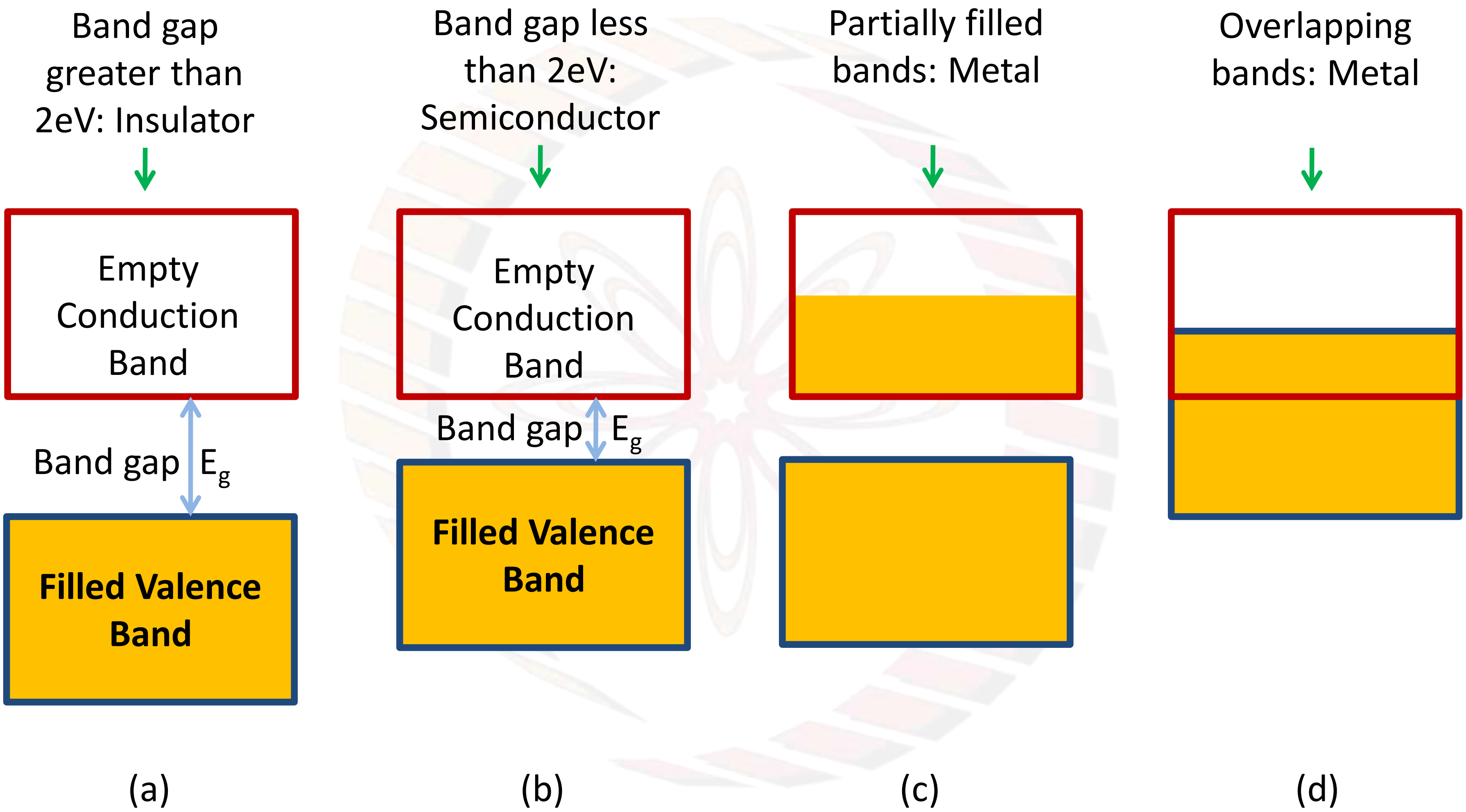
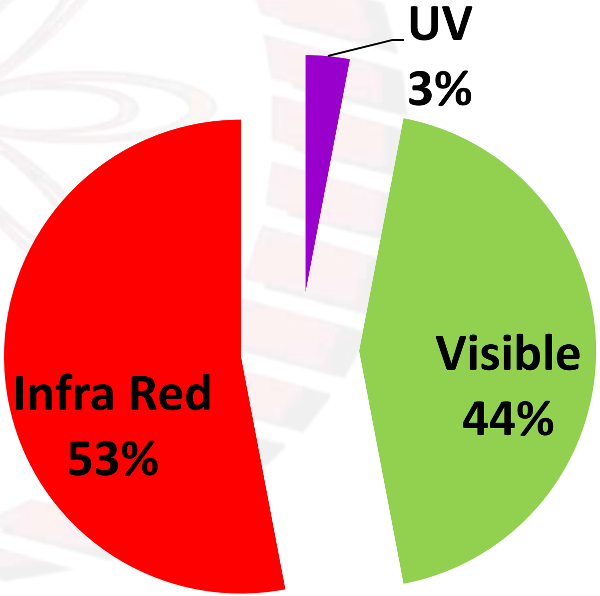
Solar Energy:
The Semiconductor

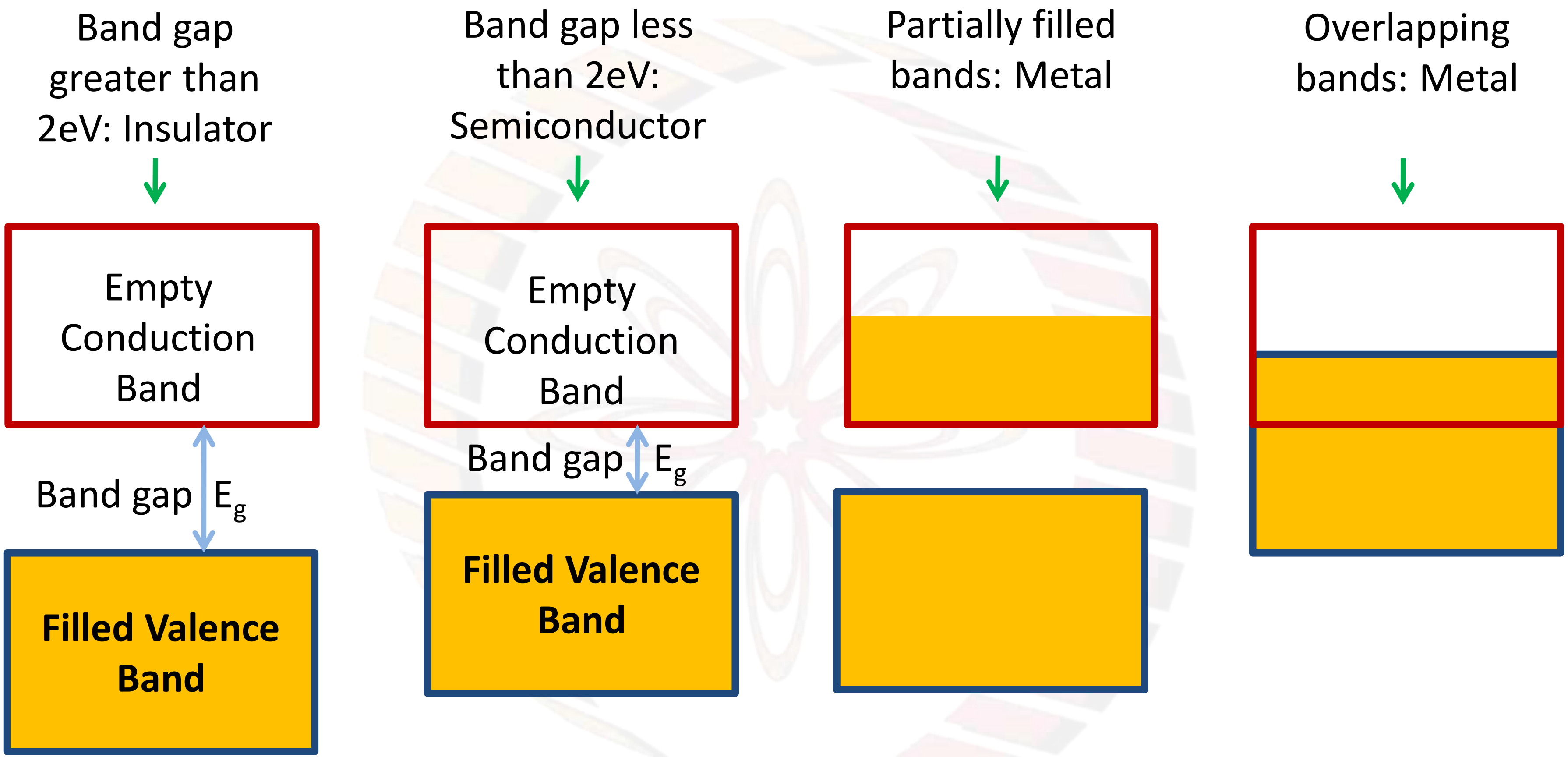
Learning objectives:

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.

