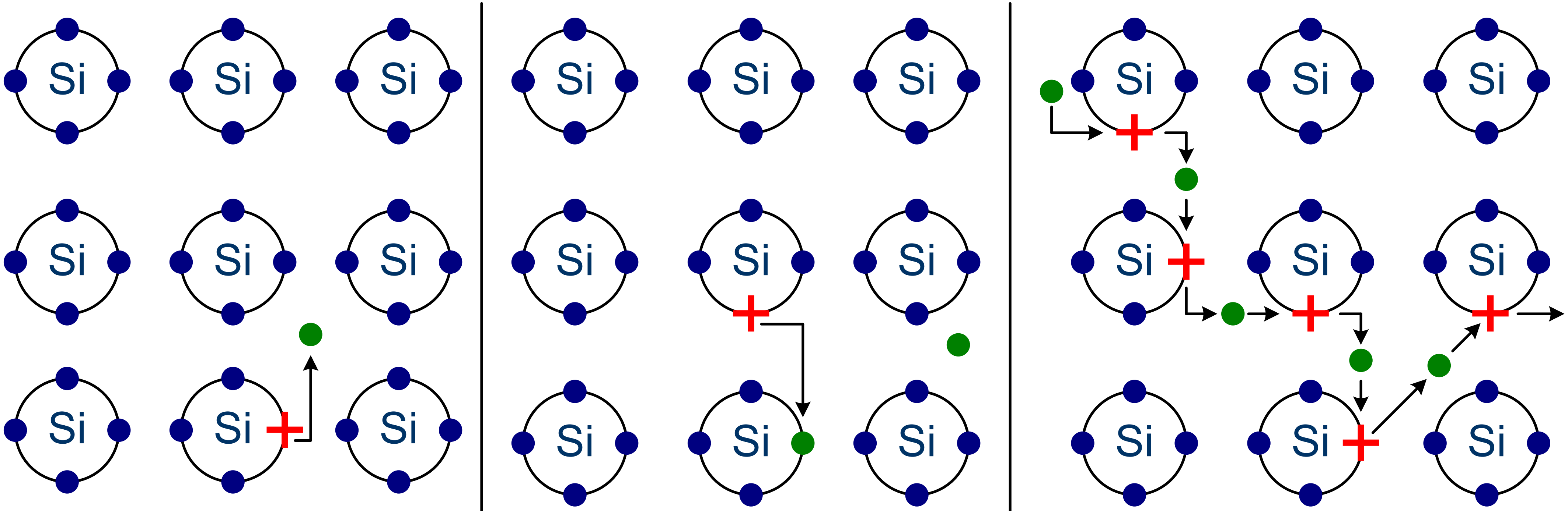
Sec 3 : Contents

- **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

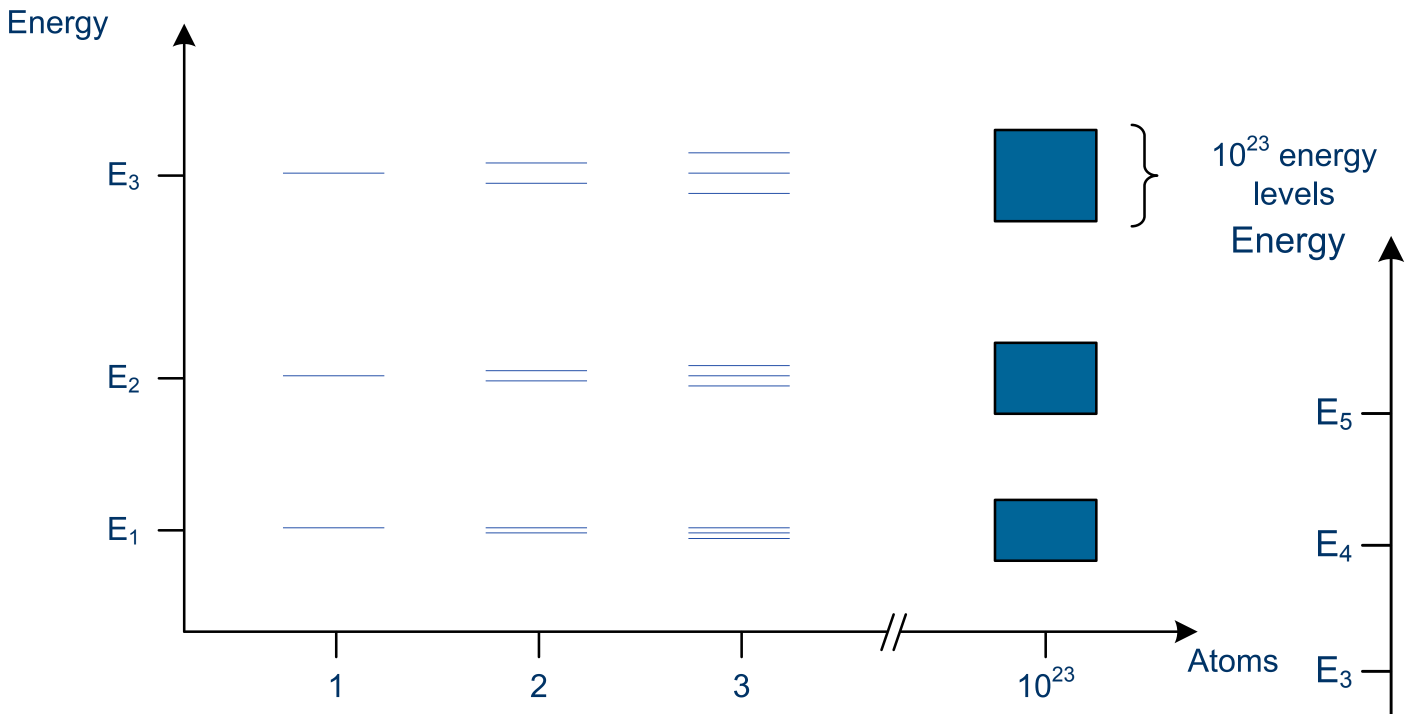


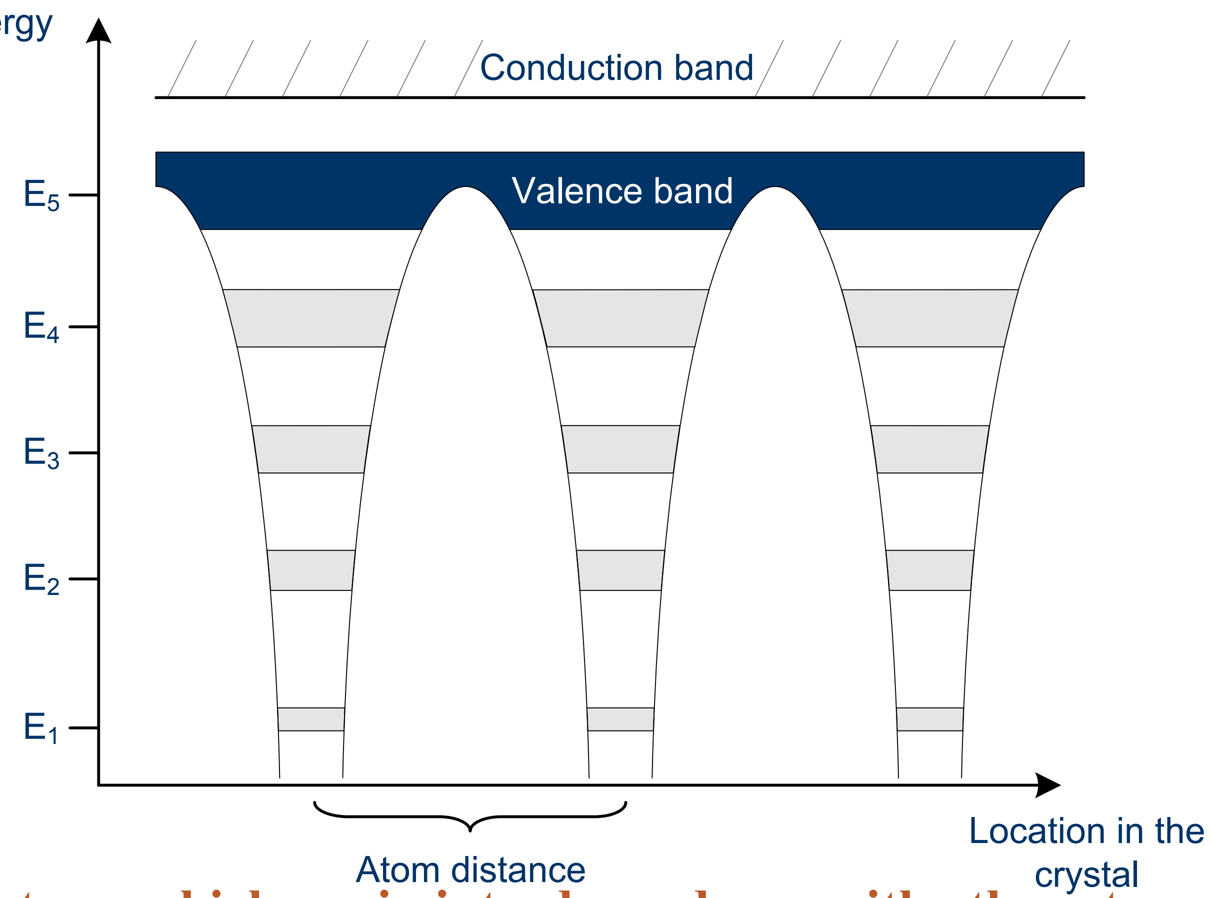
An electron detaches from an atom, a positive charged hole + is generated.

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.

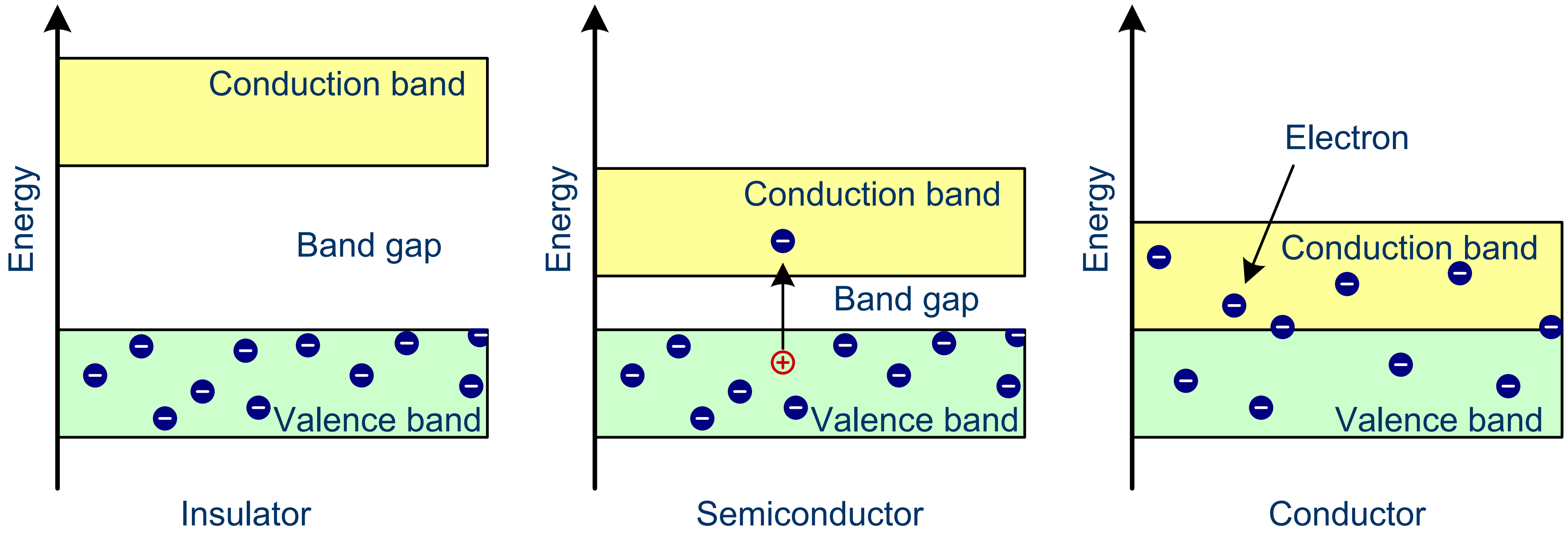
Energy levels of atoms which are in interdependency with other atoms





Energy bands of atoms which are in interdependency with other atoms

The band model



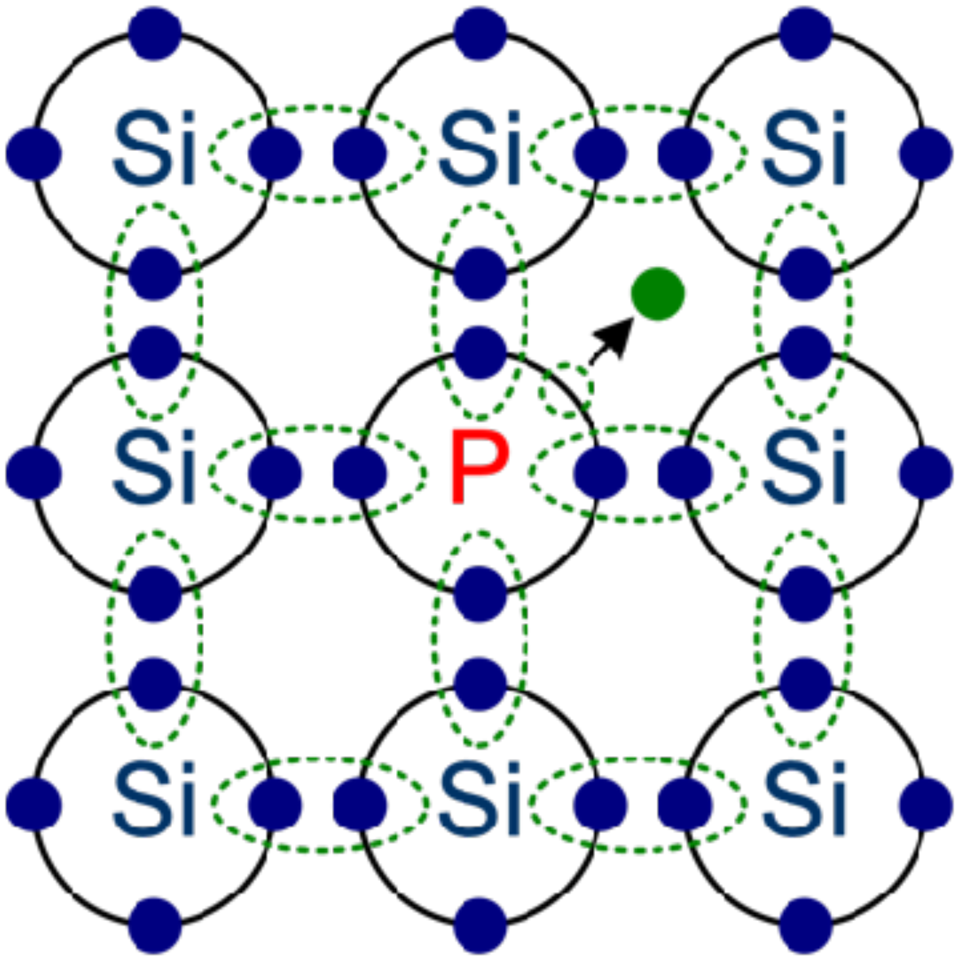
The valence band is fully occupied with electrons due to the covalent bonds. The electrons can not move because they are "locked up" between the atoms. To achieve a conductivity, electrons from the valence band have to move into the conduction band. This prevents the band gap, which lies in between the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

