Renewable Energy
MSc Lecture Notes

By

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Course Contains:

- **Renewable Energy Overview**
- **Basic of Renewable Energy Supply**
- **Solar Thermal Heat Utilization**
- **Photovoltaic Power Generation**
- **Wind Power Generation**
- **Hydroelectric Power Generation**

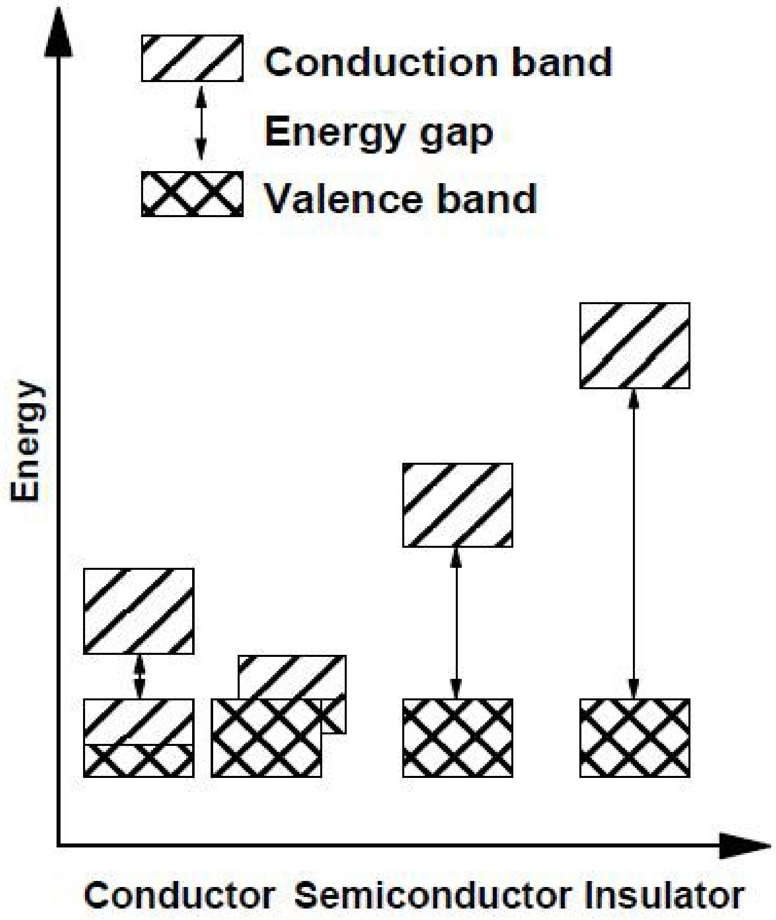
Photovoltaic Power Generation

(Lecture **4**)

Contents:

Principles- Energy Gap Model

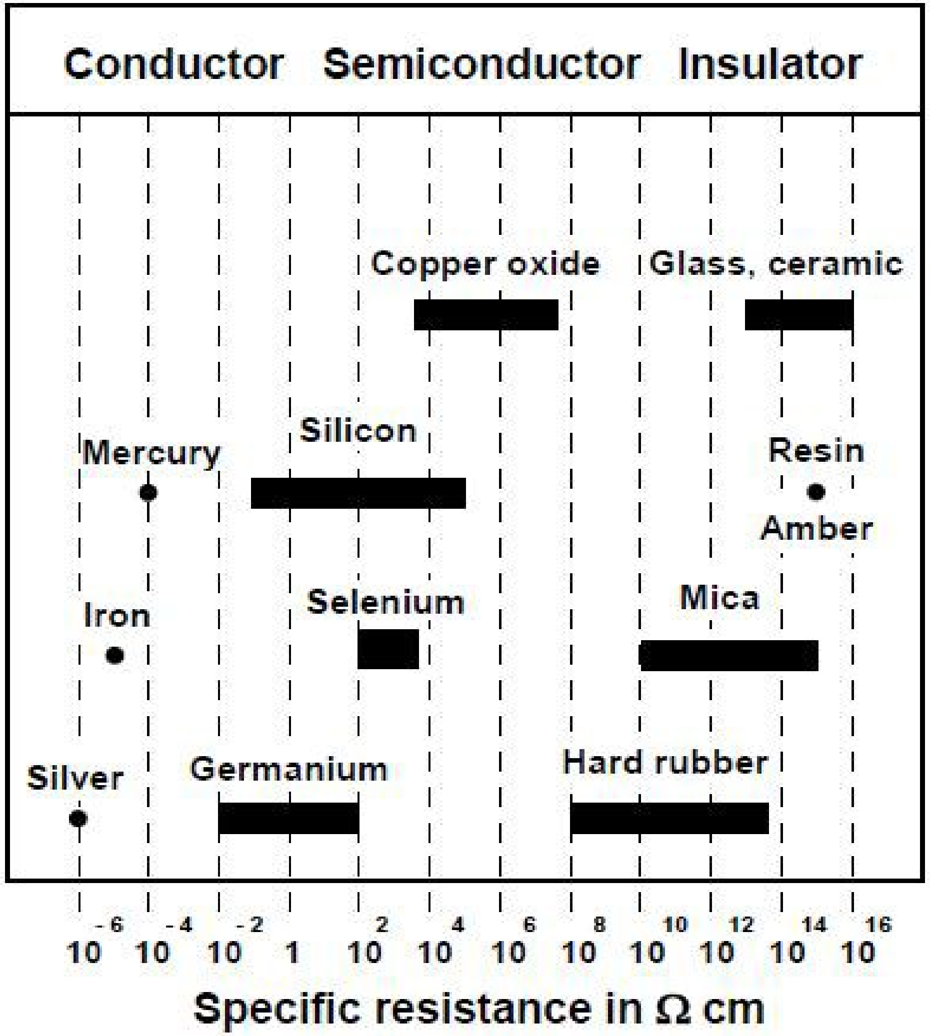
- The energy gap E_g between the valence band and conduction band is termed as "band gap“



$$E_g = E_c - E_v$$

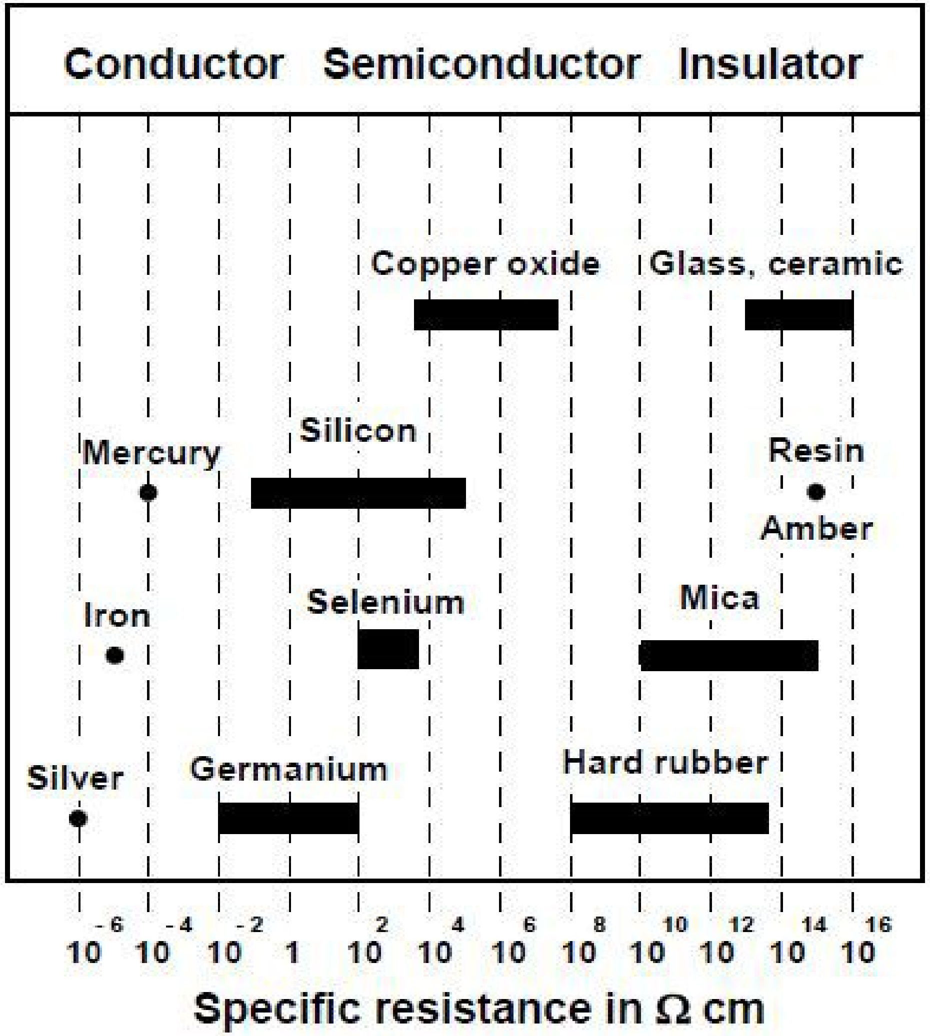
Principles- Conductor, Semiconductor & Insulator

