

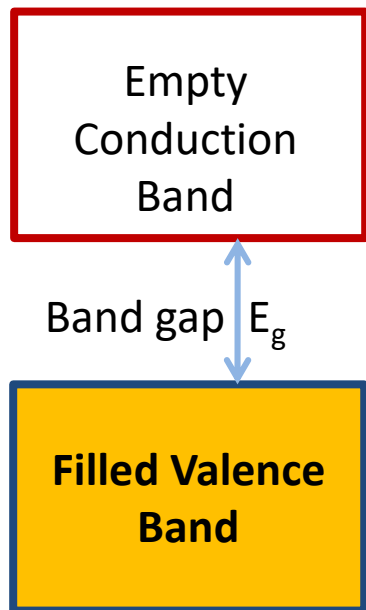


# Solar Energy: The Semiconductor

## **Learning objectives:**

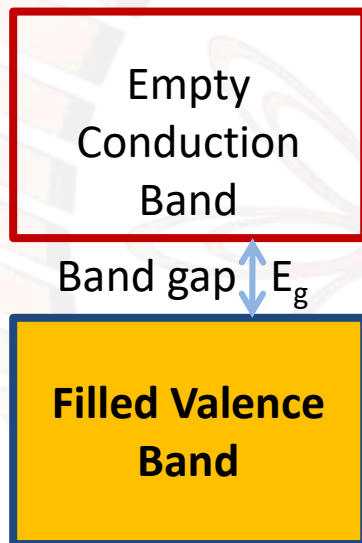
- 1) To plot the band diagrams of materials
- 2) To explain the interaction of bands with radiation
- 3) To understand the different ways in which band diagrams can be plotted.

Band gap  
greater than  
2eV: Insulator



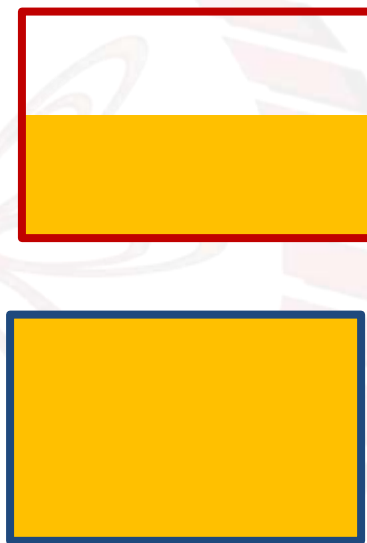
(a)

Band gap less  
than 2eV:  
Semiconductor



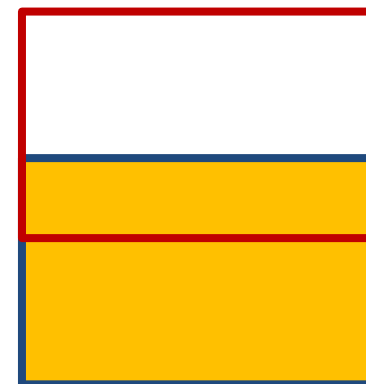
(b)

Partially filled  
bands: Metal



(c)

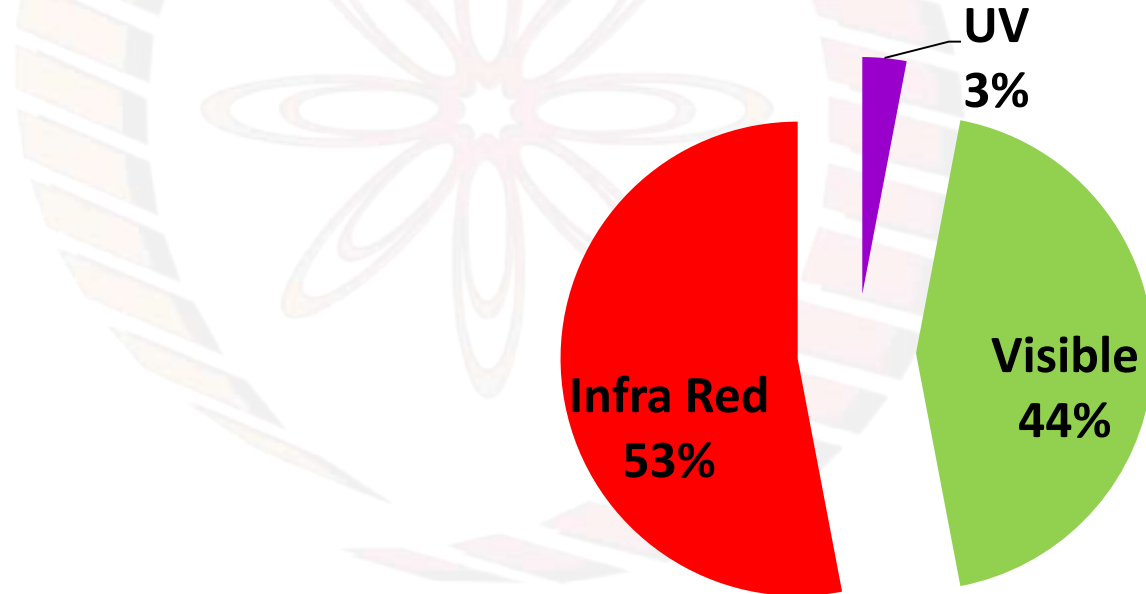
Overlapping  
bands: Metal



(d)

Visible Spectrum Wavelength: 400 nm (violet) to 700 nm (red)

Corresponding band gaps: 3.1 eV to 1.8 eV



Band gap  
greater than  
2eV: Insulator



Band gap  $E_g$



Band gap less  
than 2eV:  
Semiconductor



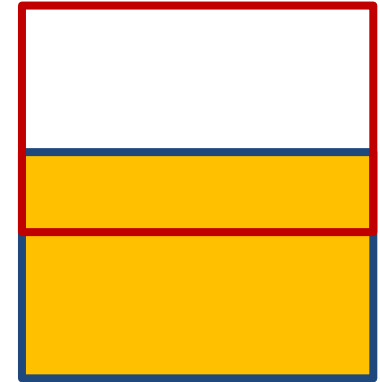
Band gap  $E_g$



Partially filled  
bands: Metal



Overlapping  
bands: Metal



Visible Spectrum Wavelength: 400 nm (violet) to 700 nm (red)  
Corresponding band gaps: 3.1 eV to 1.8 eV

Intrinsic  
semiconductor



Empty  
Conduction  
Band

$E_f$  ———

Filled Valence  
Band

(a)

n-type extrinsic  
semiconductor



Empty  
Conduction  
Band

$E_f$  ———  
Donor Levels

Filled Valence  
Band

(b)

p-type extrinsic  
semiconductor

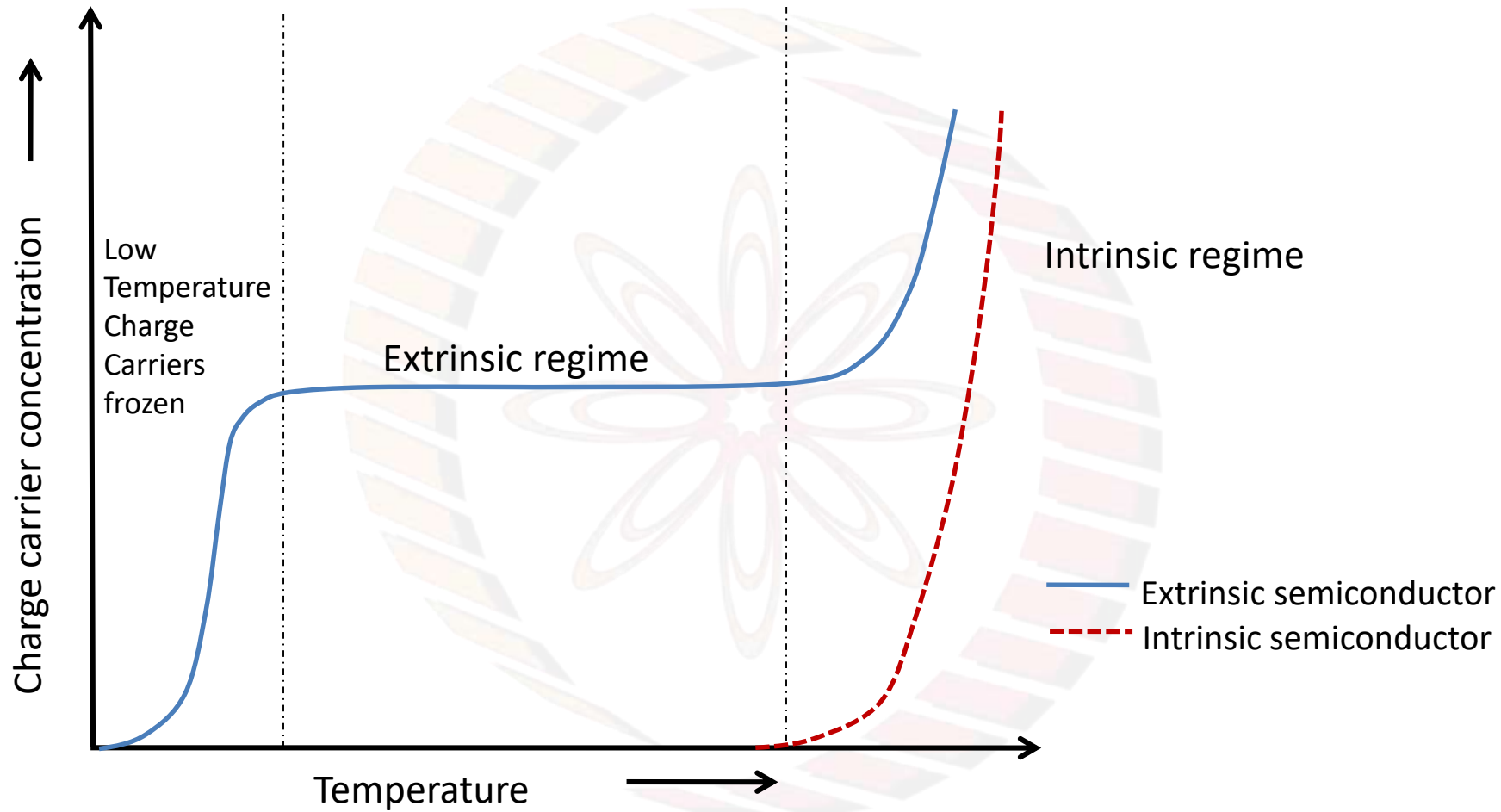


Empty  
Conduction  
Band

$E_f$  ———  
Acceptor Levels

Filled Valence  
Band

(c)



