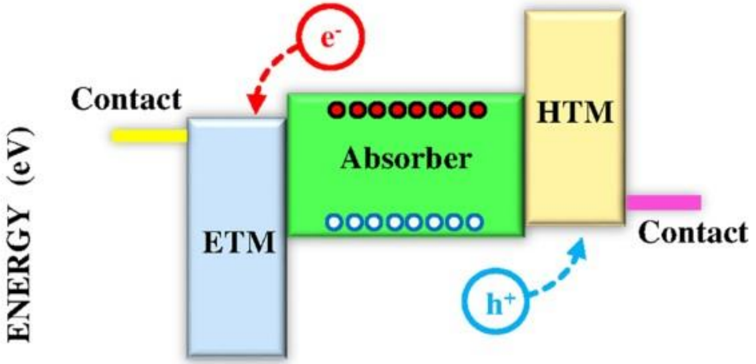


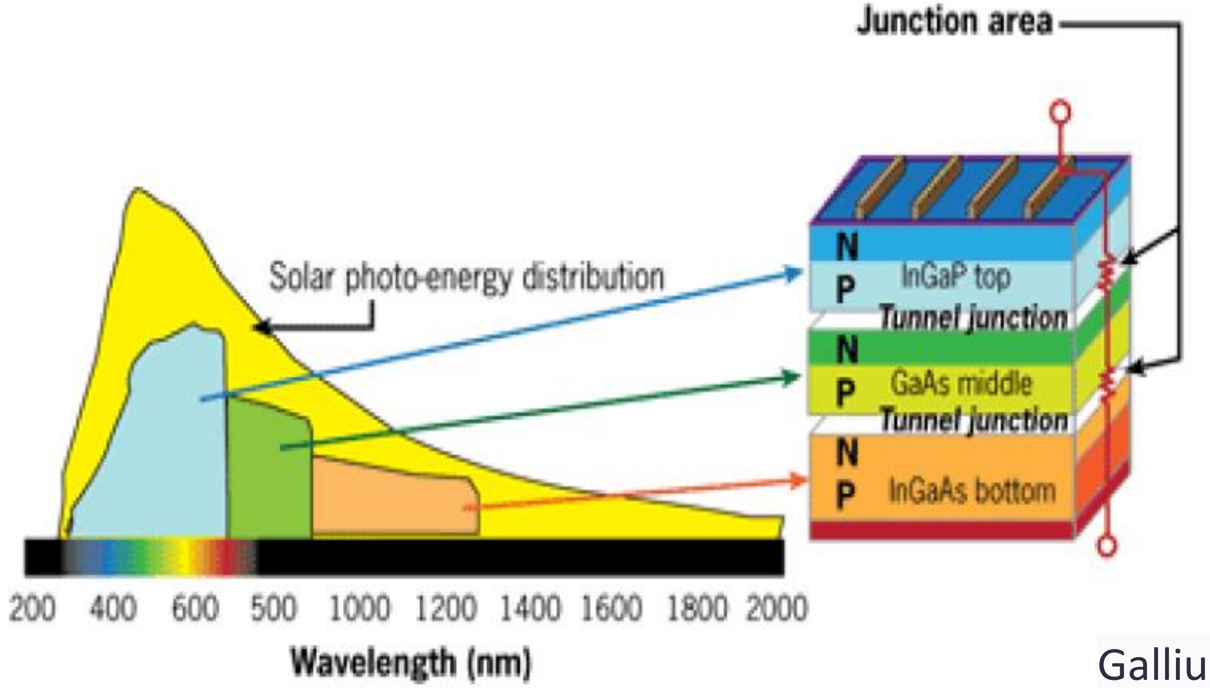


Bandgaps

- Thin Films





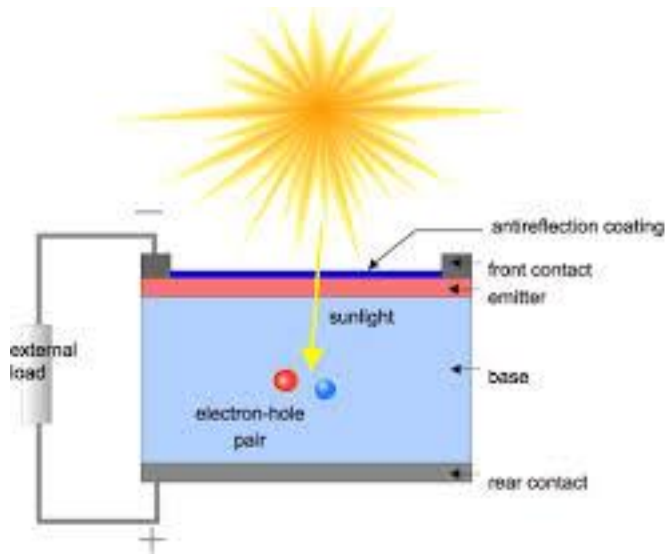


For non-concentrator solar cells at the reserach level (based on Sharp survey).

Gallium arsenide (GaAs) thin film solar cell can work to harvest solar energy in three bandgaps (250nm-700nm, 700nm-900nm, 900nm-1300nm).

Si solar cell

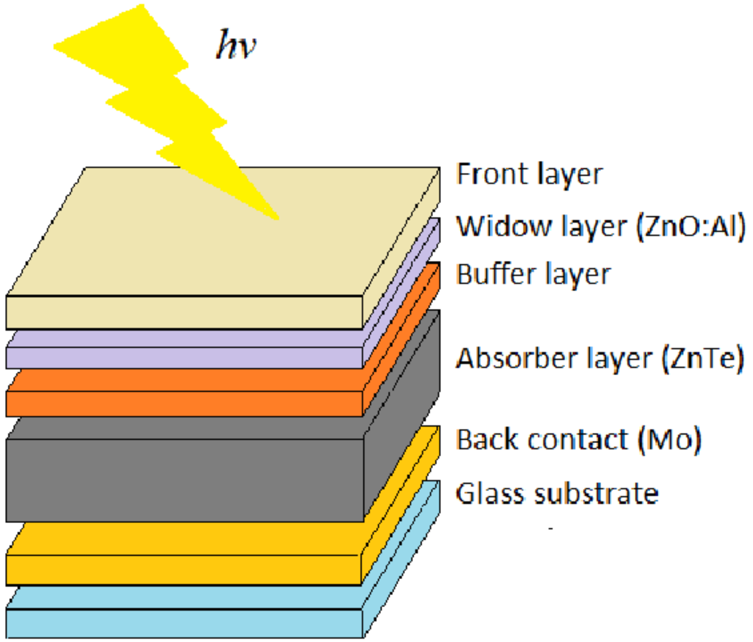
- p-n Junction

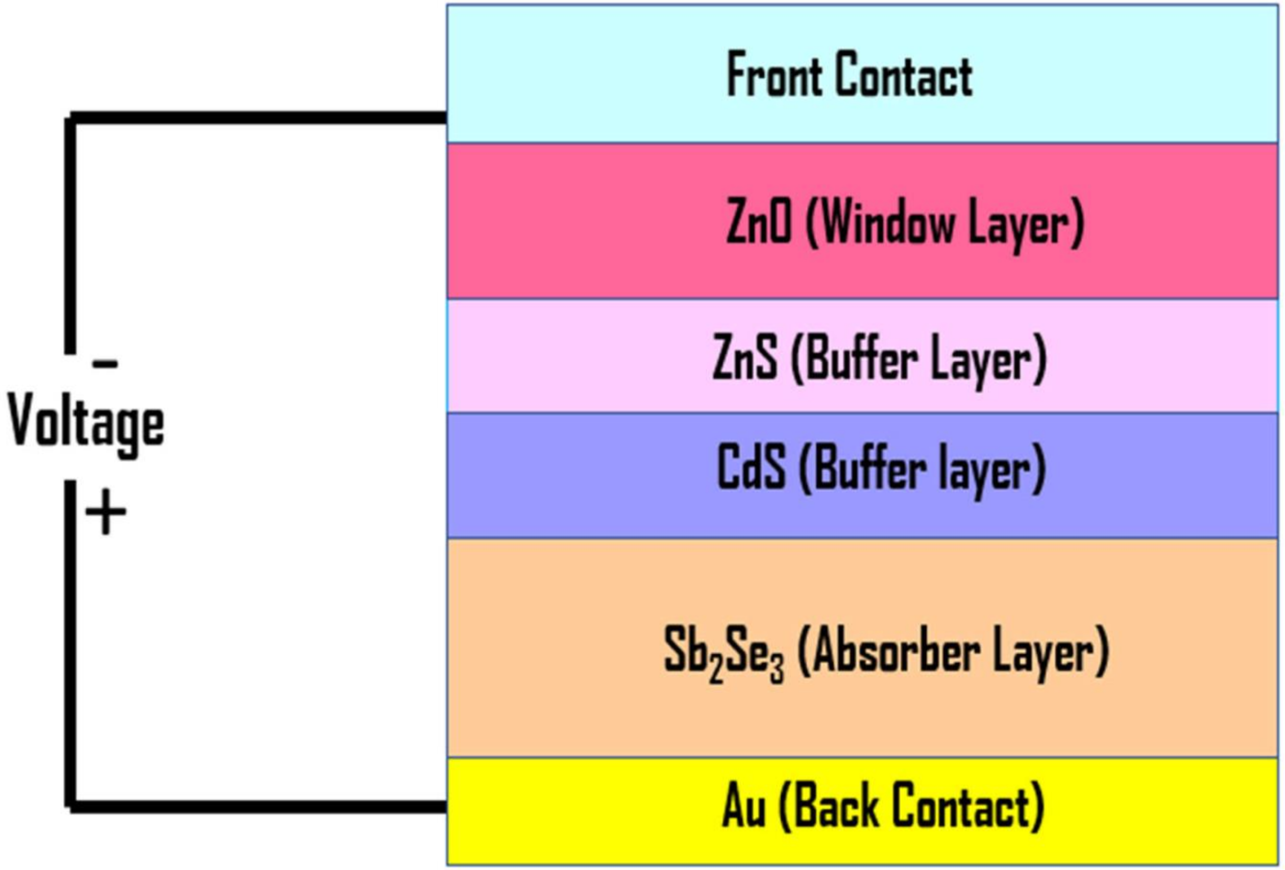


Cross section of a solar cell. Note: Emitter and Base are historical terms that don't have meaning in a modern solar cells. We still use them because there aren't any concise alternatives. Emitter and Base are very embedded in the literature and they are useful terms to show the function of the layers in a p-n junction. The light enters the emitter first. The emitter is usually thin to keep the depletion region near where the light is strongly absorbed and the base is usually made thick enough to absorb most of the light.

