

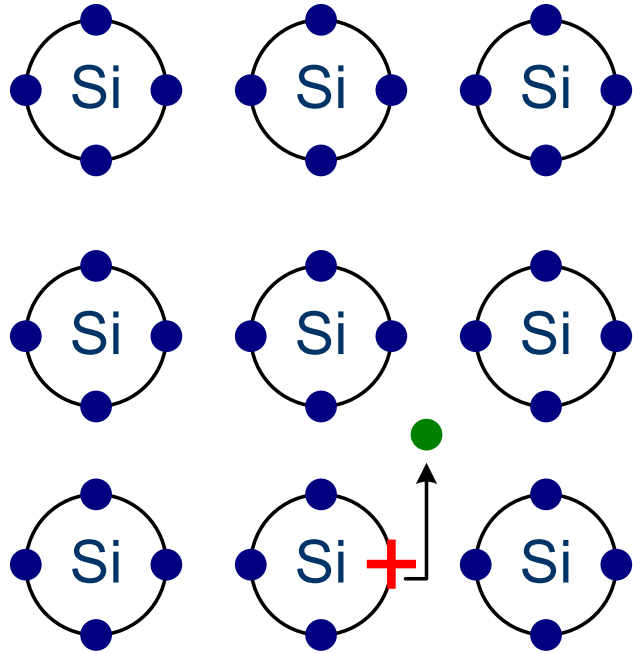
Sec 3 : Contents

- **3. Advances in Solar Energy Conversion** – Semiconductor technology, Advances in Photovoltaic technology, Device limitations, Material advances, flexible energy conversion devices, PV characterisation, Artificial photosynthesis, Solar fuels, Solar powered vehicles.
- **Case Studies:** *Device degradation, evaluation and energy conversion performance of solar technologies, Floating solar panels, Vertical solar farms, Solar – Battery integration*

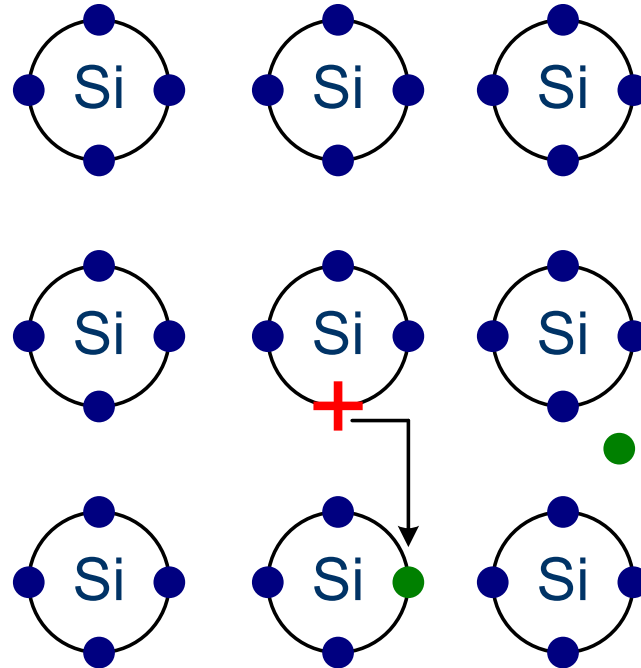
Semiconductors

- **Semiconductors are solids whose conductivity lies between the conductivity of conductors and insulators.**
- **Due to exchange of electrons to achieve the noble gas configuration - semiconductors arrange as lattice structure.**
- **Unlike metals, the conductivity increases with increasing temperature.**
- **Increasing temperatures leads to broken bonds and free electrons are generated.**
- **At the location at which the electron was placed, a so-called defect electron (“hole”) remains.**
- **The electron flow is based on the conductivity properties of semiconductors.**
- **The electronic band structure illustrates why semiconductors behave like this.**

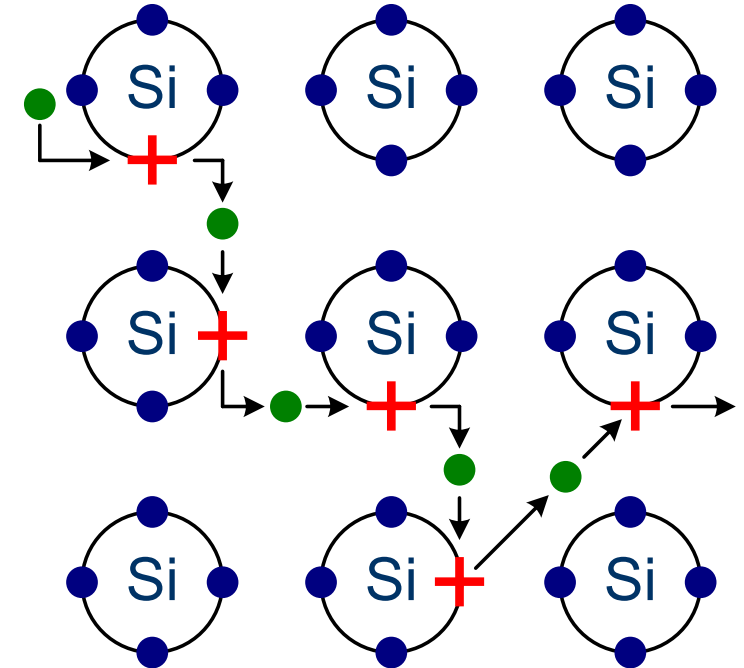
Cut-out of a silicon lattice



An electron ● detaches from an atom, a positive charged hole + is generated.

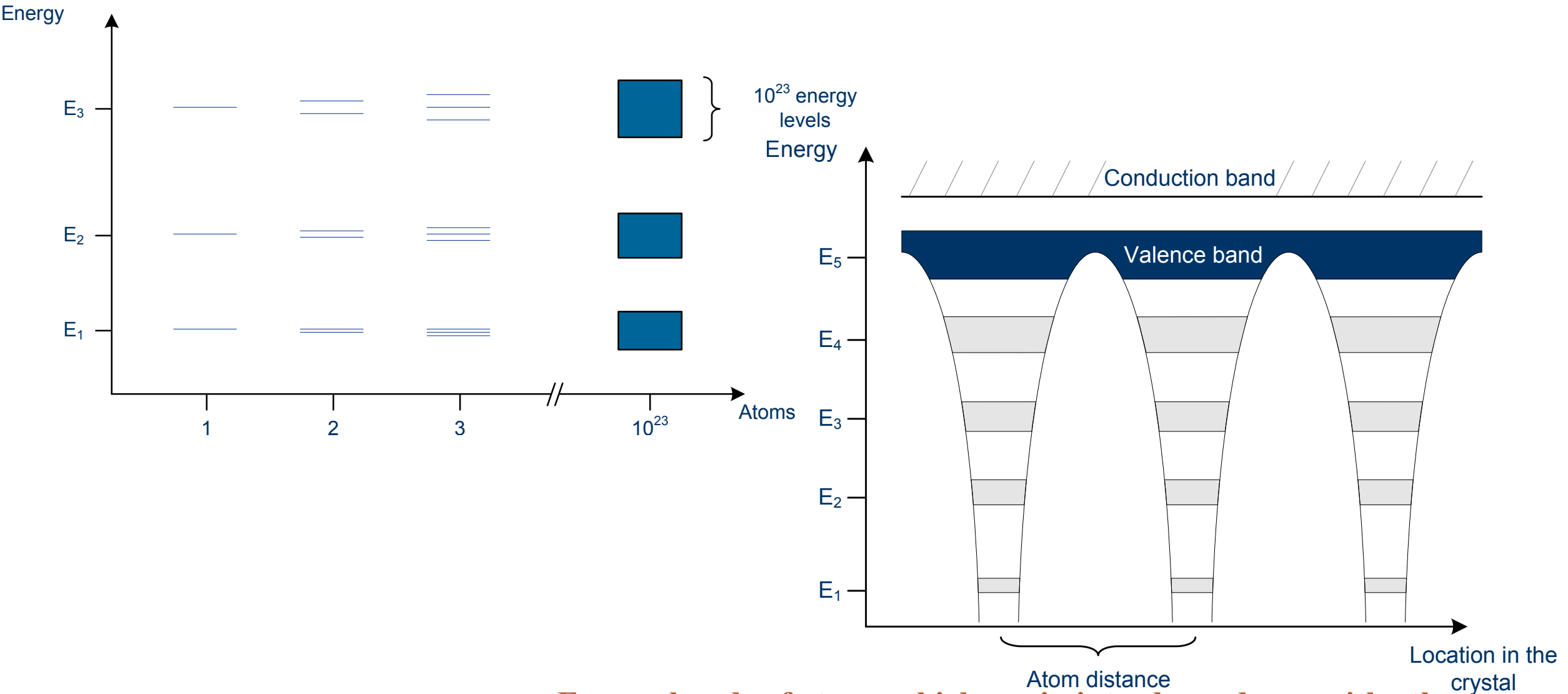


Another electron fills the hole. Thereby a new hole is generated.



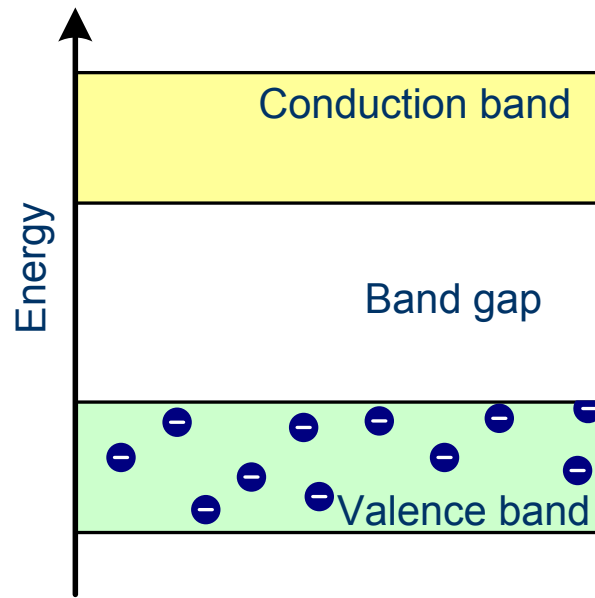
This process repeats everywhere in the lattice. While electrons move to the right, holes move to the left.

Energy levels of atoms which are in interdependency with other atoms

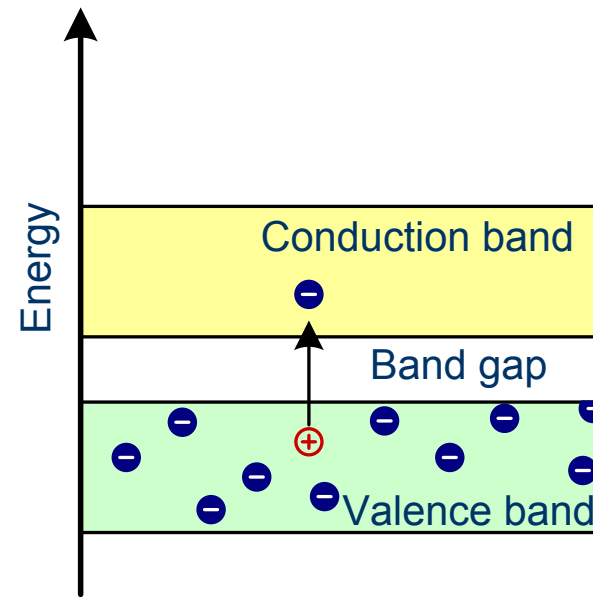


Energy bands of atoms which are in interdependency with other atoms

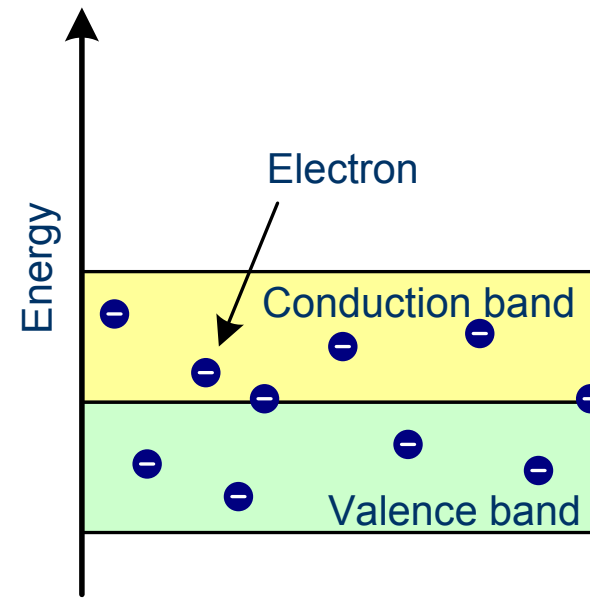
The band model



Insulator



Semiconductor



Conductor

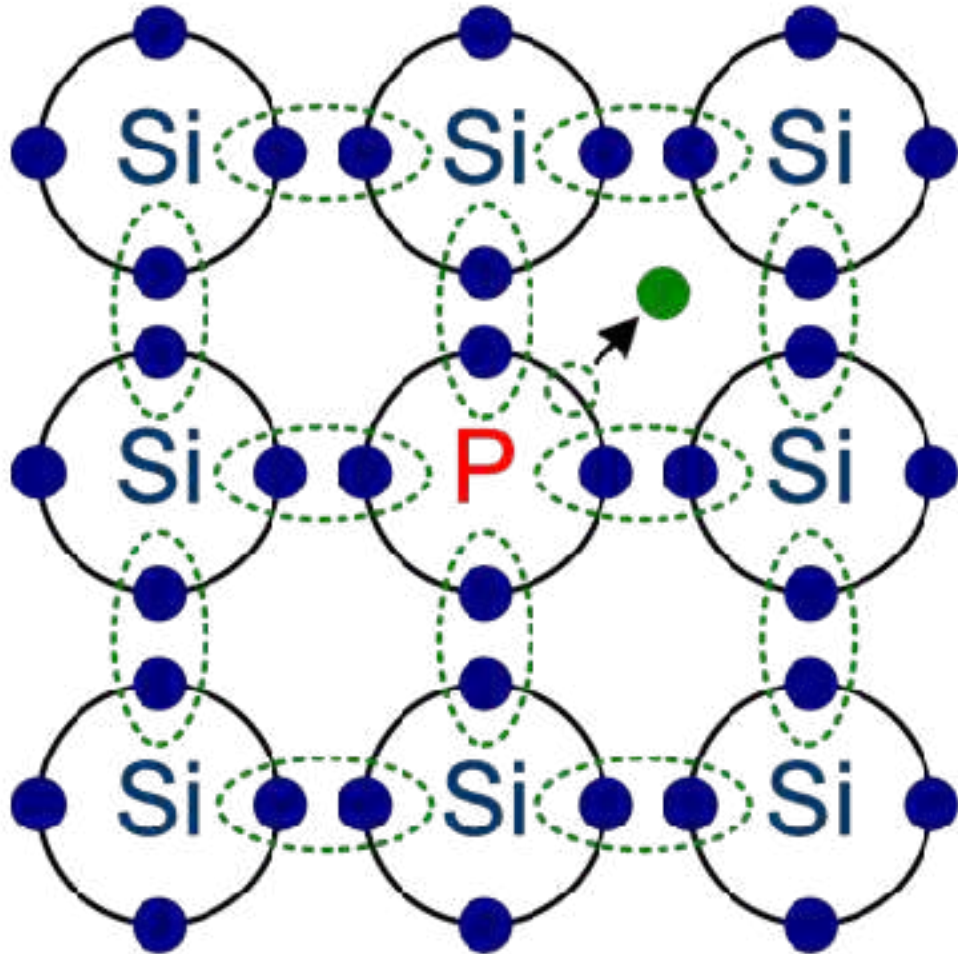
The valence band is fully occupied with electrons due to the covalent bonds. The electrons can not move because they are “locked up” between the atoms. To achieve a conductivity, electrons from the valence band have to move into the conduction band. This prevents the band gap, which lies in between the valence band and conduction band.