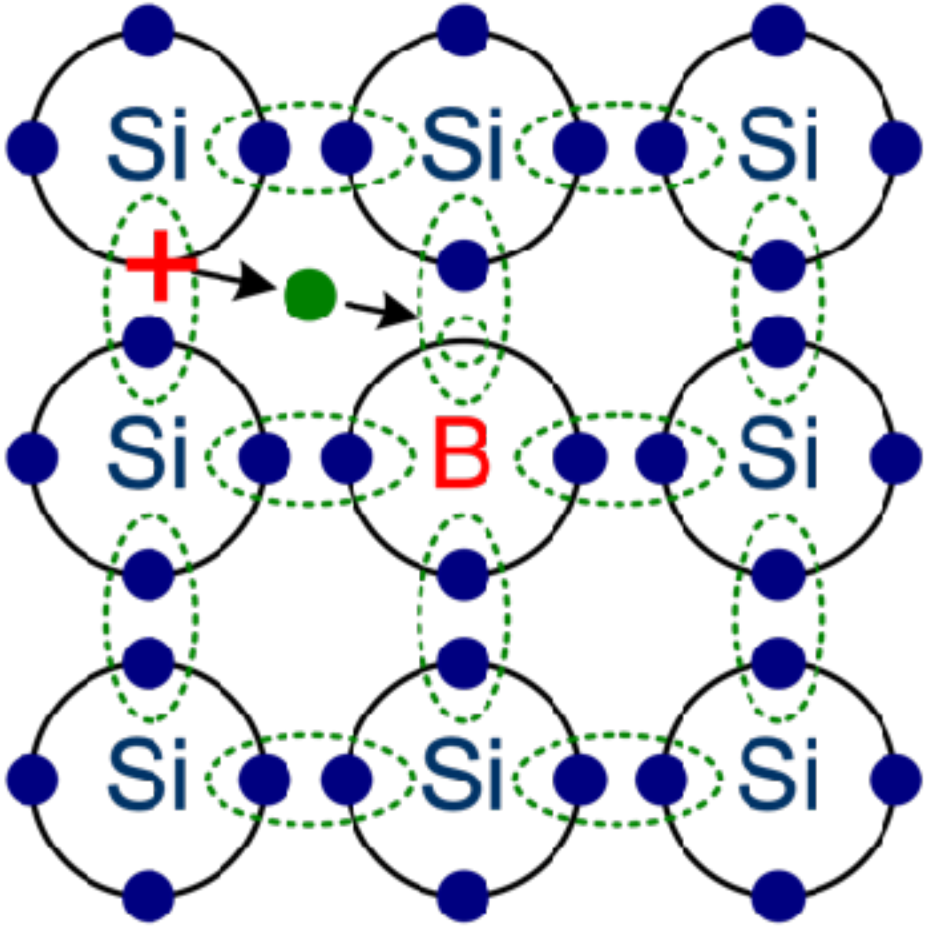
The valence band is either not fully occupied with electrons, or the filled valence band overlaps with the empty conduction band. In general, both states occur at the same time, the electrons can therefore move inside the partially filled valence band or inside the two overlapping bands. In conductors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

Doping: n- and p-semiconductors

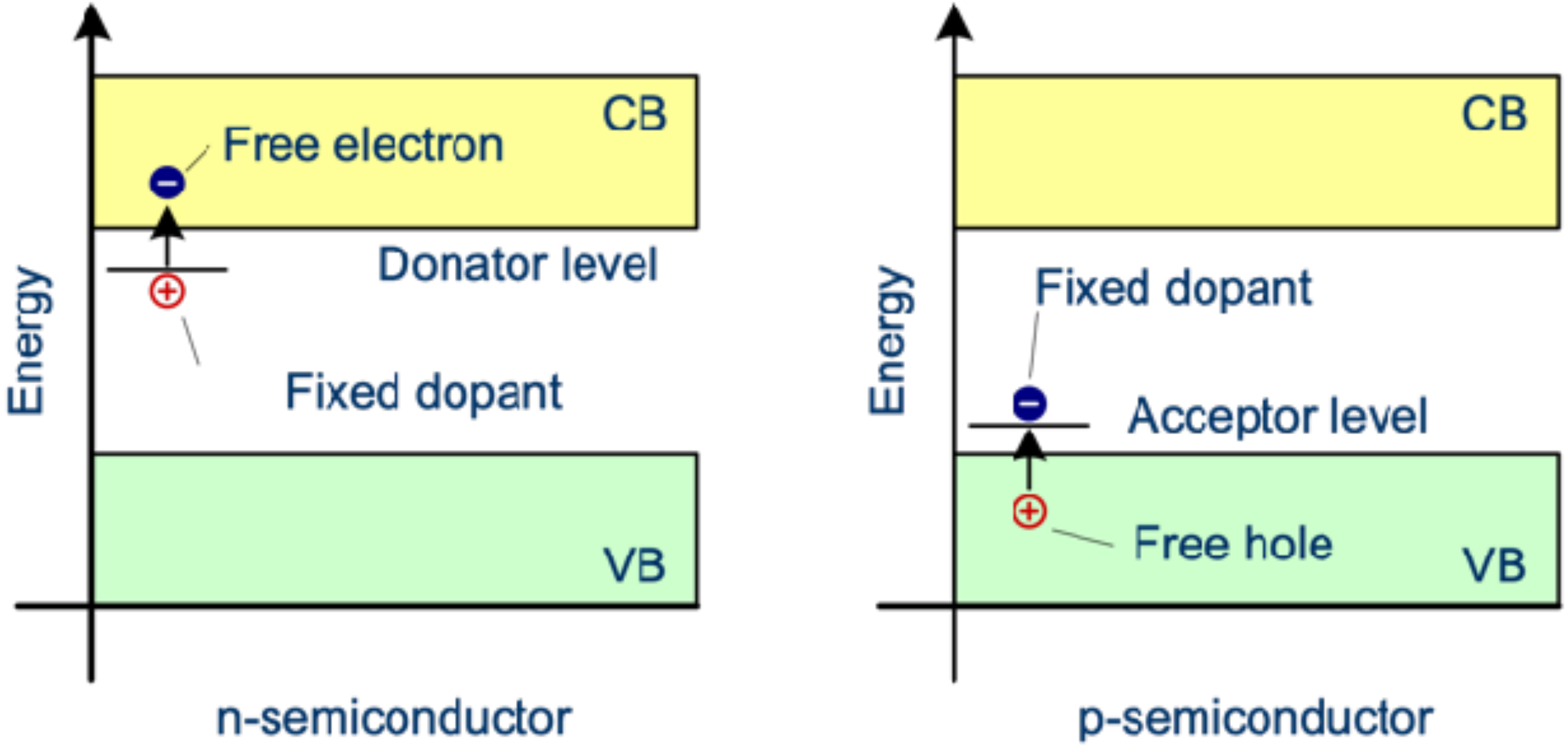
n-doping with phosphorus



p-doping with boron

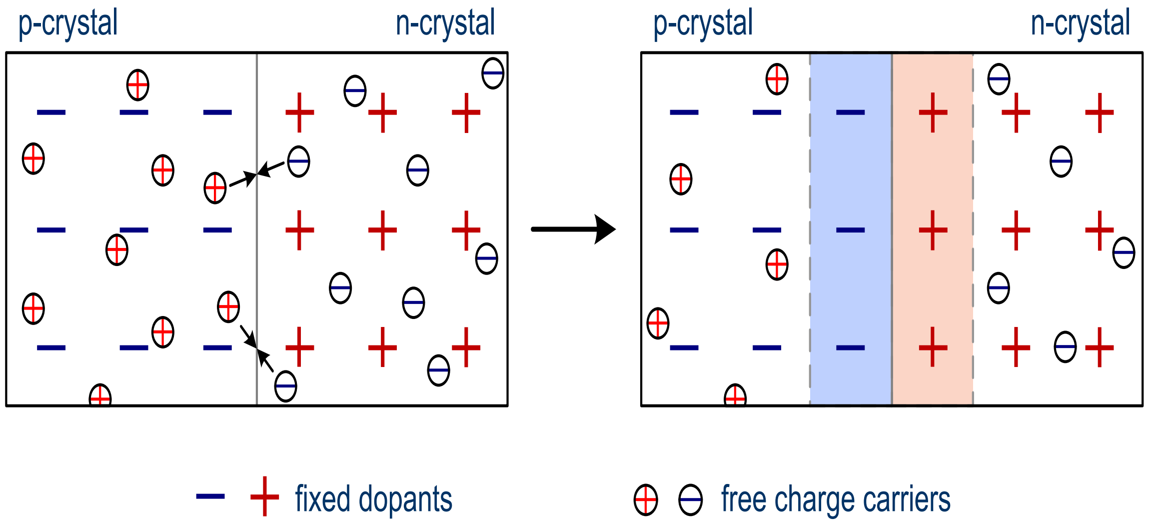


Band model of p- and n-type doped semiconductors

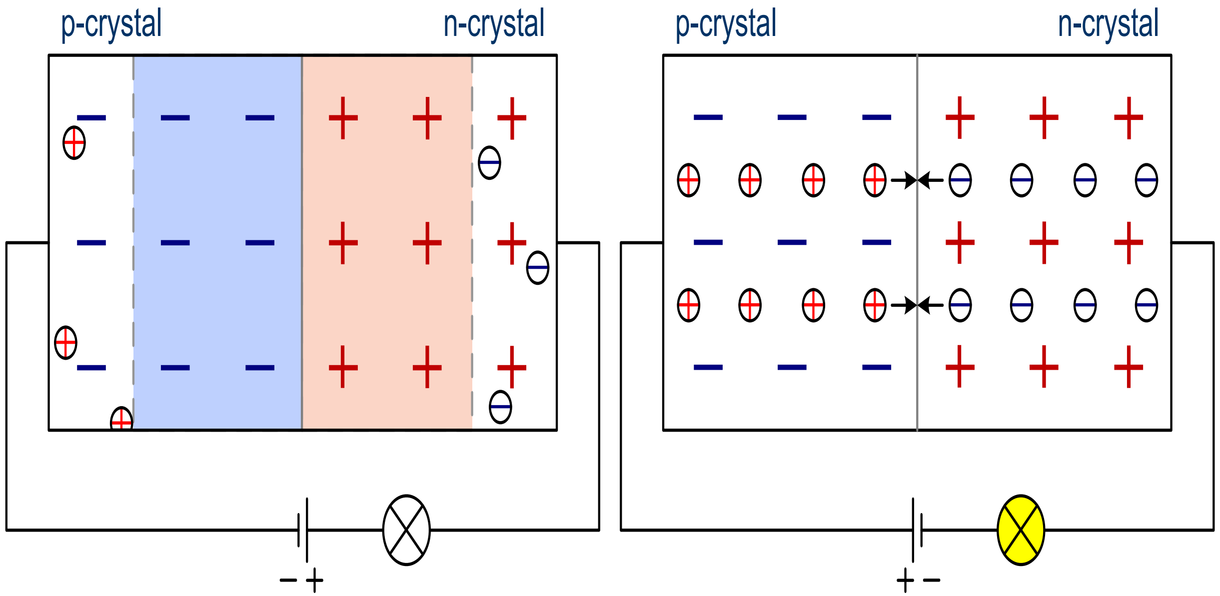


p-n junction

p-n junction without an external applied voltage



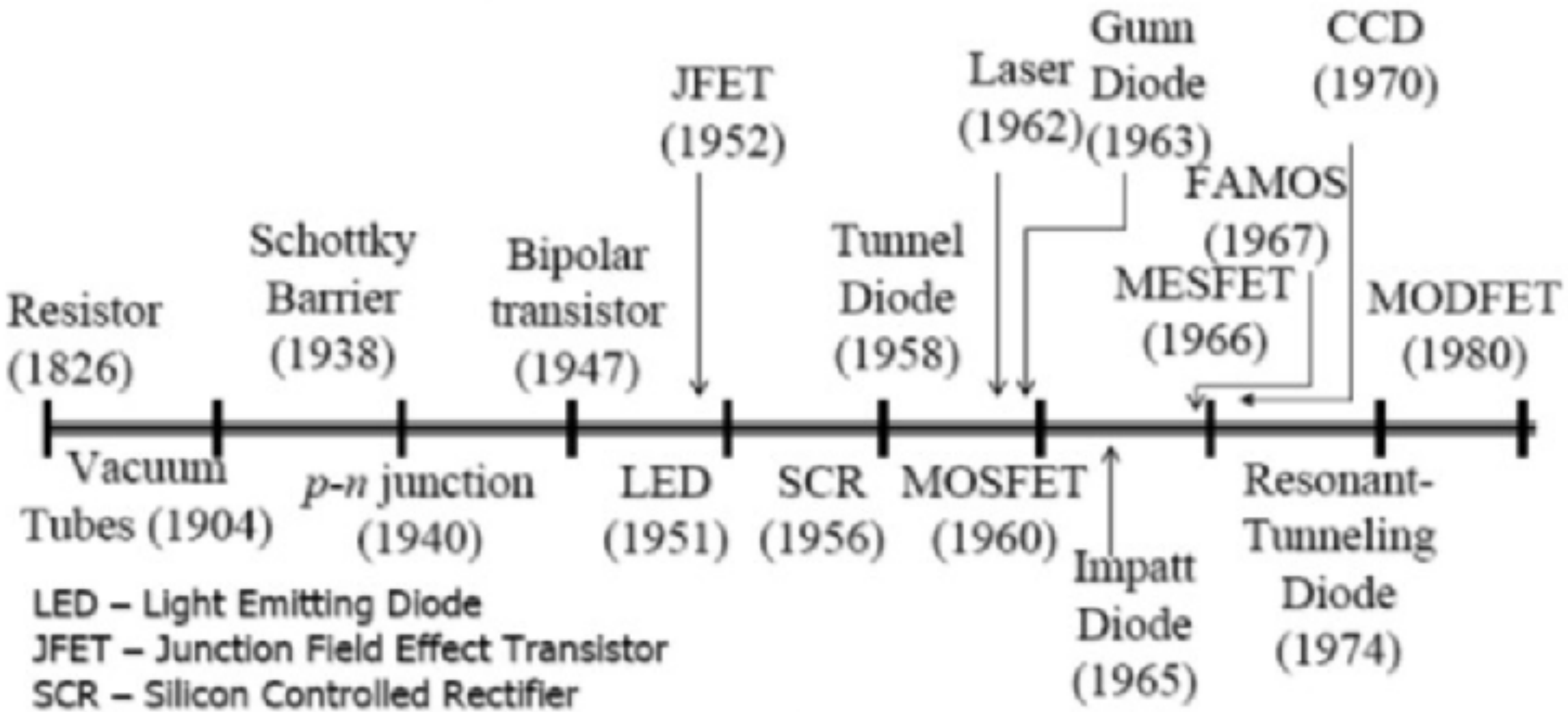
p-n junction with an external applied voltage