- **Conductors:** (metals and their alloys) two different conditions might occur:
  - The most energy-rich band (i.e. conduction band) occupied by electrons is not entirely occupied.
  - The most energy-rich band fully occupied with electrons (i.e. valence band) and the conduction band located on top overlap, so that also a partly covered band (conduction band) is formed.
- **Insulators:** (e.g. rubber, ceramics) are characterized by a valence band fully filled with electrons, a wide energy gap (Eg > 3 eV) and an empty conduction band.
  - Hence, insulators possess virtually no freely moving electrons.
  - Only at very high temperatures (strong "thermal excitation") are a small number of electrons able to overcome the energy gap.
  - Thus, ceramics, for instance, show conductivity only at *very high temperatures*



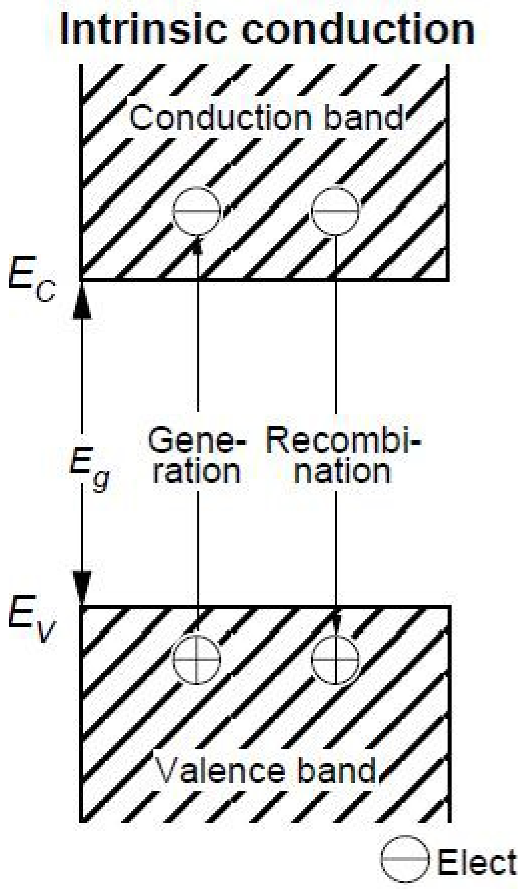
Principles- Conductor, Semiconductor & Insulator

- **Semiconductors:** (e.g. silicon, germanium, gallium-arsenide) are insulators with a relatively narrow energy gap (0.1 eV < Eg < *3* eV*)*.
  - At low temperatures=acts as an insulator.
  - Adding thermal energy, electrons are released from their chemical bond, and lifted to the conduction band.
  - Adding thermal energy, electrons are released from their chemical bond, and lifted to the conduction band and semiconductors become conductive
  - Regarding specific resistance, semiconductors are in-between conductors and insulators.



Principles- Conduction mechanisms of semiconductors

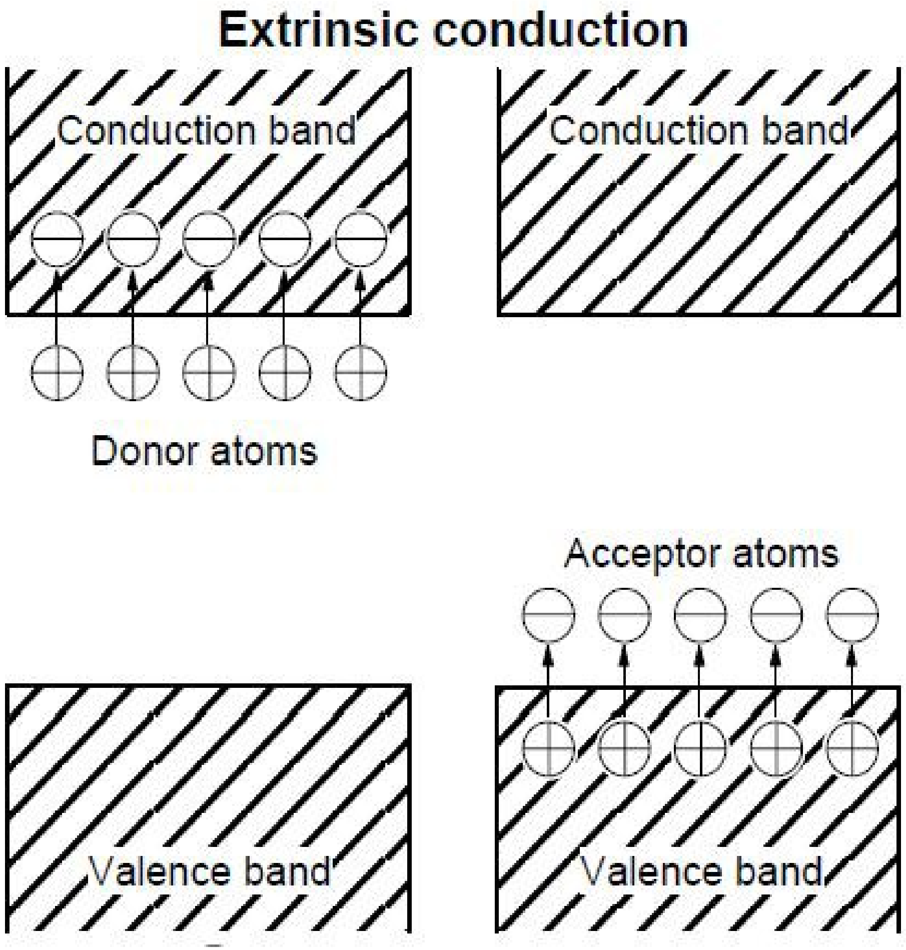
- **Intrinsic conductivity:** Semiconductors are **conductive** beyond a certain temperature level as valence electrons are released from their chemical bonds with increasing temperatures and thus reach the conduction band (intrinsic conductivity).
    - Once electrons are able to move freely through the crystal lattice (i.e. electron conduction)= Semi. Will be a conductive material.
- Movement of electron= left holes in the V.B
- Holes thus **contribute equally to conductivity** (hole conduction).
- At Semiconductor both types (e&h) of charge carriers equally exists.



Principles- Conduction mechanisms of semiconductors

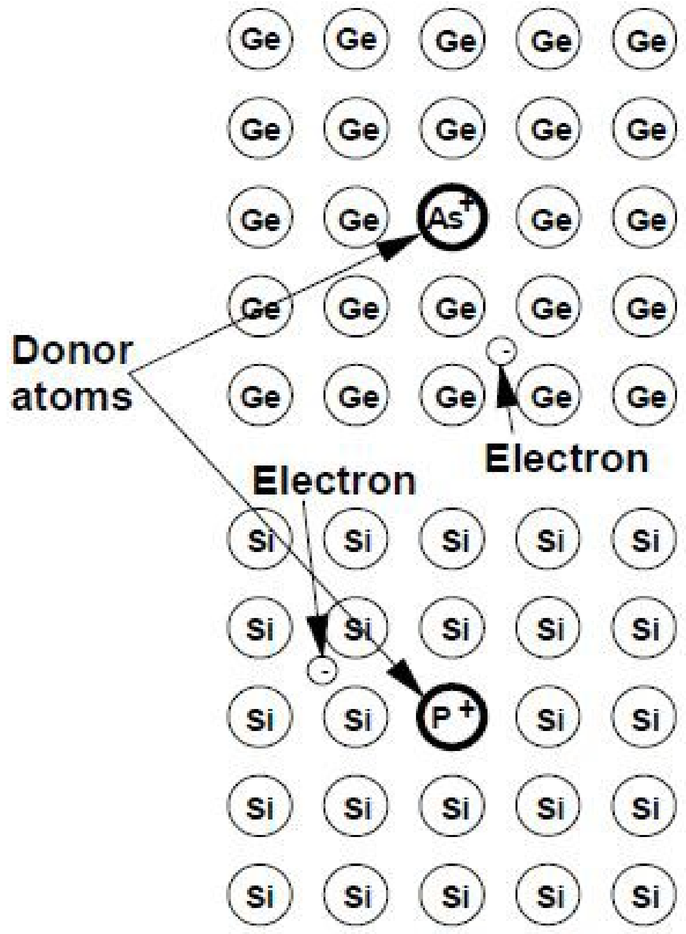
- If an external voltage is applied to such a crystal lattice from outside, **electrons move to the positive** pole while the **holes move to the negative** pole.

- **Extrinsic conduction:**
- In addition to the – low – intrinsic conduction of pure crystal lattices extrinsic conduction is created by intentional incorporation of foreign atoms ("**doping**").
- Such ***impurities*** are effective if their number of valence electrons differs from that of the base material.