There is a band gap, but compared to insulators it is so small that even at room temperature electrons from the valence band can be lifted into the conduction band. The electrons can move freely and act as charge carriers. In addition, each electron also leaves a hole in the valence band behind, which can be filled by other electrons in the valence band. Thus one gets wandering holes in the valence band, which can be viewed as positive charge carriers.

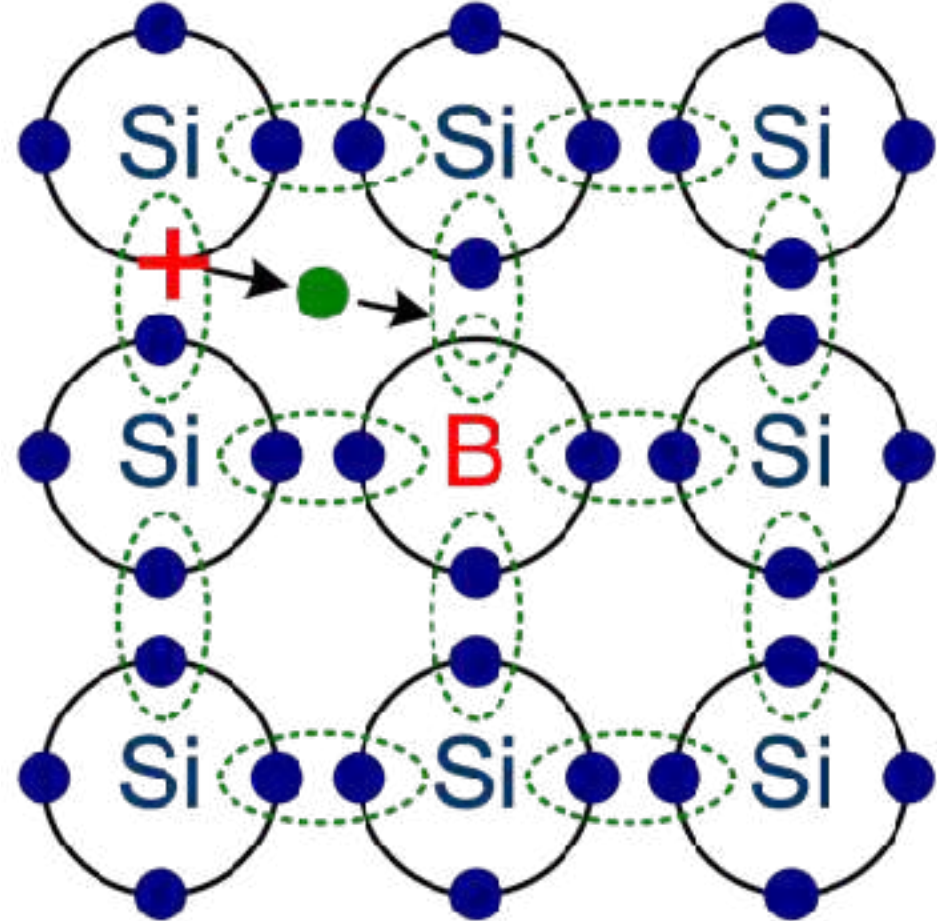
The valence band is either not fully occupied with electrons, or the filled valence band overlaps with the empty conduction band. In general, both states occur at the same time, the electrons can therefore move inside the partially filled valence band or inside the two overlapping bands. In conductors there is no band gap between the valence band and conduction band.

Doping: n- and p-semiconductors

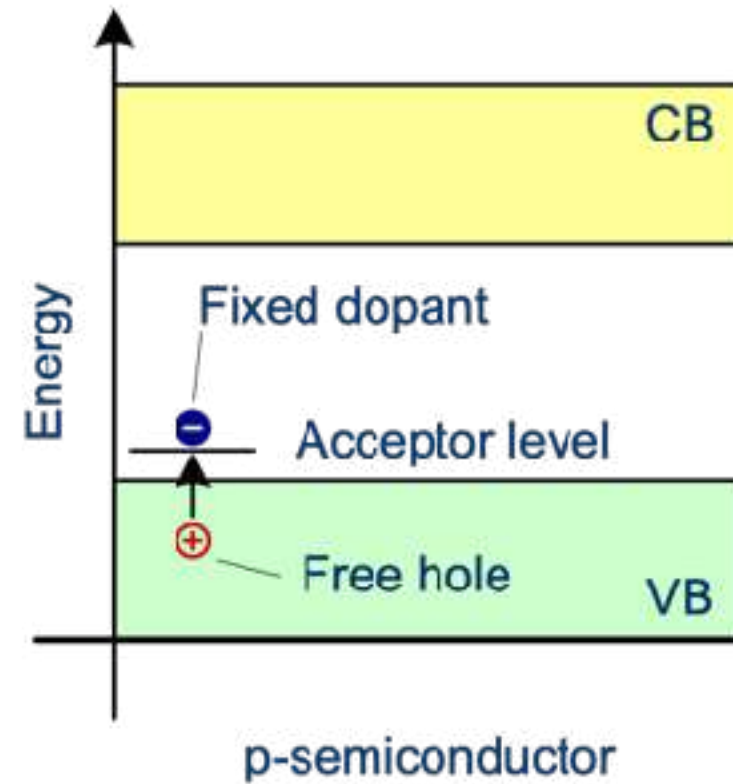
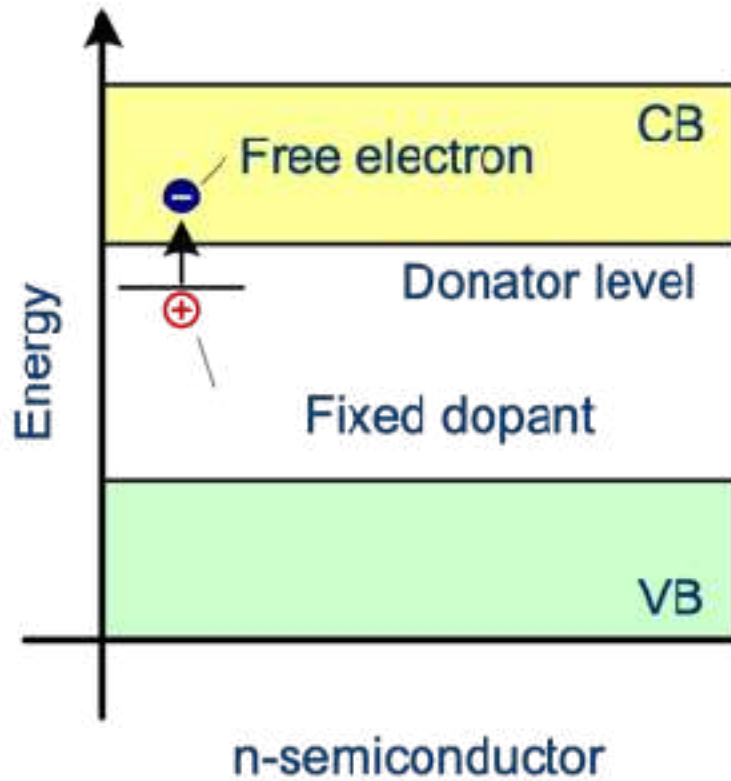
n-doping with phosphorus



p-doping with boron

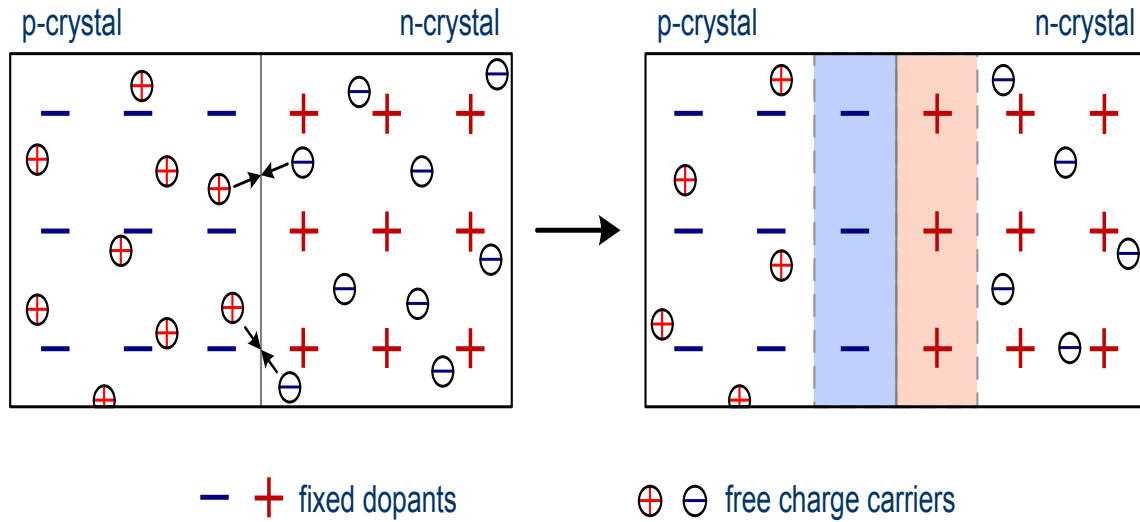


Band model of p- and n-type doped semiconductors

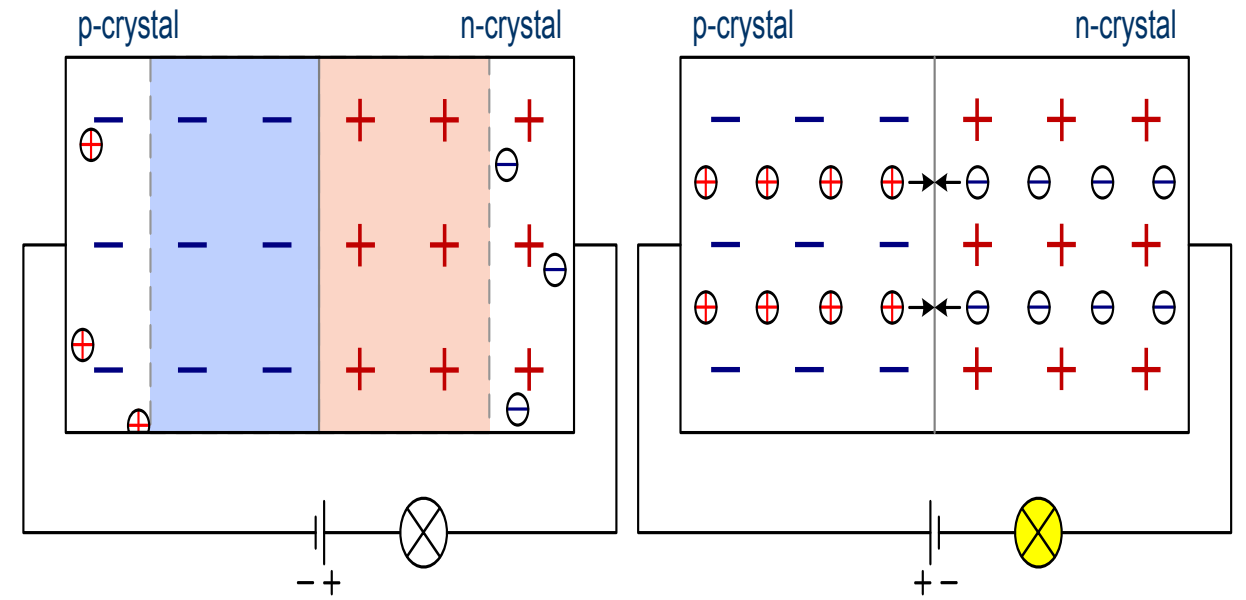


p-n junction

p-n junction without an external applied voltage



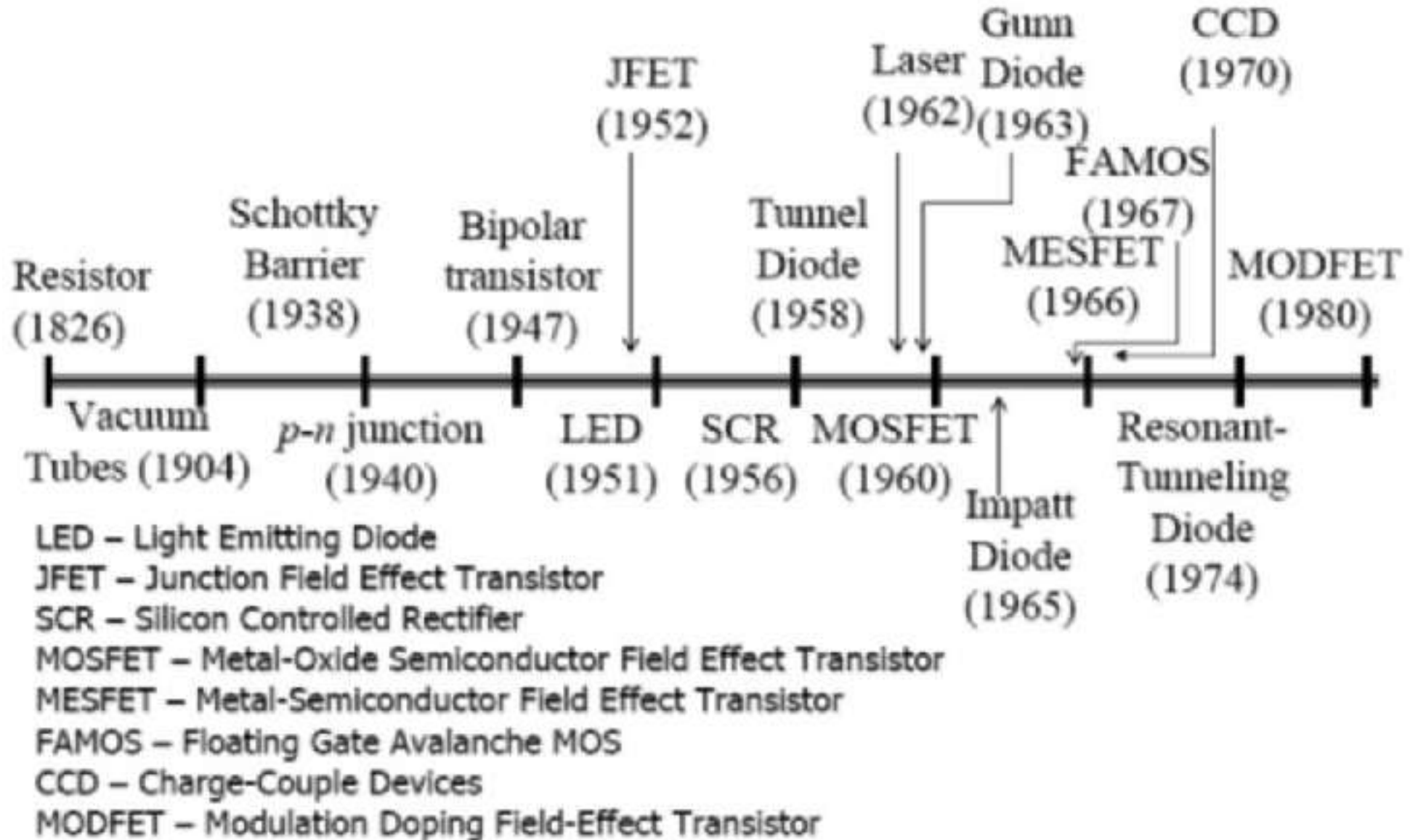
p-n junction with an external applied voltage