The basic steps in the operation of a solar cell are:
•the generation of electron-hole pairs by light
•the collection of the light-generated carries to generate a current;
•the generation of a large voltage across the solar cell; and
•the dissipation of power in the load.

Thin film solar cell



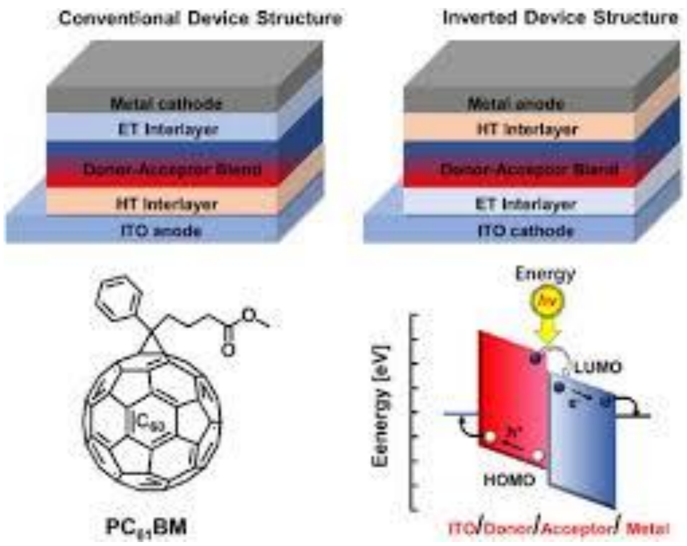


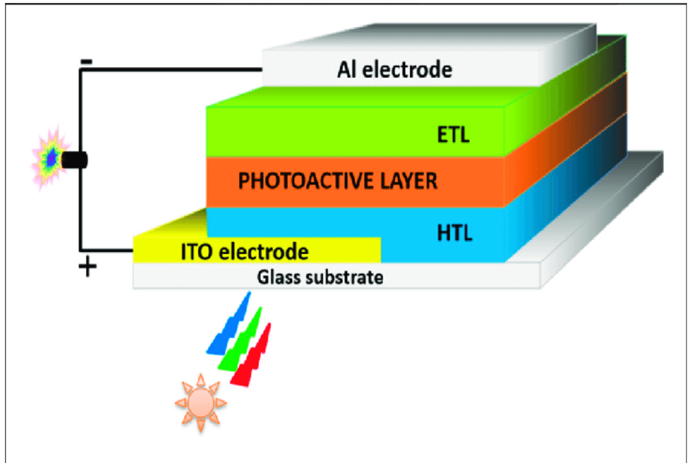
Organic solar cells

- An OPV cell (also known as an organic solar cell) is a type of solar cell where the absorbing layer is based on organic semiconductors (OSCs).
- These are either polymers or small molecules.
- For organic materials to be used in organic electronics, they will need to be semiconducting
- Conjugation of the organic molecule results in the electrons associated with the double bonds becoming delocalized across the entire length of conjugation.
- These electrons have higher energies than other electrons in the molecule and are similar to valence electrons in inorganic semiconductor materials.
- However, in organic materials, these electrons do not occupy a valence band but are part of what is called the 'highest occupied molecular orbital' (HOMO).
- Just like in inorganic semiconductors, there are unoccupied energy levels at higher energies. In organic materials, the first one is called the lowest unoccupied molecular orbital (LUMO). Between the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) of the OSC is an energy gap - often referred to as the band gap of the material.

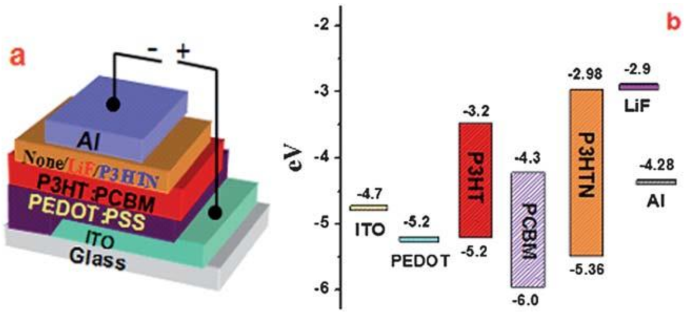
Organic solar cell (OPV)

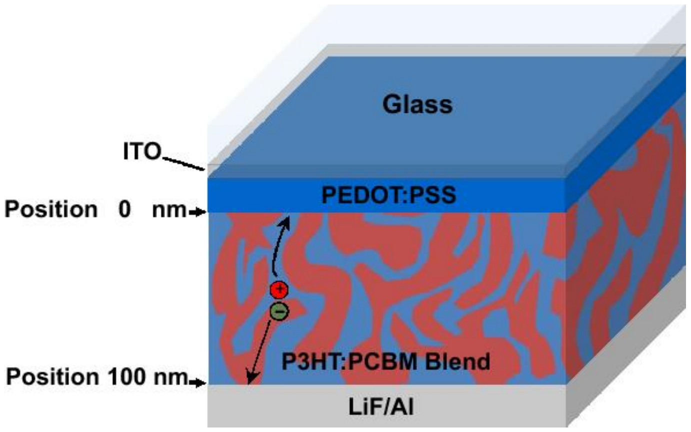
A conventional organic solar cell consist of an active layer, sandwiched between two electrodes to ensure mobility, collection and transport of charge carriers





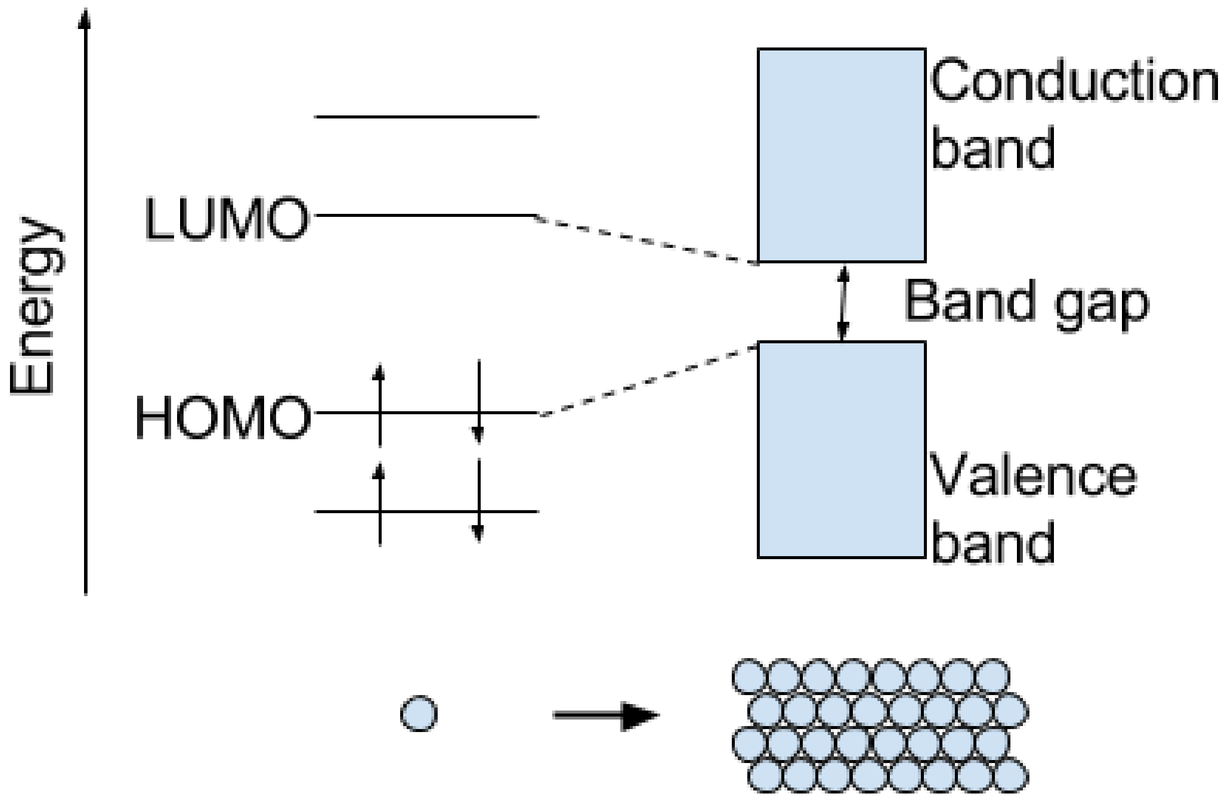
The basic principles of OSCs can be roughly boiled down to four steps: (1) Photon absorption and exciton generation: sunlight enters organic semiconductor materials, resulting in organic materials absorbing light energy to excite excitons; (2) Diffusion and dissociation of excitons: excitons diffuse to the interface





Bandgap matters

HOMO level is to organic semiconductors what the valence band maximum is to inorganic semiconductors; the same analogy exists between the LUMO level and the conduction band minimum.



The size of the band gap is also very important, as this affects the energy that can be harvested by the solar cell.
If $E_\gamma > E_g$, then the photon will be absorbed, and any energy in excess of E_g will be used to promote the electron to an energy level above the conduction band minimum.

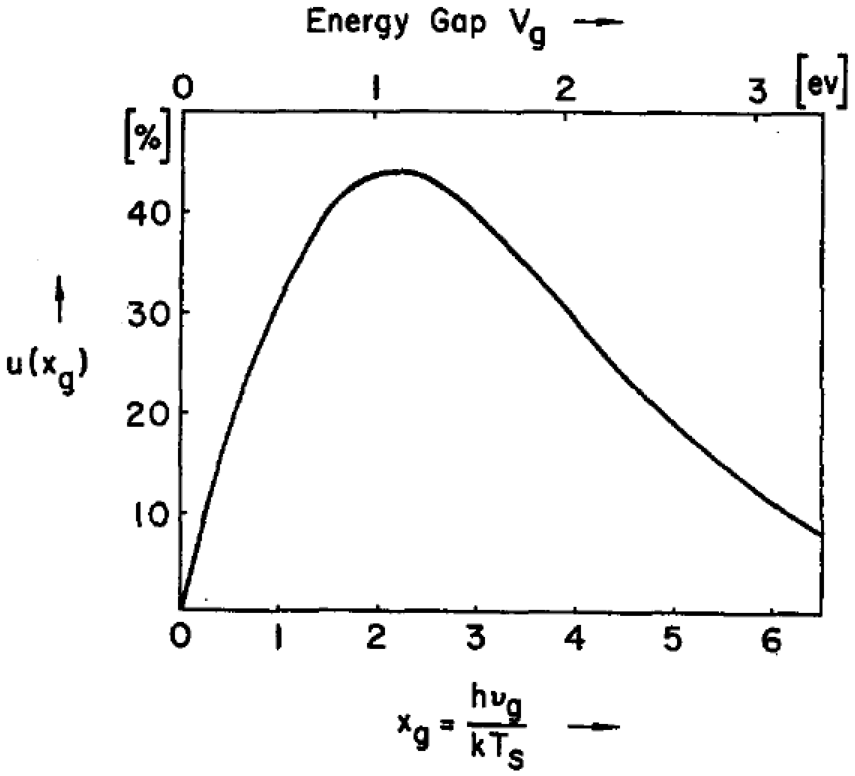
The electron will then relax down to the conduction band minimum, resulting in the loss of the excess energy.
However, if $E_\gamma < E_g$, then the photon will not be absorbed, again resulting in lost energy. (Note, the wavelength of a photon decreases as its energy increases).