Principles- Conduction mechanisms of semiconductors

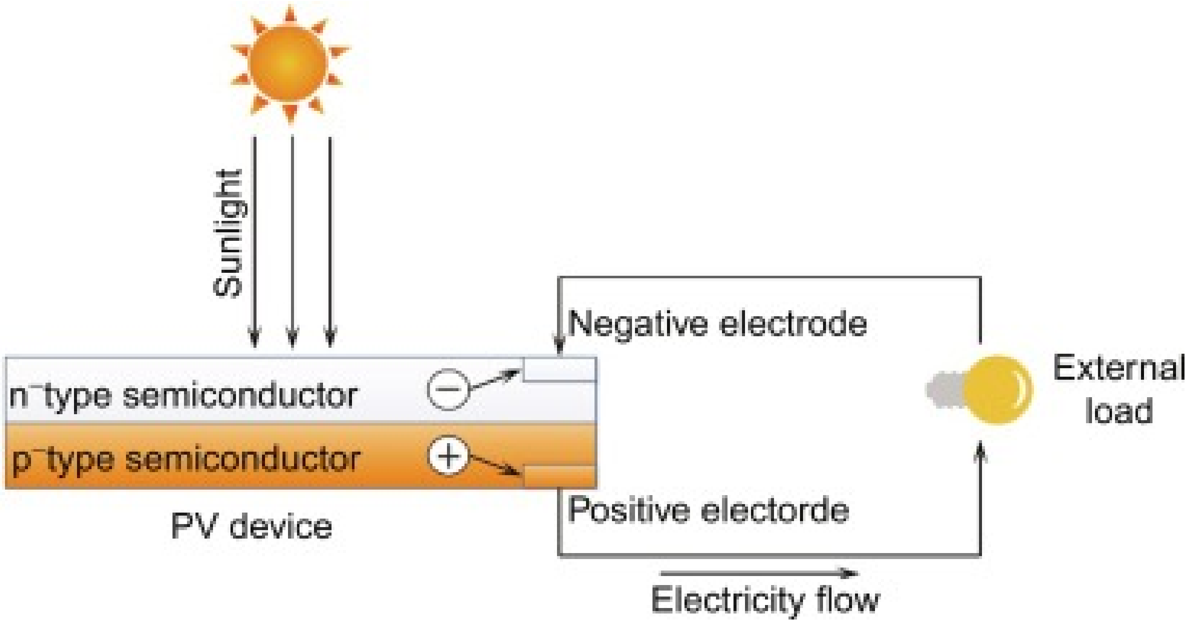
- The valence electron number of the incorporated impurities exceeds that of the lattice atom (e.g. in pentavalent arsenic (As) incorporated into tetravalent silicon (Si) lattice, the excess electron is only weakly bound to the impurity atom.
- It thus *separates easily from the impurity atom* due to thermal movements within the lattice and increases the conductivity of the crystal lattice as a freely moving electron.
- Such foreign atoms which increase the number of electrons are referred to as **donor atoms**.
- In this case electrons are called majority carriers, whereas the holes constitute the minority carriers.



Principles- Photo effect

- The term "photo effect" refers to the energy transfer from photons (i.e. quantum of electromagnetic radiation) to electrons contained inside material.

- Photon energy is thereby converted *into potential and kinetic energy of electrons*.



- The electron absorbs the entire quantum energy of the photon defined as the product of Planck's quantum and the photon frequency.

Principles- Photo effect-(P-N Junction)

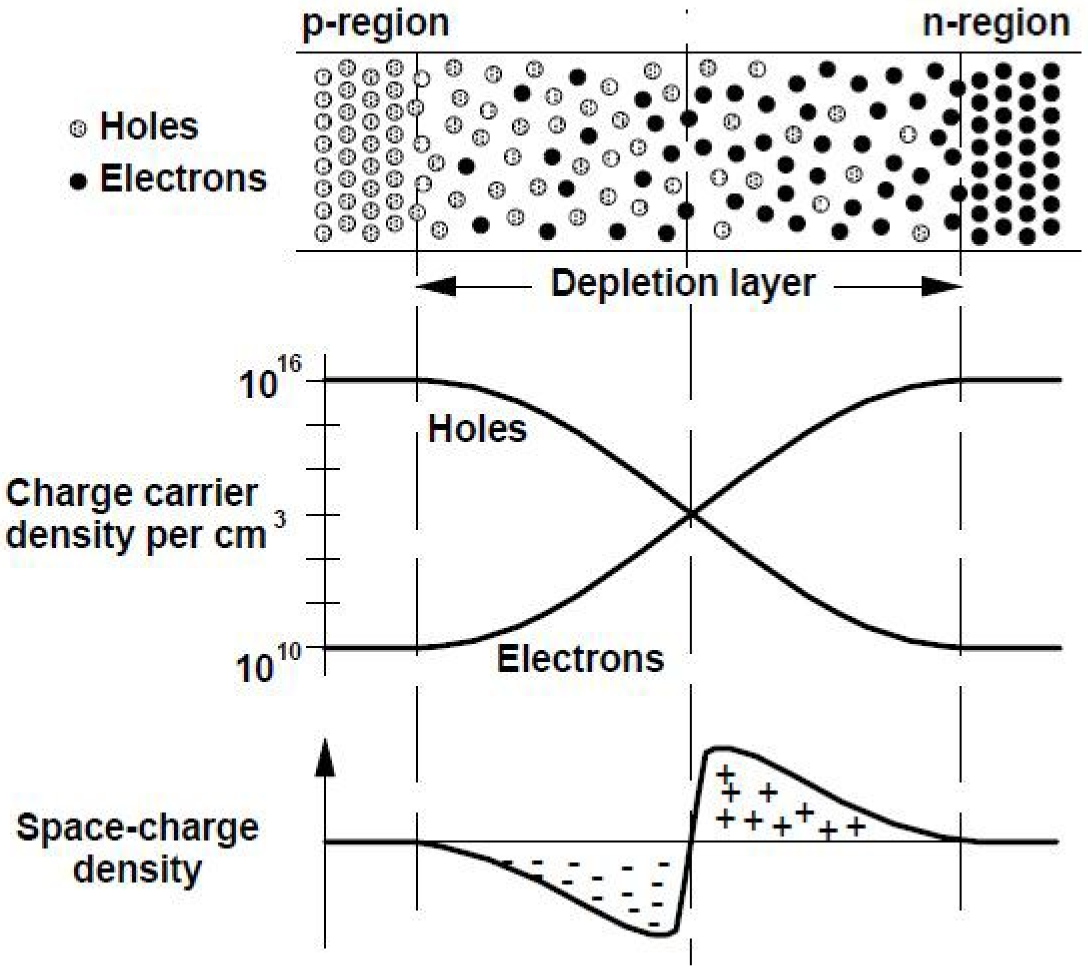
•If p- and n-doped materials brought into contact, *holes from the p-doped side diffuse into the n-type region and vice versa*.

•First a strong concentration gradient is formed at the p-n-junction, consisting of electrons inside the conduction band and holes inside the valence band.

- *gradient holes from the p-region diffuse into the n-region and vis verse .*

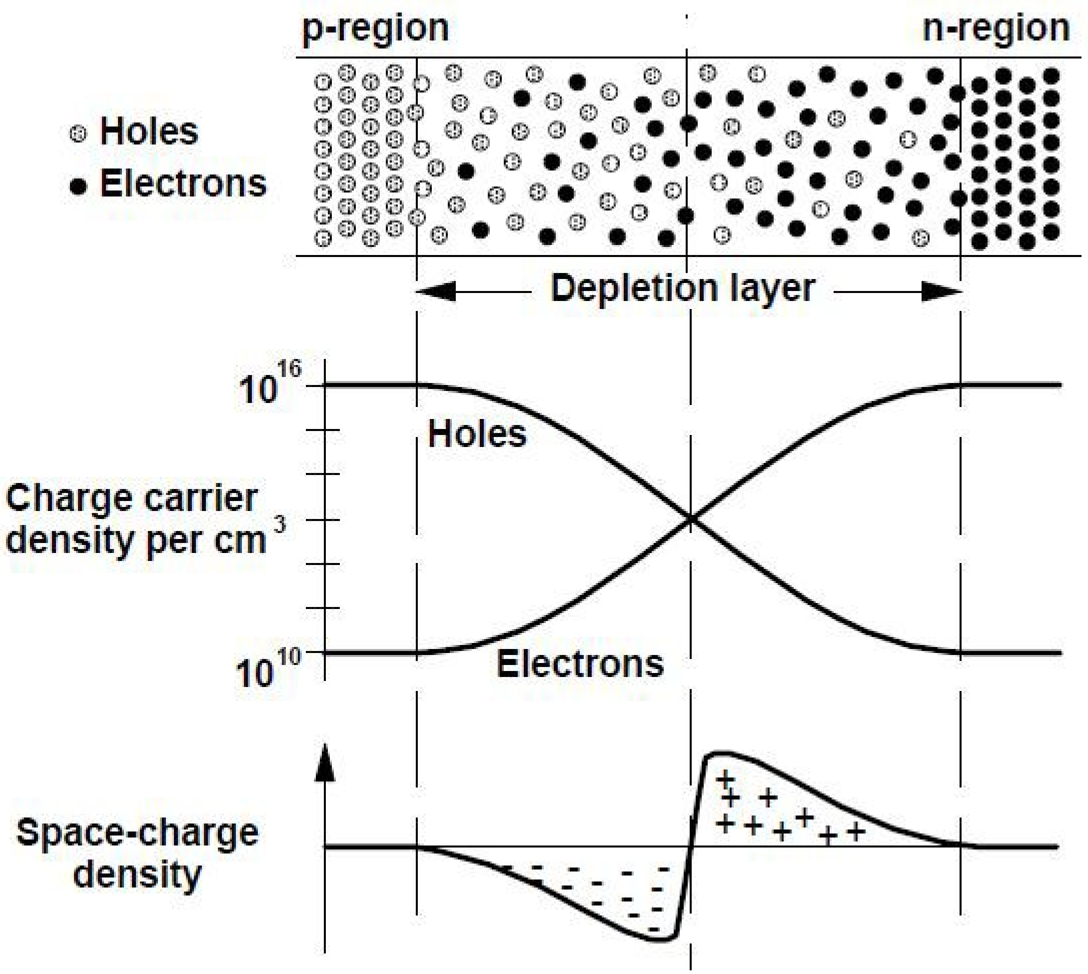
Due to the diffusion, the number of majority carriers are reduced on both sides of the p-n-junction.