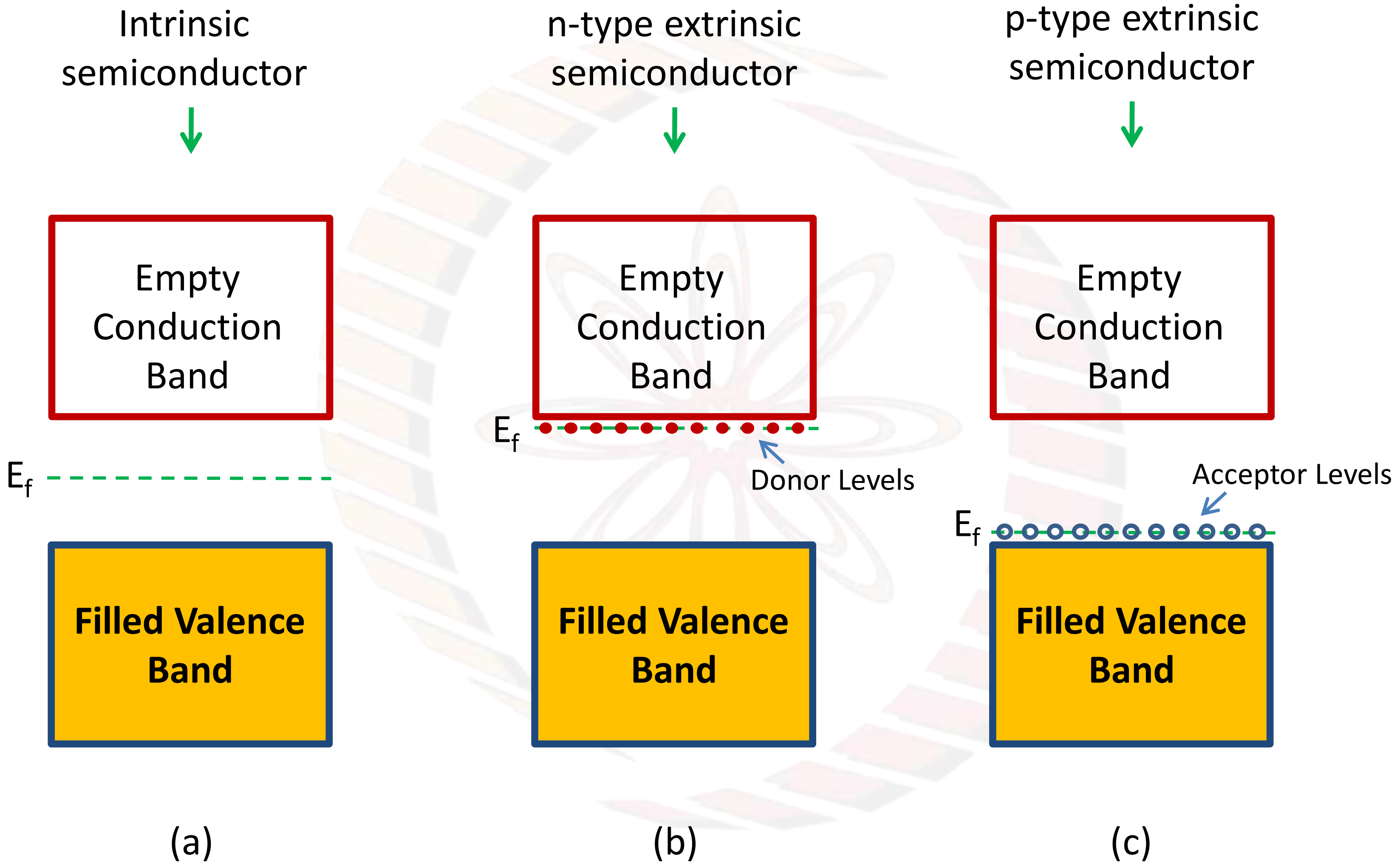

Band gap greater than 2eV: Insulator
Empty Conduction Band
Band gap E_g
Filled Valence Band
(a)
Band gap less than 2eV: Semiconductor
Empty Conduction Band
Band gap E_g
Filled Valence Band
(b)
Partially filled bands: Metal
(c)
Overlapping bands: Metal
(d)