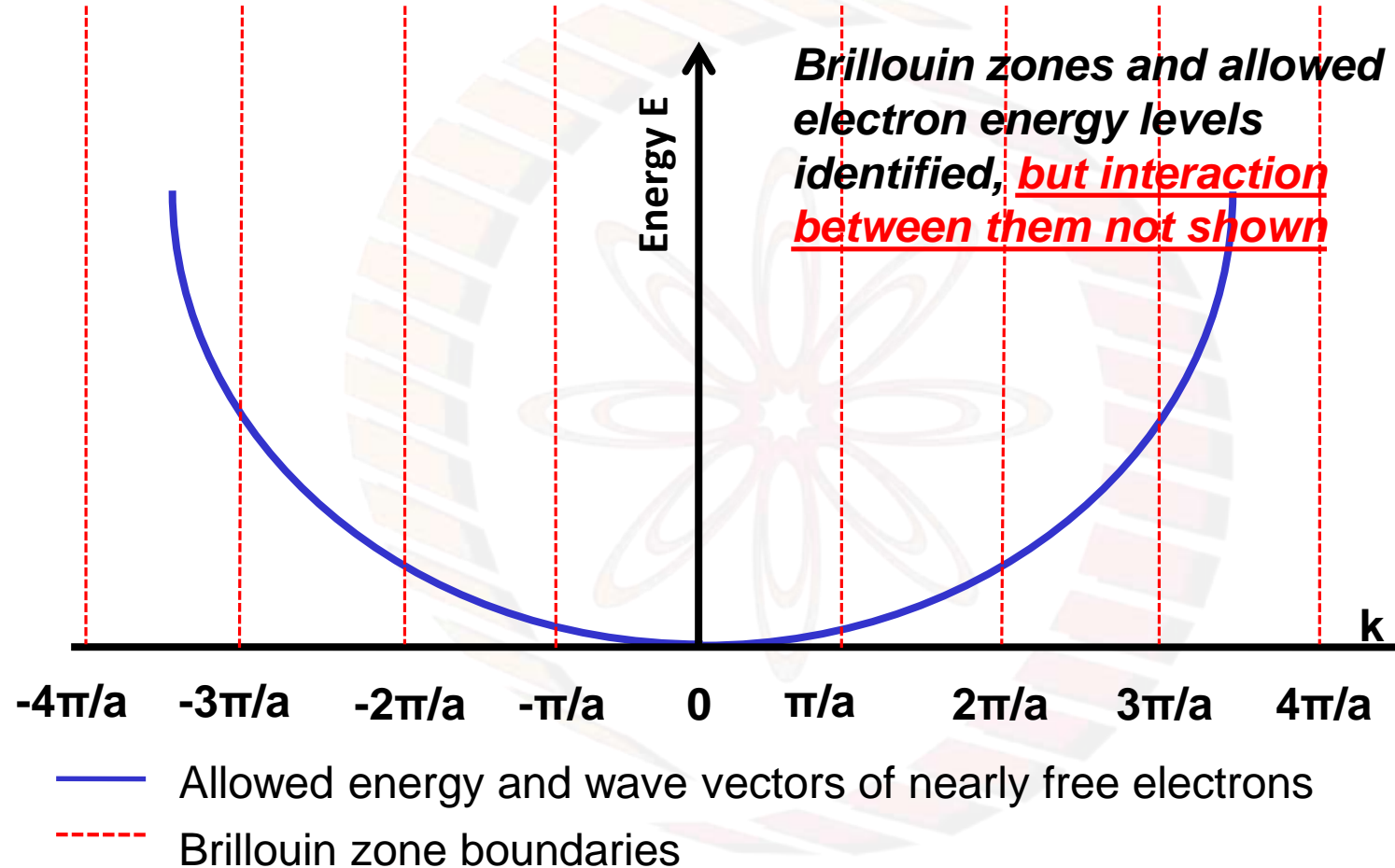

$$E = h\nu$$

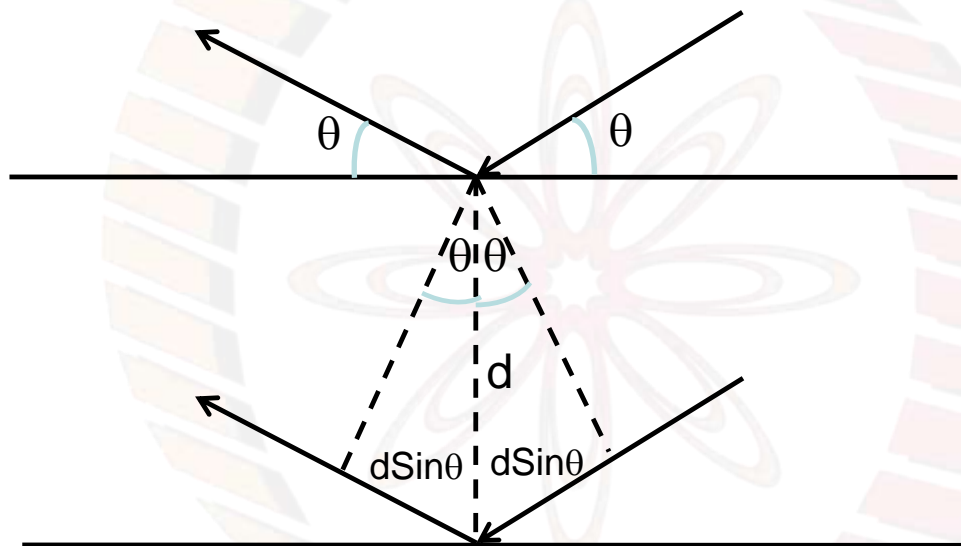
$$\lambda = \frac{h}{p}$$

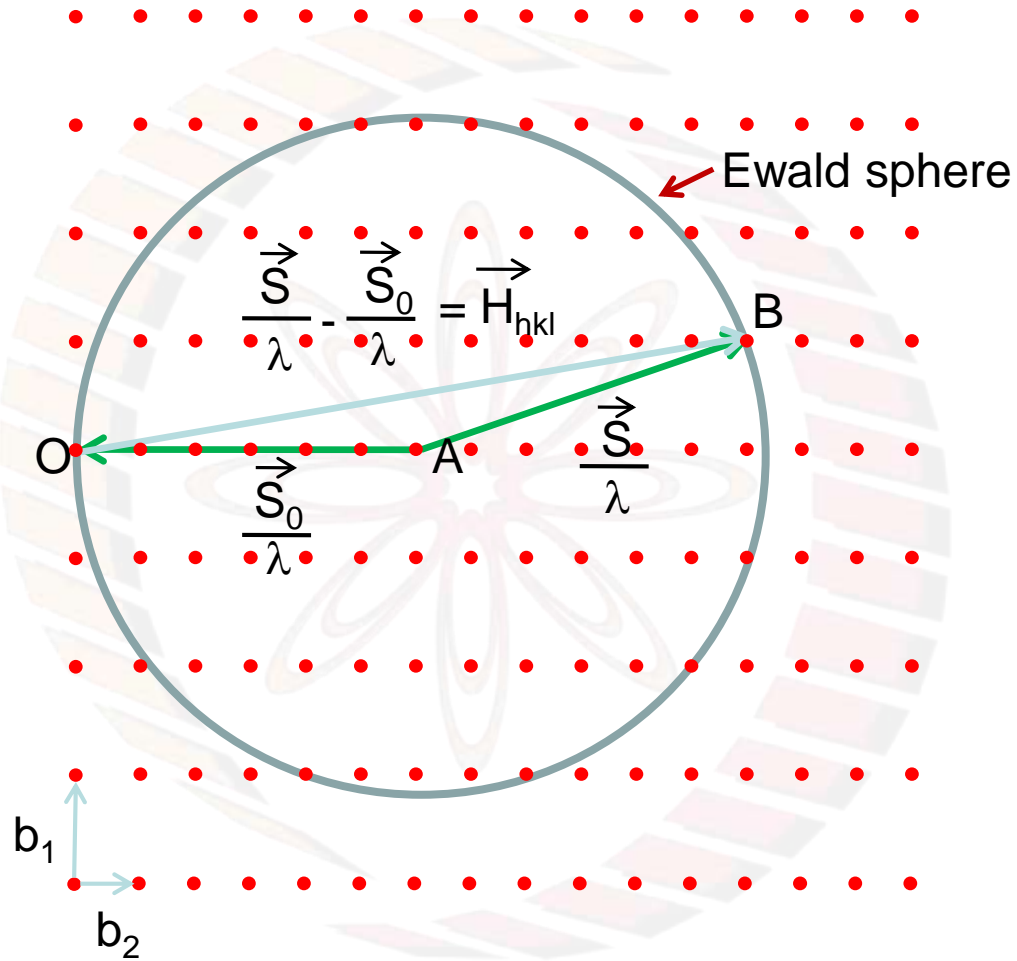
Planck  
de Broglie

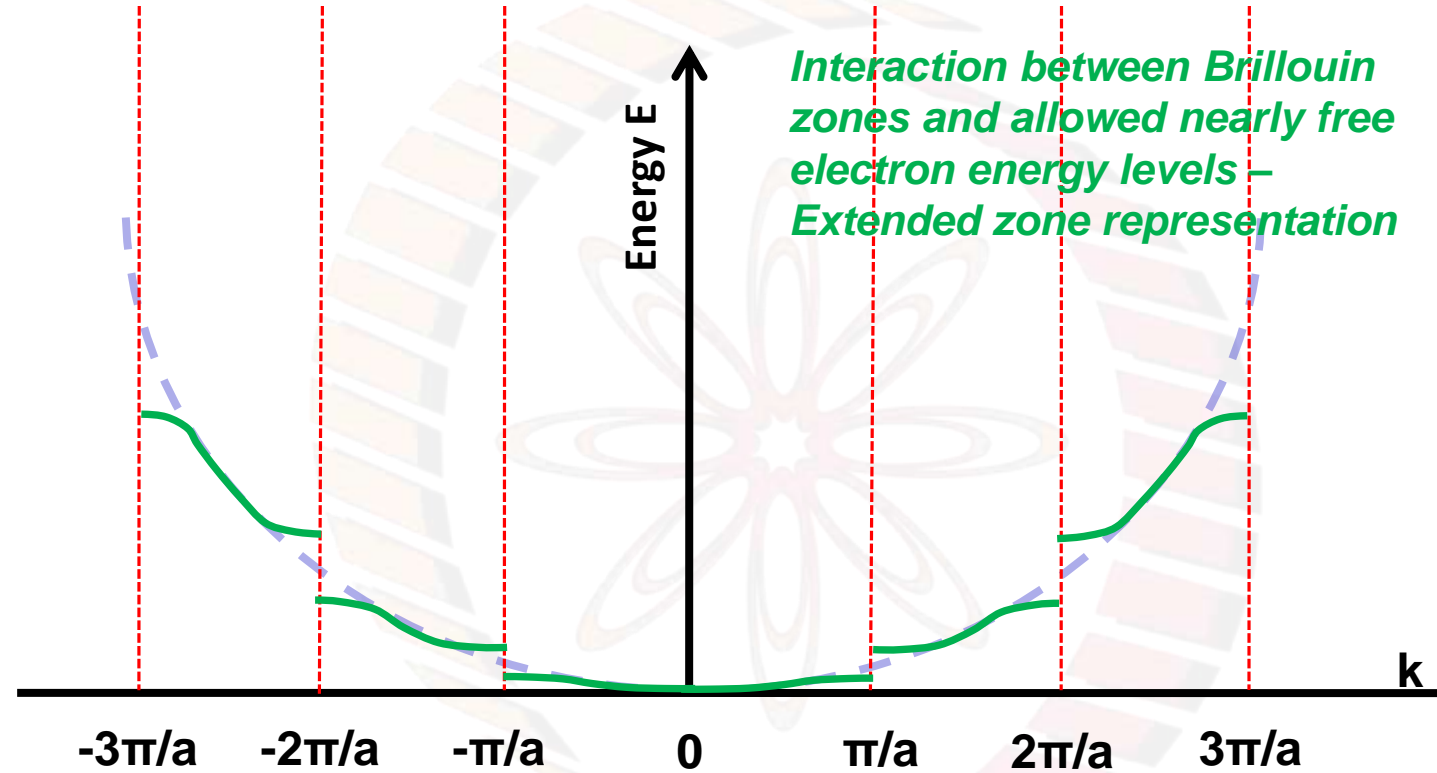
$$E = \frac{\hbar^2 k^2}{2m}$$



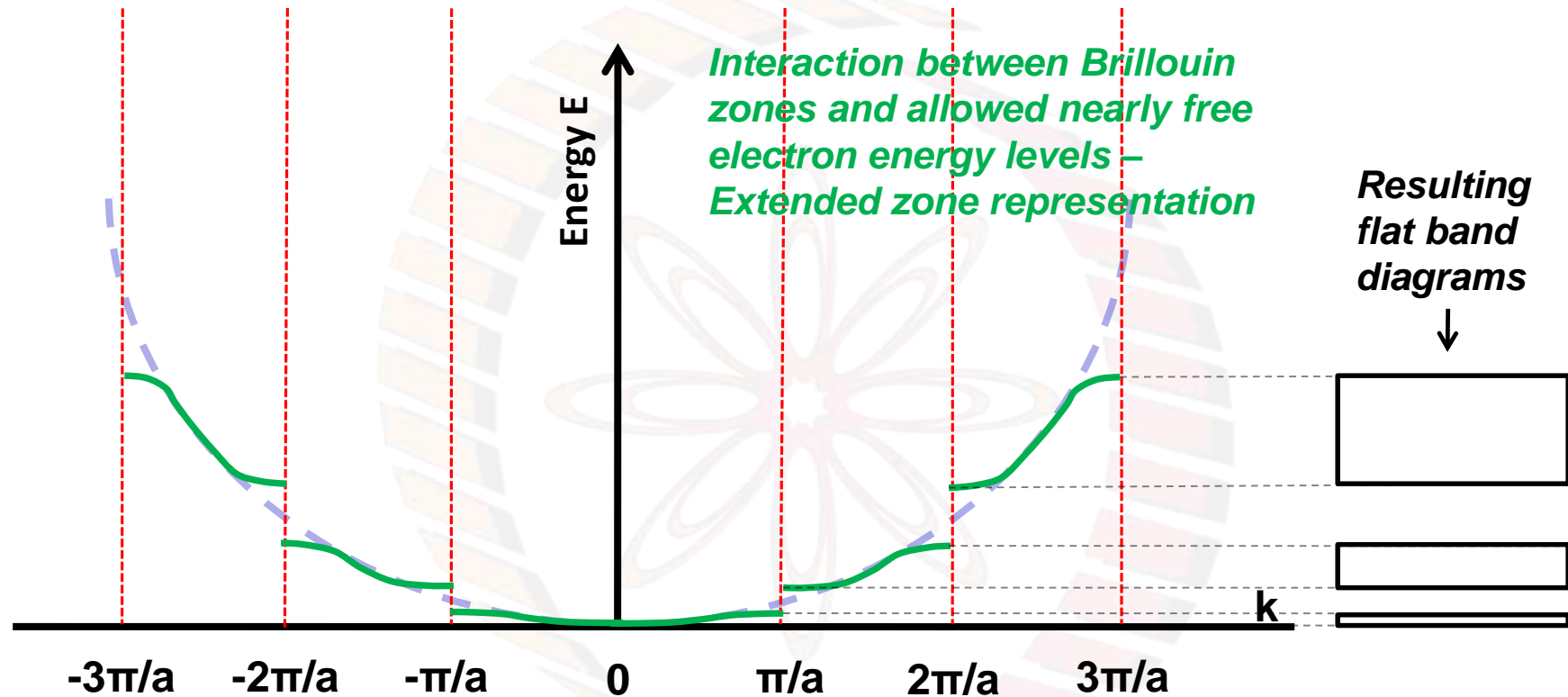




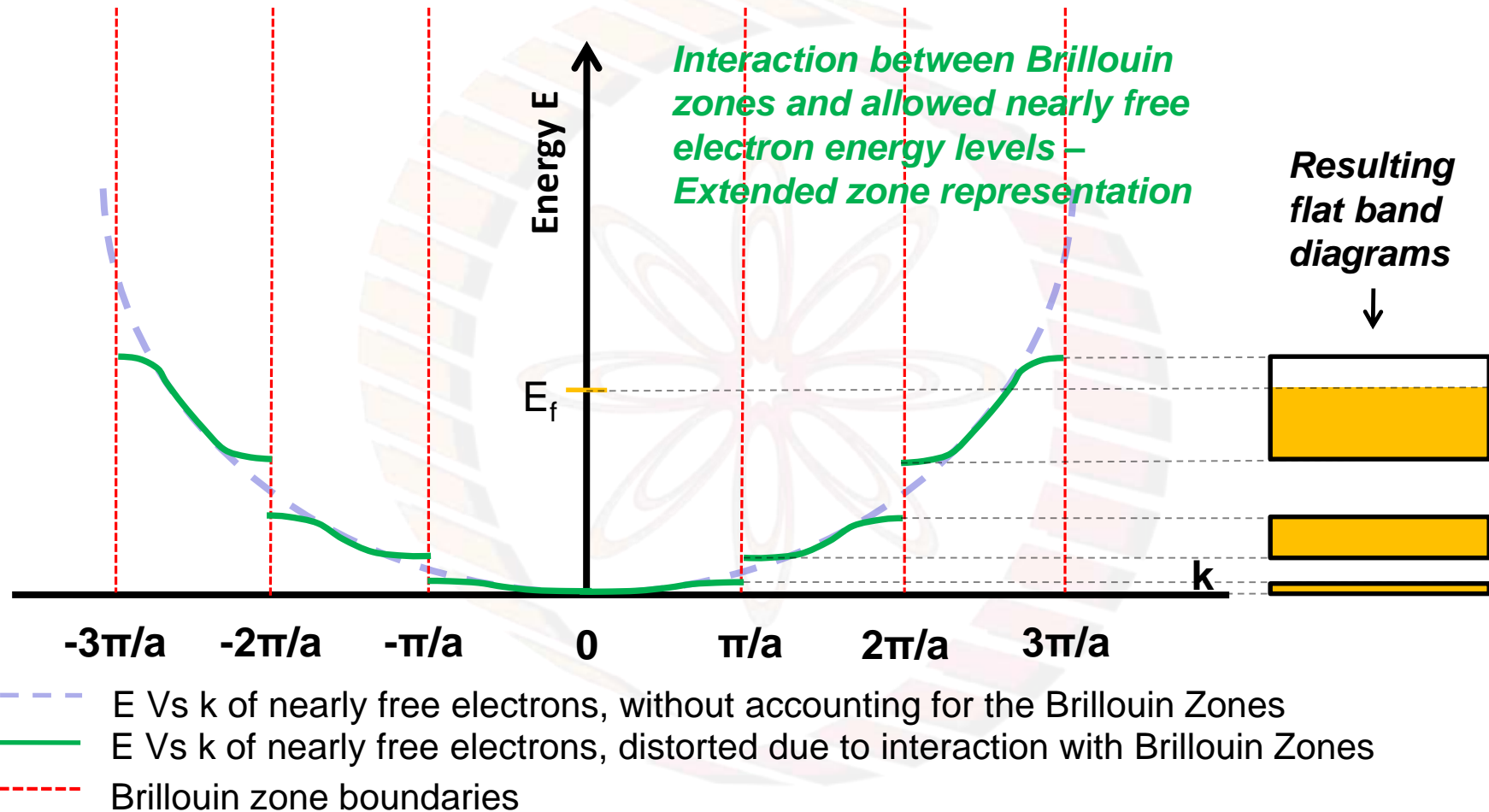


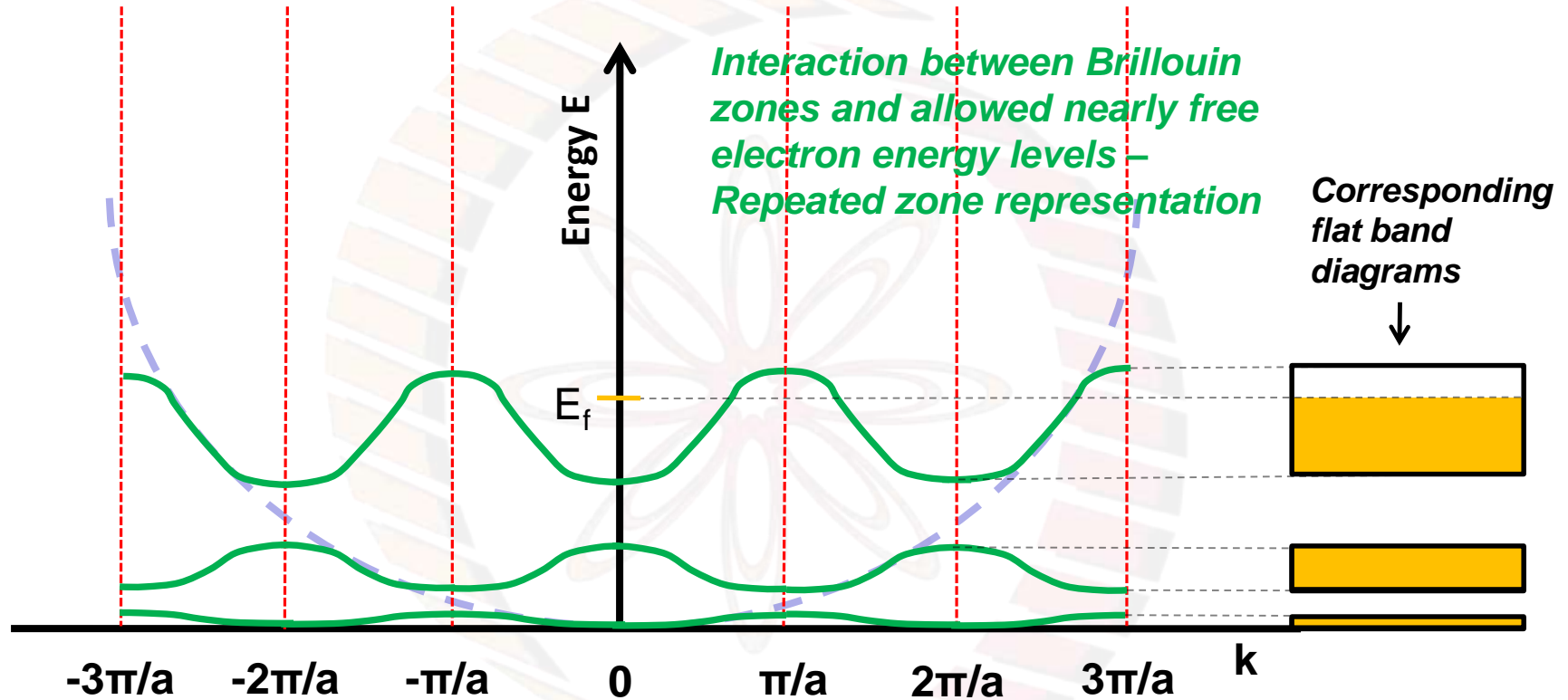


- E Vs k of nearly free electrons, without accounting for the Brillouin Zones
- E Vs k of nearly free electrons, distorted due to interaction with Brillouin Zones
- Brillouin zone boundaries

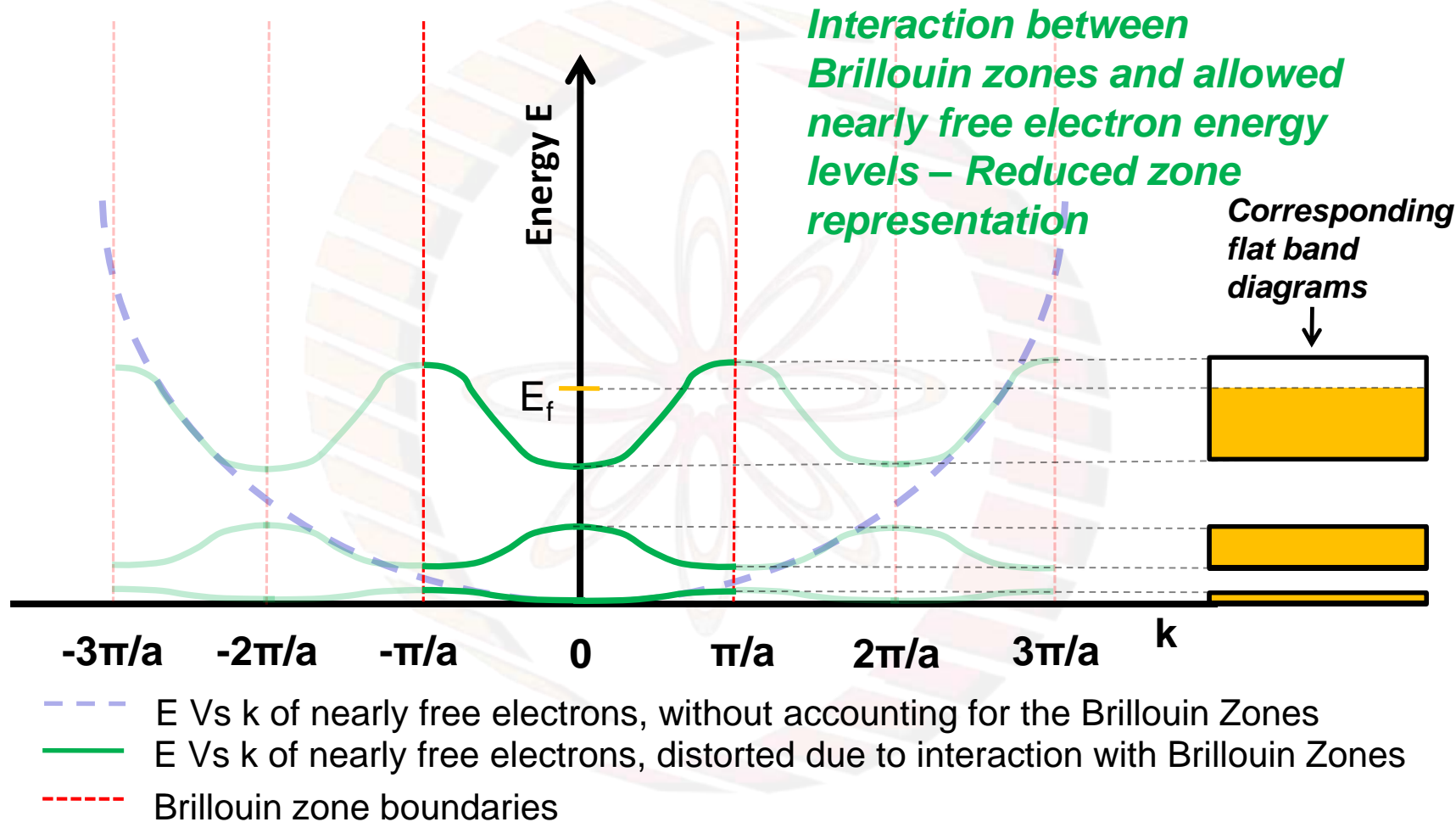


- $E$  Vs  $k$  of nearly free electrons, without accounting for the Brillouin Zones
- $E$  Vs  $k$  of nearly free electrons, distorted due to interaction with Brillouin Zones
- Brillouin zone boundaries

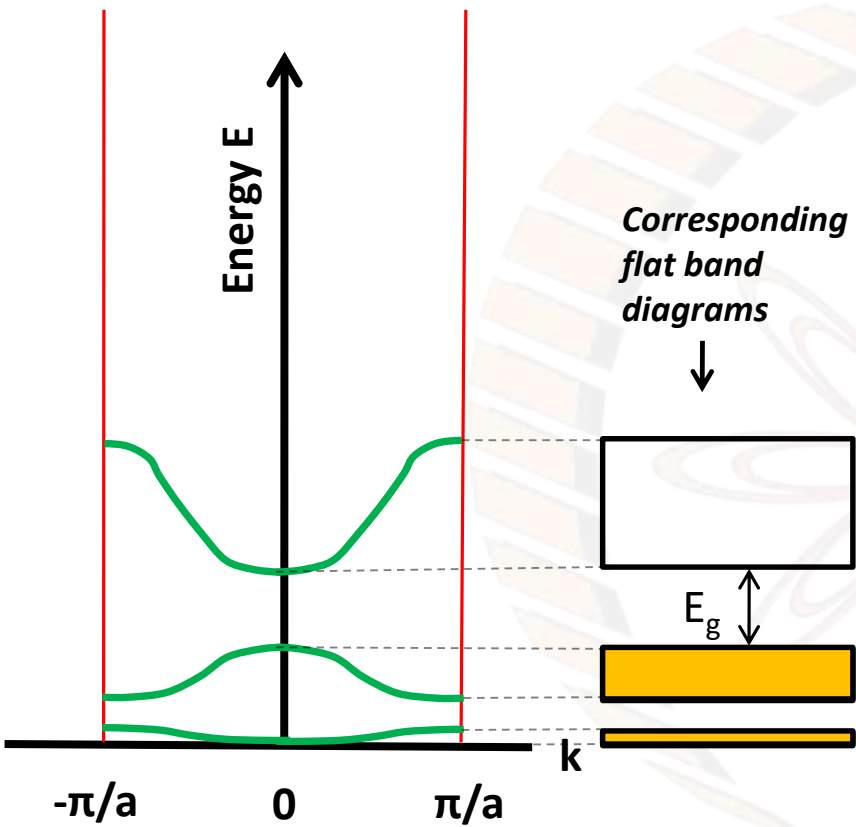




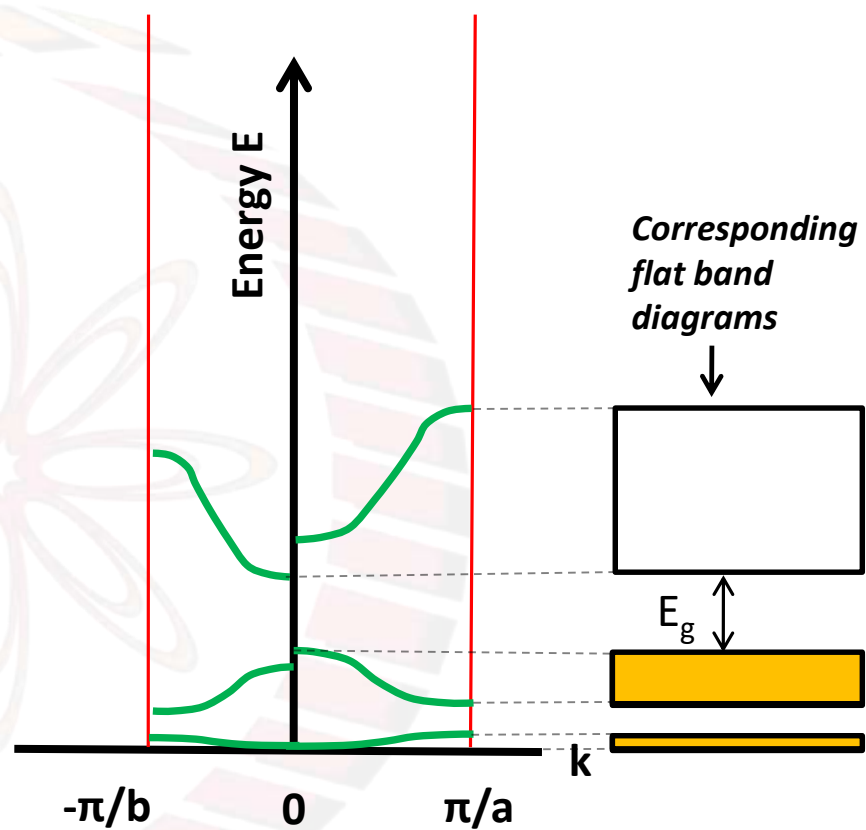
- $E$  Vs  $k$  of nearly free electrons, without accounting for the Brillouin Zones
- $E$  Vs  $k$  of nearly free electrons, distorted due to interaction with Brillouin Zones
- Brillouin zone boundaries



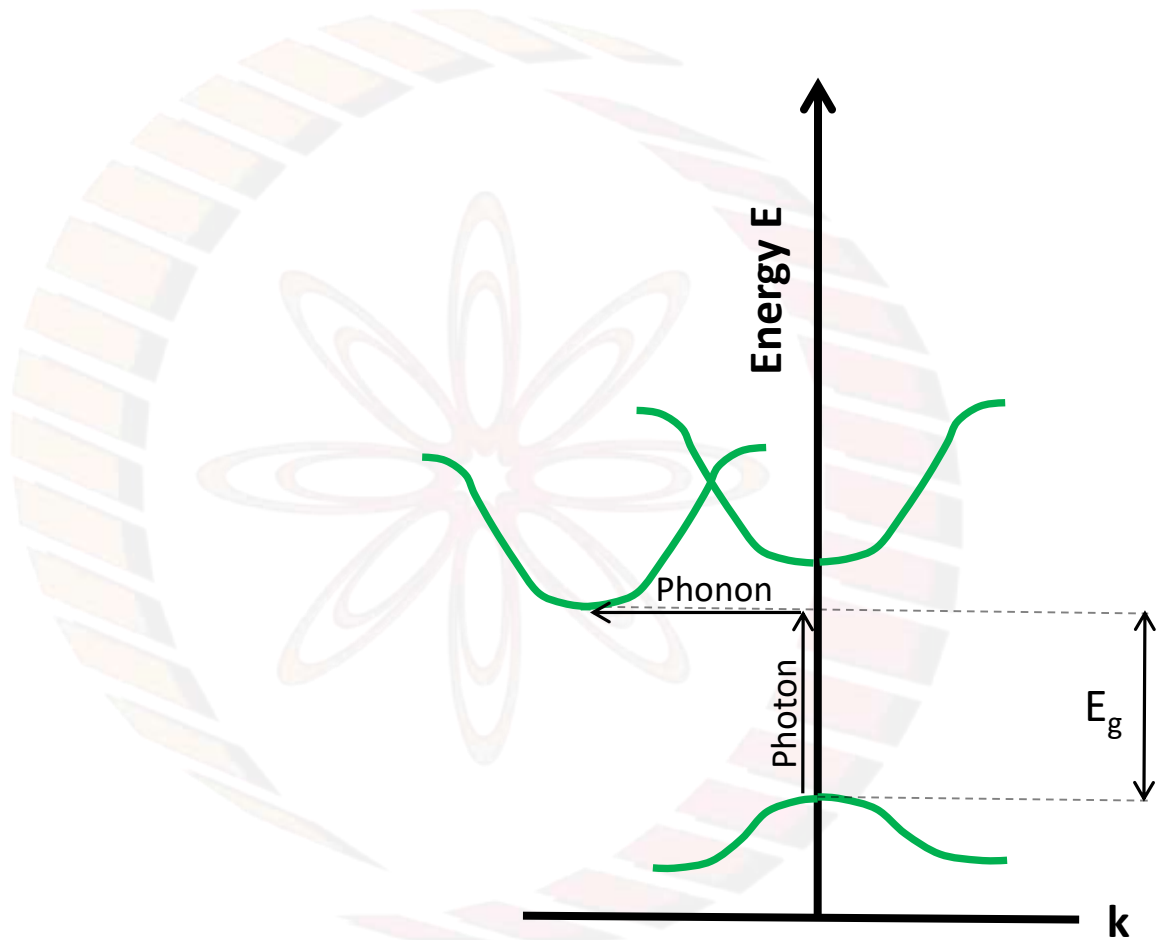




Direct bandgap semiconductor



Indirect bandgap semiconductor



## Conclusions:

- 1) There is significant variation in the band diagrams of different types of materials
- 2) Interaction of a material with radiation depends strongly on its band diagram
- 3) Visible spectrum is a small fraction of solar radiation
- 4) There is a difference in the effectiveness with which direct and indirect bandgap semiconductors interact with radiation



# Solar Energy: The p-n junction

## **Learning objectives:**

- 1) To describe the material features as well as characteristics of the p-n junction
- 2) To explain the functioning of the p-n junction

Intrinsic  
semiconductor

Empty  
Conduction  
Band

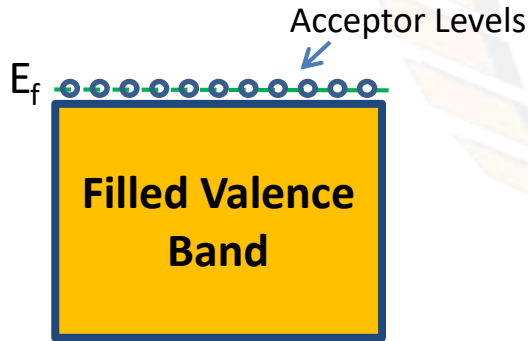
$E_f$  ———

**Filled Valence  
Band**

- Charge carrier concentration depends only temperature
- Conductivity depends only on Temperature
- Examples:
  - Elemental: Group IV A: Si (1.1 eV), Ge (0.7 eV)
  - Compound:
    - Group III A and Group V A (III-V)
      - GaAs, InSb
    - Group II B and Group VI A (II-VI)
      - CdS, ZnTe

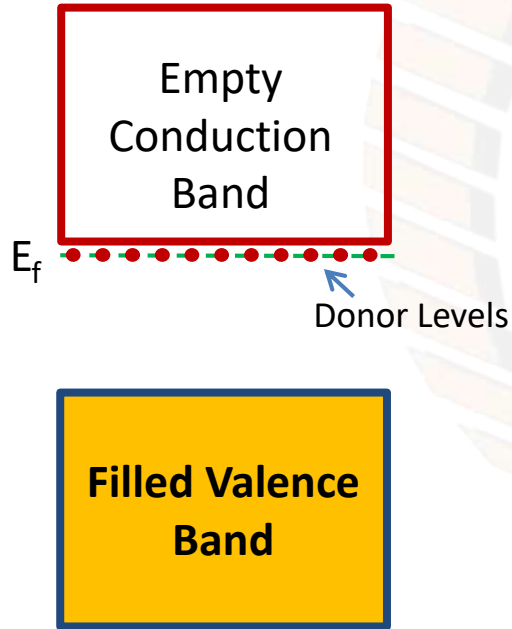
p-type extrinsic semiconductor

Empty  
Conduction  
Band



- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group III A elements: B, Al, Ga, In, Tl

n-type extrinsic semiconductor



- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group V A elements: N, P, As, Sb, Bi



Intrinsic  
semiconductor



Conduction  
Band

Electron in conduction band

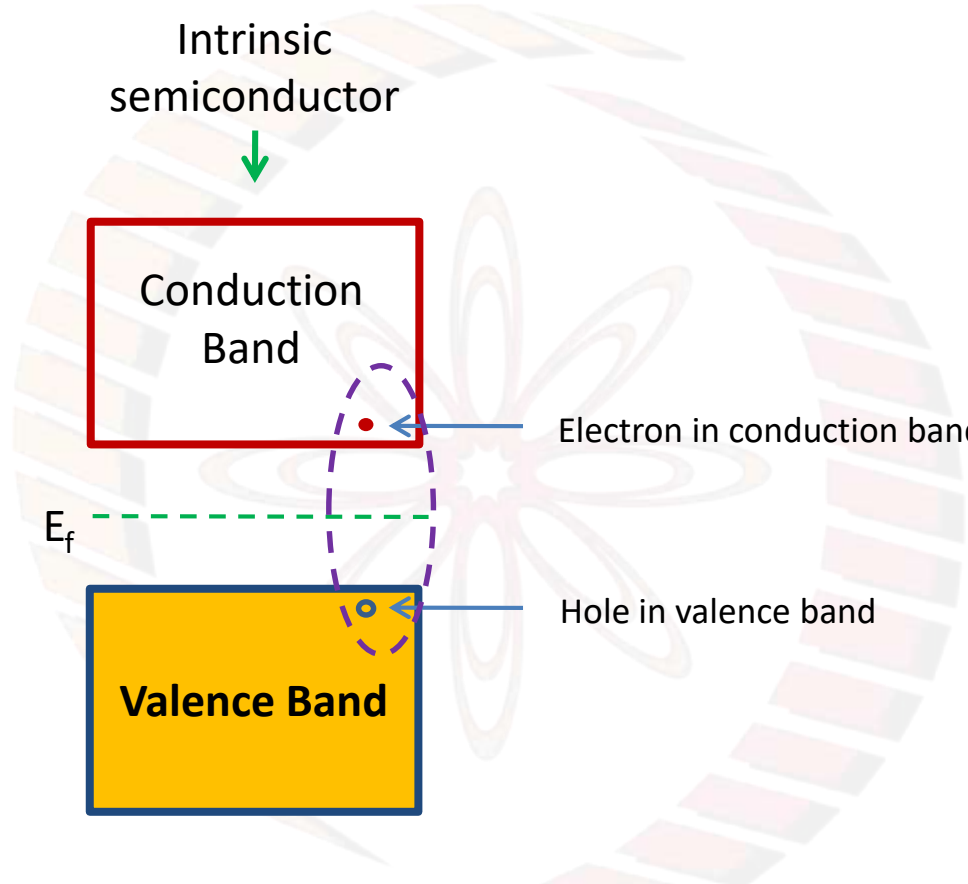
$E_f$

Hole in valence band

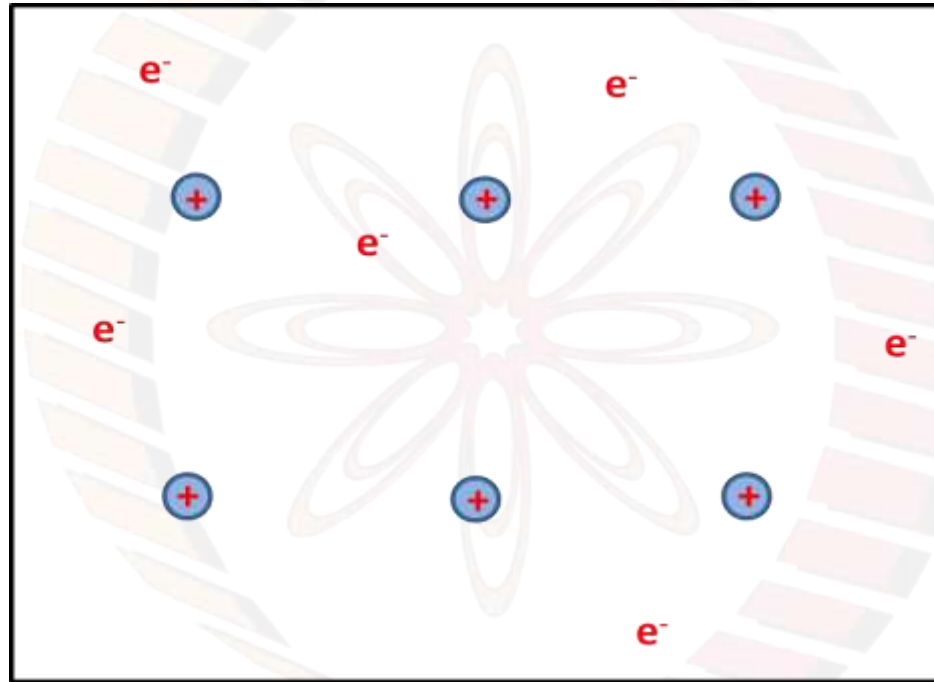
Valence Band

$$E_g = h\nu$$

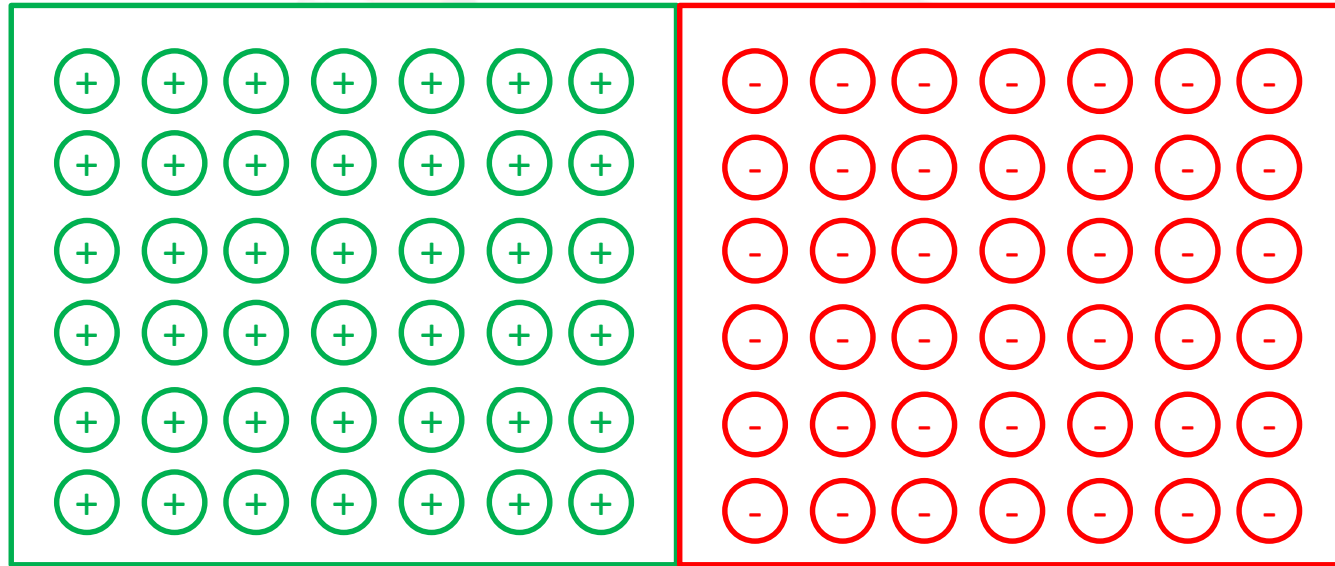
Stability of electron-hole pair?



