



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



Band gap E_g



(a)

Band gap less
than $2eV$:
Semiconductor



Band gap E_g



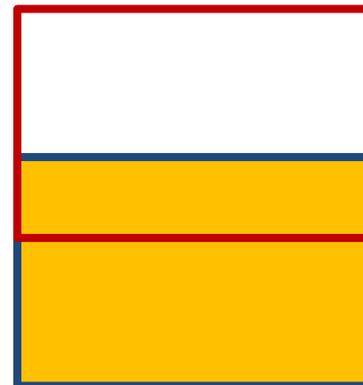
(b)

Partially filled
bands: Metal



(c)

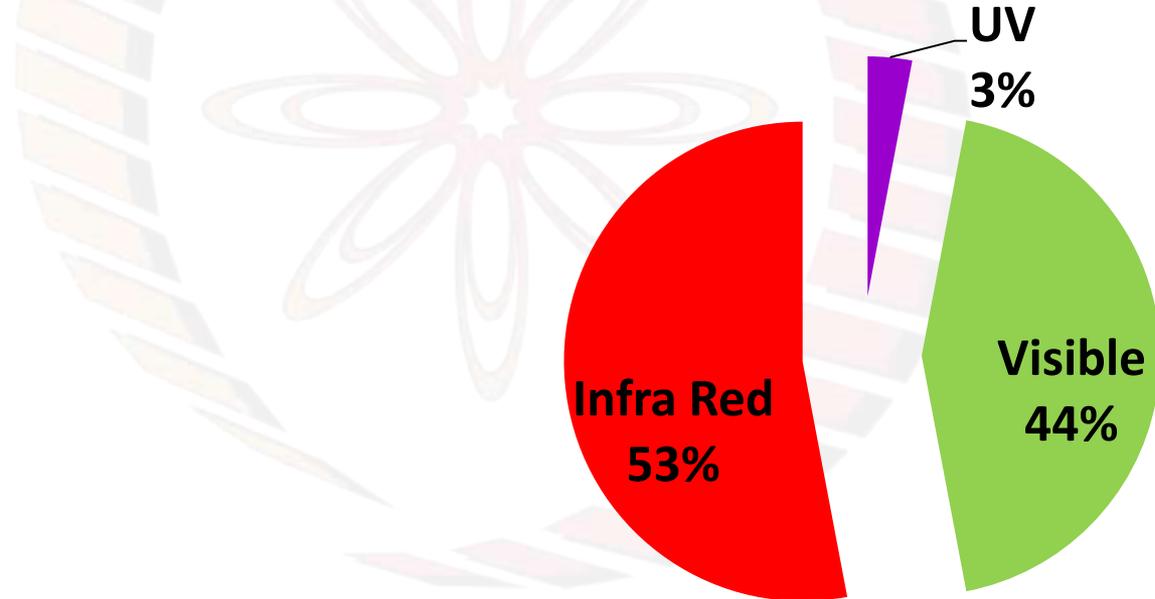
Overlapping
bands: Metal



(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



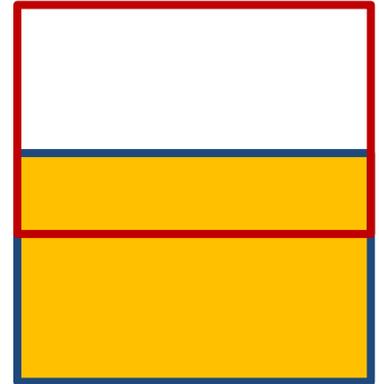
Band gap E_g



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



E_f - - - - -



(a)

n-type extrinsic
semiconductor



E_f - - - - -
Donor Levels



(b)

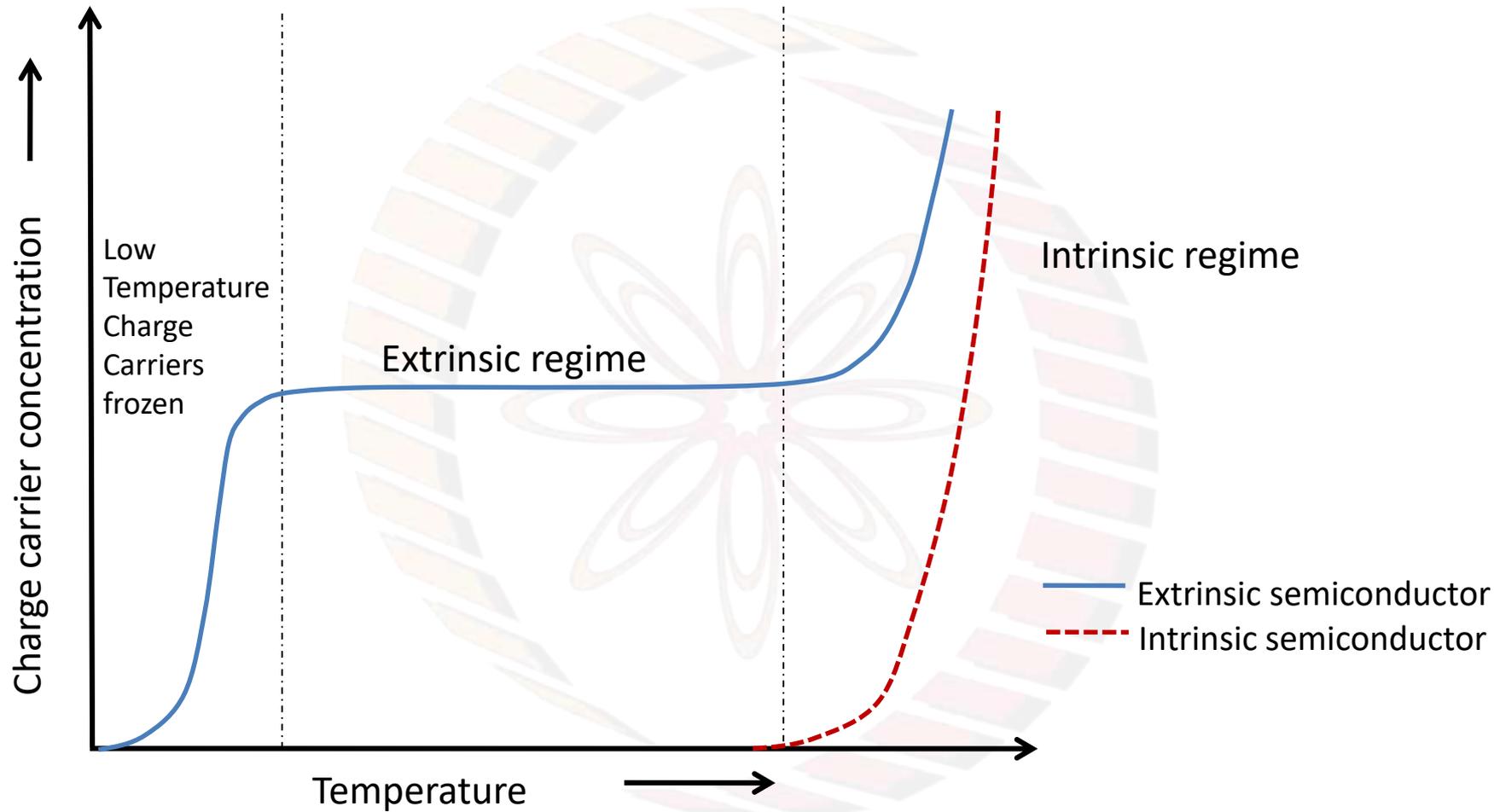
p-type extrinsic
semiconductor



E_f - - - - -
Acceptor Levels



(c)



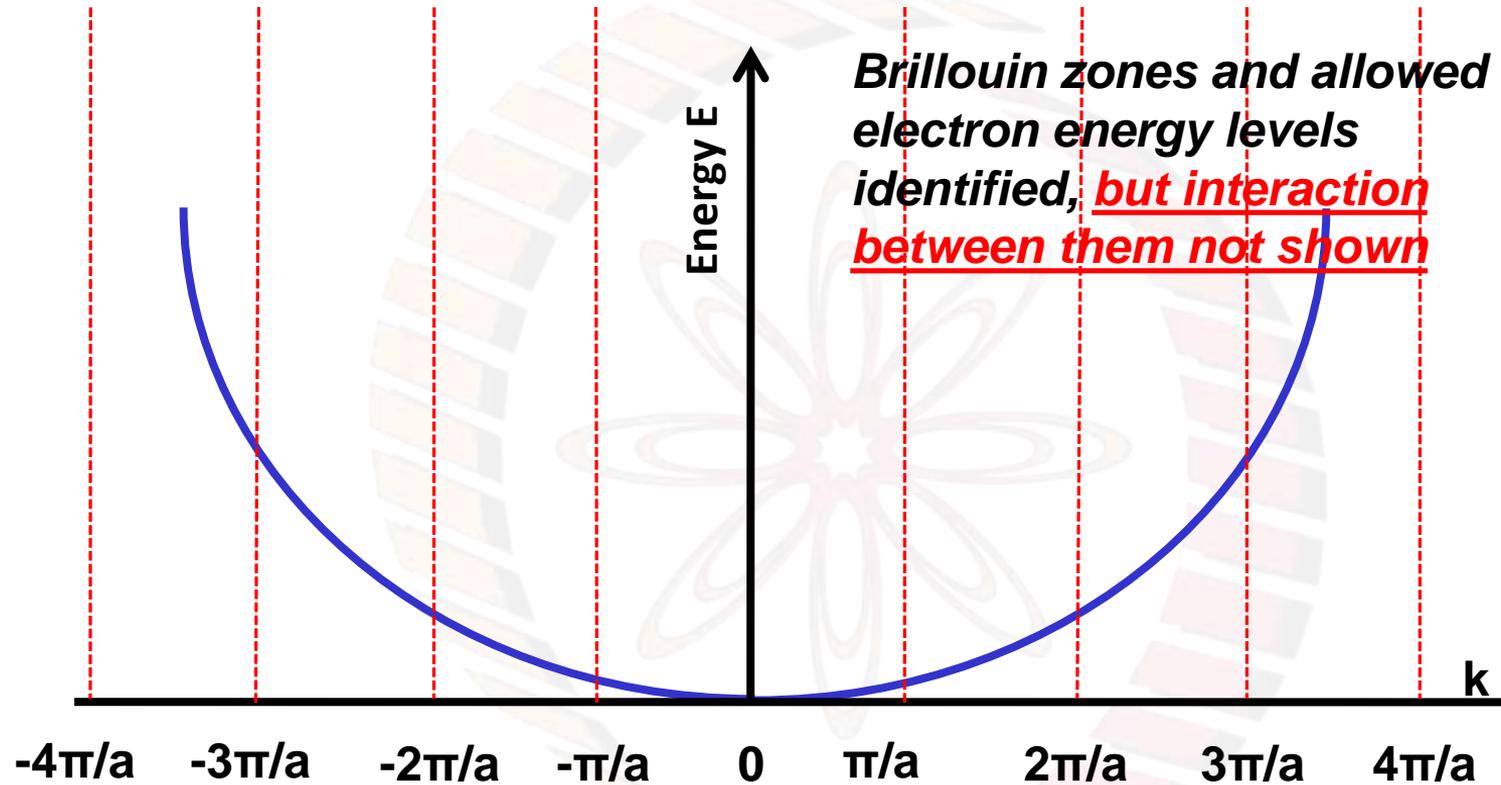
$$E = h\nu$$

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

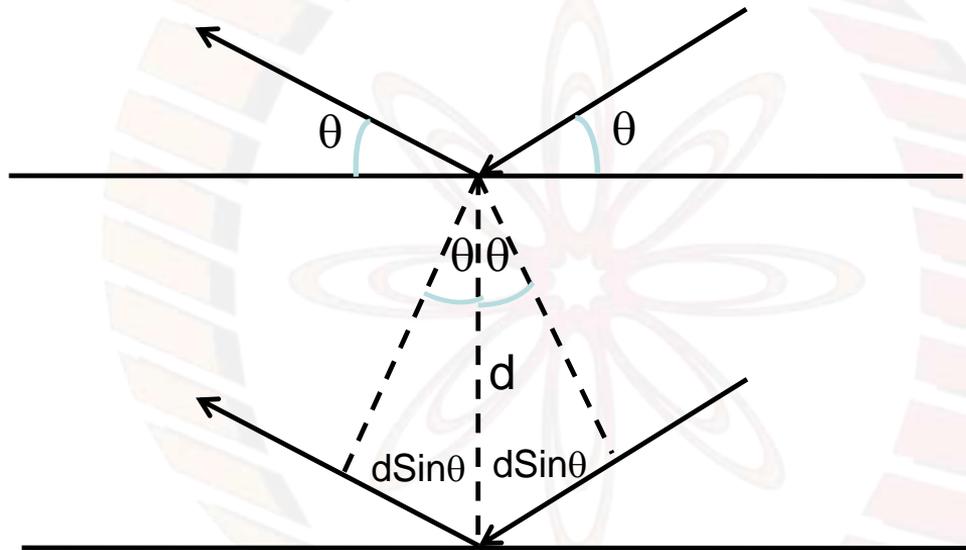
Planck

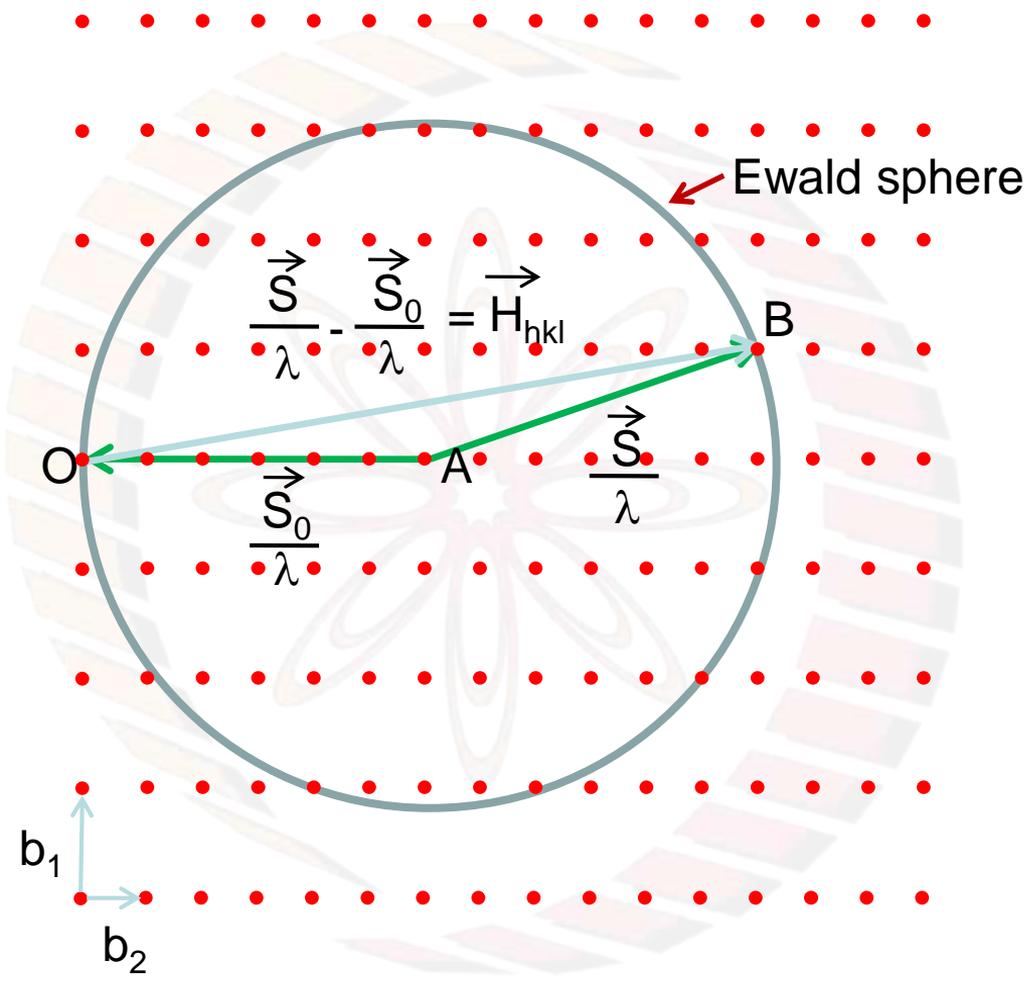
de Broglie

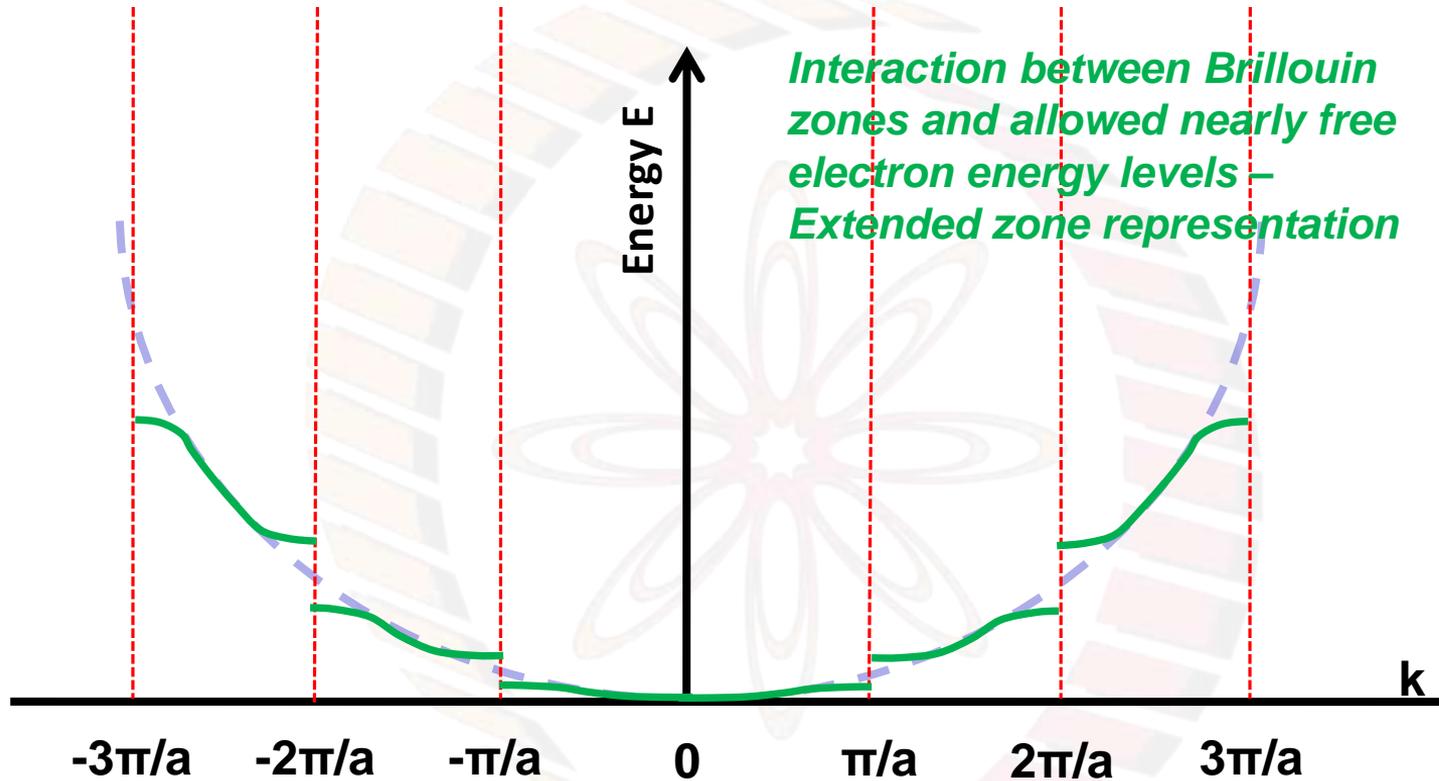
$$E = \frac{\hbar^2 k^2}{2m}$$



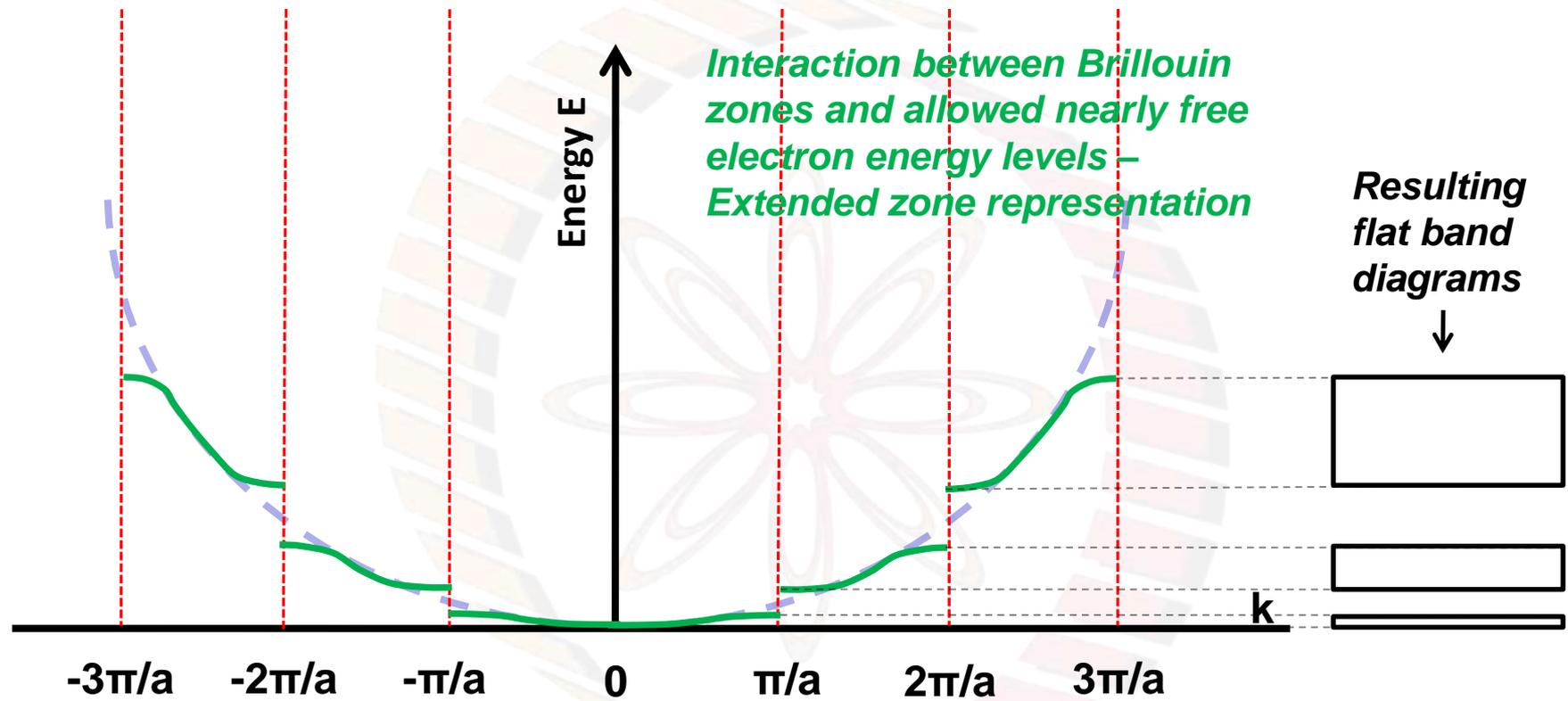
- Allowed energy and wave vectors of nearly free electrons
- - - Brillouin zone boundaries



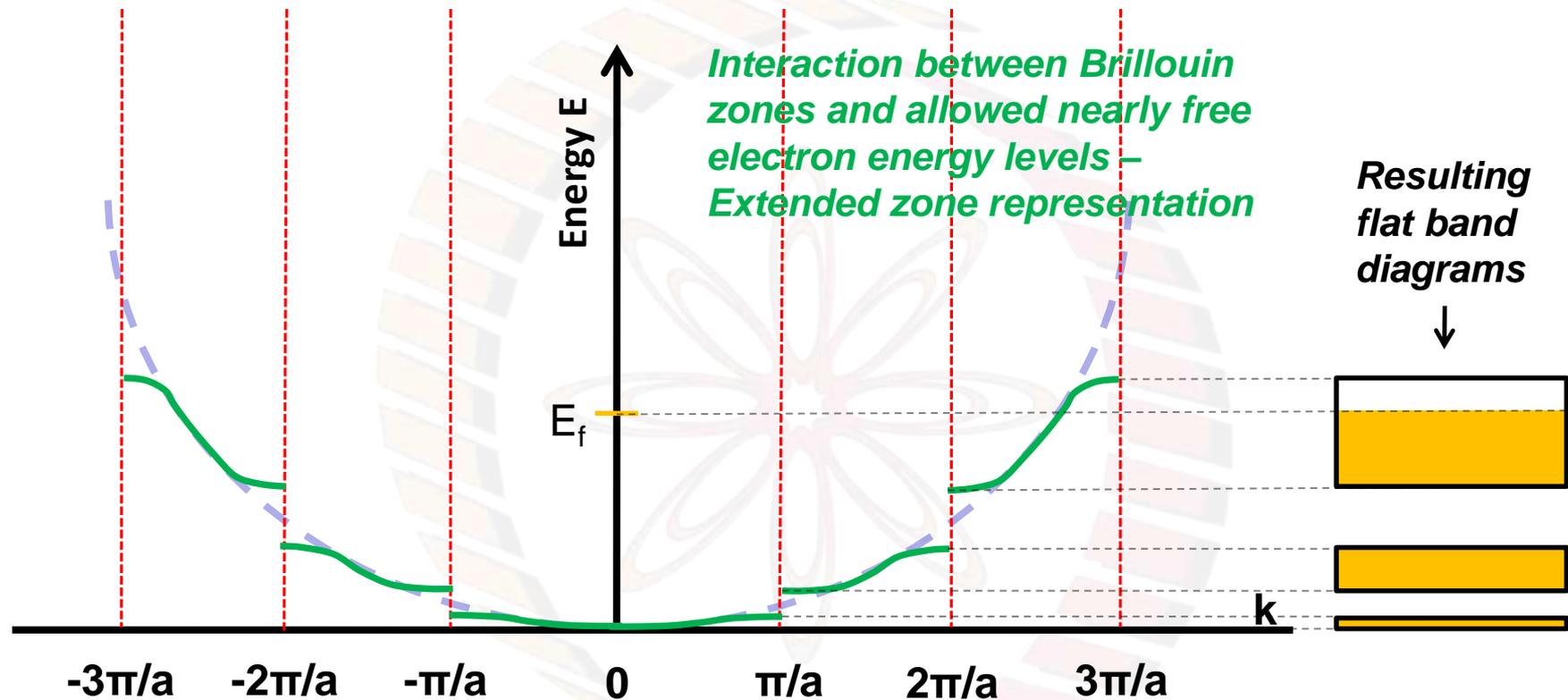




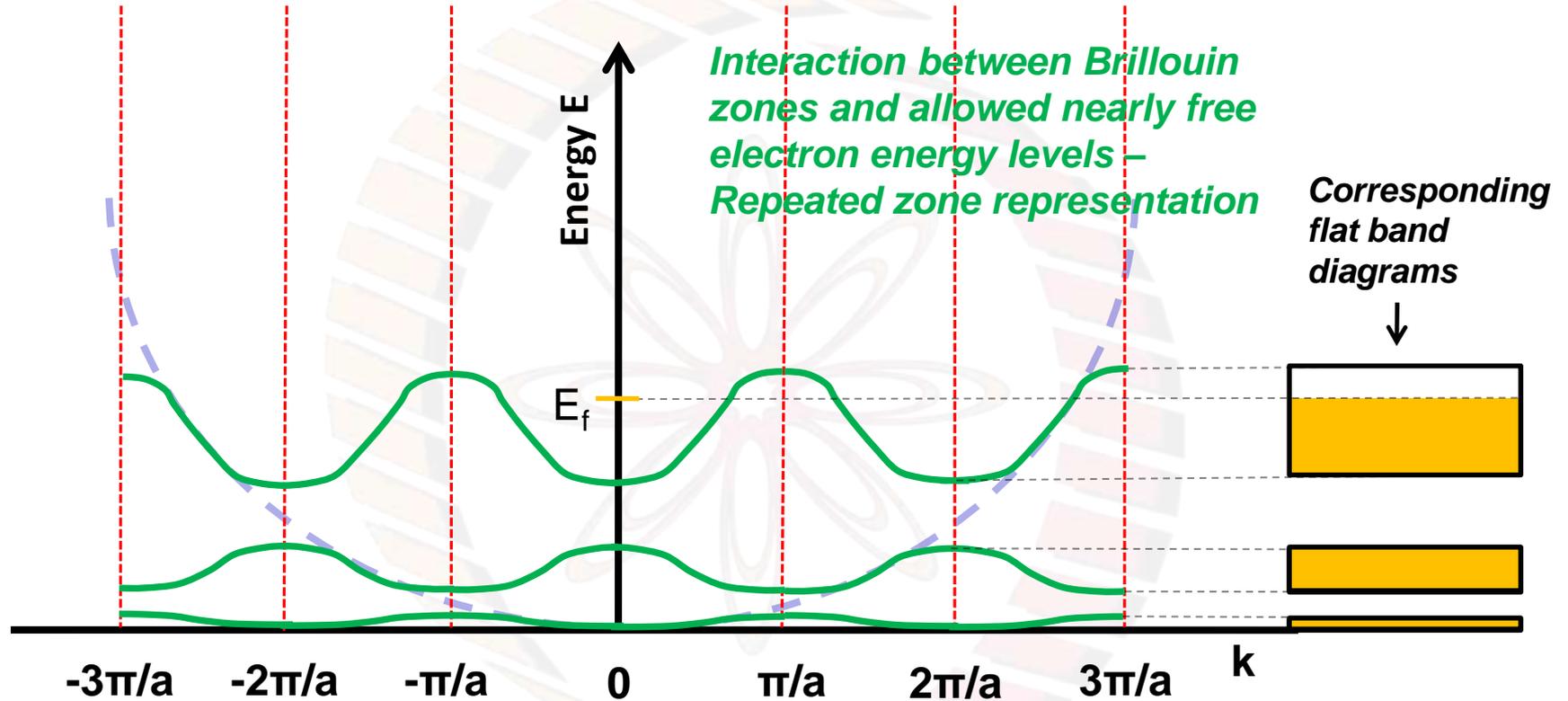
- - - E Vs k of nearly free electrons, without accounting for the Brillouin Zones
- E Vs k of nearly free electrons, distorted due to interaction with Brillouin Zones
- - - Brillouin zone boundaries