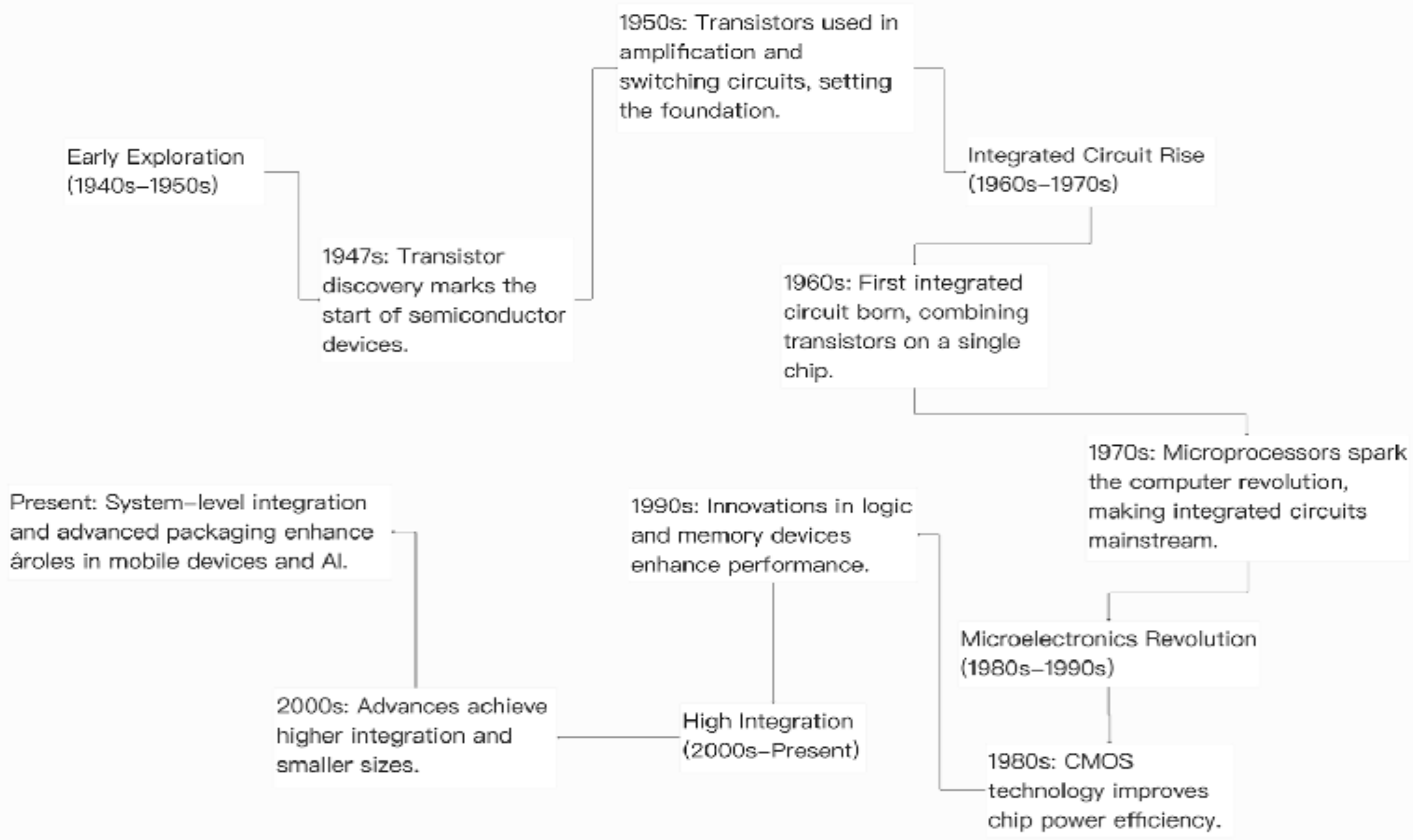
(a) reverse direction

(b) forward direction

History of Semiconductor devices



LED – Light Emitting Diode
JFET – Junction Field Effect Transistor
SCR – Silicon Controlled Rectifier
MOSFET – Metal-Oxide Semiconductor Field Effect Transistor
MESFET – Metal-Semiconductor Field Effect Transistor
FAMOS – Floating Gate Avalanche MOS
CCD – Charge-Couple Devices
MODFET – Modulation Doping Field-Effect Transistor


Early Exploration (1940s–1950s)
1947s: Transistor discovery marks the start of semiconductor devices.
1950s: Transistors used in amplification and switching circuits, setting the foundation.
Integrated Circuit Rise (1960s–1970s)
1960s: First integrated circuit born, combining transistors on a single chip.
1970s: Microprocessors spark the computer revolution, making integrated circuits mainstream.
Microelectronics Revolution (1980s–1990s)
1980s: CMOS technology improves chip power efficiency.
1990s: Innovations in logic and memory devices enhance performance.
High Integration (2000s–Present)
2000s: Advances achieve higher integration and smaller sizes.
Present: System-level integration and advanced packaging enhance åroles in mobile devices and AI.

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 10-19 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

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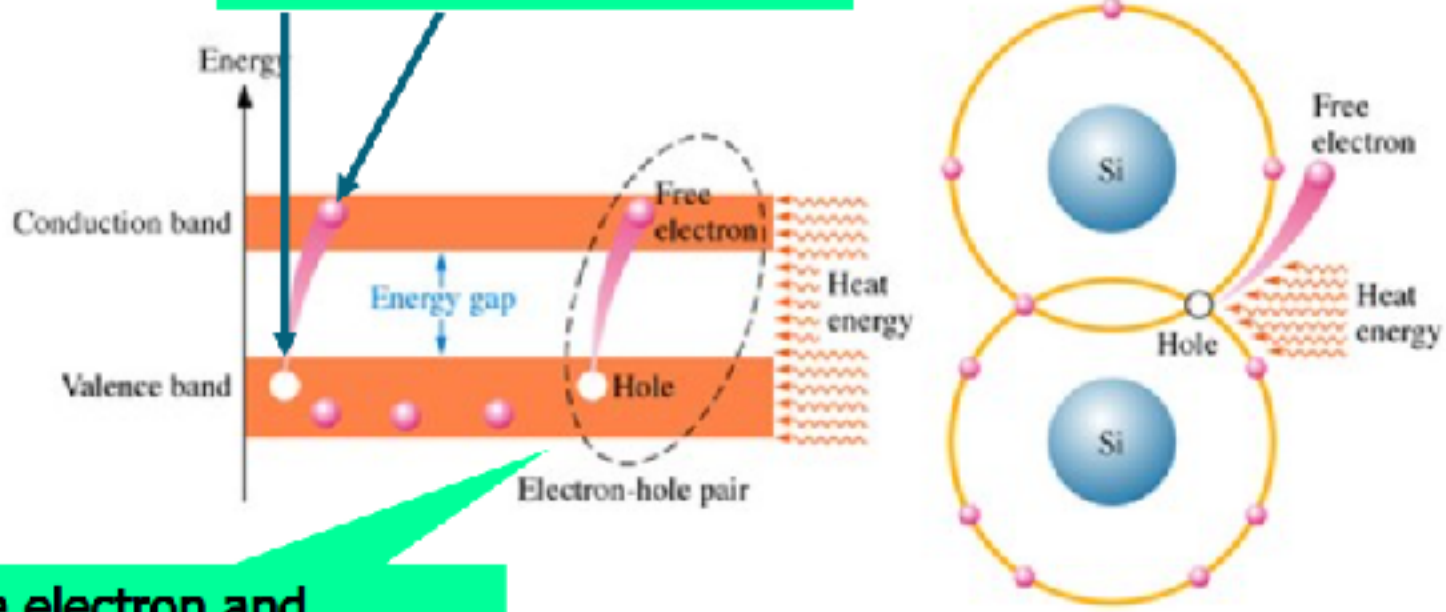
Semiconductor processes

Absorbs enough energy
(thermal energy)
to jumps



a free electron and
its matching valence
band hole –
<u>electron-hole pair</u>

<u>Recombination</u> -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 banc 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 t move an electron (charge) across a 1 V potential, eV=1.6 10-19 J
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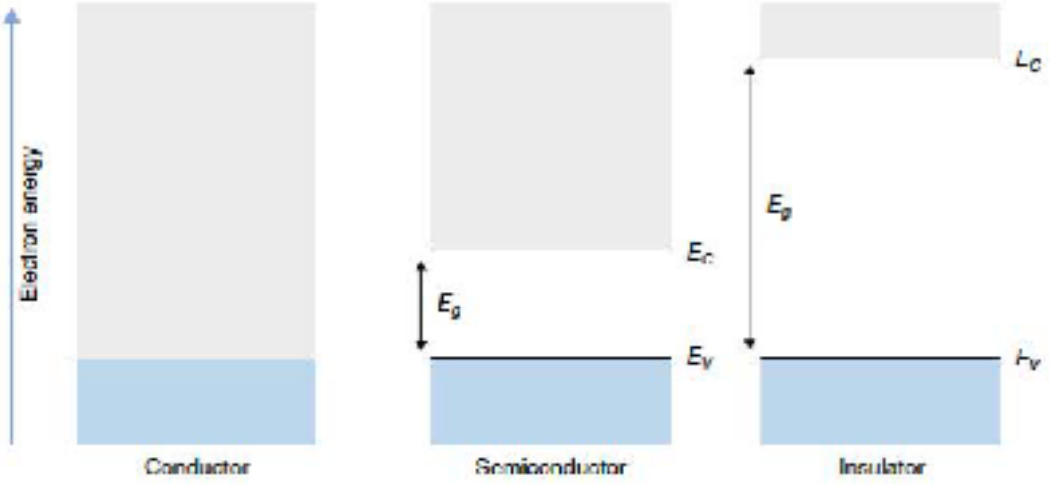


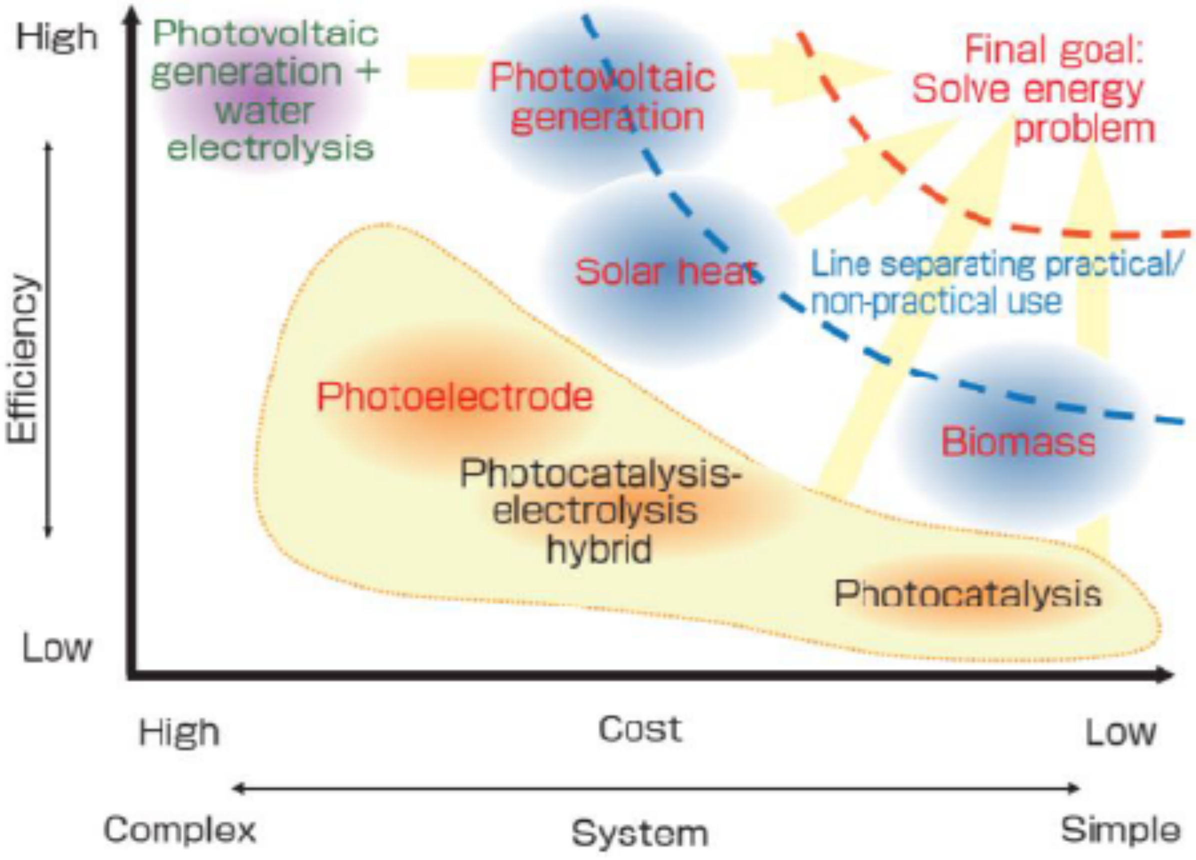
Figure 2.1.3 Energy band diagrams for a conductor, a semiconductor and an insulator