# Metal



## The p-n junction

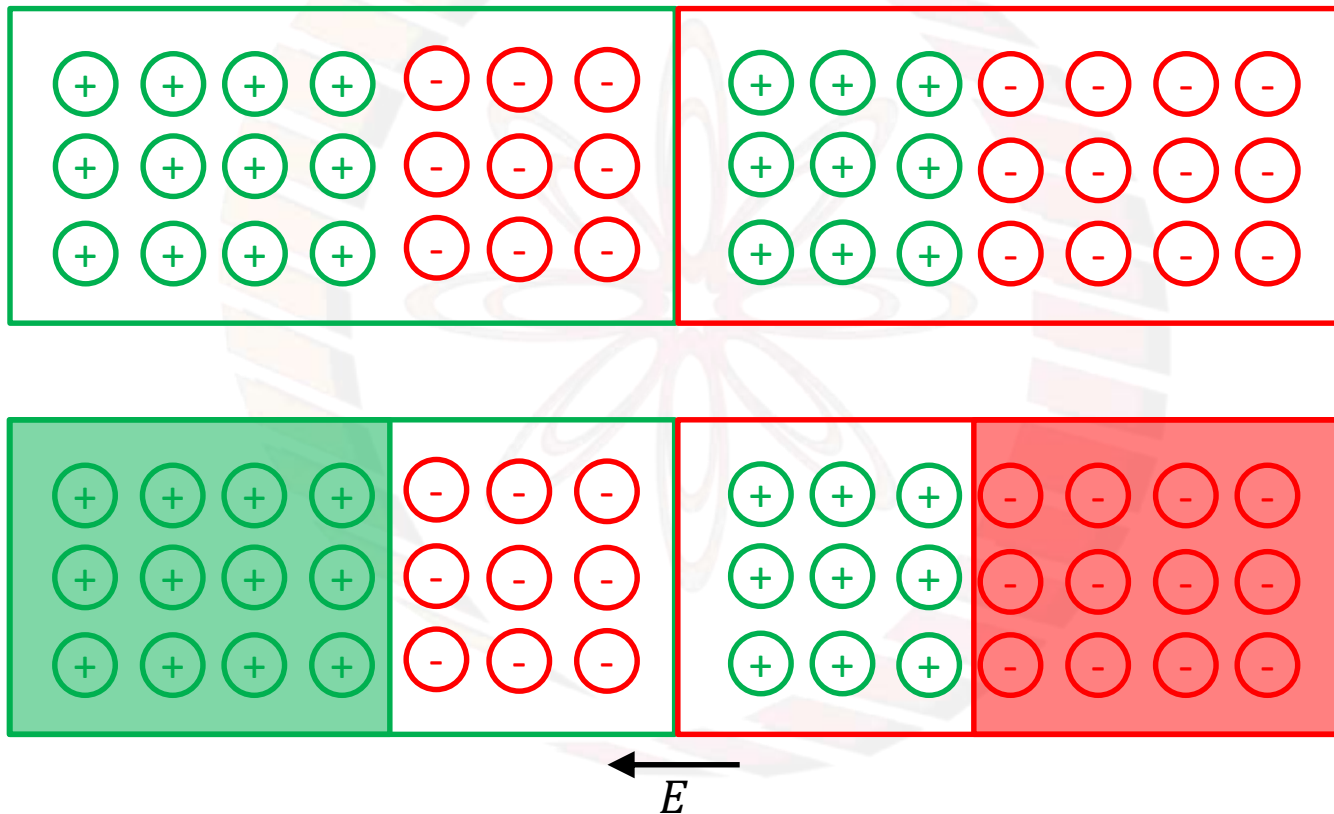


Si doped with B

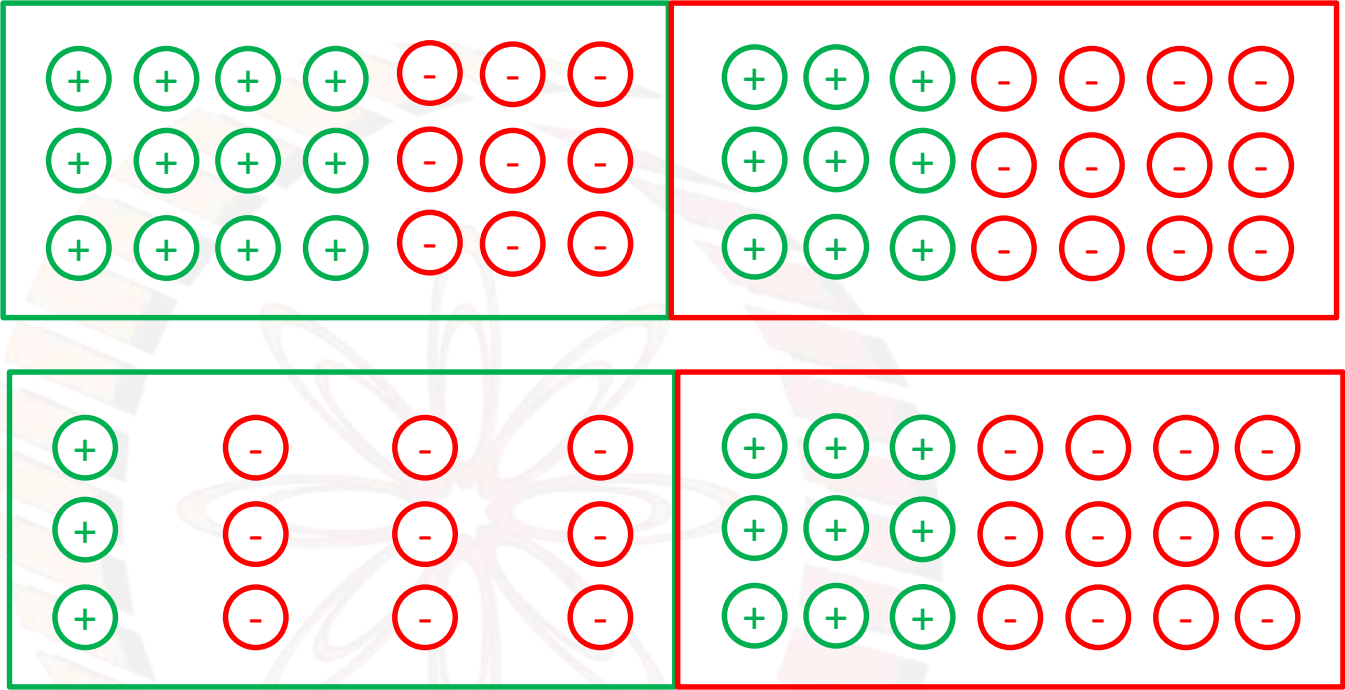
Si doped with P

$$\sigma = n|e|\mu_e + p|e|\mu_h$$

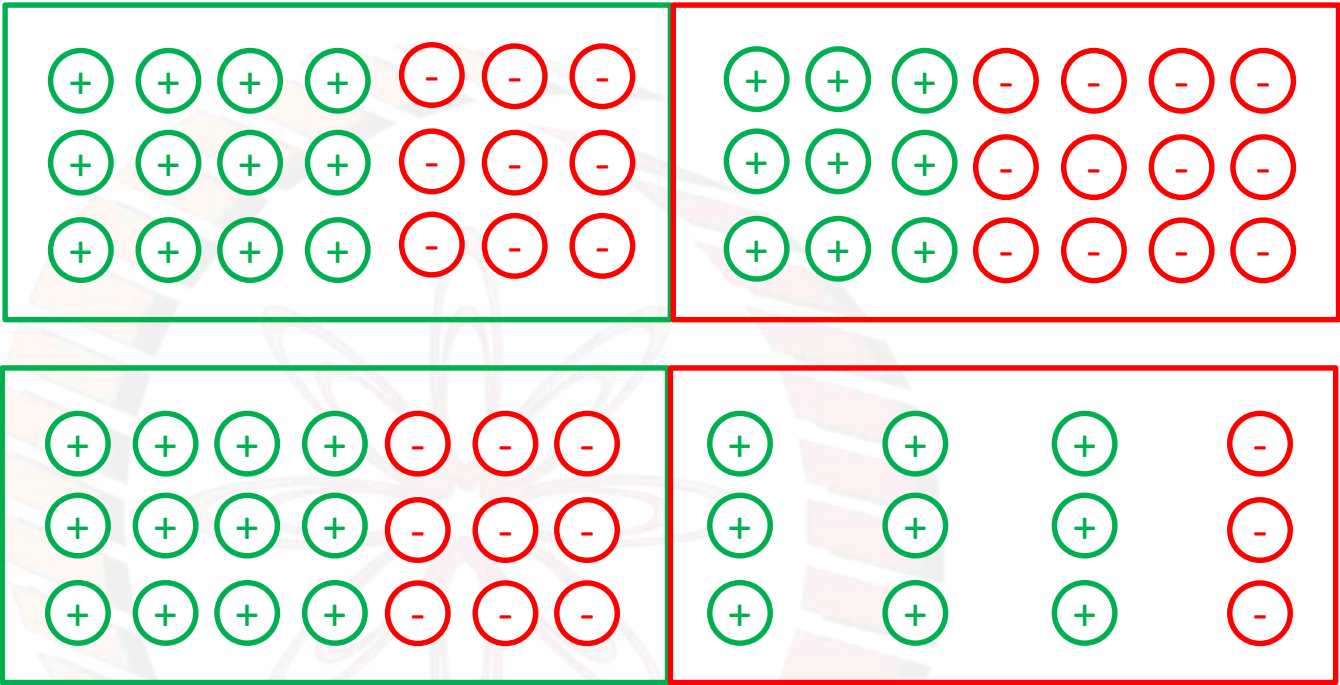
## The space charge region Depletion region

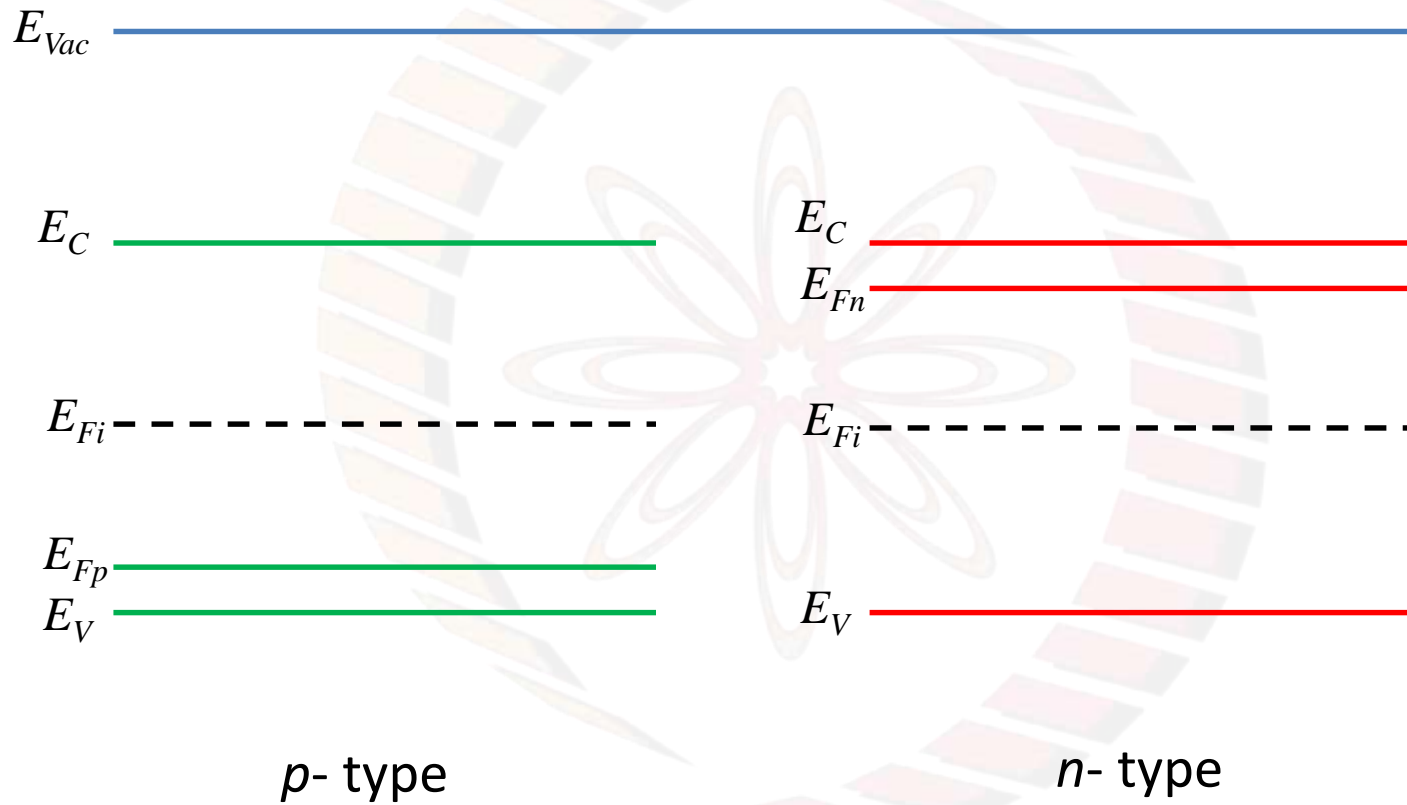


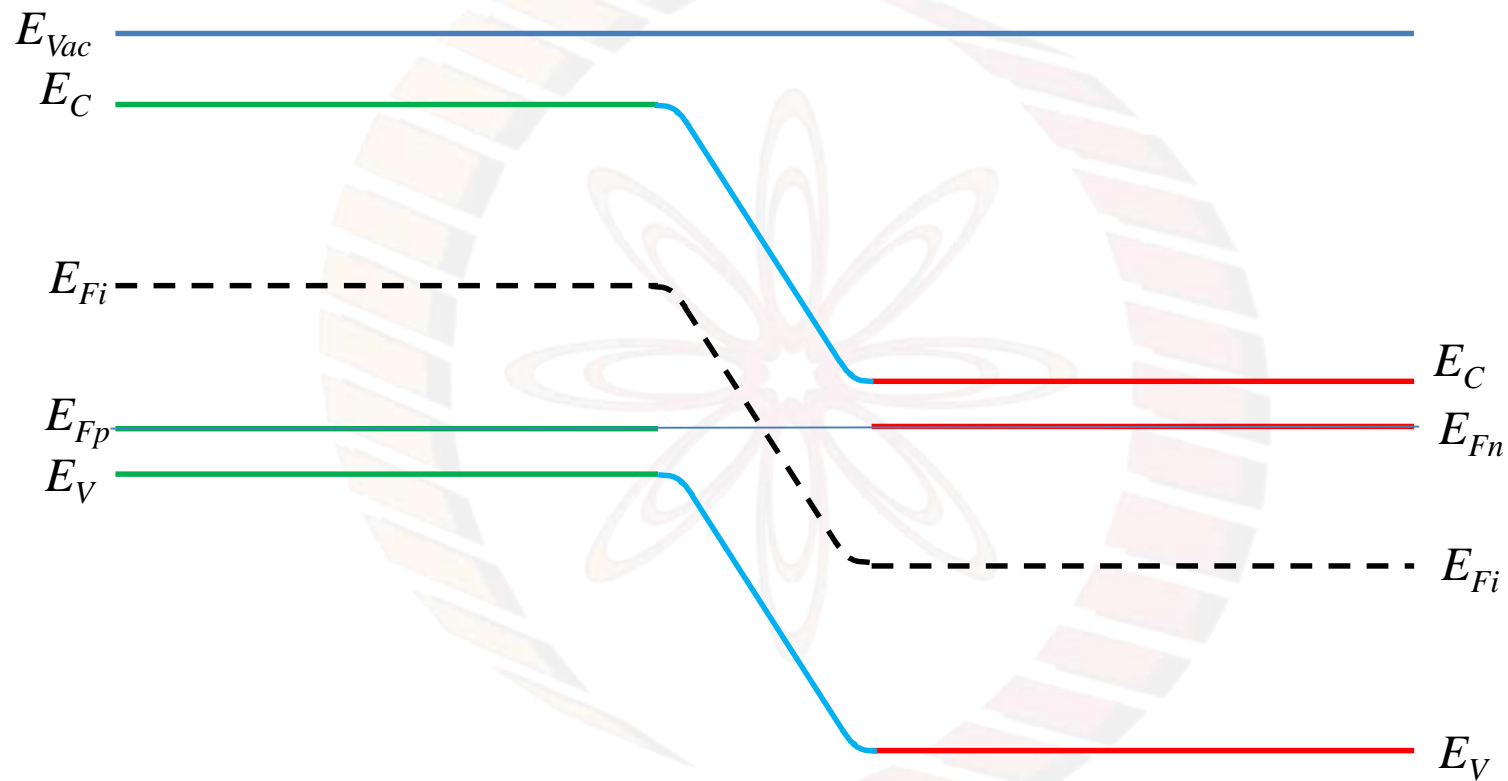
space charge region  
depletion region



space charge region  
depletion region

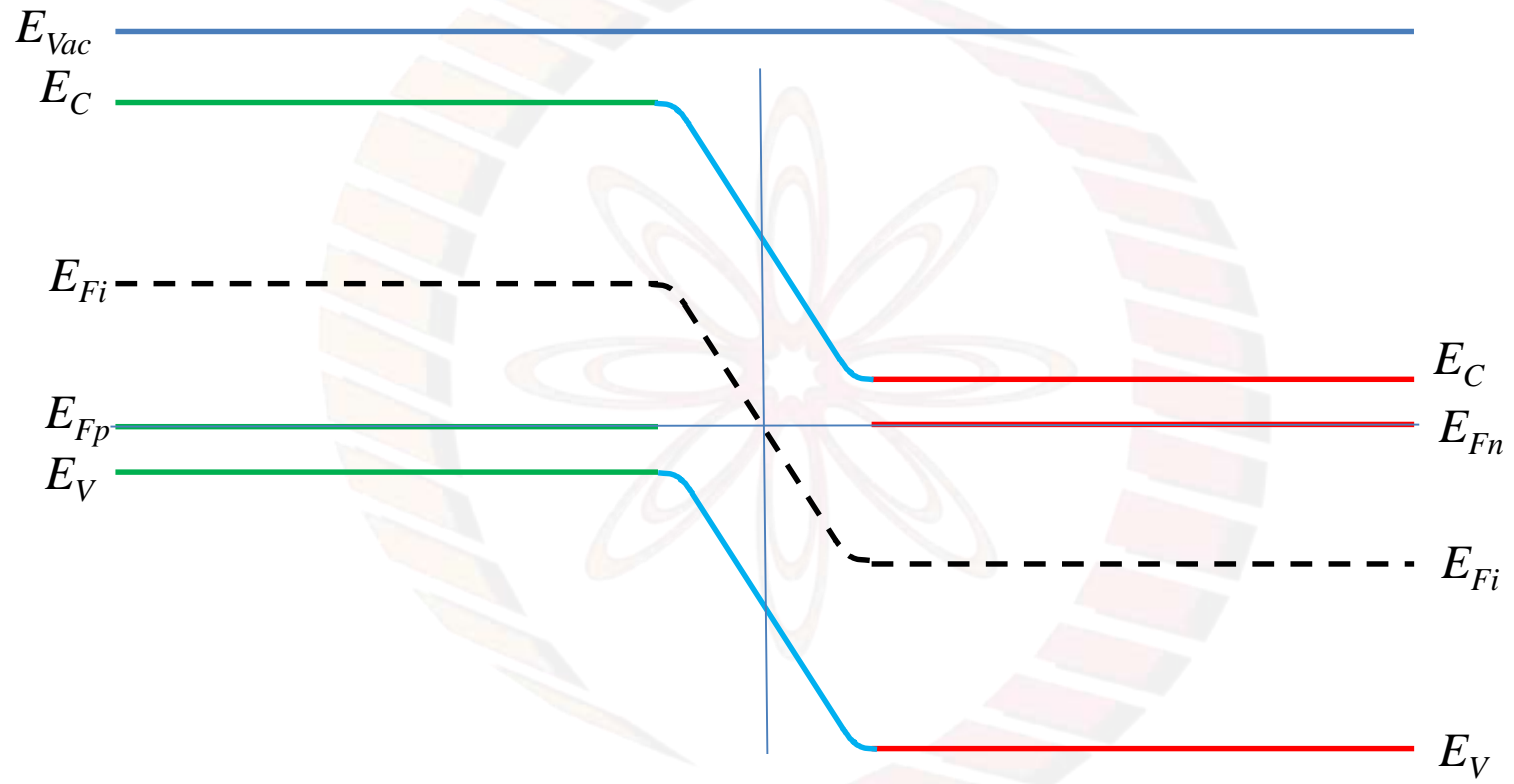






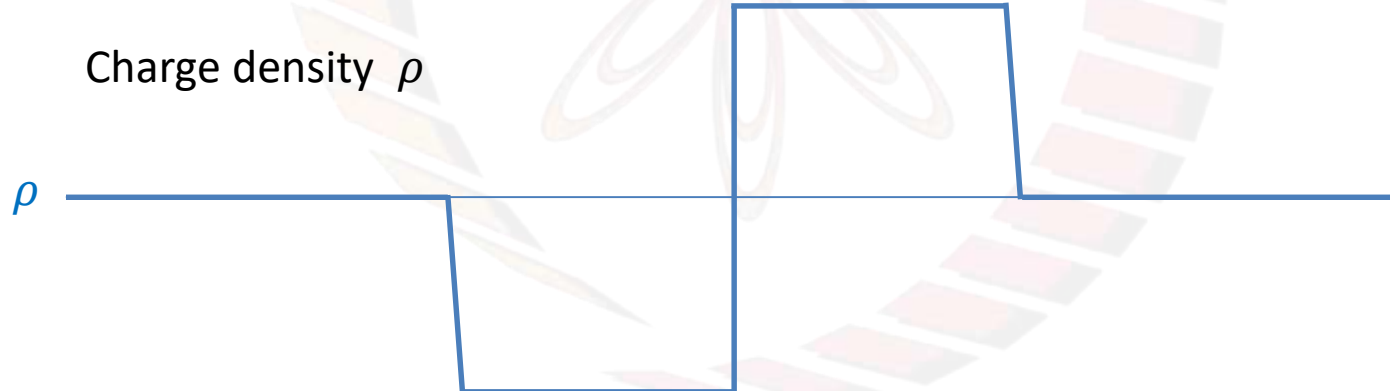
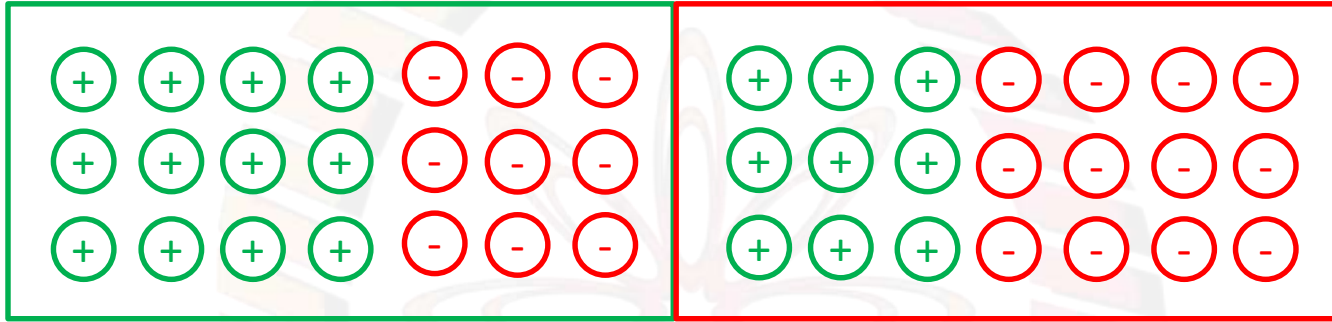
*pn*-junction