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

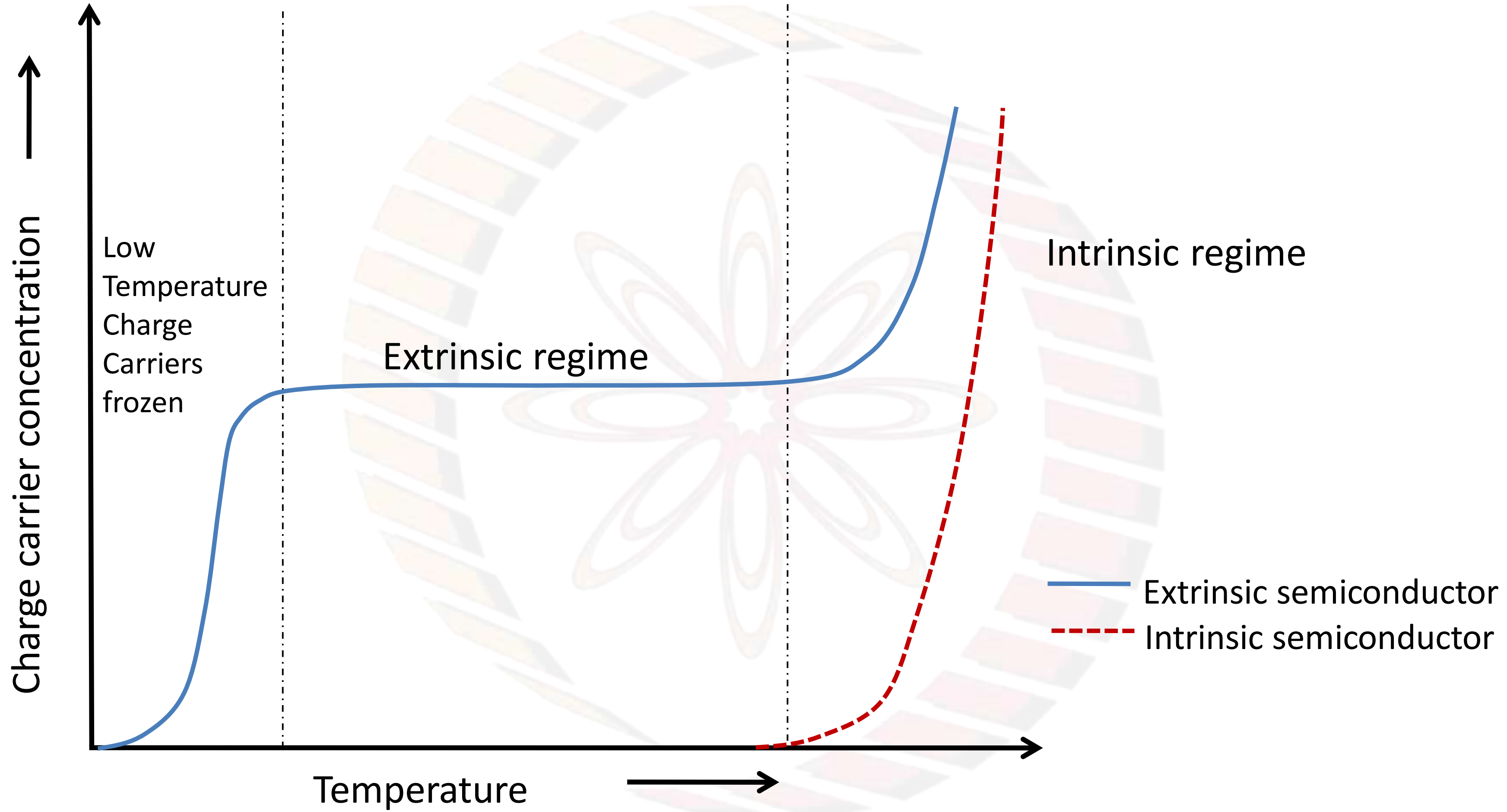




Visible Spectrum Wavelength:	**400 nm (violet)**	**to**	**700 nm (red)**
Corresponding band gaps:	**3.1 eV**	**to**	**1.8 eV**



Intrinsic semiconductor
n-type extrinsic semiconductor
p-type extrinsic semiconductor
Empty Conduction Band
Empty Conduction Band
Empty Conduction Band
E_f
E_f
Donor Levels
Acceptor Levels
E_f
Filled Valence Band
Filled Valence Band
Filled Valence Band
(a)
(b)
(c)



Charge carrier concentration
Low
Temperature
Charge
Carriers
frozen
Extrinsic regime
Intrinsic regime
Extrinsic semiconductor
Intrinsic semiconductor
Temperature