Shockley-Queisser Limit

- When considering the solar spectrum, it can larger than E_g resulting in a significant number of photons not being absorbed.
- On the other hand, a too low E_g means that a large number of photons will be absorbed, but a significant amount of energy will be lost due to the relaxation of electrons to the conduction band minimum.
- Due to this trade-off, it is possible to calculate the theoretical maximum efficiency of a standard photovoltaic device and estimate the optimum band gap for a photovoltaic material.
- Shockley and Queisser determined the theoretic maximum efficiency to be approximately 33% in 1961, which corresponds to a band gap of 1.34 eV (~930 nm).

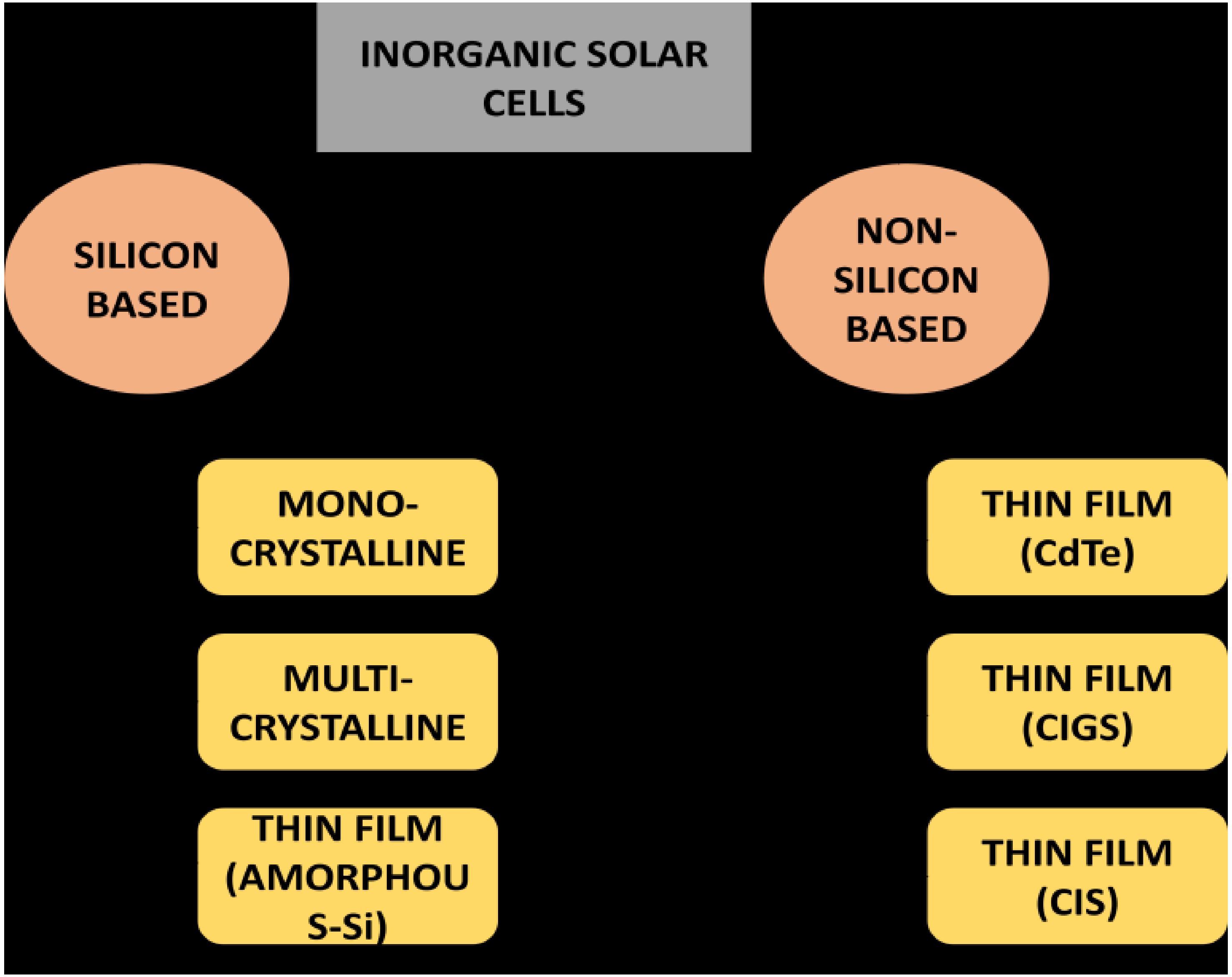
Shockley-Queisser Limit

1) Smaller bandgaps give higher short circuit current
2) Larger bandgaps give higher open-circuit voltage
3) For the given solar spectrum, an optimum bandgap exists.



W. Shockley, and H. J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", *J. Appl. Phys.,* **32**, 510, 1961.

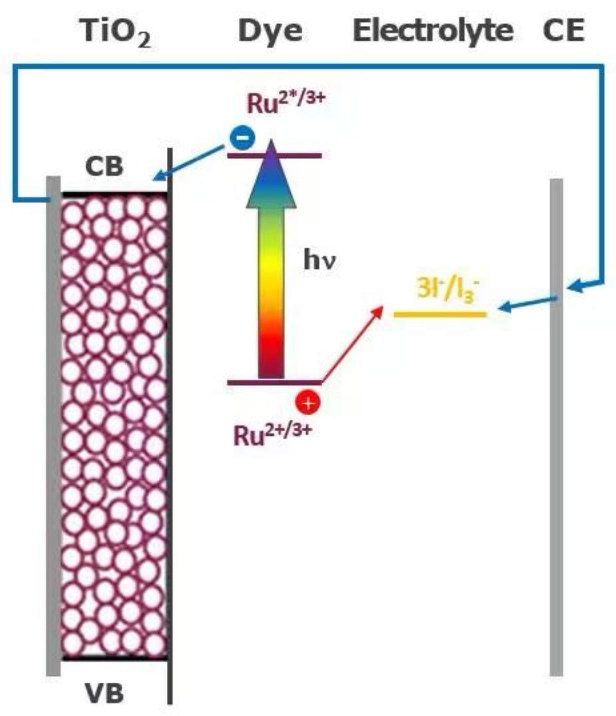
Inorganic solar cell



Dye sensitized solar cell

The working principle of a DSC:

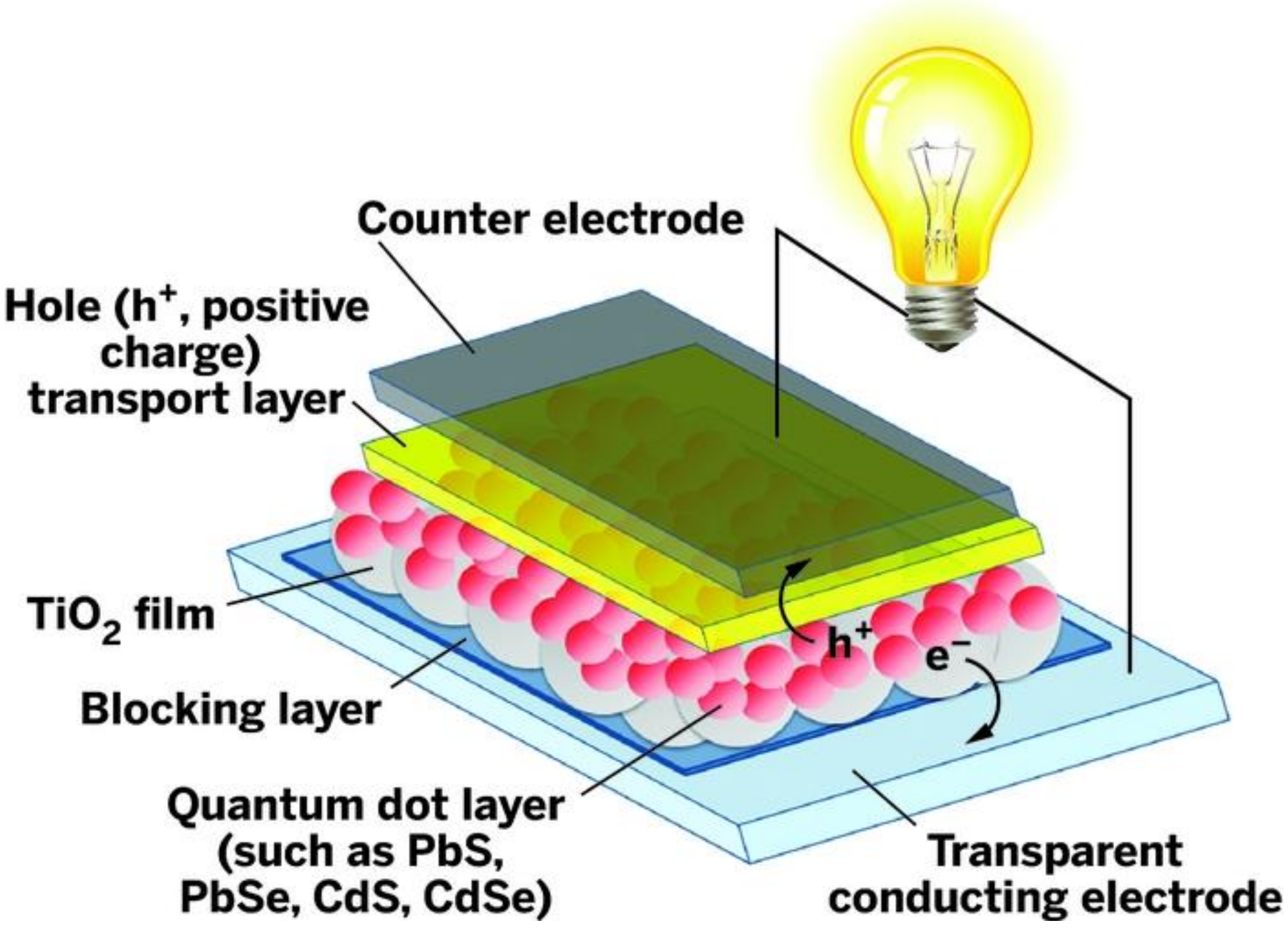
•Light is absorbed by a monomolecular layer of dye chemisorbed to a thin film of nanocrystalline TiO_2 promoting an electron from the Ru^{2+} based ground state to an excited state (Ru^{2*}).
•The excited electron is then transferred within a very short time (pico to femtoseconds – ultrafast spectroscopy) into the conduction band (CB) of TiO_2. This leads to an effective charge separation, with a negative charge within the titania phase and a positive charge on surface-adsorbed Ru^{3+}.
•The Ru^{3+} ion is then reduced very rapidly (within nanoseconds) by an iodide anion (I^-) present in the electrolyte system.
•The electron injected into TiO_2 in the previous step diffuses through the nano-network of particles until it reaches the electrically conductive surface for current collection, e.g. a thin layer of conductive transparent oxide on glass, plastic or a metallic substrate.
•The electric charge thus extracted from the photoanode as a current can be used to provide useful electric power.
•In order to close the electric circuit, the negative charges are directed to the surface of a counter electrode (CE) where I_3^- is reduced to I^-.