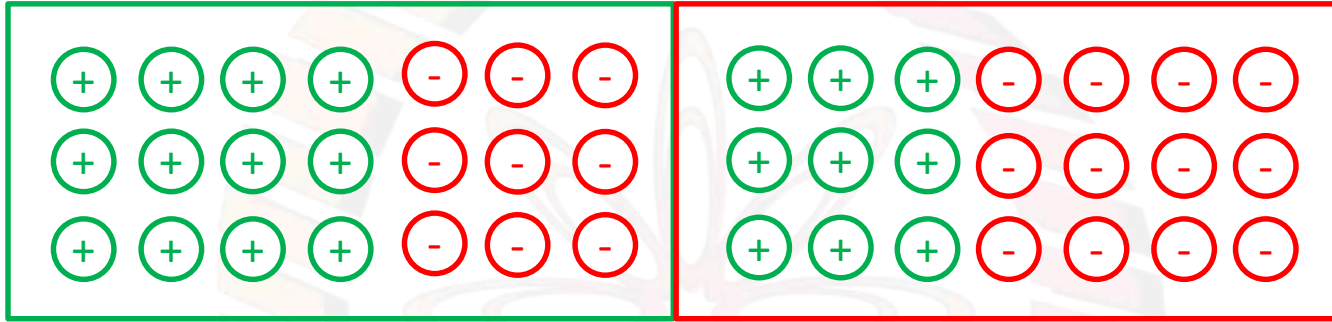


$pn$ -junction

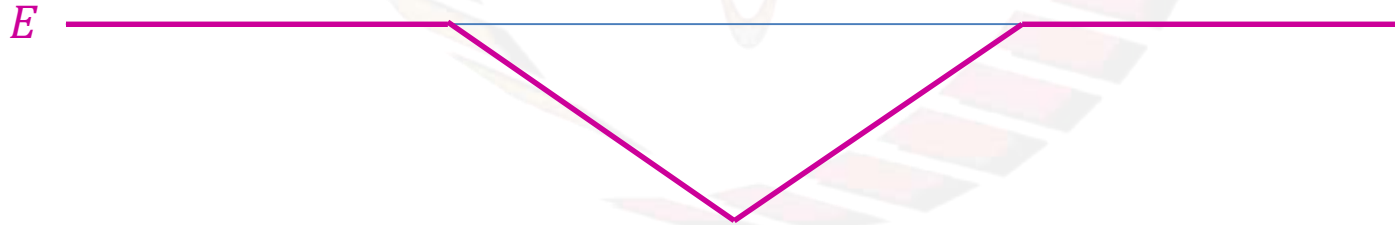
## The space charge region



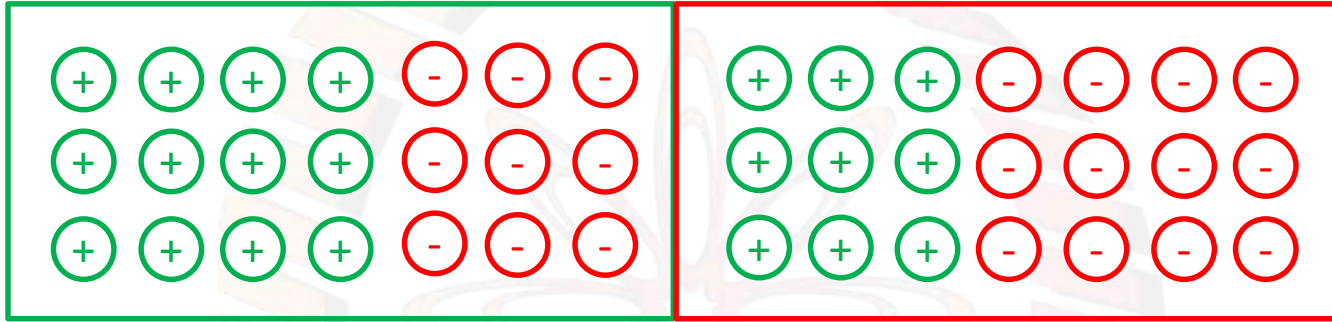
## The space charge region



$$\frac{\partial E}{\partial x} = \frac{\rho}{\epsilon}$$



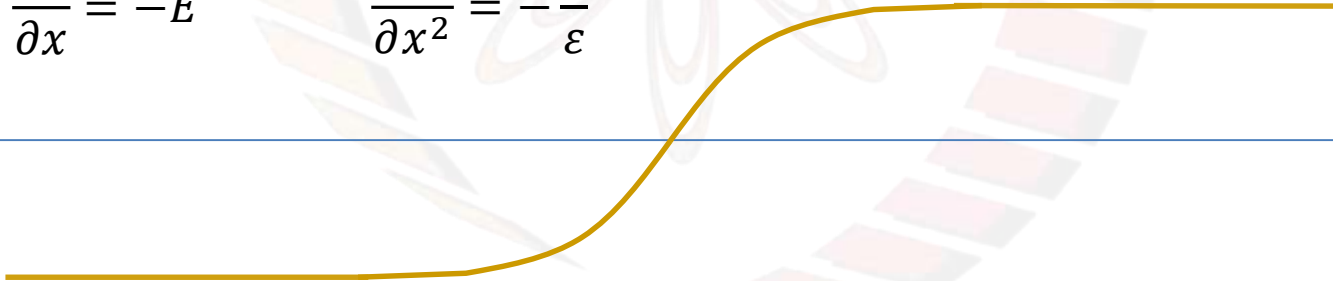
## The space charge region

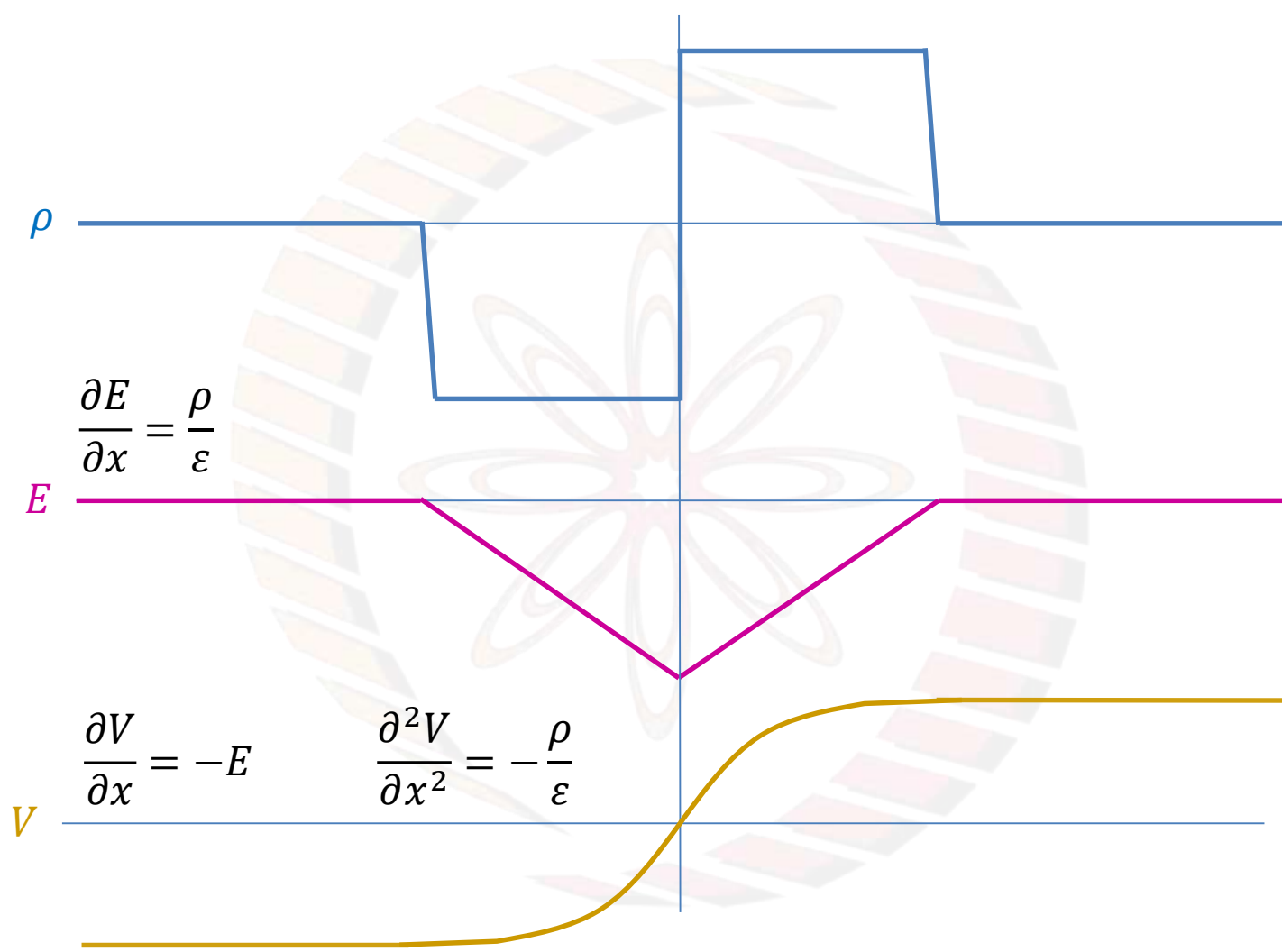


$$\frac{\partial V}{\partial x} = -E$$

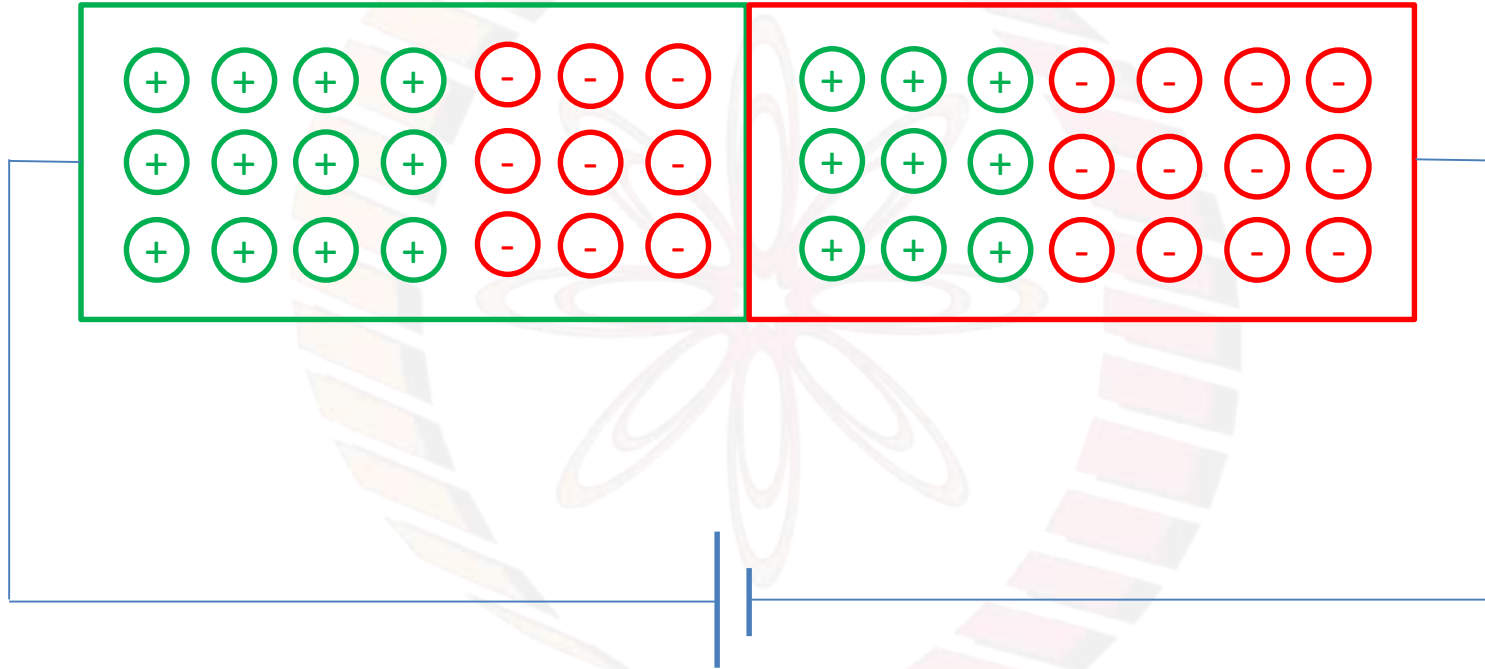
$$\frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\epsilon}$$

$V$

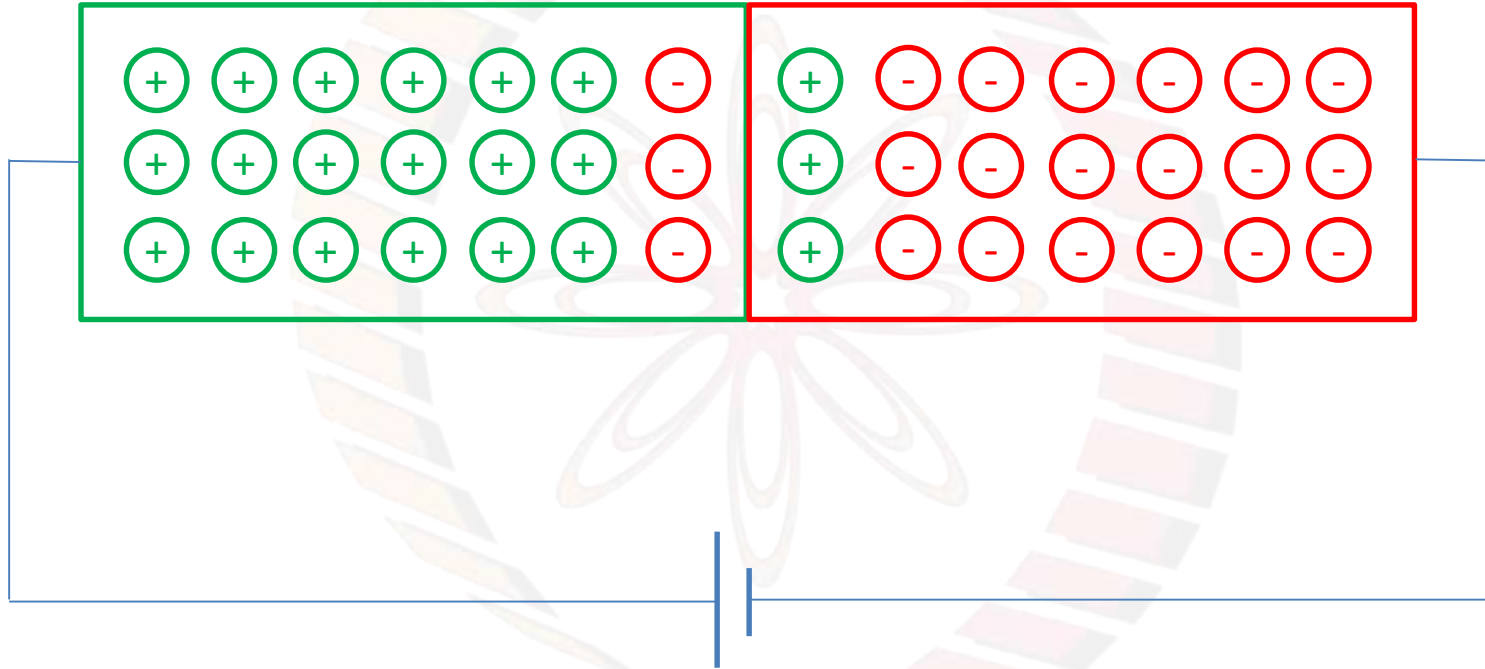




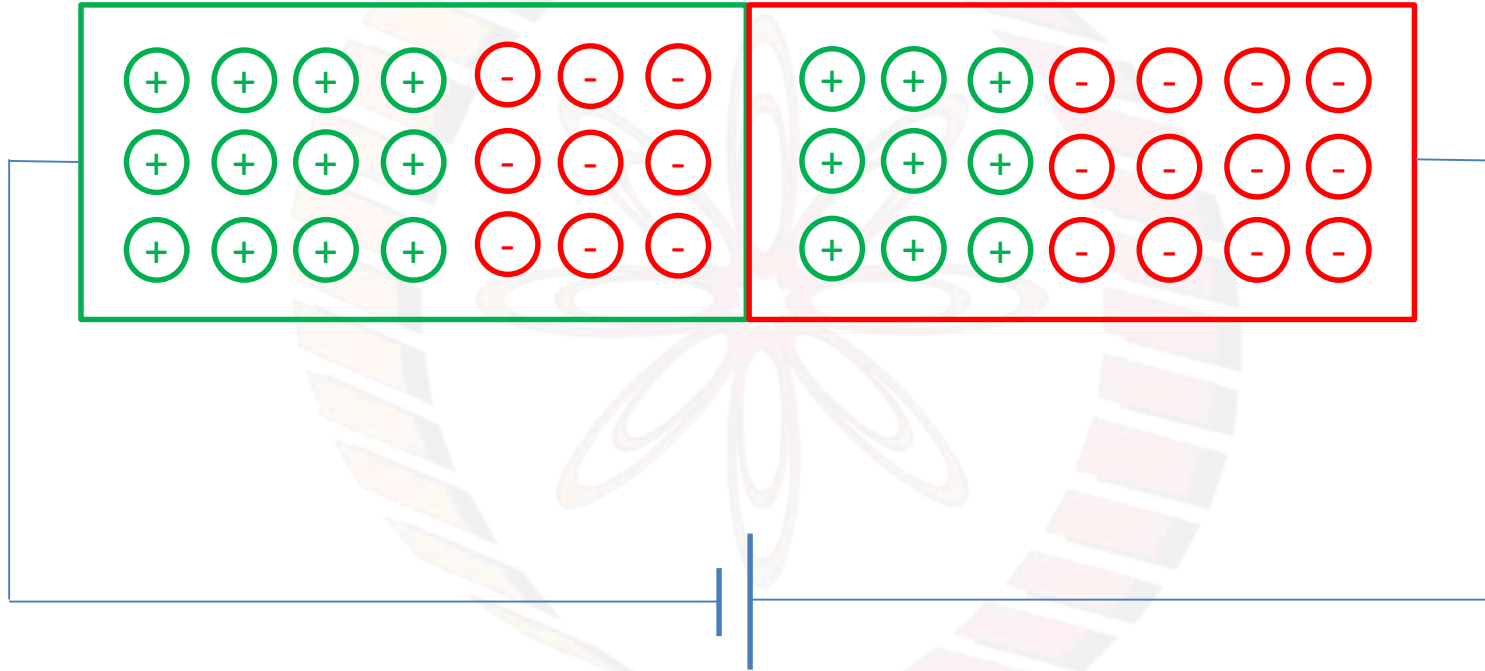
## Forward bias



## Forward bias

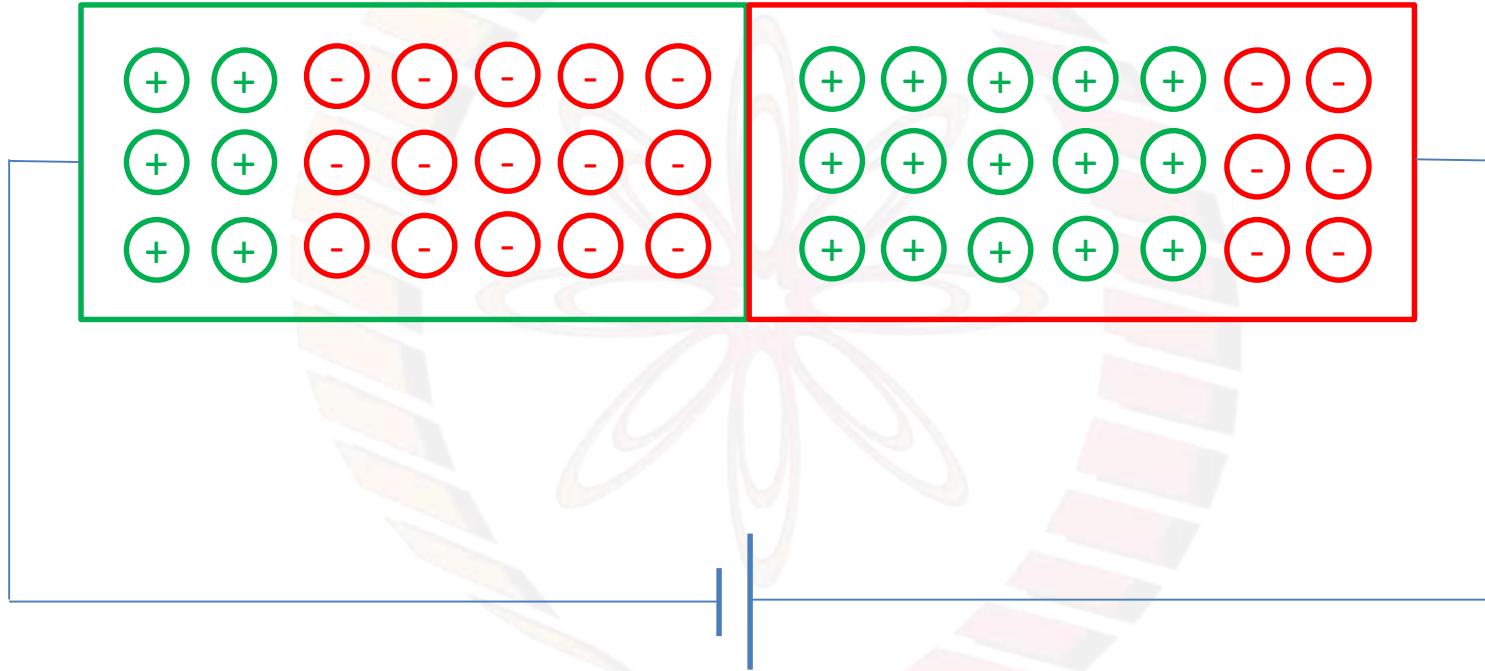


## Reverse bias

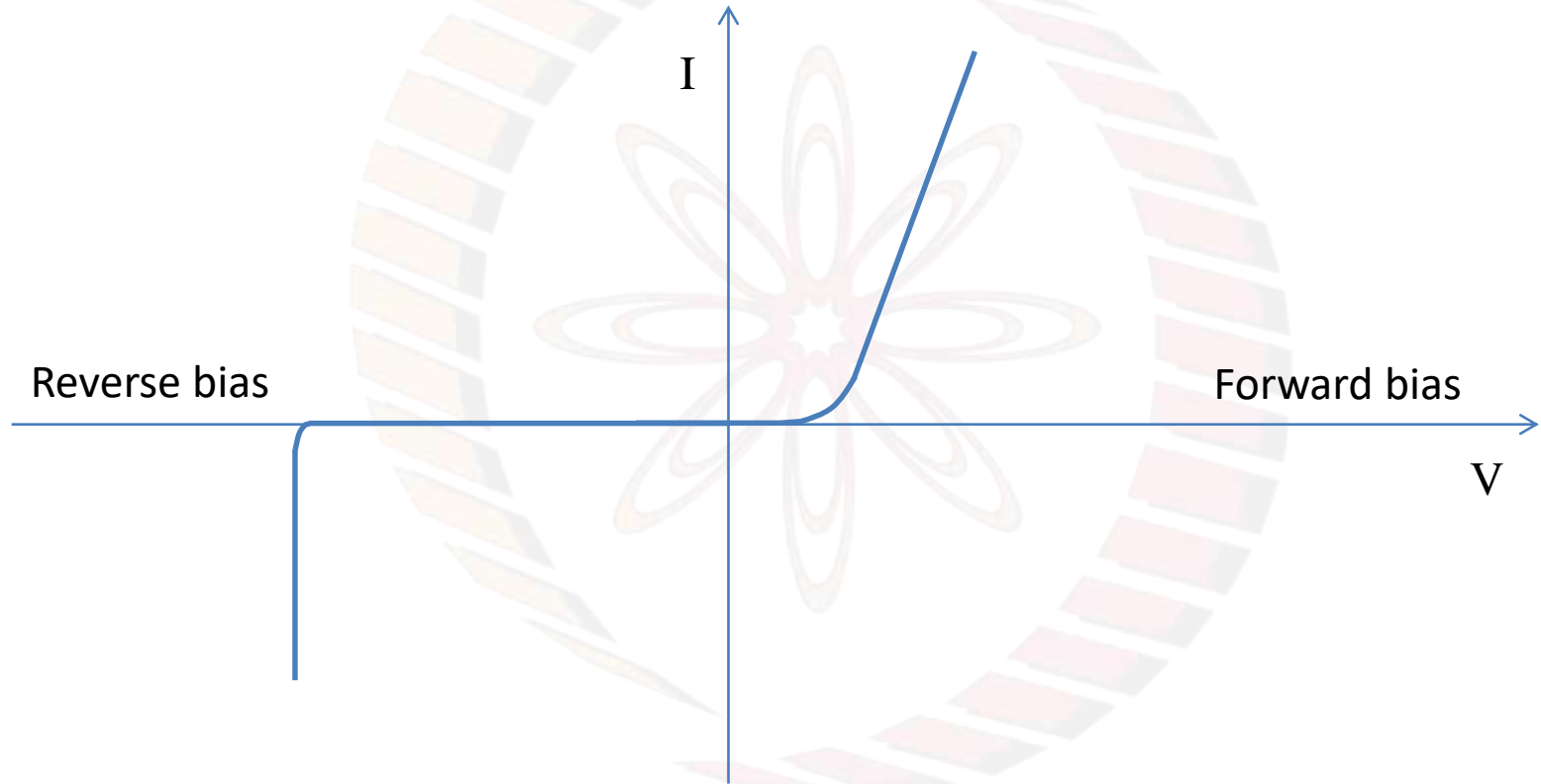




## Reverse bias



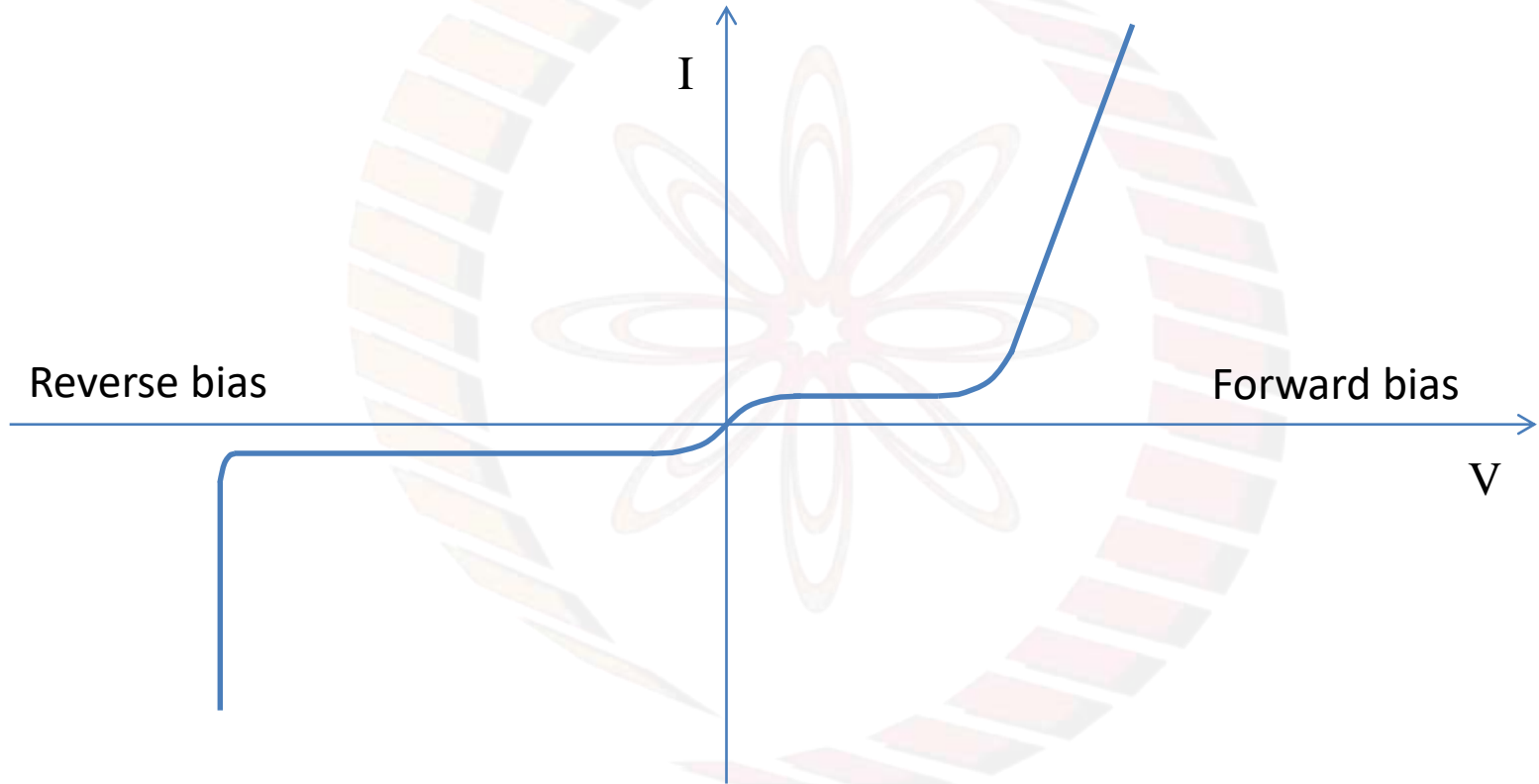
## I-V characteristics



## Conclusions:

- 1) A p-n junction can be formed using appropriately doped materials that are processed carefully
- 2) Charge, Field and Potential depend on the location in a p-n junction
- 3) A p-n junction has interesting I-V characteristics

## I-V characteristics

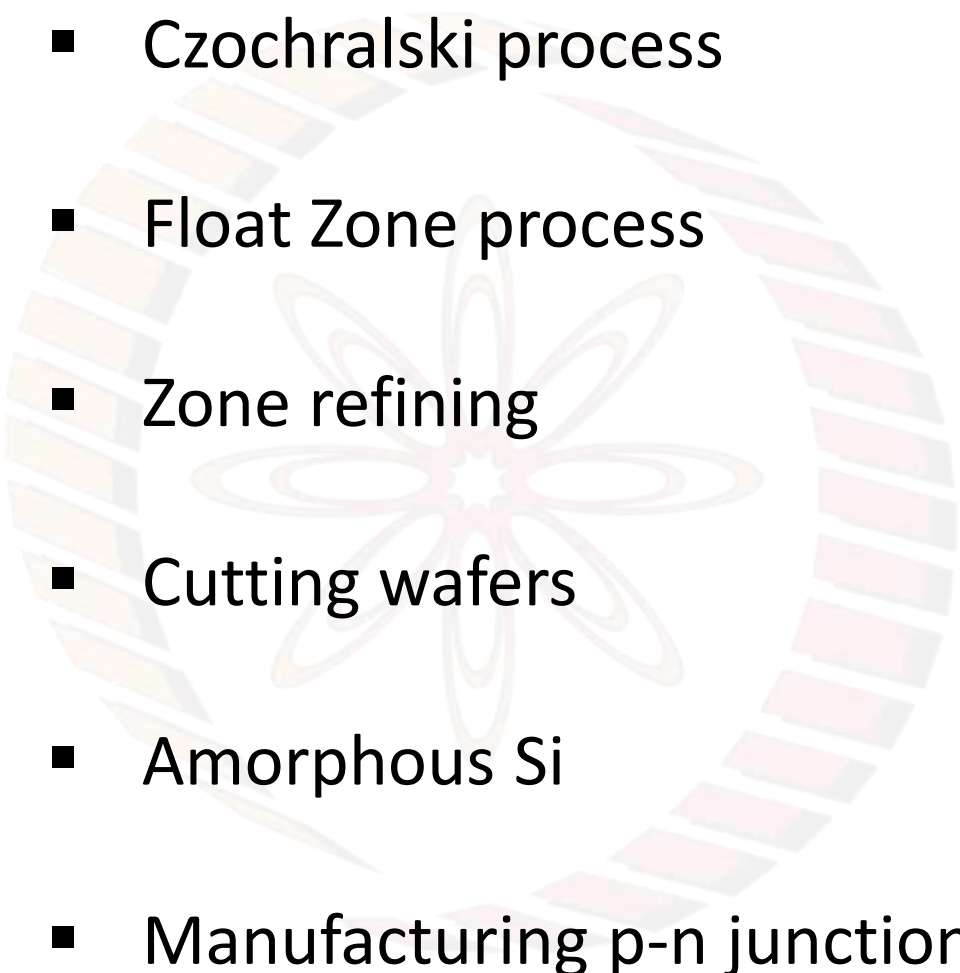




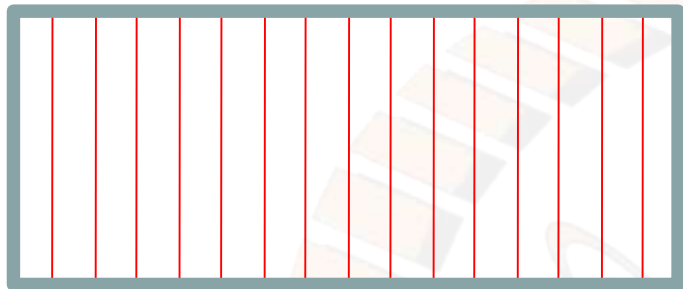
# Solar Cell: Growing the single crystal and making the p-n junction