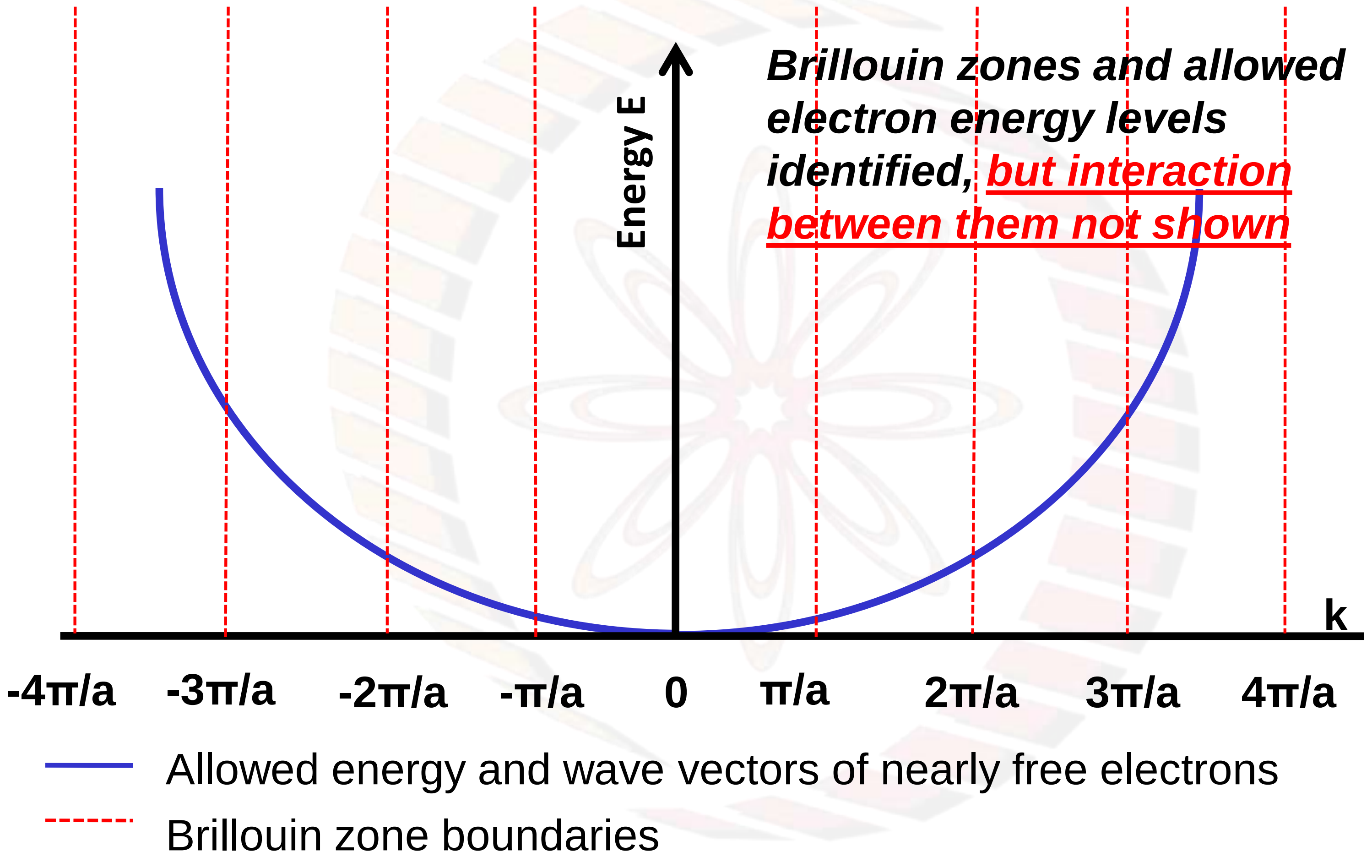
Planck

$$E = h\nu$$

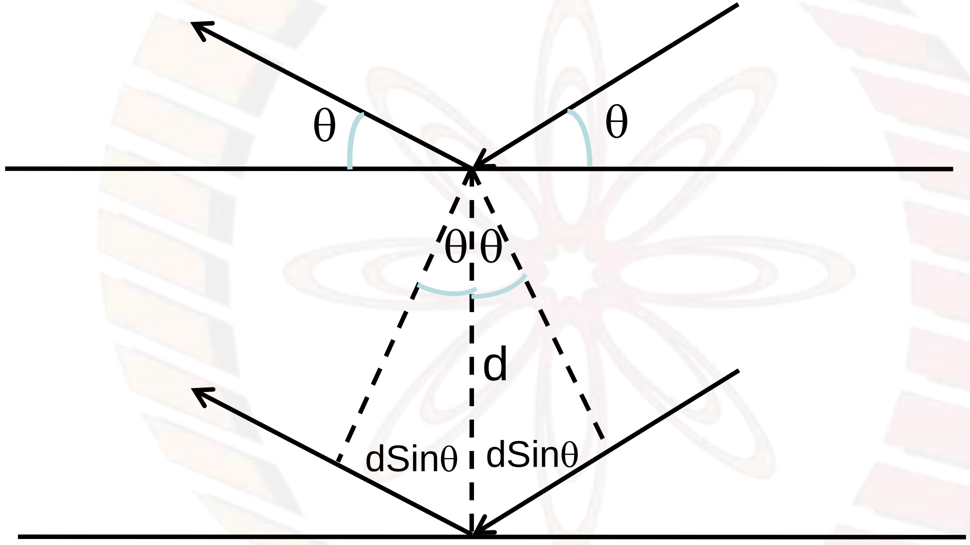
de Broglie

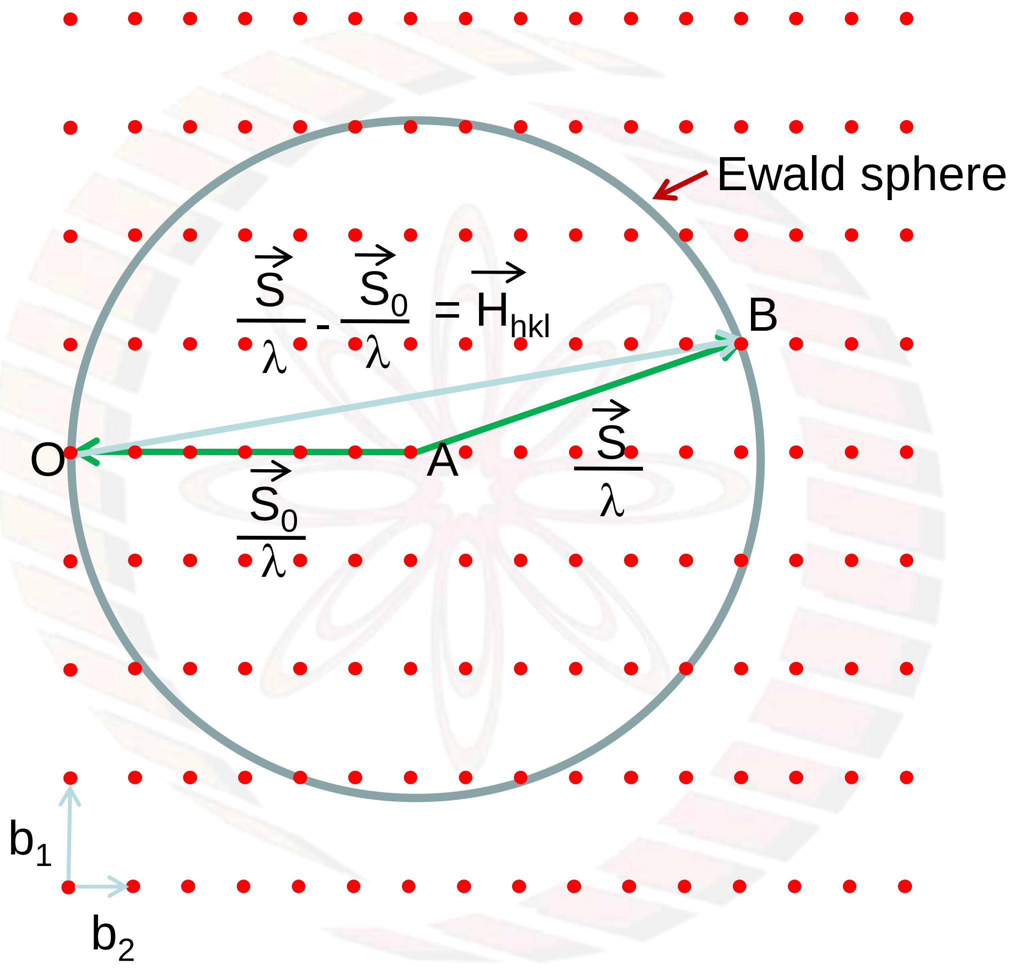
$$\lambda = \frac{h}{p}$$

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

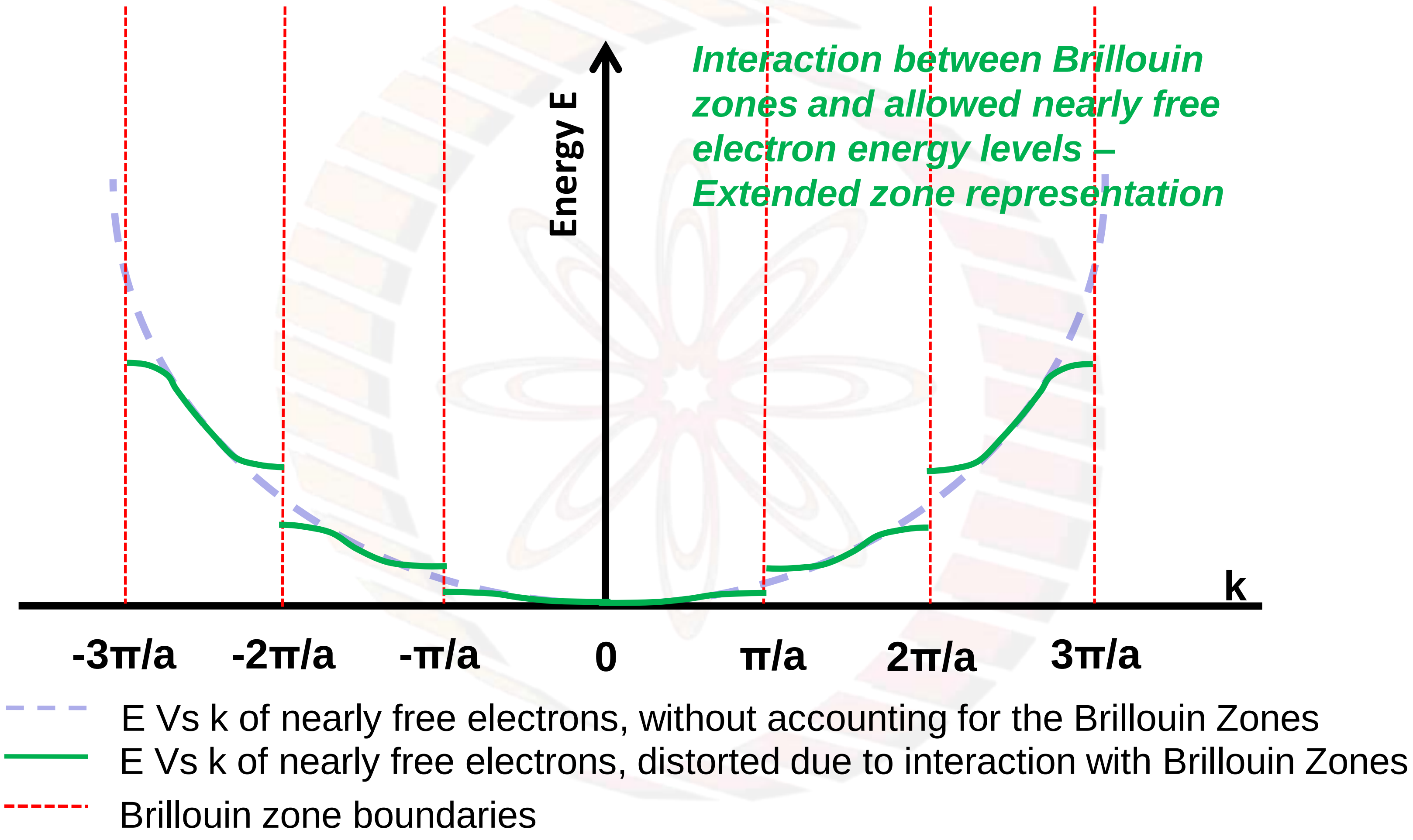


Brillouin zones and allowed electron energy levels identified, but interaction between them not shown
Energy E
k
-4π/a
-3π/a
-2π/a
-π/a
0
π/a
2π/a
3π/a
4π/a
Allowed energy and wave vectors of nearly free electrons
Brillouin zone boundaries