•The charge attached to the stationary donors or acceptors then creates a negative space charge on the p-side of the transition area and a positive space charge on the n-side.

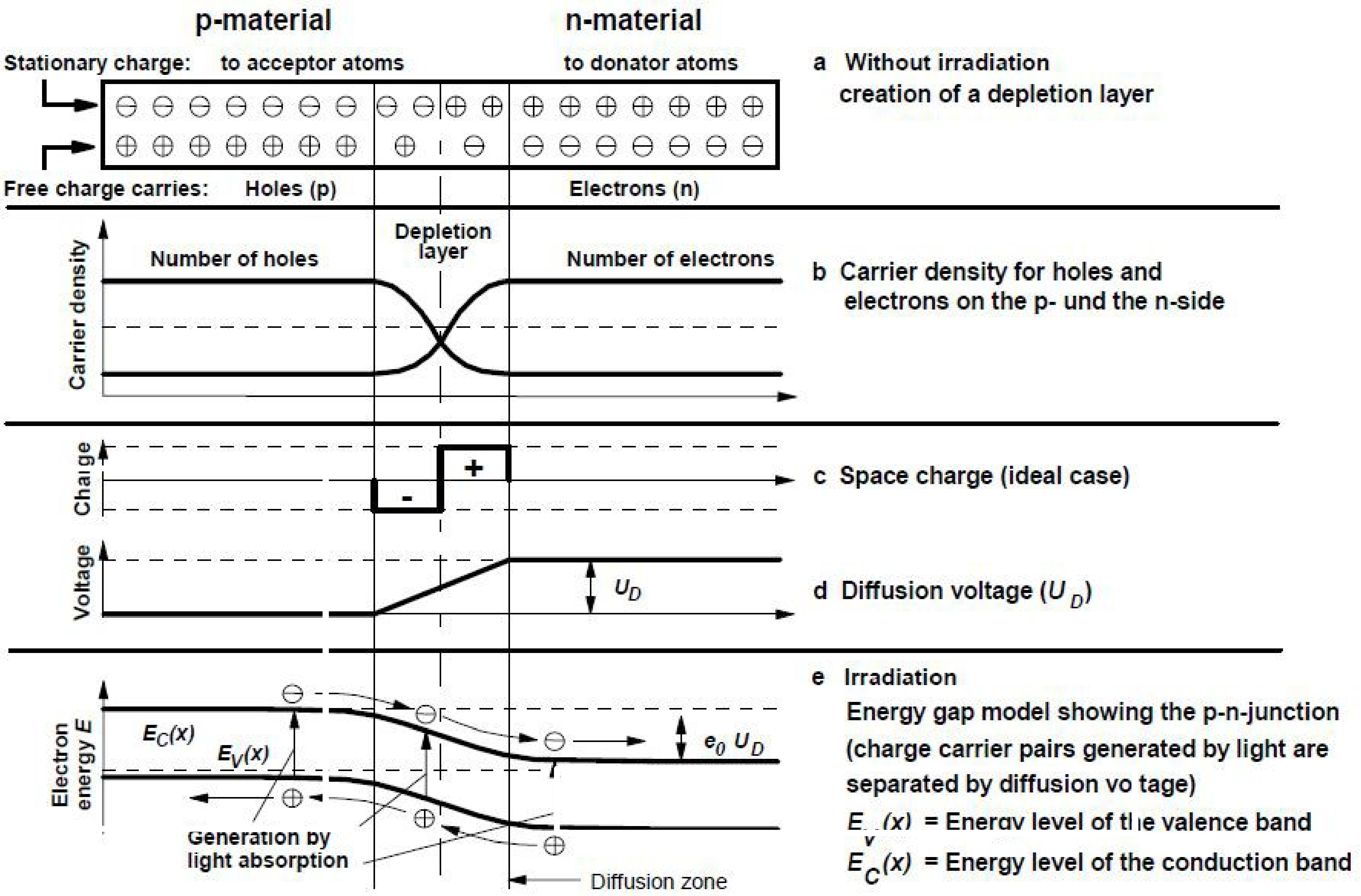


Principles- Photo effect-(P-N Junction)

- At equilibrium state = electrical field is built up across the border interface (p-n-junction).
- The described process creates a depletion layer in which diffusion flow and reverse current compensate each other.
- The no longer compensated stationary charges of donors and acceptors define a depletion layer whose width is dependent on the doping concentration



Principles- Photo effect-(P-N Junction within a solar cell)



Principles- Photo effect-(P-N Junction within a solar cell)

- Due to the charge separation during irradiation, electrons accumulate within the n- region, whereas holes accumulate in the p-region.
- i.e. until the electrical potential created by the accumulation of electrons and holes is balanced by the diffusion potential of the p-n junction.
- Then the **open-circuit voltage** of the solar cell is reached.
- The time to achieve these conditions is almost **immeasurably short**.

✓If p- and n-sides are short-circuited by an external connection, the short-circuit c
is measured.
✓In this operating mode the diffusion voltage at the p-n junction is restored.
✓According to the operating principle of a solar cell, short circuit current increase proportional and almost linear to solar irradiance

Principles- Photovoltaic cell and module

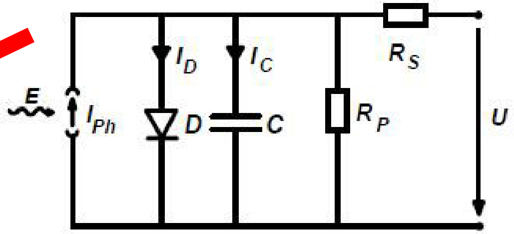
Structure:

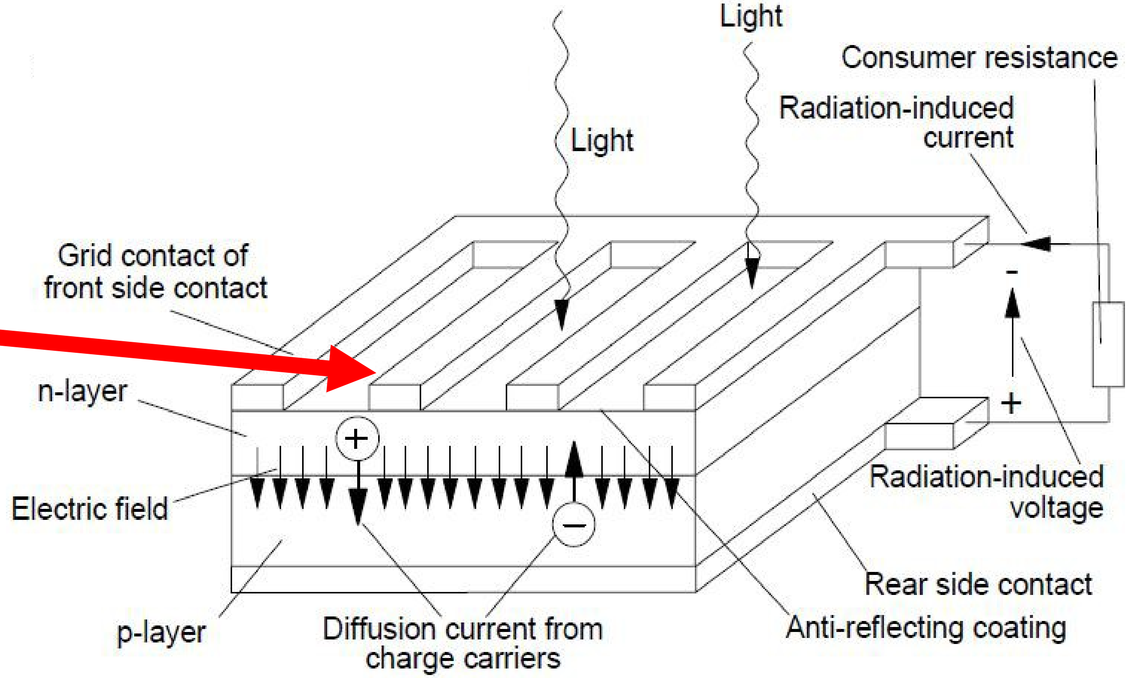
- The photovoltaic cell consists a p-conducting base material and an n-conducting layer on the topside.
- The *entire cell rear side* is covered with a metallic contact while *the irradiated side* is
- equipped with a finger-type contact system to minimize shading losses.
- Also full cover, transparent conductive layers are used.
- To reduce reflection losses the cell surface may additionally be provided with an anti-reflecting coating.
- A silicon solar cell with such construction usually has a blue color. By the incorporation of **inverse pyramids into the surface reflection losses** are further reduced.
- The inclination of the pyramid surfaces is such that photons are reflected onto another pyramid surface, and thus considerably enhance the possibility of photon penetration into the crystal.
- Absorption of the solar light by these cells is almost complete, the cells appear **black**.