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

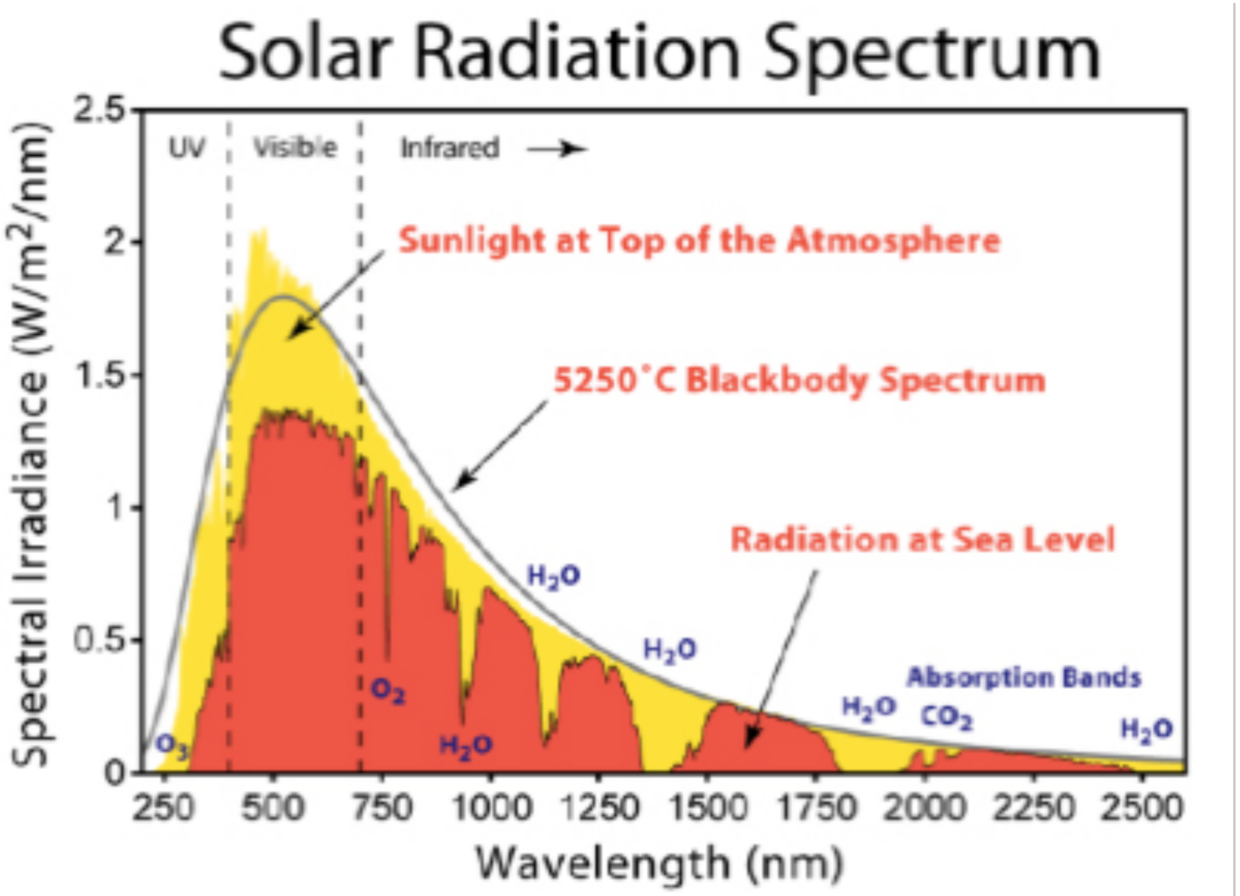
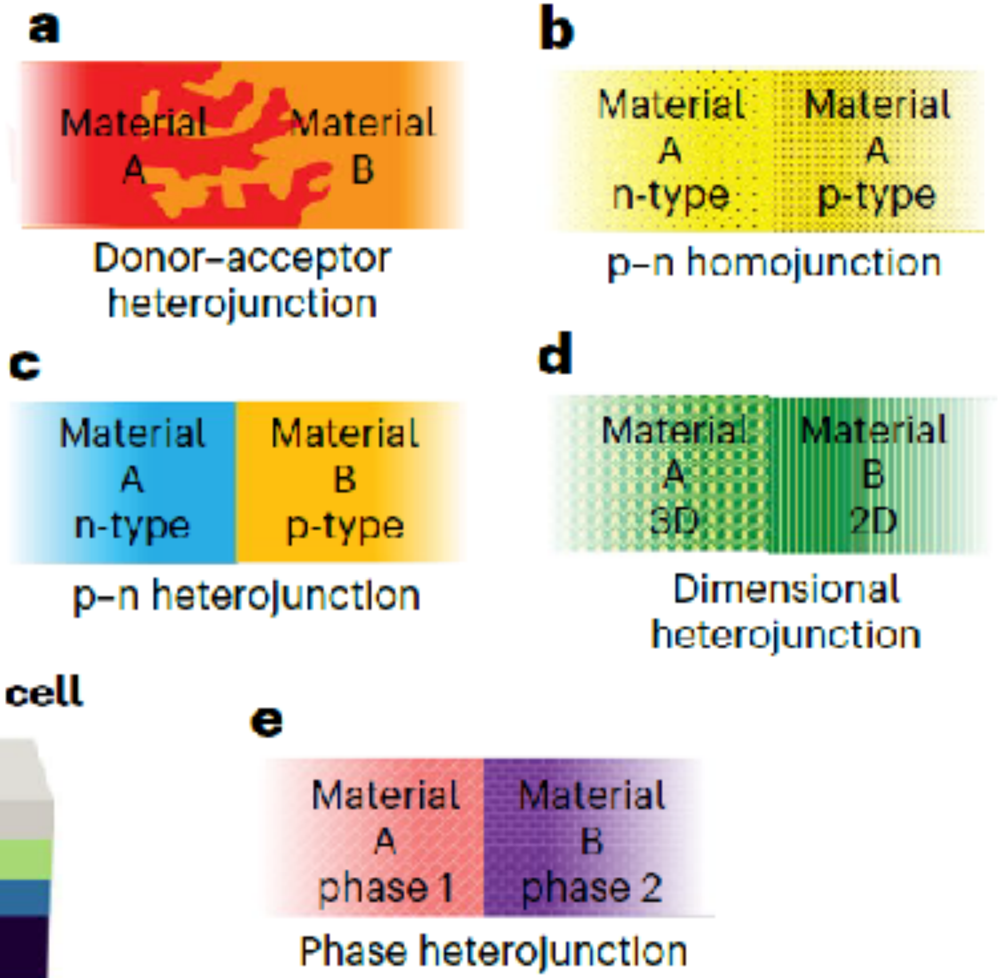
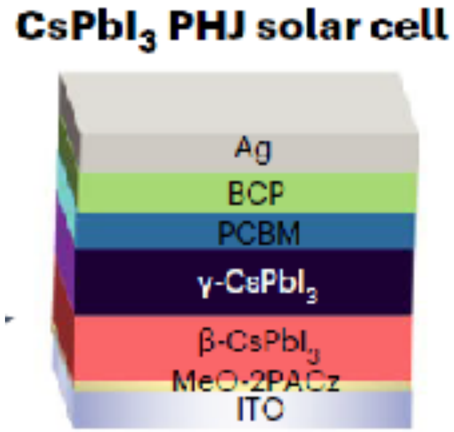


Figure 3: The solar spectrum above the atmosphere and at sea level

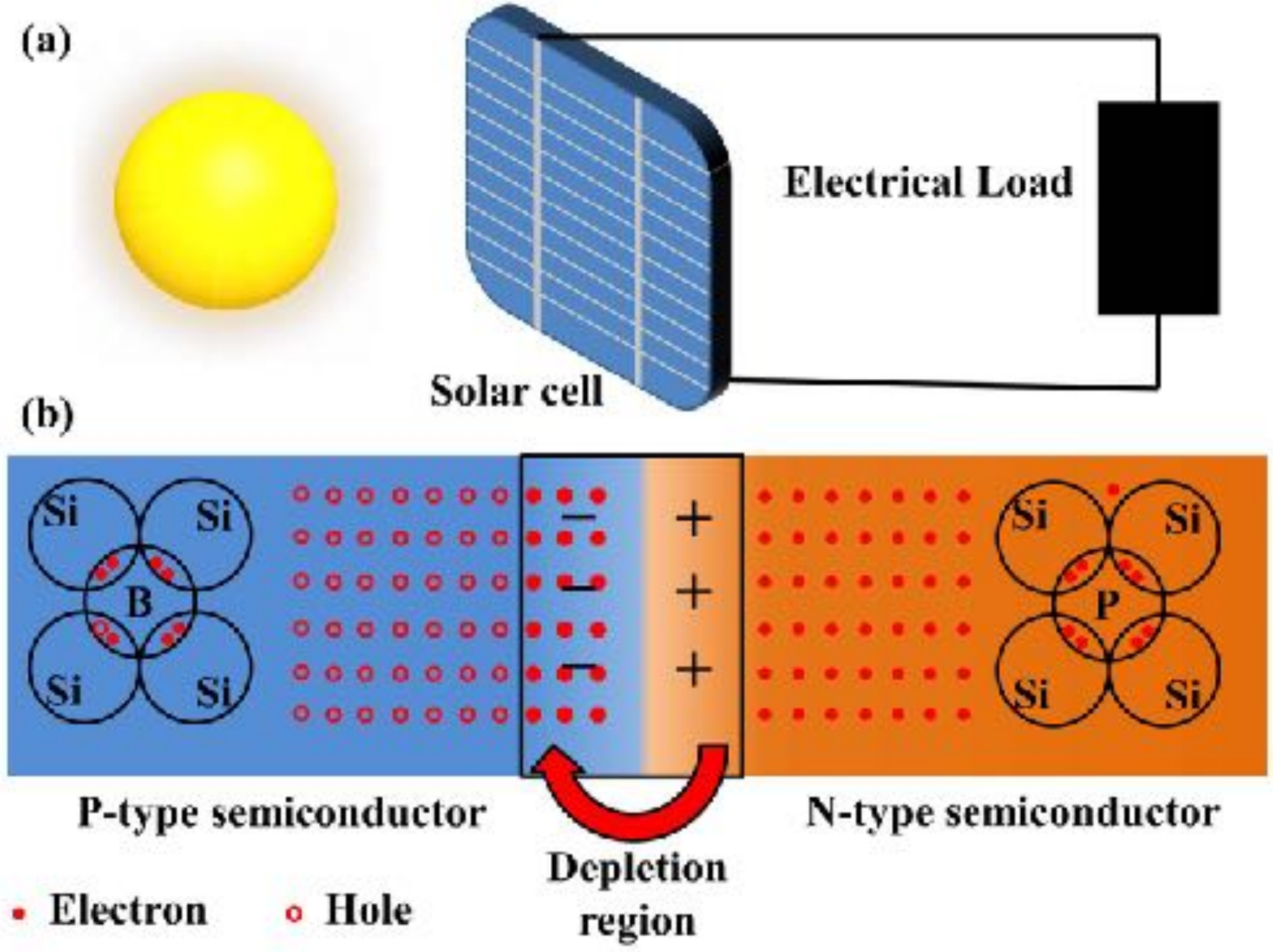
Advances in Photovoltaic systems

- 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



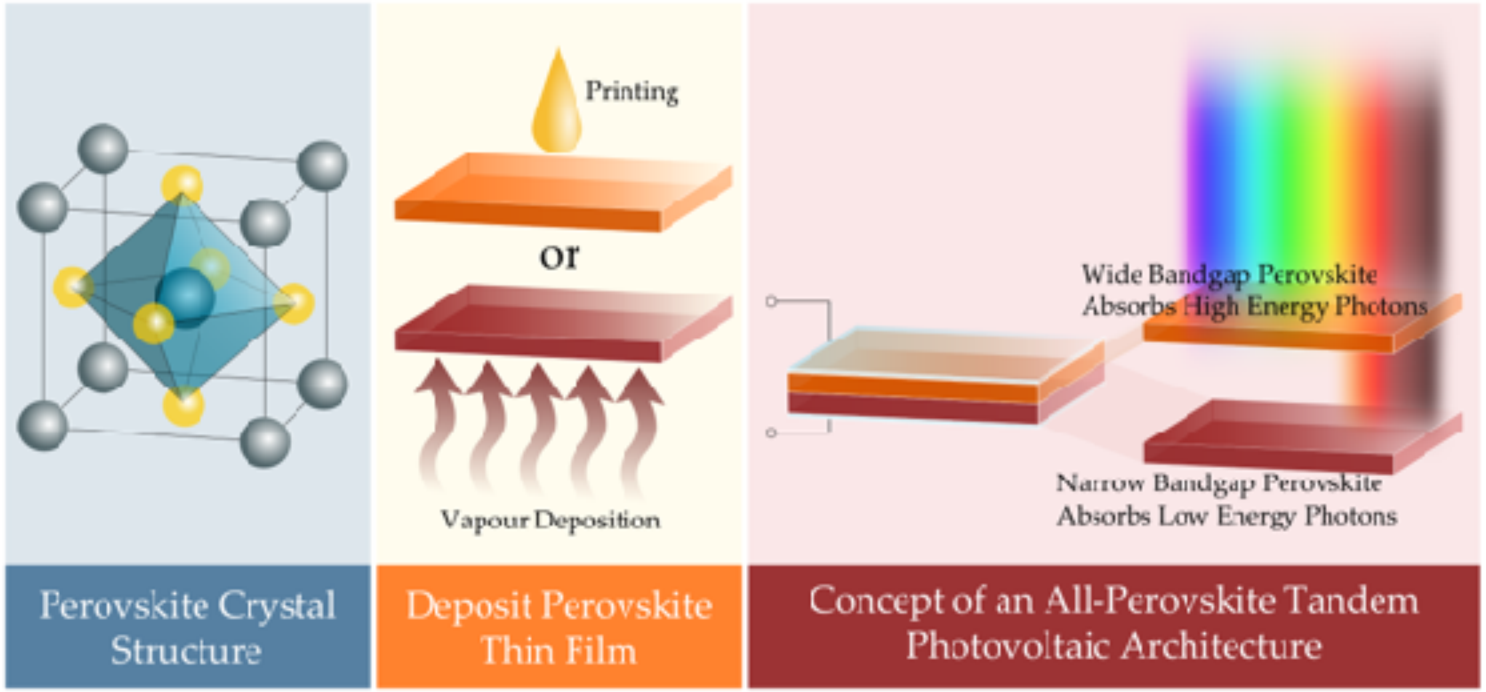


PV structure and operation



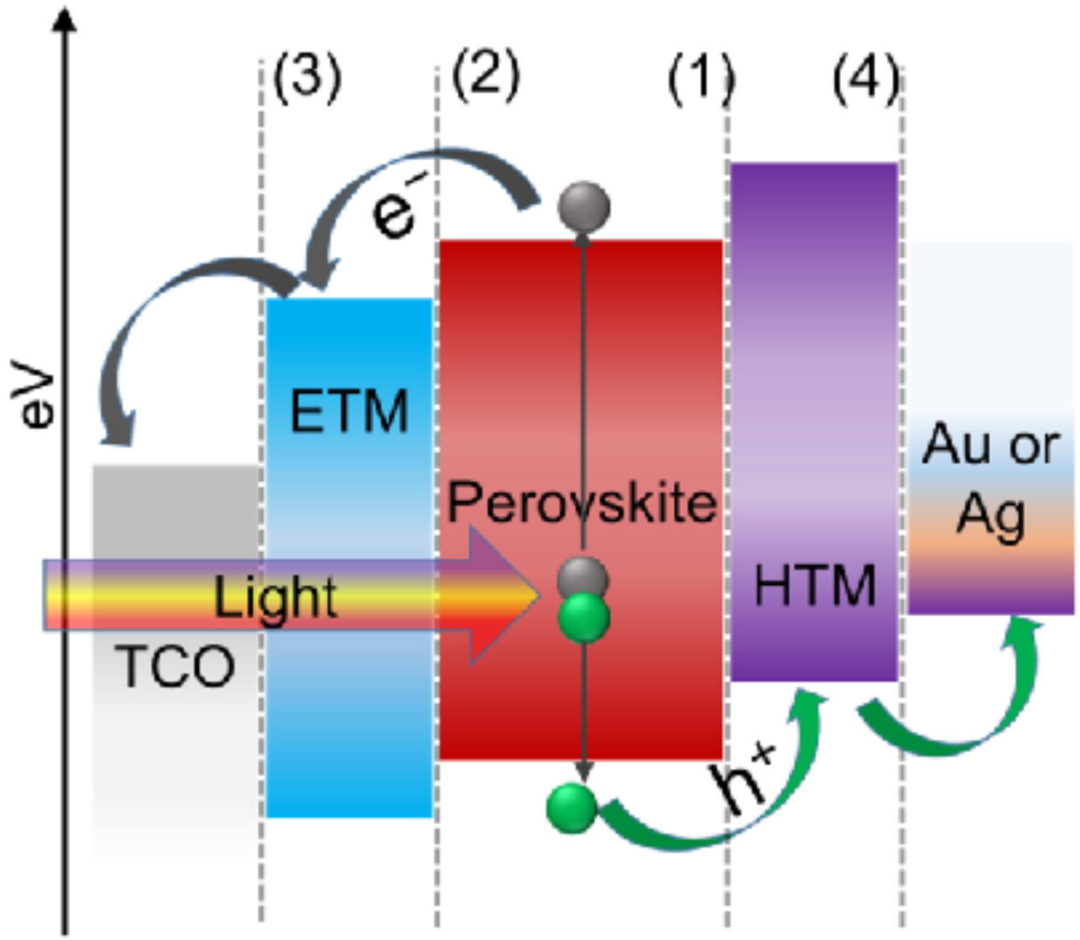
- Solar to electric (photovoltaics)
- P-type and n-type materials
- Potential barrier formation
- PB enhance charge separation
- Reduce recombination losses
- Efficiency improvements with other non silicon heterojunctions
- Broad visible light absorption