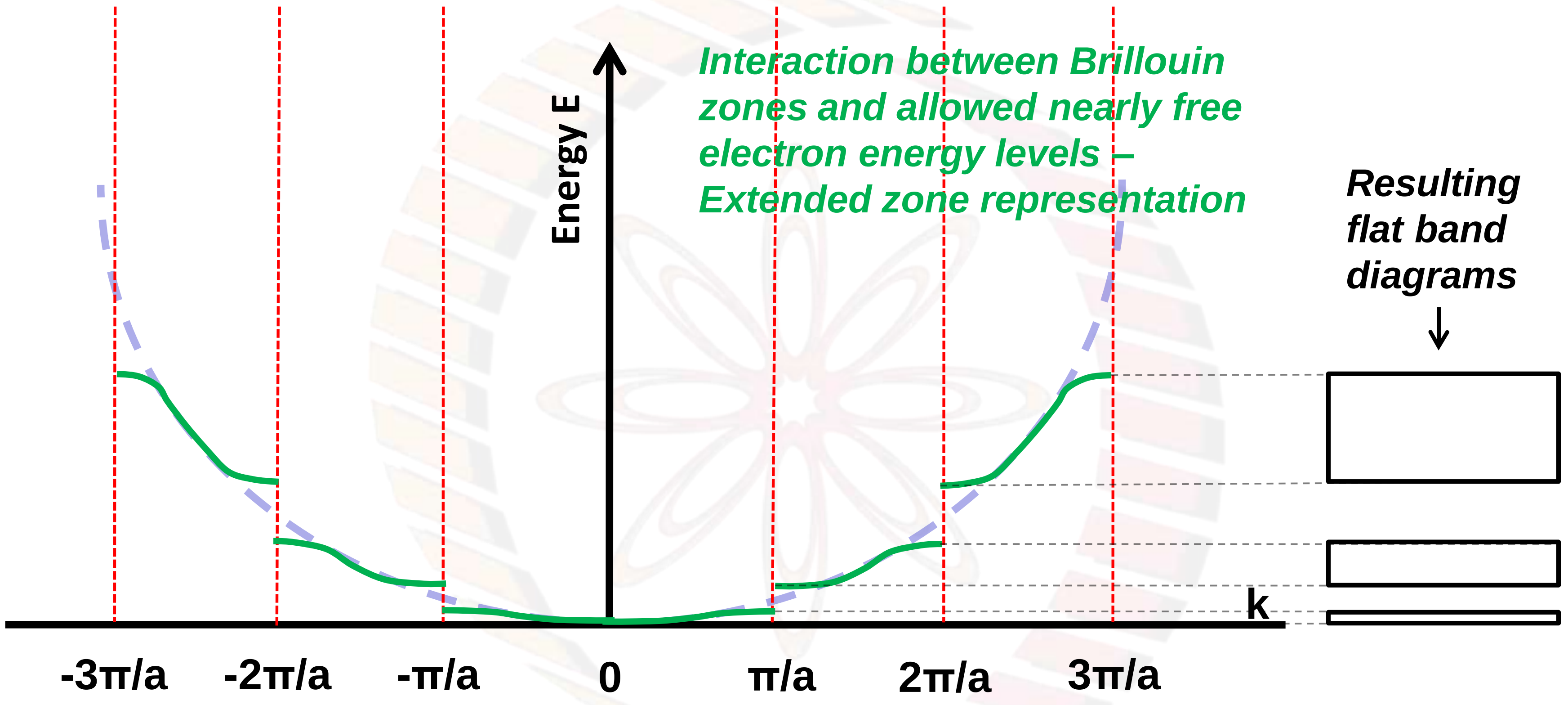

θ
θ
θ θ
d
dSinθ
dSinθ



Ewald sphere
$\frac{\vec{S}}{\lambda} - \frac{\vec{S_0}}{\lambda} = \vec{H}_{hkl}$
B
O
A
$\frac{\vec{S}}{\lambda}$
$\frac{\vec{S_0}}{\lambda}$
b_1
b_2



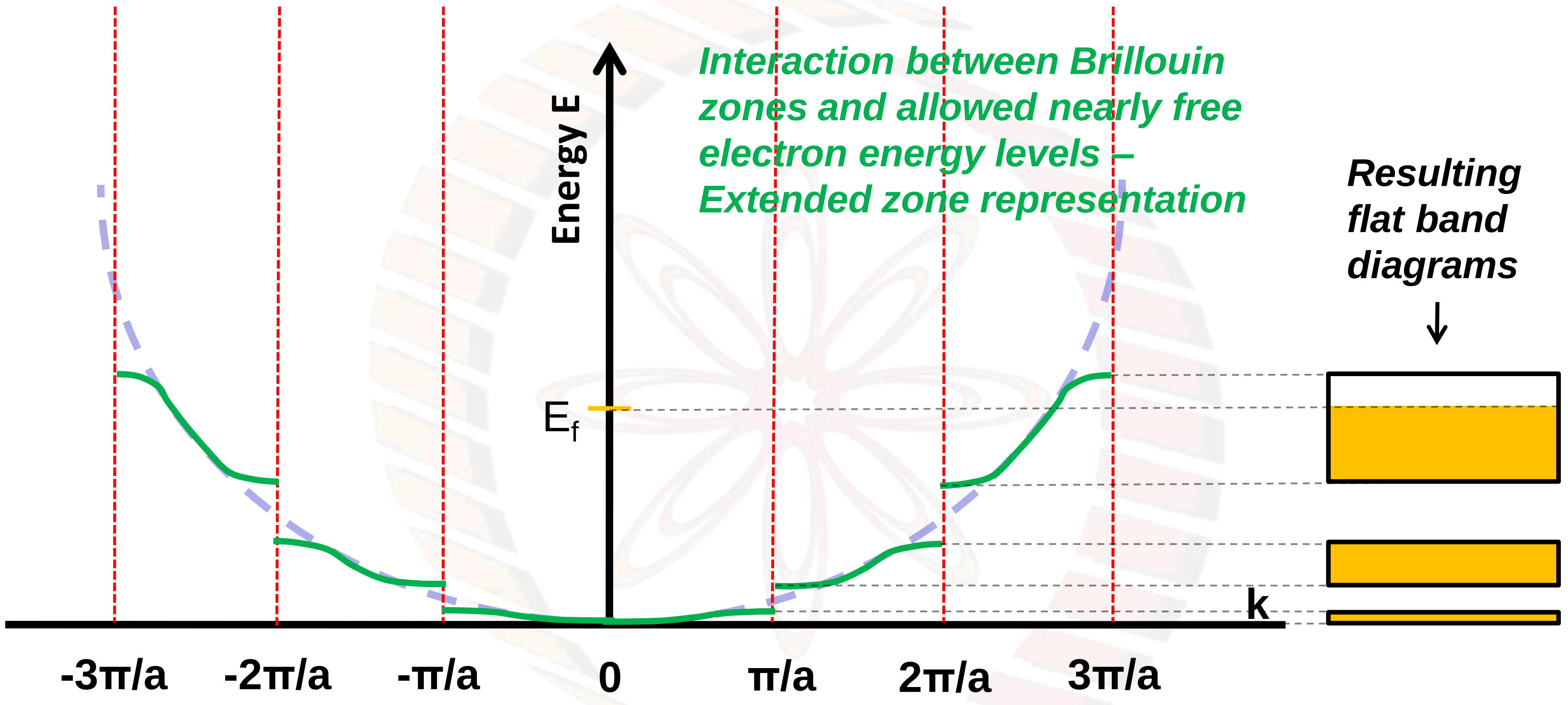
Interaction between Brillouin zones and allowed nearly free electron energy levels – Extended zone representation
Energy E
k
-3π/a
-2π/a
-π/a
0
π/a
2π/a
3π/a
E Vs k of nearly free electrons, without accounting for the Brillouin Zones
E Vs k of nearly free electrons, distorted due to interaction with 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