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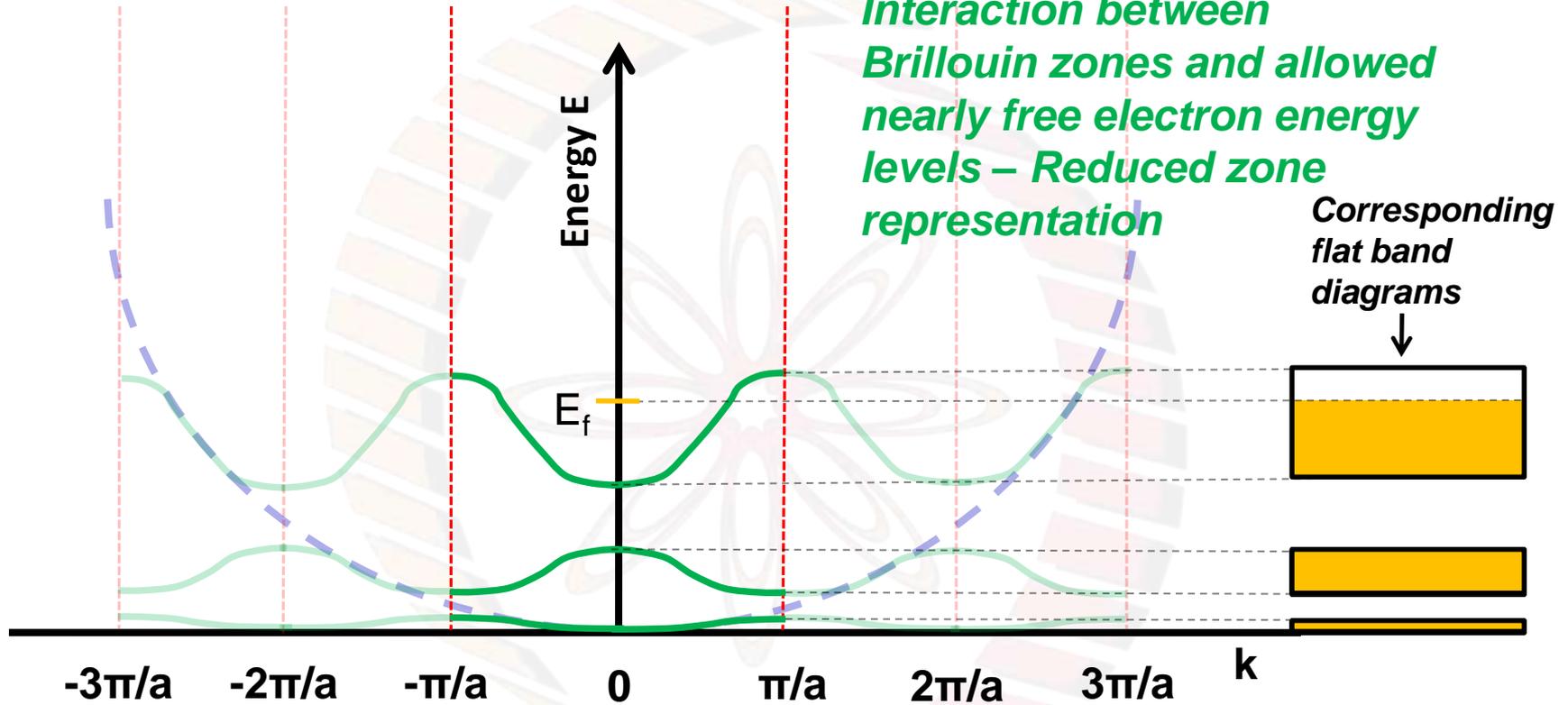


- - - E Vs k of nearly free electrons, without accounting for the Brillouin Zones
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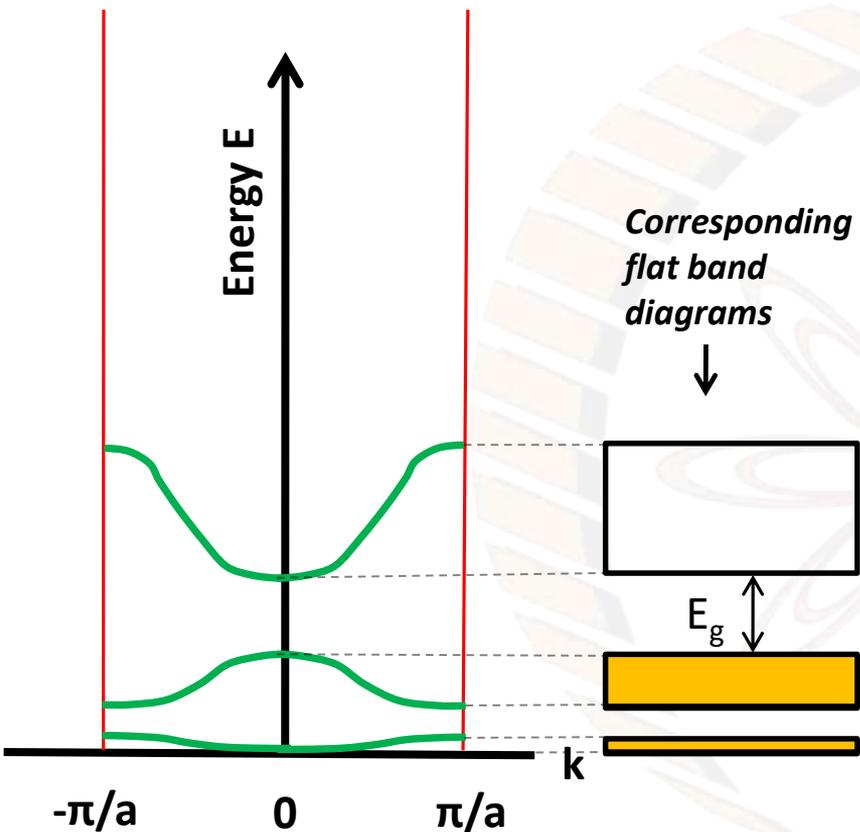


- E Vs k of nearly free electrons, without accounting for the Brillouin Zones
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- Brillouin zone boundaries

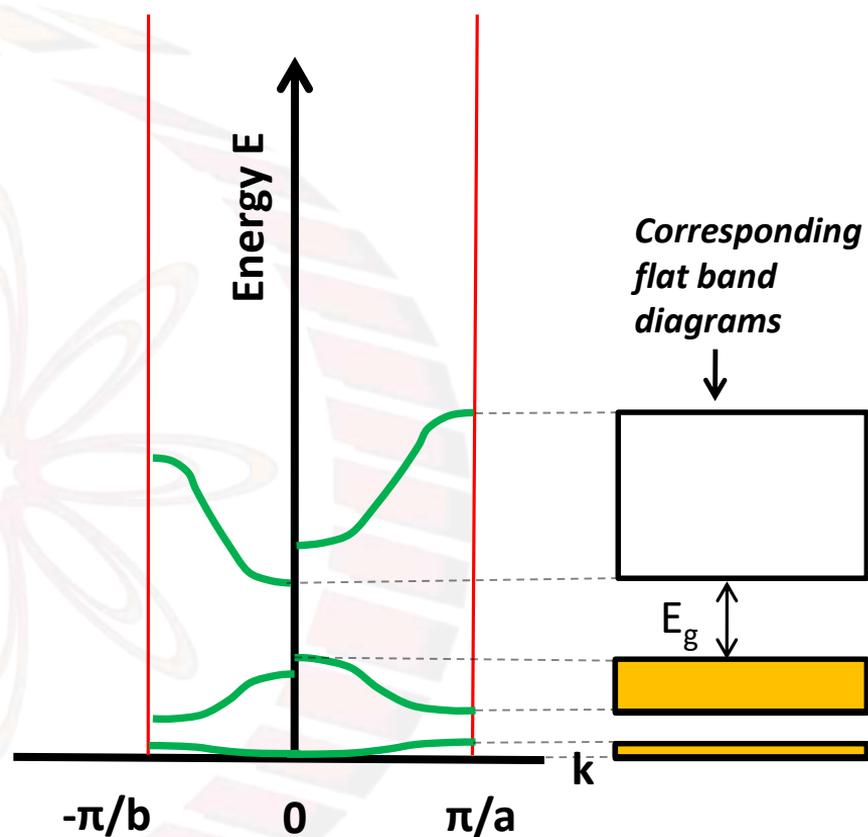
Interaction between Brillouin zones and allowed nearly free electron energy levels – Reduced zone representation



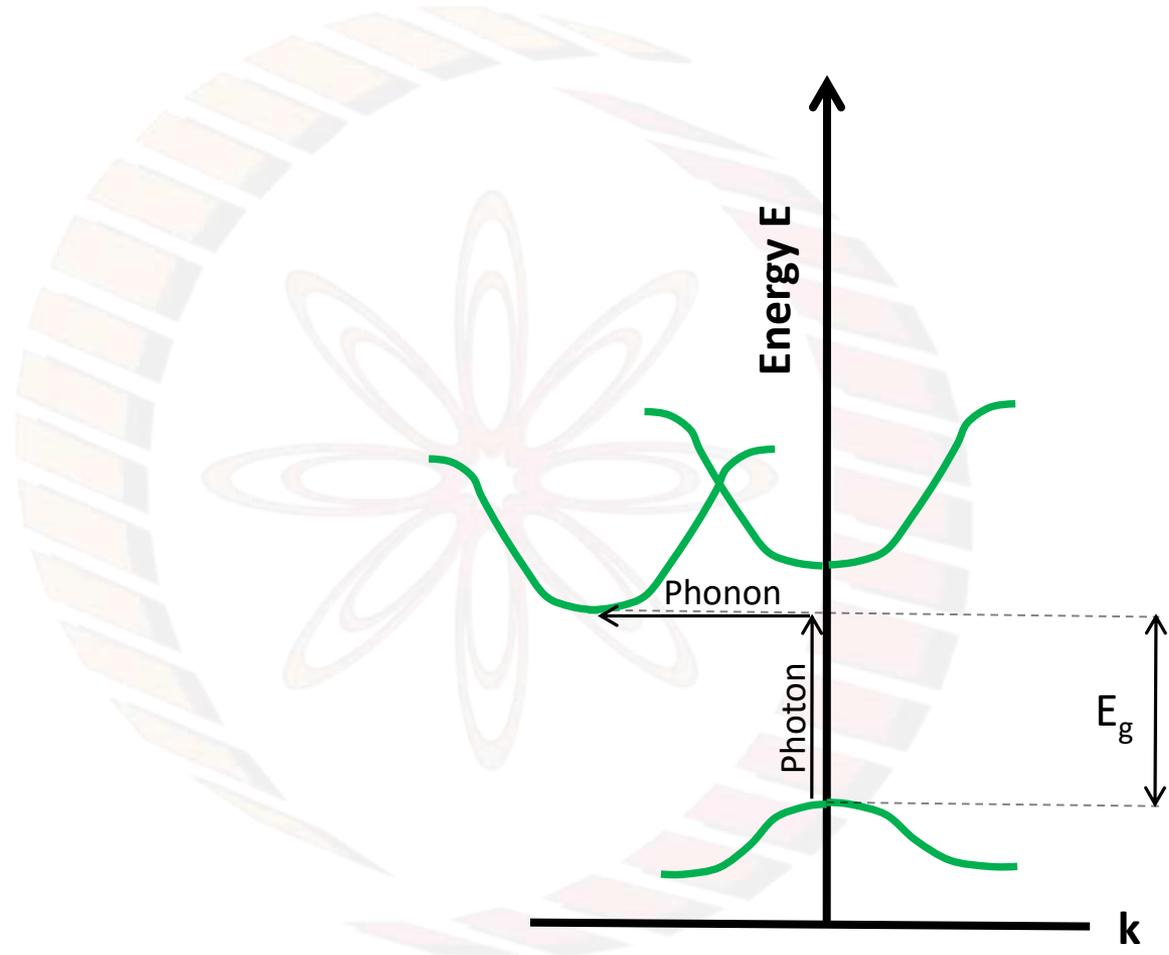
- — — E Vs k of nearly free electrons, without accounting for the Brillouin Zones
- — — E Vs k of nearly free electrons, distorted due to interaction with Brillouin Zones
- - - - Brillouin zone boundaries



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

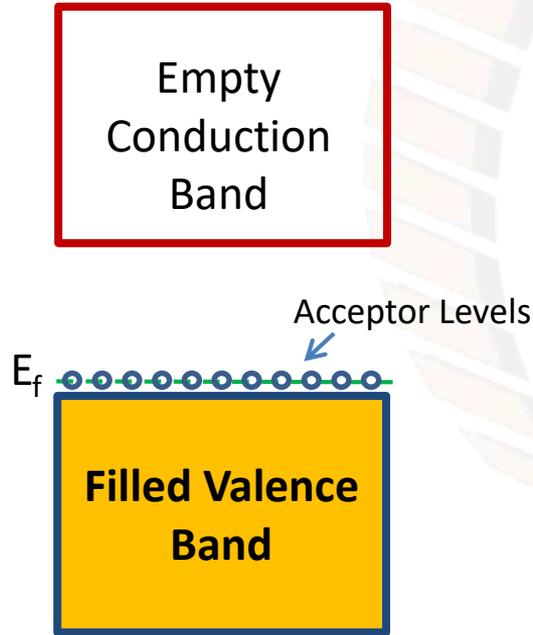
Empty
Conduction
Band

E_f - - - - -

Filled Valence
Band

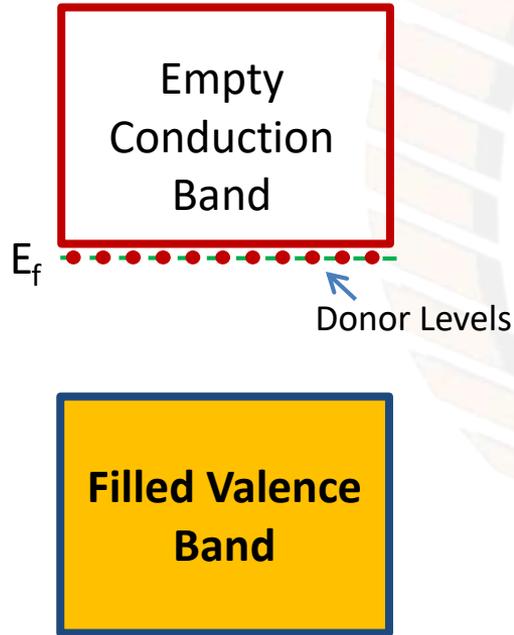
- Charge carrier concentration depends only temperature
- Conductivity depends only on Temperature
- Examples:
 - Elemental: Group IV A: Si (1.1 eV), Ge (0.7 eV)
 - Compound:
 - Group III A and Group V A (III-V)
 - GaAs, InSb
 - Group II B and Group VI A (II-VI)
 - CdS, ZnTe

p-type extrinsic semiconductor



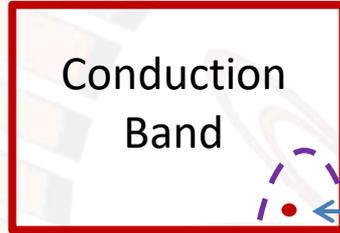
- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
 - Group IV A elements doped with small quantities of Group III A elements: B, Al, Ga, In, Tl

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



Electron in conduction band

E_f

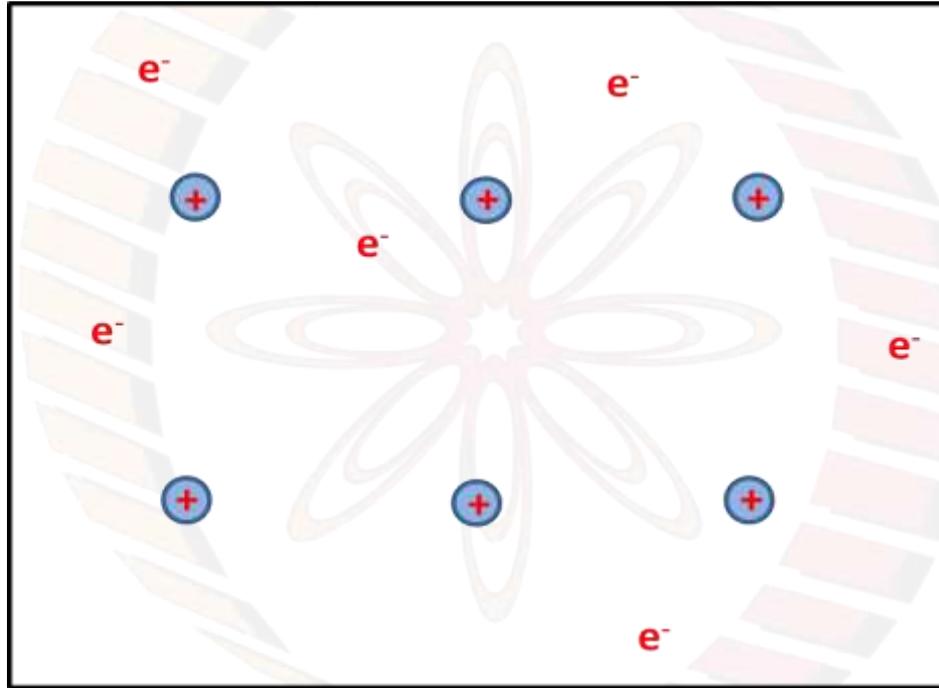


Hole in valence band

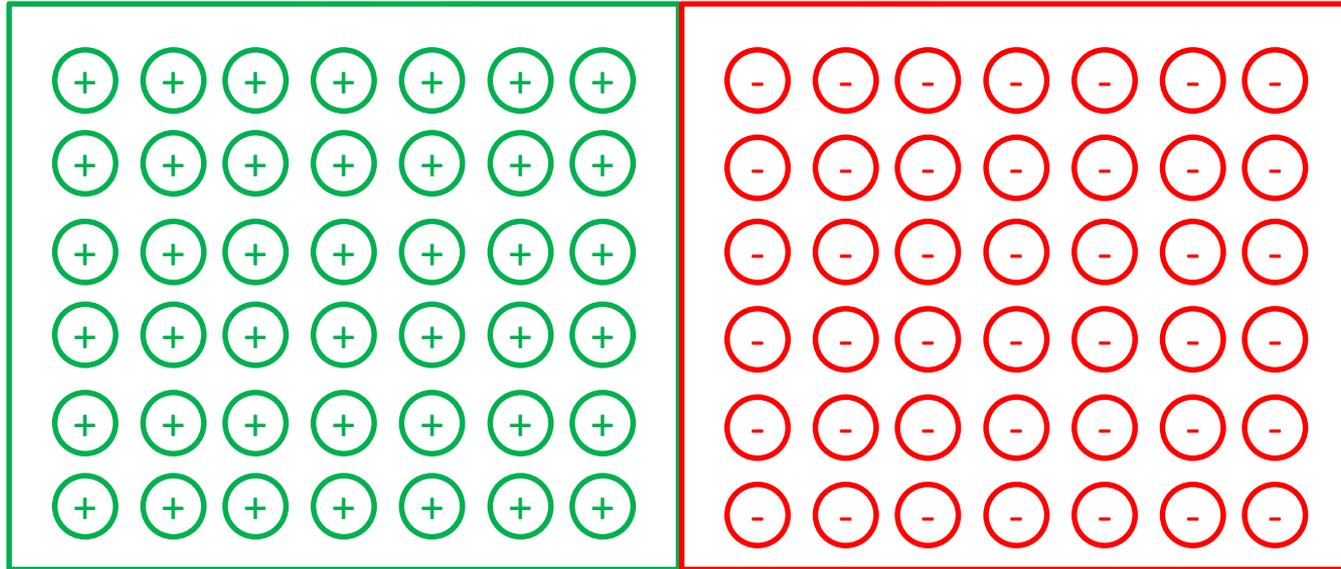
$$E_g = h\nu$$

Stability of electron-hole pair?

Metal



The p-n junction



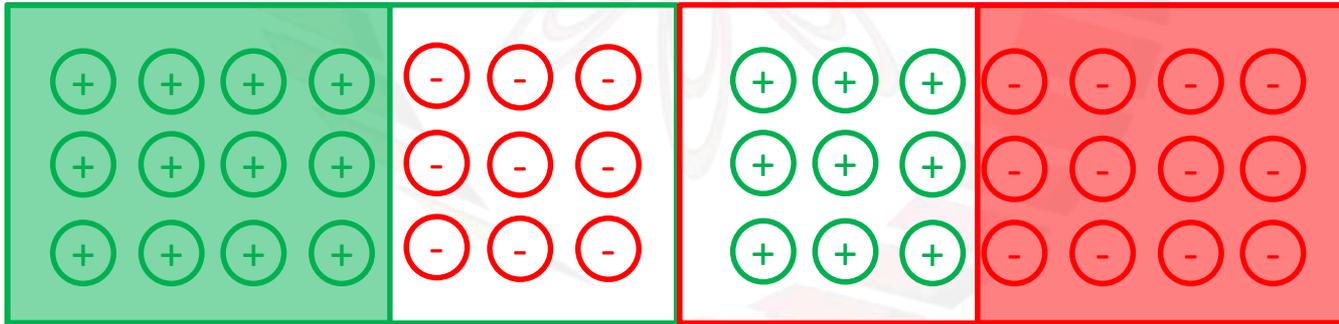
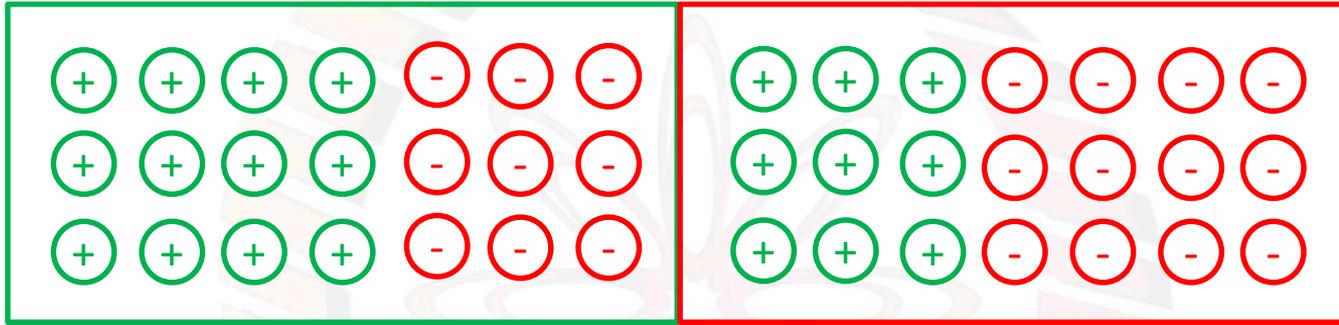
Si doped with B

Si doped with P

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

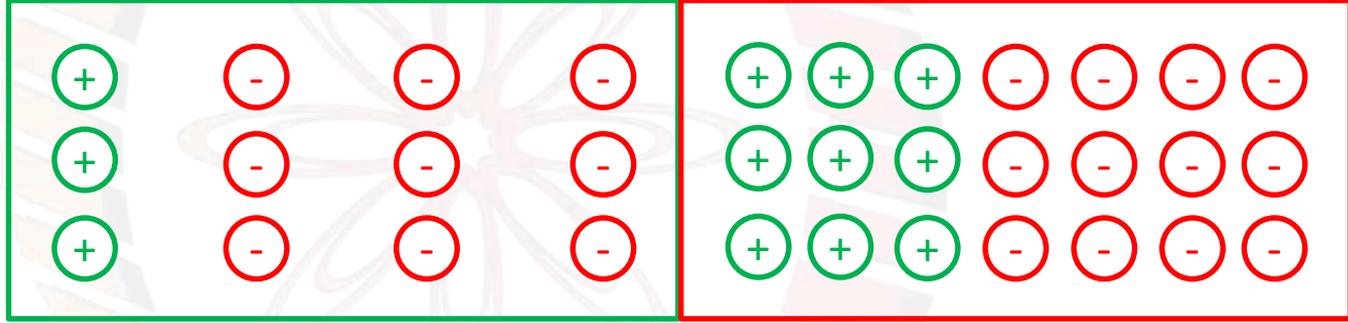
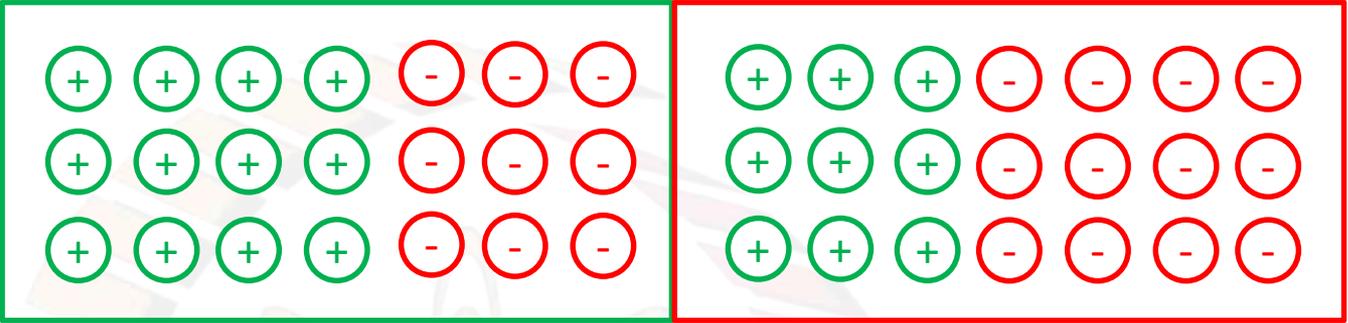
The space charge region