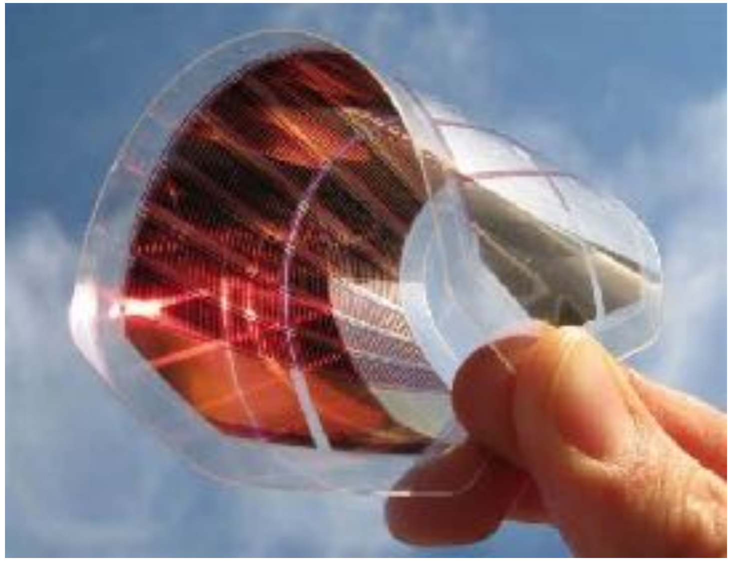
Novel perovskite solar cell



- 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

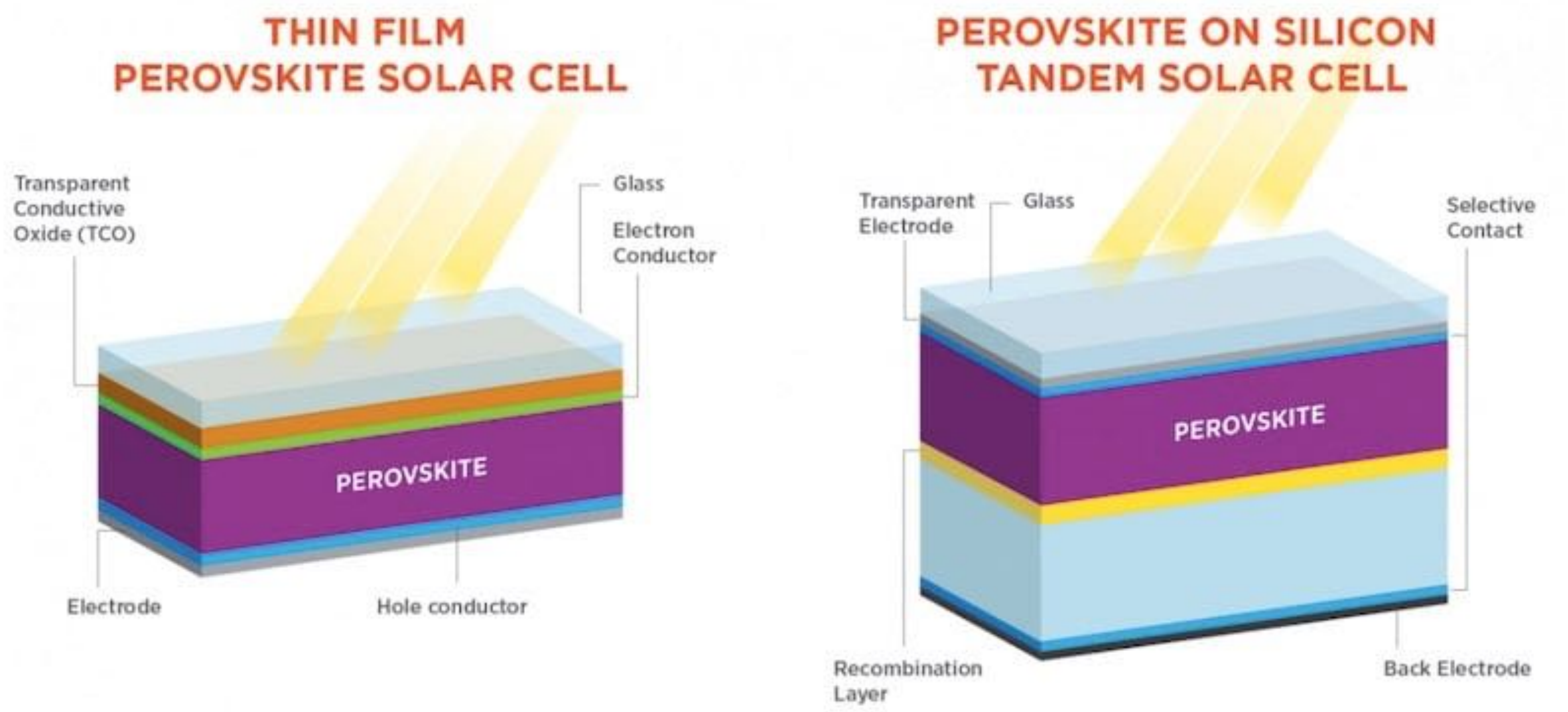
Perovskite the future Tandem solar cell



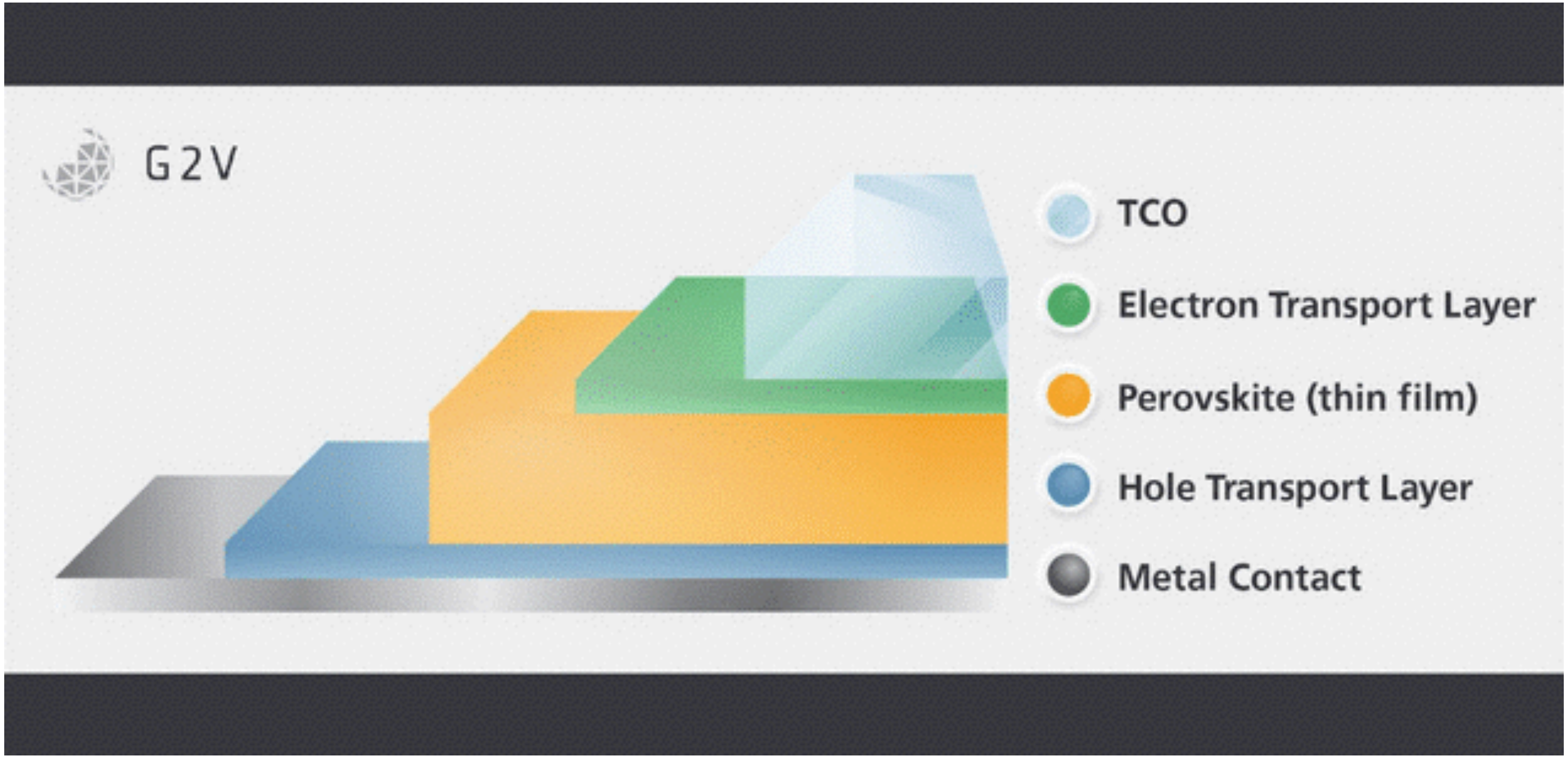


- Use flexible polymer as substrate
- Good charge separation with HTM and ETM
- Higher efficiency, band gap modulation
- Low cost material
- ETM- Electron transport materials
- HTM – Hole transport materials

PV comparison

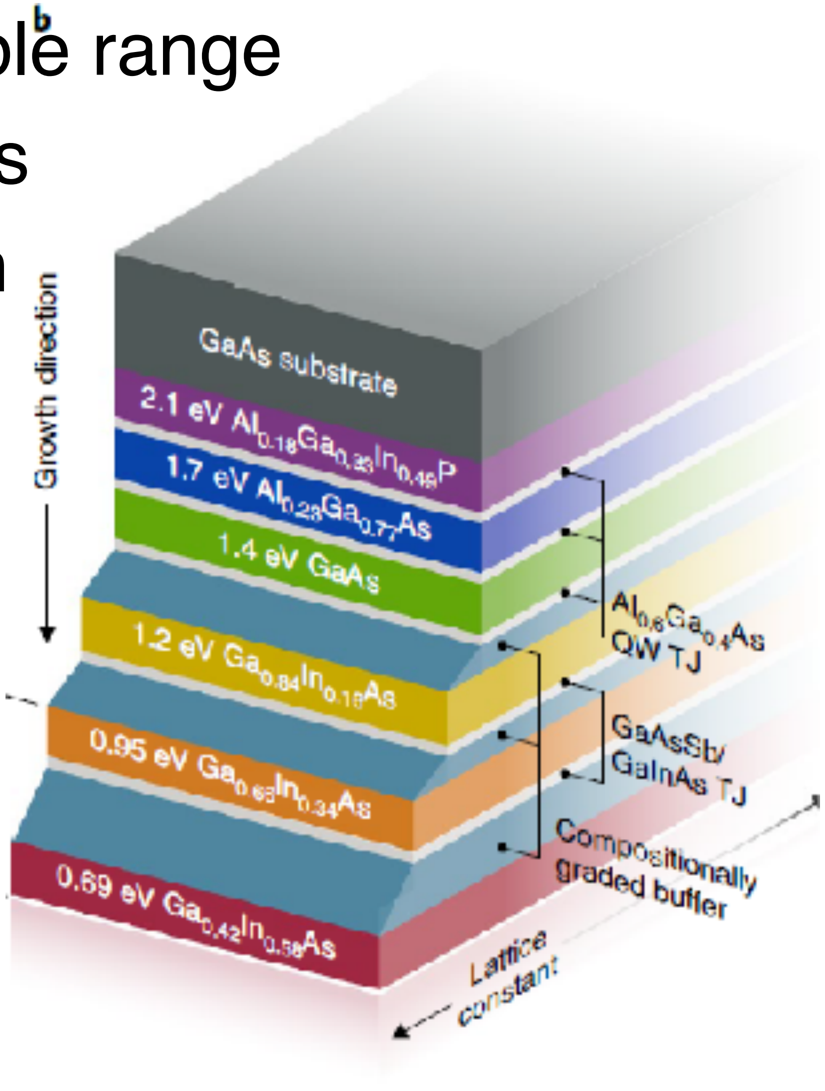


PV Fabrication and characterisation

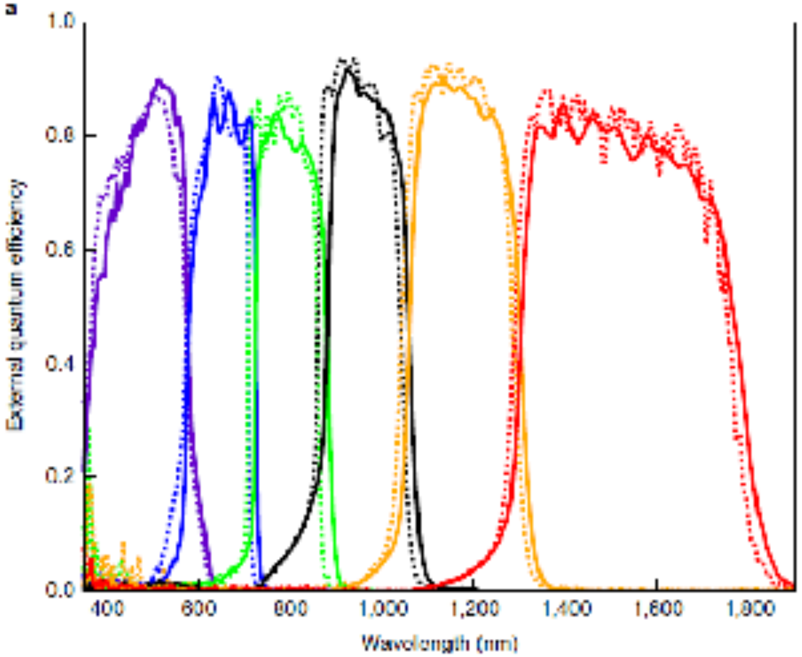


Heterojuction solar cell – 47 % lab efficiency -

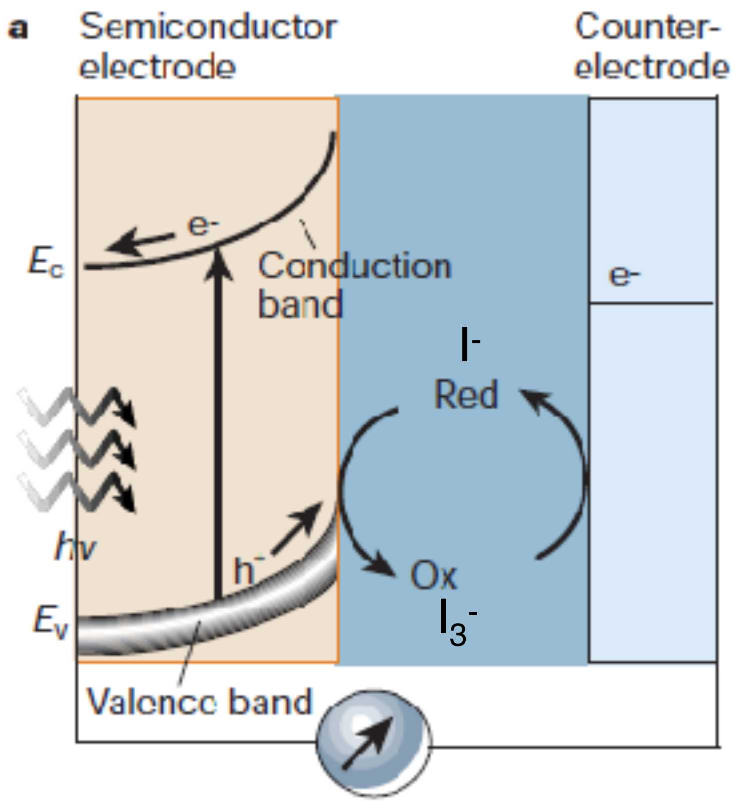
- Wide absorption in visible range
- Multi band gap junctions
- Easy charge separation
- Crystalline thin film
-