Principles- Photovoltaic cell and module

Current-voltage characteristic and equivalent circuit

Structure of a typical solar cell and an equivalent circuit diagram





$$I = I_{Ph} - I_0\left(e^{\frac{e_0 U}{kT}} - 1\right)$$

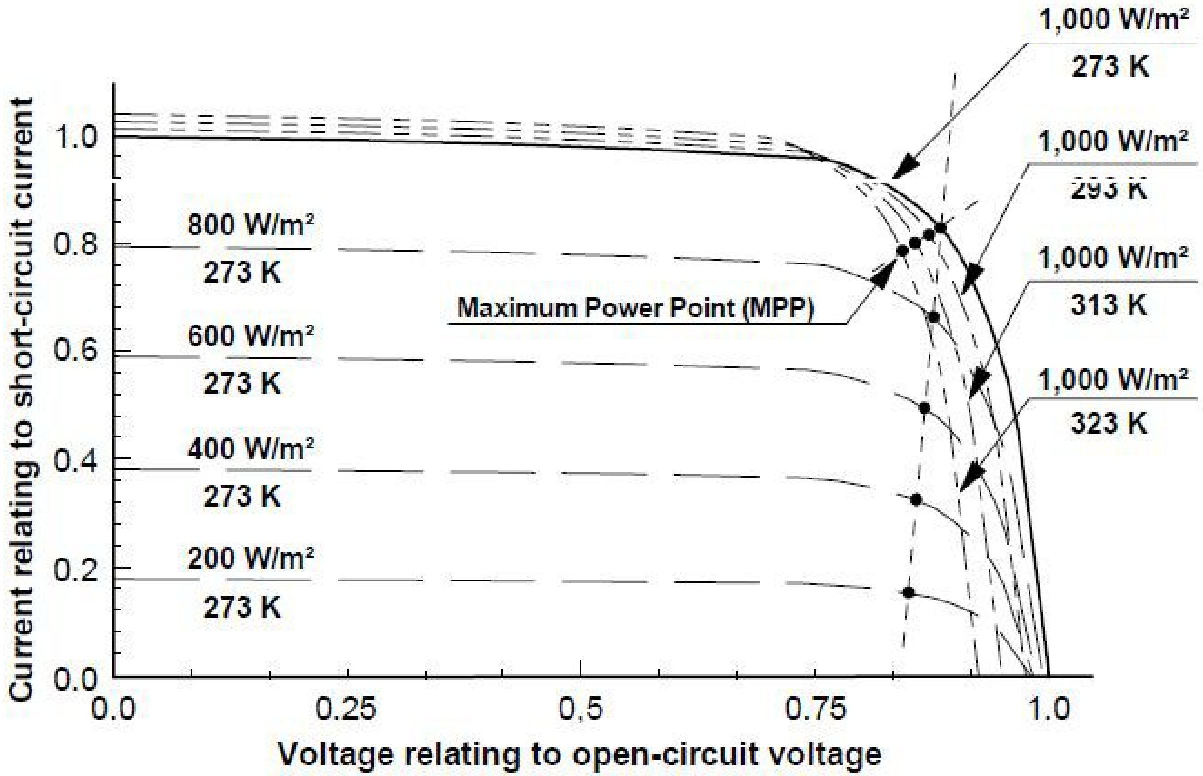
$$U = \frac{k}{e_0}\cdot T\cdot ln\left(1-\frac{I-I_{Ph}}{I_0}\right)$$

I : current flowing through the terminals
I_{Ph} : photocurrent
I_0 : saturation current of the diode e_0 represents the elementary charge (1.6021 10^{-19} C)

- An illuminated solar cell **ideally** can be considered as a current source provided with a parallel diode.
- The photocurrent I_{Ph} is assumed *to be proportional to the photon flow incident on the cell*.
- The Shockley equation for ideal diodes describes the interdependence of current and voltage (current-voltage characteristic) of a solar cell.

Principles- Photovoltaic cell and module

- **Under realistic conditions:**
- Without irradiation, the solar cell is equal to an ordinary semiconductor diode whose effect is also maintained at the incidence of light.
- This is why diode D has been connected in parallel to the photovoltaic cell in the equivalent circuit diagram.
- Each p-n-junction also has a certain depletion layer capacitance, which is, however, typically neglected for modeling of solar cells.
- At increased inverse voltage the depletion layer becomes wider so that the capacitance is reduced similar to stretching the electrodes of a plate capacitor.
- Thus, solar cells represent variable capacitances whose magnitude depends on the present voltage.
- This effect is considered by the capacitor C located in parallel to the diode.
- Series resistance R_S consists of the resistance of contacts and cables as well as of the resistance of the semiconductor material itself.
- To minimize losses, cables should be provided with a maximum cross-section.
- Parallel or shunt resistance R_P includes the "leakage currents" at the photovoltaic cell edges at which the ideal shunt reaction of the p-n-junction may be reduced.
- However, for good mono-crystalline solar cells shunt resistance usually is within the kΩ region and thus has almost no effect on the current-voltage characteristic.



Typical shape of a I-V curve for various operating modes (i.e. changing irradiation and temperature).

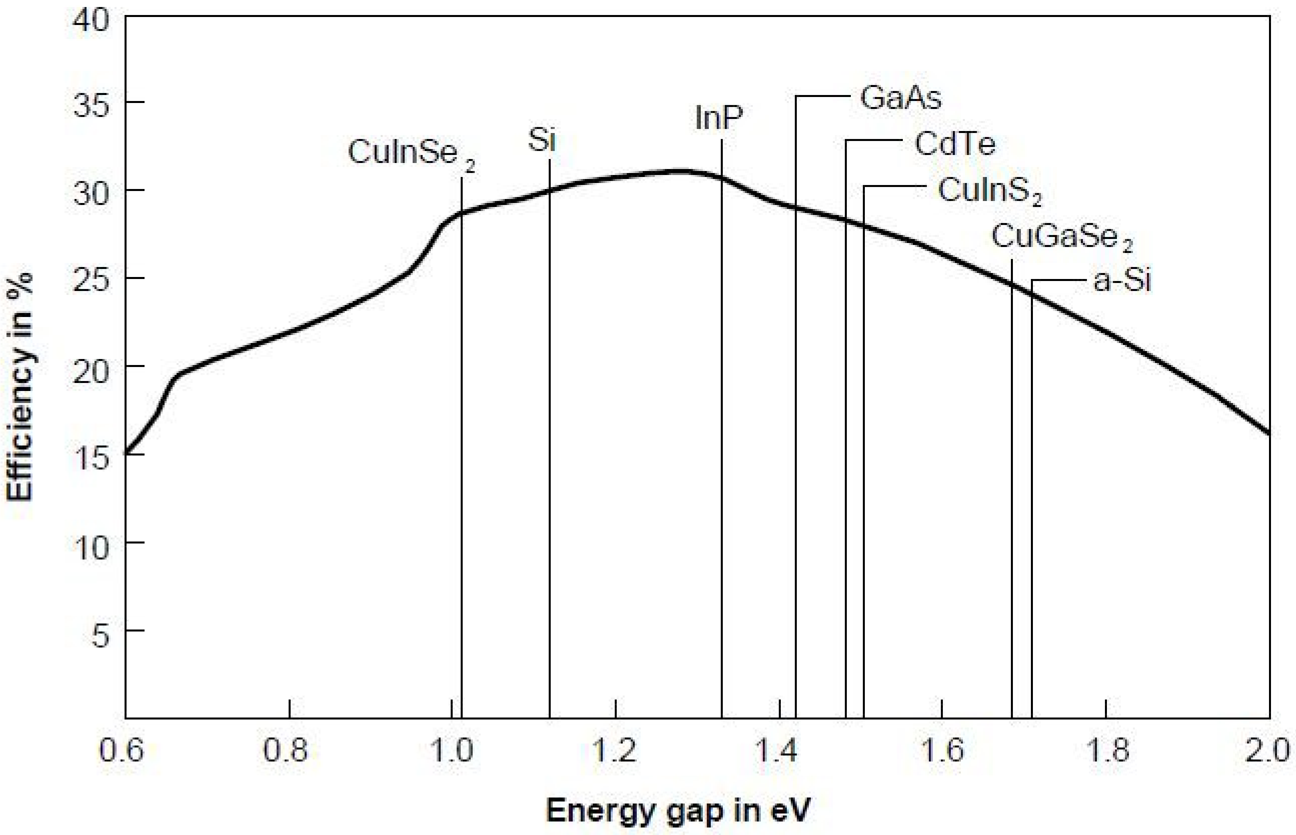
- At the intercept points of the curve and the axes the short-circuit current I_{SC} is supplied at $U = 0$ and the open-circuit voltage U_{OC} at $I = 0$.
- Starting with the short-circuit current, the cell current is at first only slightly reduced and decreases over-proportionally shortly before reaching open-circuit voltage when increasing the cell voltage continuously.