Depletion region

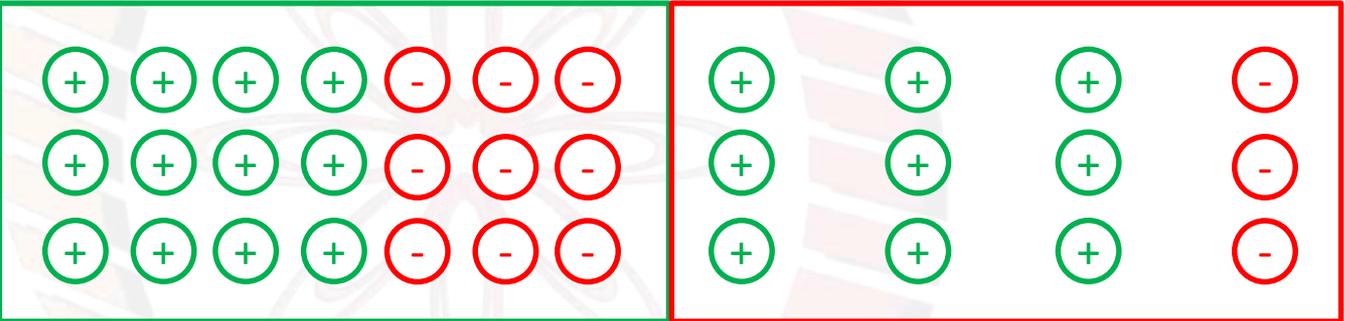
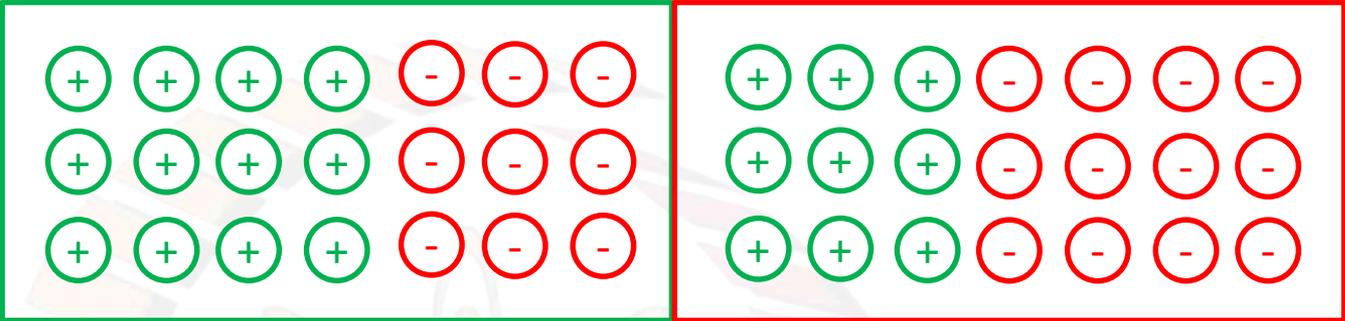


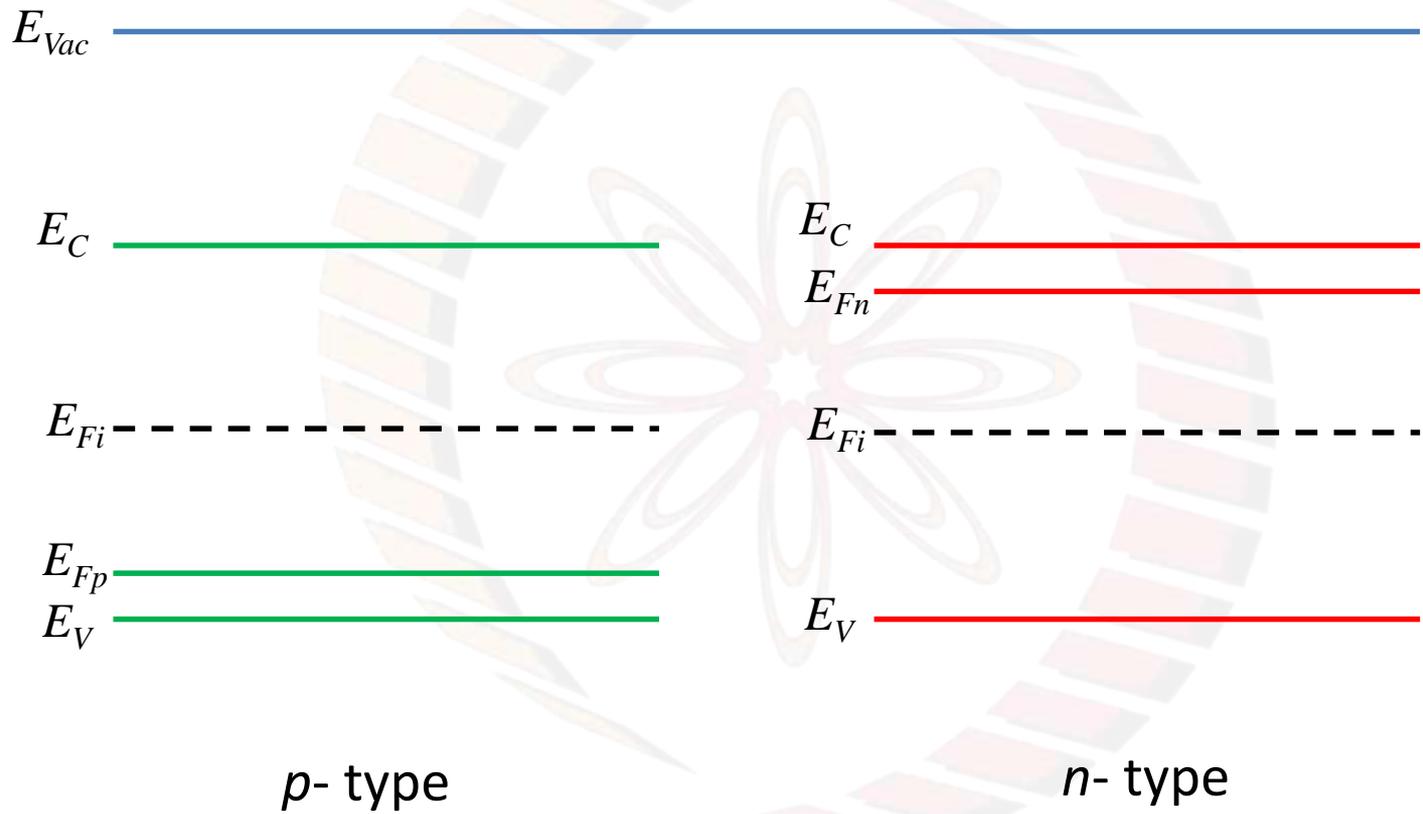
E

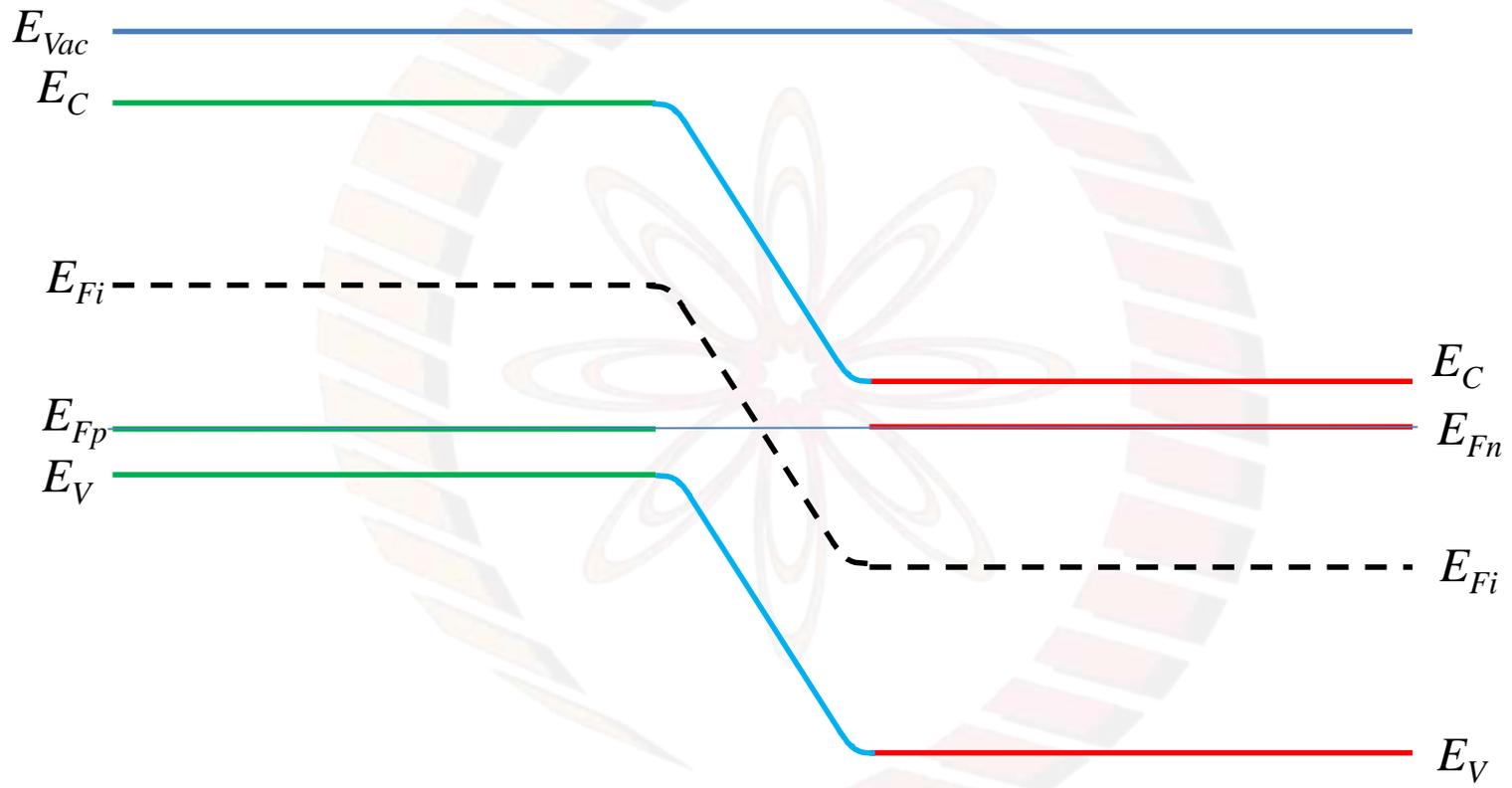
space charge region
depletion region



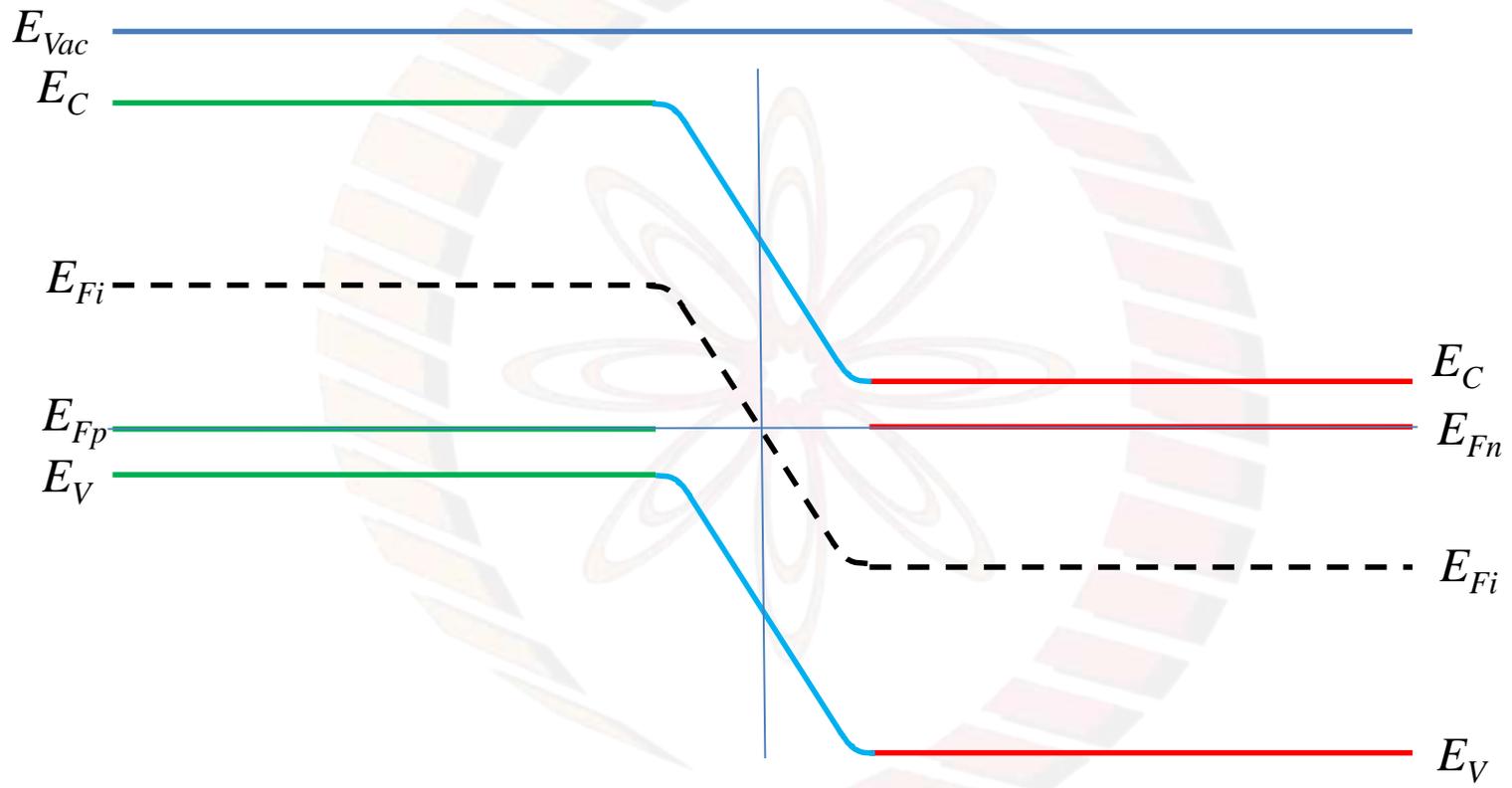
space charge region
depletion region





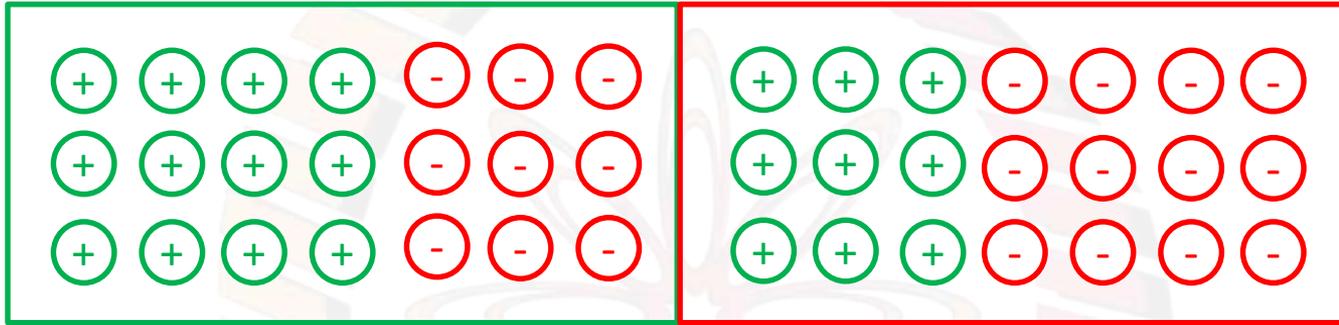


pn-junction



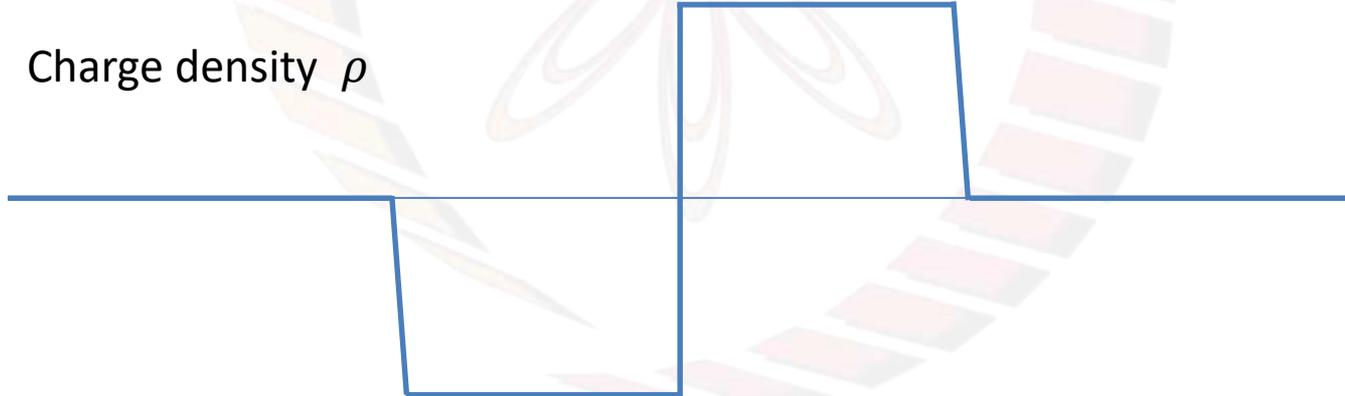
pn-junction

The space charge region

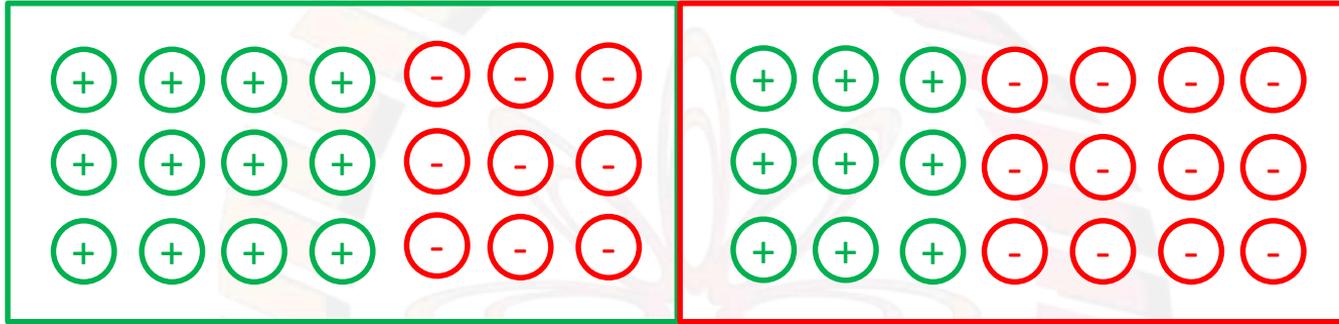


Charge density ρ

ρ

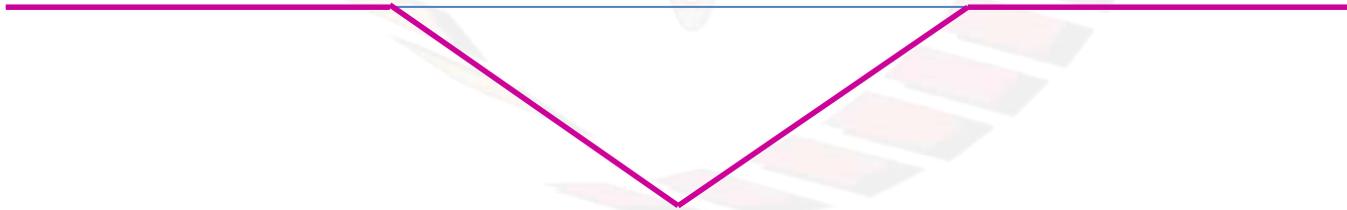


The space charge region

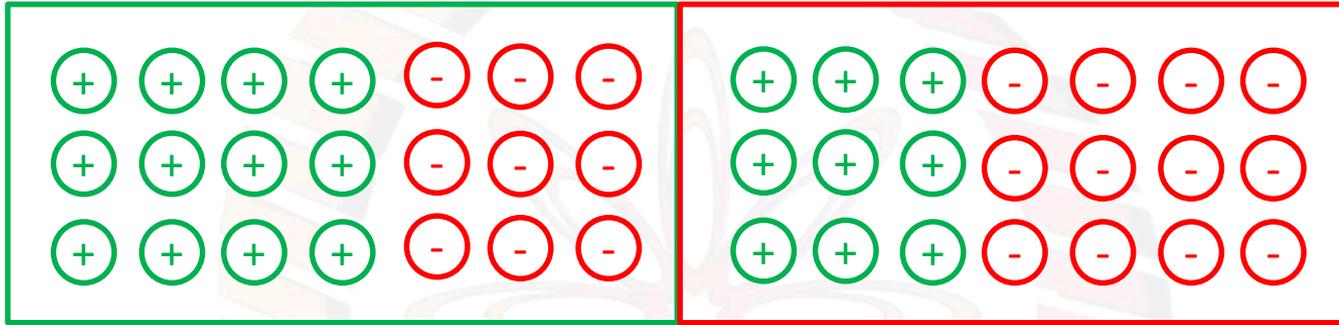


$$\frac{\partial E}{\partial x} = \frac{\rho}{\epsilon}$$

E



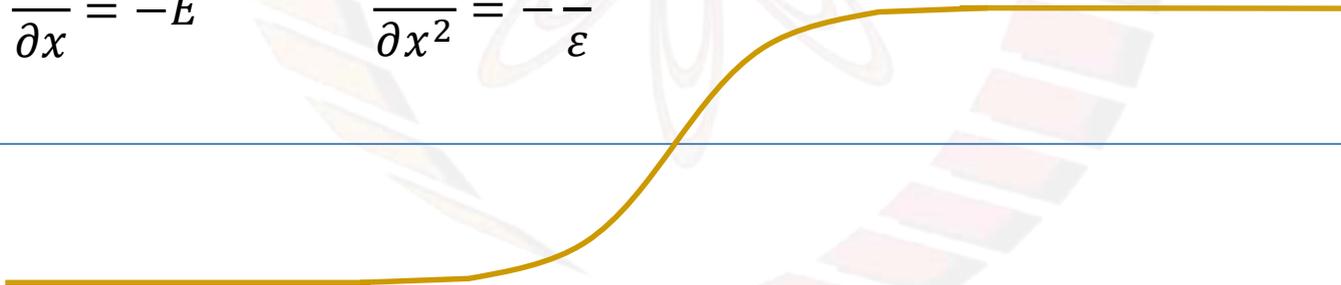
The space charge region

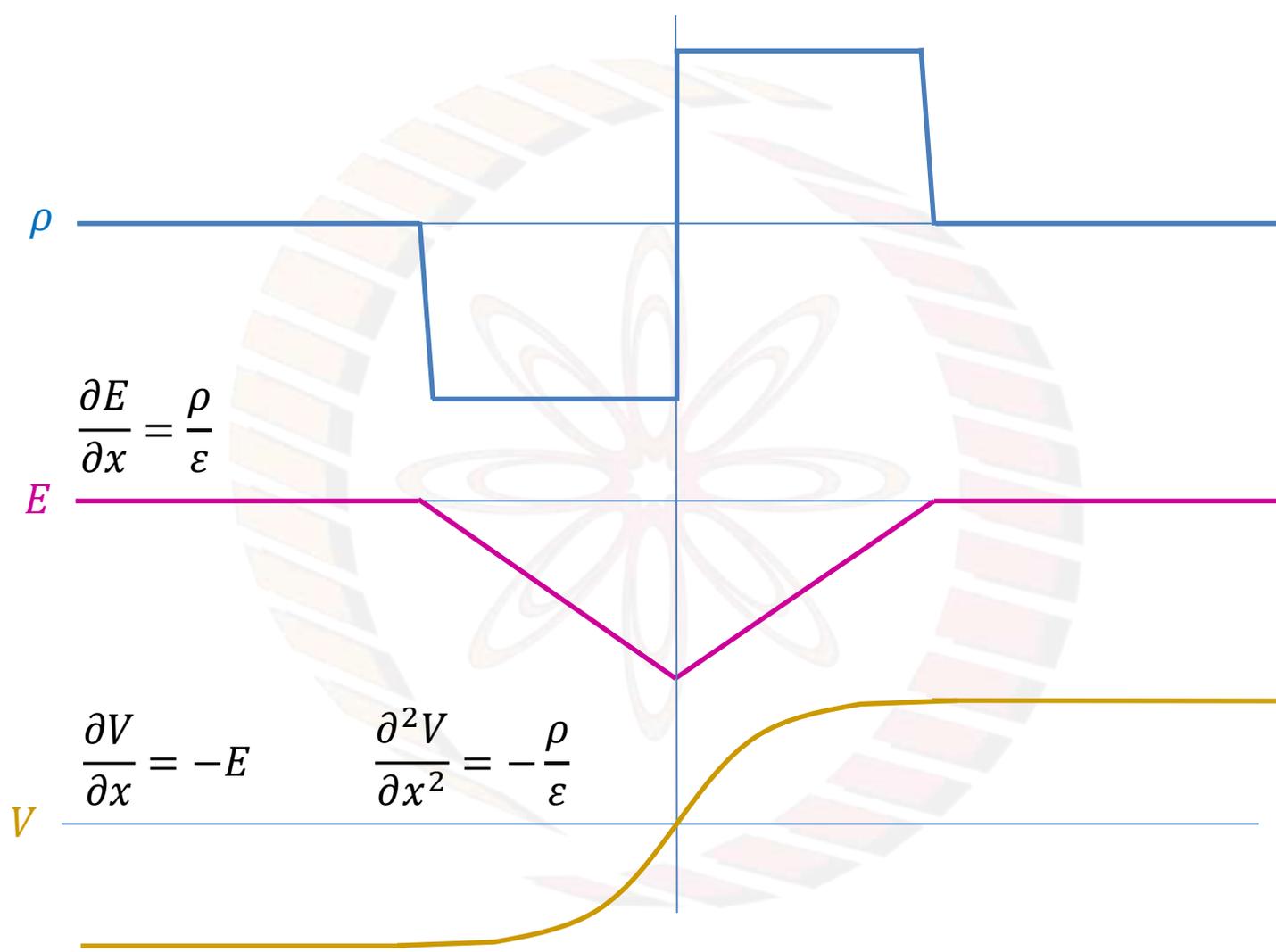


$$\frac{\partial V}{\partial x} = -E$$

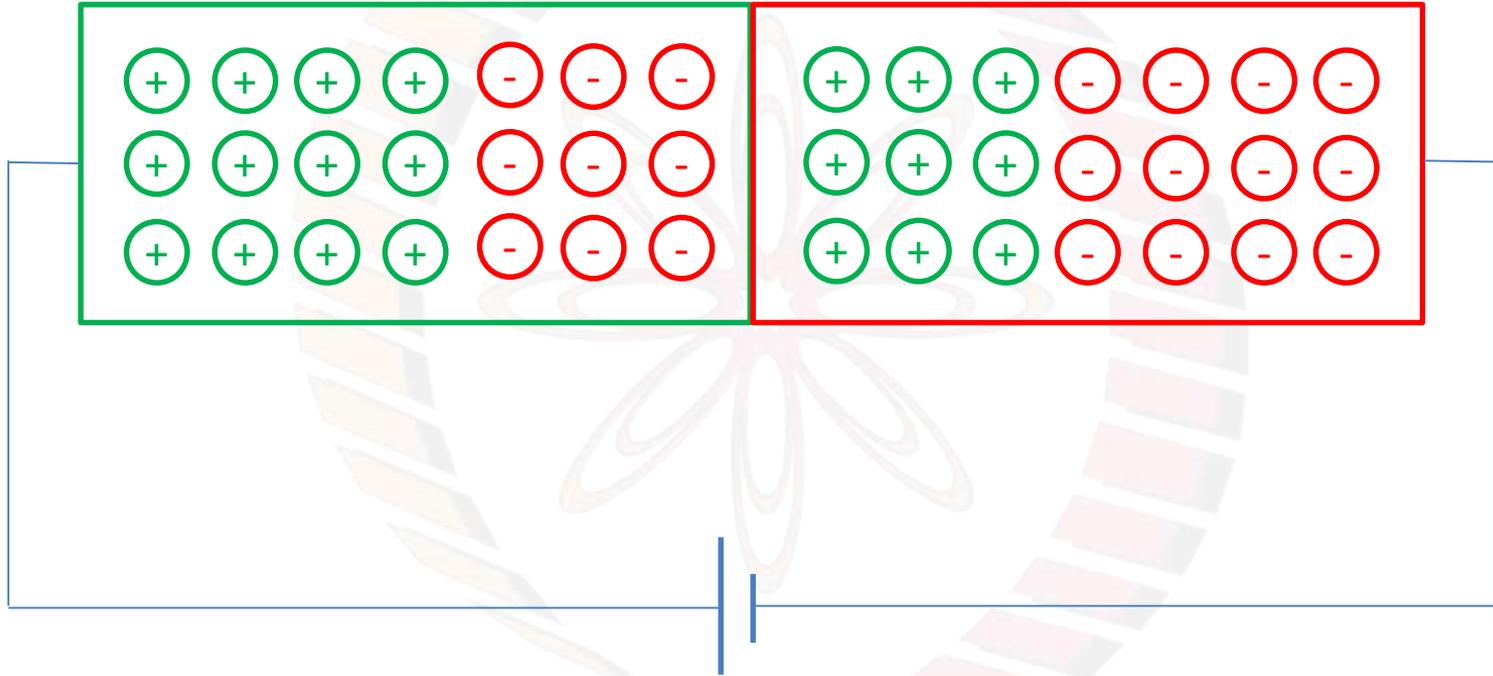
$$\frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\epsilon}$$