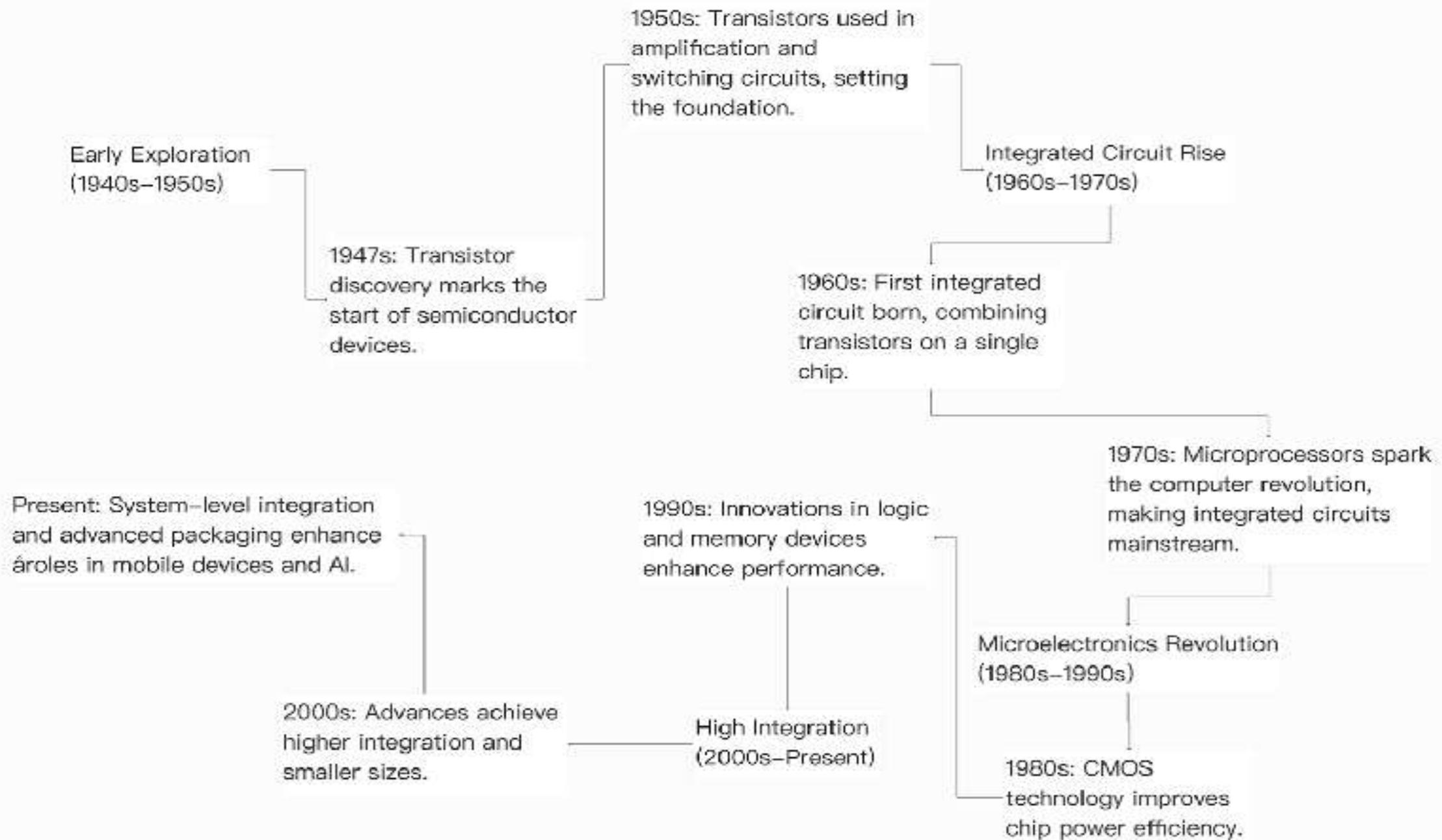


(a) reverse direction

(b) forward direction

History of Semiconductor devices





Essentials in semiconductor technology

- Need of semiconductor with band gap within 3 eV to 1 eV
- Broad absorption in visible spectral region
- Photoactive materials should be direct band gap semiconductor
- As indirect bandgap semiconductor require higher thickness of thin film for good absorption
- However higher thickness always result in higher recombination rates
- Diodes, triodes, transistor, FET, Ferroelectric transistor, electronic switches, sensors
- Development of semiconductor memory devices, computing devices , Integrated circuits

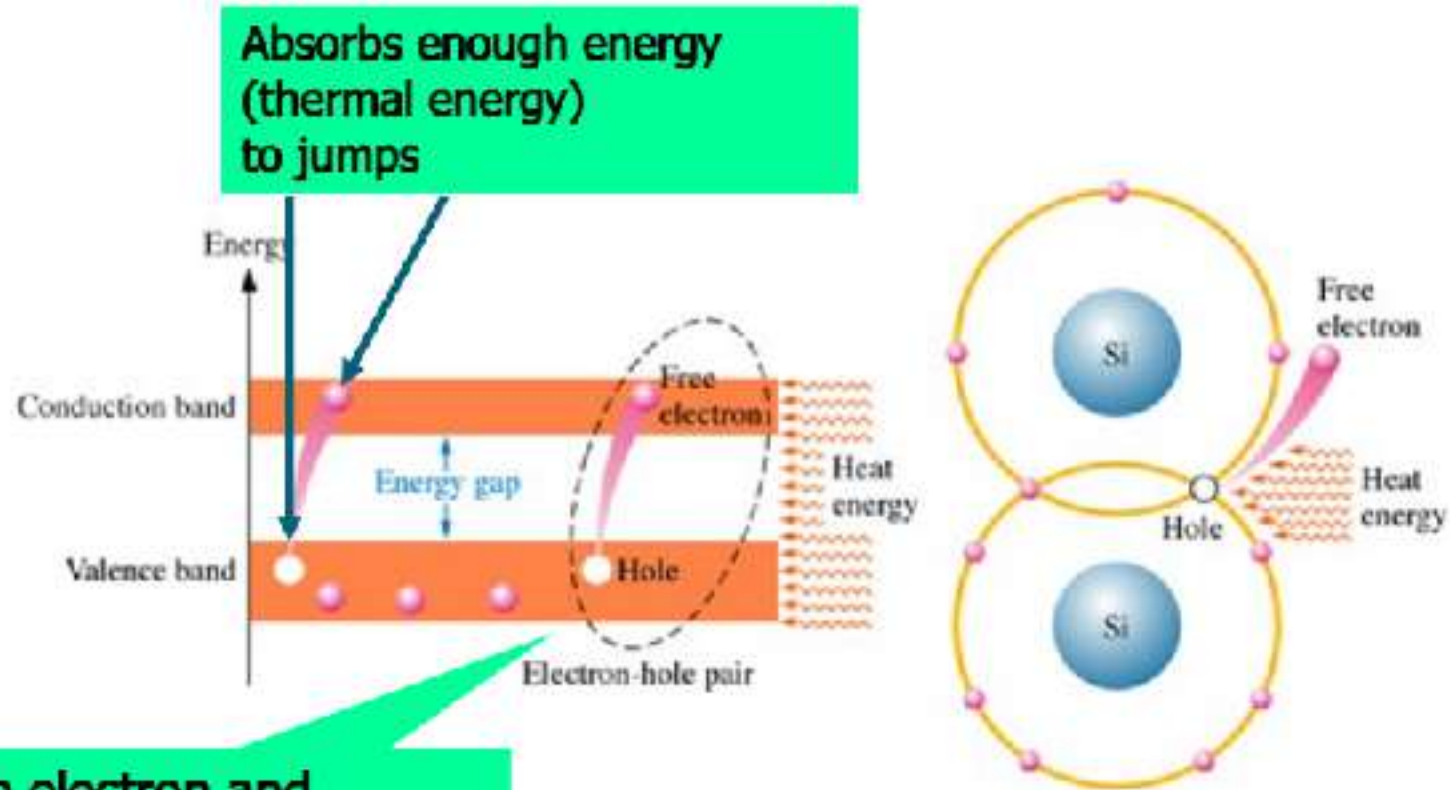
Advances in semiconductor technology

- Development of semiconductor memory devices
 - Semiconductors in processing units – quantum computing
 - Transistors of micro and nano dimensions – chip development
 - LED, Photodetectors, Lasers, Amplifiers, Integrated circuits
 - MOS based transistors smallest (30 nm) for fast processing – Intel
 - Microchips for 400 million calculation in fraction of second
 - Semiconductors in photoconversion technologies
-
- The energy required to pull electrons from the valence band to the *conduction band* is called the *bandgap*. Electrons in the (electrical or thermal) conduction band are free to move within the
 - The electron volt [eV] is the energy semiconductor. required to move an electron (charge) across a 1 V potential, $eV = 1.6 \times 10^{-19} \text{ J}$
 - *Intrinsic semiconductors* have intermediate bandgap values (<3 eV). They have average number of valence electrons (4 in the case of silicon)
 - When *doped* with other metal, they can increase or decrease the number of electron in their valence band depending on the dopant.

Advances in semiconductor technology

- Semiconductors in photoconversion technologies
- The energy required to pull electrons from the valence band to the *conduction band* is called the *bandgap*. Electrons in the (electrical or thermal) conduction band are free to move
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Semiconductor processes



a free electron and its matching valence band hole – electron-hole pair

Recombination -when a conduction electron loses energy and fall back into hole in valence band

Advances in semiconductor technology

- **Band** is collection of molecular orbitals with close energy levels
- The energy required to pull electrons from the valence band to the **conduction band** is called the **bandgap**. Electrons in the (electrical or thermal) conduction band are free to move
- The electron volt [eV] is the energy semiconductor required to move an electron (charge) across a 1 V potential, $1\text{ eV} = 1.6 \times 10^{-19}\text{ J}$
- **Intrinsic semiconductors** have intermediate bandgap value ($< 3\text{ eV}$). They have average number of valence electrons (the case of silicon)
- When **doped** with other metal, they can increase or decrease the number of electron in their valence band depending on the dopant.

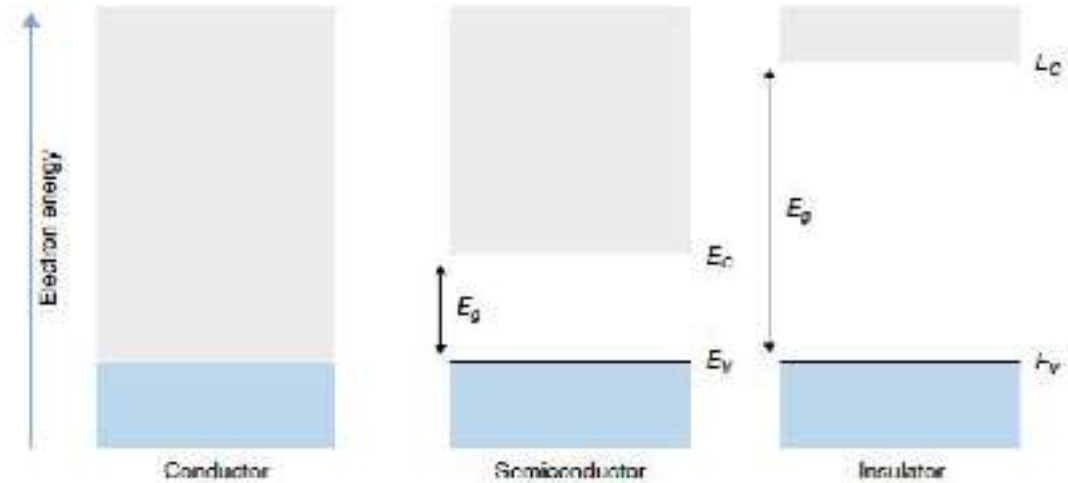


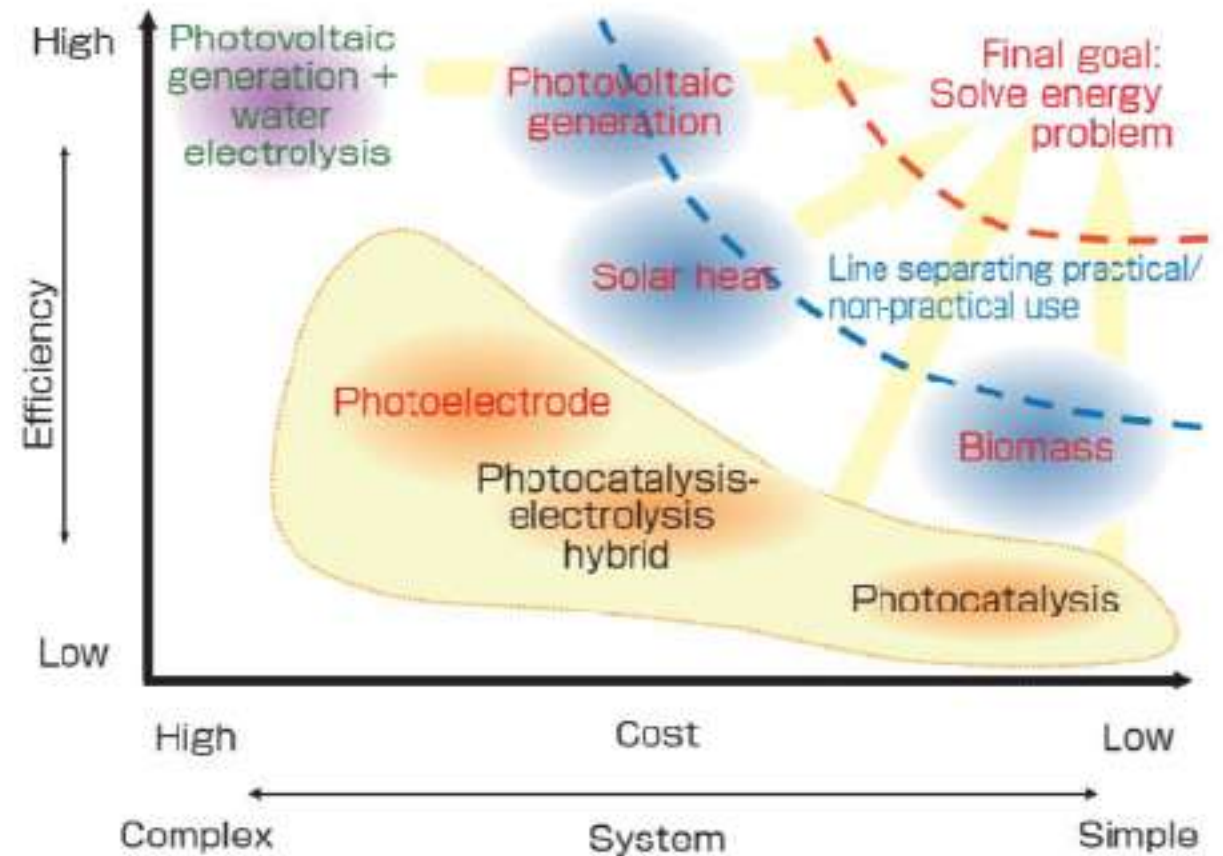
Figure 2.1.3 Energy band diagrams for a conductor, a semiconductor and an insulator

Importance of semiconductor

- Band gap of materials govern the electronic transitions
- Crystallinity for long range charge transport
- Facile charge separation
- Low recombination rates
- Cheap materials and easy processability
- Broad range of spectral or energy absorption
- Heterostructures for efficient charge separation, wide band absorption in whole visible spectrum
- Improve incident photon conversion efficiency

Photoconversion systems

- Solar to electric (photovoltaics)
- Solar to heat (solar heater)
- Solar to light (LED)
- Solar to fuel
(photoelectrosynthesis)
- Solar desalination
- Solar to water purification
(photocatalysis)



Solar radiation spectrum

- Visible radiation is 45-47 %
- UV - 3 %
- IR – 50- 52 %
- UV and Vis will excite the Valence band electron to the Conduction band based on the Band gap
- IR can only do bond vibration