Efficiencies and Losses

CuInSe: Copper indium diselenide

InP: Indium phosphide

CdTe: Cadmium telluride



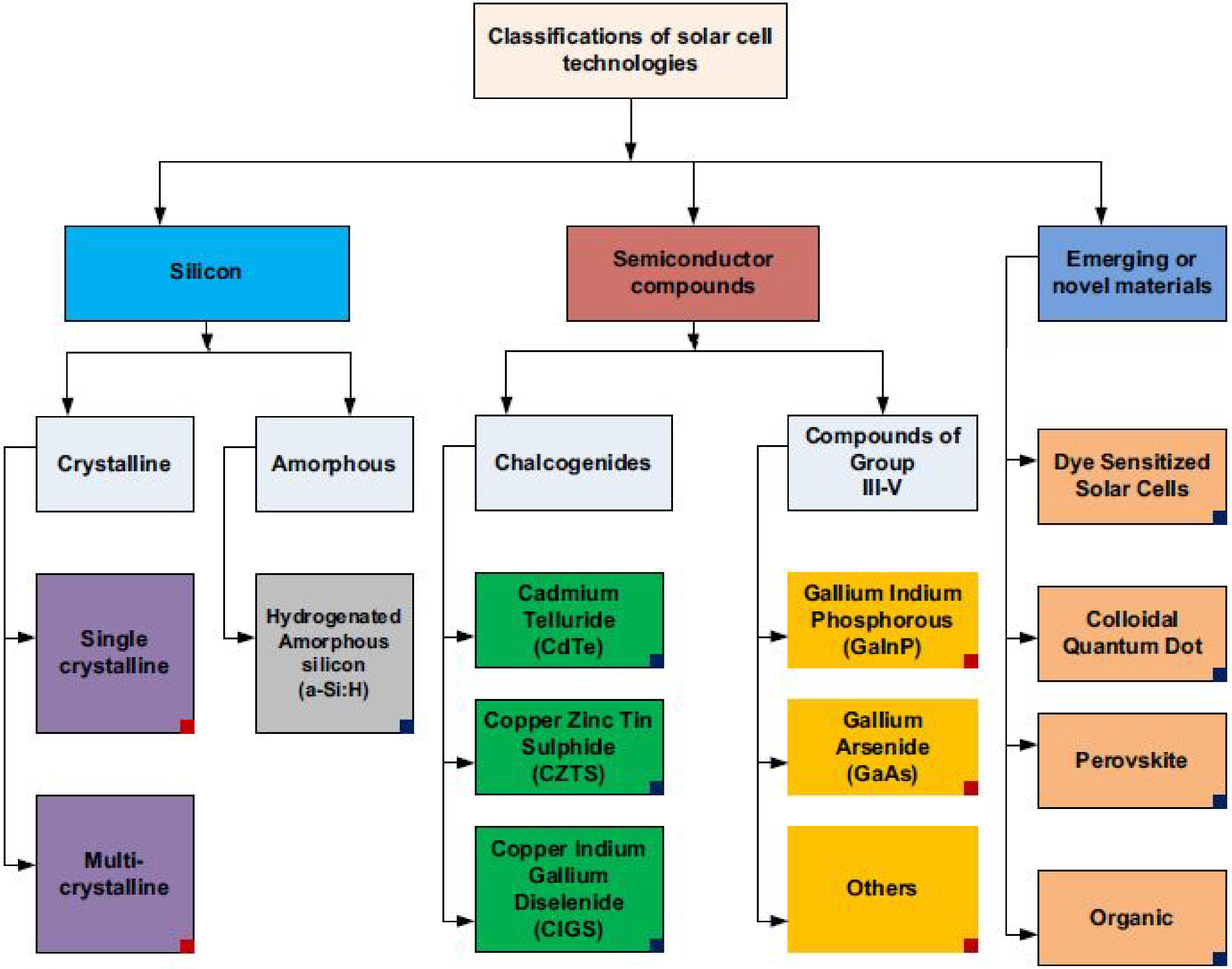
Theoretical efficiencies of various types of simple solar cells under average conditions

Efficiencies and Losses

Table 6.1 Efficiencies of solar cells (also refer to /6-16/; only cells with a cell surface larger than 1 cm^2 have been considered)

Material	Type	Efficiency Lab.	Manufac. in %	State of technology[a]
Silicon	monocrystalline	24.7	14.0 – 18.0	1
Polysilicon, simple	polycrystalline	19.8	13.0 – 15.5	1
MIS inversion layer (silicon)	monocrystalline	17.9	16.0	2
Concentrator solar cell (silicon)	monocrystalline	26.8	25.0	2
Silicon on glass substrate	transfer technol.	16.6		3
Amorphous silicon, simple	thin film	13.0	8.0	1
Tandem 2 layers, amorphous silicon	thin film	13.0	8.8	2
Tandem 3 layers, amorphous silicon	thin film	14.6	10.4	1
Gallium indium phosphate / Gallium arsenide[b]	tandem cell	30.3	21.0	2
Cadmium-telluride[c]	thin film	16.5	10.7	2
Copper indium di-selenium[d]	thin film	18.4	12.0	2

Lab. Laboratory; Manufac. Industrial manufacturing; technol. technology; [a] 1 large scale production, 2 small scale production, 3 pilot production, 4 development on a laboratory scale; [b] GaInP/GaAs; [c] CdTe; [c] $CuInSe_2$