V

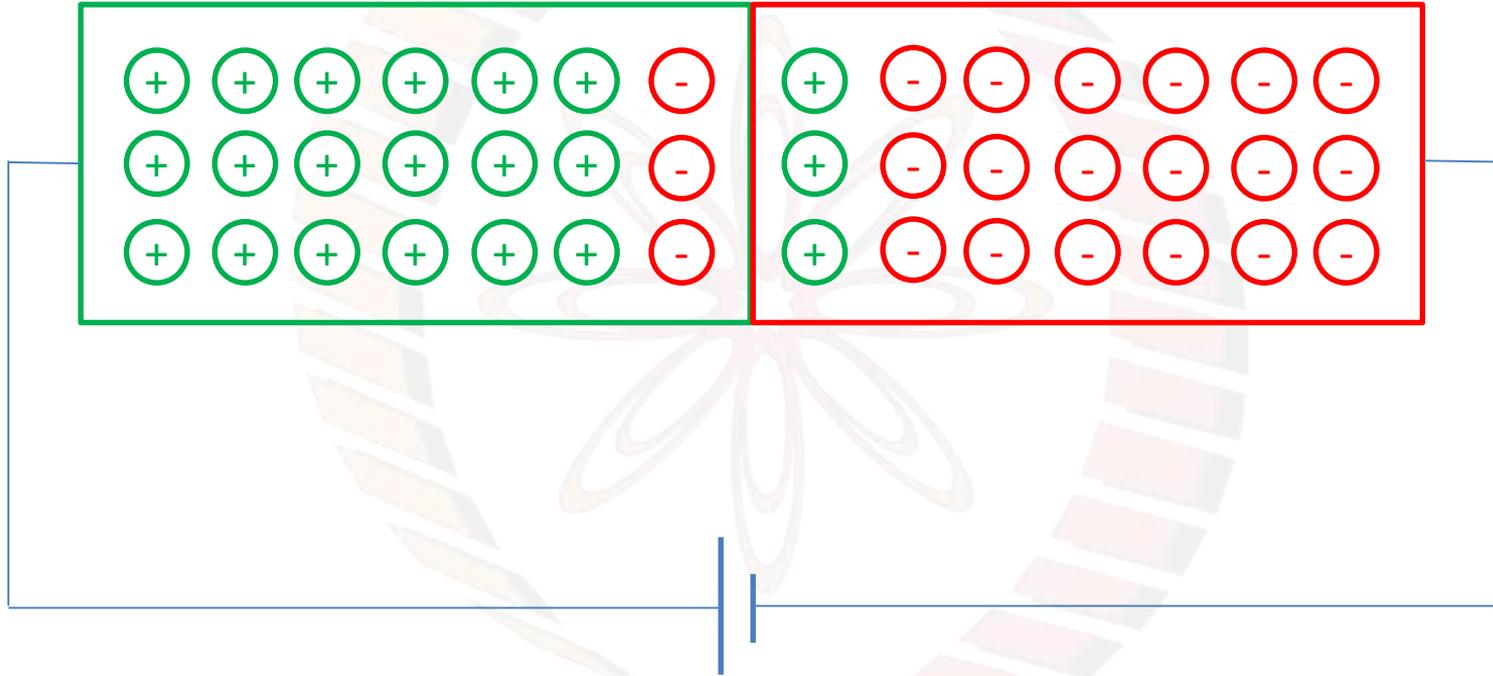




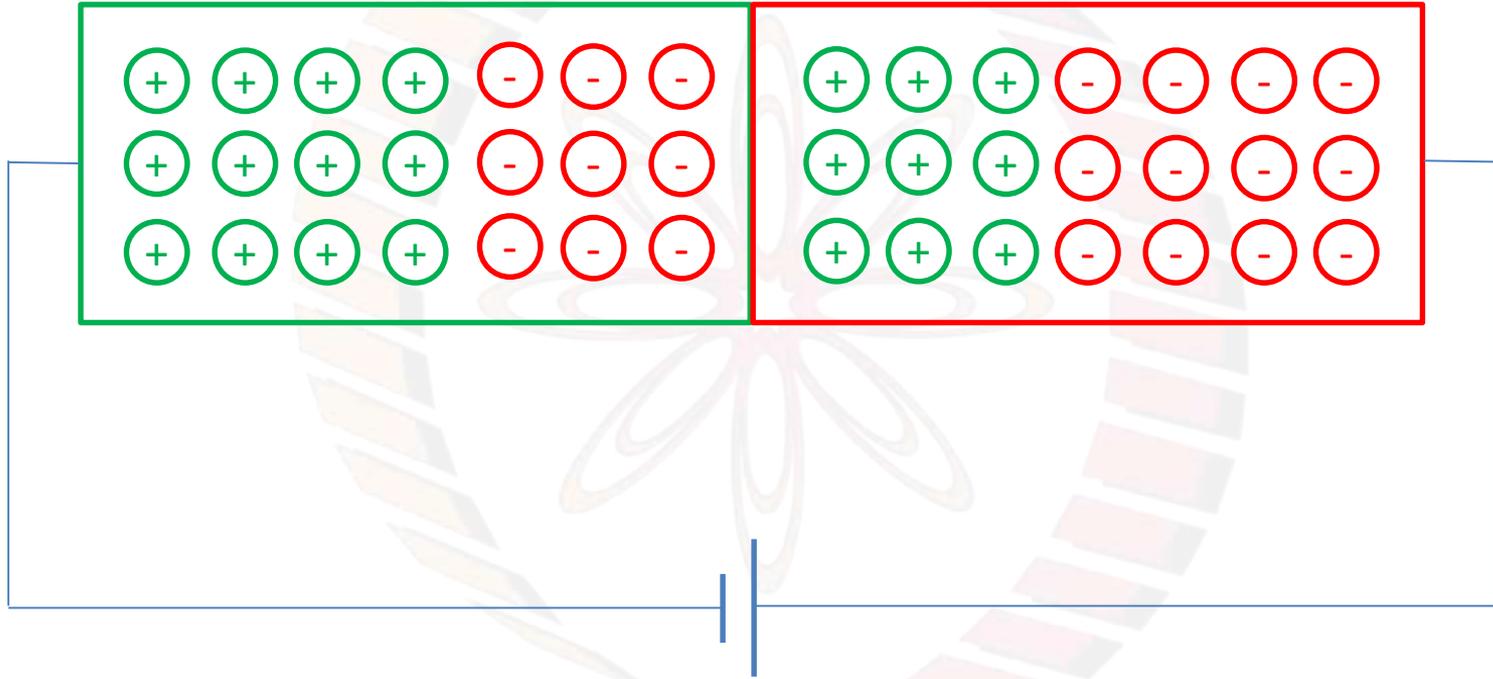
Forward bias



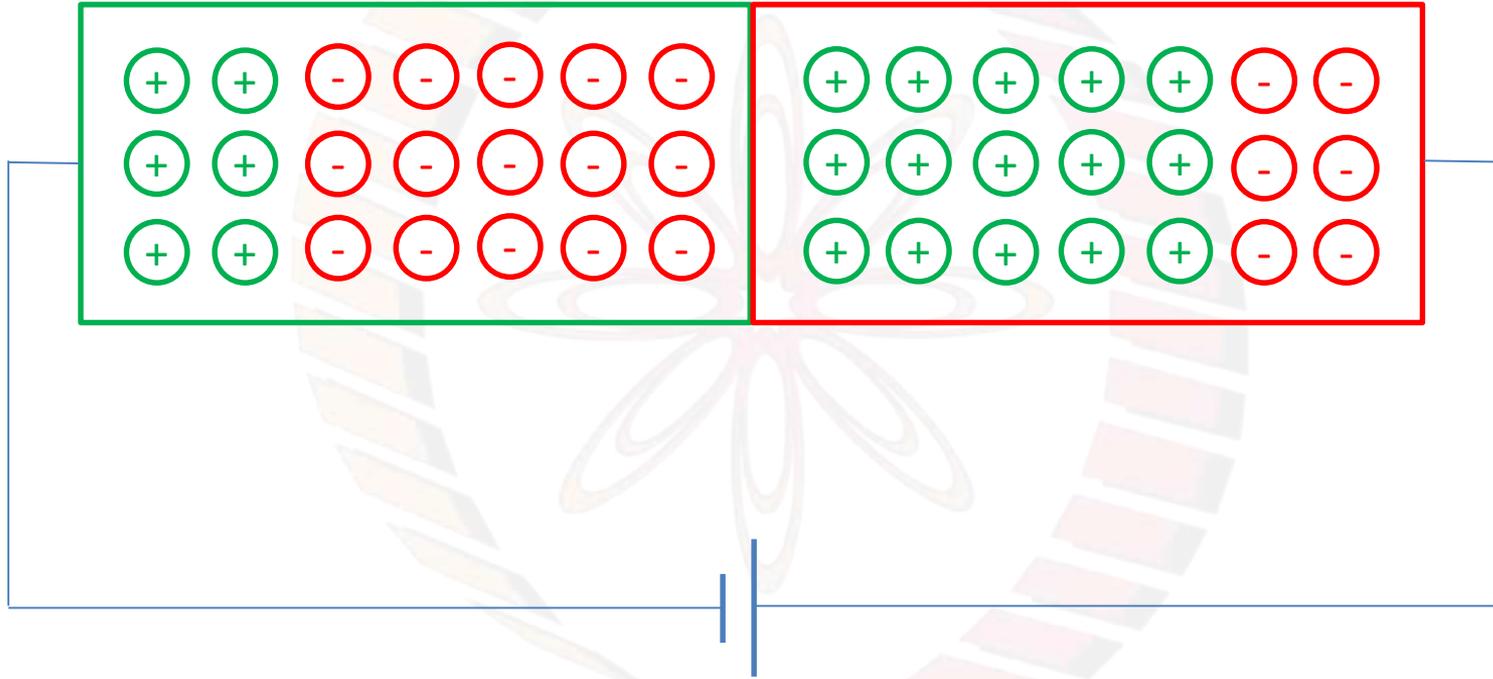
Forward bias



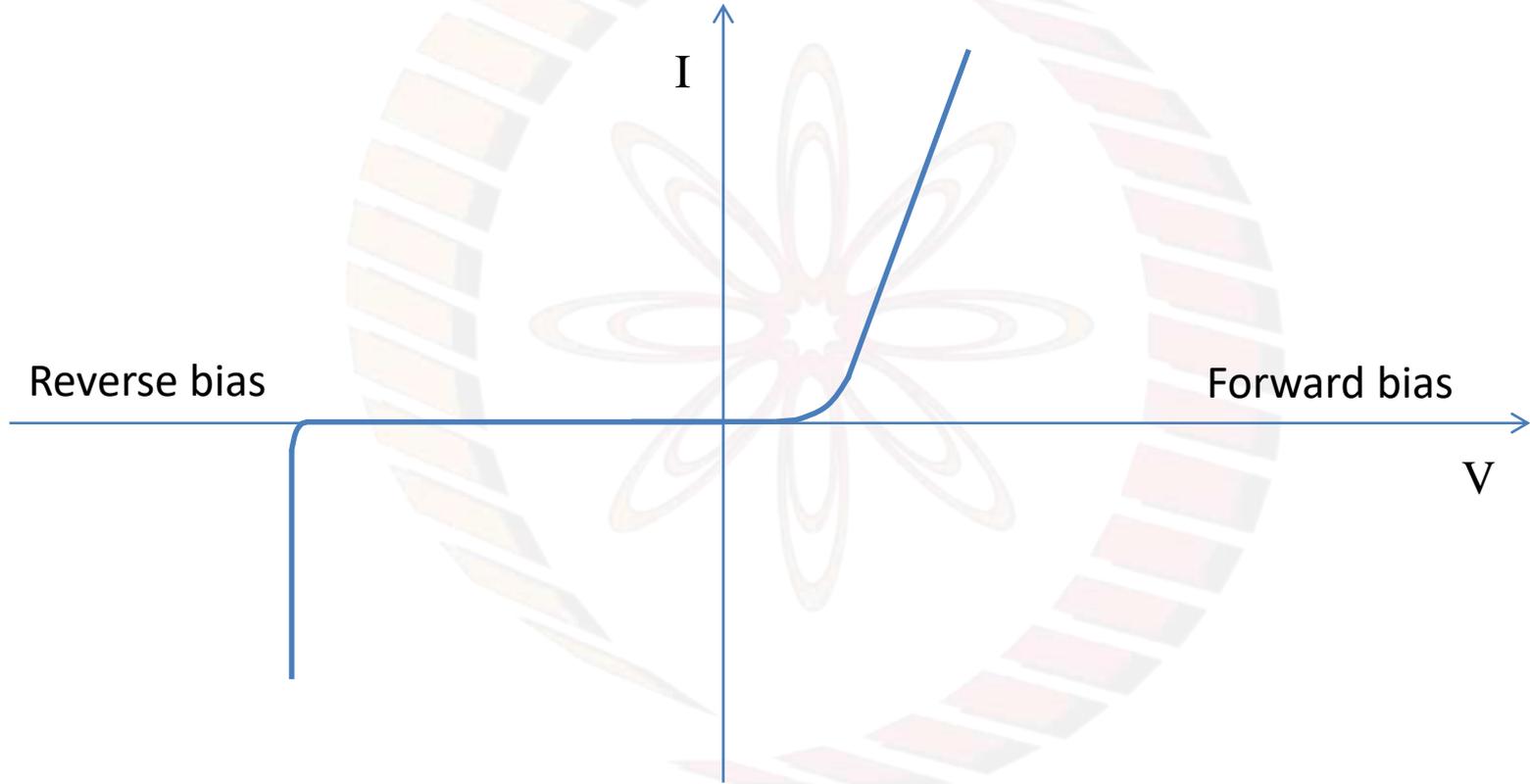
Reverse bias



Reverse bias



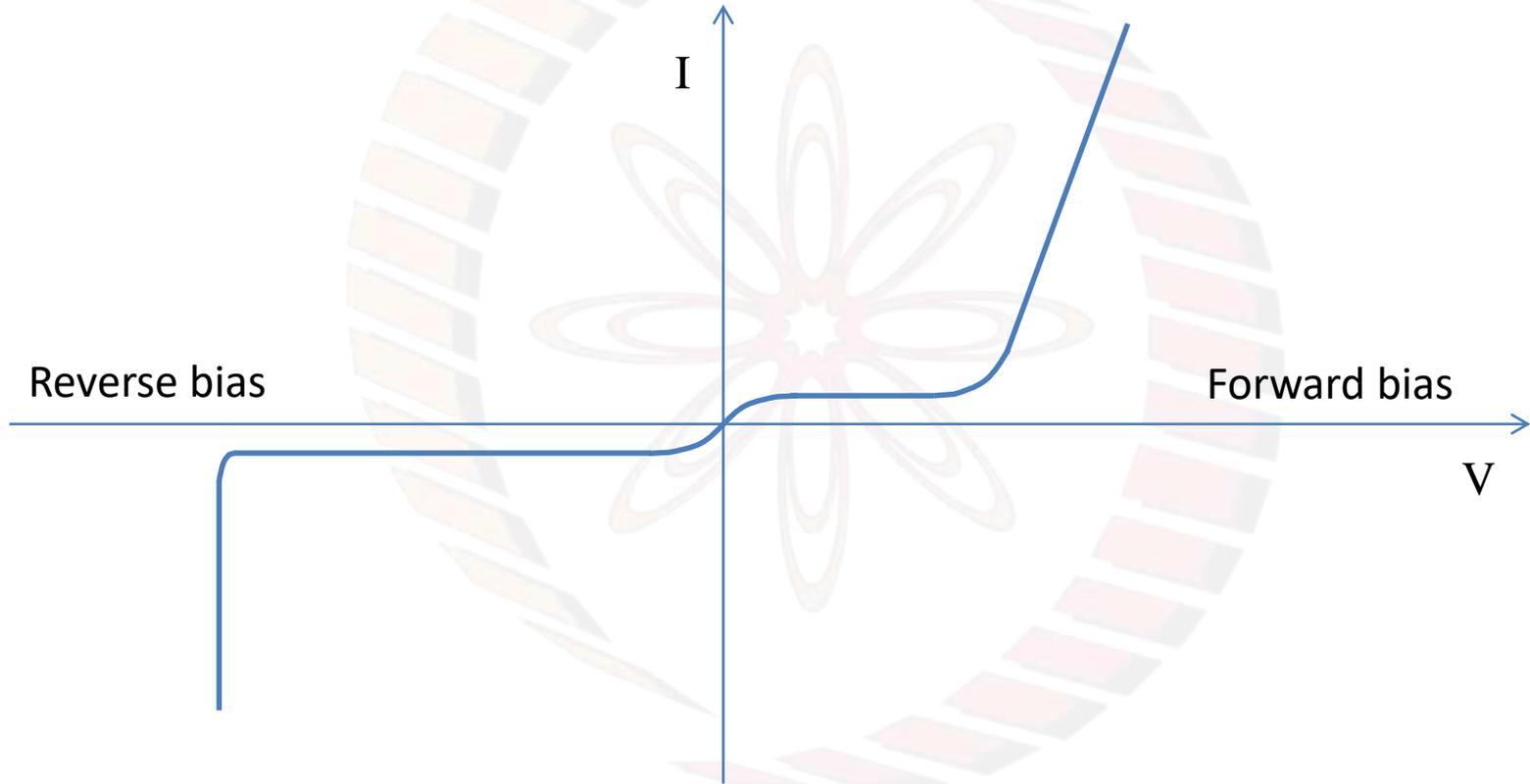
I-V characteristics

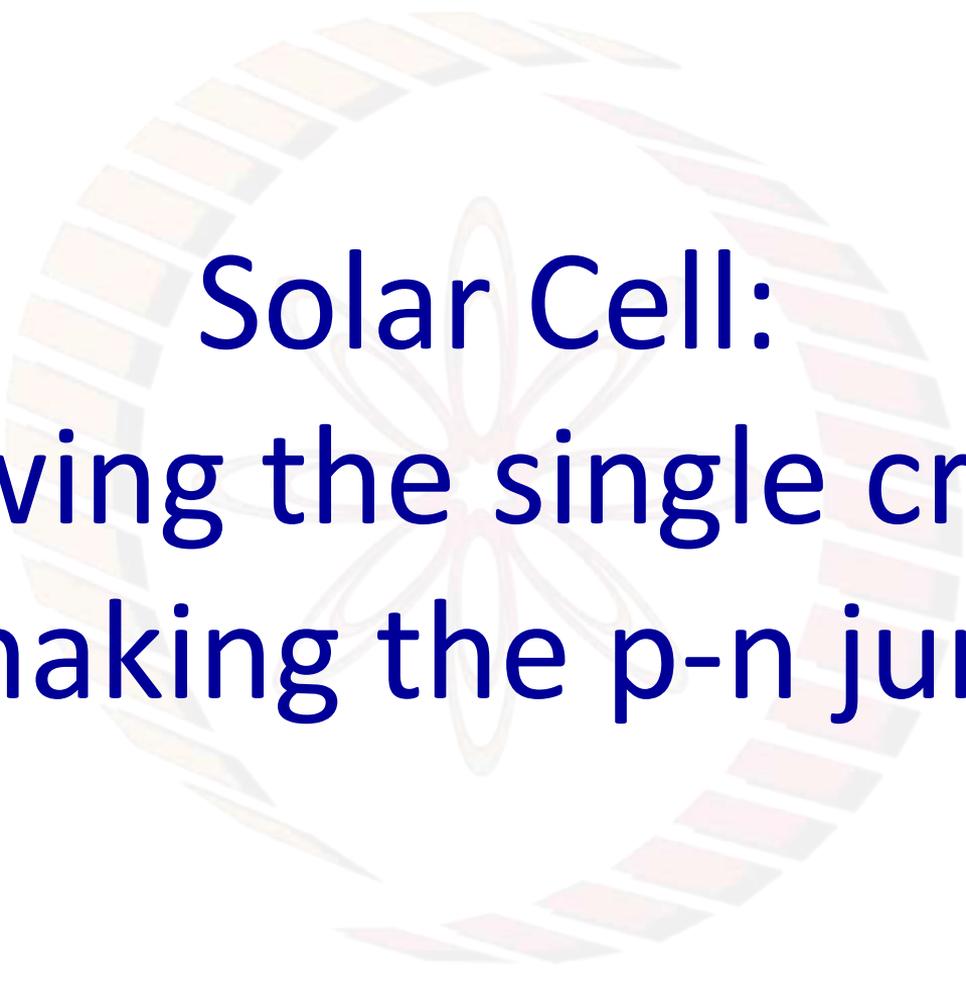


Conclusions:

- 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

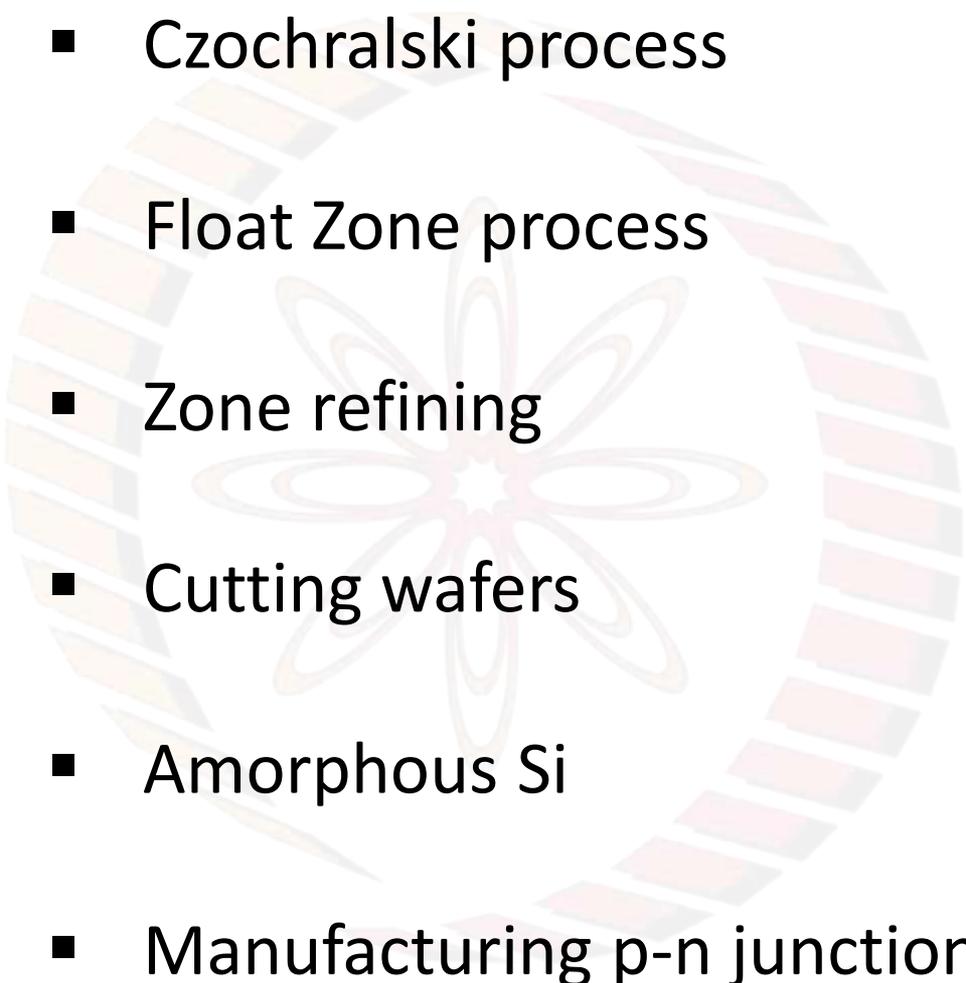




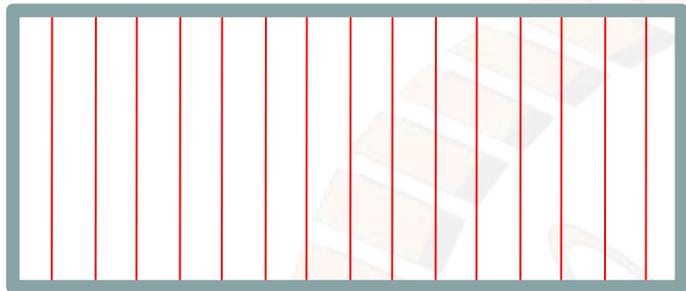
Solar Cell: Growing the single crystal and making the p-n junction

Learning objectives:

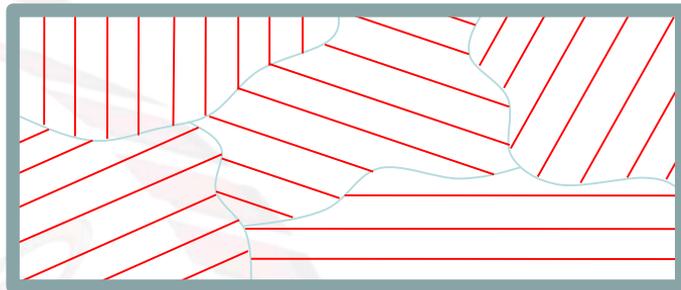
- 1) To become familiar with the techniques used to make single crystal as well as amorphous Si
- 2) To understand the method to manufacture the p-n junction

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

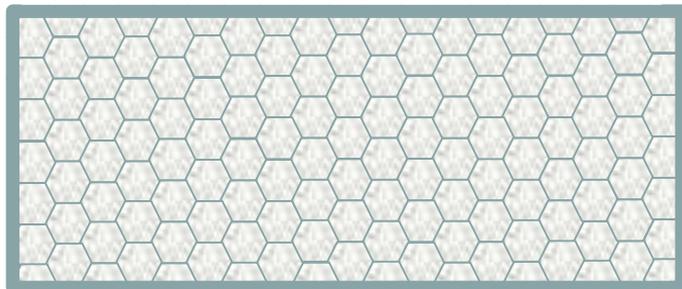
(a)