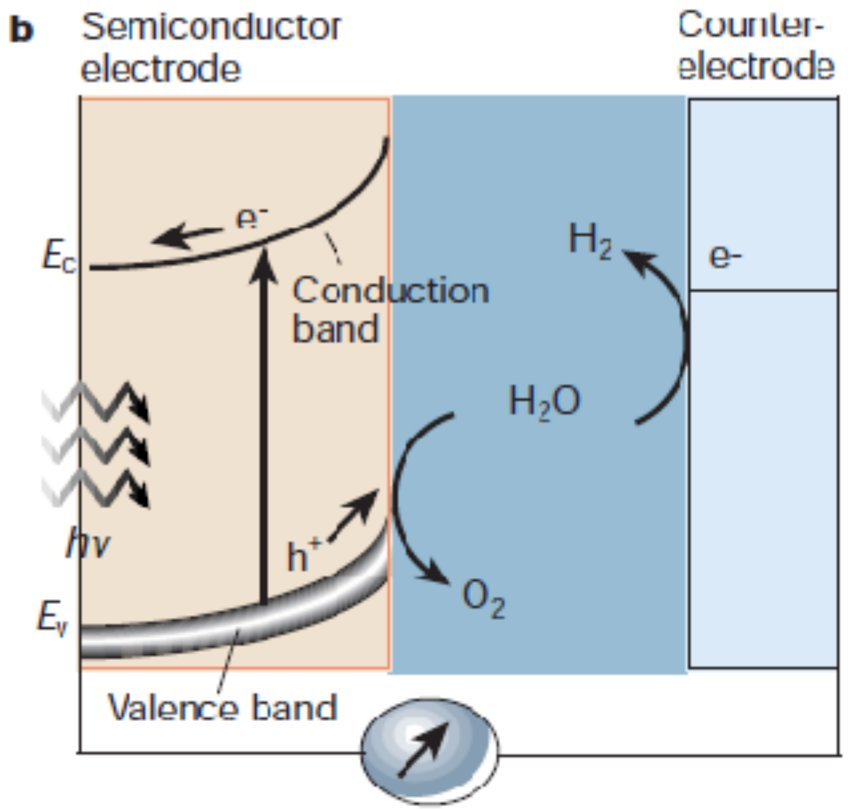
6J IMM structure



Photoelectrochemical cells



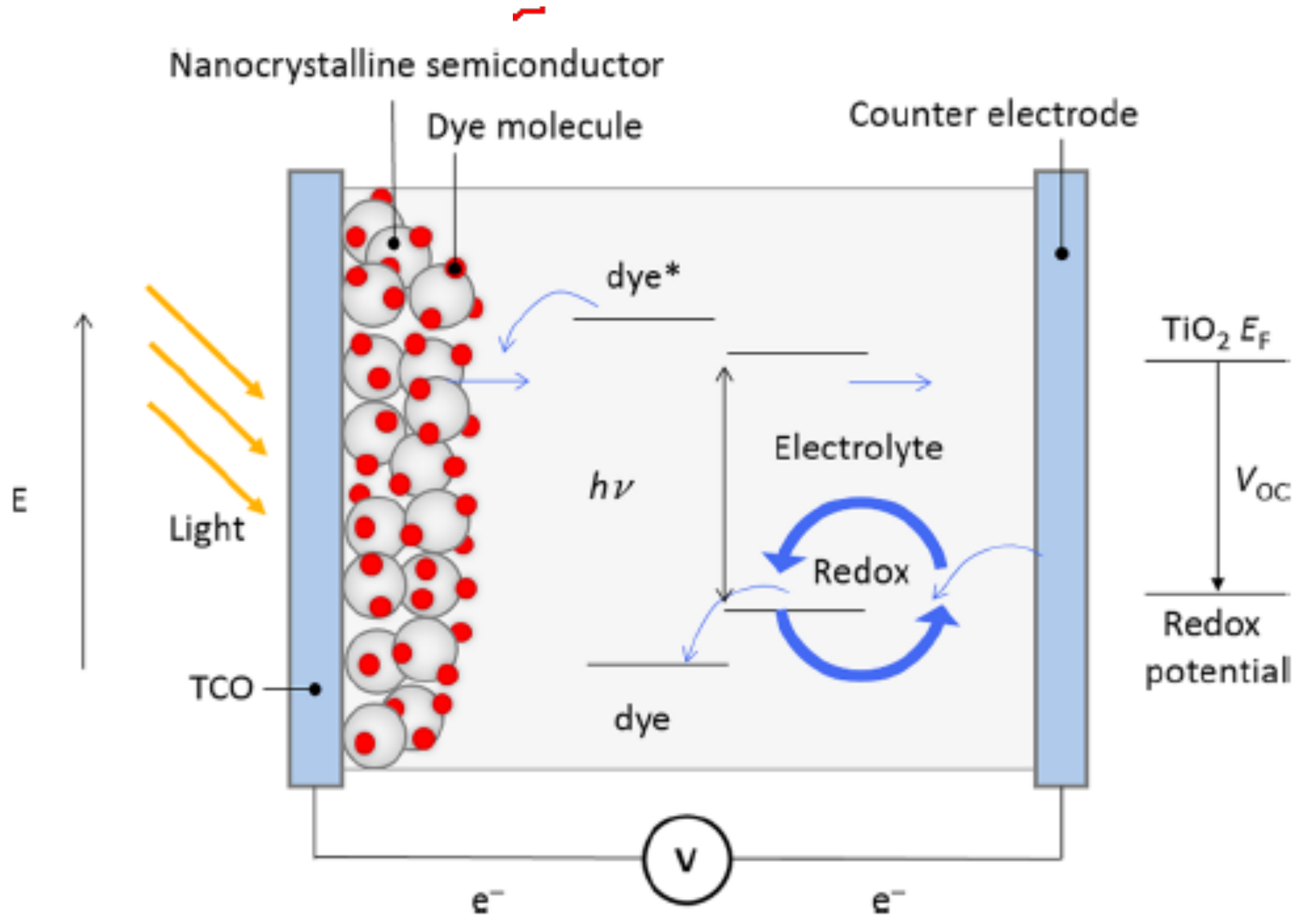
a. Photoelectrochemical regenerative solar cell



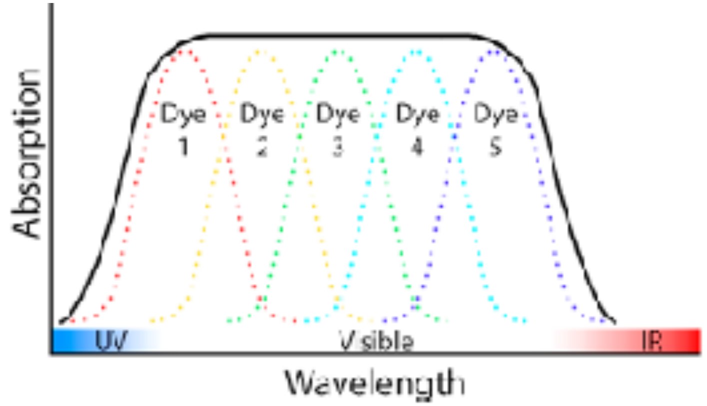
b. Photoelectrochemical solar to fuel cell

M. Graetzel et al, Nature

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 produce the photoelectrode from / corrosion

PA

$I^- \underset{-}{\overset{+}{\rightleftharpoons}} I_3^-$ $(I_2 + I^-)$ I^-/I_3^-