## Learning objectives:

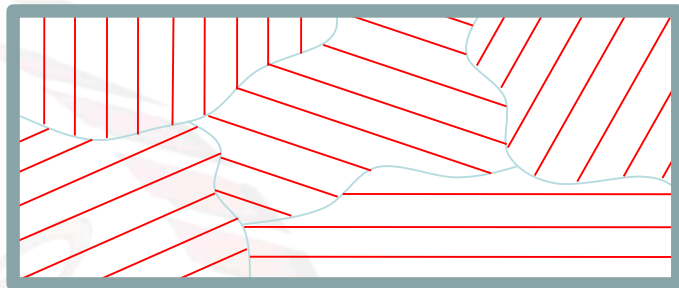
- 1) To become familiar with the techniques used to make single crystal as well as amorphous Si
- 2) To understand the method to manufacture the p-n junction

- 
- Czochralski process
  - Float Zone process
  - Zone refining
  - Cutting wafers
  - Amorphous Si
  - Manufacturing p-n junctions

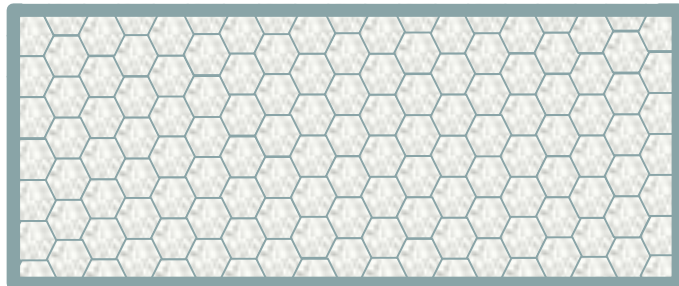
(a)



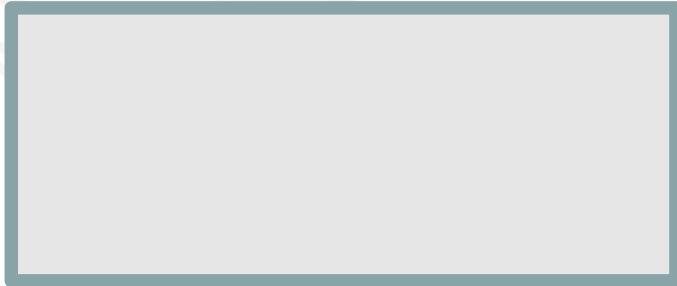
(b)



(c)



(d)





Quartzite  $\longrightarrow$  Metallurgical Grade Silicon (MGS)  
(relatively pure sand)

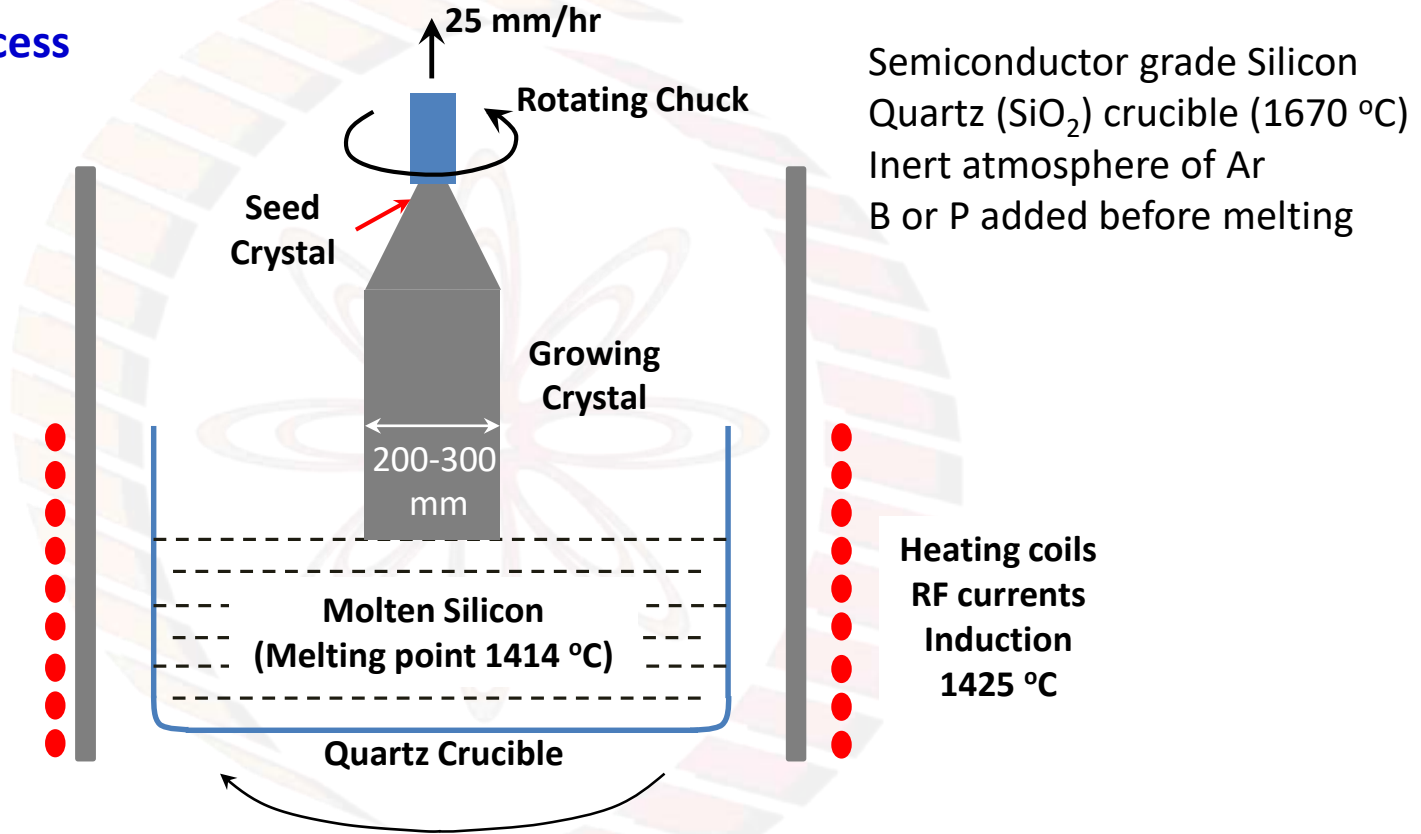


Metallurgical Grade Silicon (MGS)  $\longrightarrow$  Electronic Grade Silicon (EGS)  
98% purity ppm (C, O) to ppb (metals)



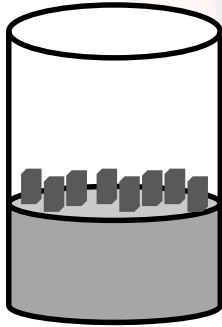
Si converted to Trichlorosilane, which is purified and reduced back to Si

## Czochralski process

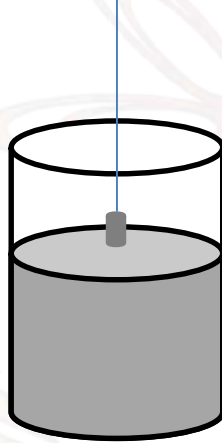


## Czochralski process

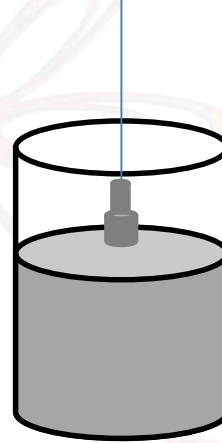
Melting of  
polycrystalline  
Silicon and  
adding of  
dopants



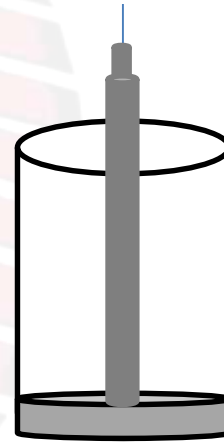
Introduction  
of seed  
crystal



Growth of  
crystal

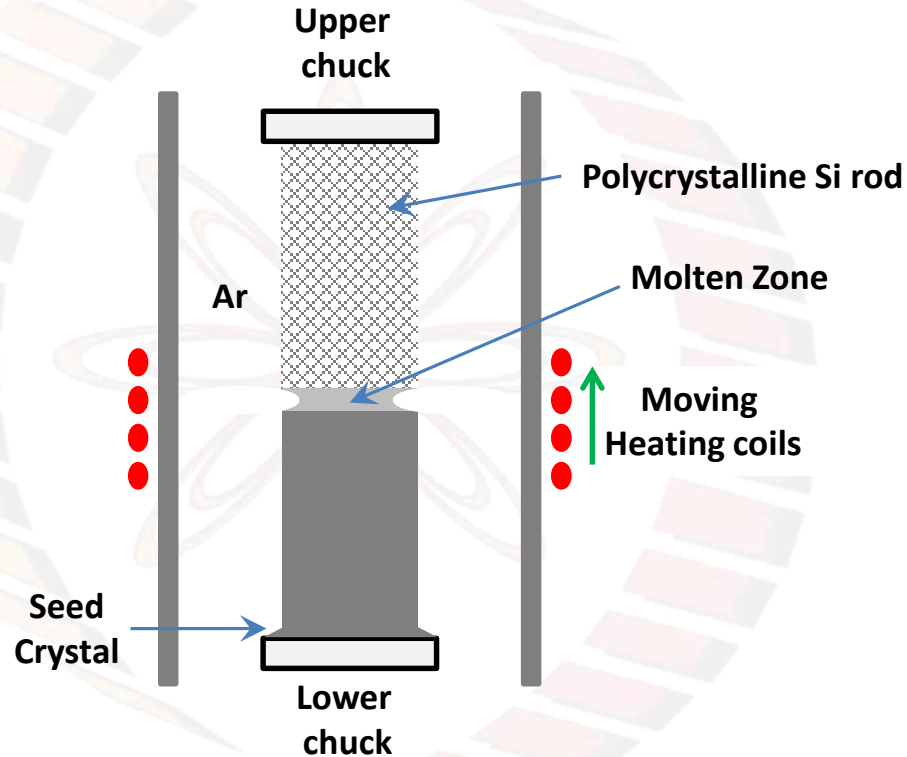


Completed  
crystal

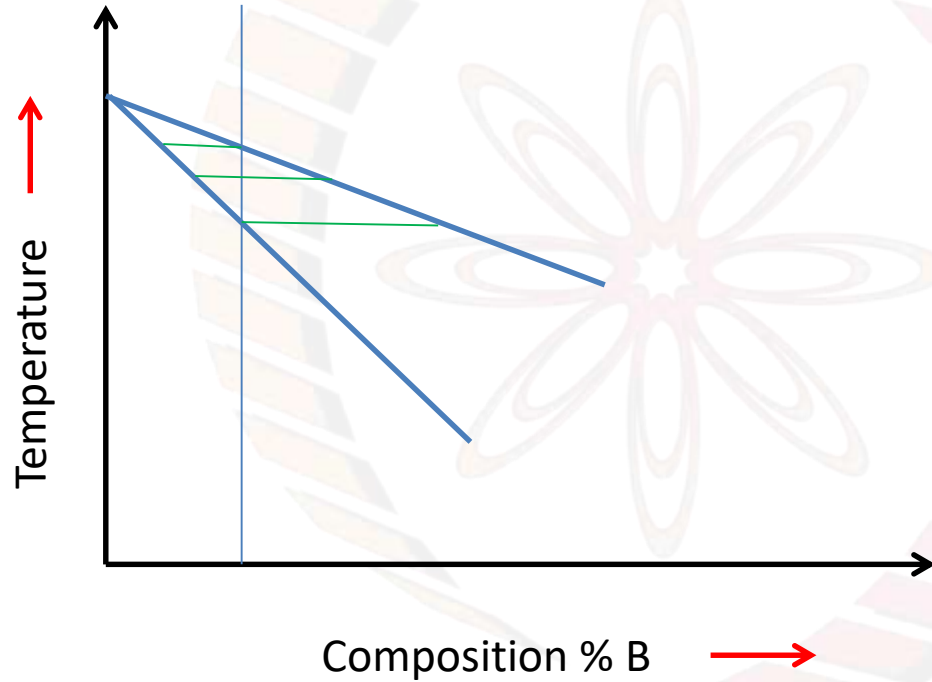


## Float zone process

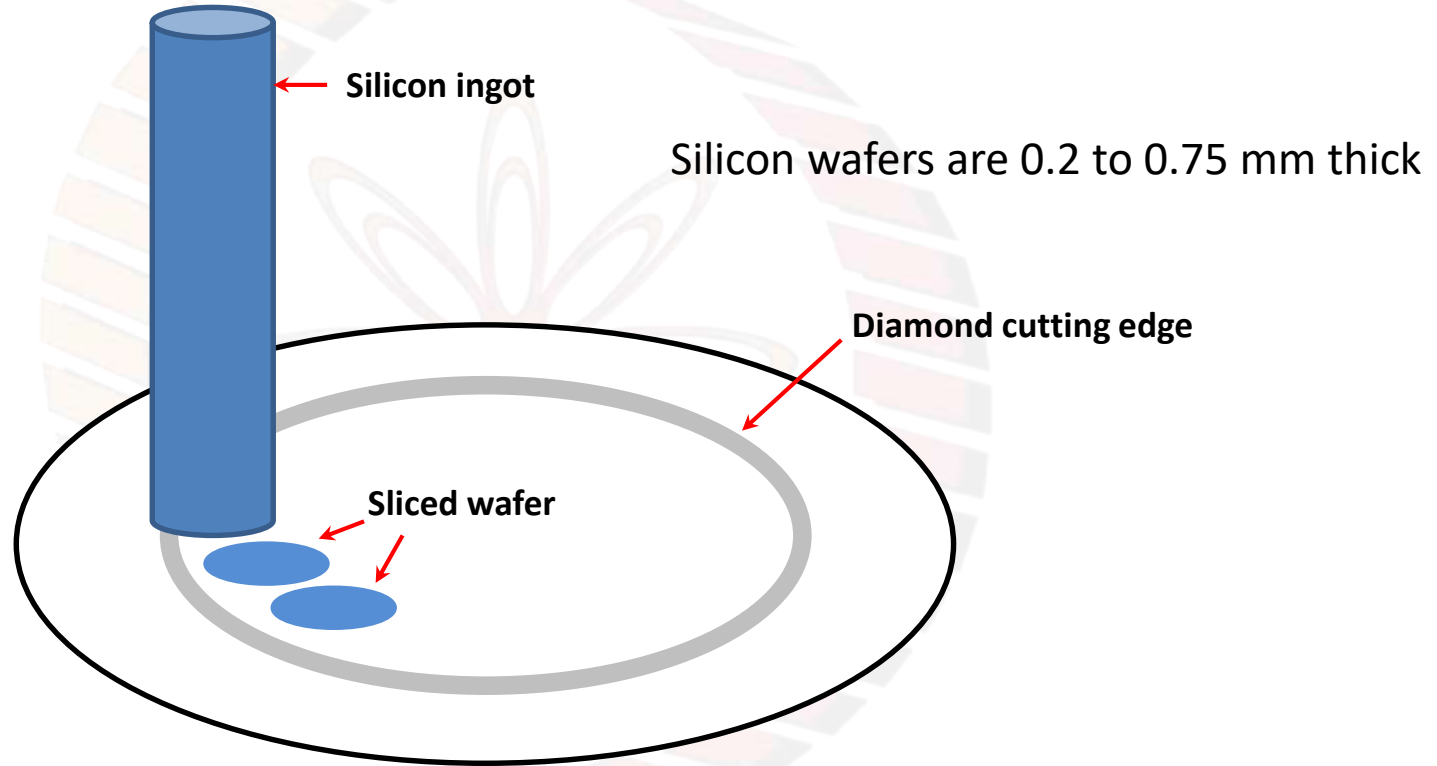
- Smaller diameter (150mm) due to surface tension
- Higher purity



## Zone refining

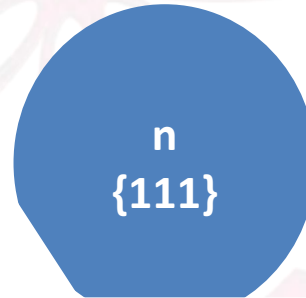
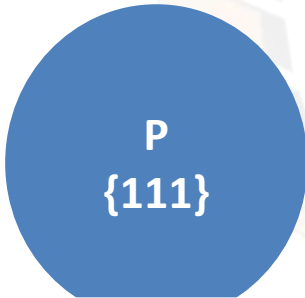
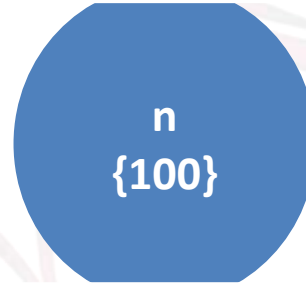
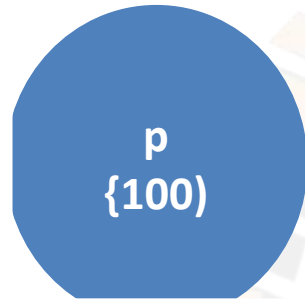


## Inner diameter slicing of Si ingot



Can produce one wafer at a time

Wire saw uses fast moving thin wire with abrasive slurry, can cut several wafers at the same time



Notches typically used to indicate orientation and doping

# Amorphous Si

CVD process

Has dangling bonds (defects)

Hydrogenated amorphous Silicon, a-Si:H by deposition  
from Silane gas  $\text{SiH}_4$

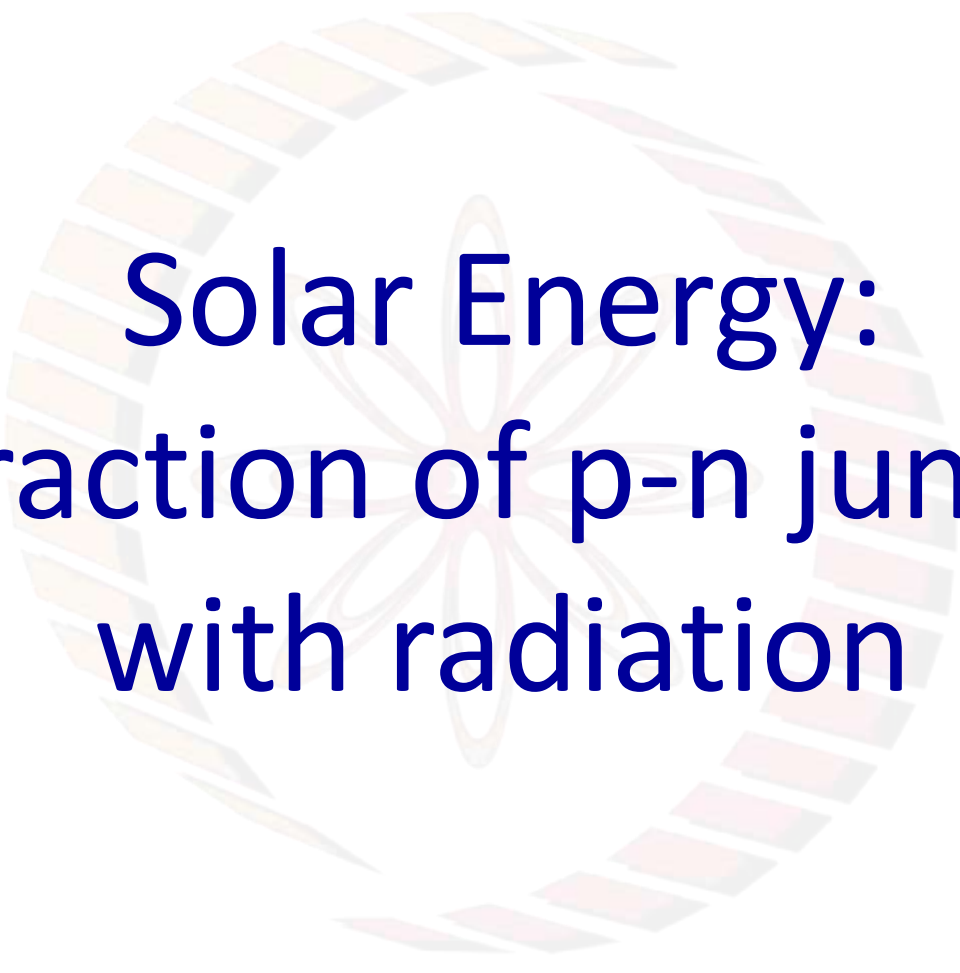


## p-n junction

- Ion implantation: Low temperature process, ionized dopants accelerated using electric fields. Annealing required
- Diffusion: Vapour phase deposition followed by high temperature diffusion
- Epitaxy: Under high vacuum, gaseous elements condense on substrate wafer

## Conclusions:

- 1) It is quite challenging to produce single crystal Si
- 2) Multiple process steps involved
- 3) Purity and dimensions can have significant impact on costs
- 4) Amorphous Si is an option

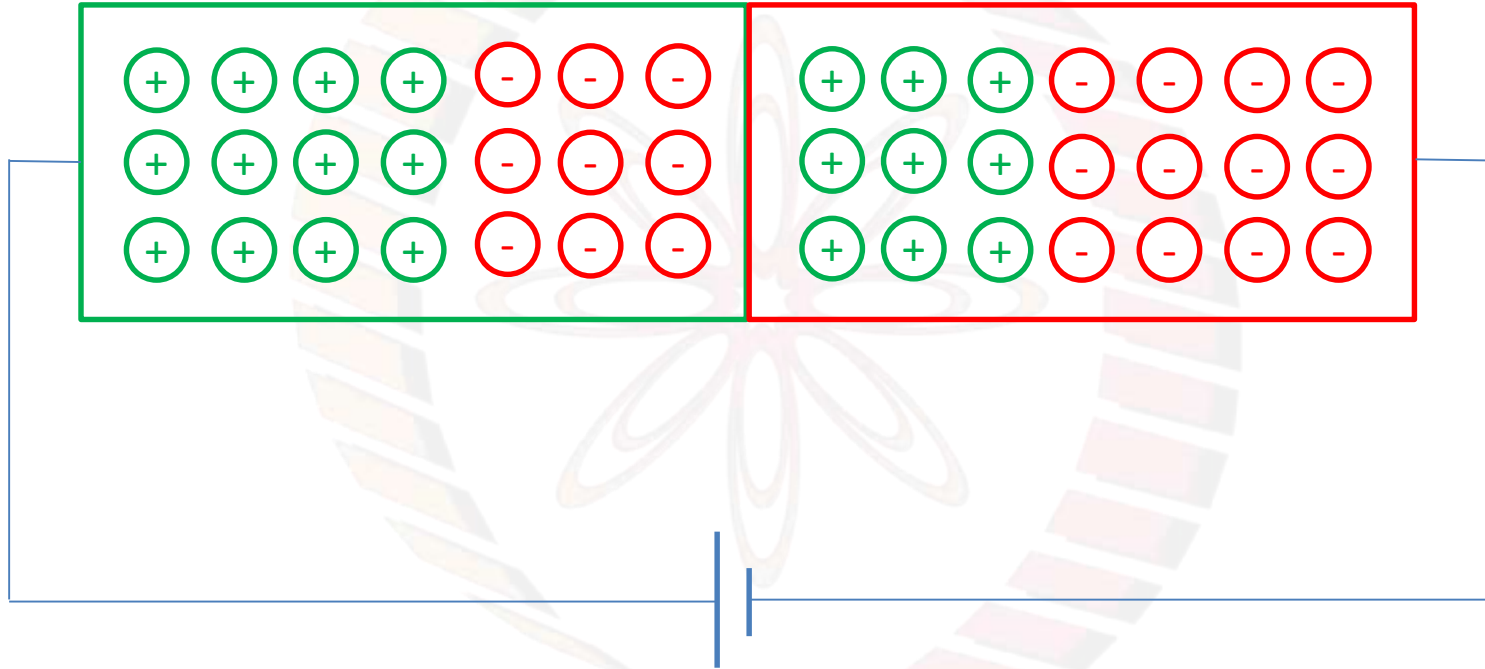


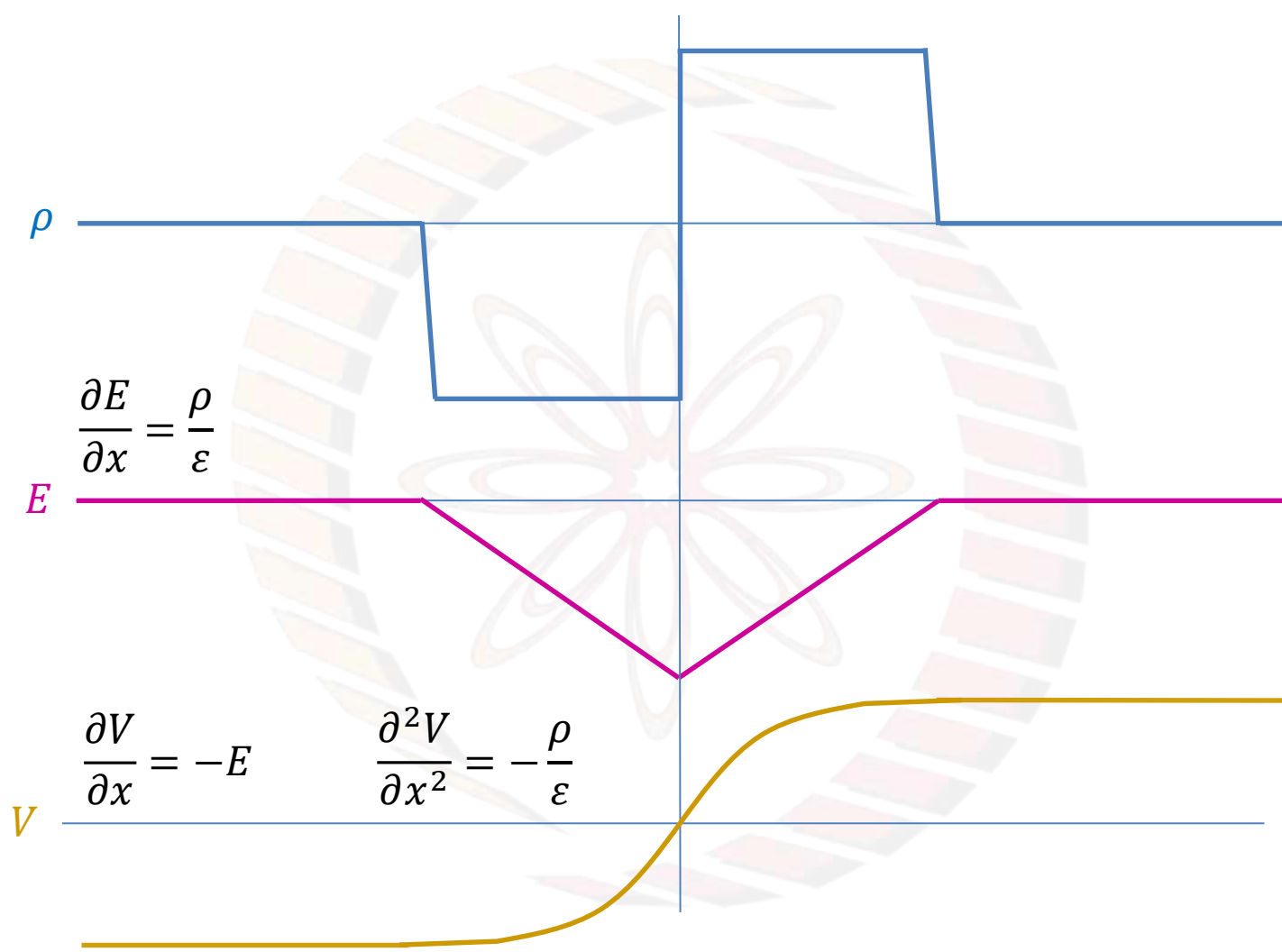
# Solar Energy: Interaction of p-n junction with radiation