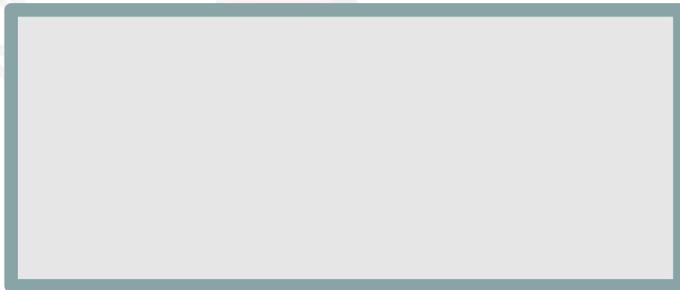
(b)



(c)



(d)



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

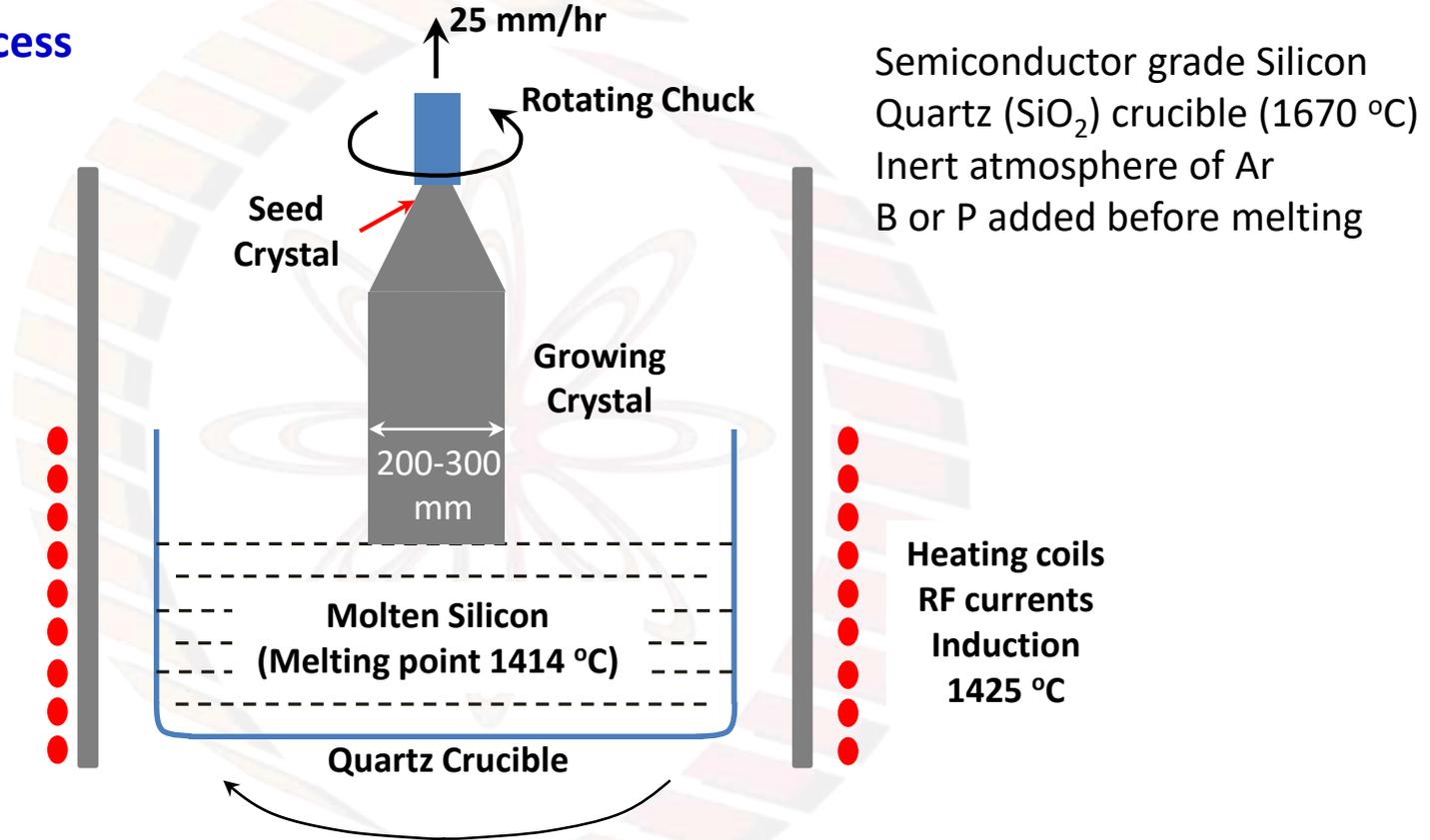


Metallurgical Grade Silicon (MGS) \longrightarrow Electronic Grade Silicon (EGS)
98% purity ppm (C, O) to ppb (metals)

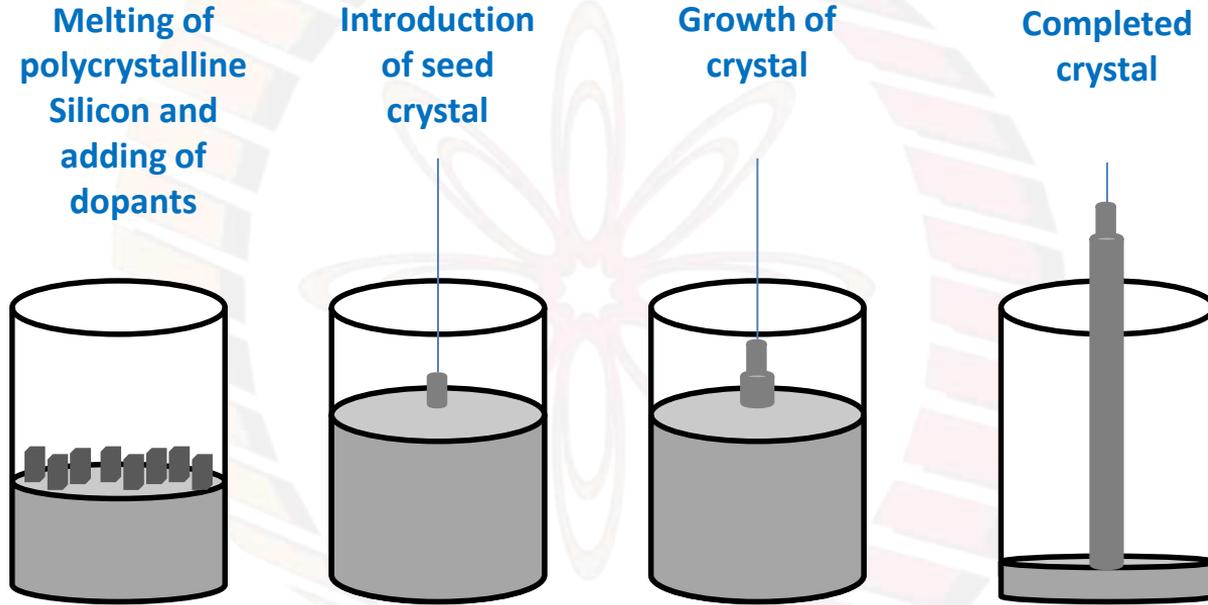


Si converted to Trichlorosilane, which is purified and reduced back to Si

Czochralski process

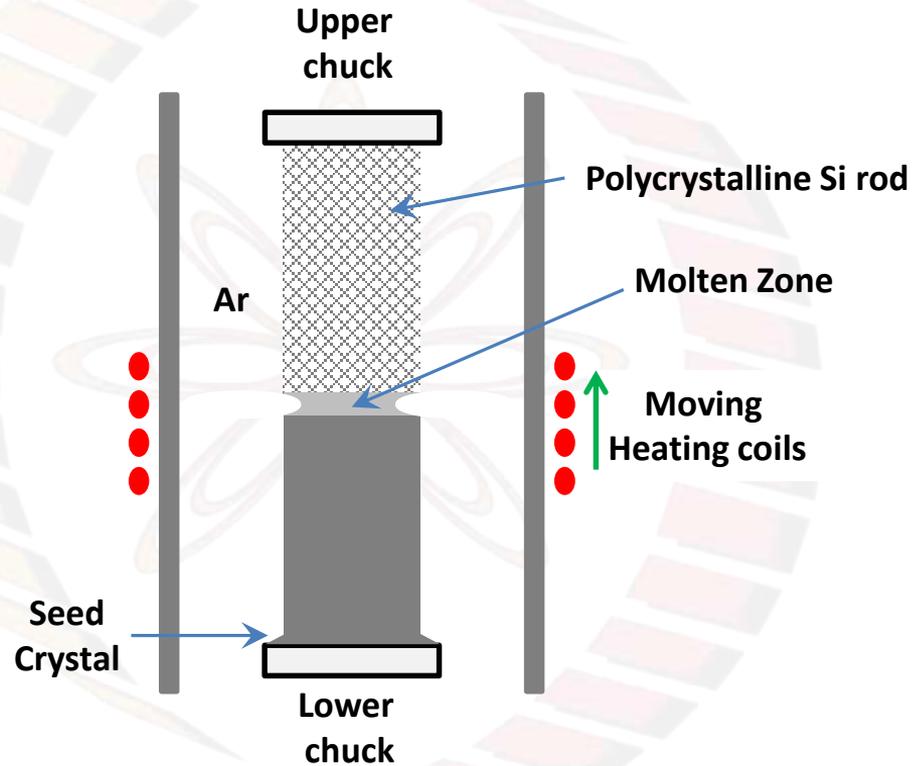


Czochralski process

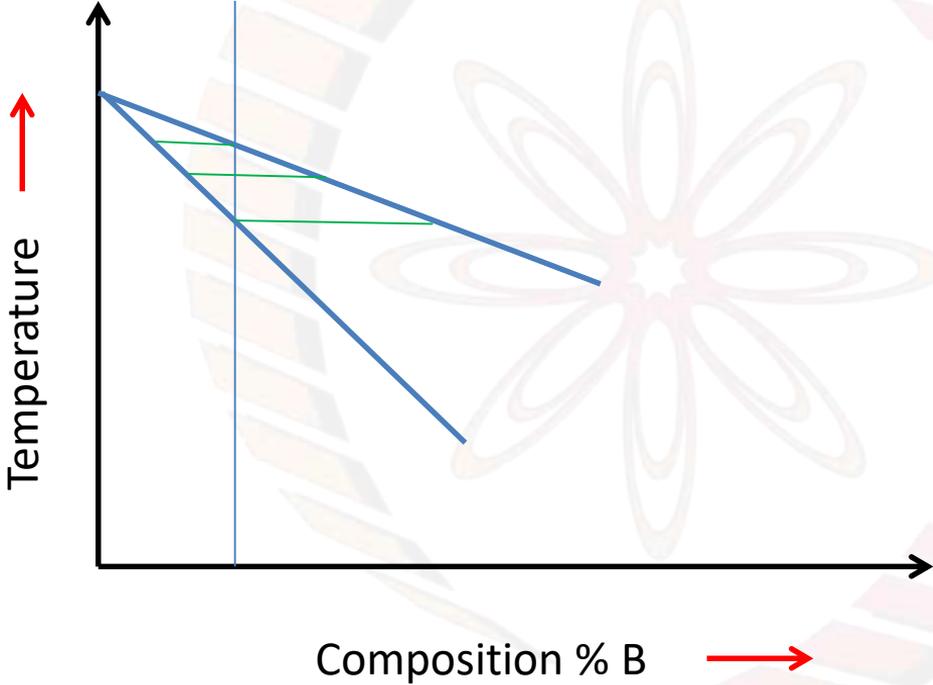


Float zone process

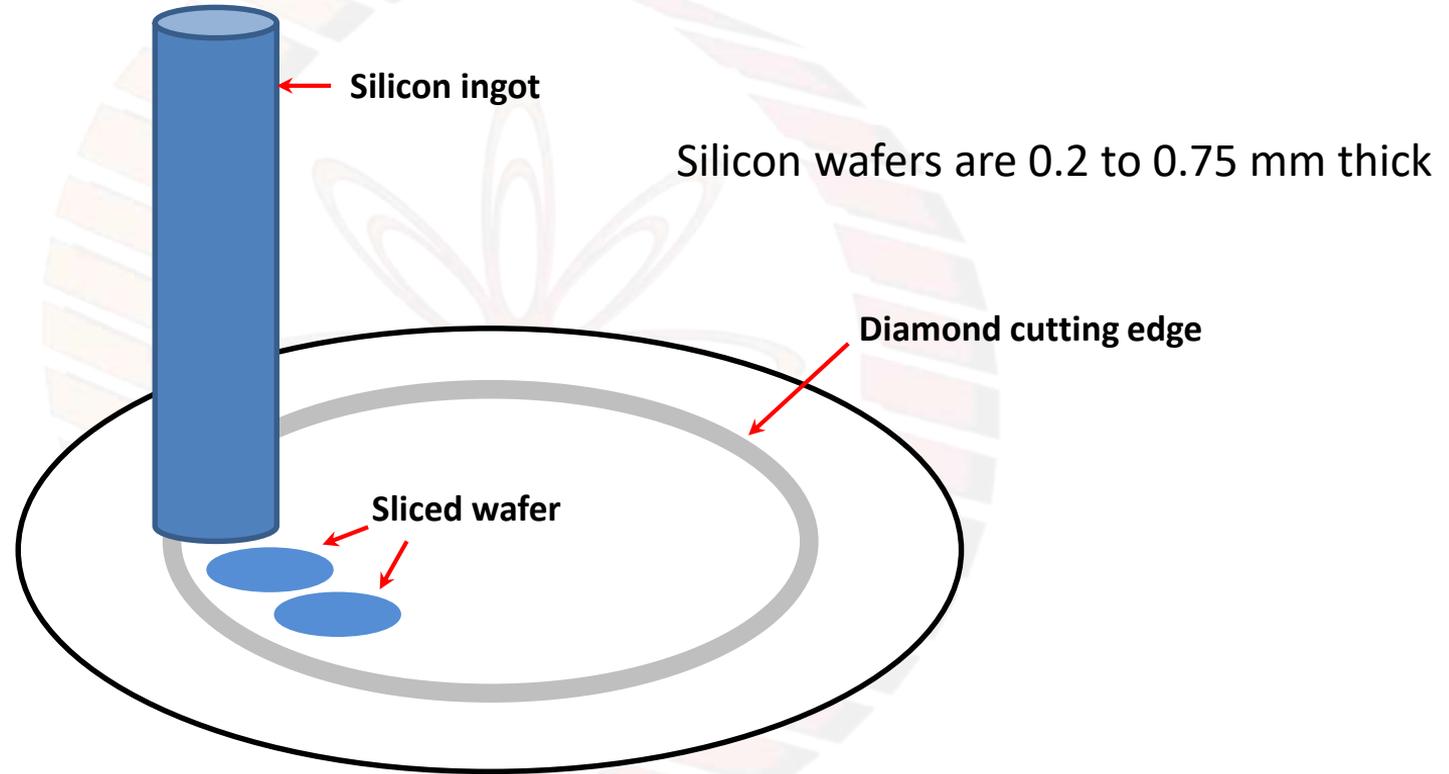
- Smaller diameter (150mm) due to surface tension
- Higher purity



Zone refining

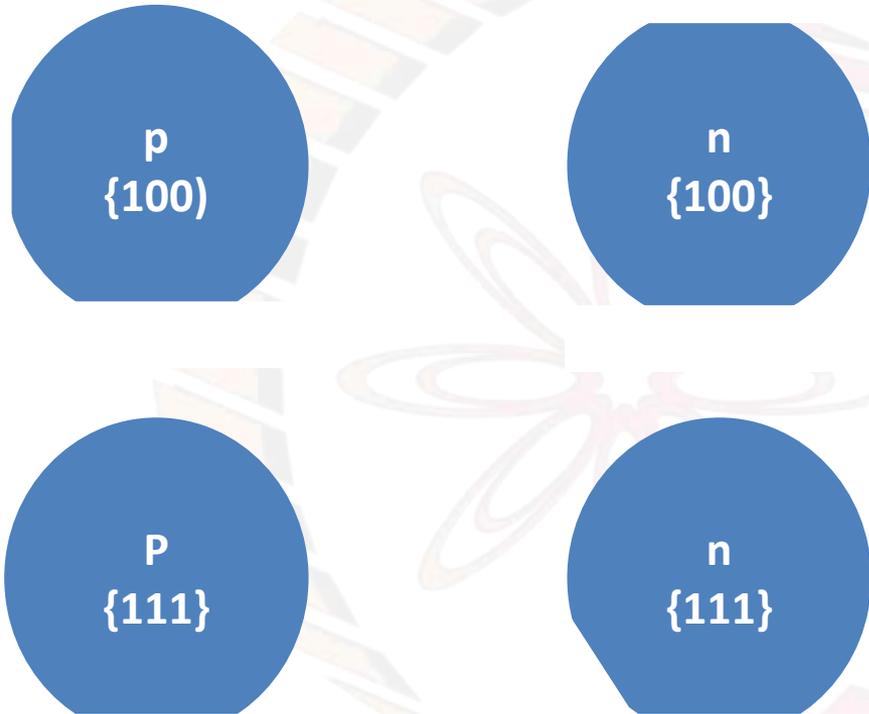


Inner diameter slicing of Si ingot



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)

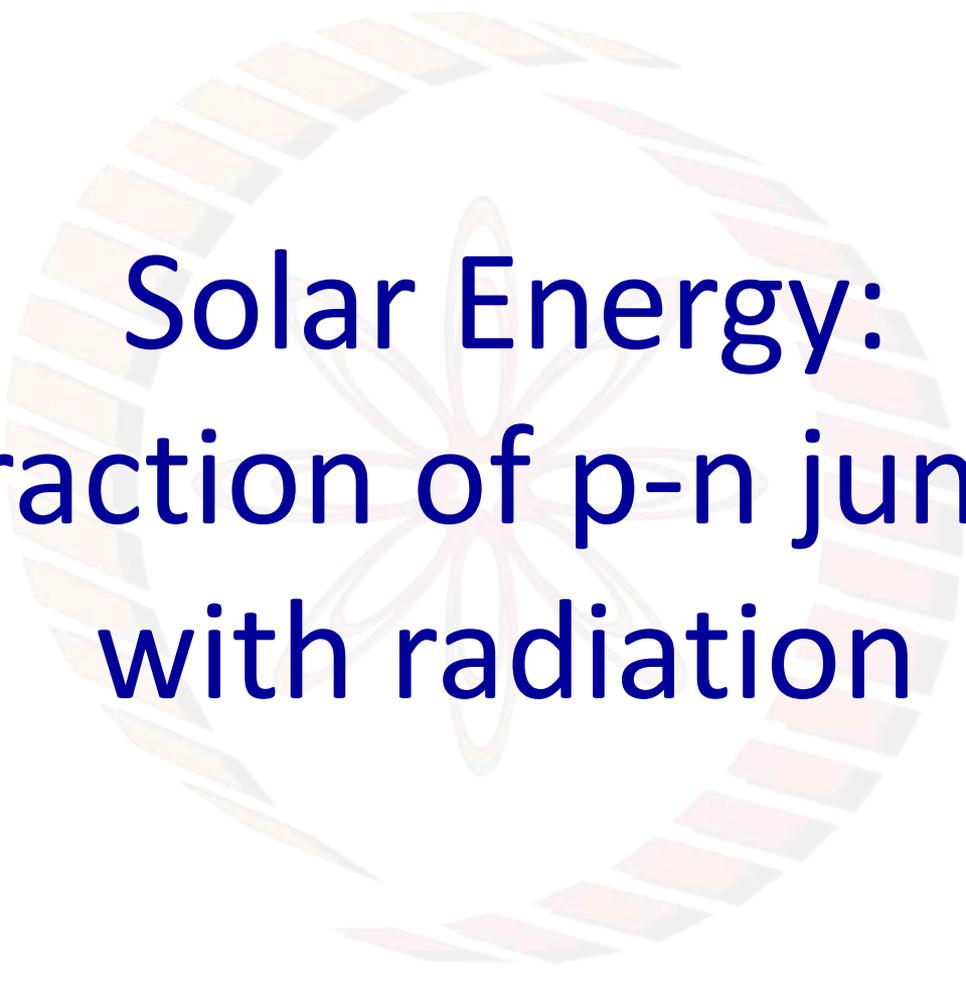
Hydrogenated amorphous Silicon, a-Si:H by deposition
from Silane gas SiH_4

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

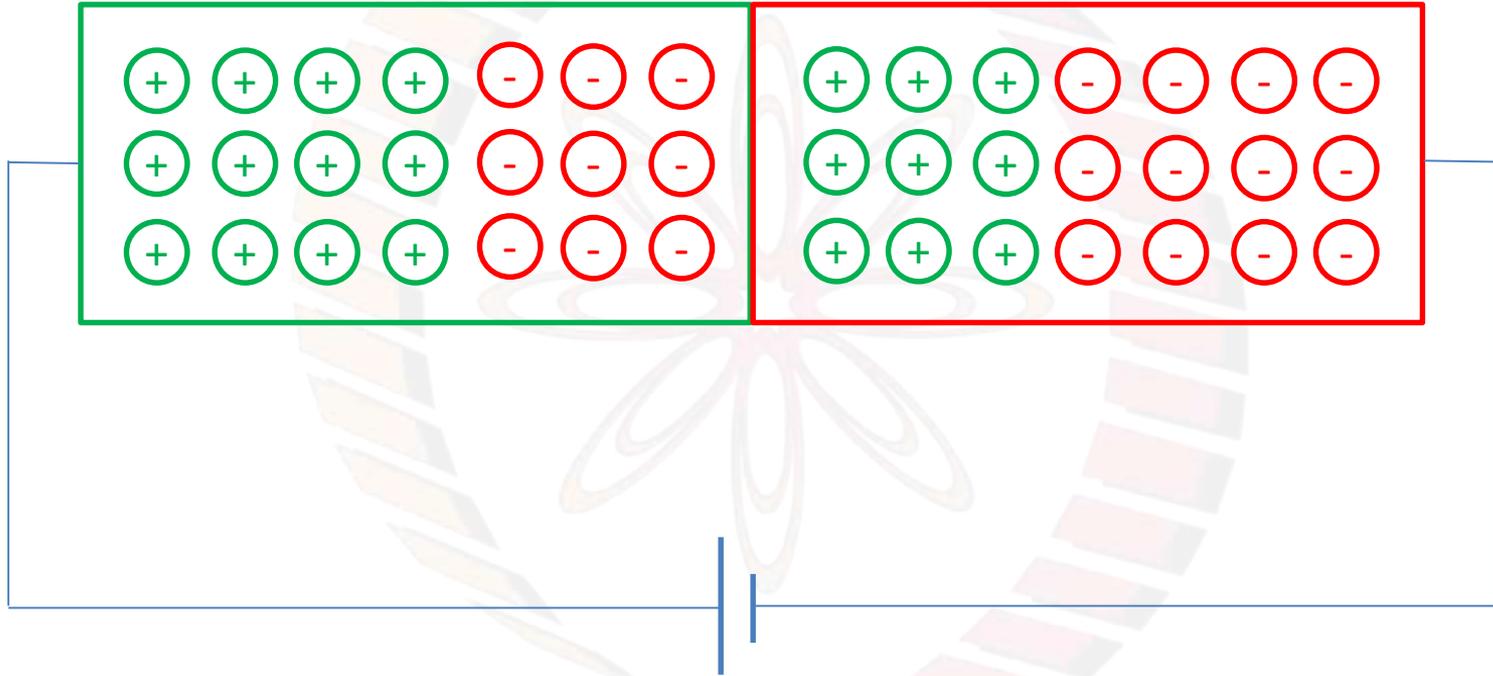


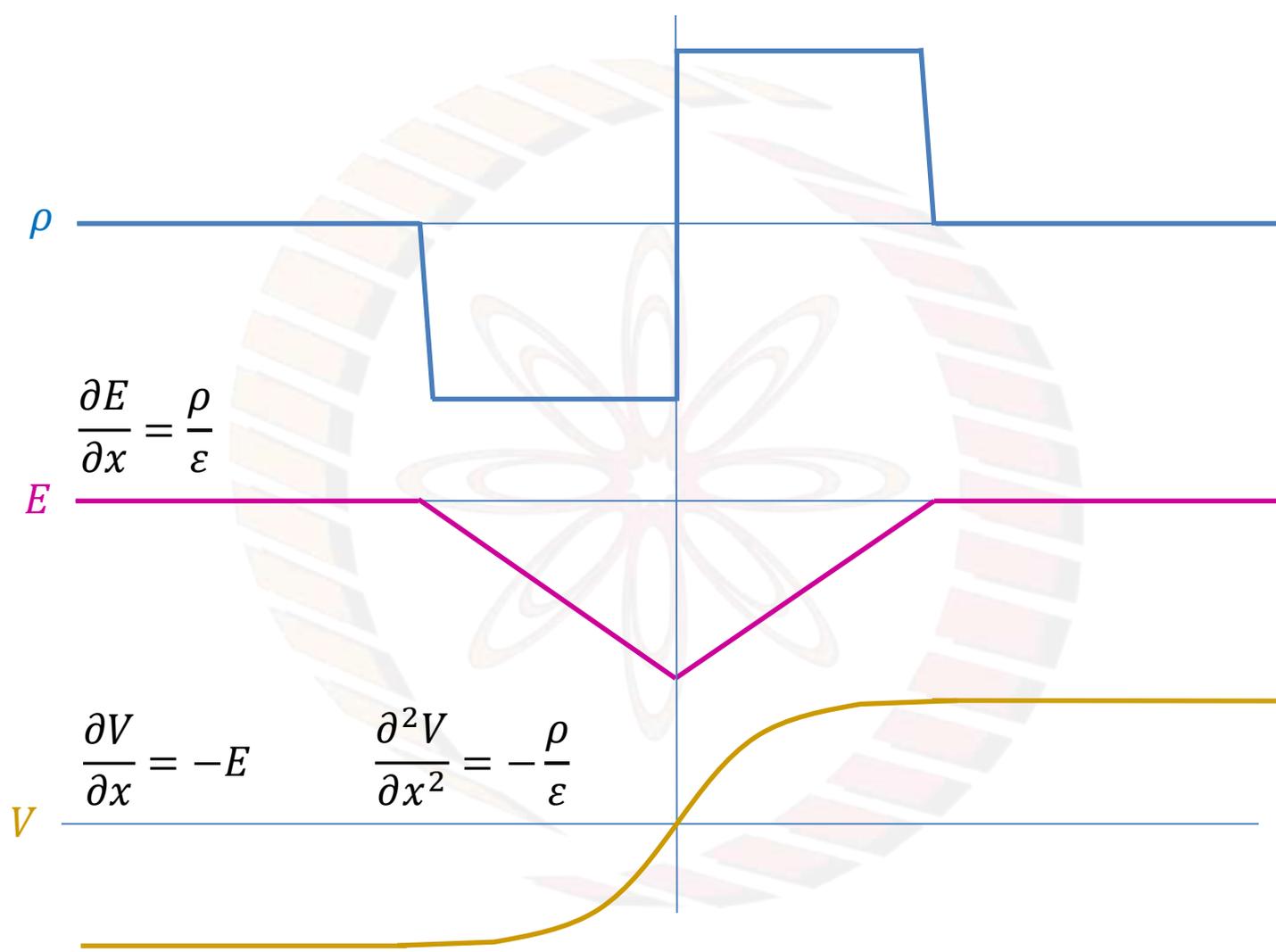
Solar Energy: Interaction of p-n junction with radiation

Learning objectives:

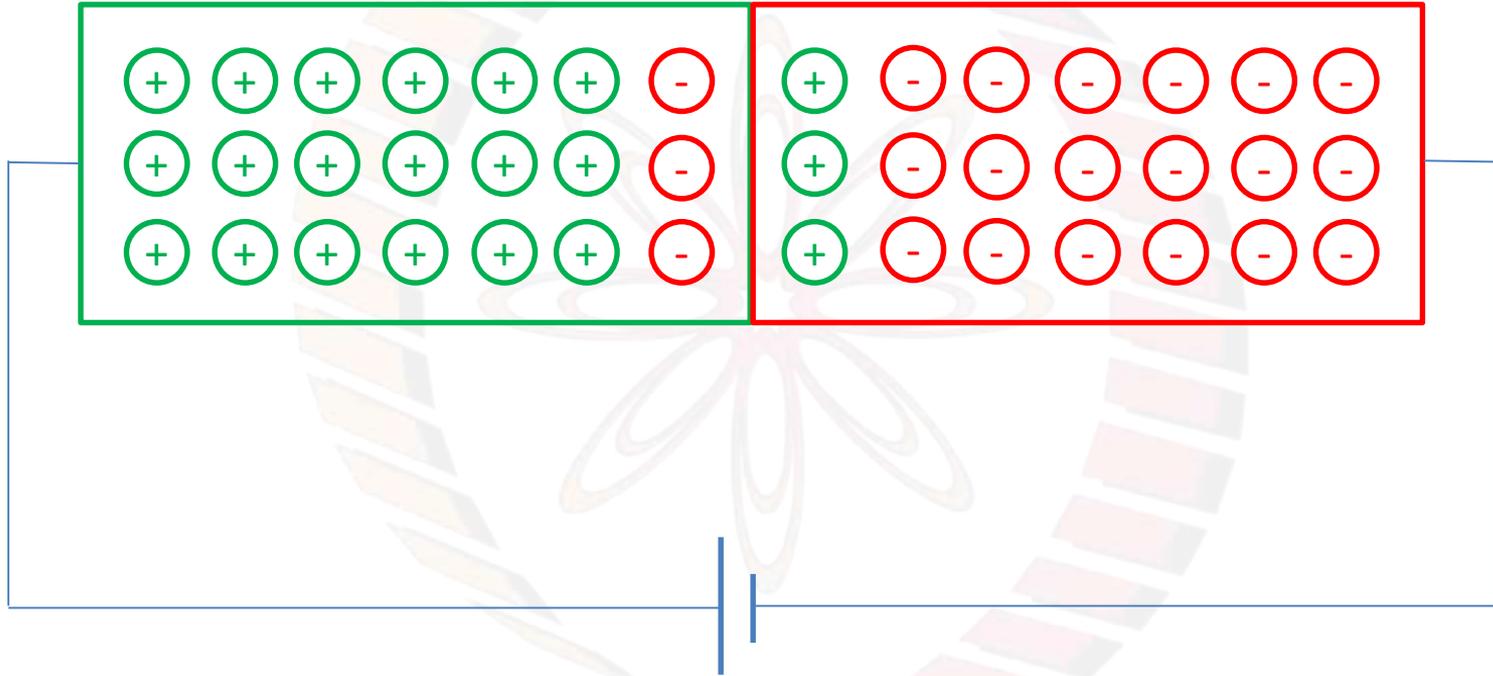
- 1) To describe the interaction of a p-n junction with radiation
- 2) To explain the functioning of the p-n junction solar cell