$S^{2-} \underset{-}{\overset{+}{\rightleftharpoons}} S_2^{2-}$ A

PC

$Ce^{3+} \underset{-}{\overset{+}{\rightleftharpoons}} Ce^{4+}$

Fe_2O_3 / Dye / elect

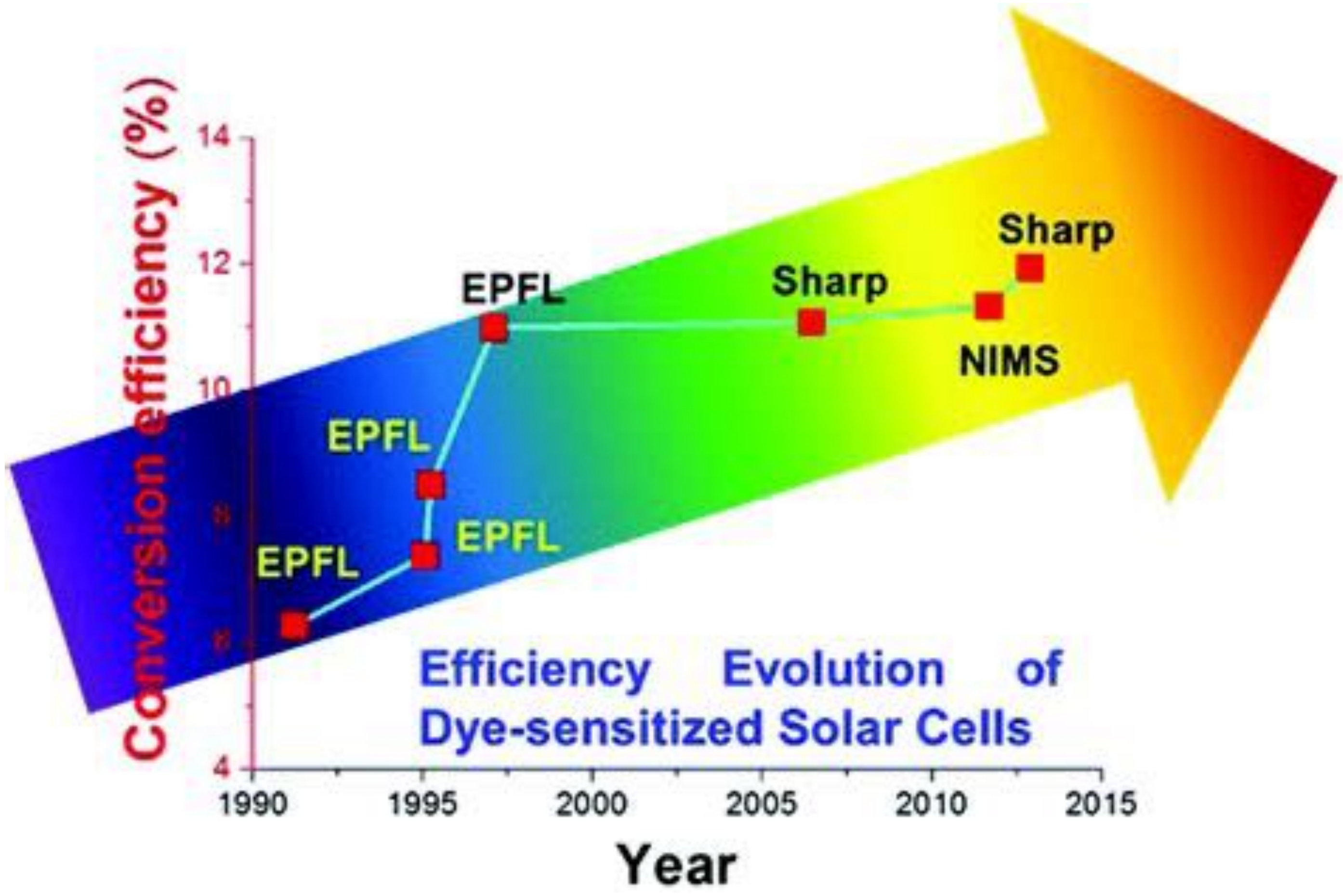
TiO_2 H^+

$Fe_2O_3 + H^+ \rightarrow Fe^{2+/3+}$

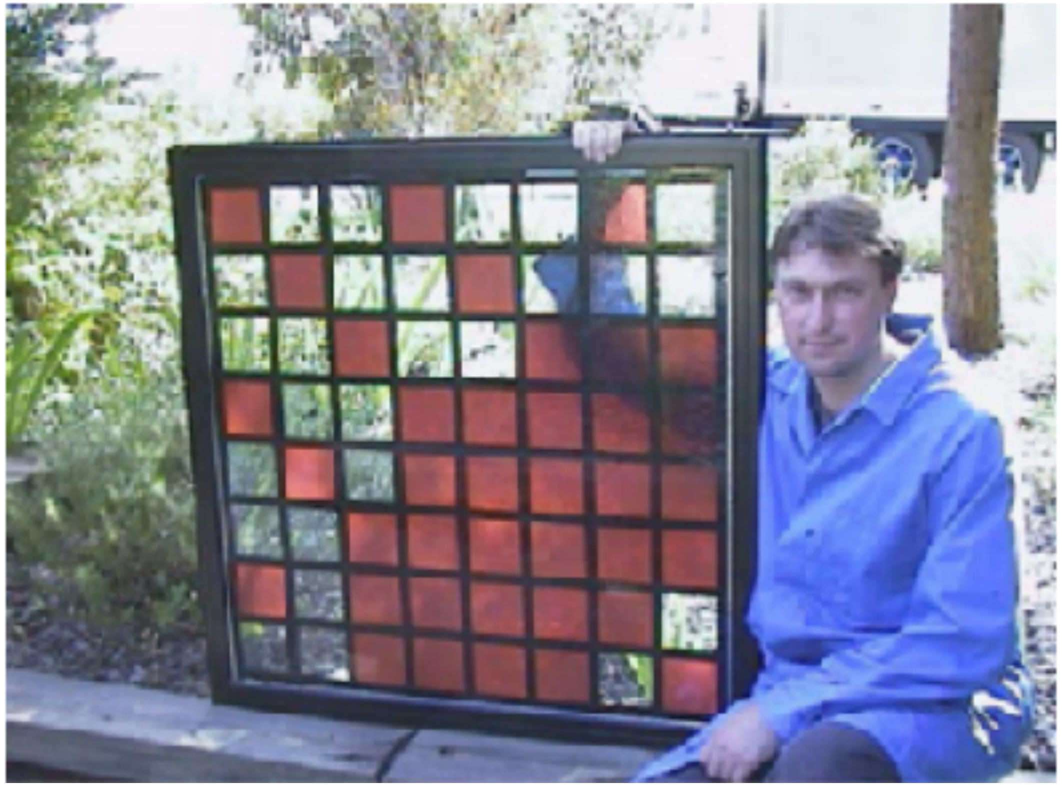
Liquid - Junction - Solar - Cell

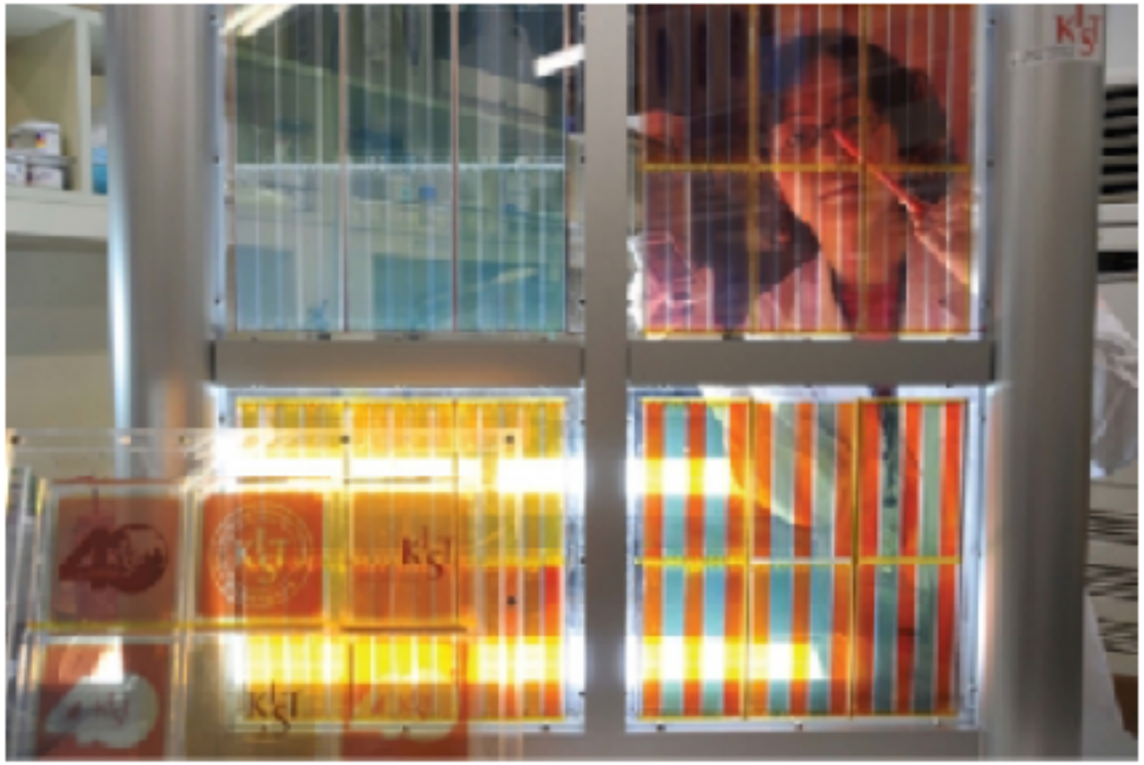
⇒ DSSC

Dye sensitized solar cells

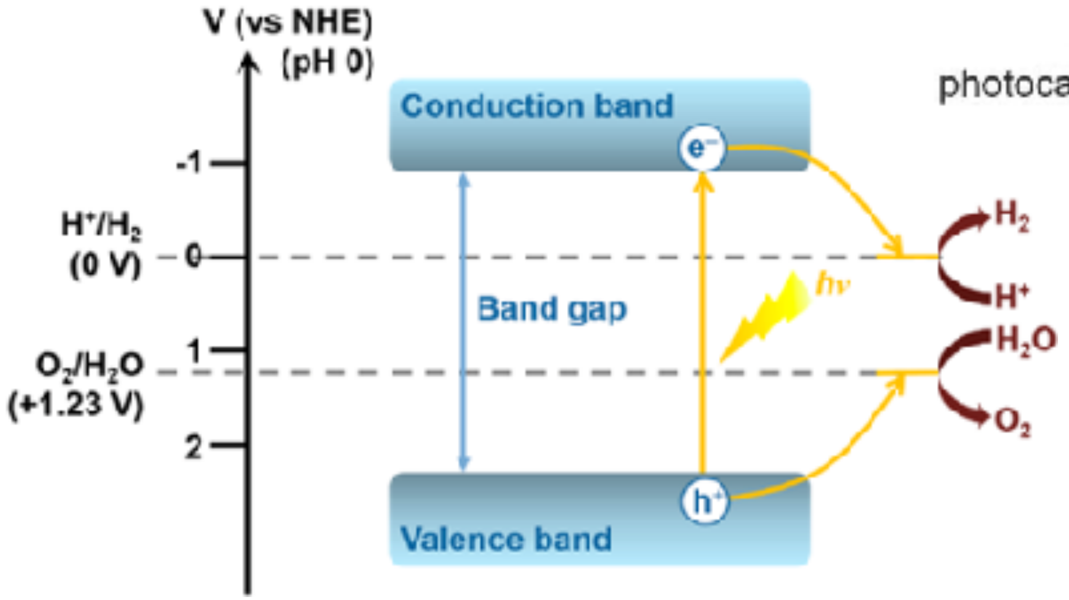


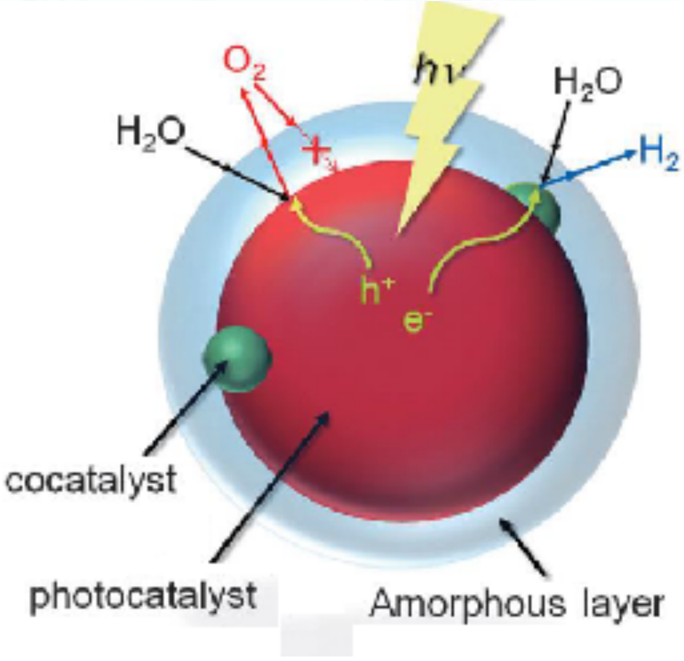
Transparent DSSC windows

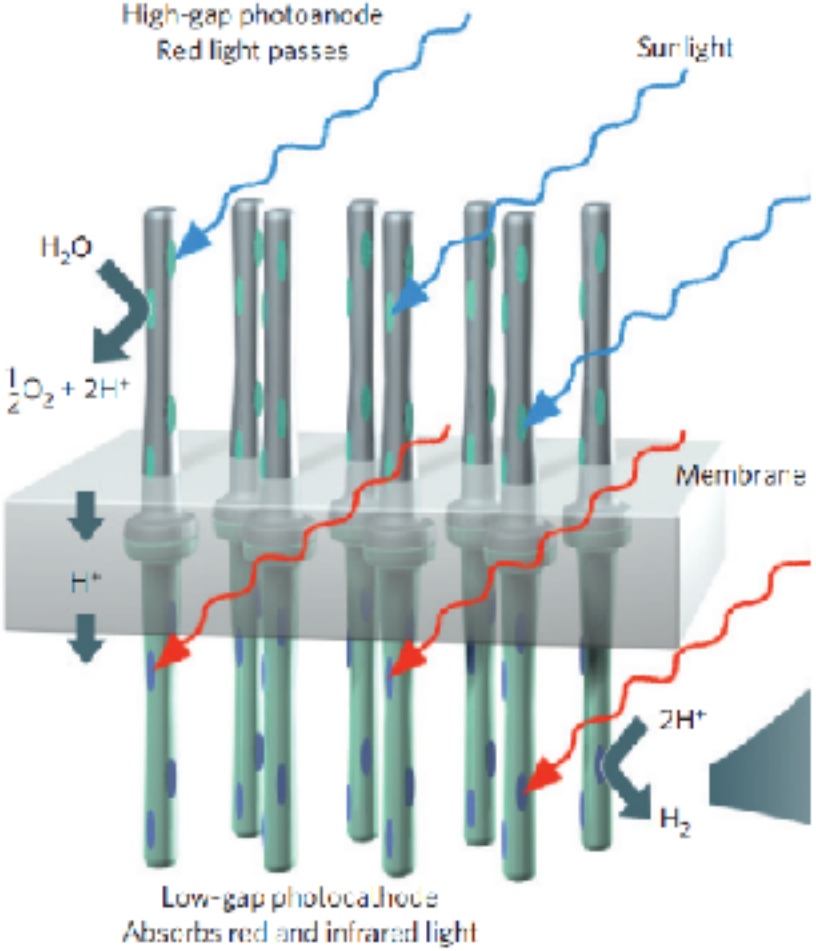




Photocatalyst – Photoelectrode comparison

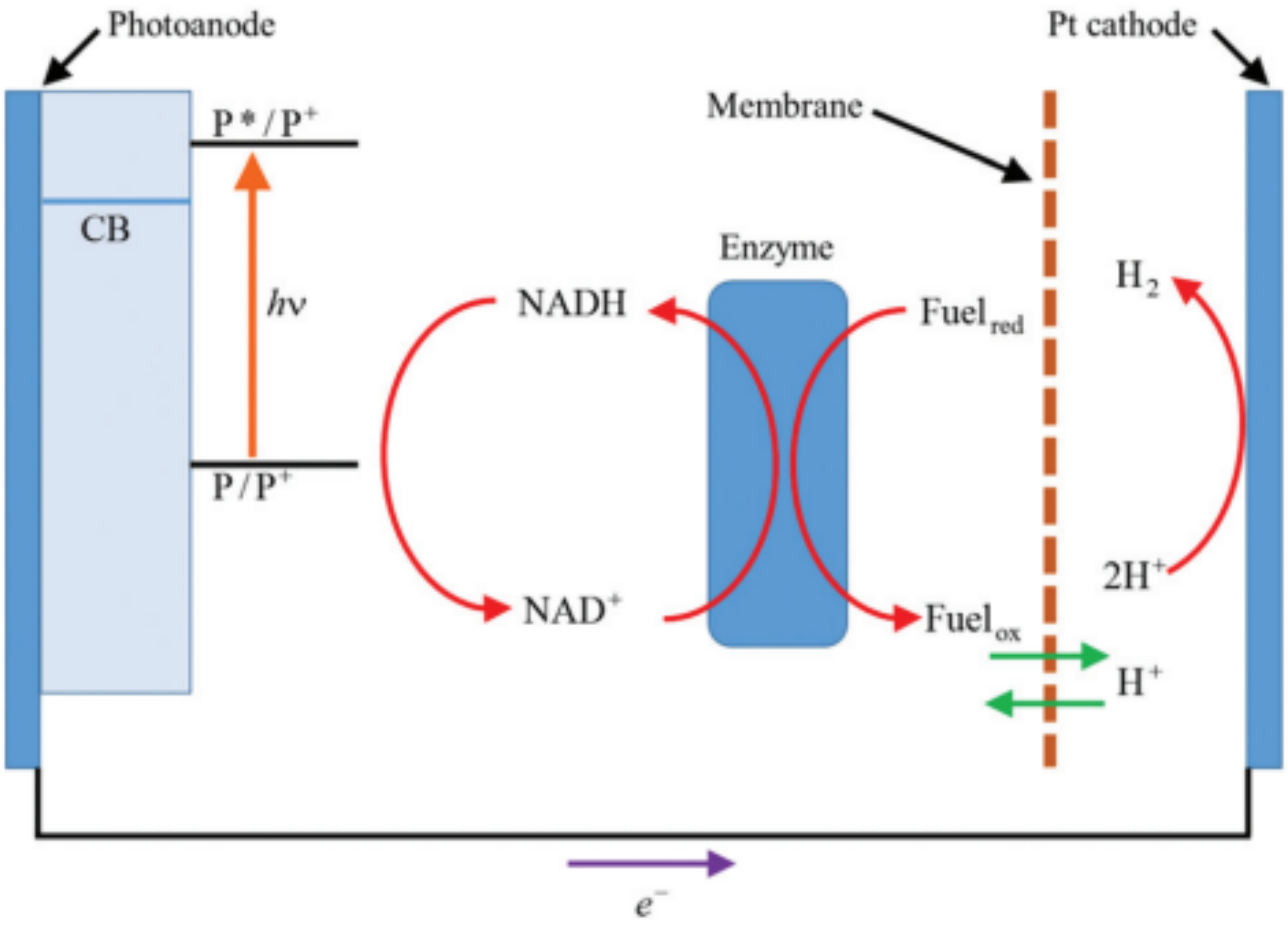




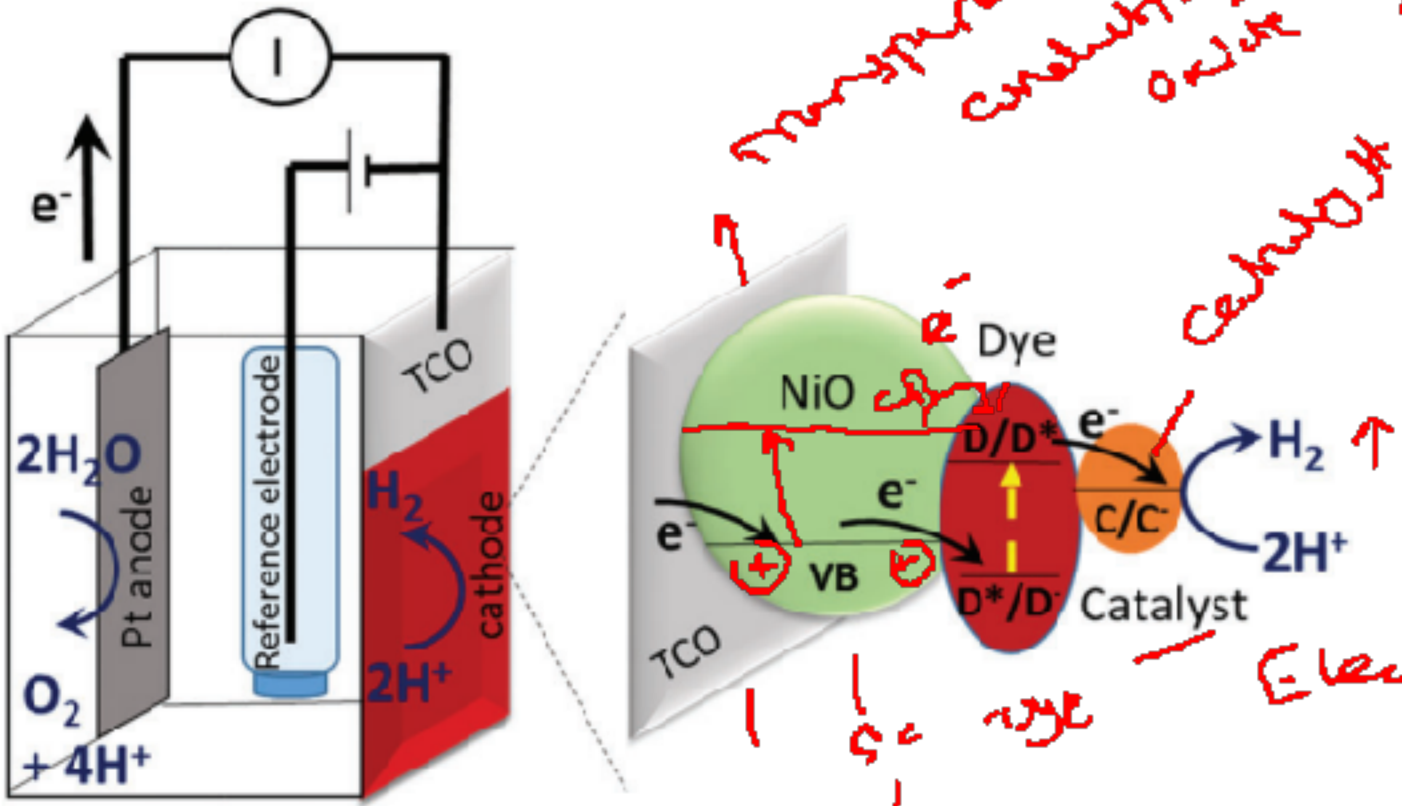


Y.Hu et. Al., 2011, Nature Materials

Photoelectrochemical biofuel cell



Photoelectrodes in DS - photoelectrosynthesis



transparent conducting oxide

glass / ITO

cathode

artificial photosynthesis

Electrolyte

$CO_2 + H^+ + e^-$

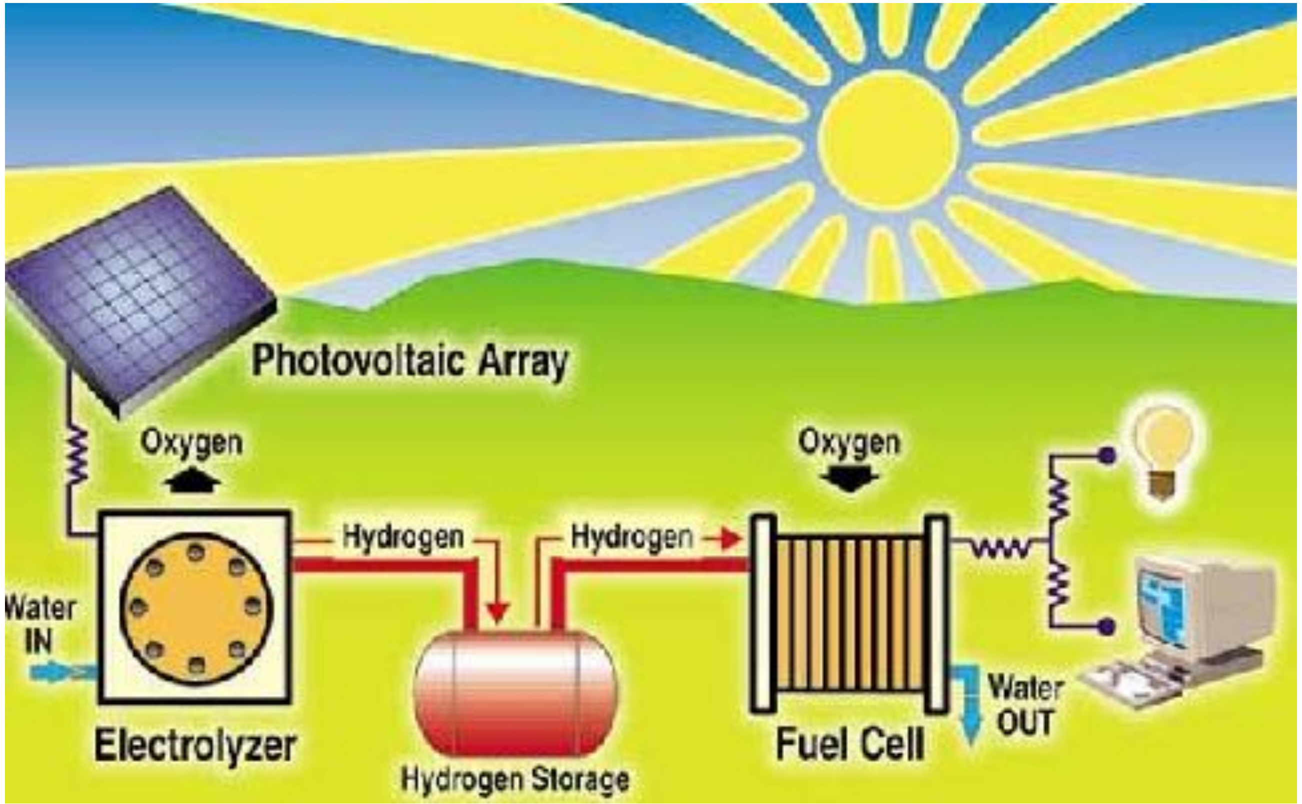
$\downarrow$

CH_4, CH_3OH

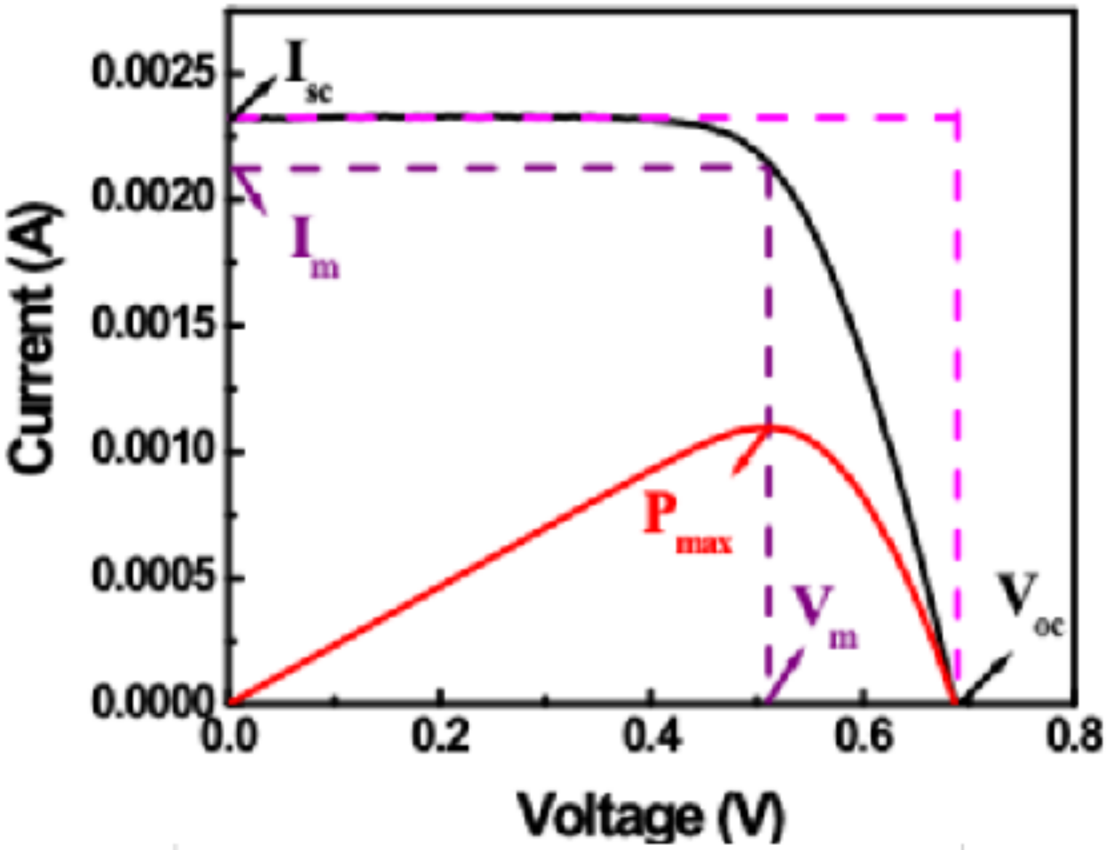
P - Cu_2O / Dye

P - NiO