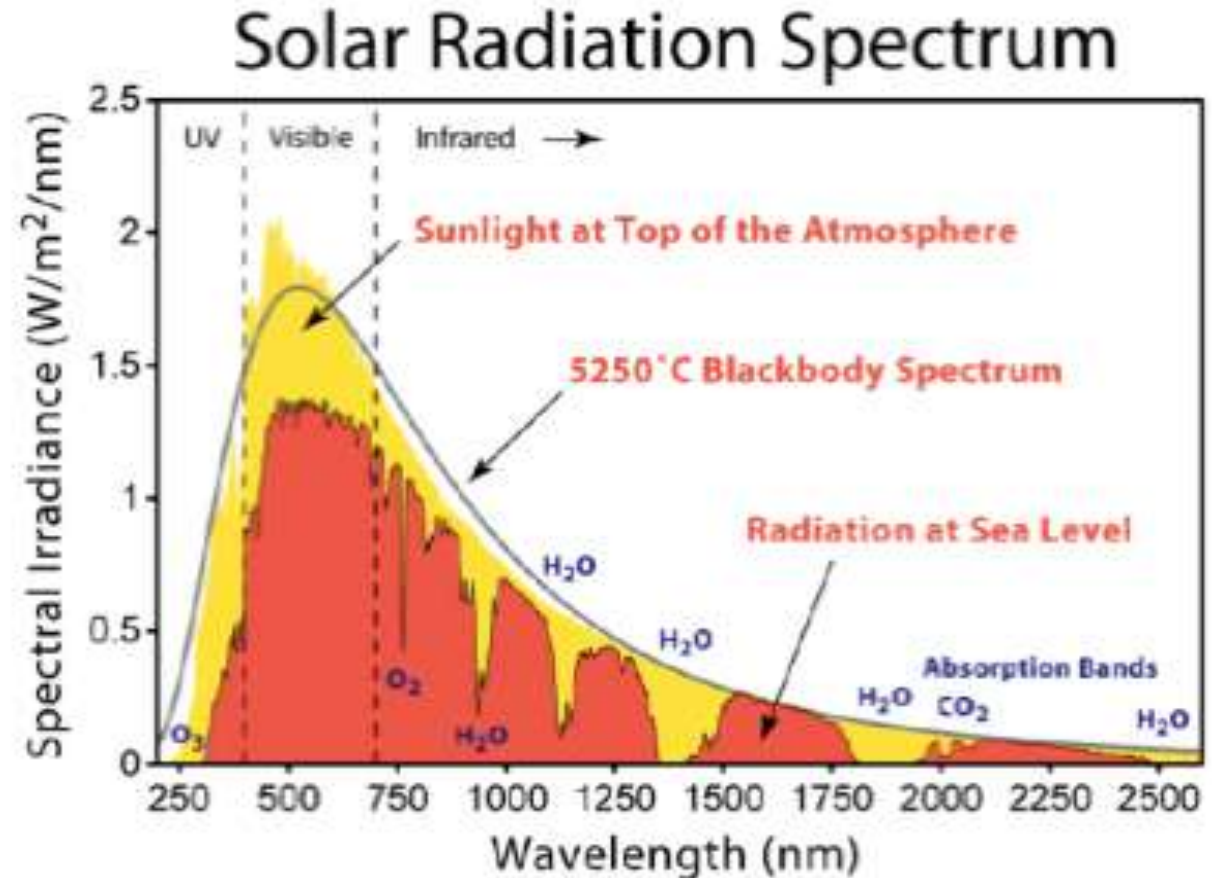
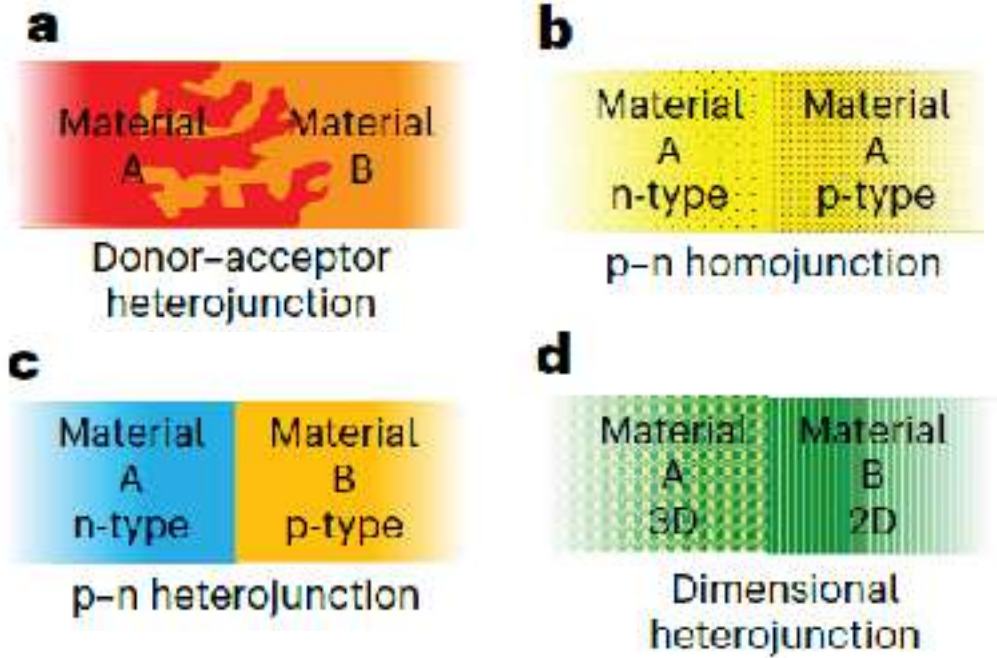


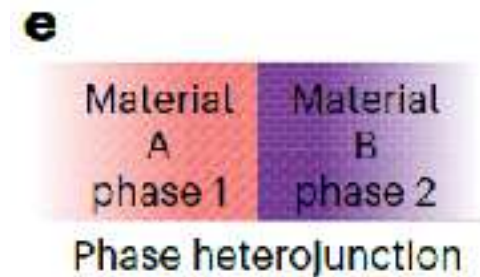
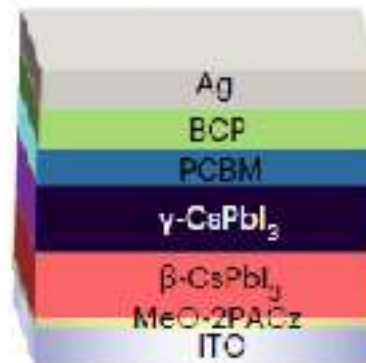
Figure 3: The solar spectrum above the atmosphere and at sea level

Advances in Photovoltaic systems

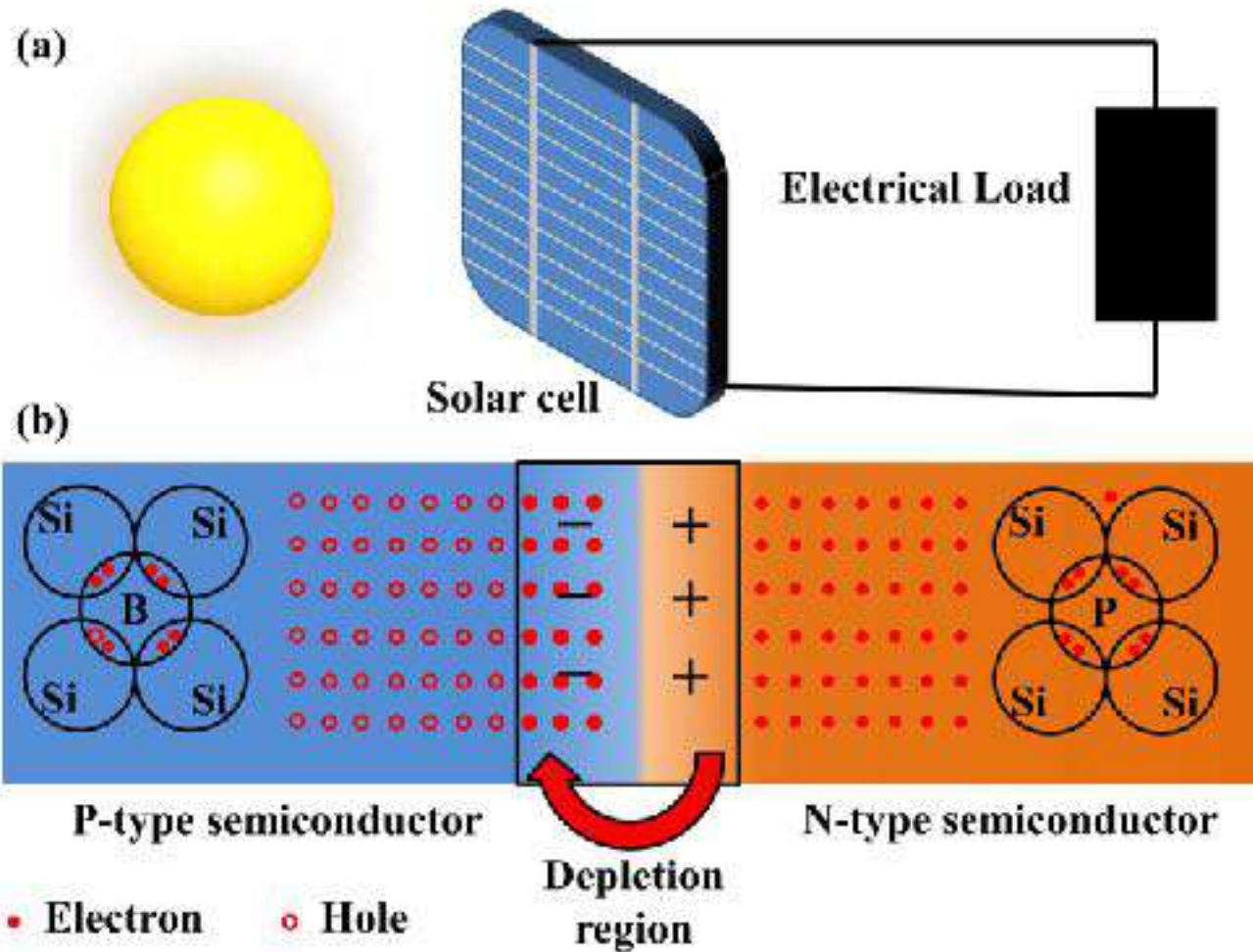
- Solar to electric (photovoltaics)
- Photon conversion efficiency
- Modern PV with Heterostructured junctions
- Increase in efficiency upto 43 % lab scale achieved
- Non silicon Pervoskite heterojunction next generation solar cell



CsPbI₃ PHJ solar cell

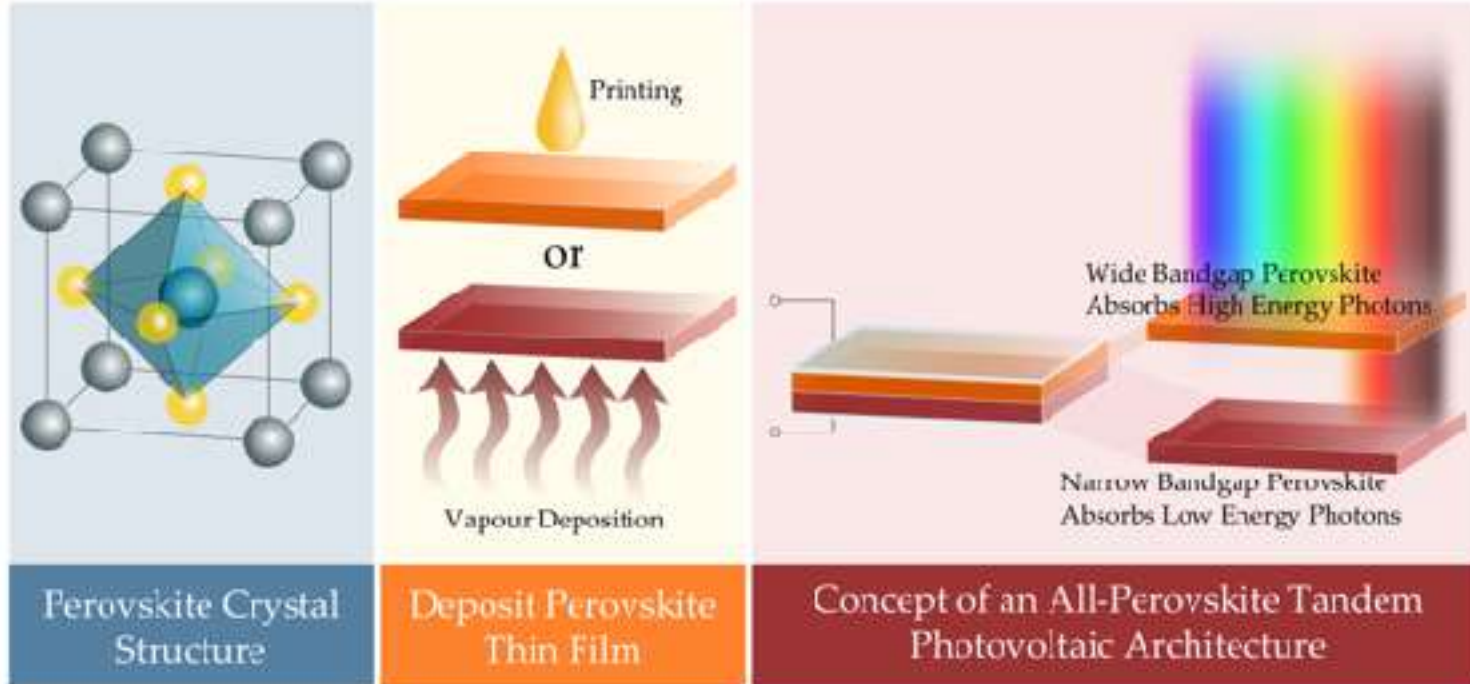


PV structure and operation



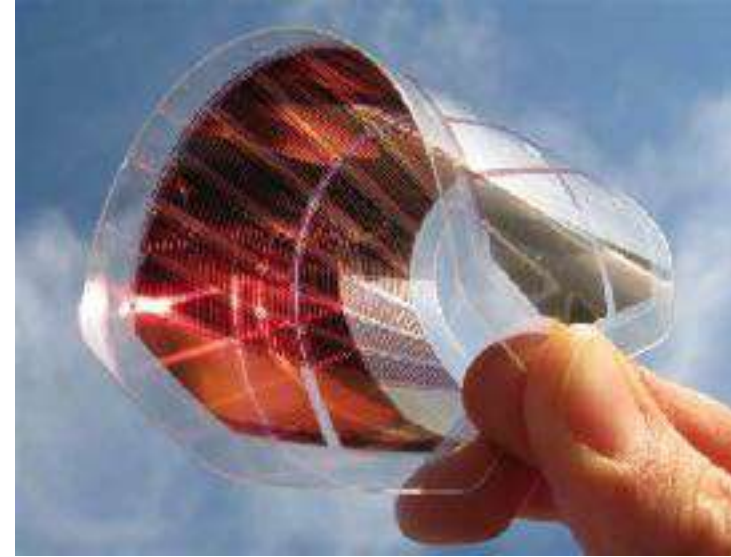
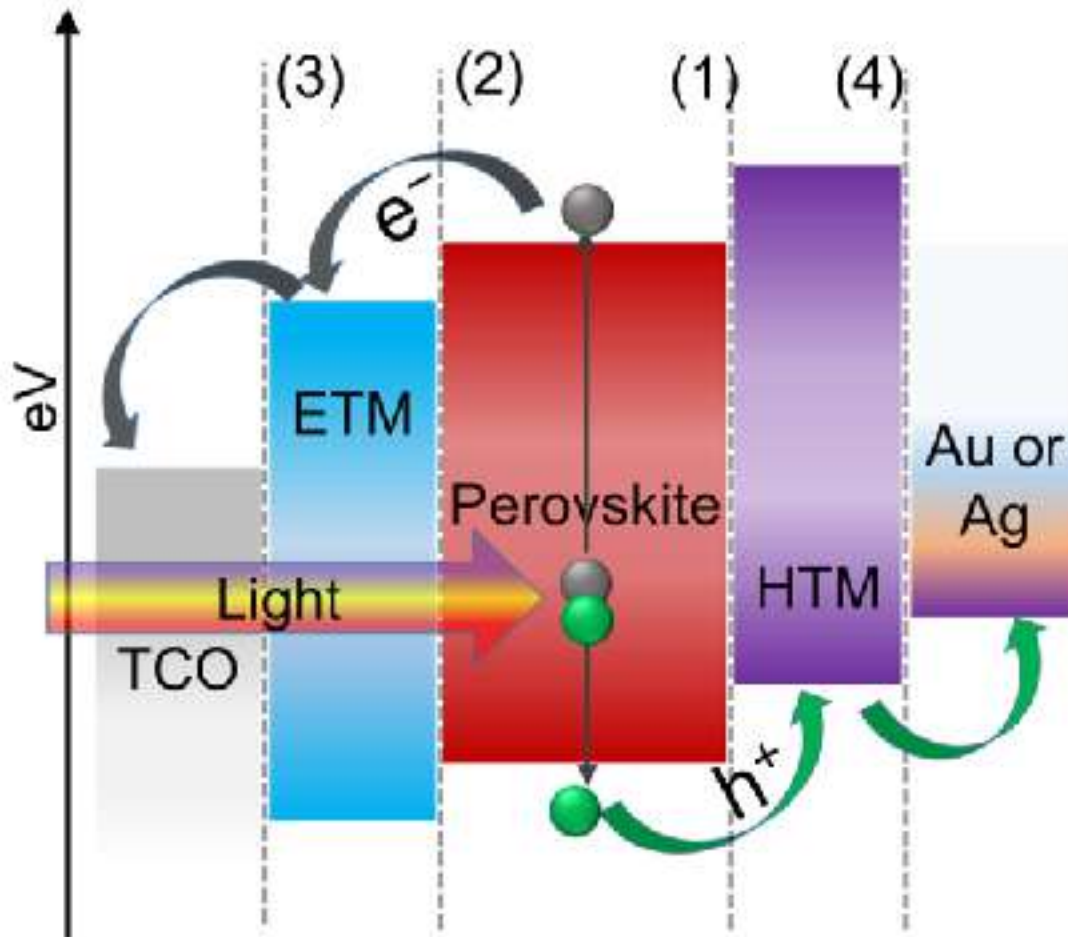
- Solar to electric (photovoltaics)
- P-type and n-type materials
- Potential barrier formation
- PB enhance charge separation
- Reduce recombination losses
- Efficiency improvements with other non silicon heterojunctions
- Broad visible light absorption