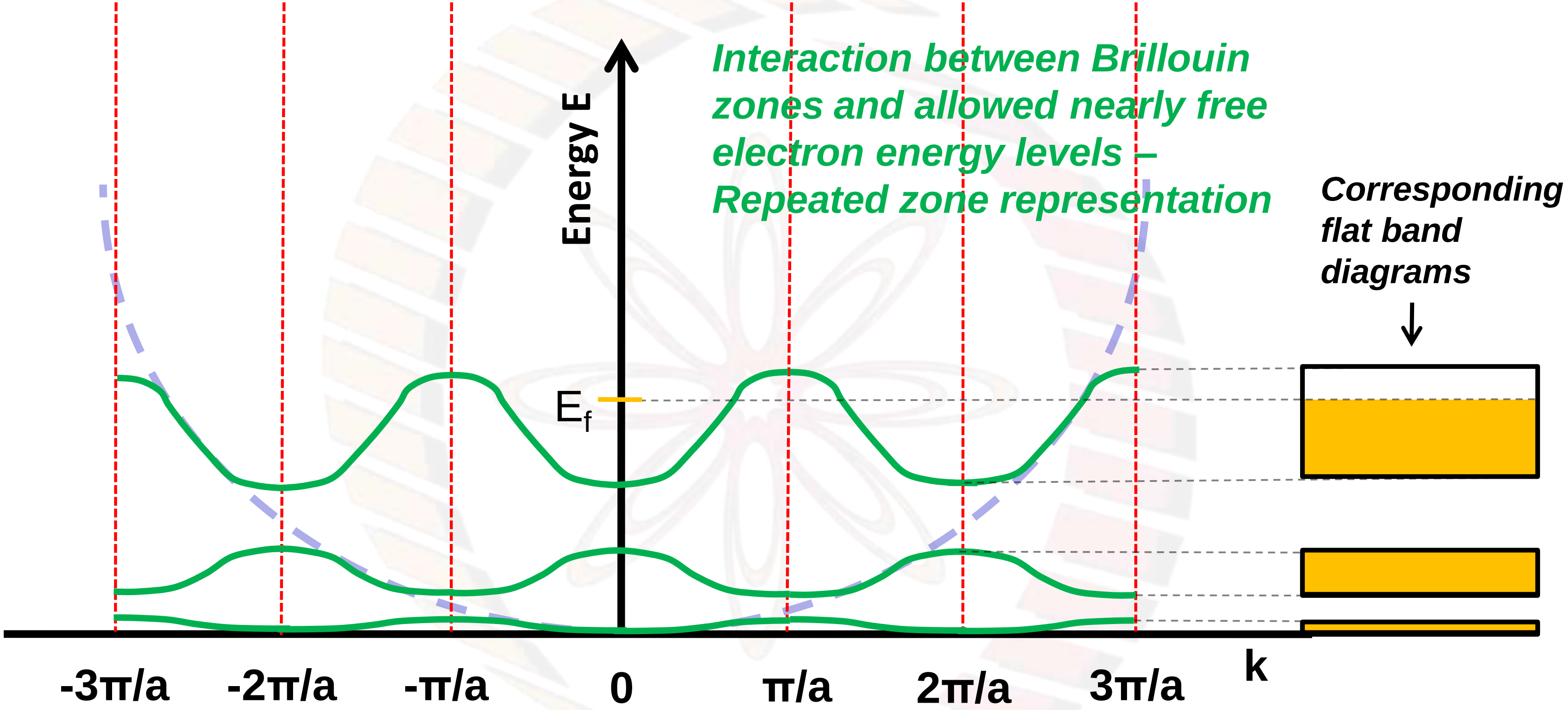
Brillouin zone boundaries



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

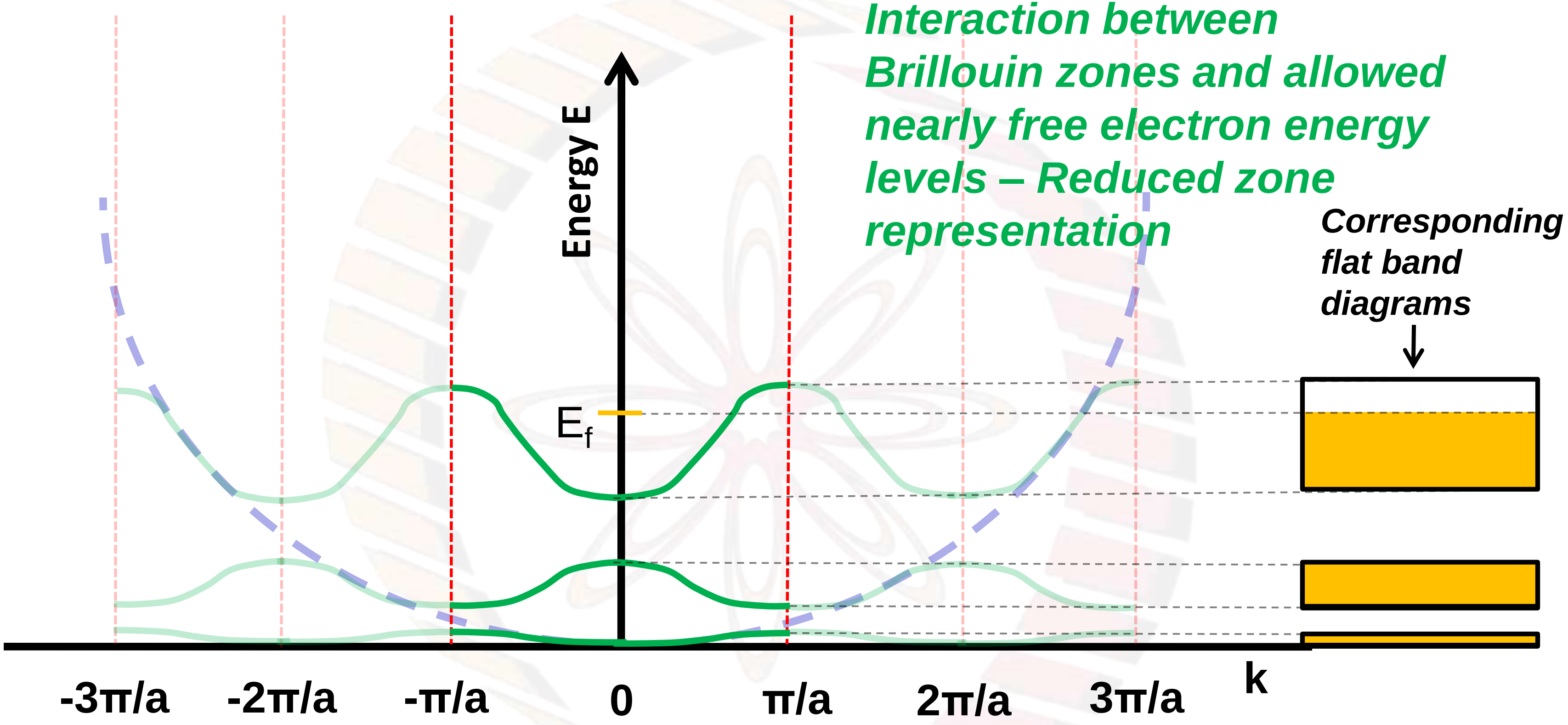


E Vs k of nearly free electrons, without accounting for the Brillouin Zones

E Vs k of nearly free electrons, distorted due to interaction with Brillouin Zones

Brillouin zone boundaries

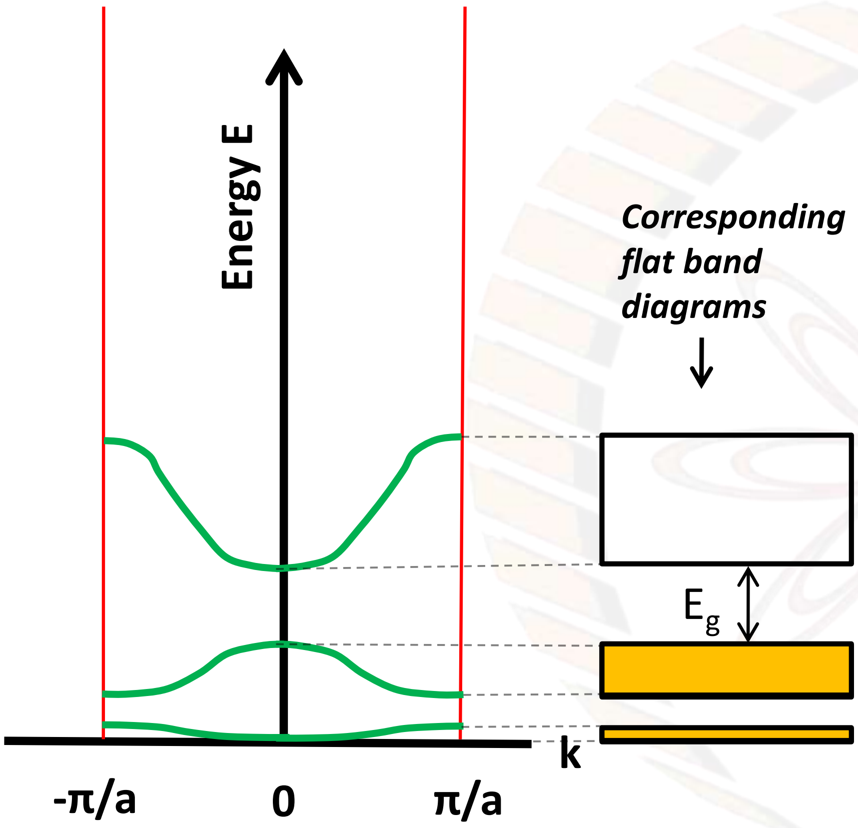
Interaction between Brillouin zones and allowed nearly free electron energy levels – Reduced zone representation