Quantum dots

A quantum dot solar cell (QDSC) is a solar cell design that uses quantum dots as the captivating photovoltaic material.

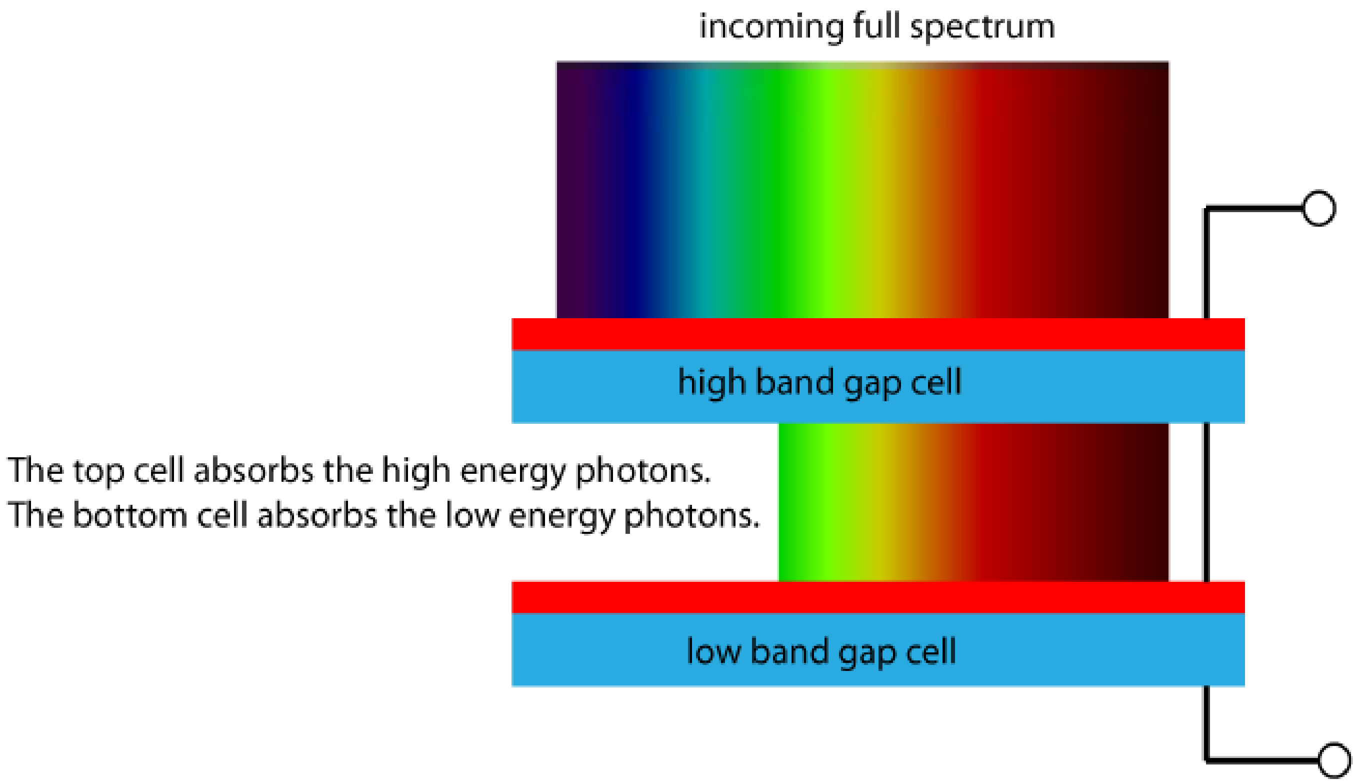
It attempts to replace bulk materials such as silicon, copper indium gallium selenide (CIGS) or cadmium telluride (CdTe).



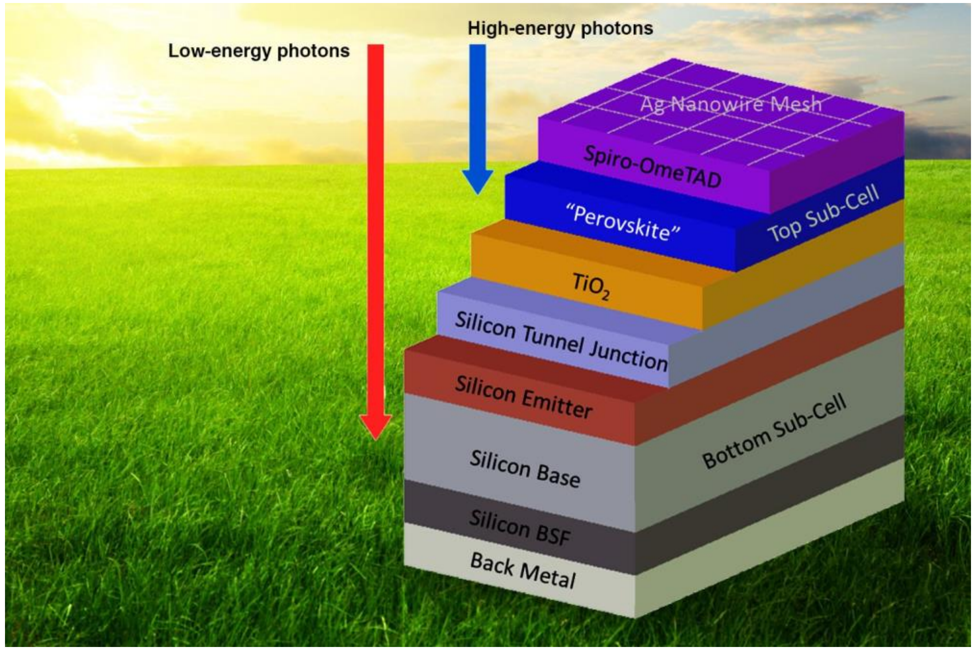
Tandem solar cells

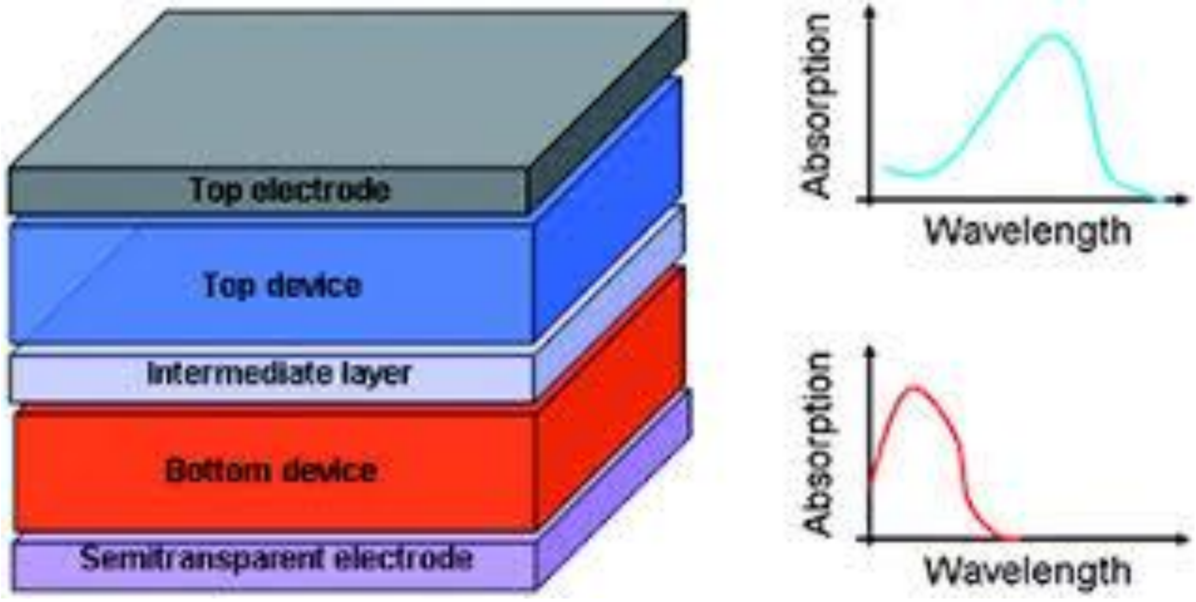
Tandem cells are stacks of p-n junctions, each of which is formed from a semiconductor of different bandgap energy.

Each responds to a different section of the solar spectrum, yielding higher overall efficiency.