Novel perovskite solar cell



- Perovskite photovoltaics
- Low cost materials
- Tunable position and band gap
- Wide visible light absorption
- Reduce recombination losses
- Ease fabrication
- Non silicon heterojunctions
- Flexible PV systems
- Photon conversion efficiency enhancement

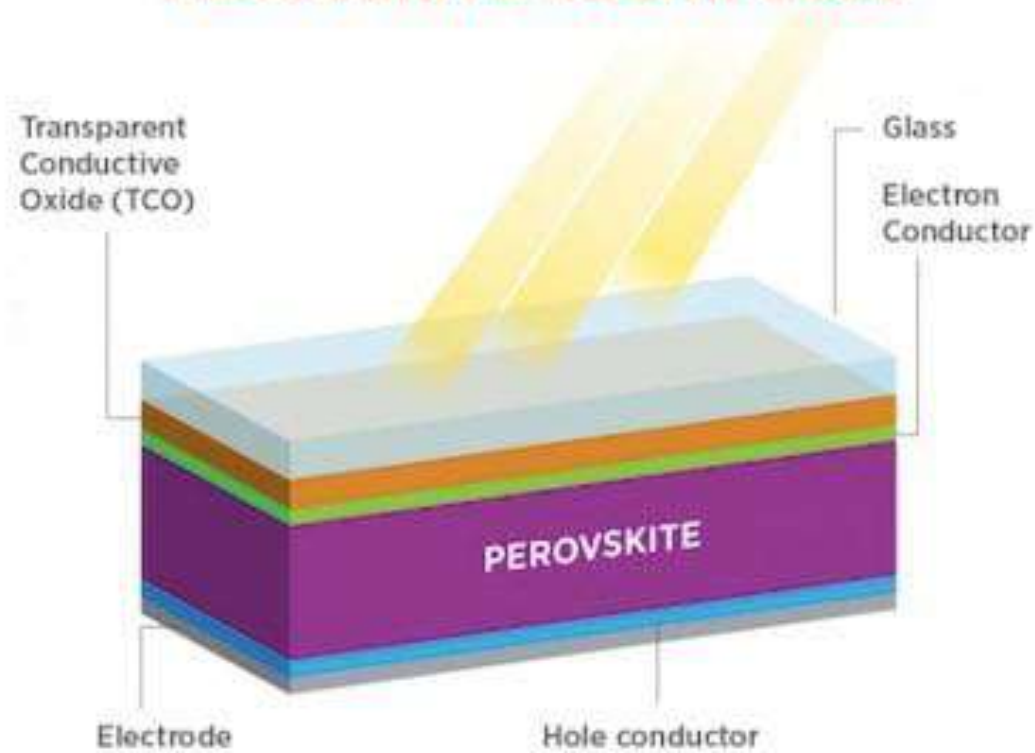
Perovskite the future Tandem solar cell



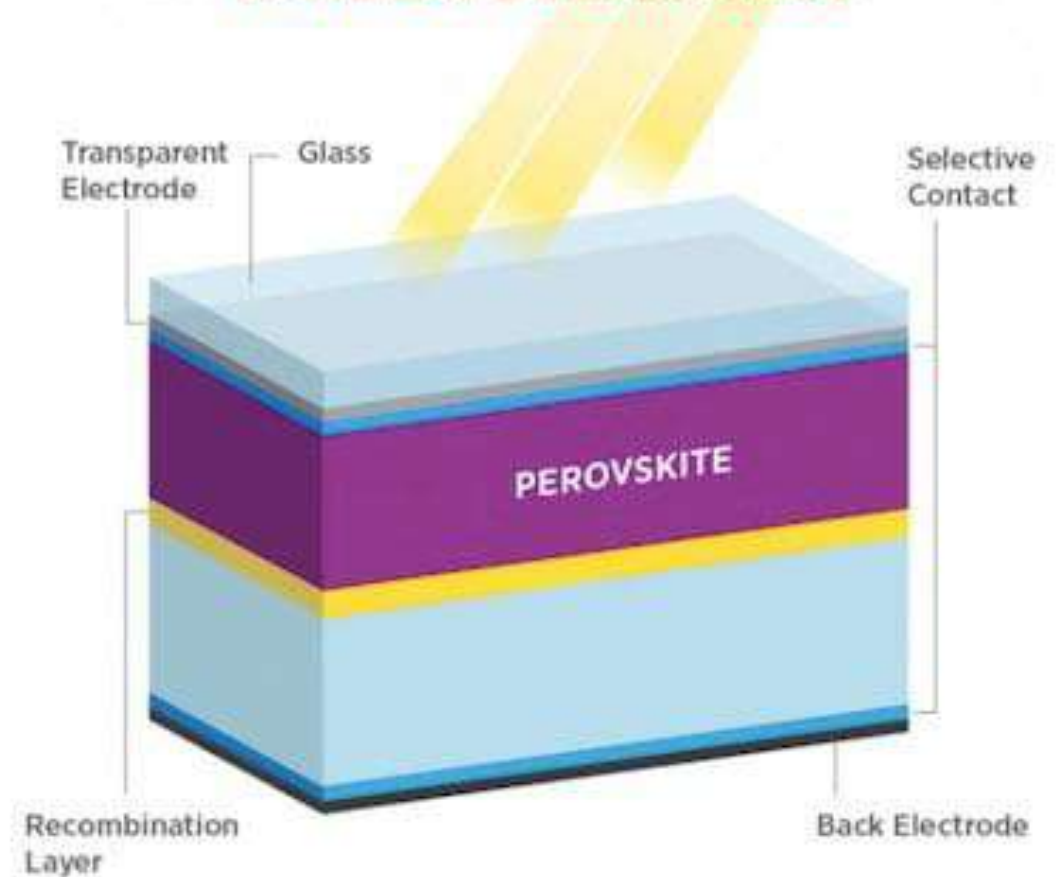
- Use flexible polymer as substrate
- Good charge separation with HTM and ETM
- Higher efficiency, band gap modulation
- Low cost material
- ETM- Electron transport materials
- HTM – Hole transport materials

PV comparison

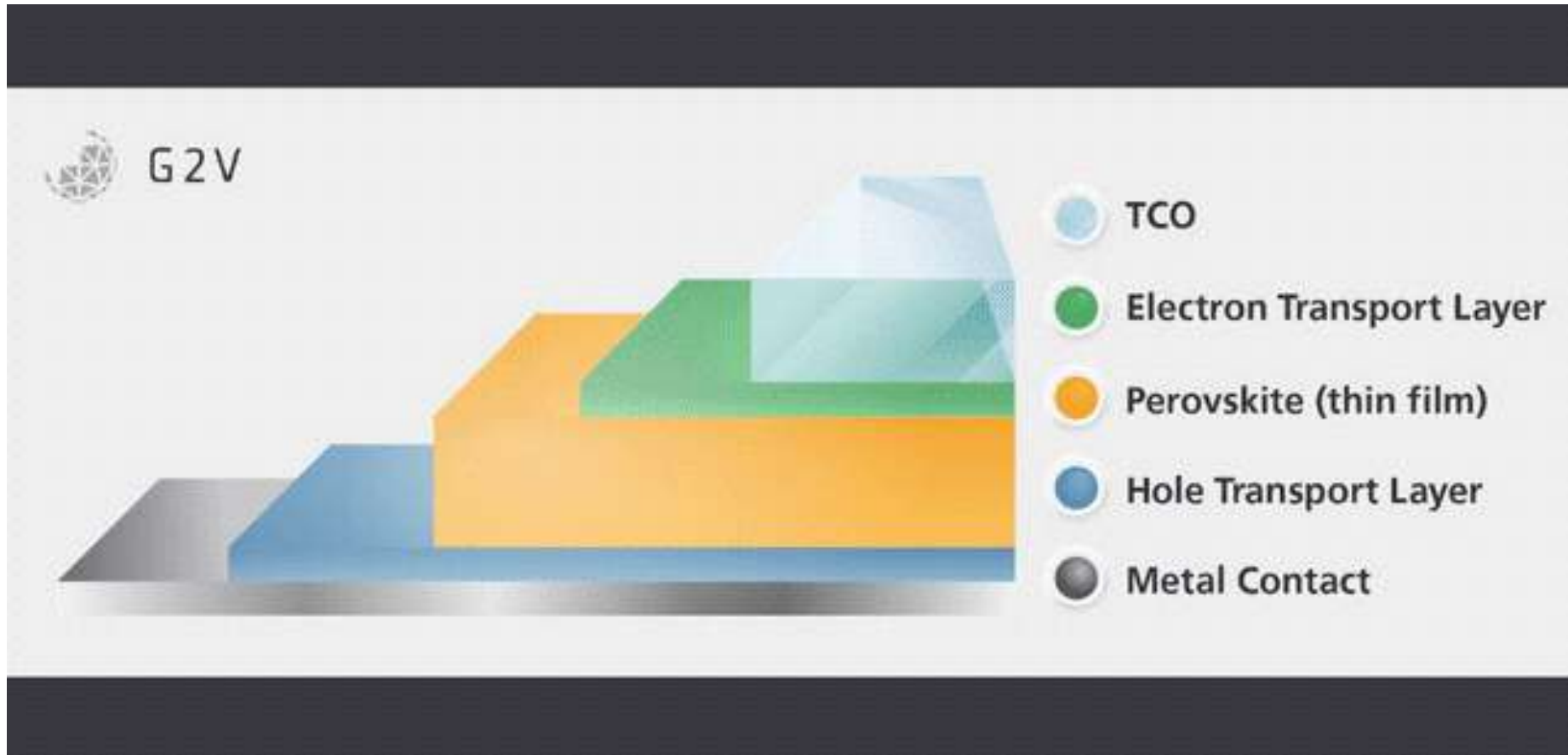
**THIN FILM
PEROVSKITE SOLAR CELL**



**PEROVSKITE ON SILICON
TANDEM SOLAR CELL**

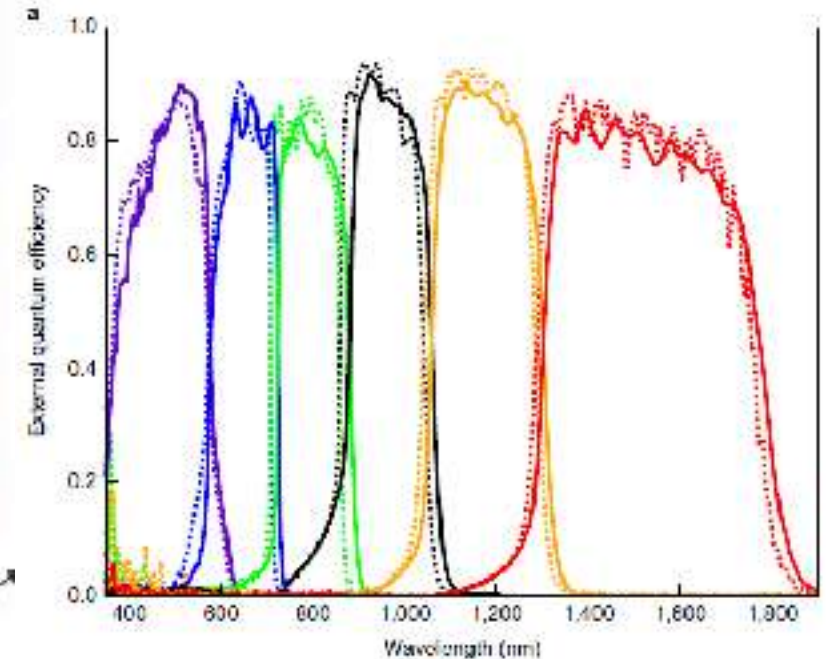
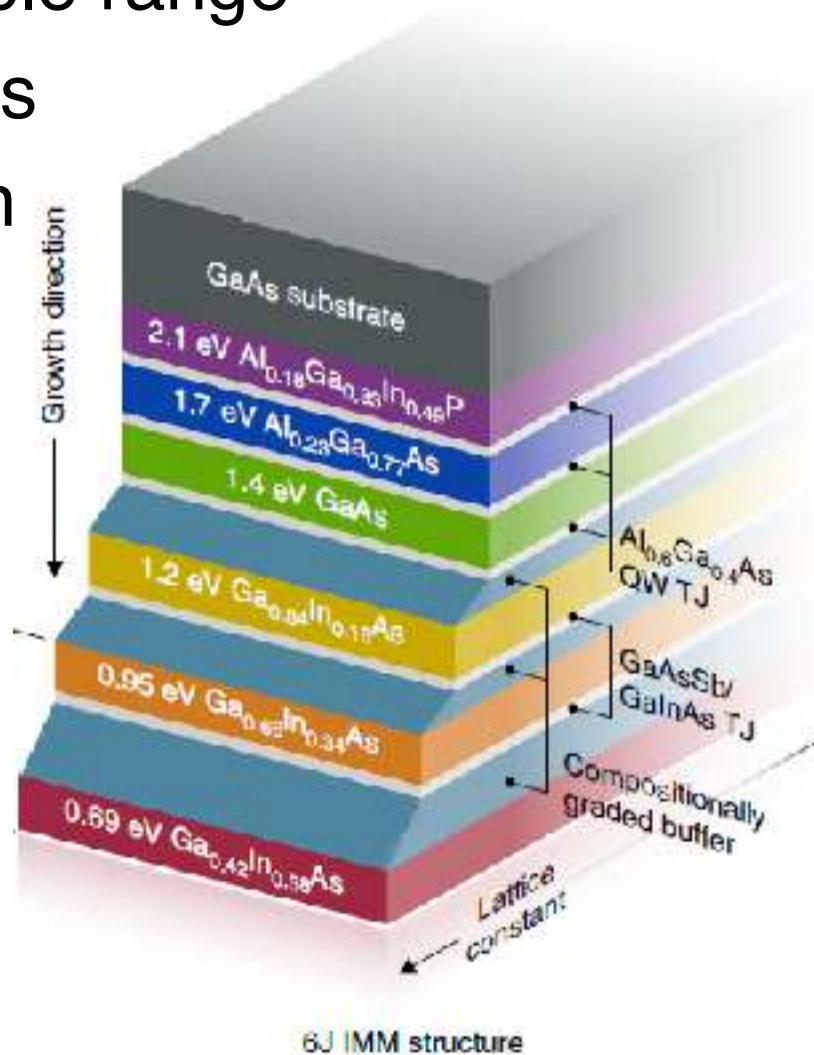