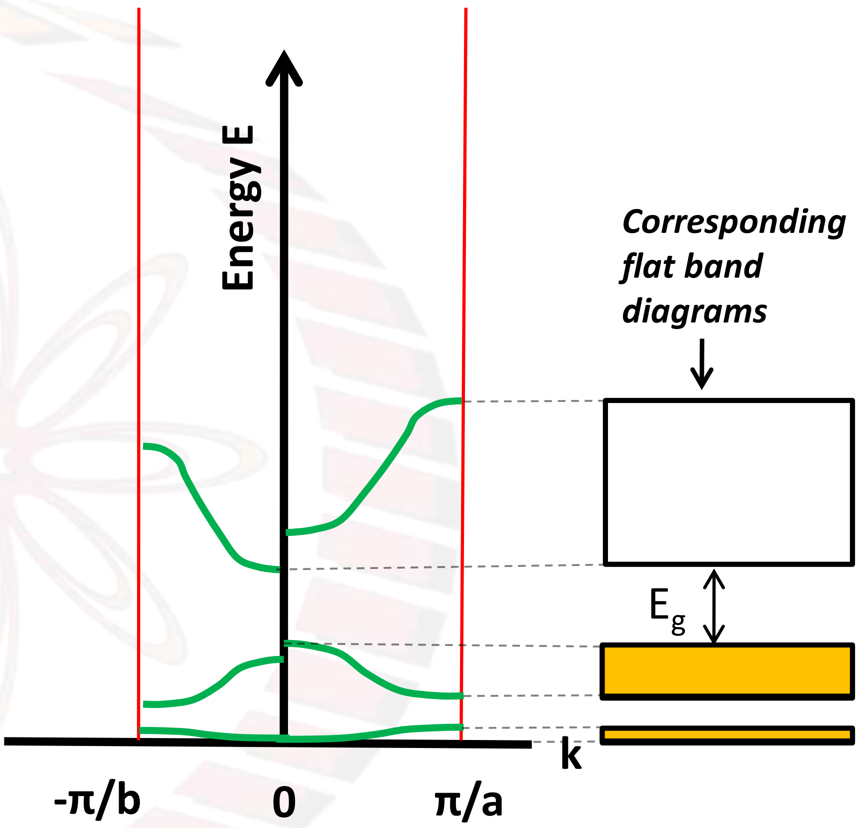
E Vs k of nearly free electrons, without accounting for the Brillouin Zones

E Vs k of nearly free electrons, distorted due to interaction with Brillouin Zones

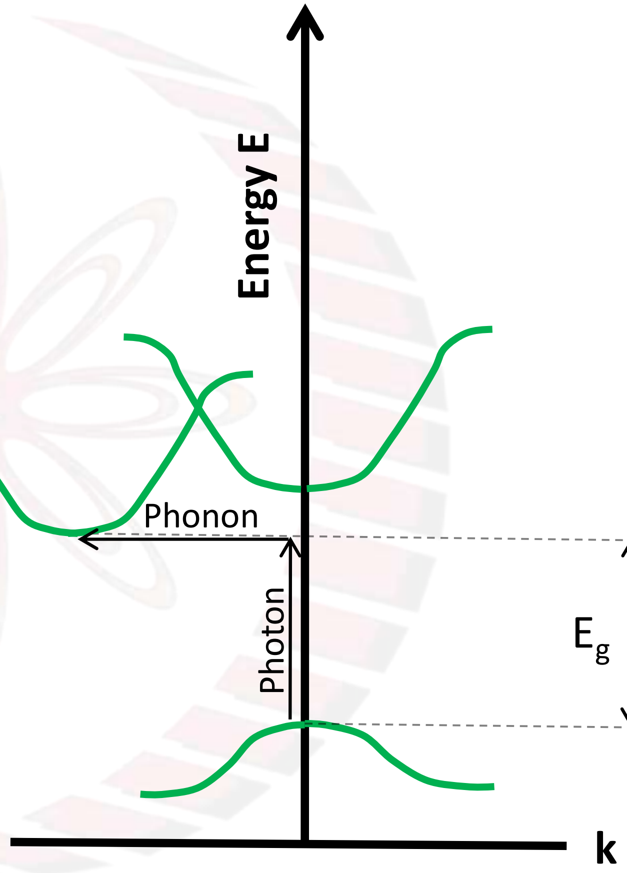
Brillouin zone boundaries



Direct bandgap semiconductor



Indirect bandgap semiconductor



Energy E
Phonon
Photon
E_g
k

Conclusions:

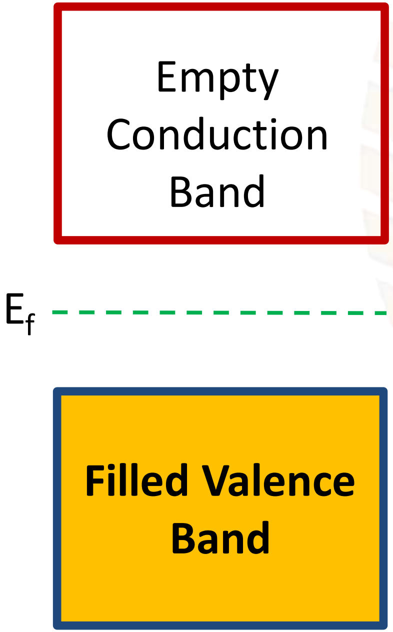
1) There is significant variation in the band diagrams of different types of materials
2) Interaction of a material with radiation depends strongly on its band diagram
3) Visible spectrum is a small fraction of solar radiation
4) There is a difference in the effectiveness with which direct and indirect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

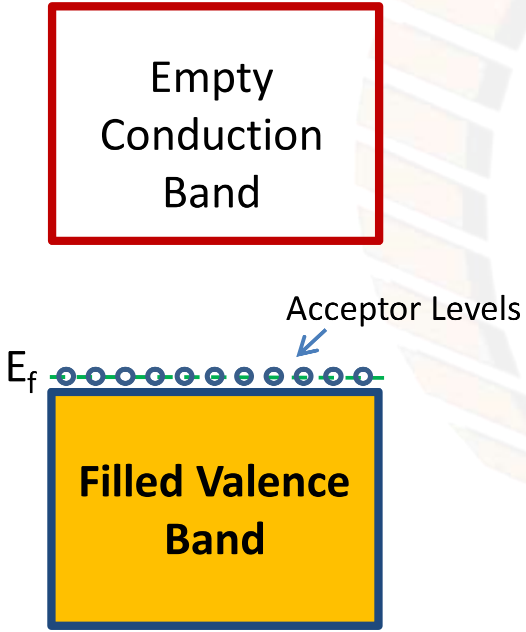


- Charge carrier concentration depends only temperature

- Conductivity depends only on Temperature

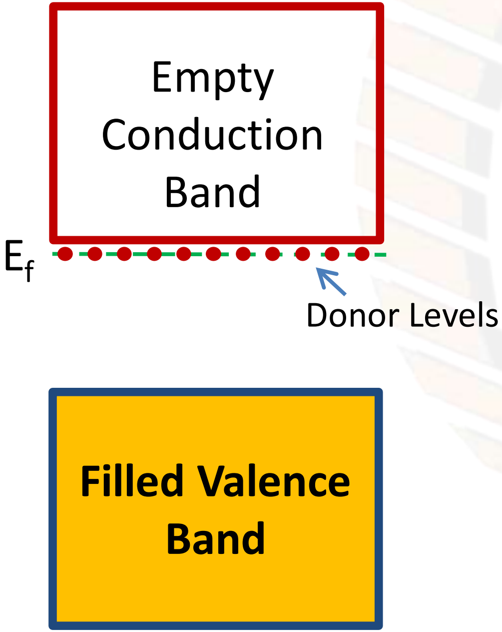
- Examples:
  - Elemental: Group IV A: Si (1.1 eV), Ge (0.7 eV)
  - Compound:
    - Group III A and Group V A (III-V)
      - GaAs, InSb
    - Group II B and Group VI A (II-VI)
      - CdS, ZnTe