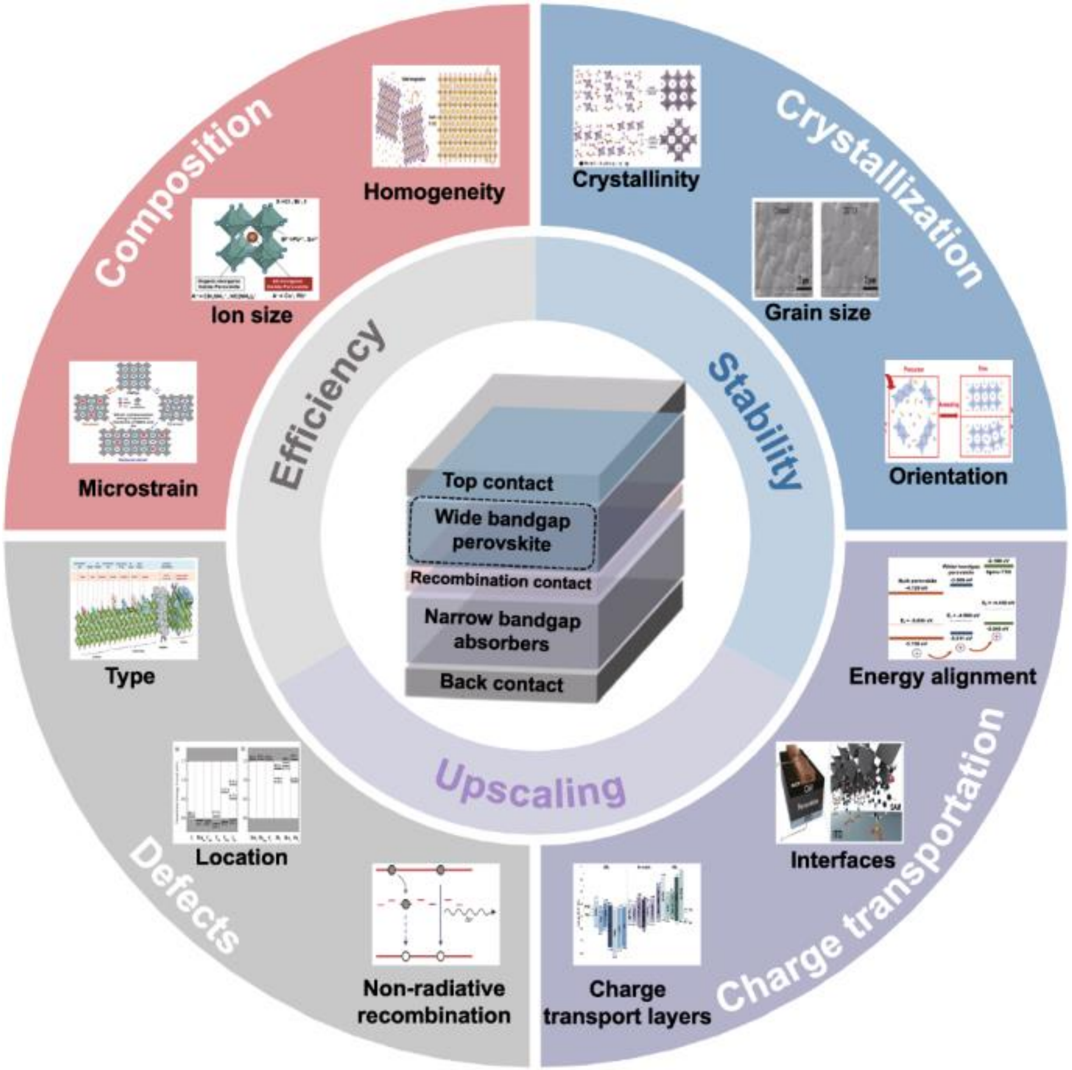


Silicon –perovskite tandem solar cell

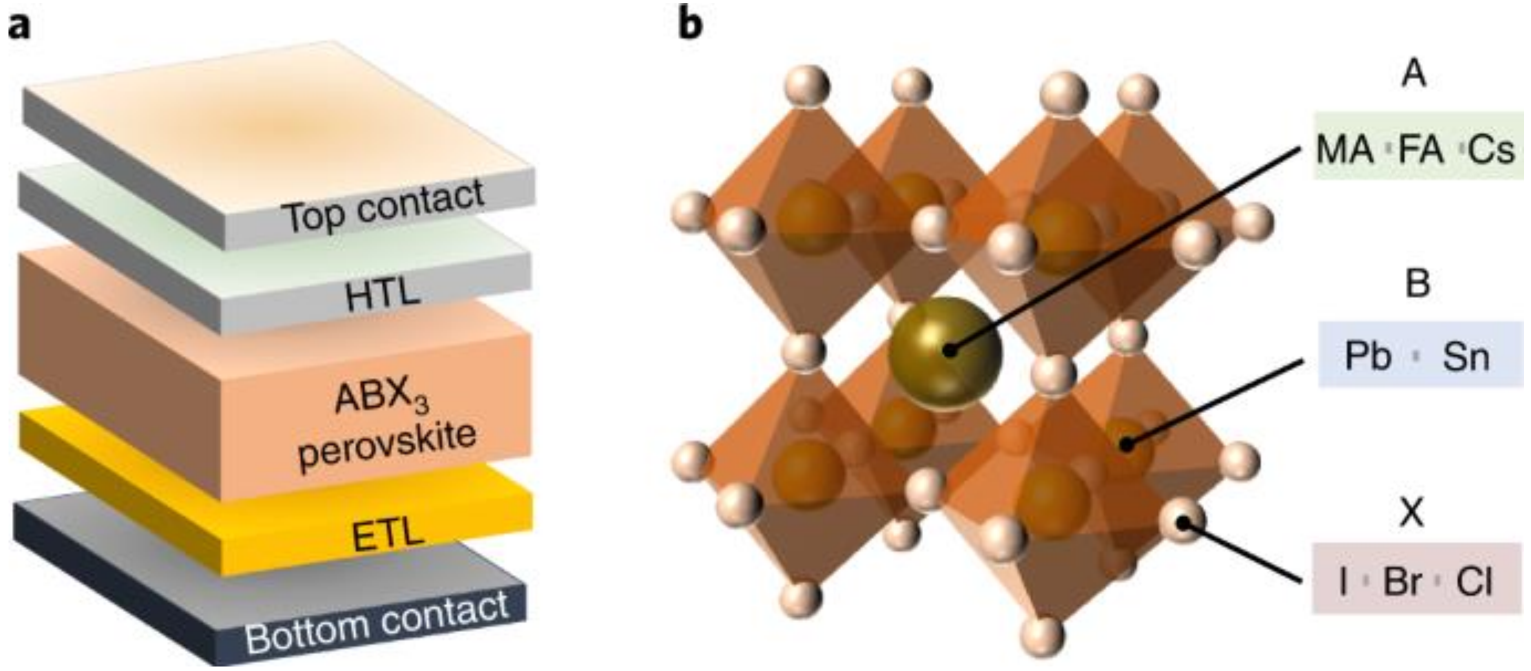




Perovskites for devices

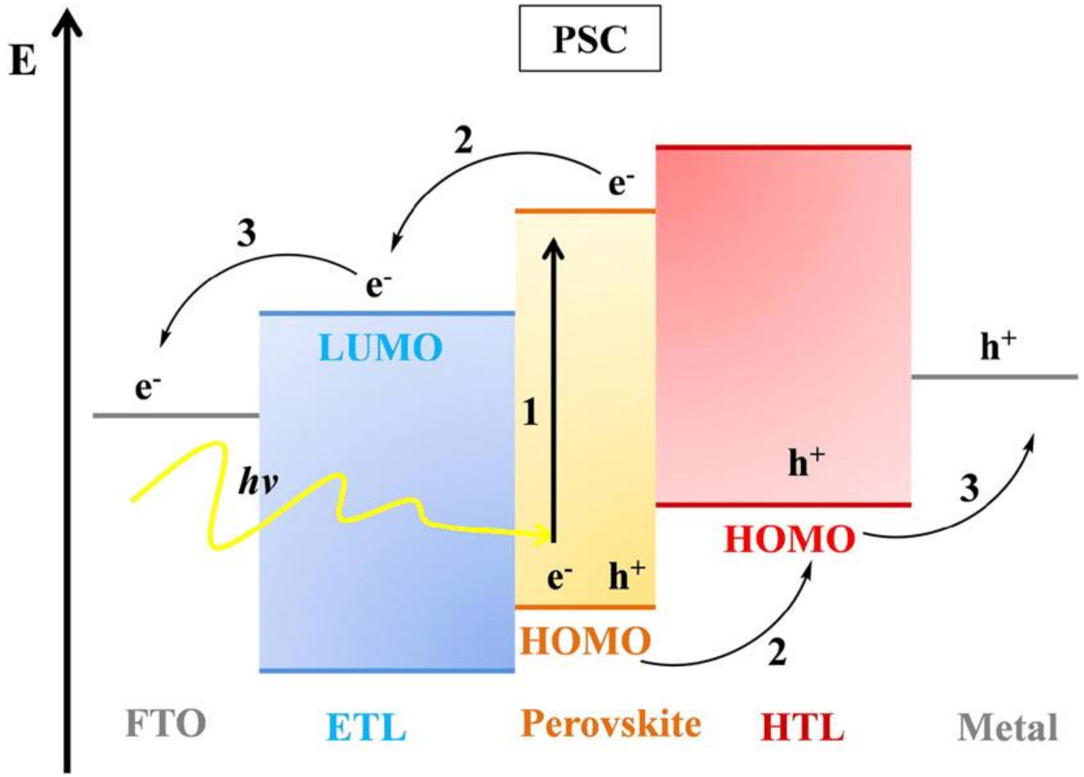


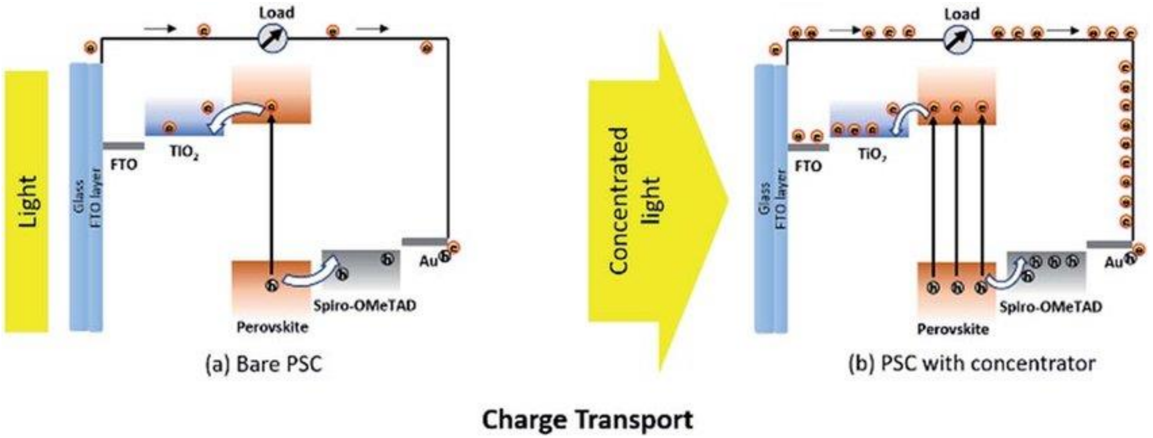
Perovskite solar cells



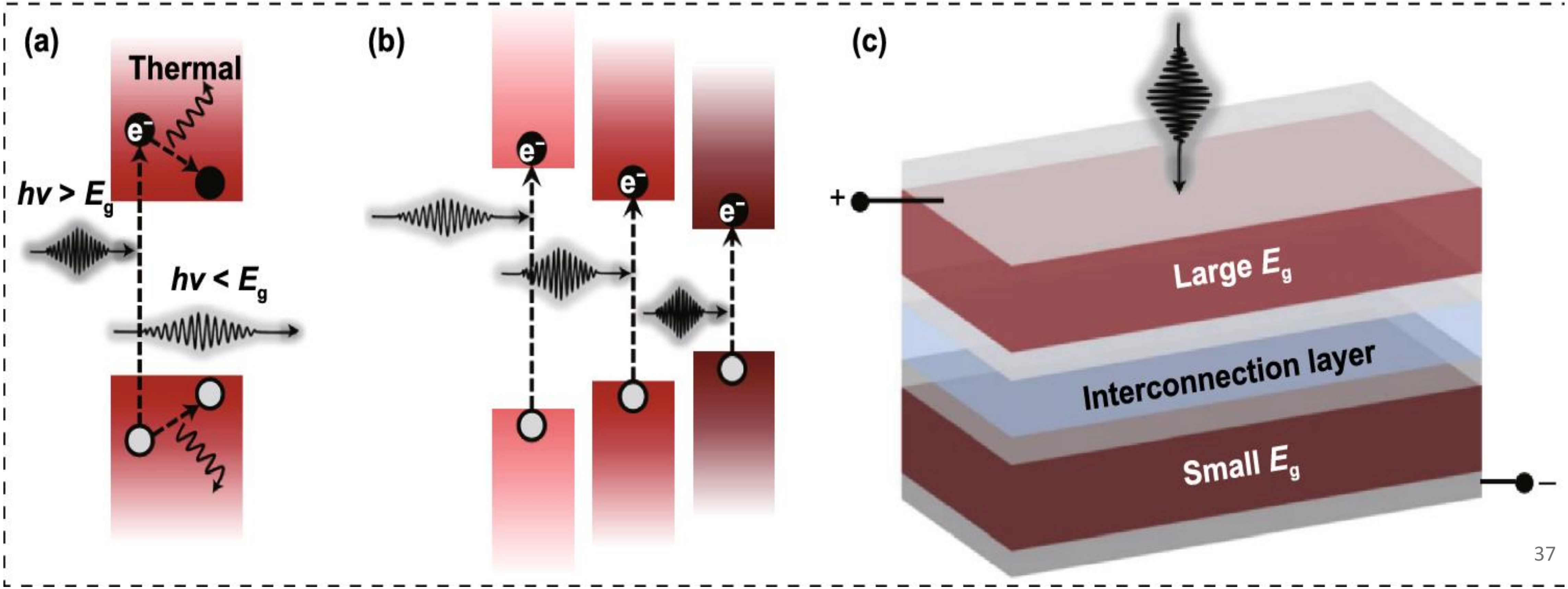
How does it work

- The perovskite solar cell are made of an active layer stacked between ultrathin carrier transport materials, such as a hole transport layer (HTL) and an electron transport layer (ETL). The band alignment depends on their energy level, electron affinity, and ionization potential.