PV Fabrication and characterisation

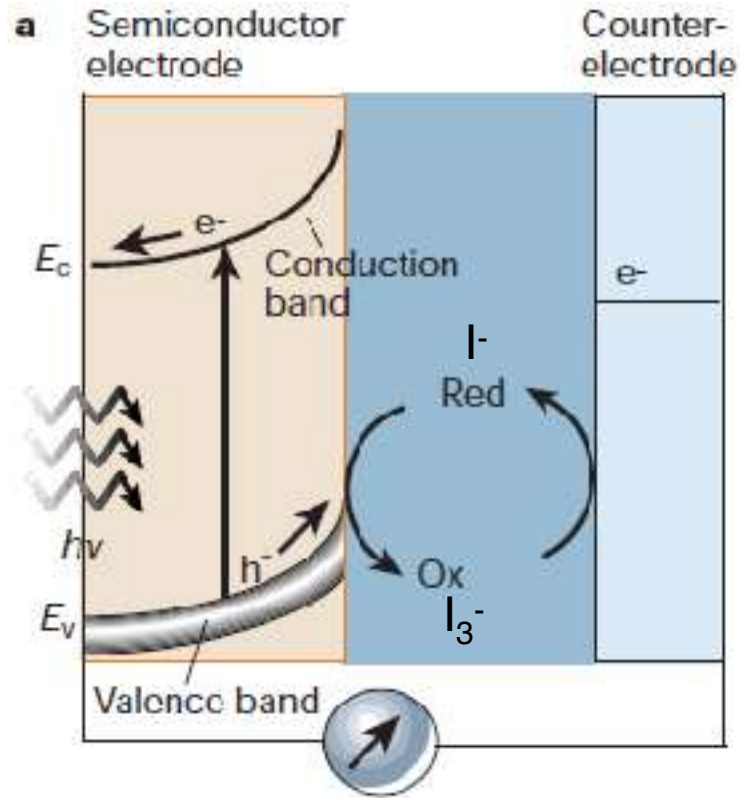


Heterojunction solar cell – 47 % lab efficiency

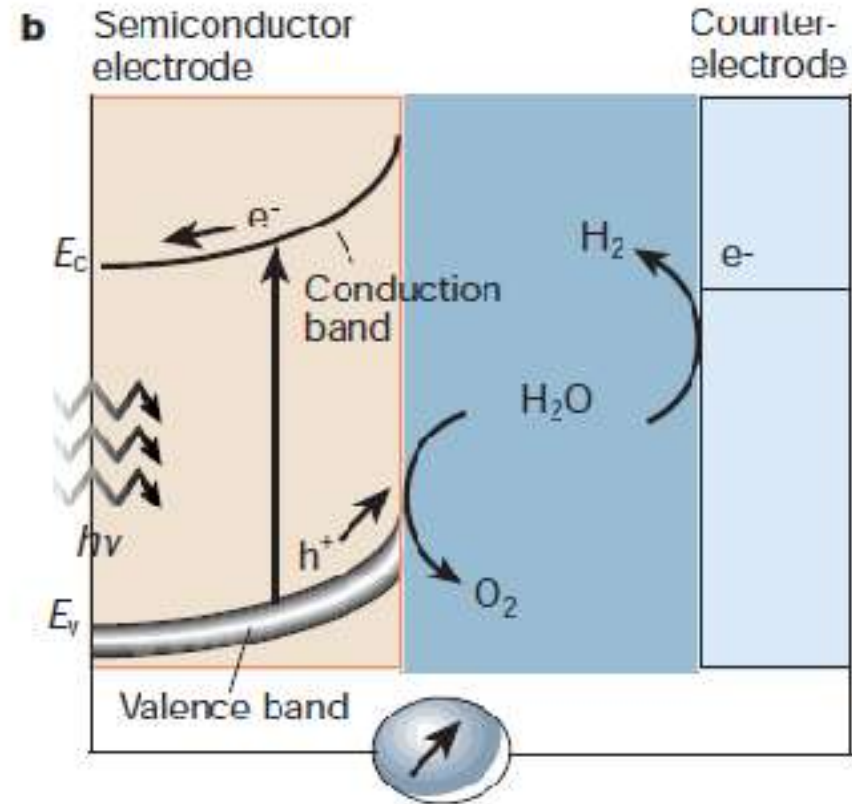
- Wide absorption in visible range
- Multi band gap junctions
- Easy charge separation
- Crystalline thin film
-



Photoelectrochemical cells

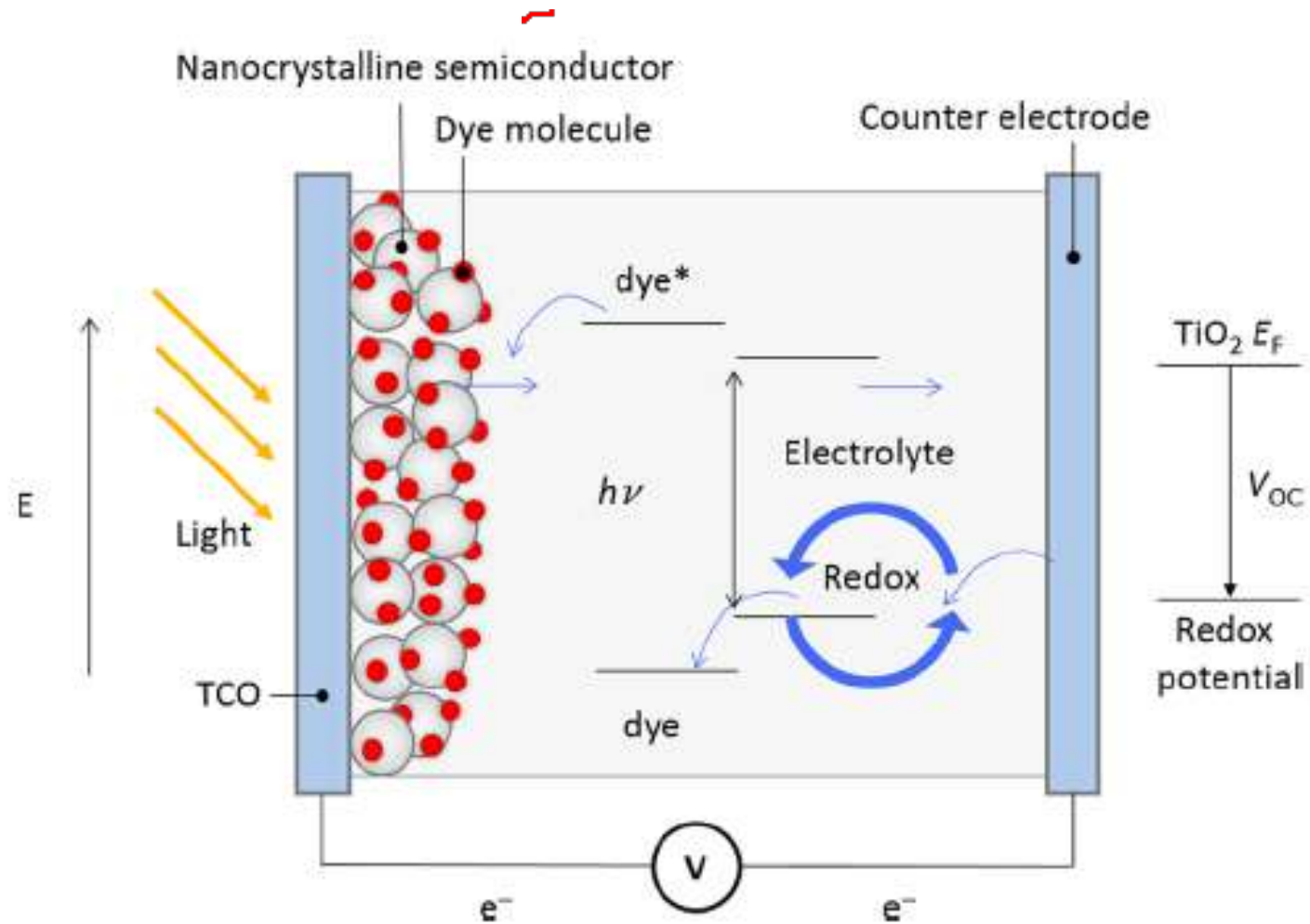


a. Photoelectrochemical regenerative solar cell

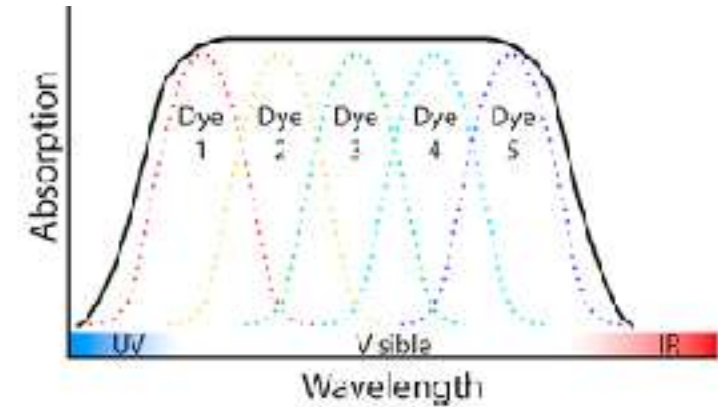


b. Photoelectrochemical solar to fuel cell

Dye sensitized solar cell (DSSC) – Graetzel cell



Visible absorption by dyes



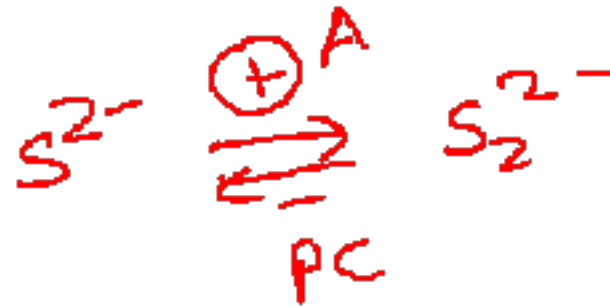
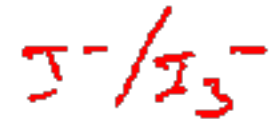
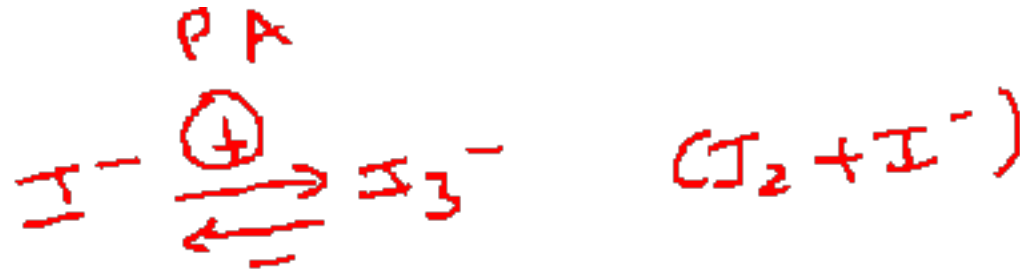
- Dye for sensitization and broad spectrum light absorption
- Works on the principle of redox shuttling to generate Reversible solar cell
- Can enhance the charge separation and injection
- Protect the underlying inorganic semiconductor photoelectrode

DSSC – Photoinduced redox reactions

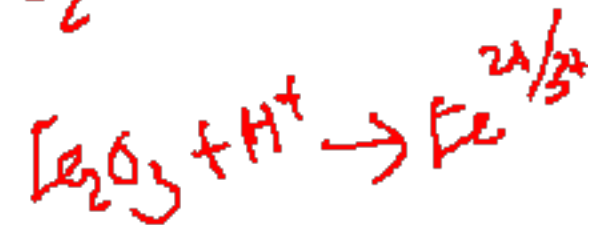
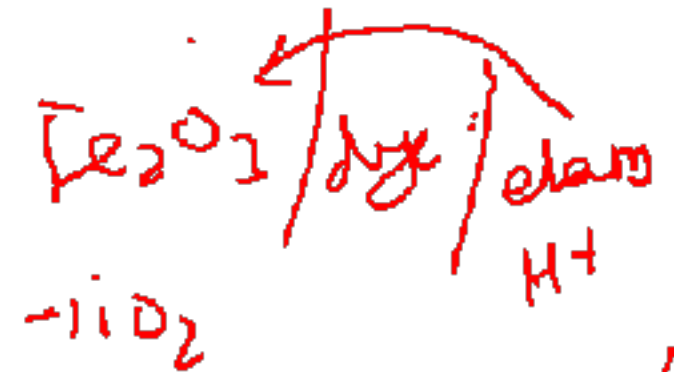
Photo induced redox reactions

Dye - Abs - visible

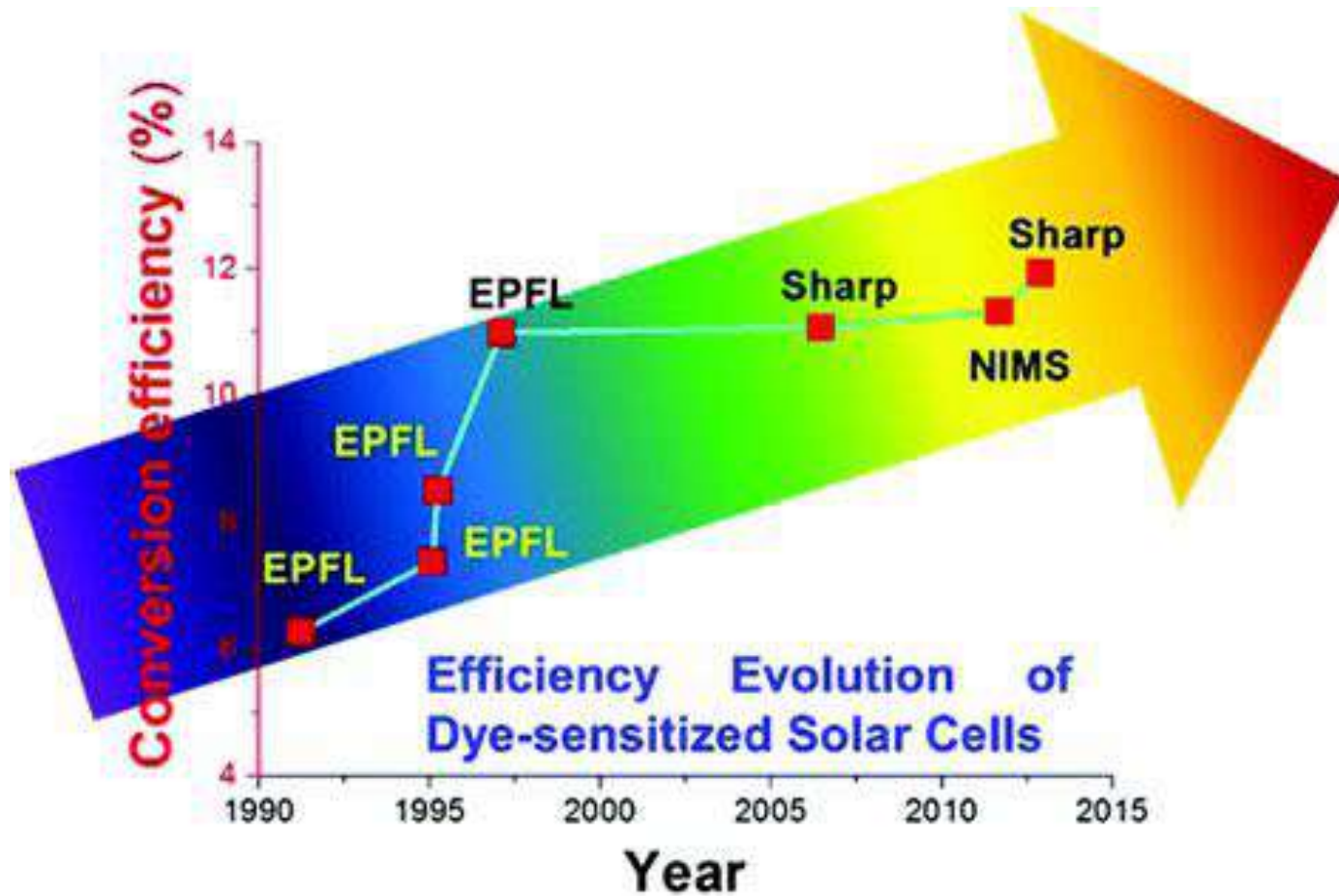
→ can protect the photocell from corrosion