## **Learning objectives:**

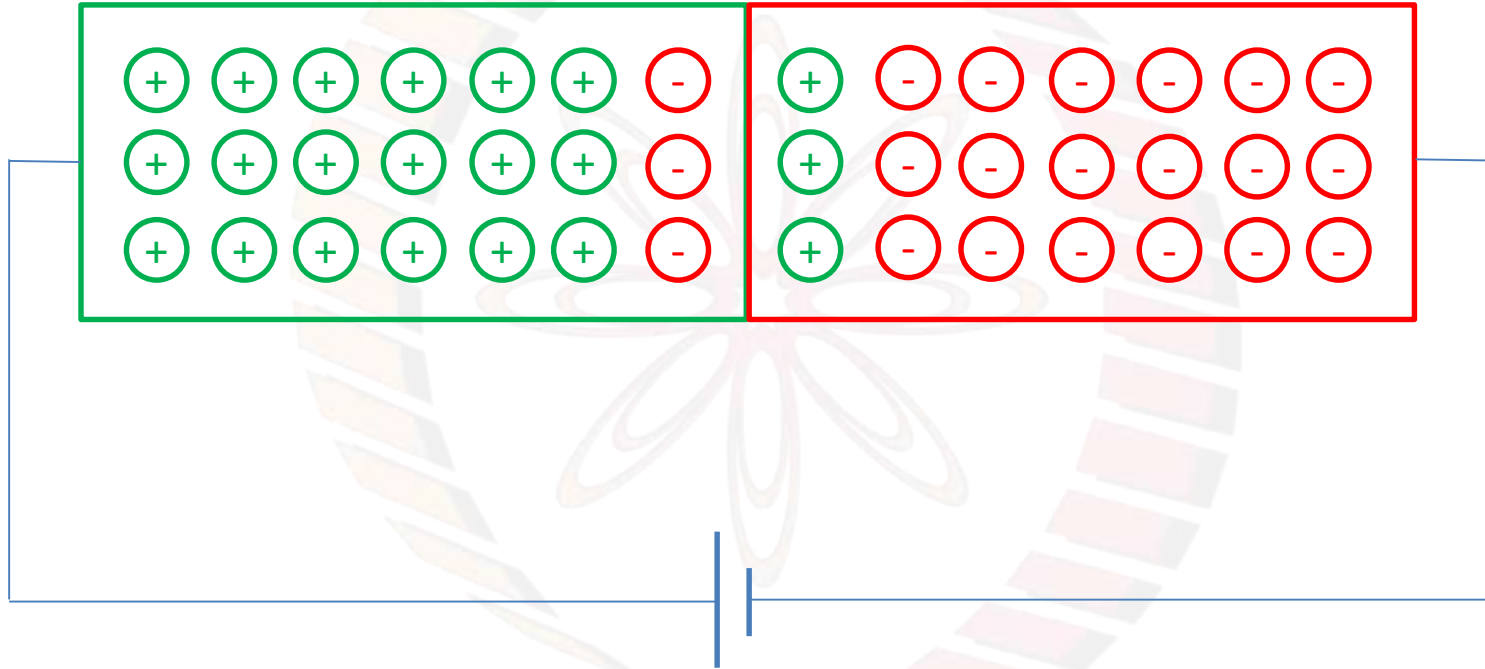
- 1) To describe the interaction of a p-n junction with radiation
- 2) To explain the functioning of the p-n junction solar cell