Forward bias

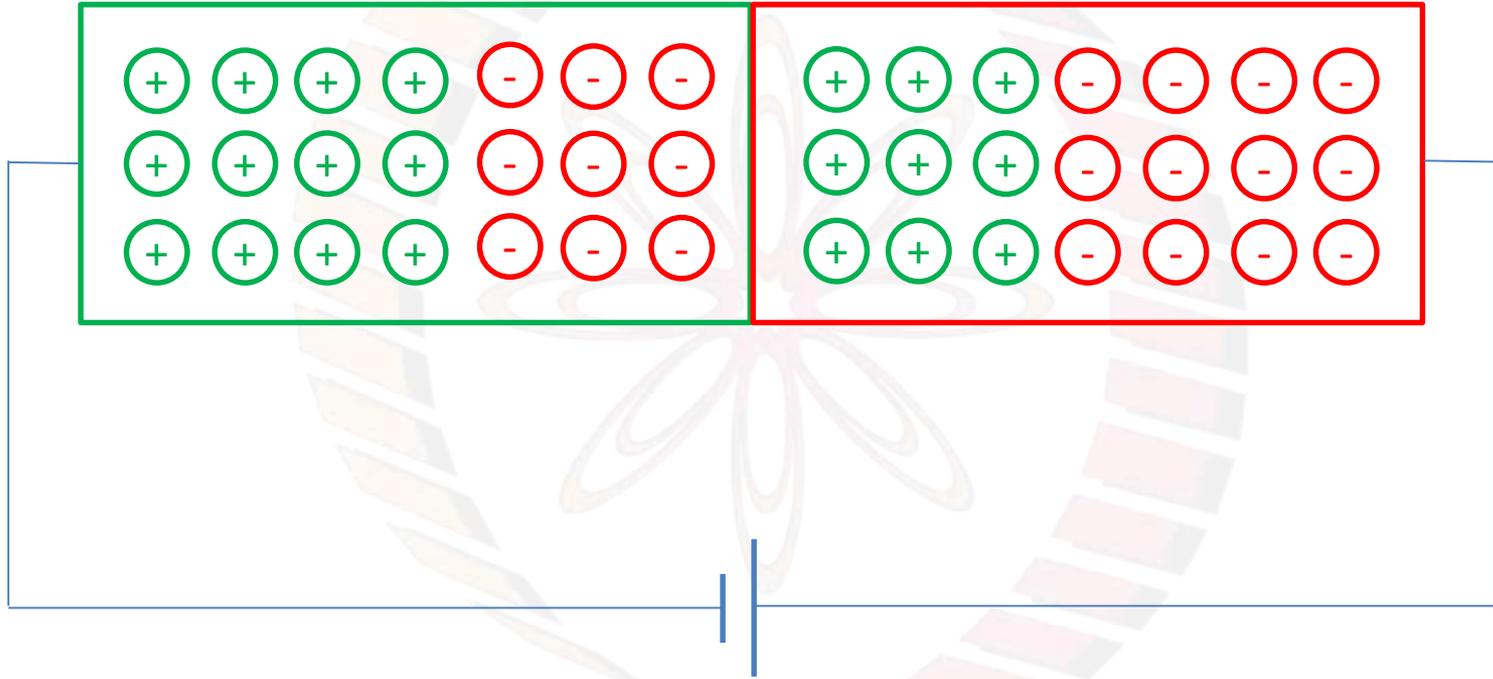




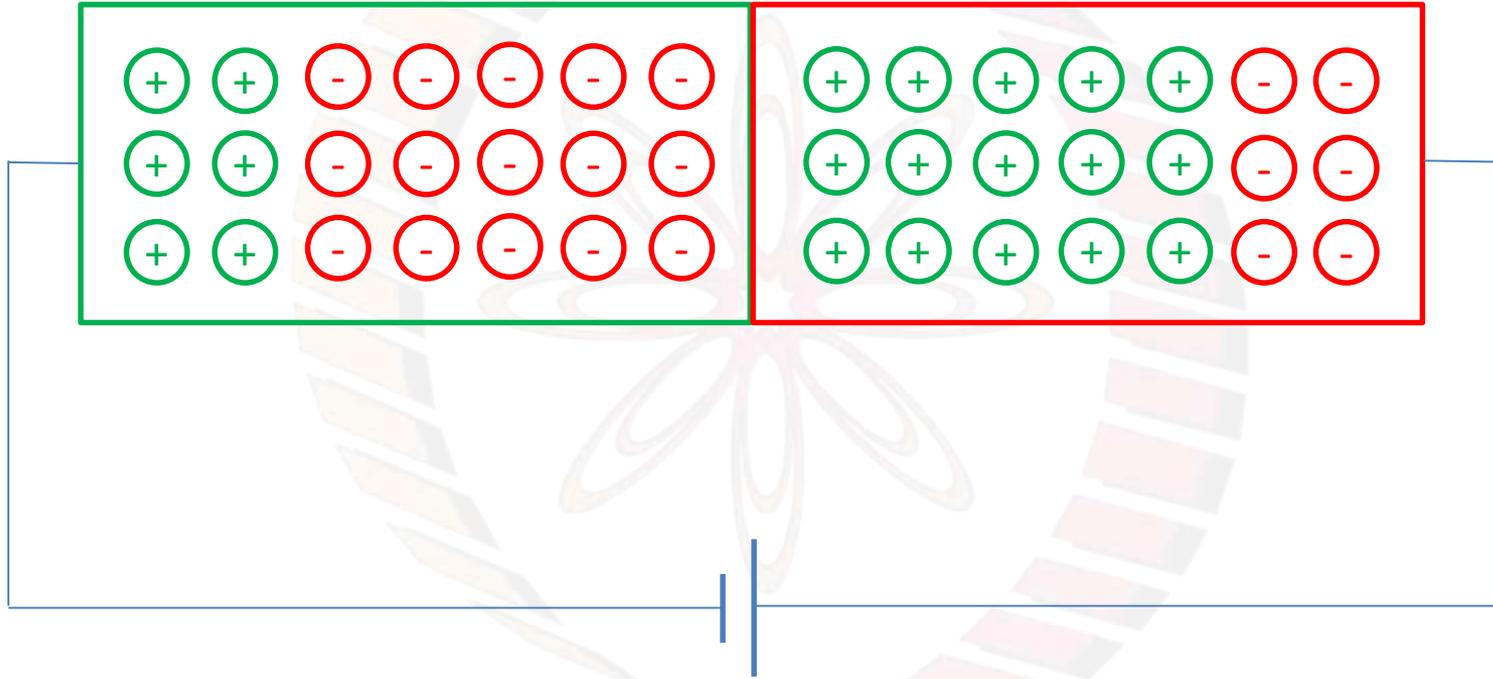
Forward bias



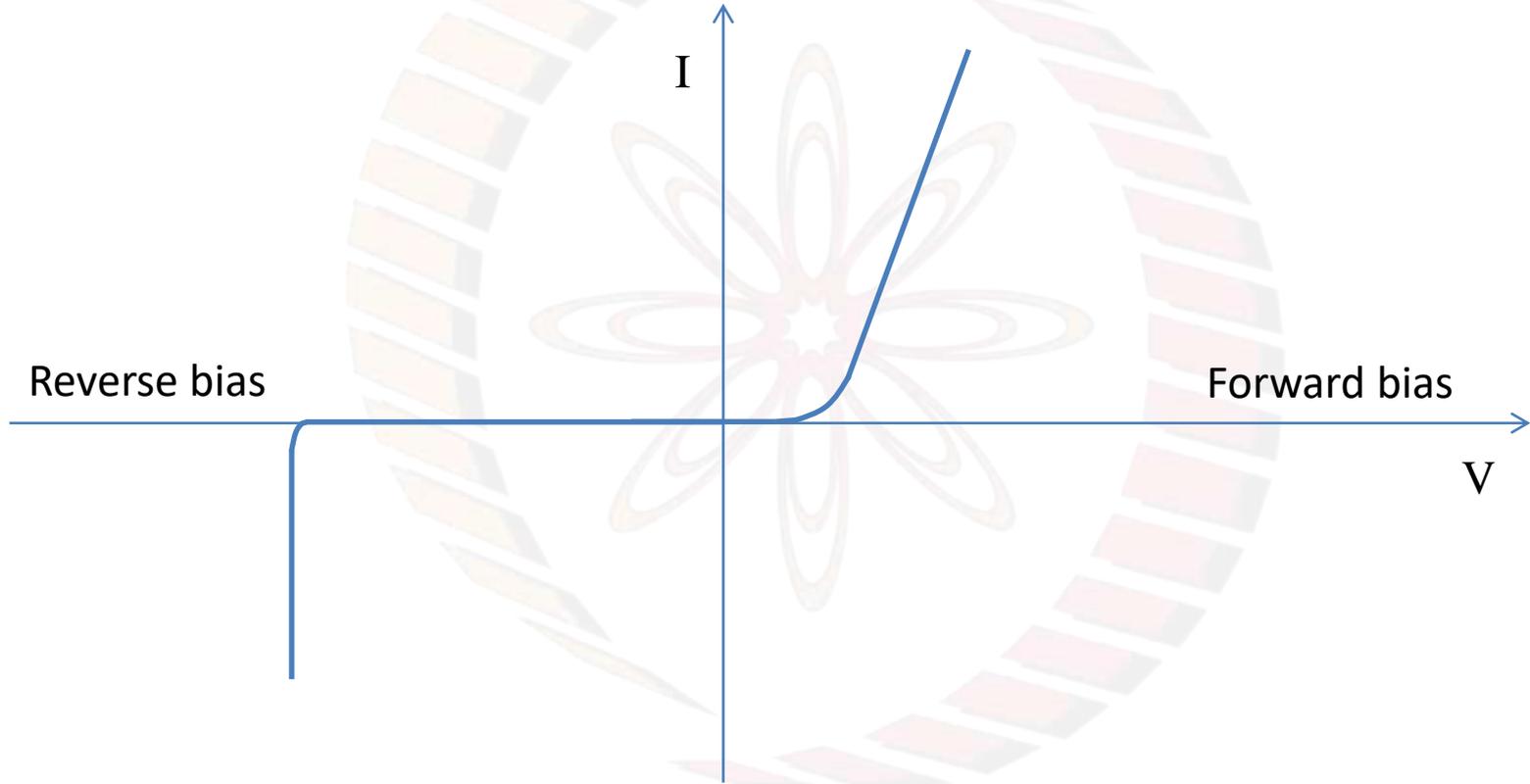
Reverse bias

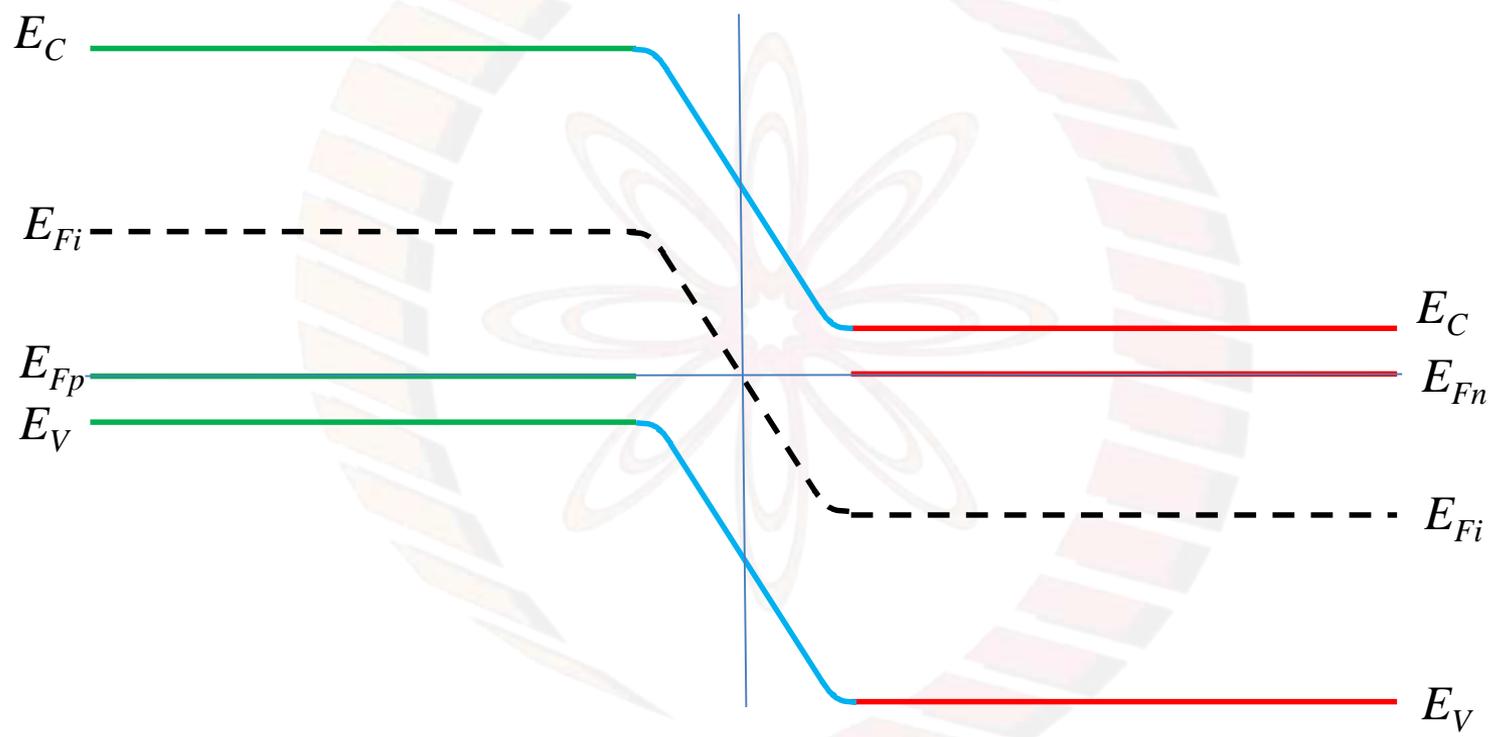


Reverse bias

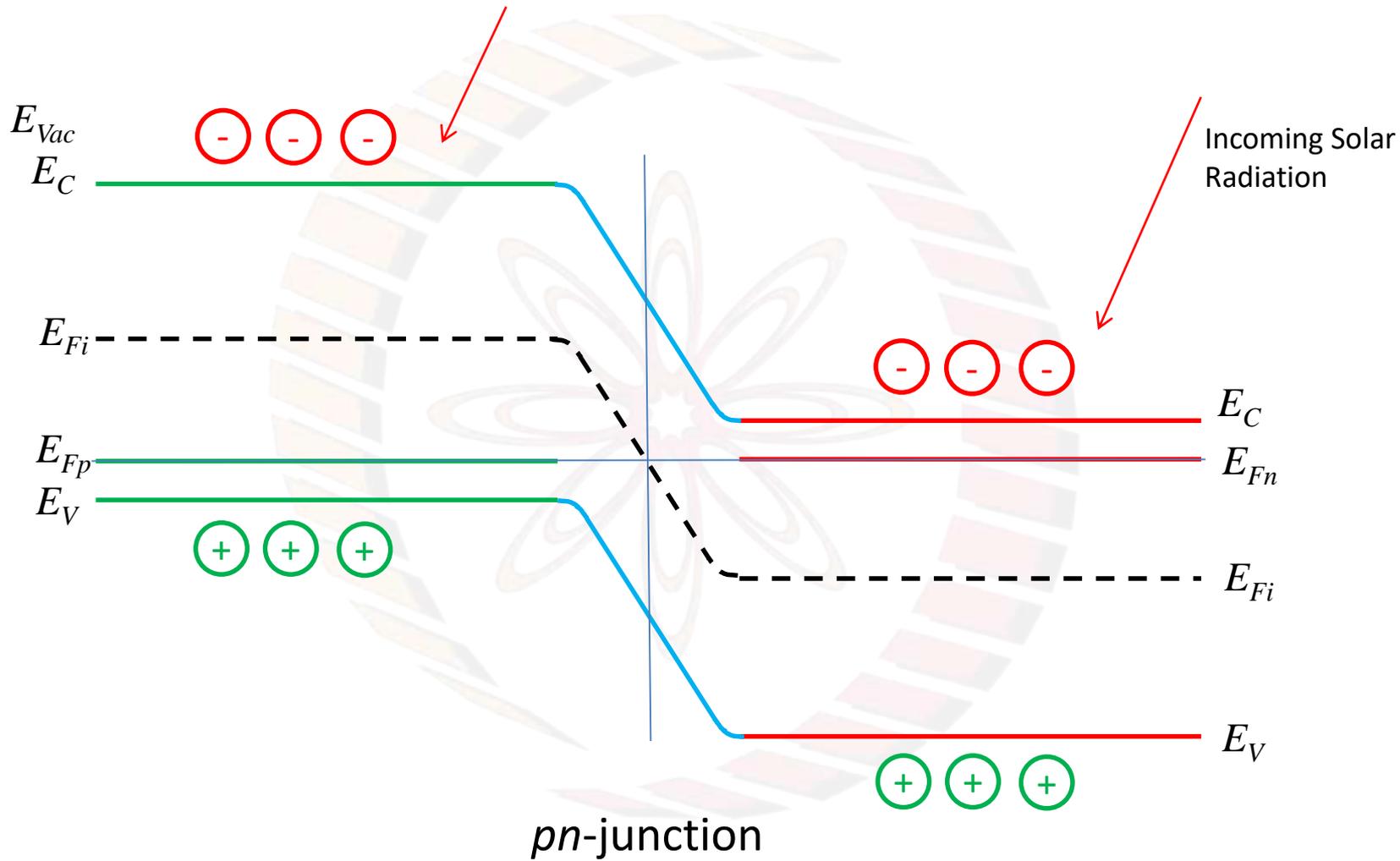


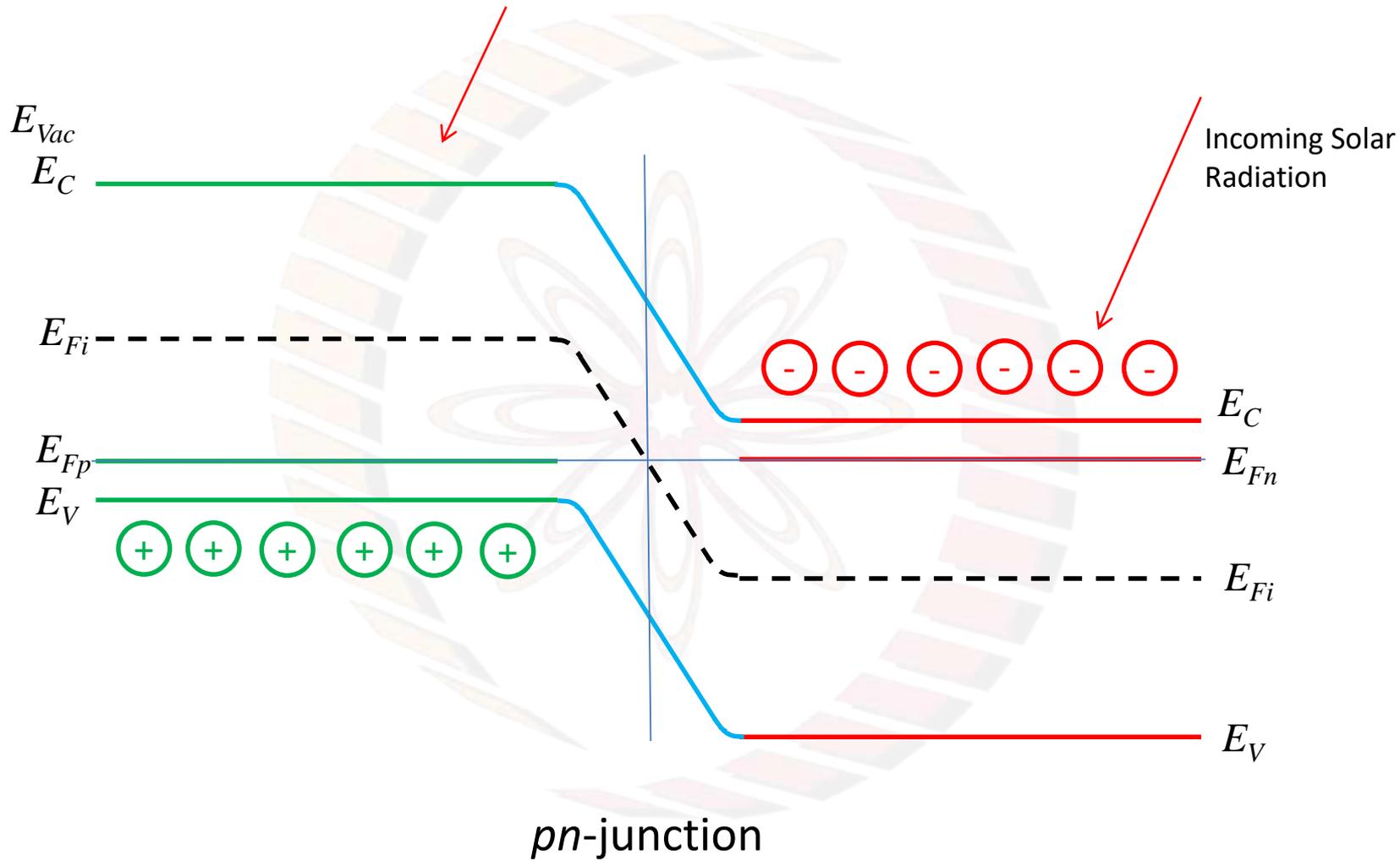
I-V characteristics

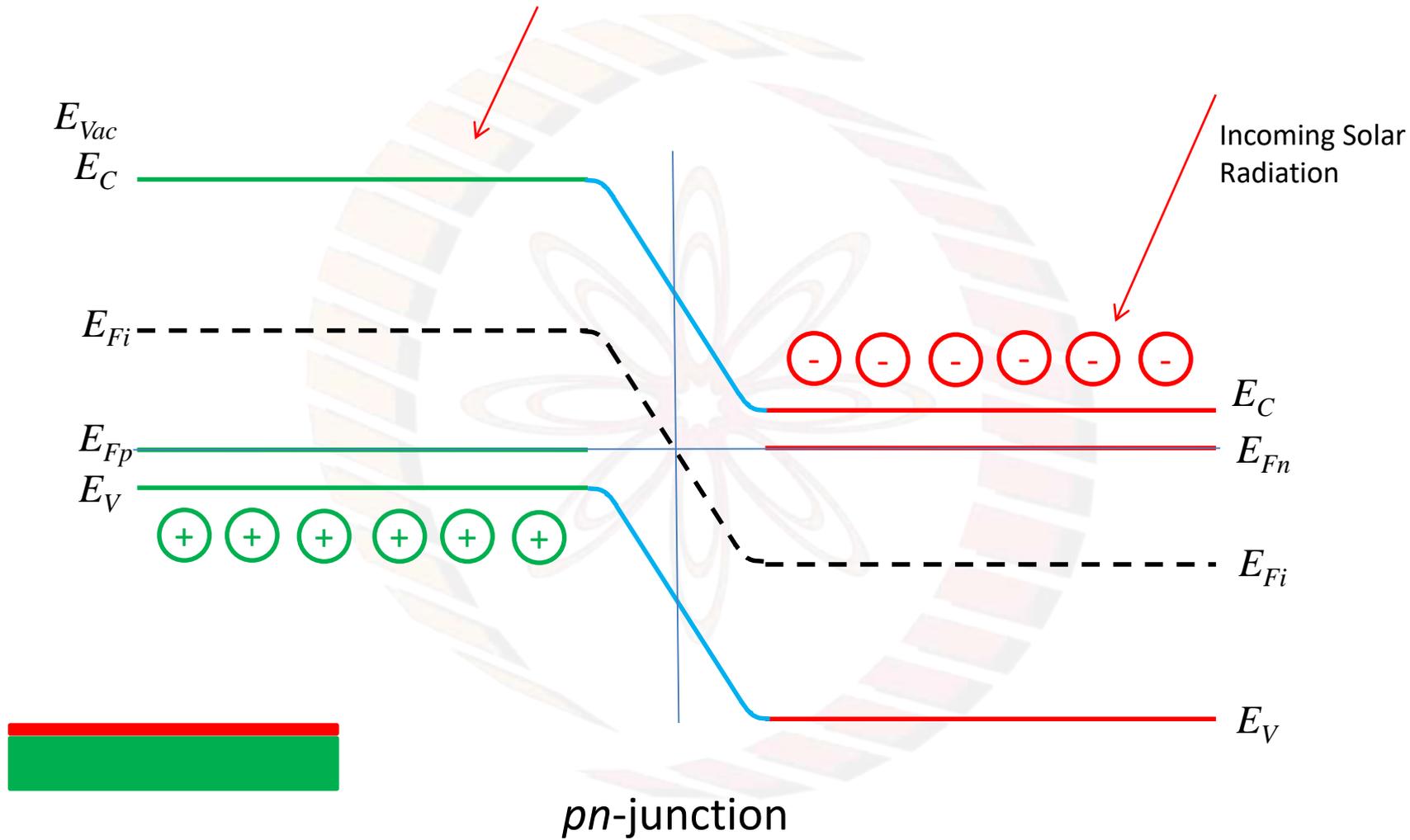


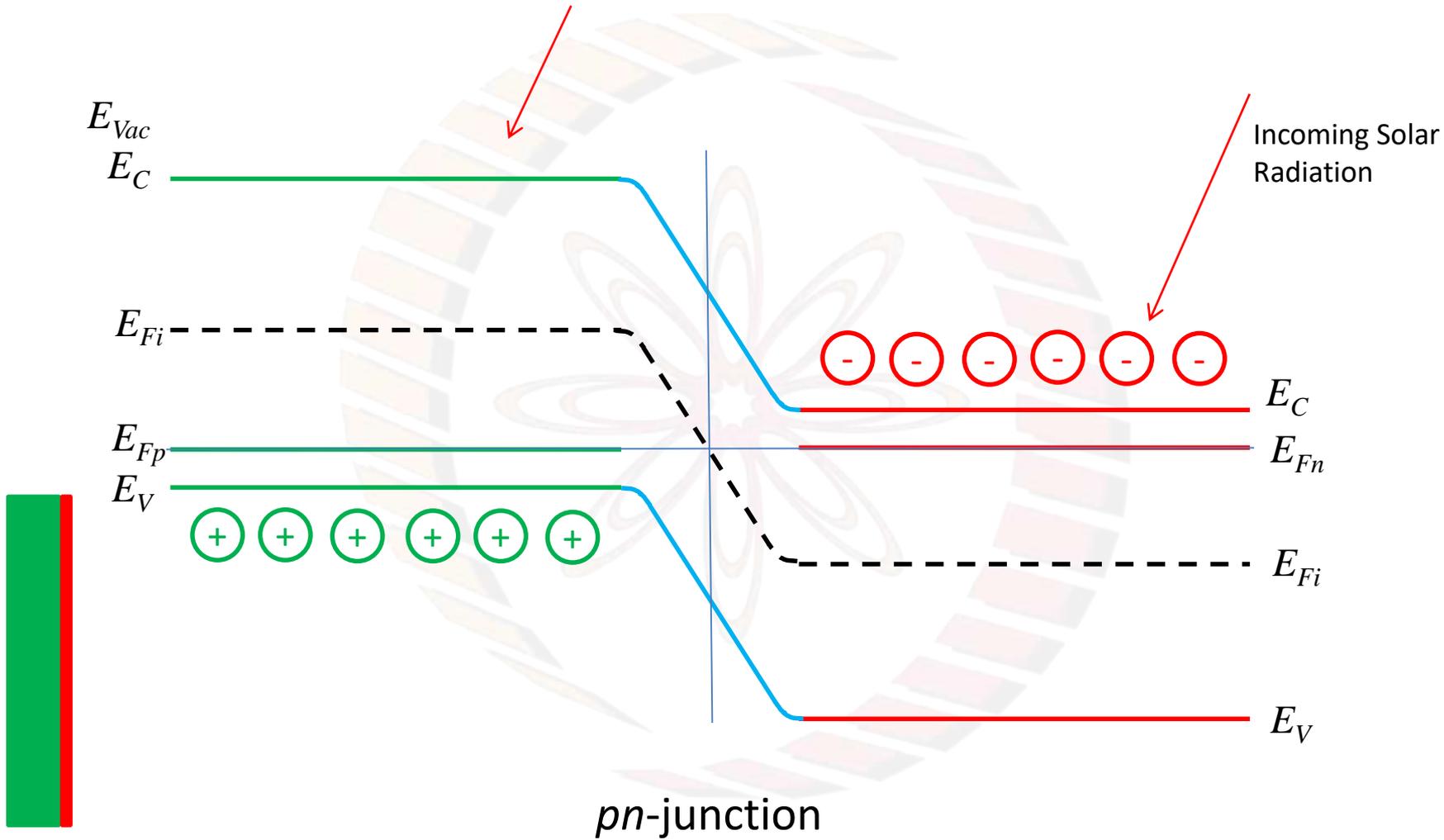


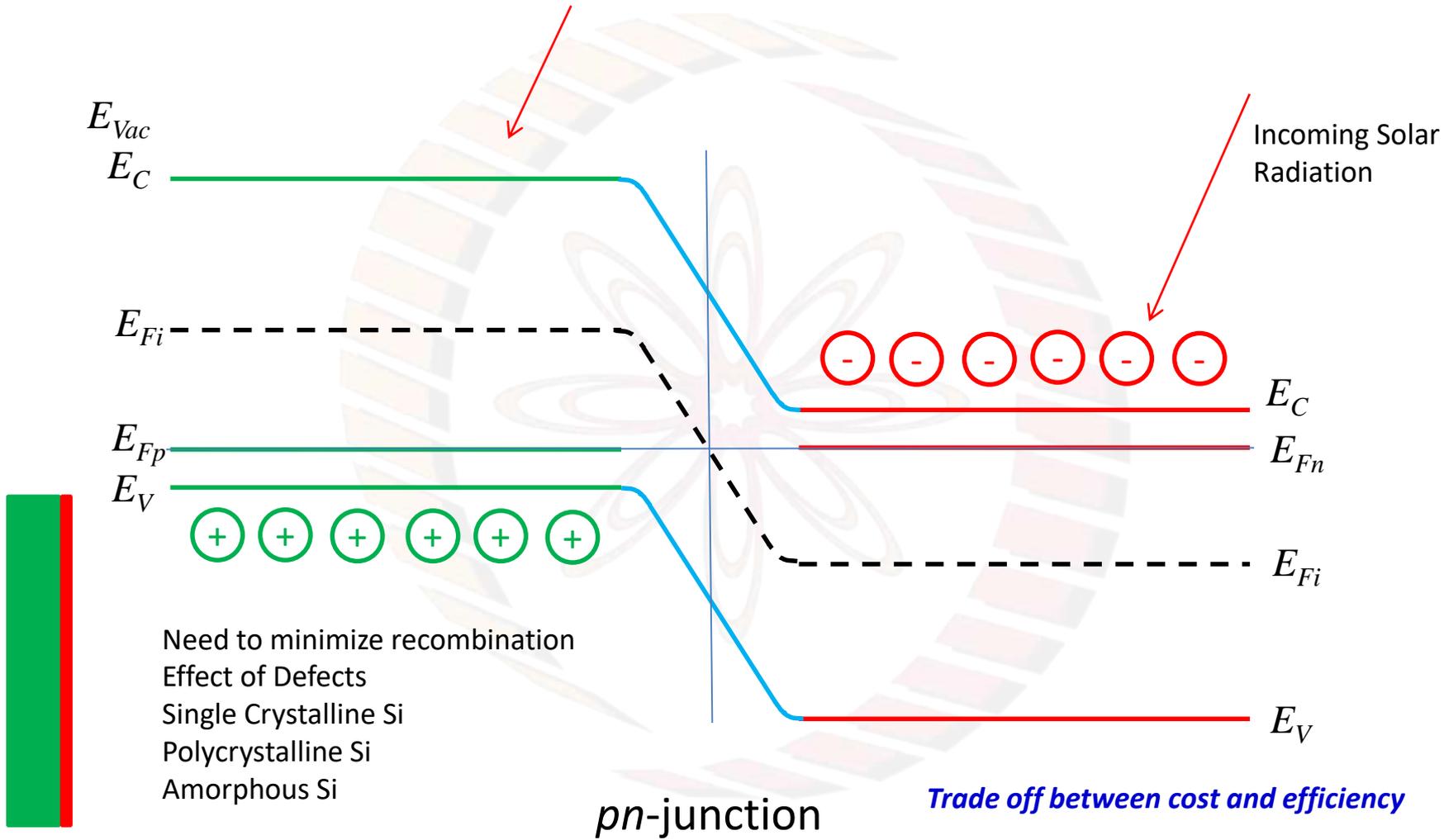
pn-junction







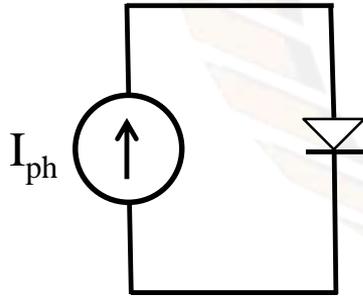


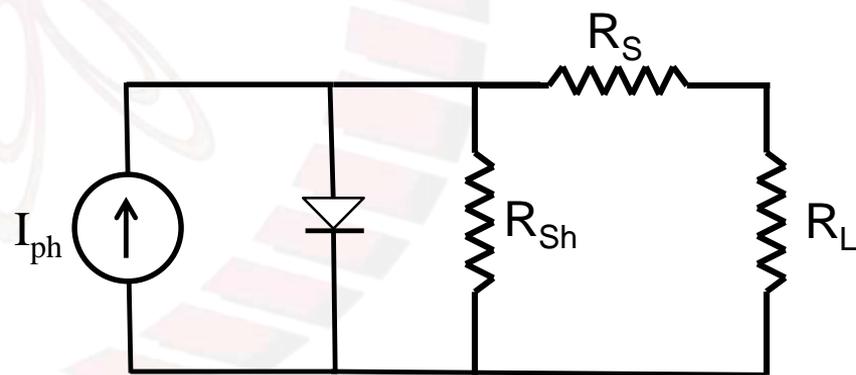
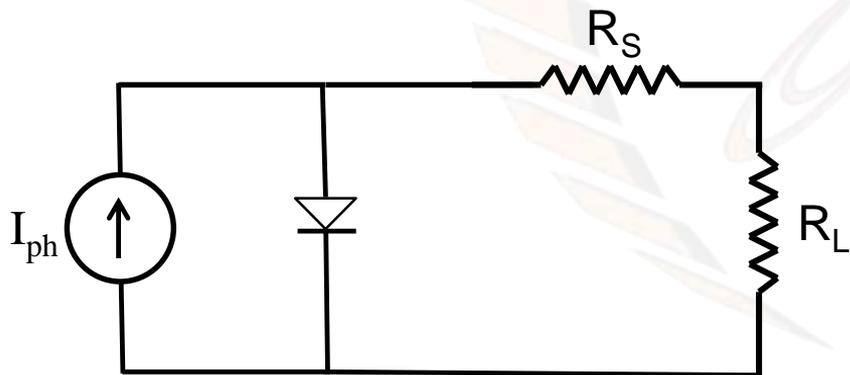
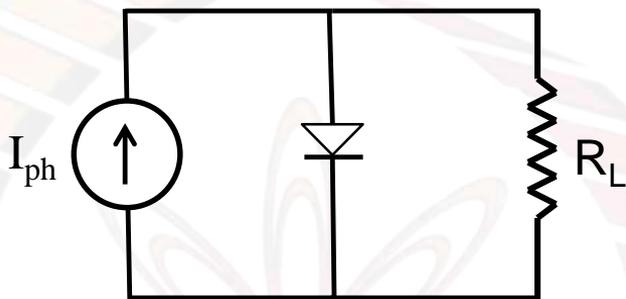
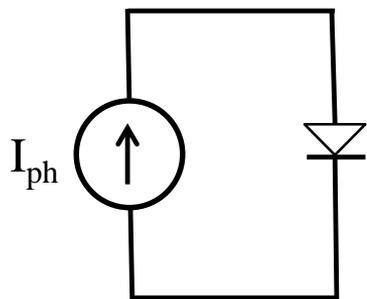


Solar Cell is a current source

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

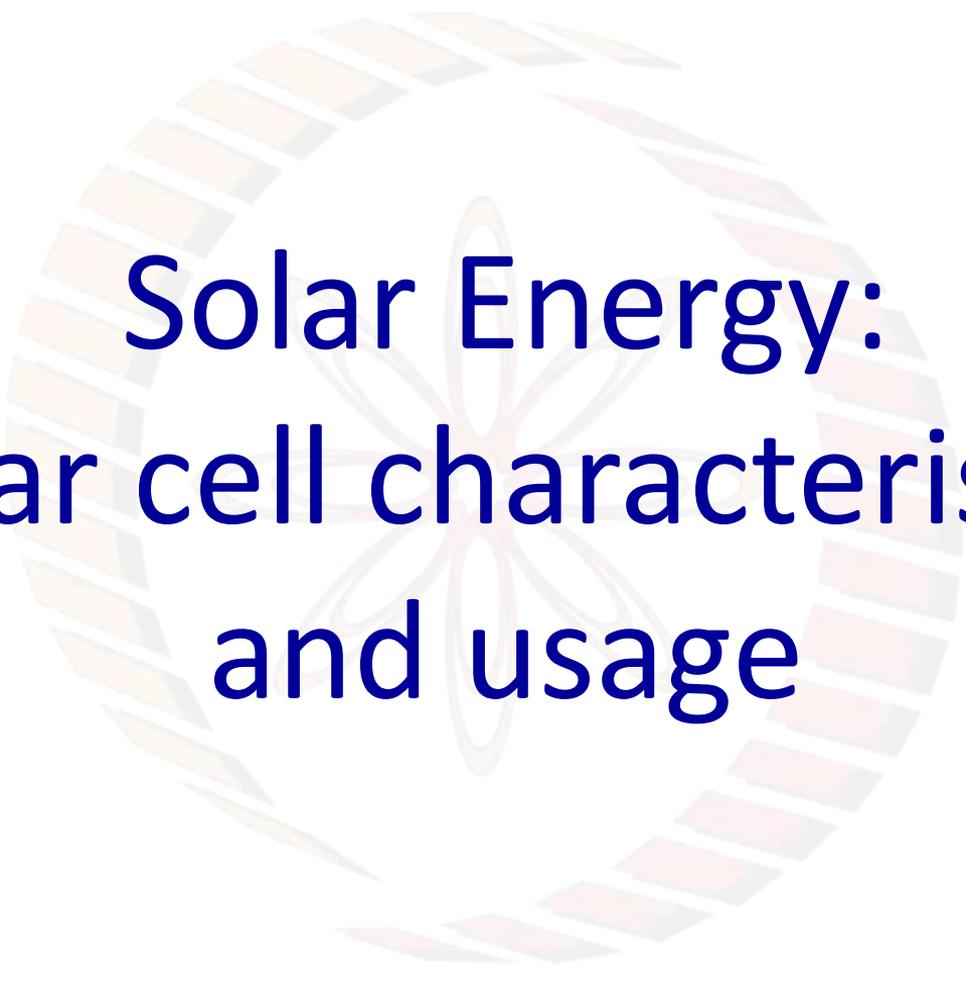
Without external load, the pn junction is forward biased, and internally shorts





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

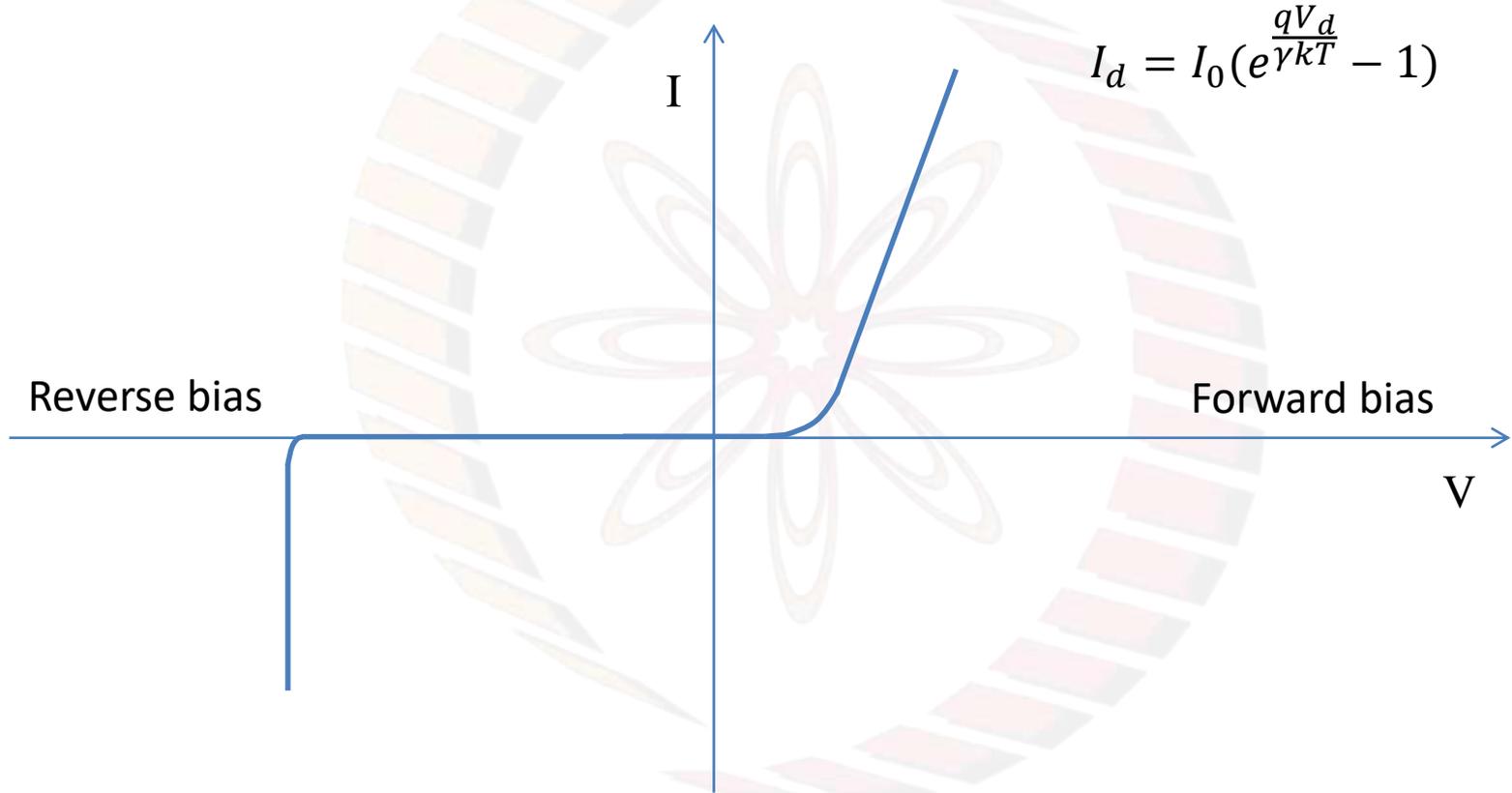


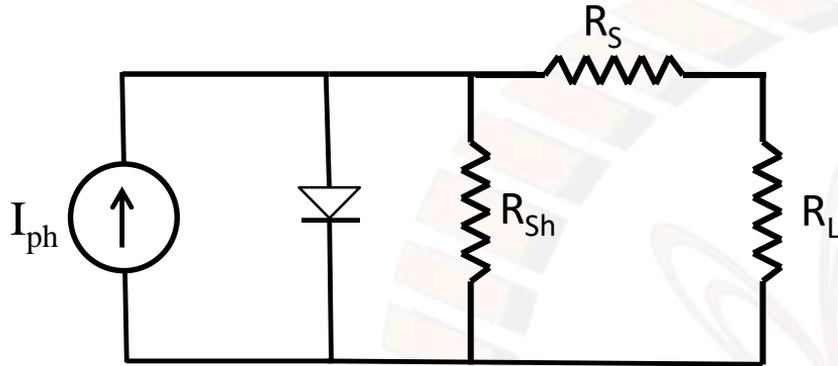
Solar Energy: Solar cell characteristics and usage

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)

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

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

$$V_d = V_L + I_L R_S$$

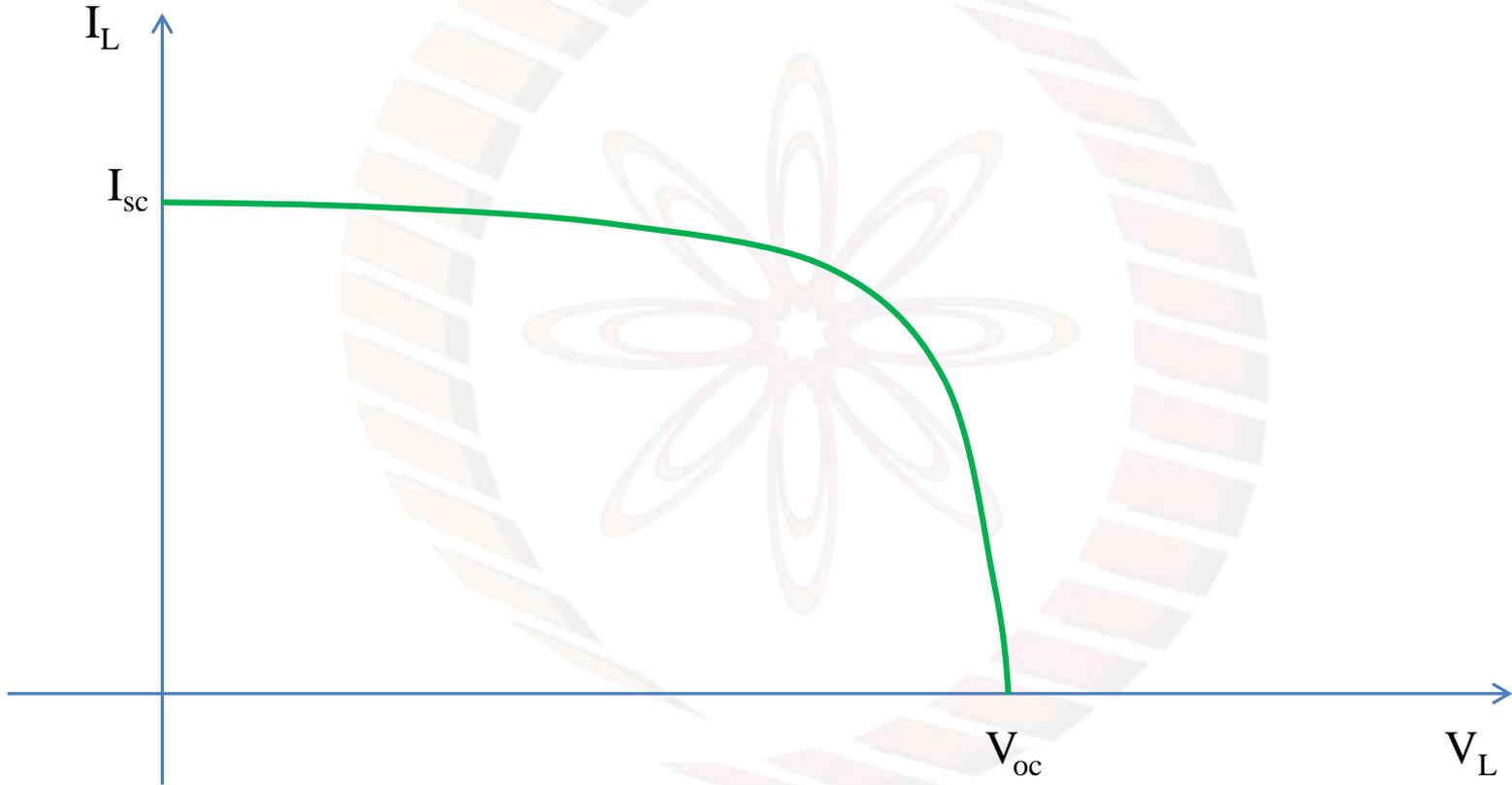
$$V_L = \frac{\gamma kT}{q} \ln \left\{ \frac{I_{ph} - I_L}{I_0} + 1 \right\} - I_L R_S$$