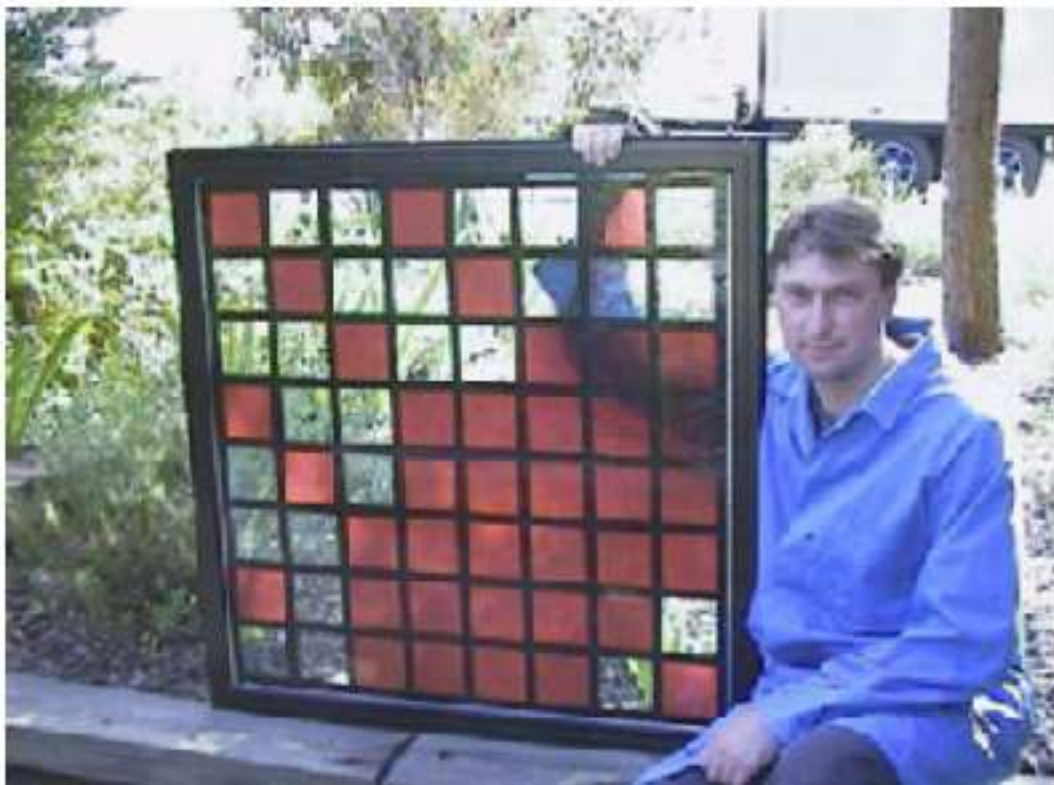
Liquid Junction - Solar-cell
→ DSSC



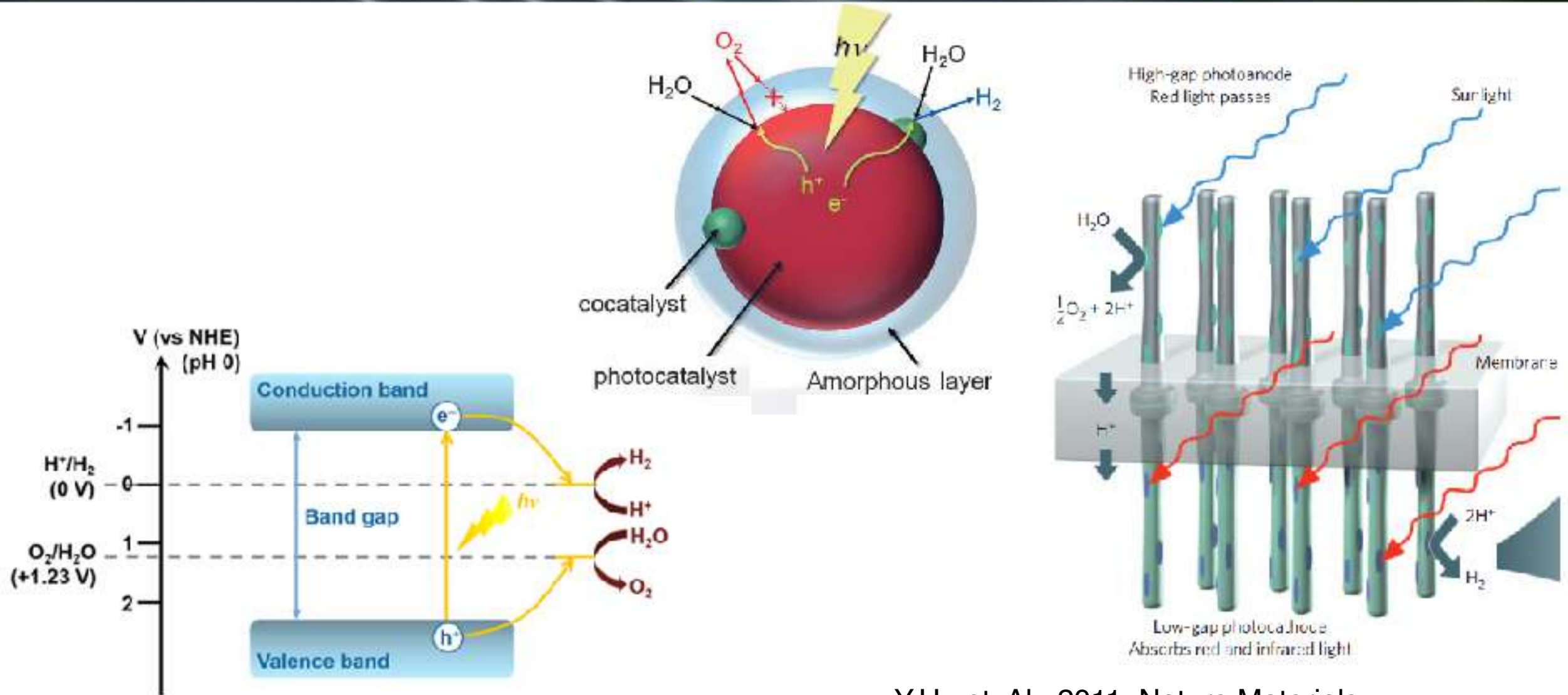
Dye sensitized solar cells



Transparent DSSC windows

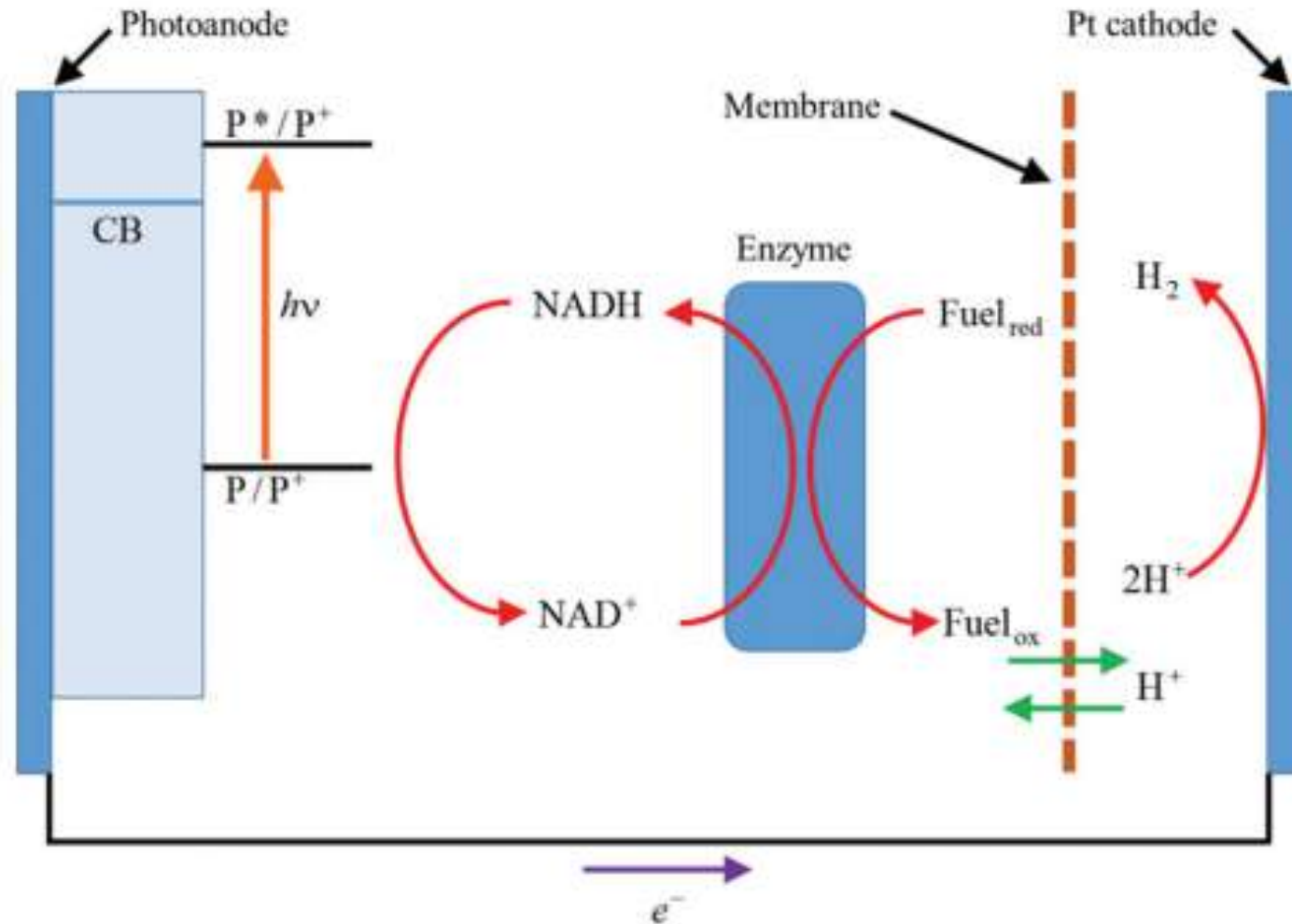


Photocatalyst – Photoelectrode comparison

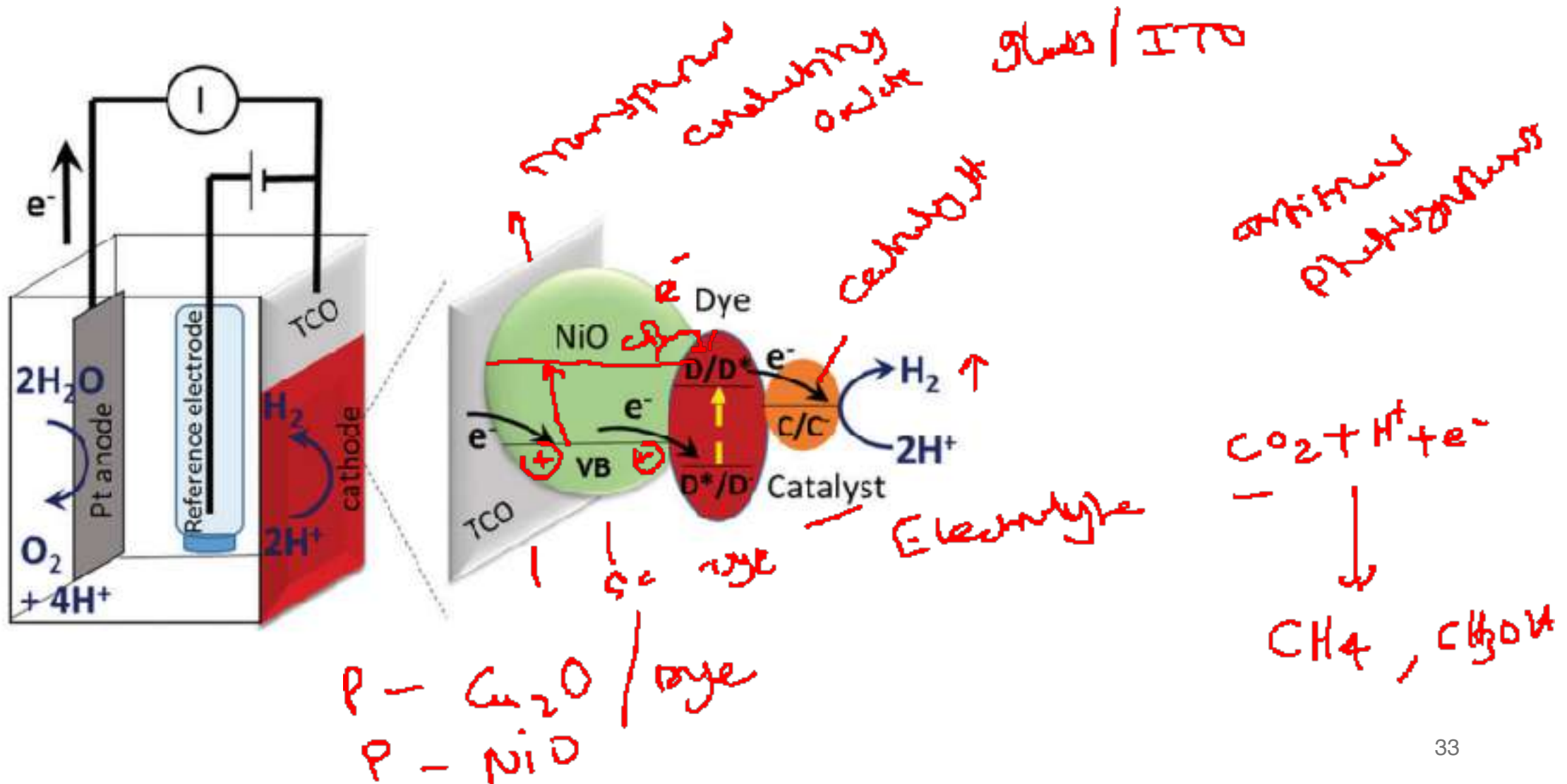


Y.Hu et. Al., 2011, Nature Materials

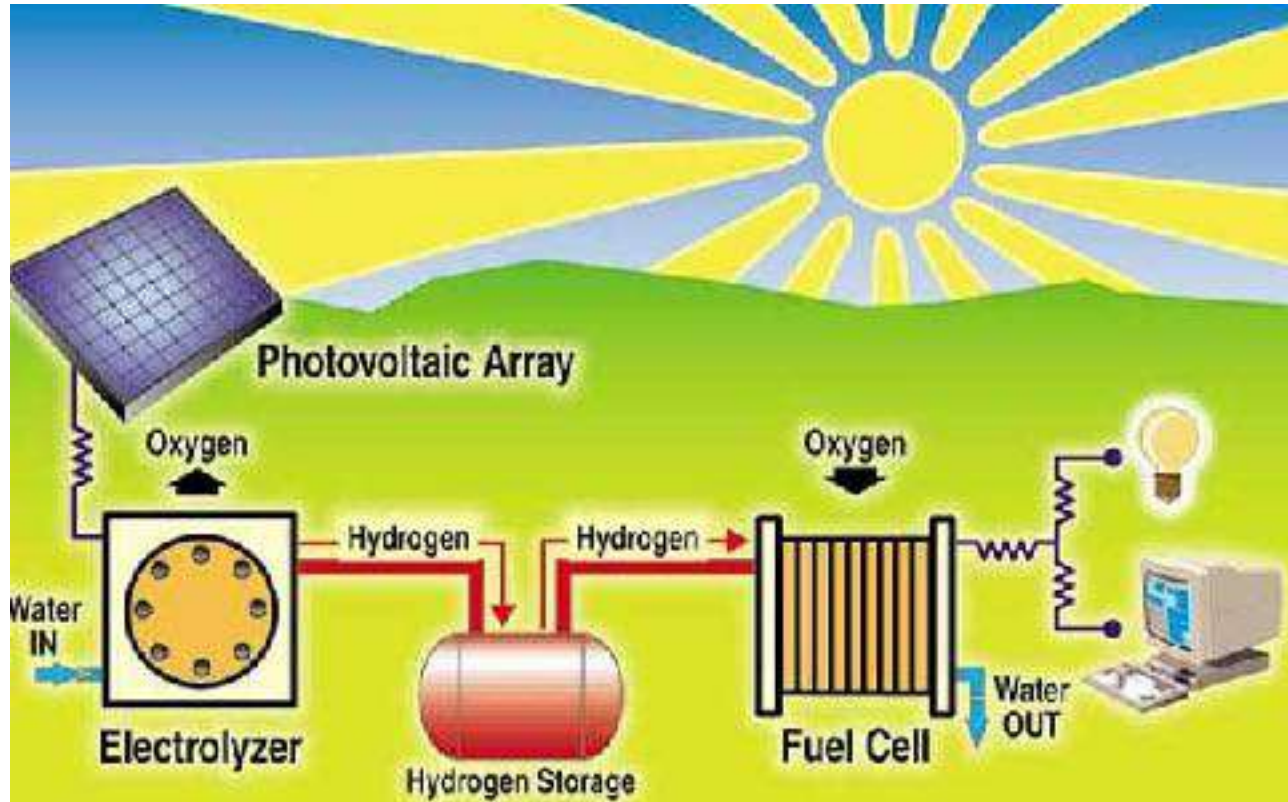
Photoelectrochemical biofuel cell



Photoelectrodes in DS - photoelectrosynthesis



PV- Water electrolyzer – Fuel cell integration



Solar cell test parameters

V_{oc} : Open Circuit Voltage

I_{sc} : Short Circuit Current

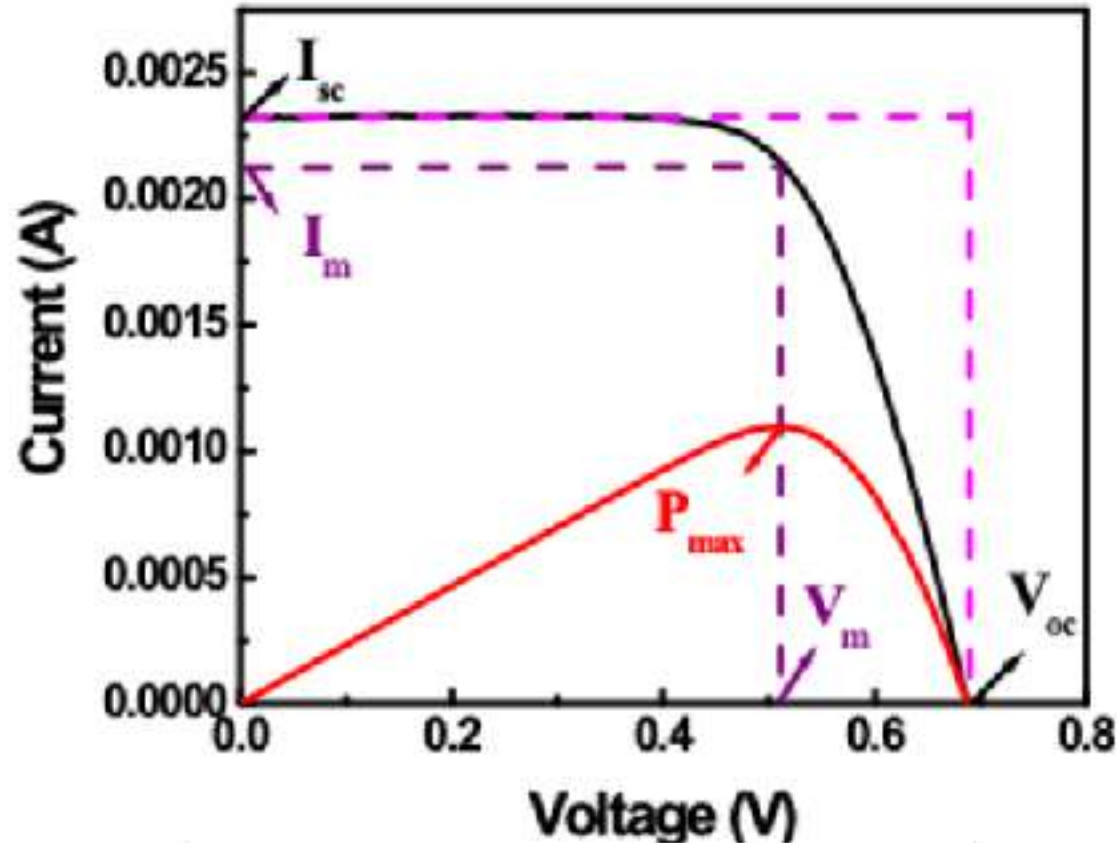
P_{max} : Maximum Power Delivered

V_m : Voltage corresponding to P_{max}

I_m : Current corresponding to P_{max}

FF (Fill Factor):
$$FF = \frac{V_m \times I_m}{V_{oc} \times I_{sc}} \times 100\%$$

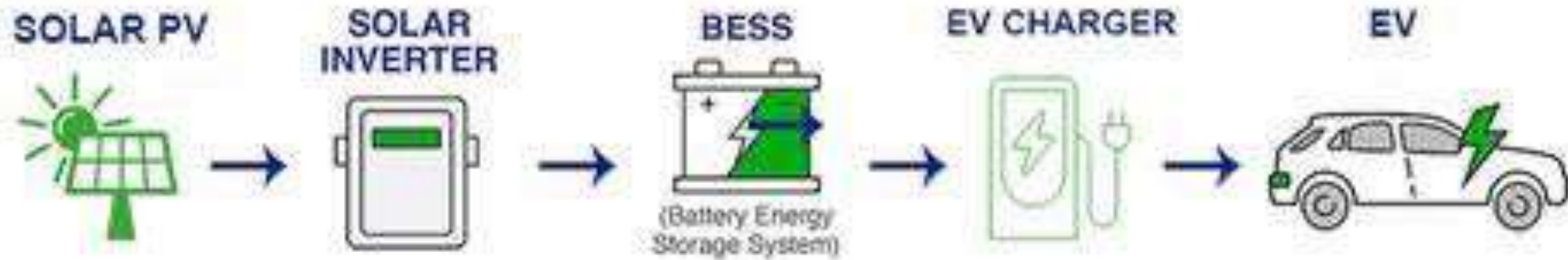
Efficiency =
$$\frac{P_{max}}{P_{in}} = \frac{V_{oc} \times I_{sc}}{P_{in}} \times FF\%$$



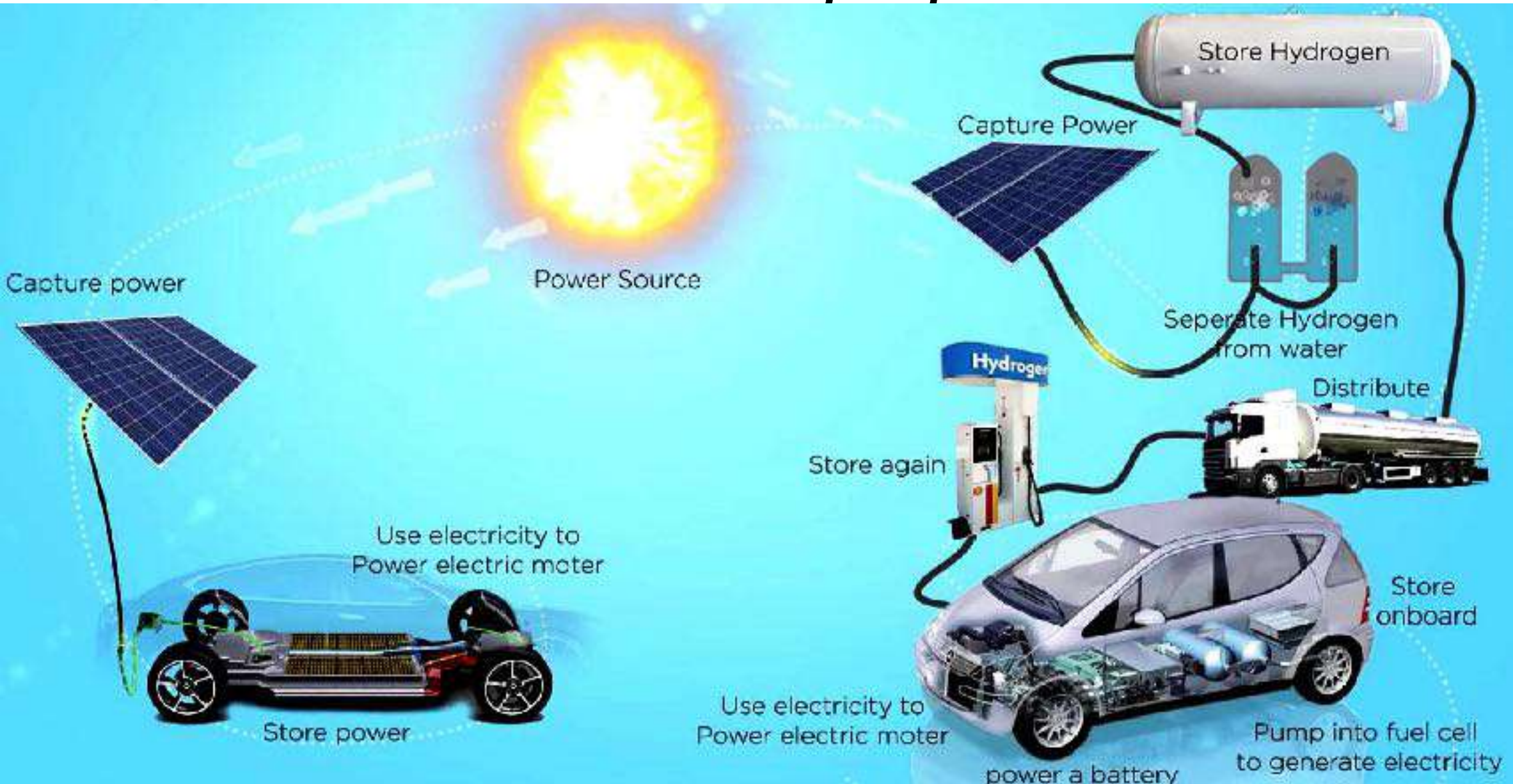
FACTORS AFFECTING VARIOUS PARAMETERS IN SOLAR CELL I-V CURVE