## Forward bias

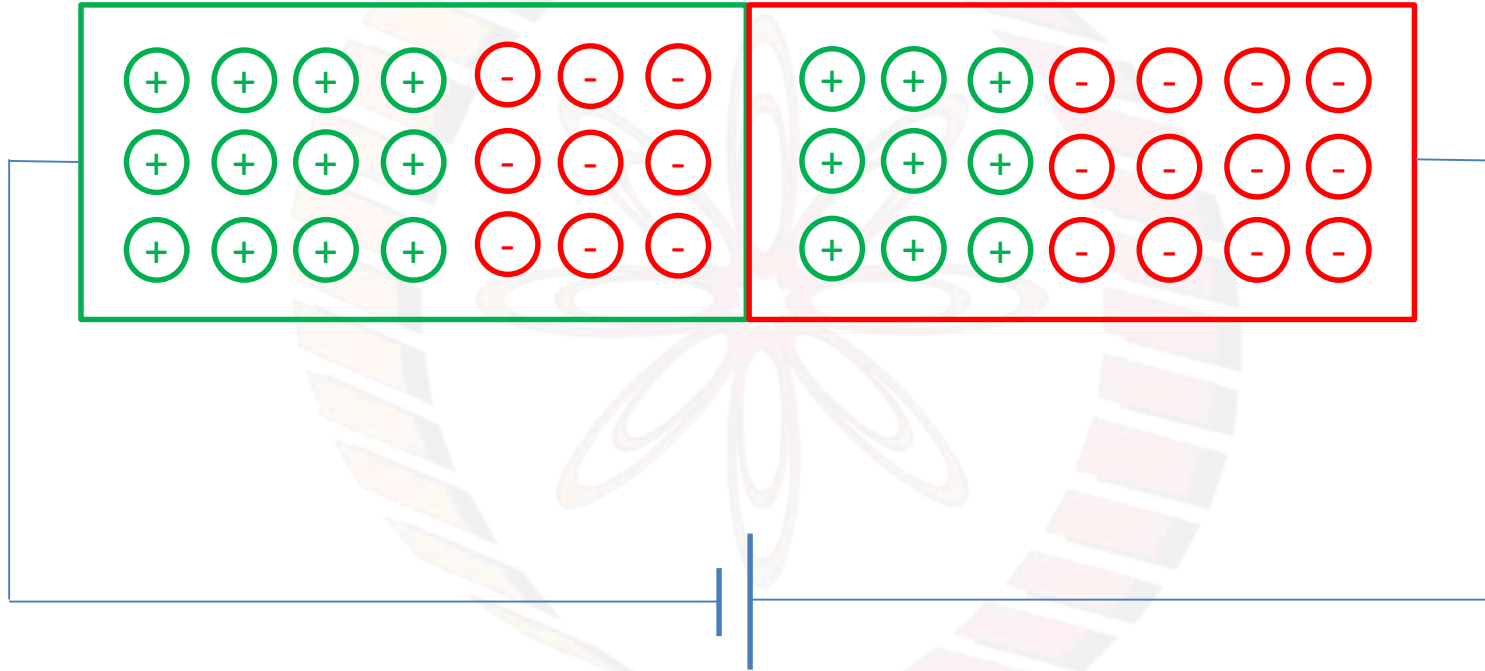




## Forward bias

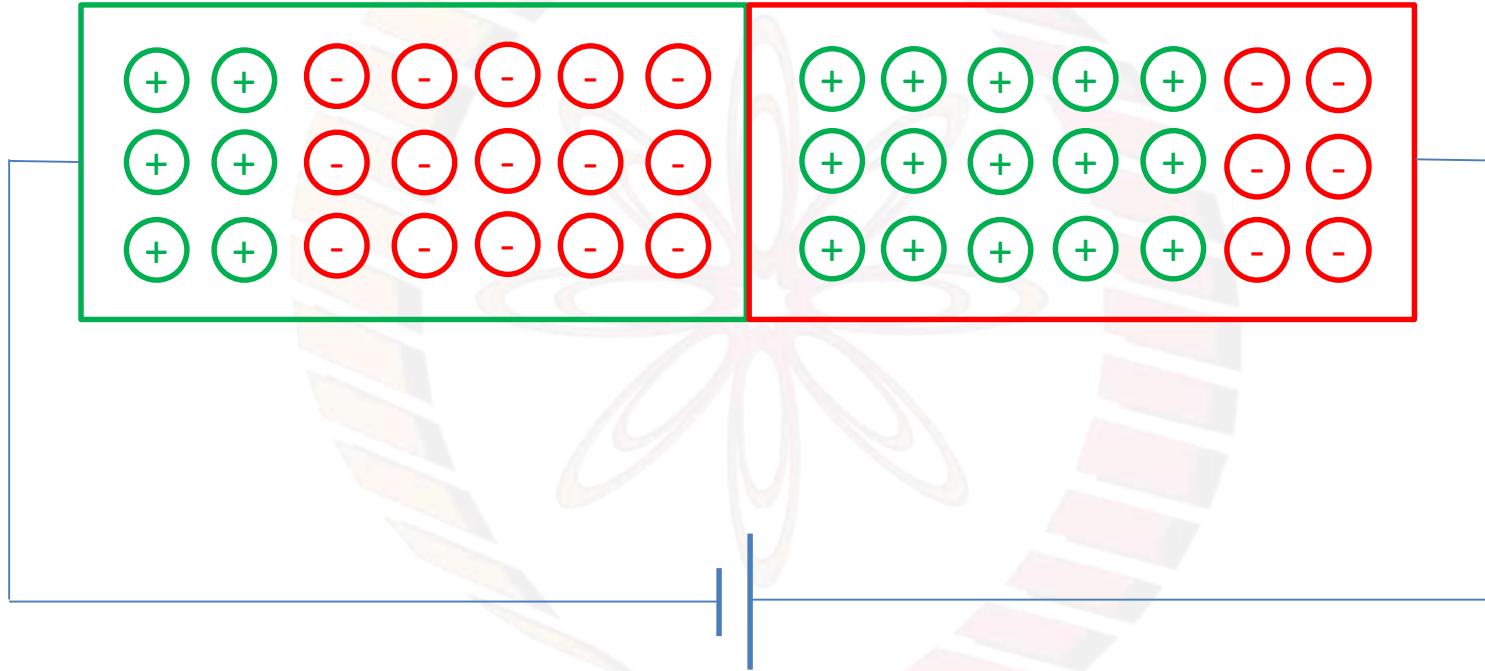


## Reverse bias

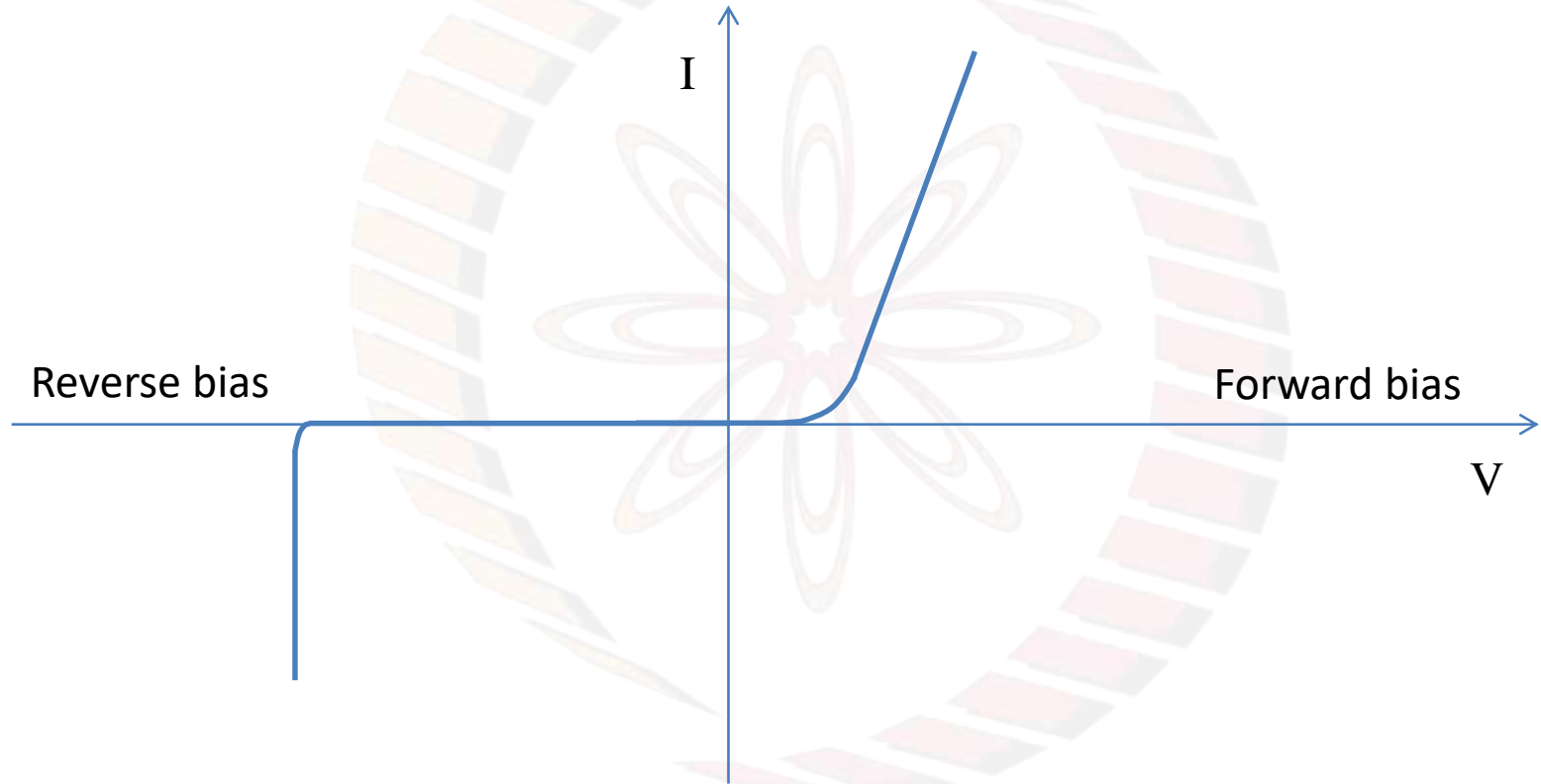


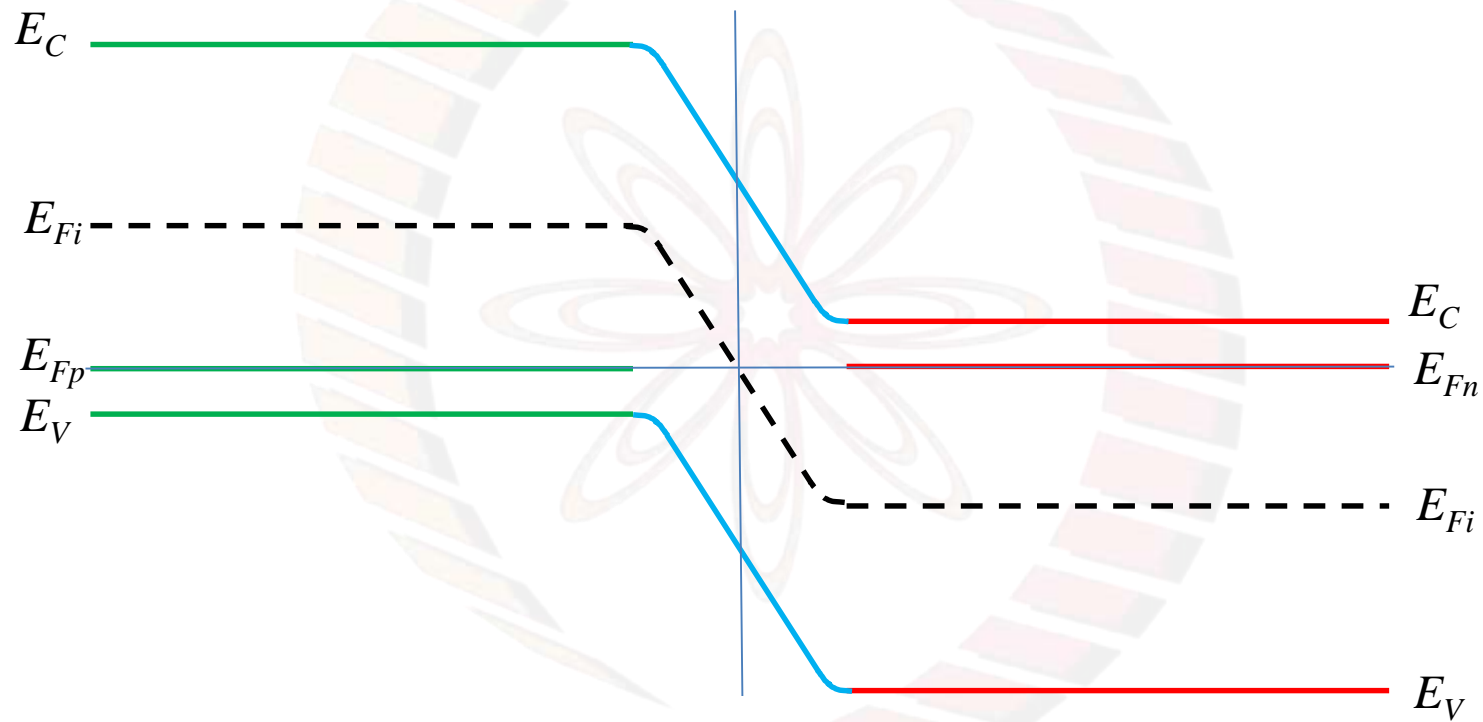


## Reverse bias

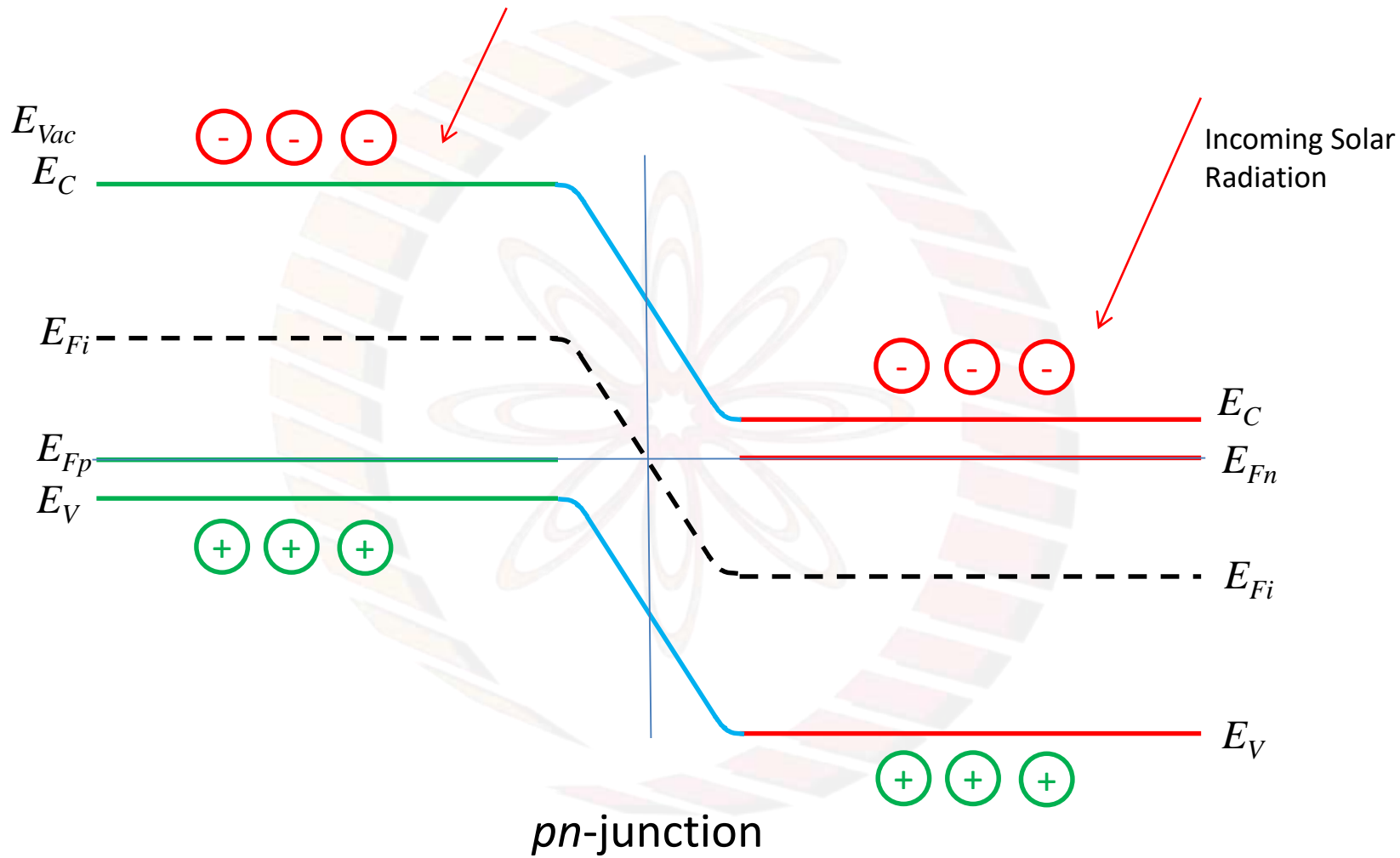


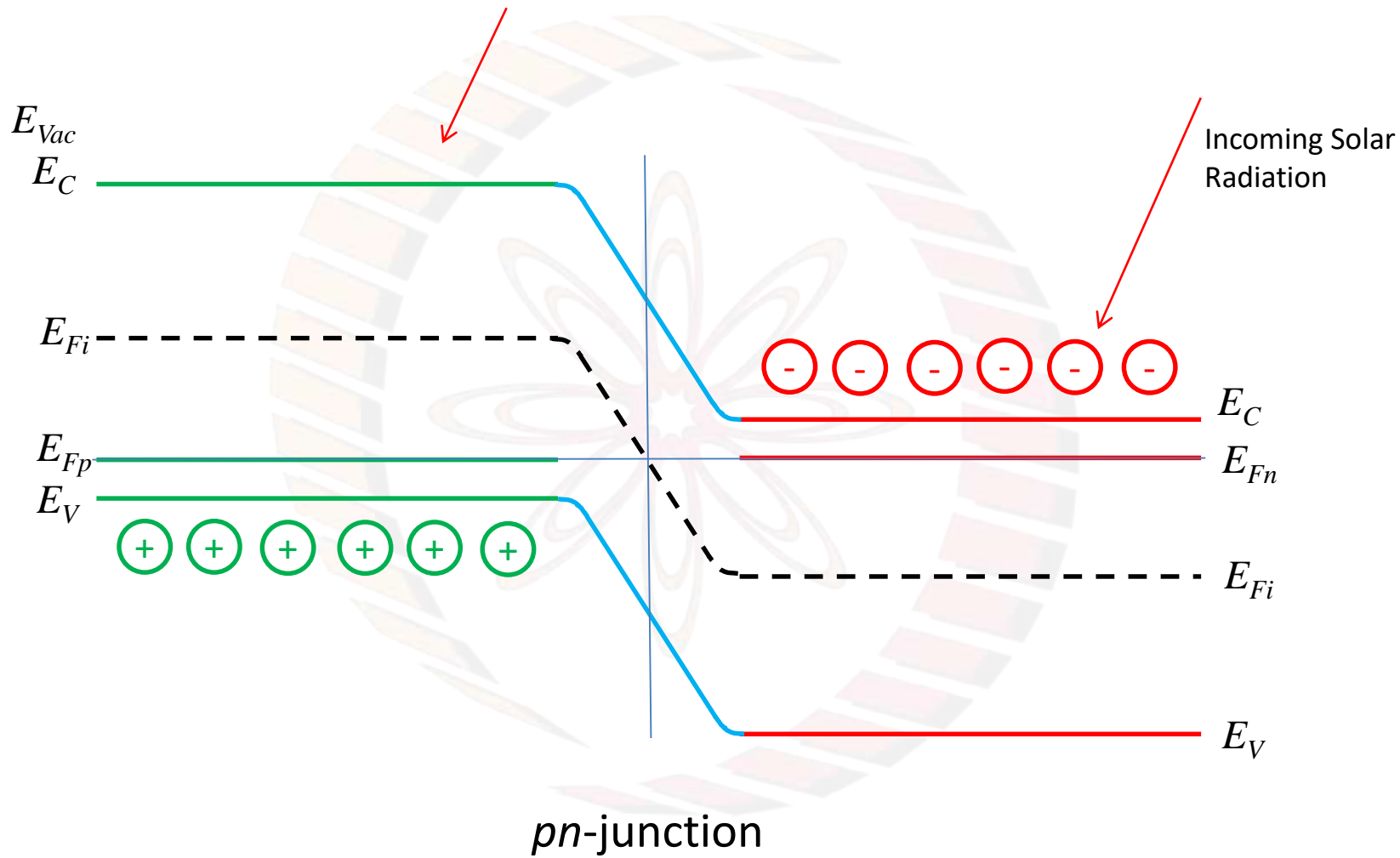
## I-V characteristics

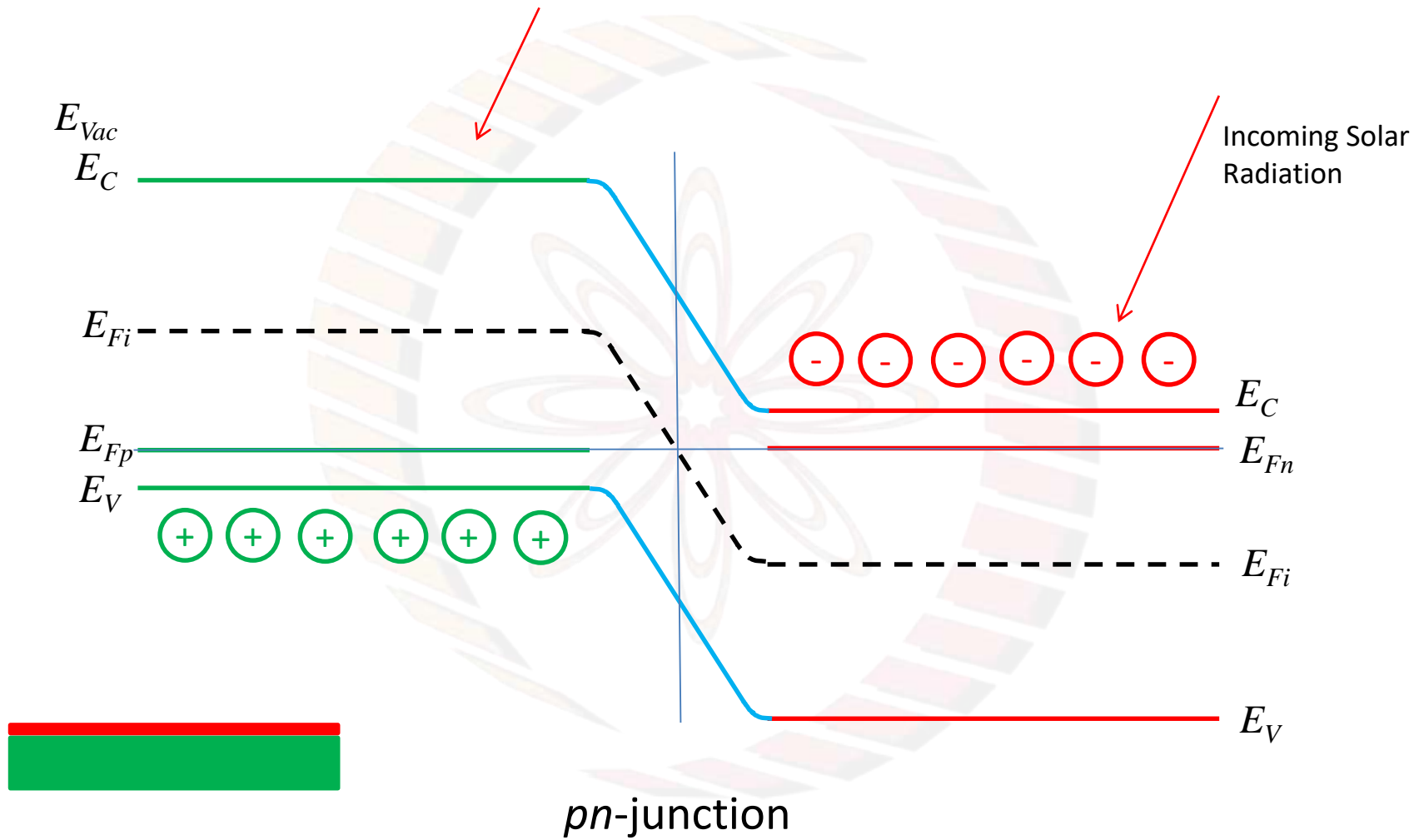


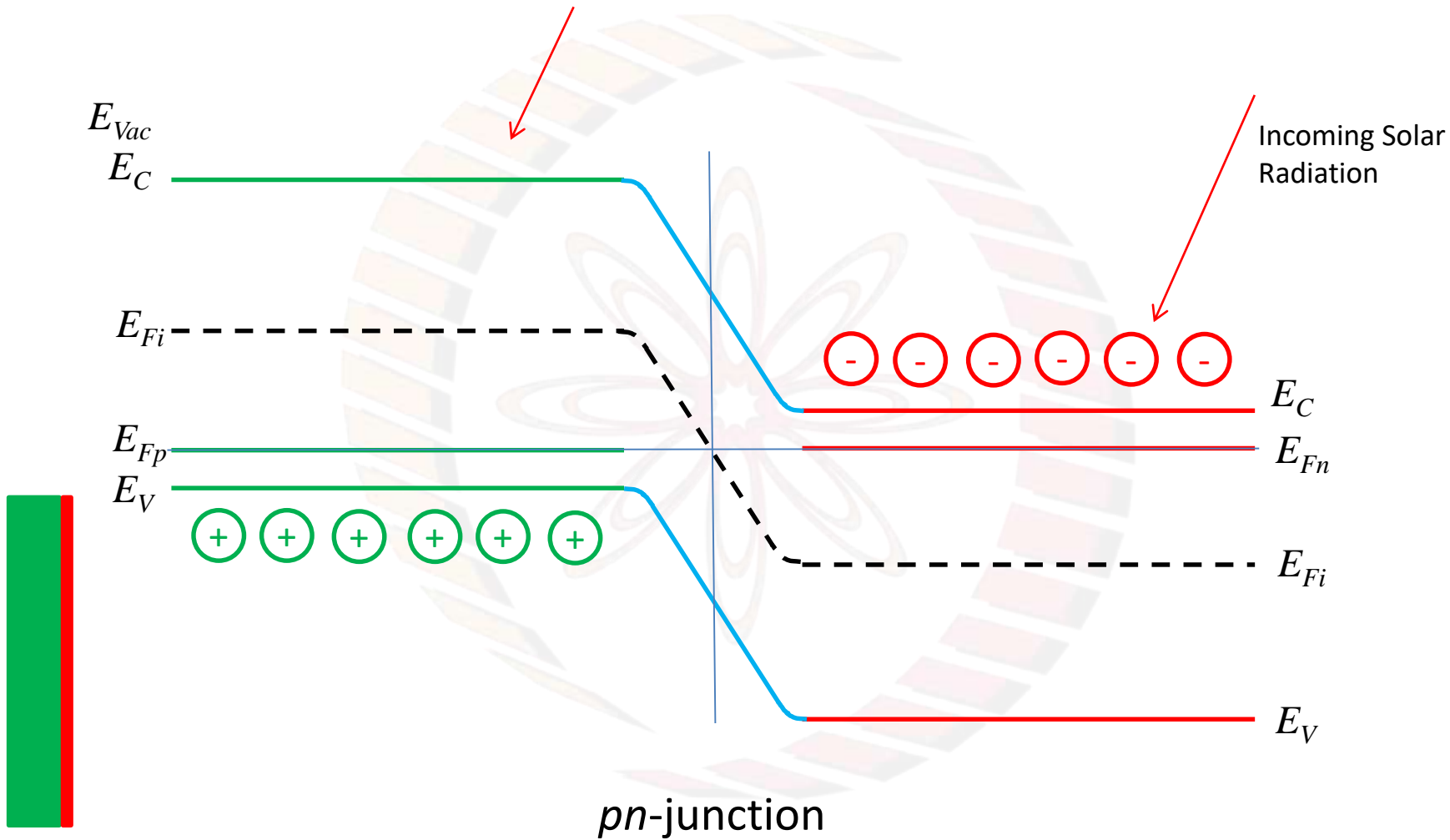


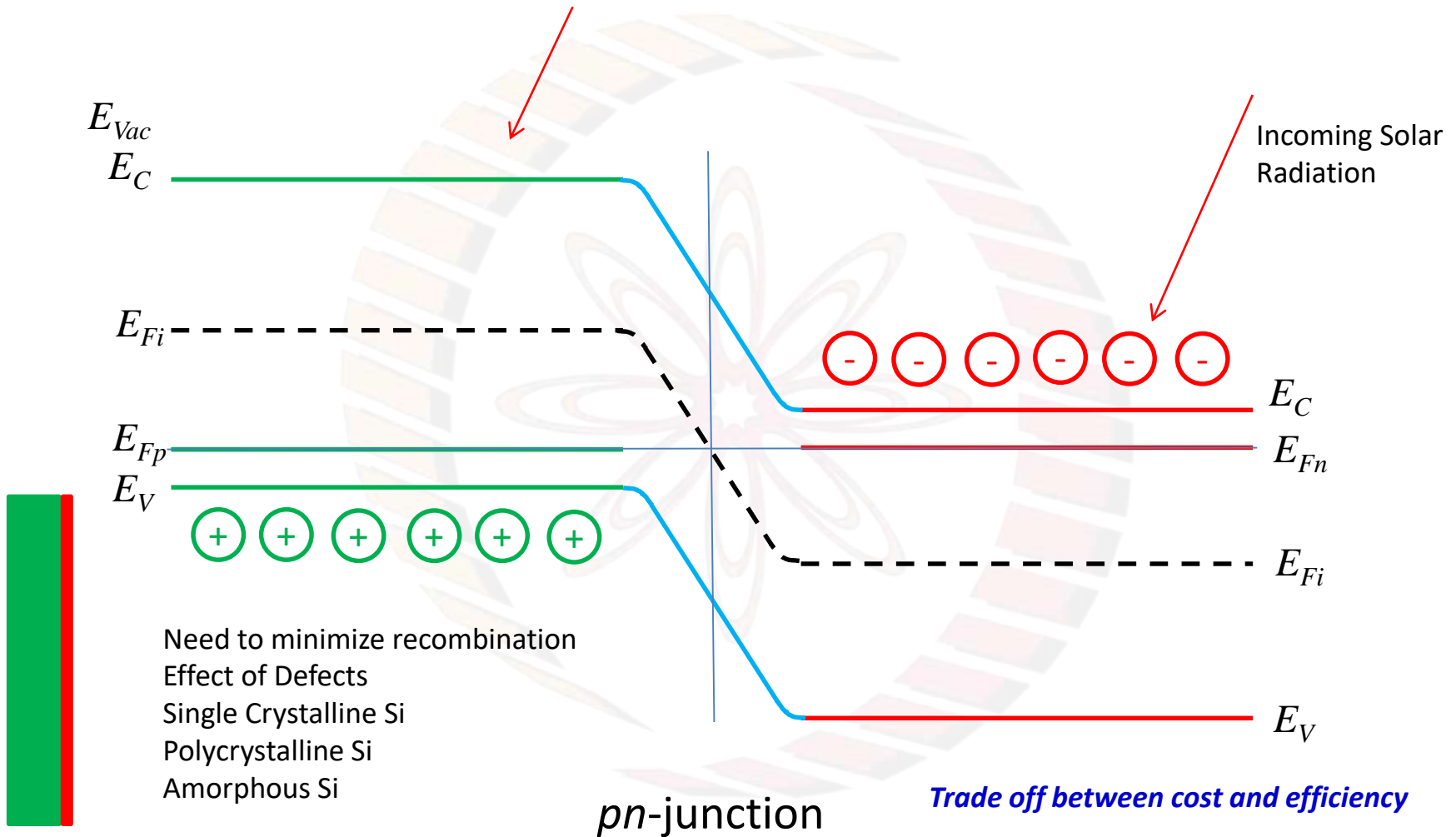
$pn$ -junction









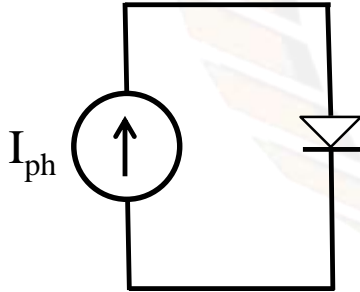


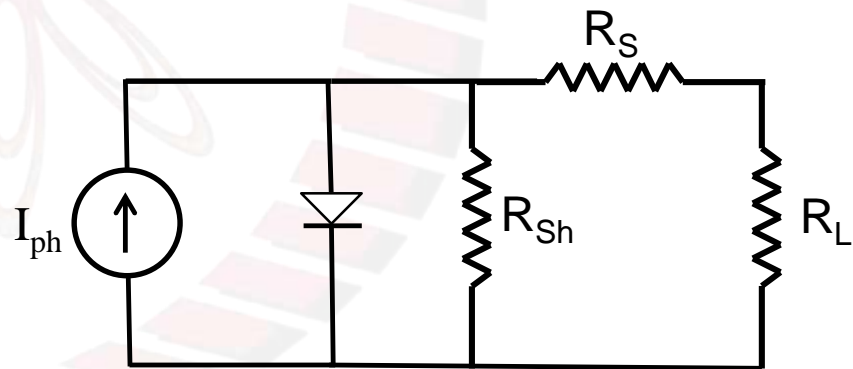
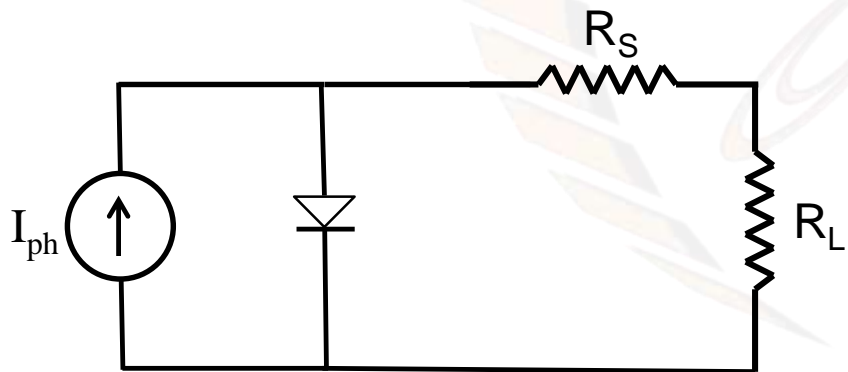
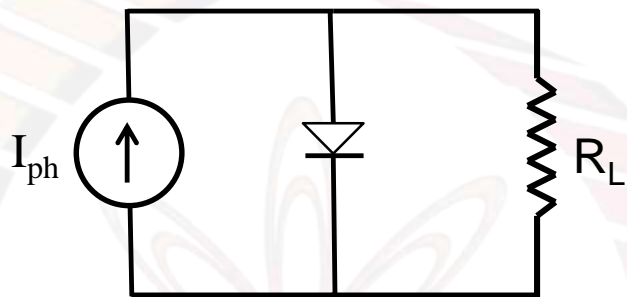
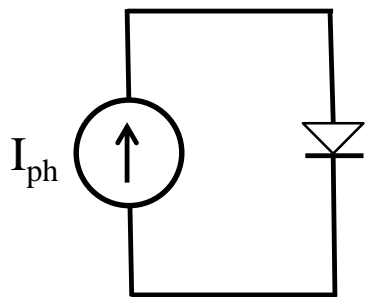


Solar Cell is a current source

Charge carriers created by sunlight received: Photocurrent  $I_{ph}$

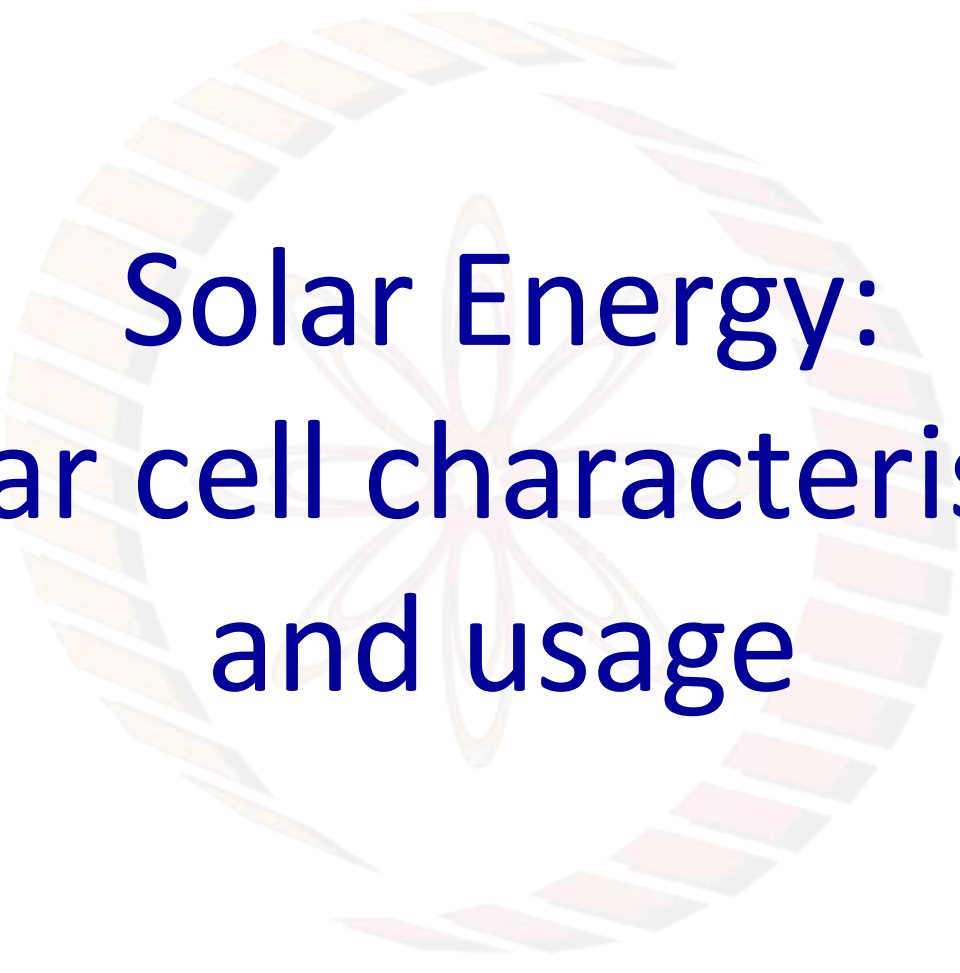
Without external load, the pn junction is forward biased, and internally shorts





## Conclusions:

- 1) The p-n junction stabilizes the electron-hole pair
- 2) The p-n junction solar cell is a current source and has to be used accordingly

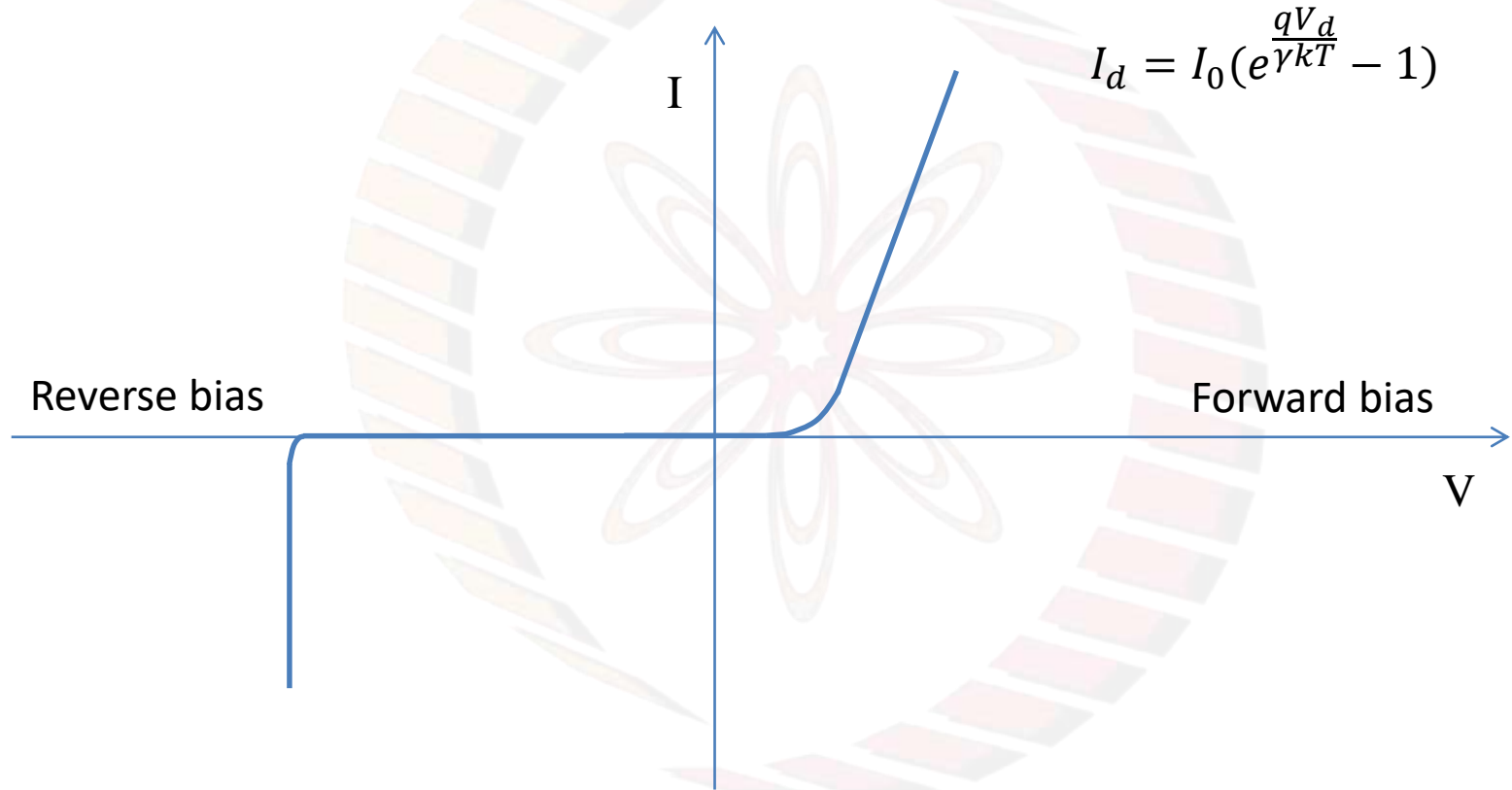


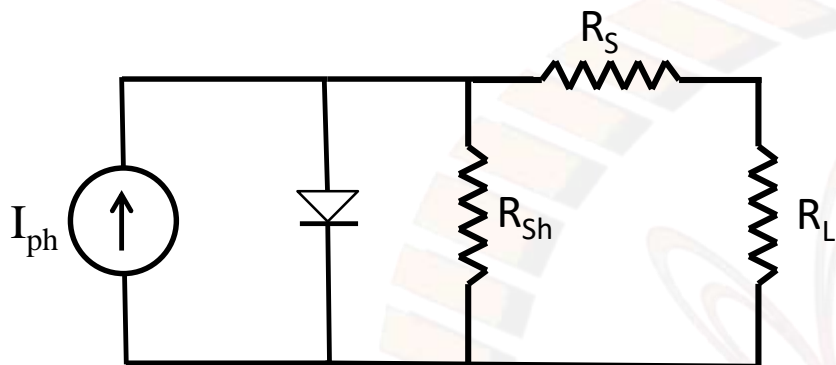
# Solar Energy: Solar cell characteristics and usage

## **Learning objectives:**

- 1) To determine the operational characteristics of a p-n junction based solar cell
- 2) To understand the best way to use the solar cell

## I-V characteristics





(Assuming recombination current is low)

$$I_{ph} - I_d = I_L$$

$$I_d = I_0 \left( e^{\frac{qV_d}{\gamma kT}} - 1 \right)$$

$$V_d = V_L + I_L R_s$$

$$V_L = \frac{\gamma kT}{q} \ln \left\{ \frac{I_{ph} - I_L}{I_0} + 1 \right\} - I_L R_s$$

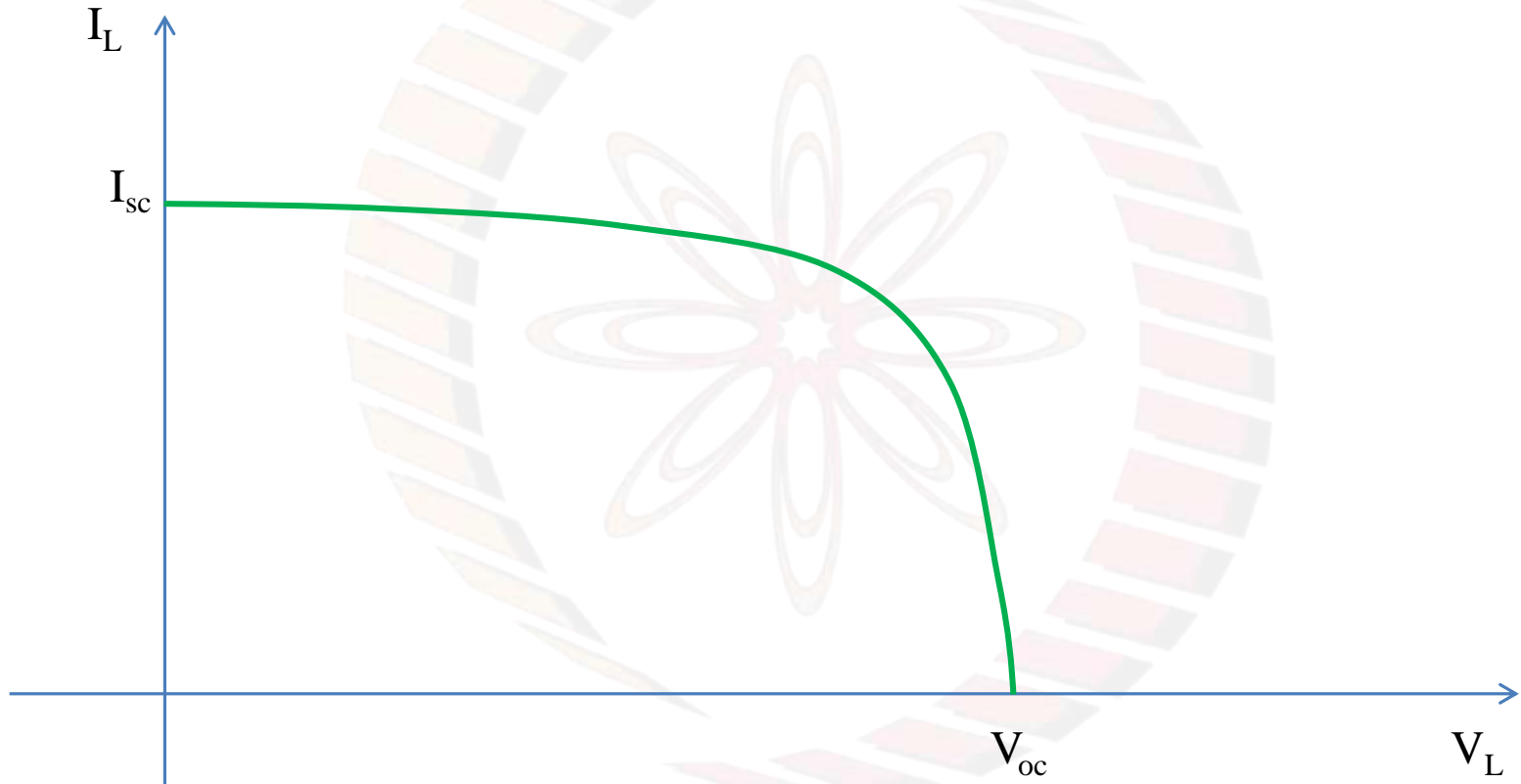
$$V_{OC} = \frac{\gamma kT}{q} \ln \left\{ \frac{I_{ph}}{I_0} + 1 \right\}$$

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$$I_{ph} - I_d - I_{sh} = I_L$$

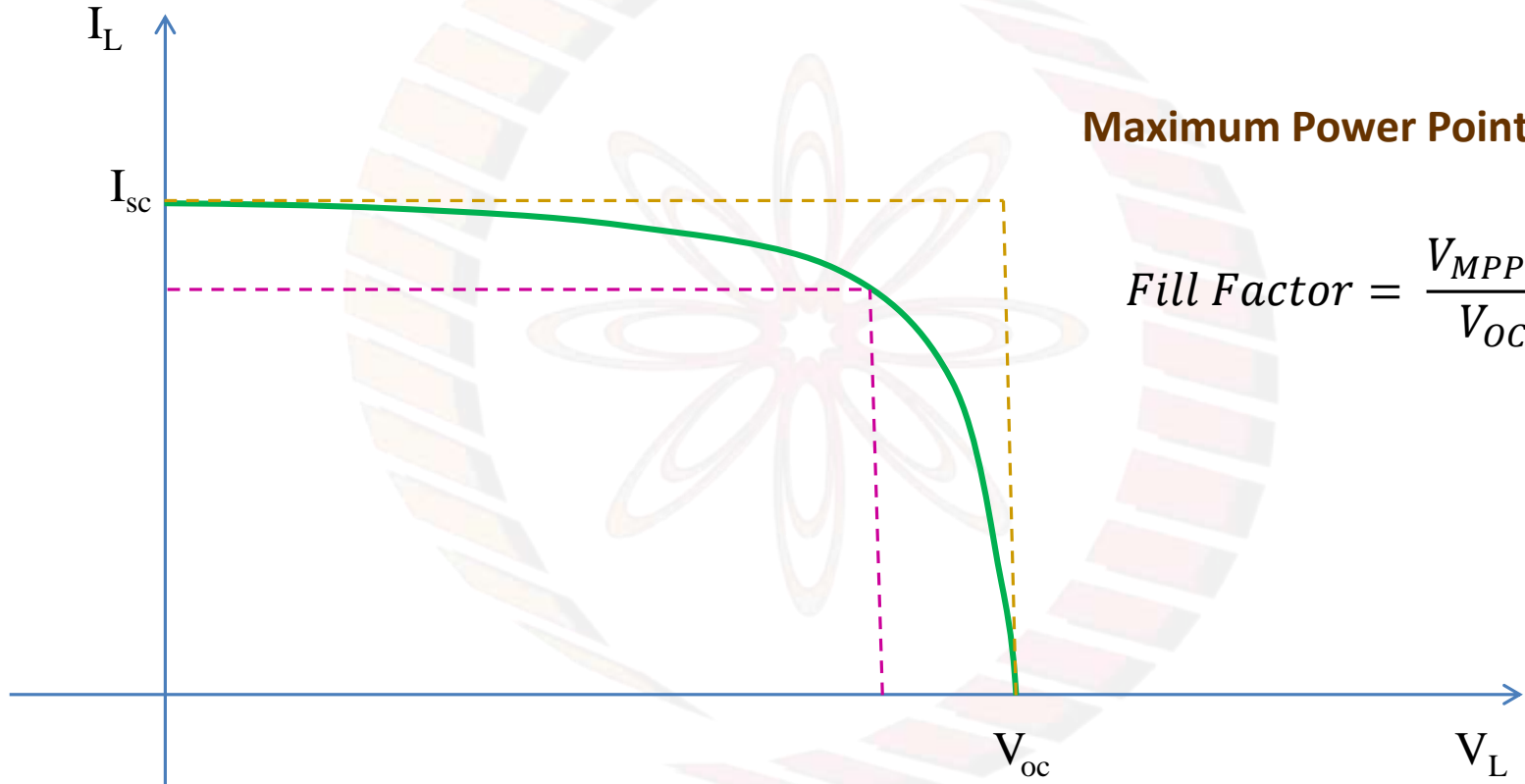
$$I_L = I_{ph} - I_0 \left( e^{\frac{q(V_L + I_L R_s)}{\gamma kT}} - 1 \right) - \left( \frac{V_L + I_L R_s}{R_{sh}} \right)$$