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

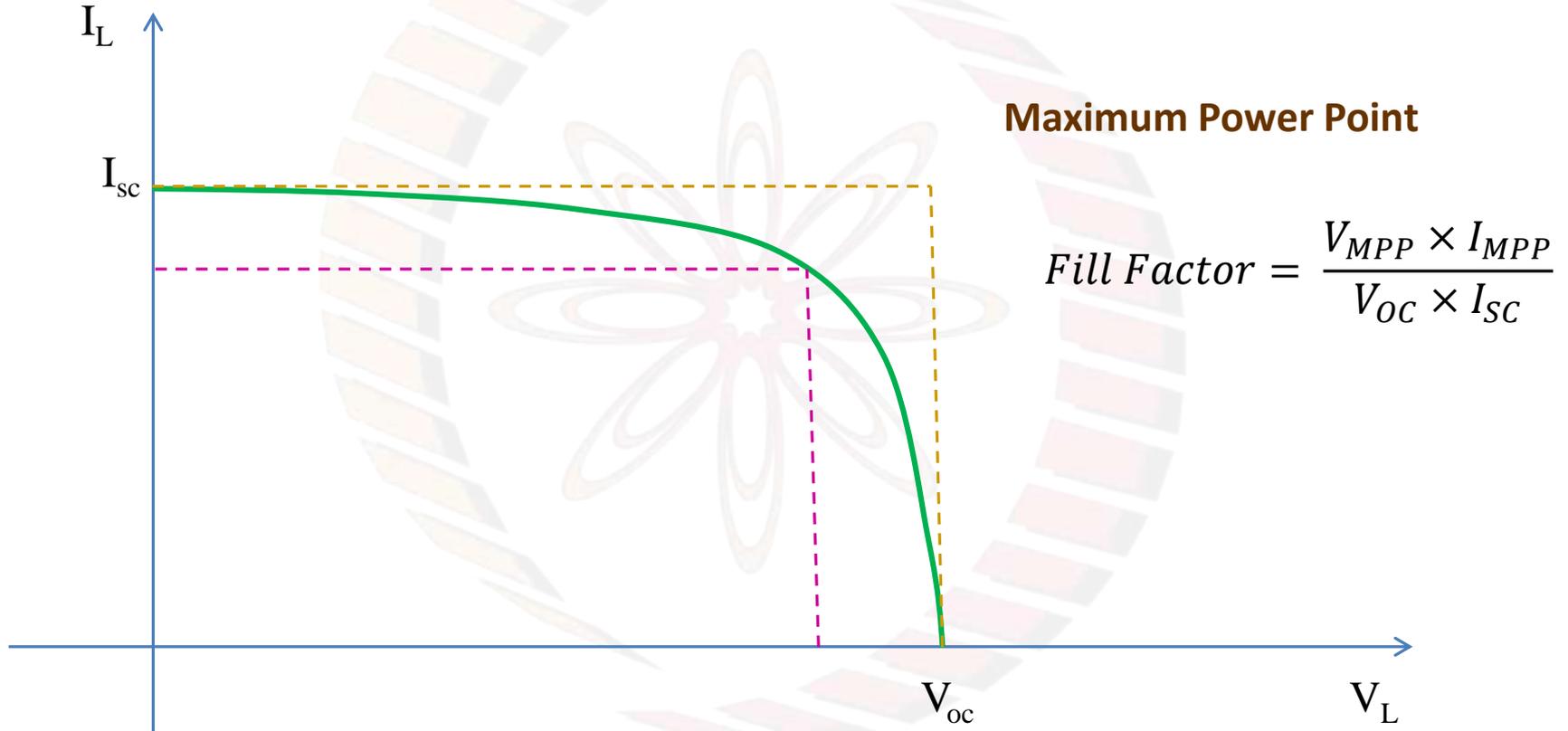
$$I_{ph} - I_d - I_{Sh} = I_L$$

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

I-V characteristics

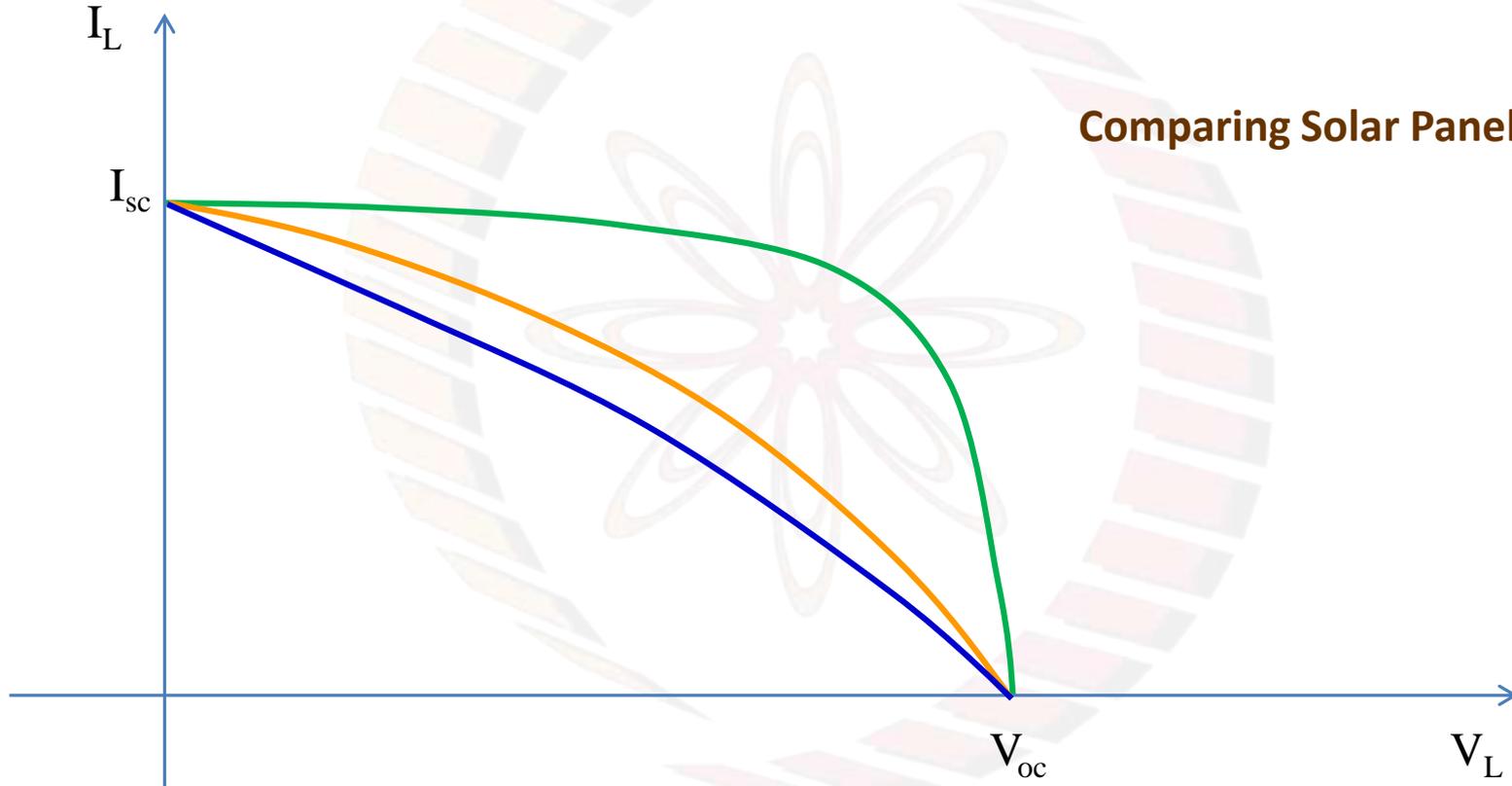


I-V characteristics

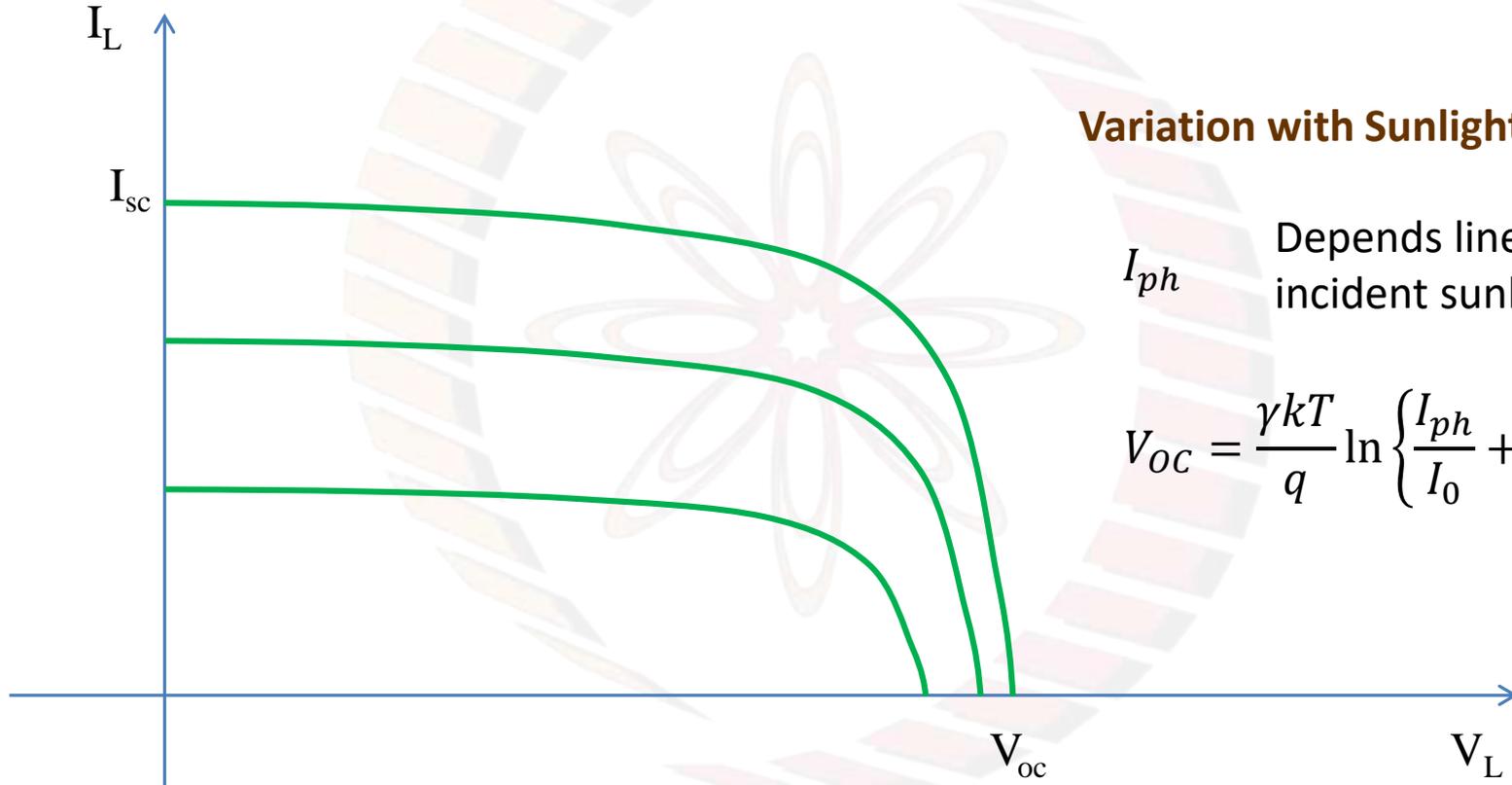


I-V characteristics

Comparing Solar Panels



I-V characteristics

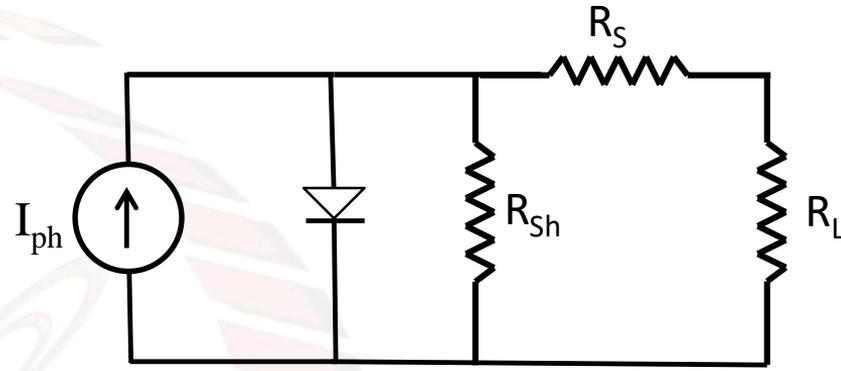
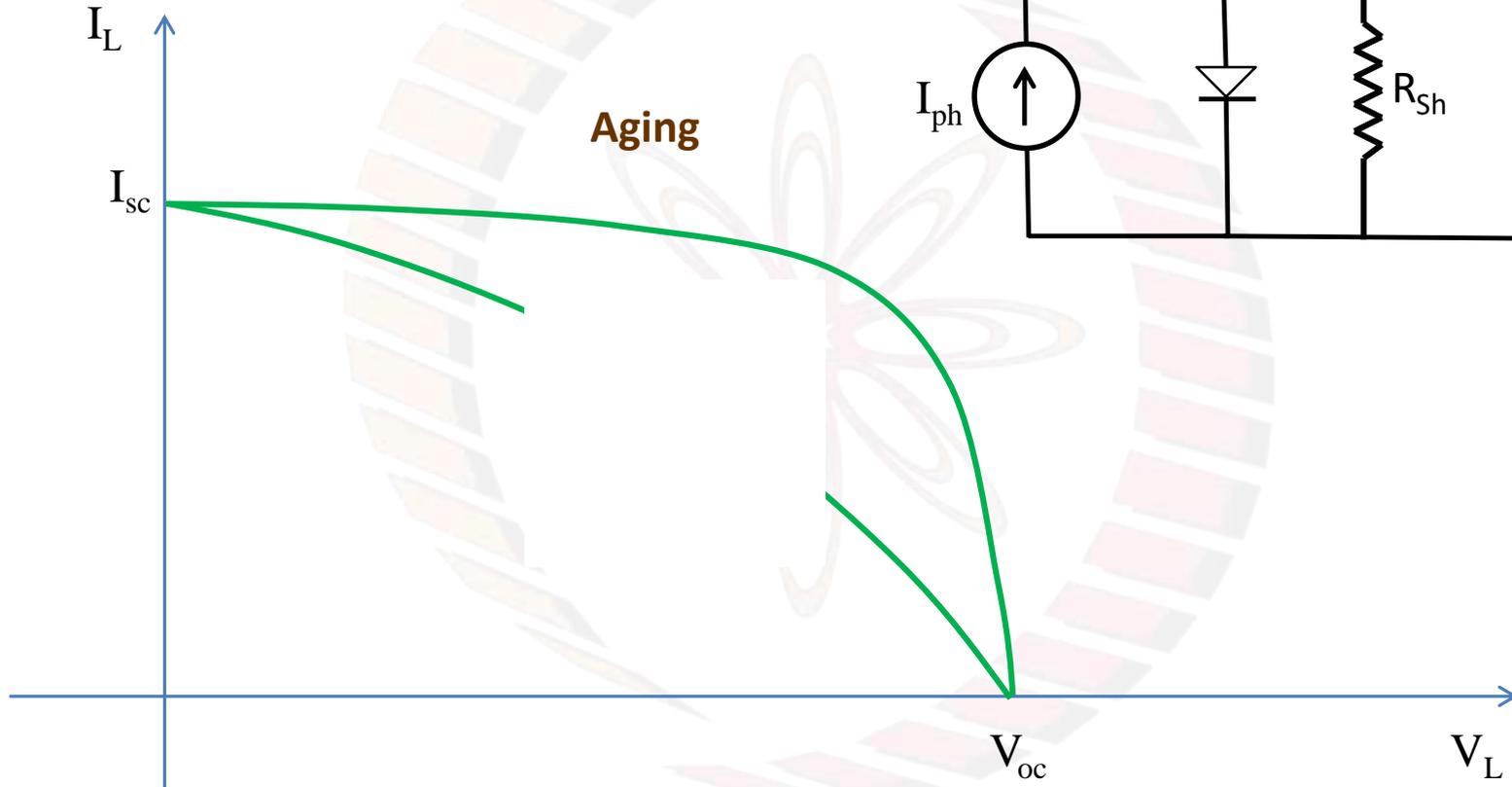


Variation with Sunlight

I_{ph} Depends linearly on incident sunlight

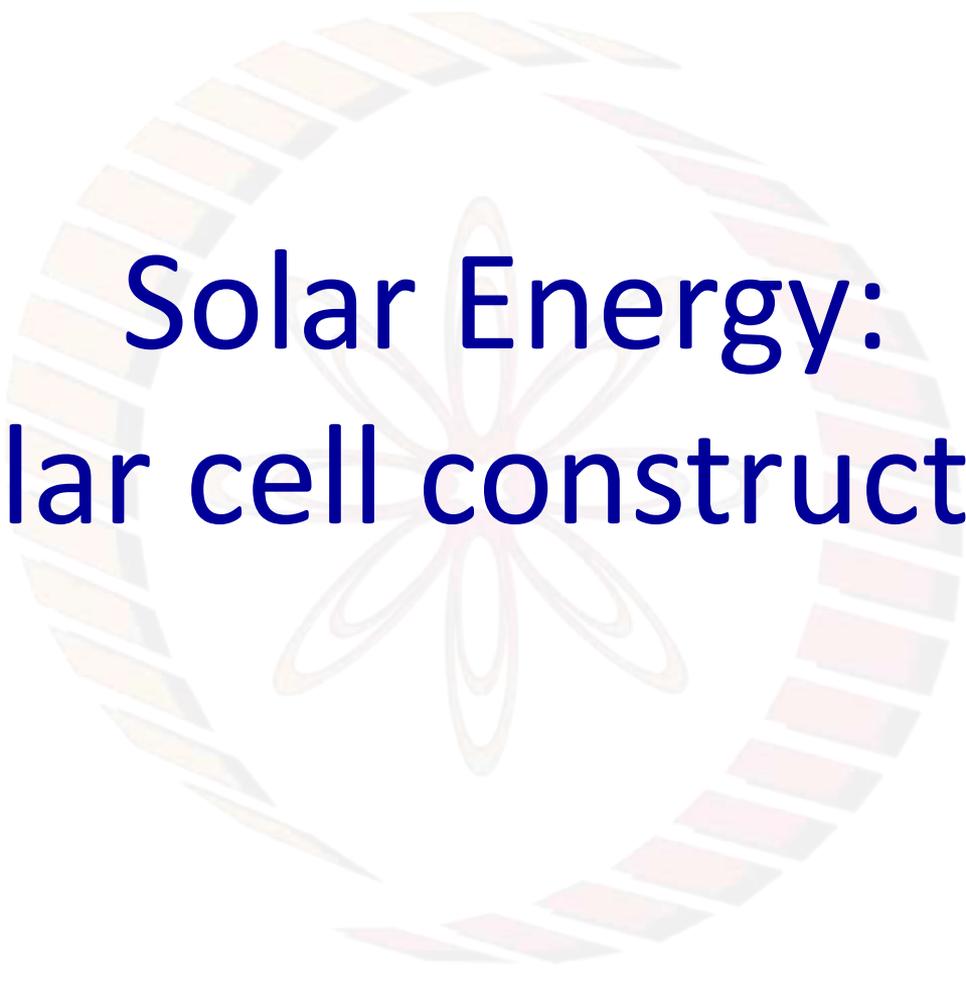
$$V_{oc} = \frac{\gamma k T}{q} \ln \left\{ \frac{I_{ph}}{I_0} + 1 \right\}$$

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

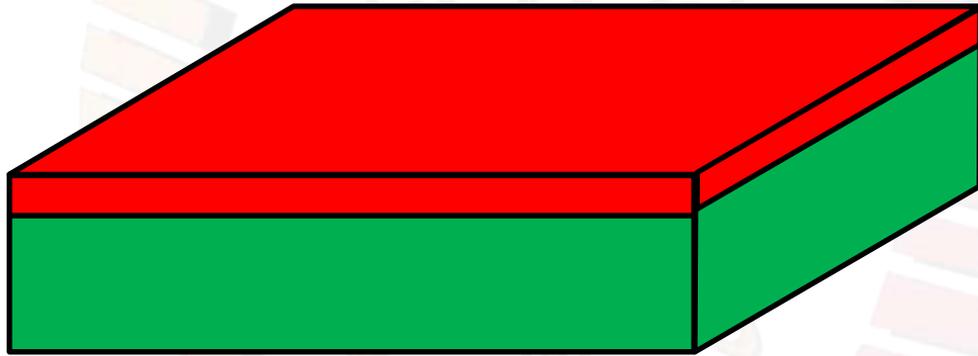
Shockley-Quiesser limit

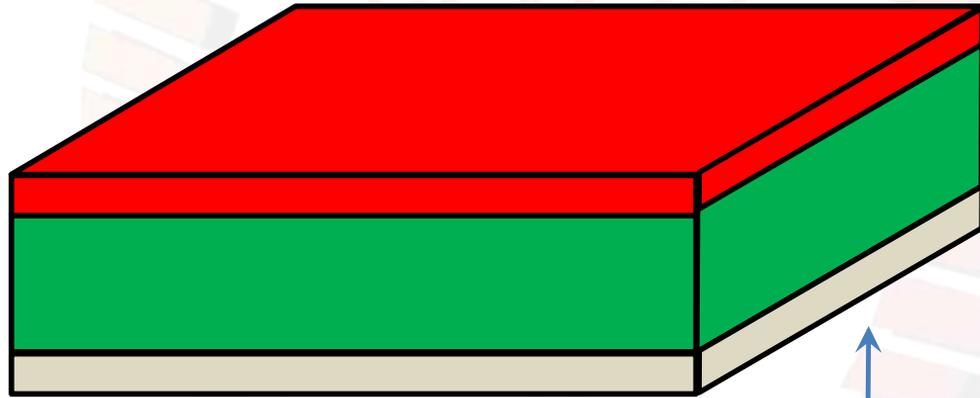
In unconcentrated, AM 1.5 Solar radiation with a band gap of 1.34 eV, 33.4 % efficiency is obtained

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

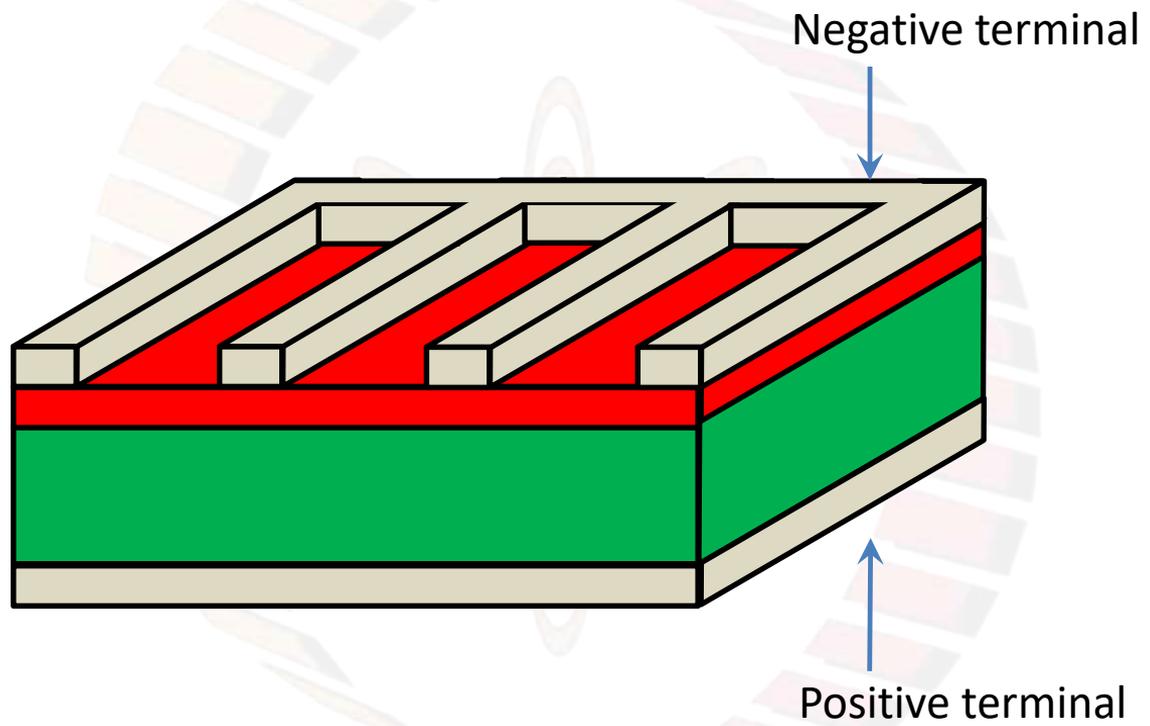
***Air Mass Coefficient: Optical path length relative to path length vertically upward
AM 1.5 typically used for evaluating panels***

Blackbody radiation	7% (At room T, actual T~ 75 °C)
Recombination losses	10%
Spectrum losses	19% unabsorbed, 33% excess ν , total 52%

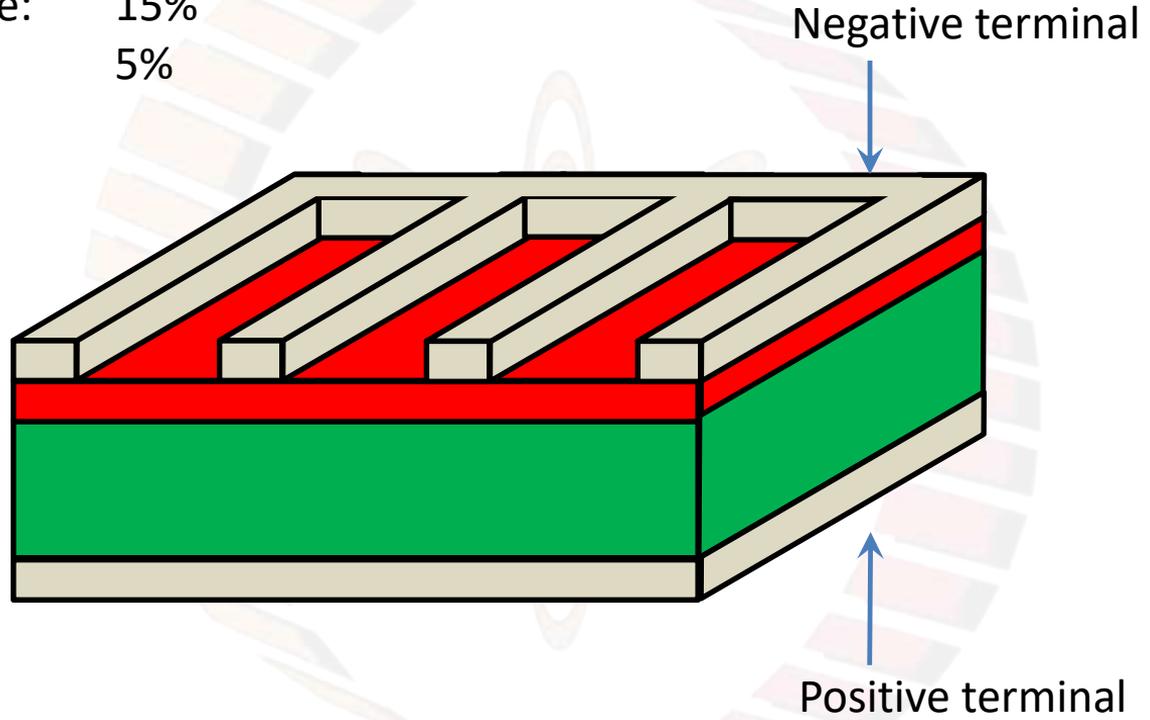




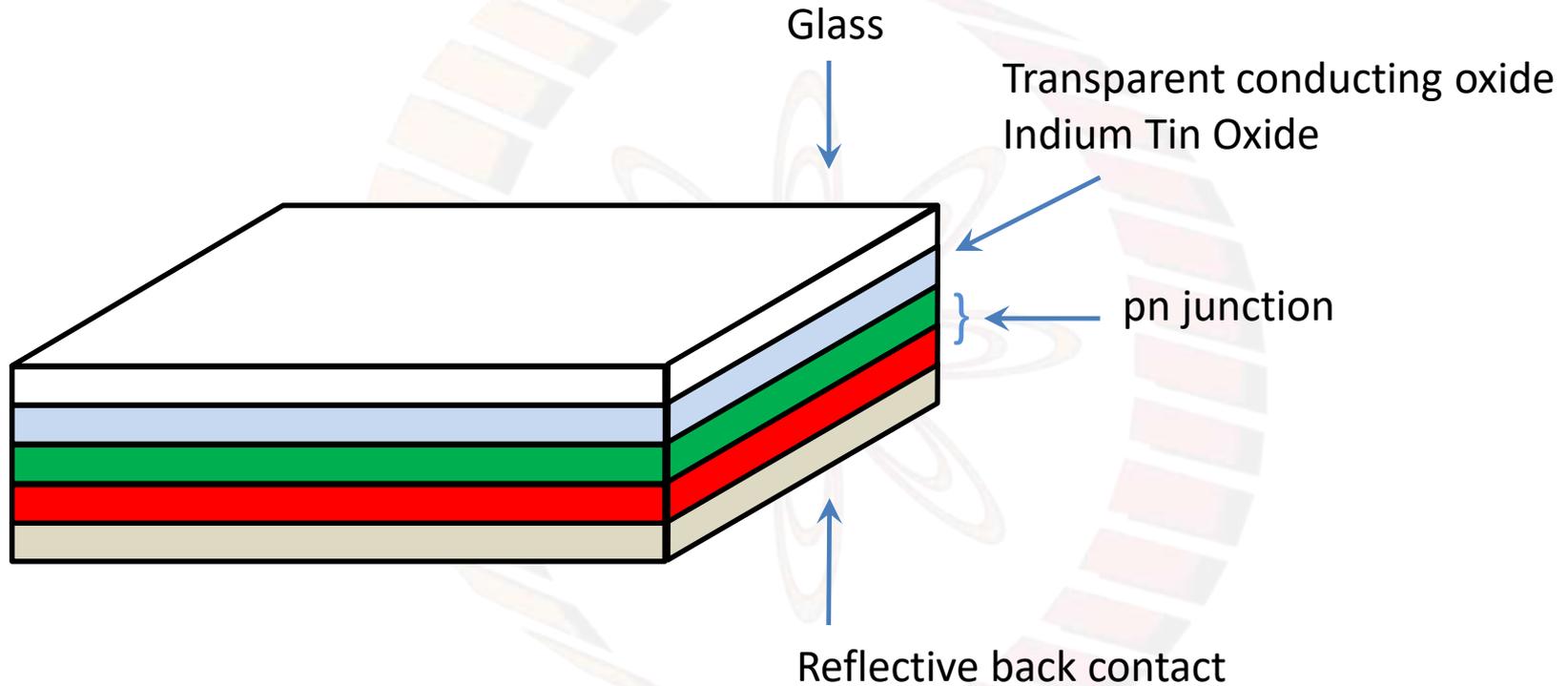
Positive terminal



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



Amorphous Silicon Solar Cell



Anti-reflective coatings

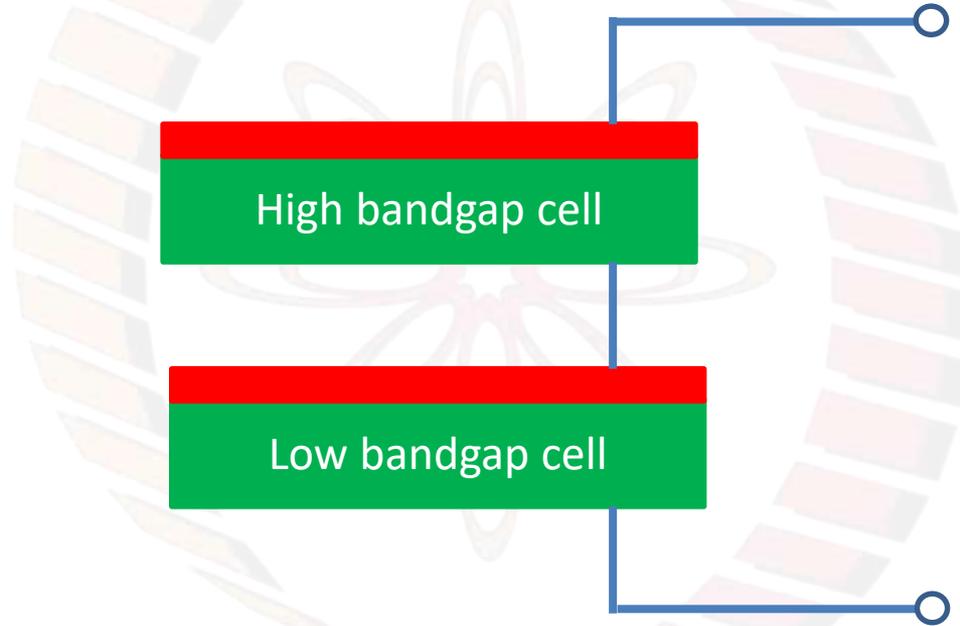
$$n_1 = \sqrt{n_0 n_s}$$

Glass $n_s = 1.5$

Air $n_0 = 1$

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