PV- Water electrolyzer – Fuel cell integration



Solar cell test parameters



Voc: Open Circuit Voltage

Isc : Short Circuit Current

Pmax: Maximum Power Delivered

Vm: Voltage corresponding to Pmax

Im: Current corresponding to Pmax

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

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

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.

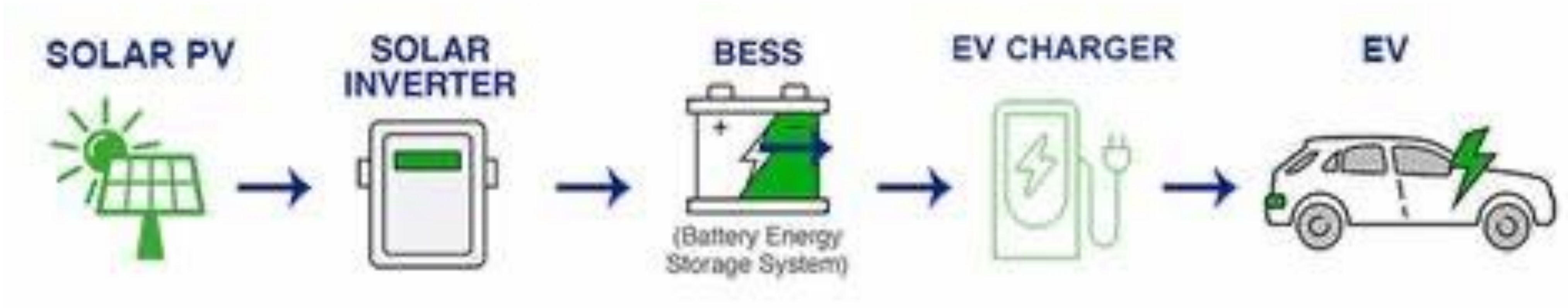
3. Series Resistance: Depends on ohmic losses at front contact (n type semiconductor and metal). Ideally = 0

4. Shunt Resistance: Depends on leakage current within solar cell. Ideally = ∞

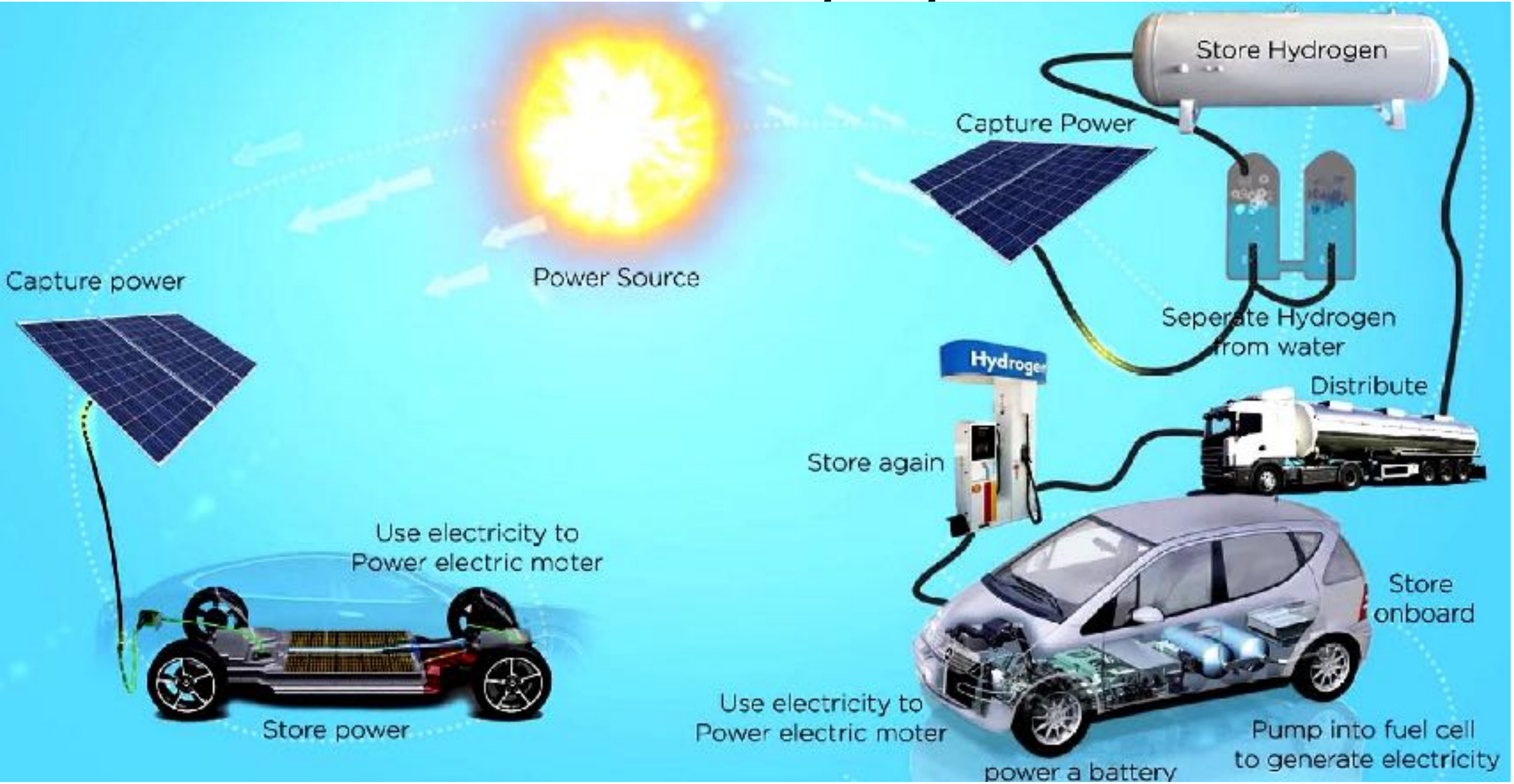
5. FF (Fill Factor): Depends on values of series and shunt resistance. Ideally = 100. i.e. The IV loop should look as 'rectangular' as possible.

6. Efficiency: Depends on Voc, Isc and Fill Factor.

PV- Electric charging integration



Solar assisted charging



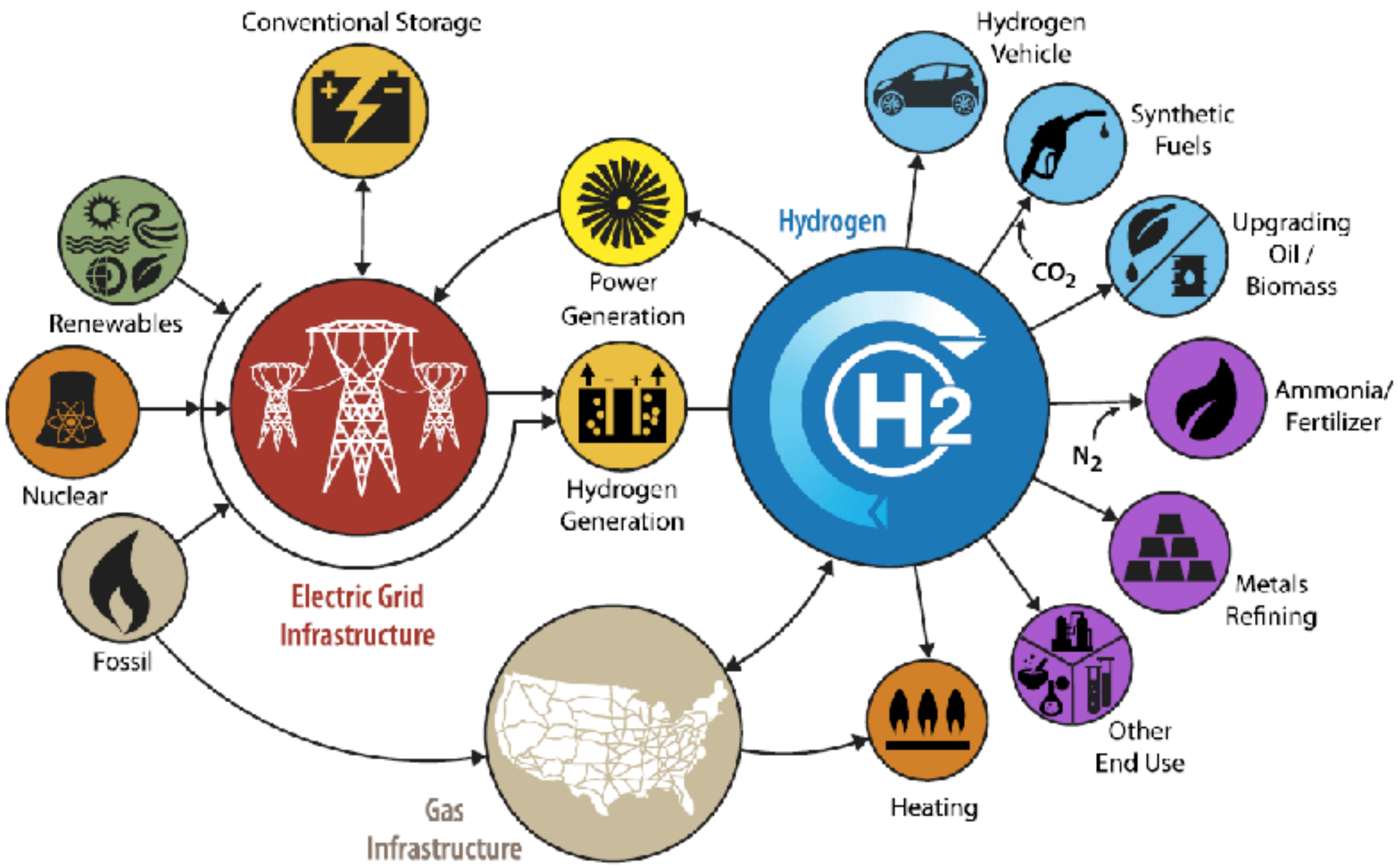


Figure 1. Role of Hydrogen Technologies in Future Energy Systems

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