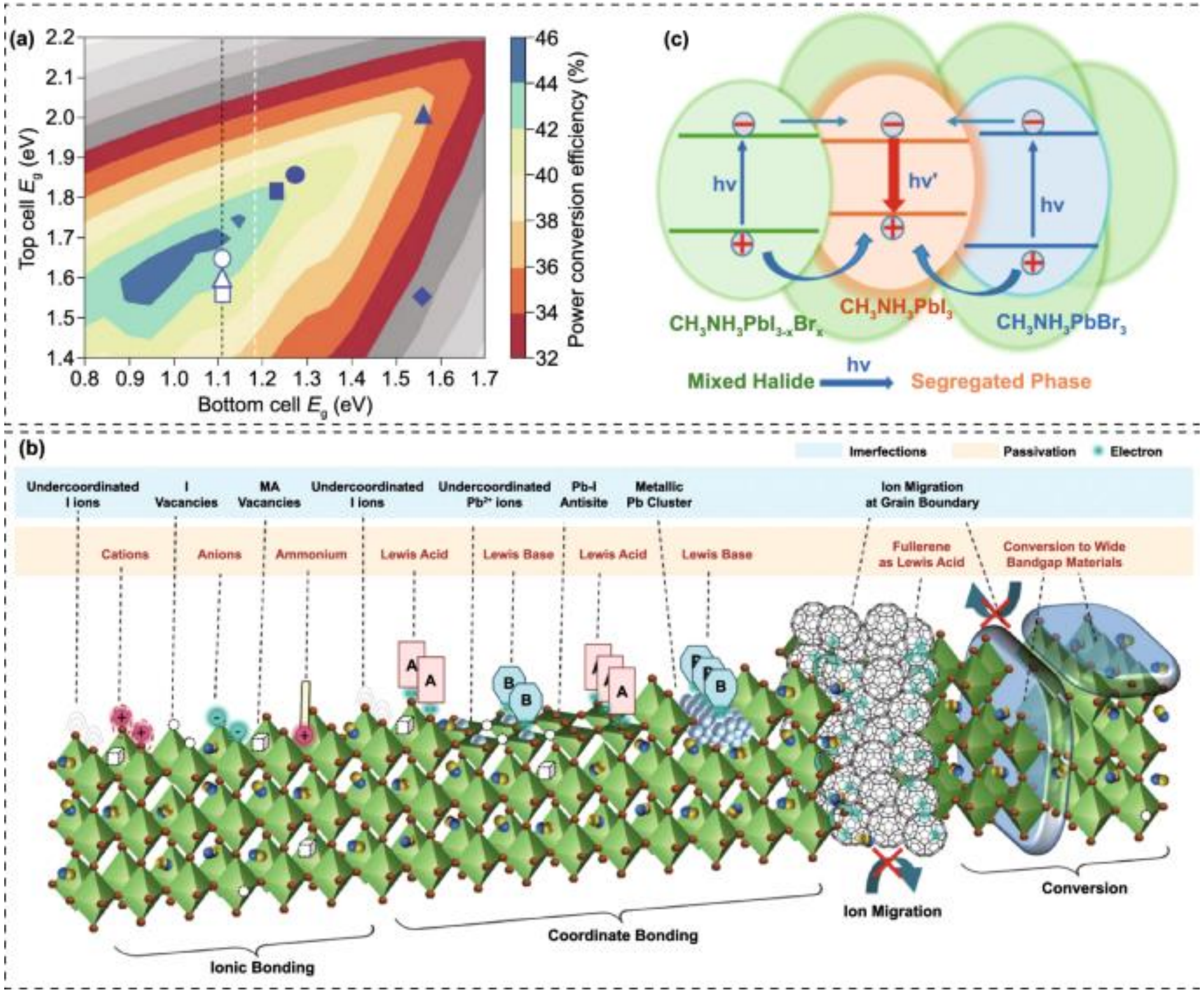




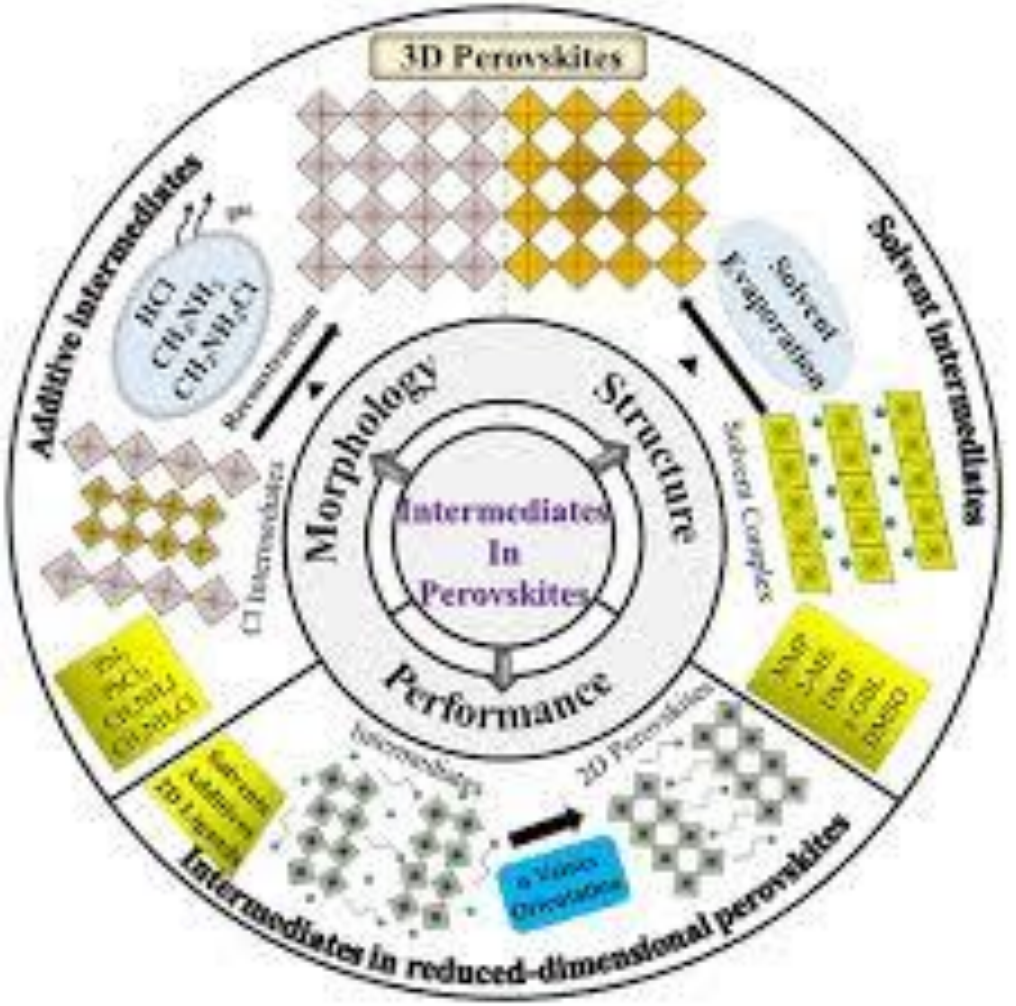
Tandem perovskites solar cells

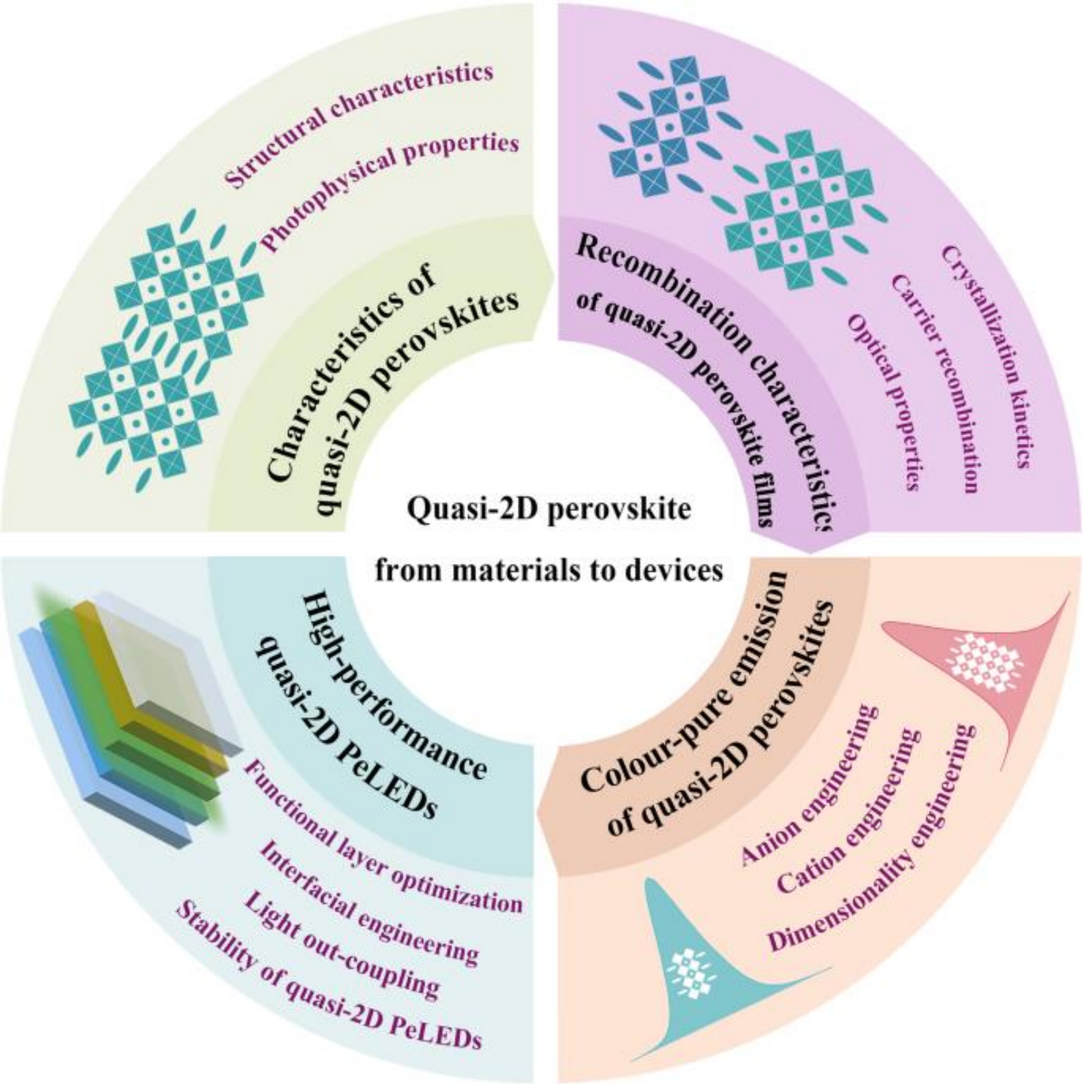


The making of Perovskites