## I-V characteristics



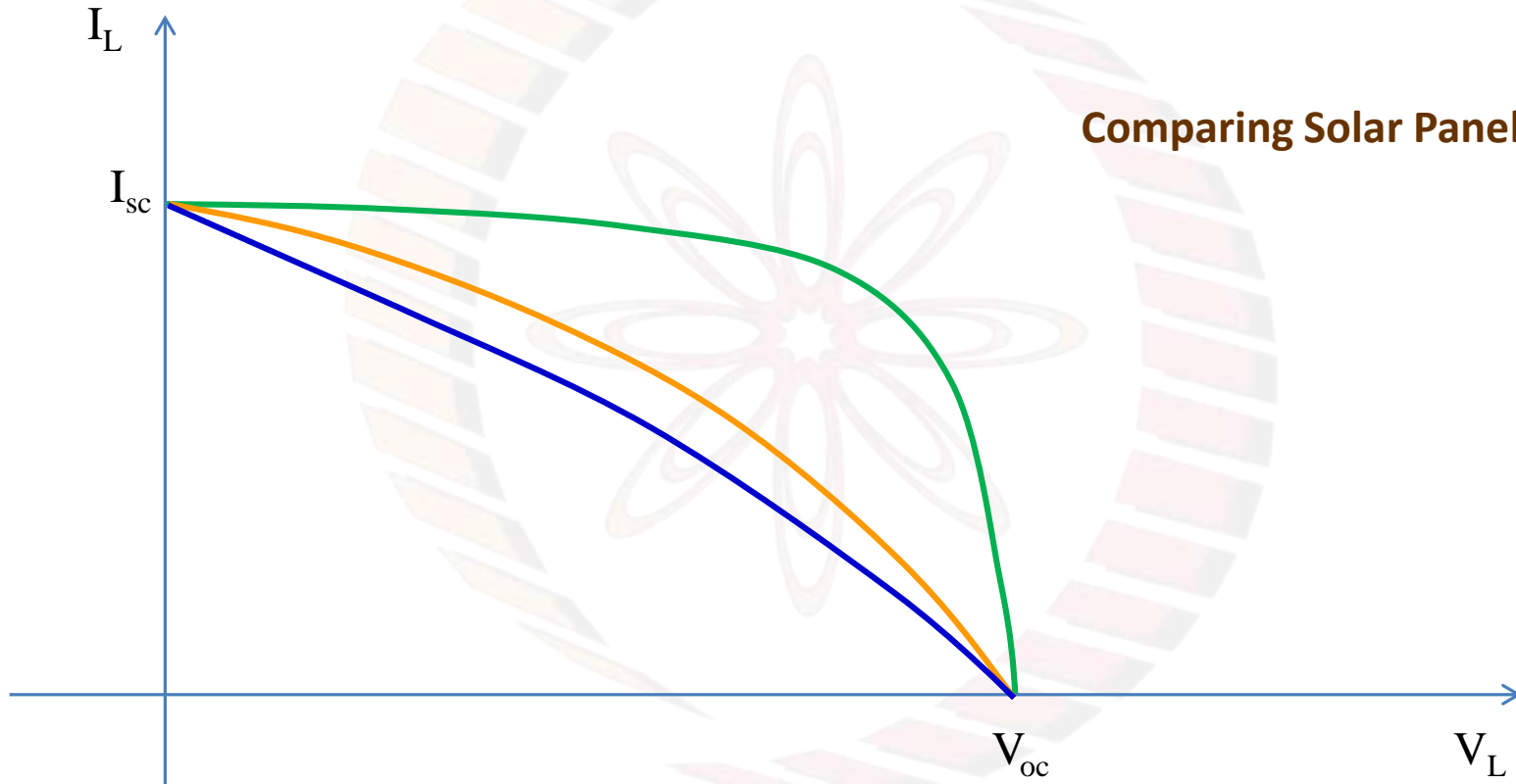


## I-V characteristics

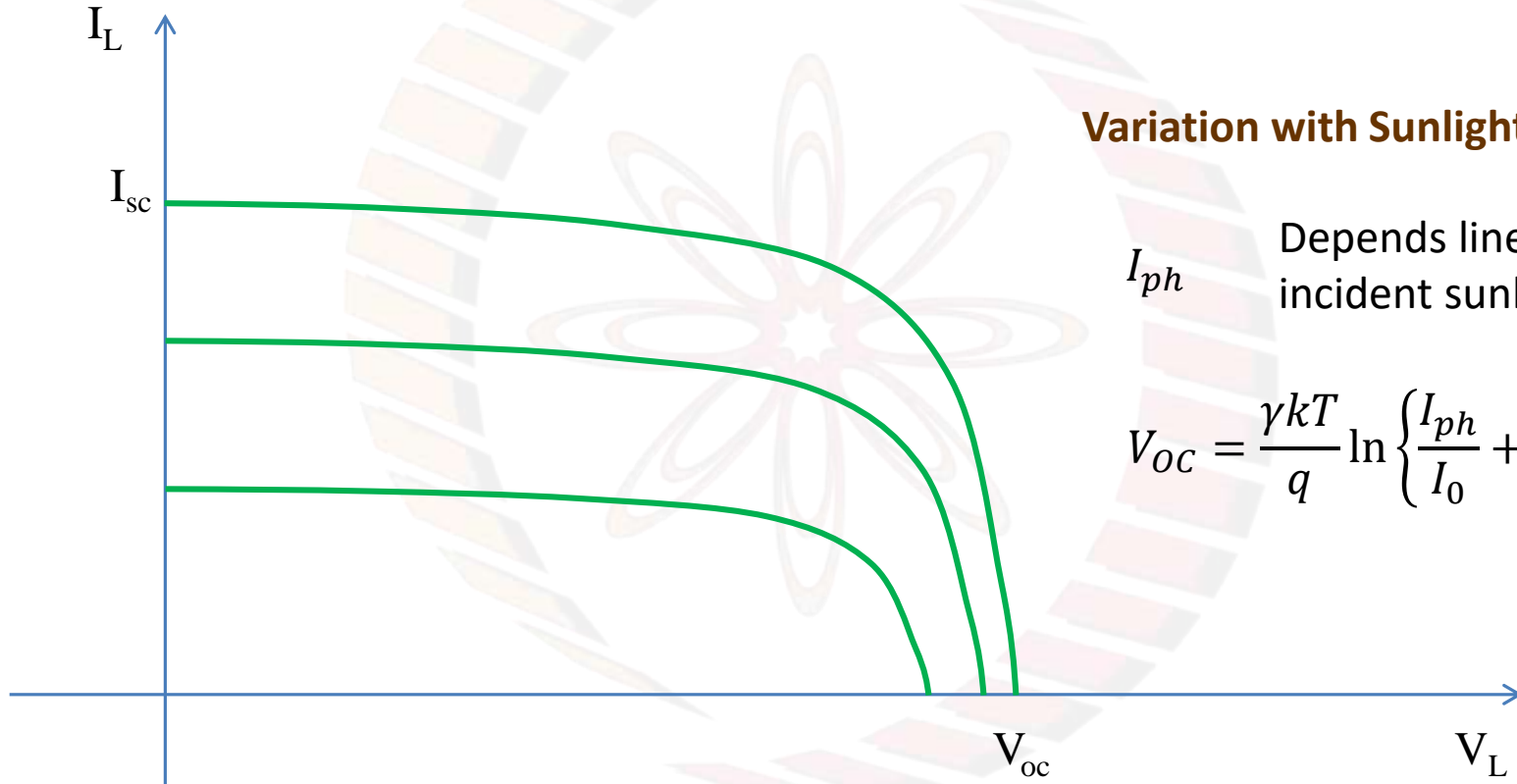


## I-V characteristics

Comparing Solar Panels



## I-V characteristics

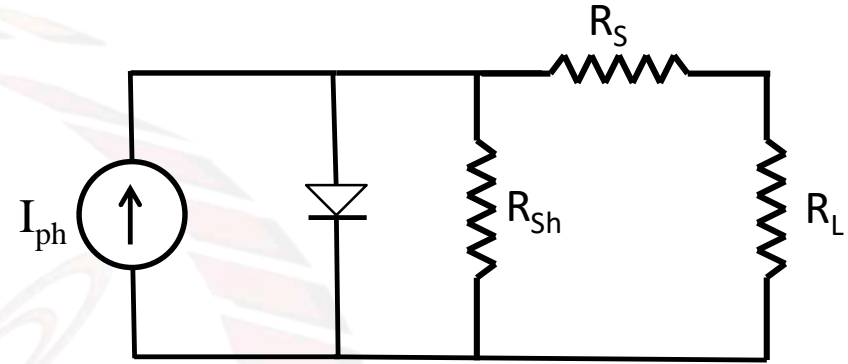
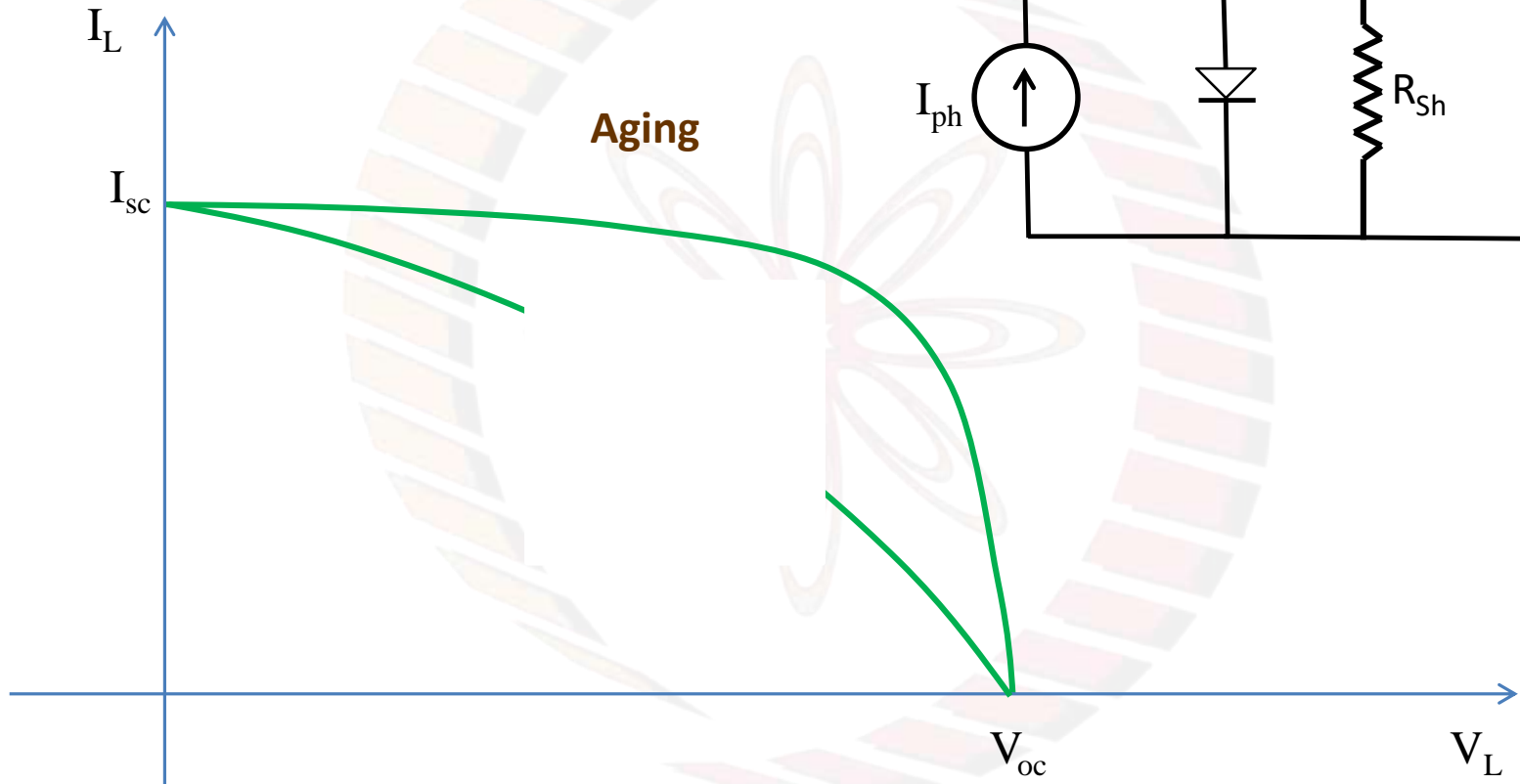


### Variation with Sunlight

$I_{ph}$  Depends linearly on  
incident sunlight

$$V_{oc} = \frac{\gamma k T}{q} \ln \left\{ \frac{I_{ph}}{I_0} + 1 \right\}$$

## I-V characteristics



## Conclusions:

- 1) The solar cell is a current source
- 2)  $I$ -  $V$  relationship is complicated
- 3) OCV is not the most important parameter
- 4) Fill factor of a solar cell is important
- 5) Solar cell must be coupled with an end use that utilizes the MPP



# Solar Energy: Solar cell construction

## **Learning objectives:**

- 1) To indicate the limitations of single junction solar cells
- 2) To describe how solar cells are constructed
- 3) To describe the functioning of tandem solar cells

# Shockley-Queisser limit

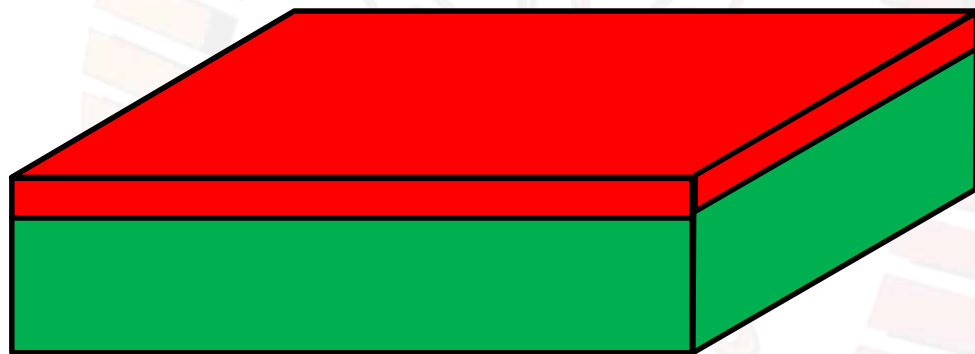
In unconcentrated, AM 1.5 Solar radiation with a band gap of 1.34 eV, 33.4 % efficiency is obtained

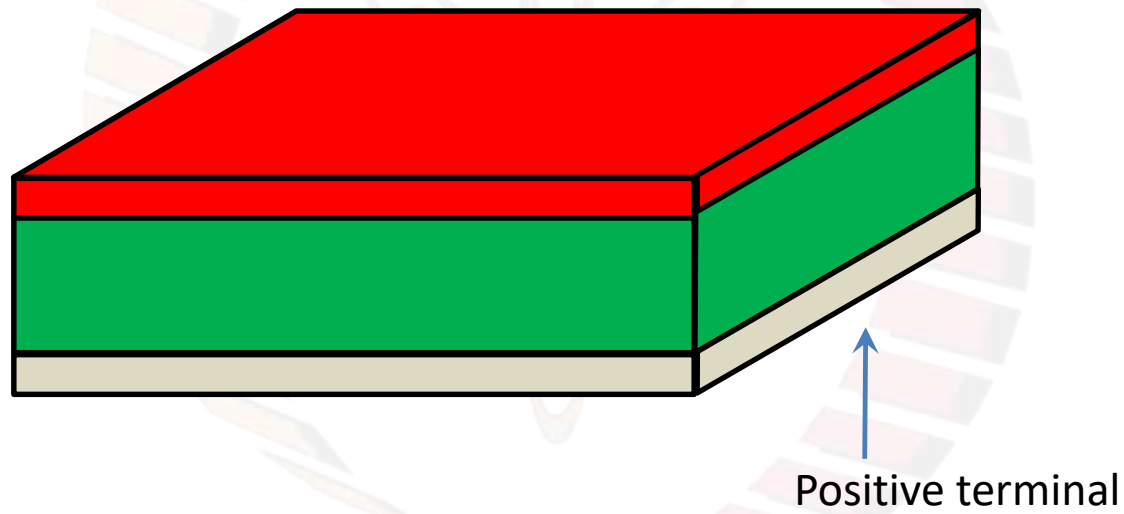
Si, 1.1 eV, 32 % efficiency is the best.  
Practically 24% accomplished

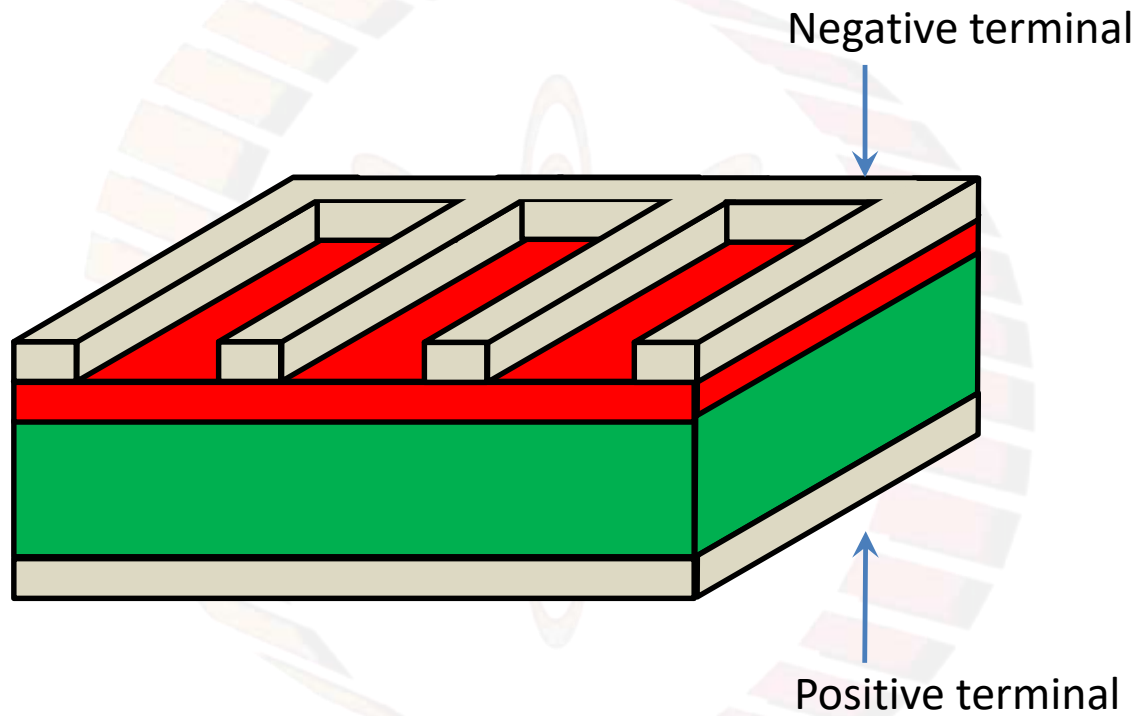
***Air Mass Coefficient: Optical path length relative to path length vertically upward  
AM 1.5 typically used for evaluating panels***

Blackbody radiation	7% (At room T, actual $T \sim 75^\circ\text{C}$ )
Recombination losses	10%
Spectrum losses	19% unabsorbed, 33% excess $\nu$ , total 52%

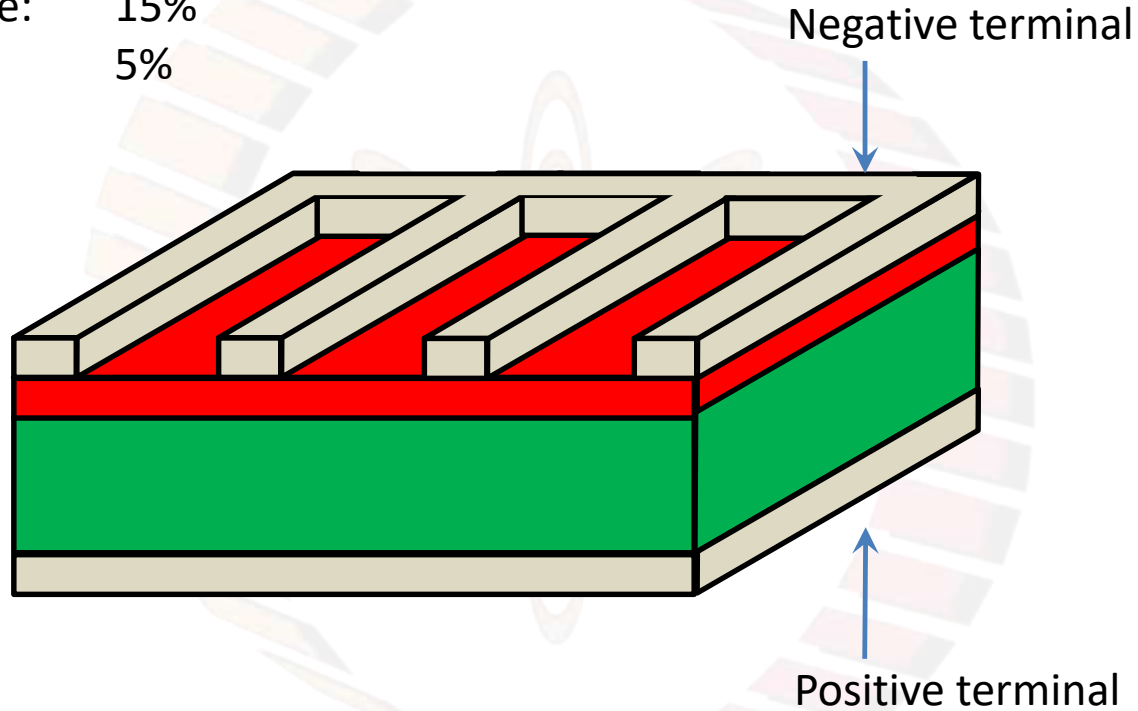




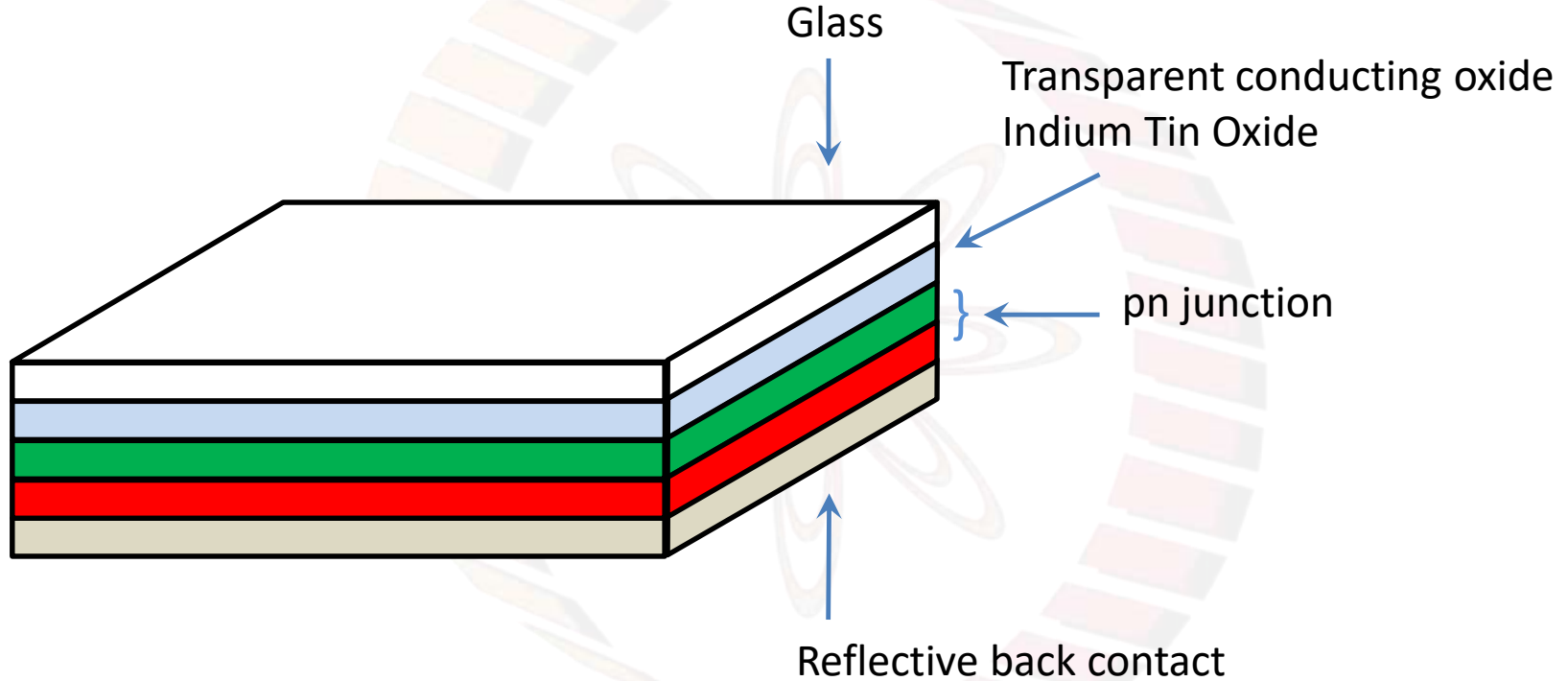




Single crystalline: 25%  
Poly crystalline: 15%  
Amorphous: 5%



## Amorphous Silicon Solar Cell



## ***Anti-reflective coatings***

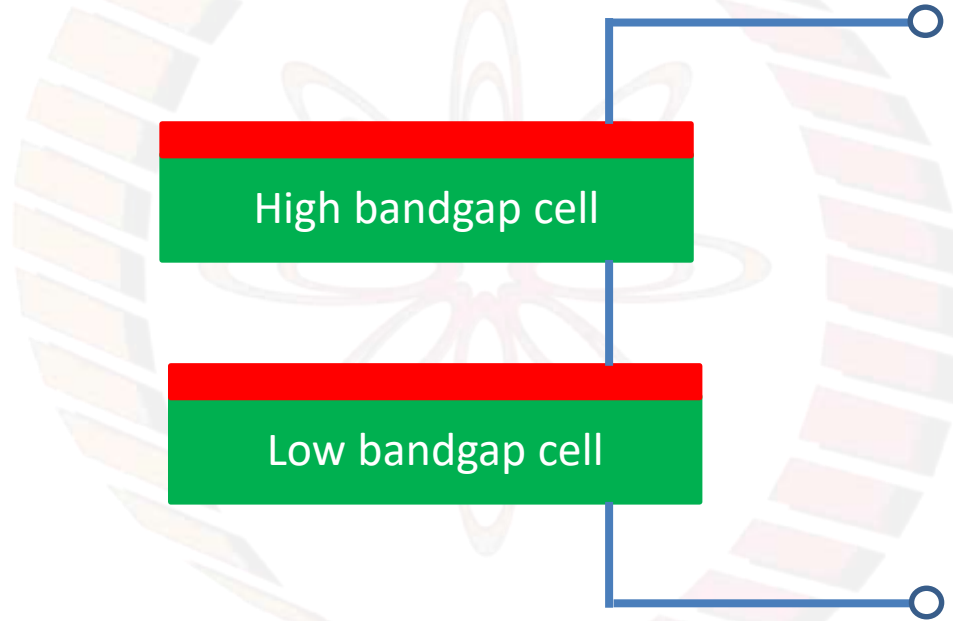
$$n_1 = \sqrt{n_0 n_s}$$

Glass  $n_s = 1.5$

Air  $n_0 = 0$

Film  $n_1 = 1.225$

## Tandem Cells



With several tandem cells and concentrated sunlight, theoretically  $> 80\%$  efficiency possible

Visible Spectrum Wavelength: 400 nm (violet) to 700 nm (red)

Corresponding band gaps: 3.1 eV to 1.8 eV

PbS, a direct bandgap semiconductor

Bandgap of bulk PbS: 0.41 eV (3020 nm)

Bandgap of nanocrystalline PbS: Can be varied to 4.0 eV



## Conclusions:

- 1) Parts of a solar cell are designed to increase the efficiency of the solar cell
- 2) Shockley-Queisser limit indicates the limitation of a single junction solar cell
- 3) Tandem solar cells can overcome these limitations