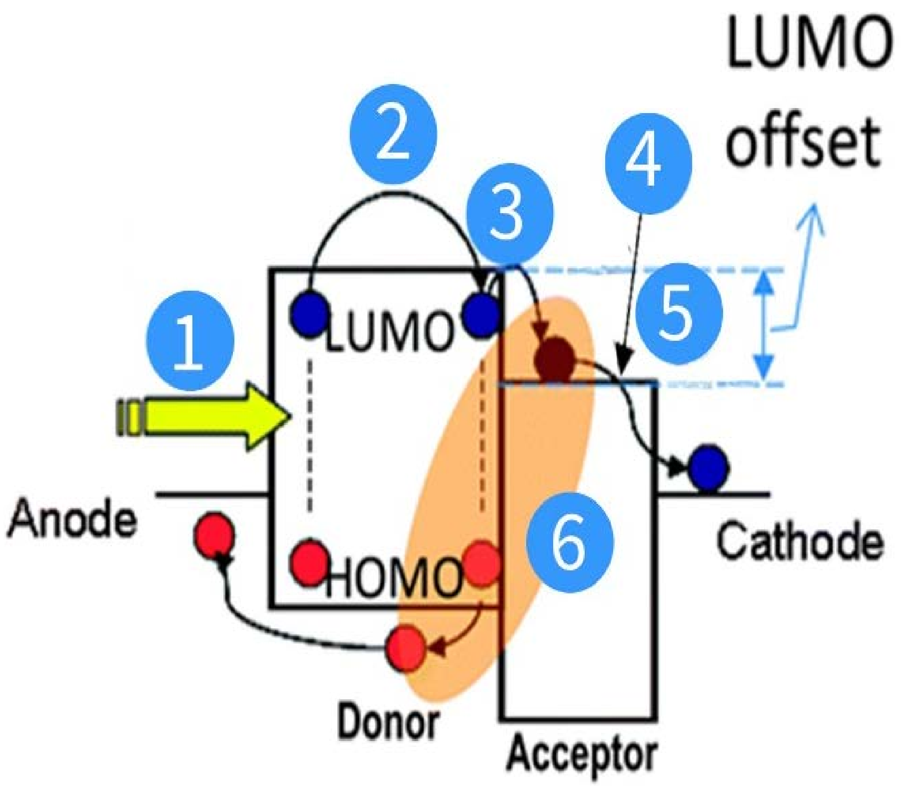


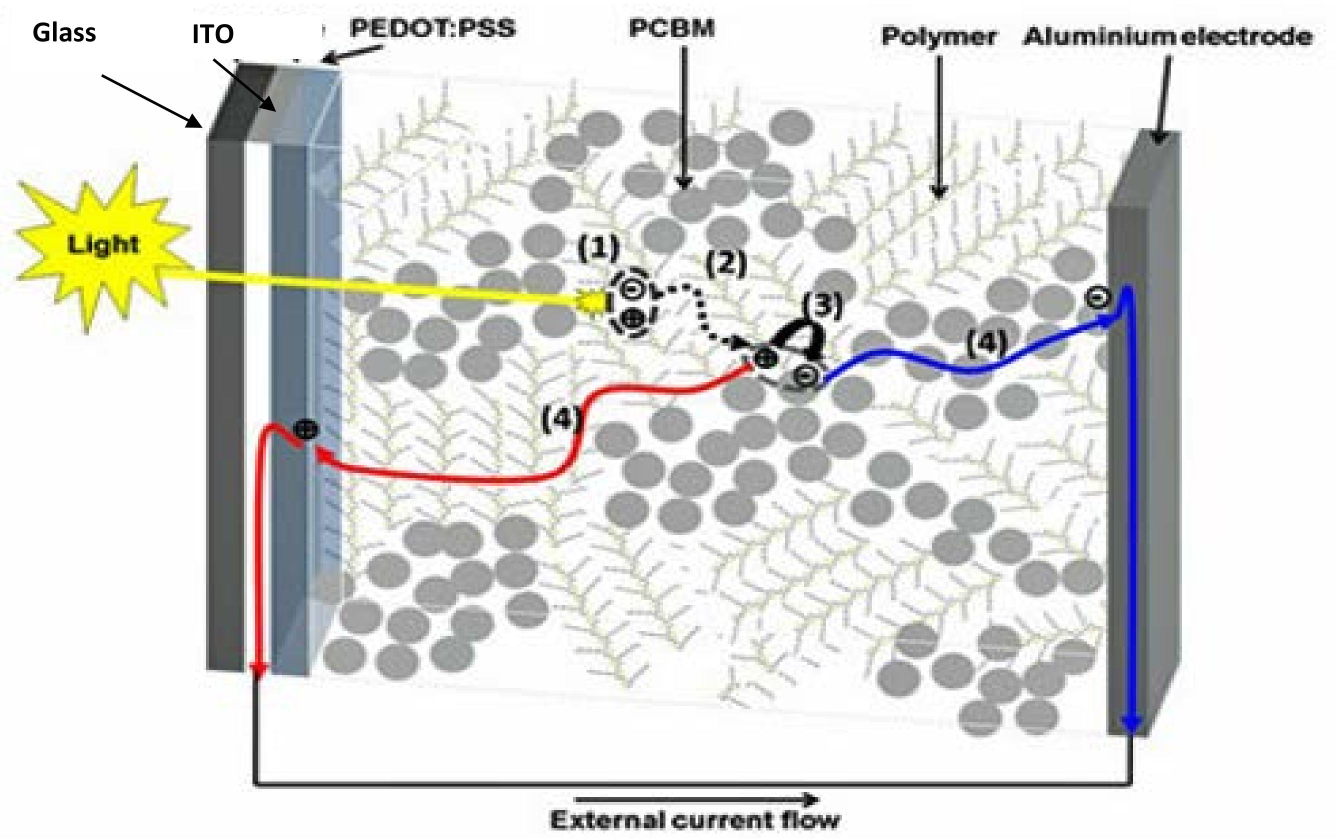
Classifications of solar cell technologies
Silicon
Semiconductor compounds
Emerging or novel materials
Crystalline
Amorphous
Chalcogenides
Compounds of Group III-V
Single crystalline
Multi-crystalline
Hydrogenated Amorphous silicon (a-Si:H)
Cadmium Telluride (CdTe)
Copper Zinc Tin Sulphide (CZTS)
Copper Indium Gallium Diselenide (CIGS)
Gallium Indium Phosphorous (GaInP)
Gallium Arsenide (GaAs)
Others
Dye Sensitized Solar Cells
Colloidal Quantum Dot
Perovskite
Organic

Organic Photovoltaic Devices

(Lecture **4**- Part 2)

What is an OPV?

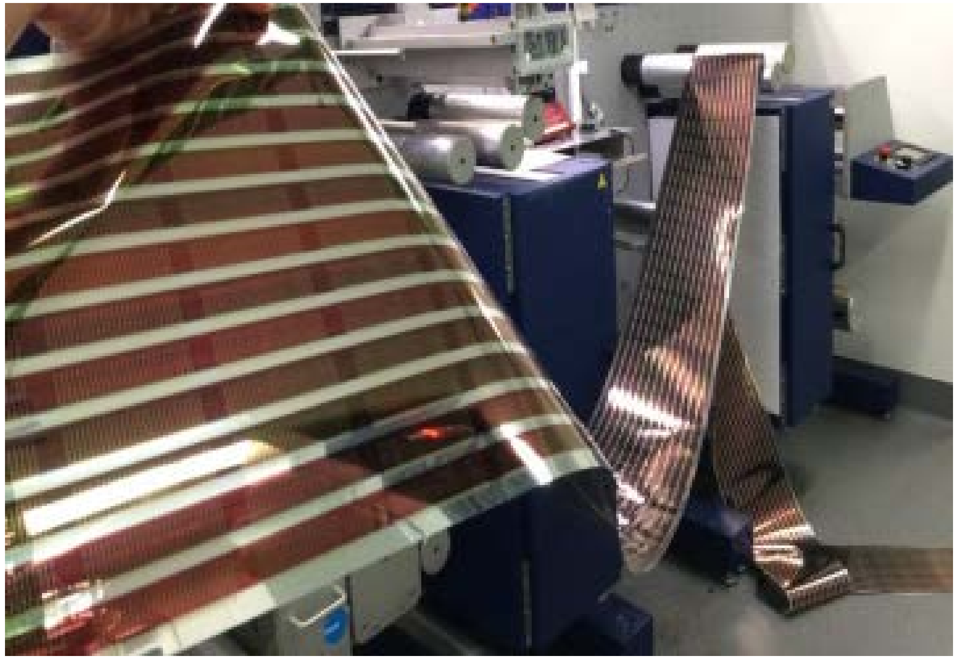


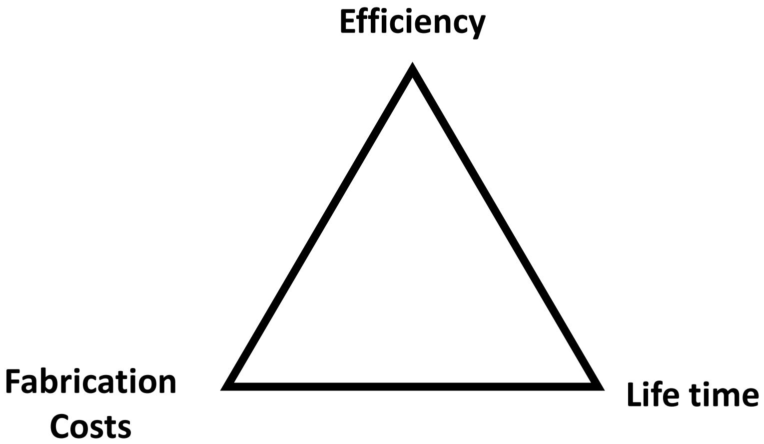


[1] Gómez, R. Segura, J, L. Plastic Solar Cells: A Multidisciplinary Field to Construct Chemical Concepts from Current Research, Journal of Chemical Education, 84

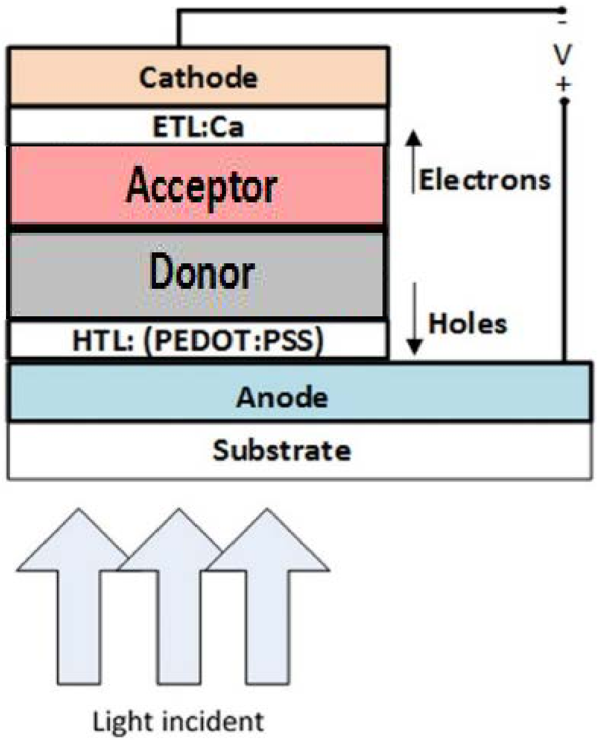
Why are OPVs Attractive?