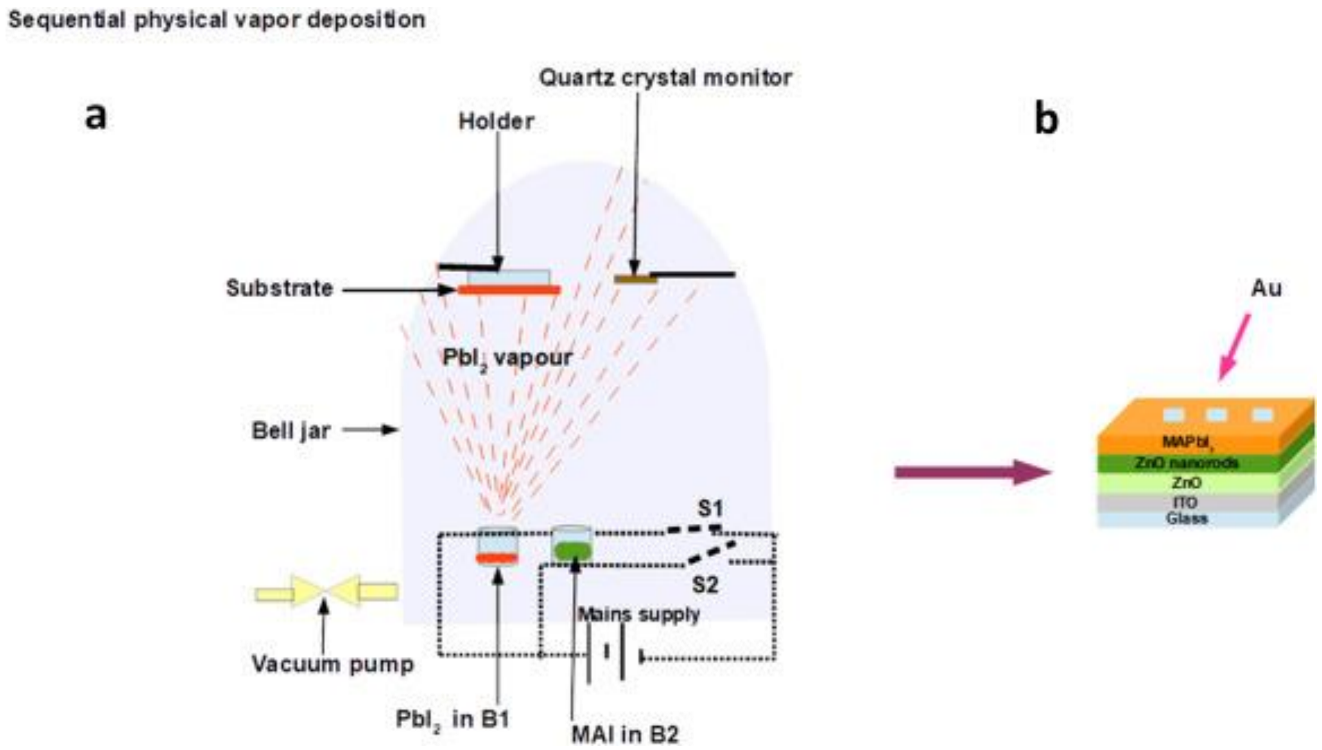


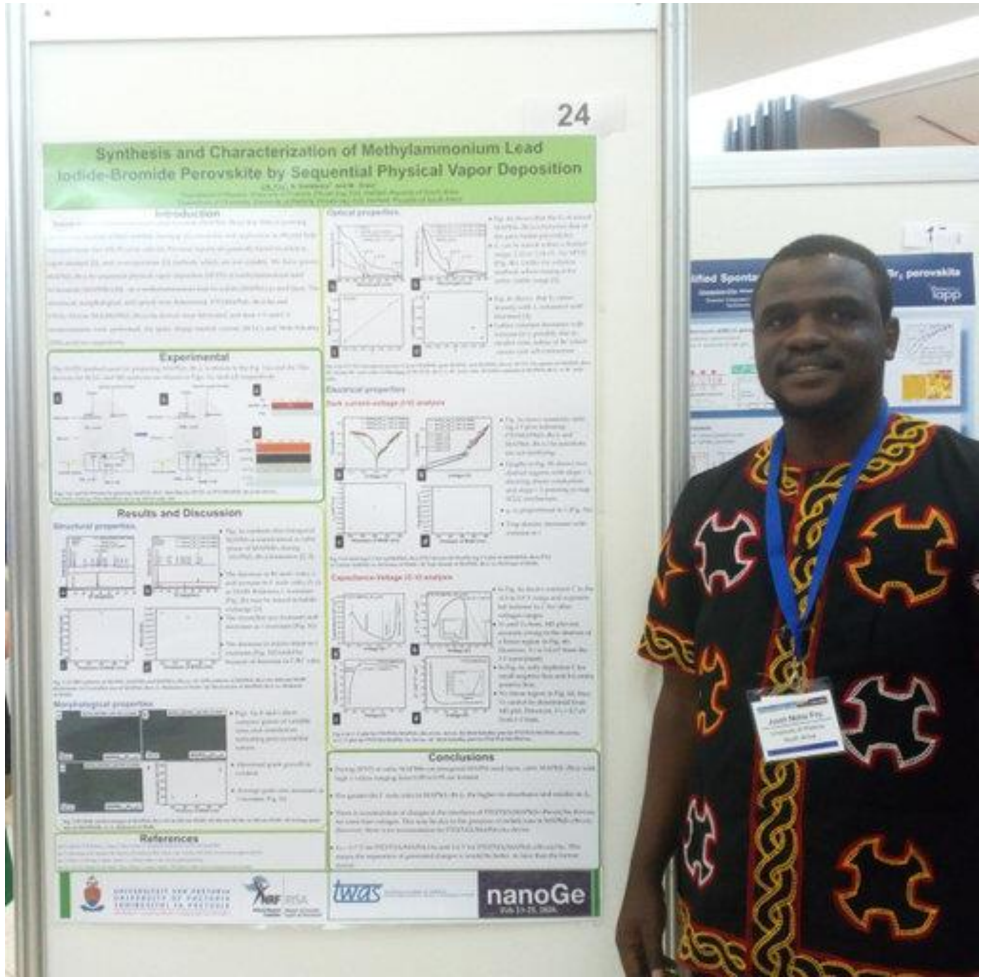
Perovskites



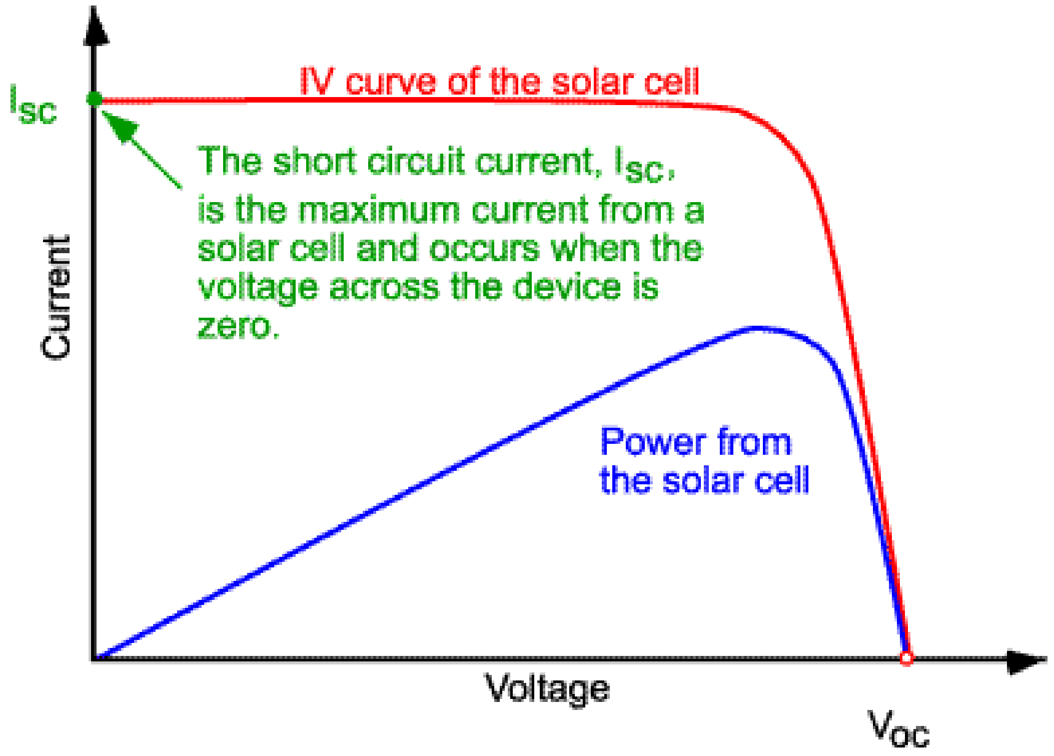


Sequential physical vapour deposition (SPVD)