1. V_{oc} : Depends on difference between the fermi energy of p and n type semiconductor or semiconductor band gap. Ideal limit = E_{gap}/q
2. J_{sc} or I_{sc} : Absorption properties of semiconductor i.e. band gap and recombination rate of electron-hole pairs.
3. Series Resistance: Depends on ohmic losses at front contact (n type semiconductor and metal). Ideally = 0
4. Shunt Resistance: Depends on leakage current within solar cell. Ideally = ∞
5. FF (Fill Factor): Depends on values of series and shunt resistance. Ideally = 100. i.e. The IV loop should look as 'rectangular' as possible.
6. Efficiency: Depends on V_{oc} , I_{sc} and Fill Factor.

PV- Electric charging integration



Solar assisted charging



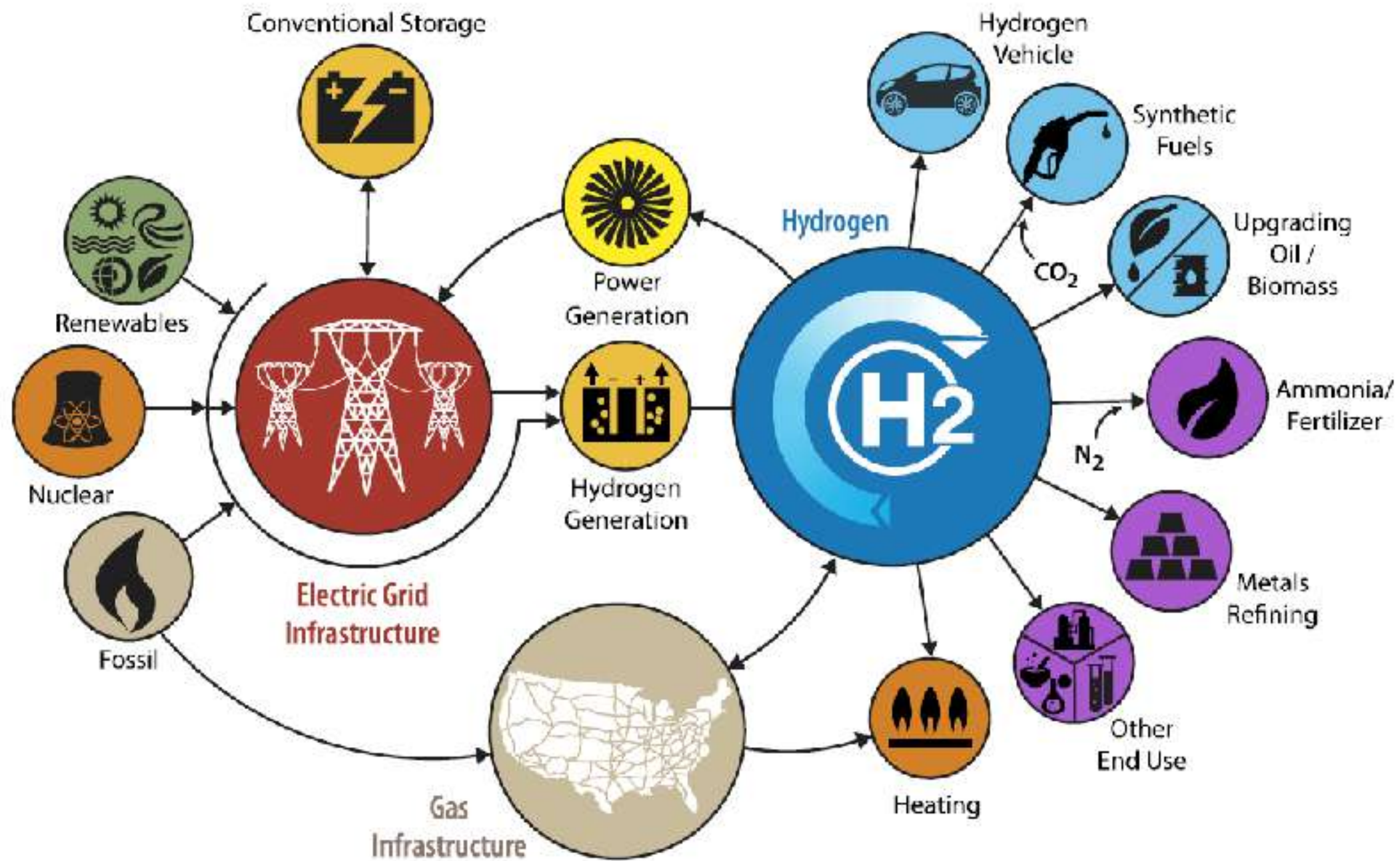


Figure 1. Role of Hydrogen Technologies in Future Energy Systems

Organic solar cell – Green house top

- Solar to electric (photovoltaics)
 - Low cost photovoltaic tech
 - Semitransparent organic
- Solar cells – green house top
- Appropriate design to
- Implement in building, agriculture
- And locomotives