- Solution processed device
- Access printing fabrication on flexible substrates.
  - Large area, fast deposition
  - Low cost
- **However**, the <u>materials costs</u> for efficient devices <u>still high</u>

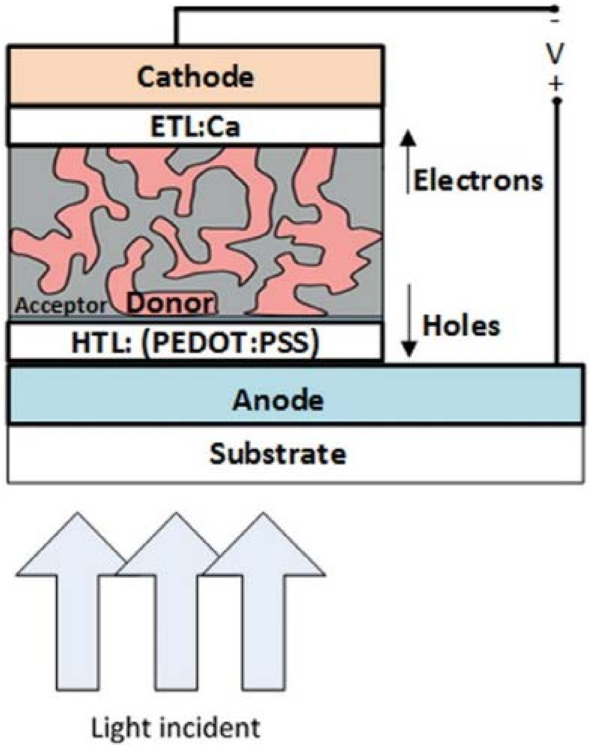




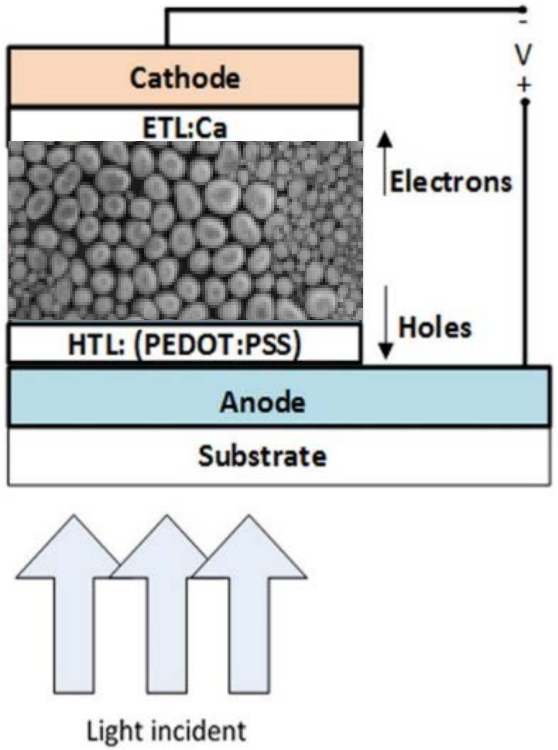
OPVs Device Architectures



(a) Bilayer OPV



(b) BHJ device structure



(c) NPs device structure

What we are need in OPVs?

<u>(1) Light absorption</u>

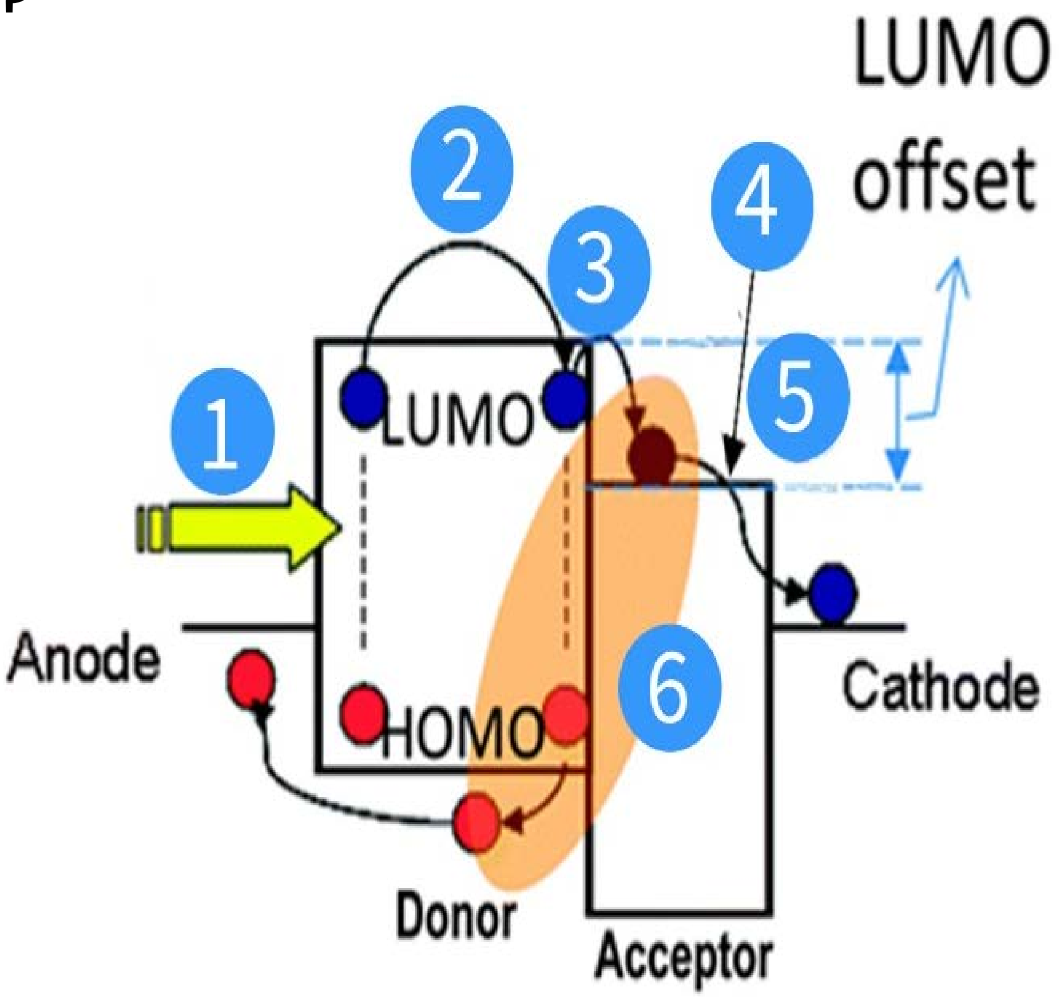
(2) Exciton diffusion

(3) Exciton dissociation

(4) Charge carrier transport

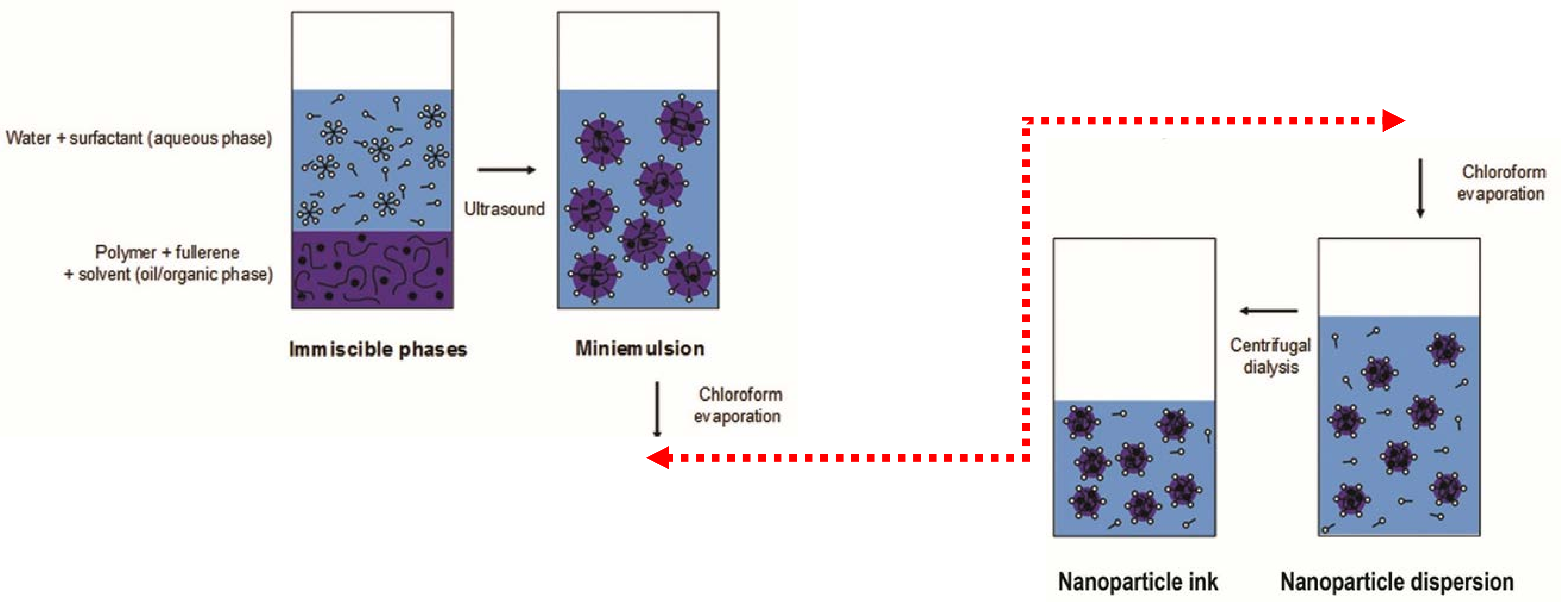
(5) Charge extraction

(6)Charge carrier recombination



A good device should has a charge transport process higher than recombination losses.

Fabrication steps of Organic Nanoparticle ink.



Preparing OPV –P3HT:PCBM (NPs)

- Devices prepared by **standard procedures**
  - Active layer thickness **~100 nm**
  - HTL→ PEDOT:PSS (**40 nm**)
- Active area **(5 cm^2)**
- Device JV properties were measured with **AM1.5 lamp** at clean room before and after preformed the transient PAIOS measurements.