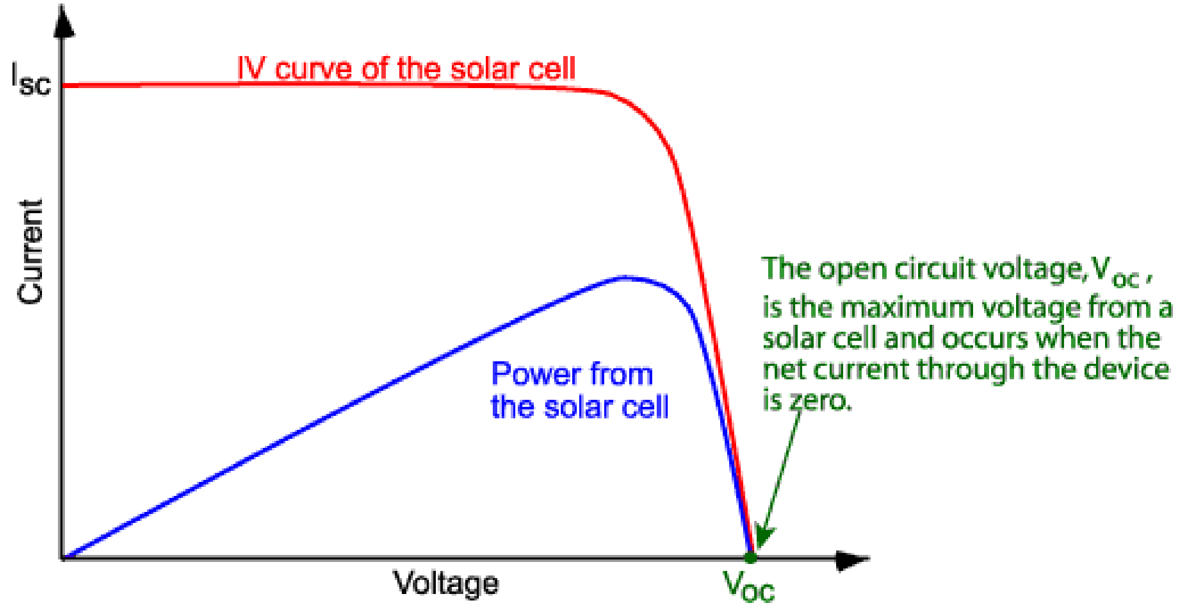




Solar cell parameters

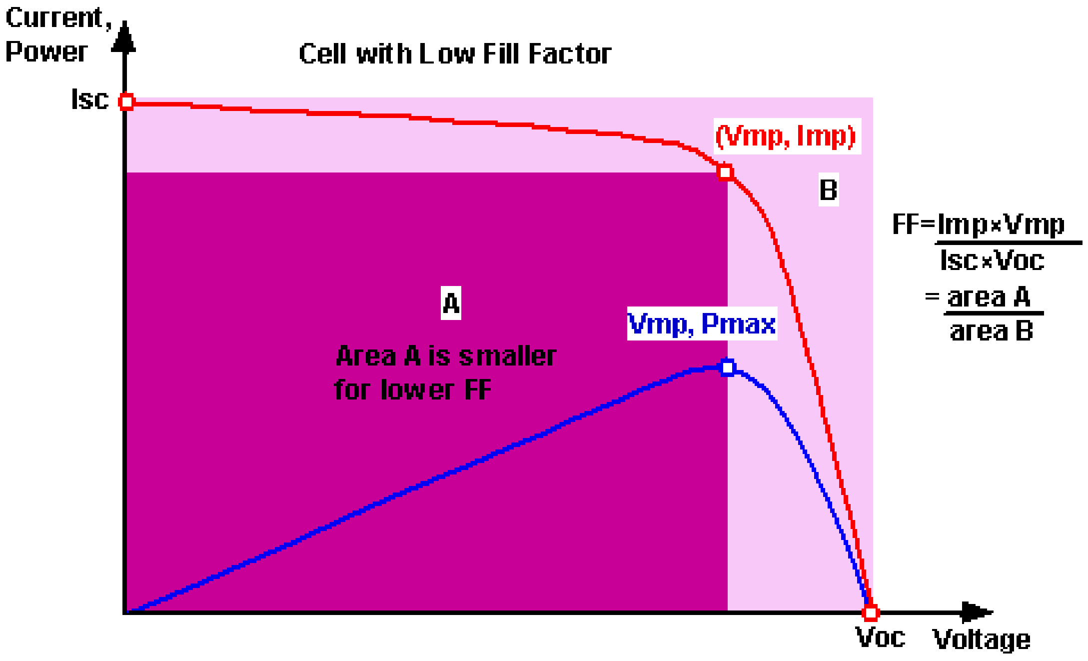


The short-circuit current



The open-circuit voltage, V_{OC},

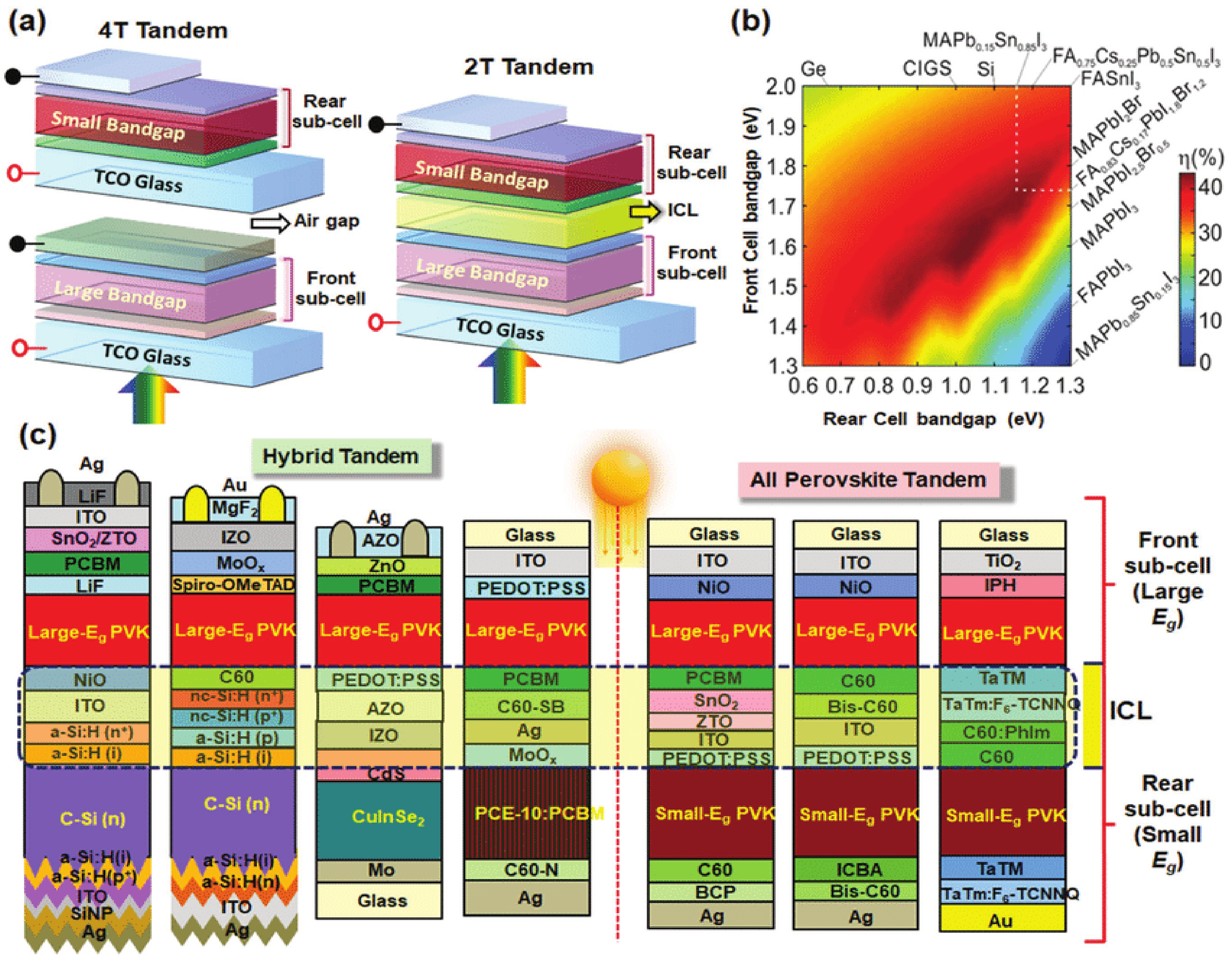
Solar cell parameters



Graphically, the FF is a measure of the "squareness" of the solar cell and is also the area of the largest rectangle which will fit in the IV curve.

Solar cell efficiency

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another.



(a)
4T Tandem
Small Bandgap
Rear sub-cell
TCO Glass
Air gap
Large Bandgap
Front sub-cell
TCO Glass
2T Tandem
Small Bandgap
Rear sub-cell
ICL
Large Bandgap
Front sub-cell
TCO Glass
(b)
Front Cell bandgap (eV)
Rear Cell bandgap (eV)
η(%)
Ge
CIGS
Si
MAPbI3
FAPbI3
FASnI3
(c)
Hybrid Tandem
All Perovskite Tandem
Front sub-cell (Large Eg)
ICL
Rear sub-cell (Small Eg)
Large-Eg PVK
Small-Eg PVK
C-Si (n)
CuInSe2
PCE-10:PCBM

Take home message

- Research direction – innovation
  - Climate change
  - Energy efficiency
  - Solar cell

- Early career researcher – none age – willin
  to start

Thank you!