p-type extrinsic semiconductor

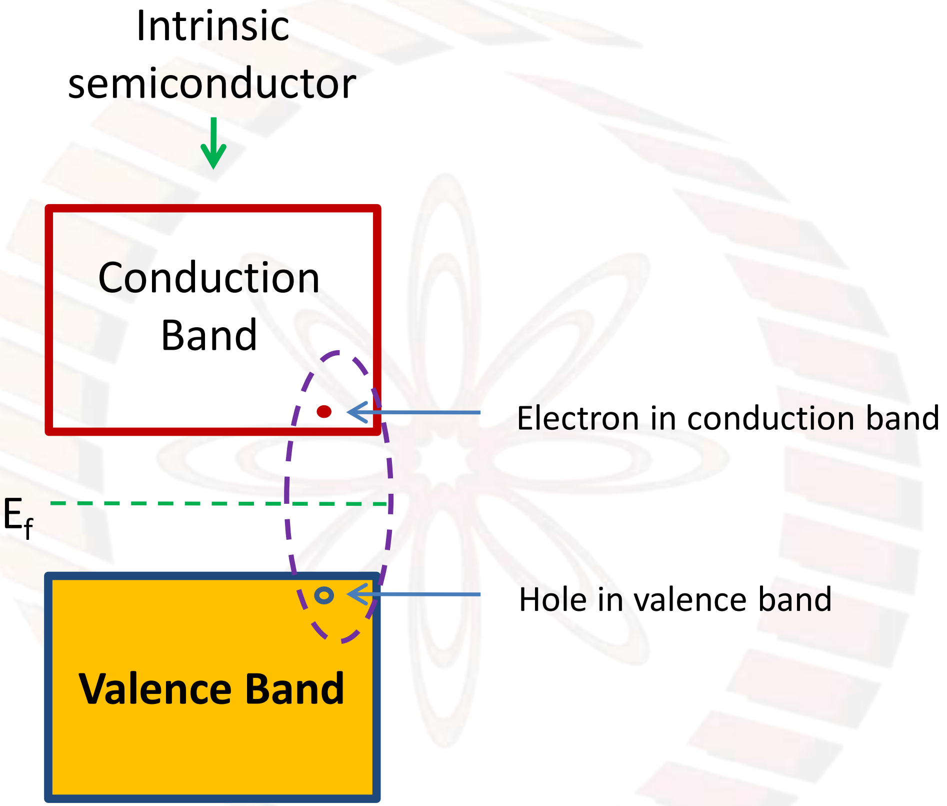


- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group III A elements: B, Al, Ga, In, Tl

n-type extrinsic semiconductor



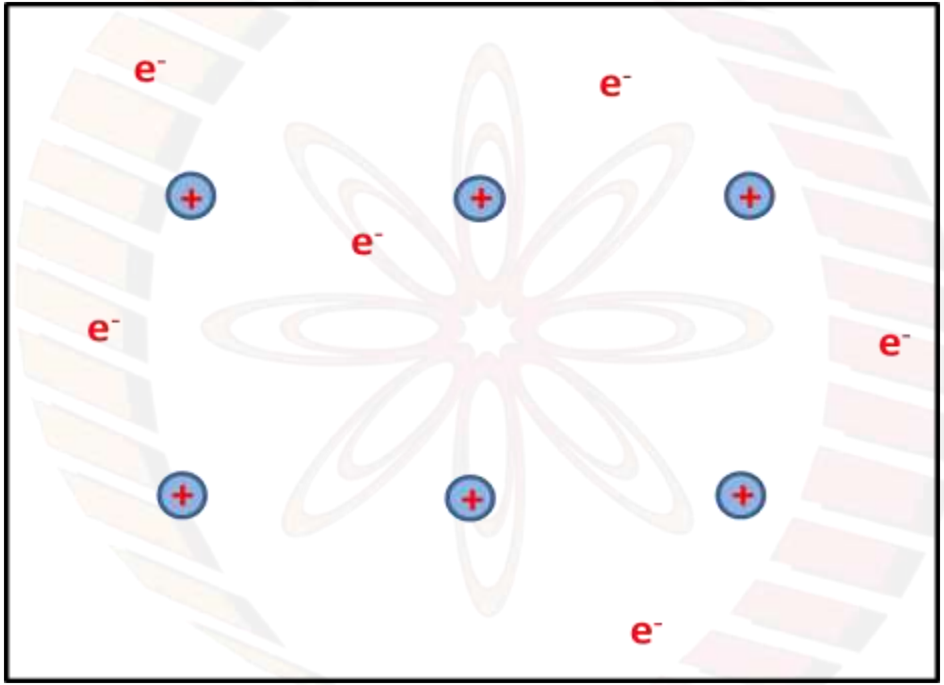
- Charge carrier concentration depends on dopant concentration
- Conductivity depends on dopant concentration
- Examples:
  - Group IV A elements doped with small quantities of Group V A elements: N, P, As, Sb, Bi



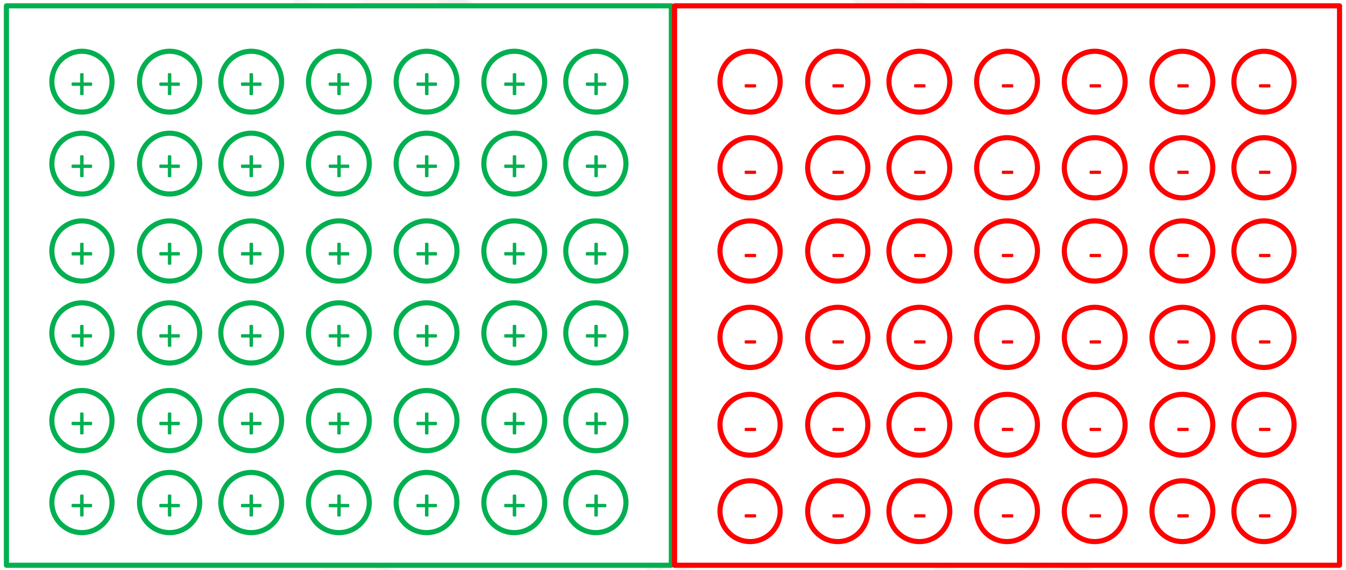
$$E_g = hv$$

Stability of electron-hole pair?

Metal



The p-n junction

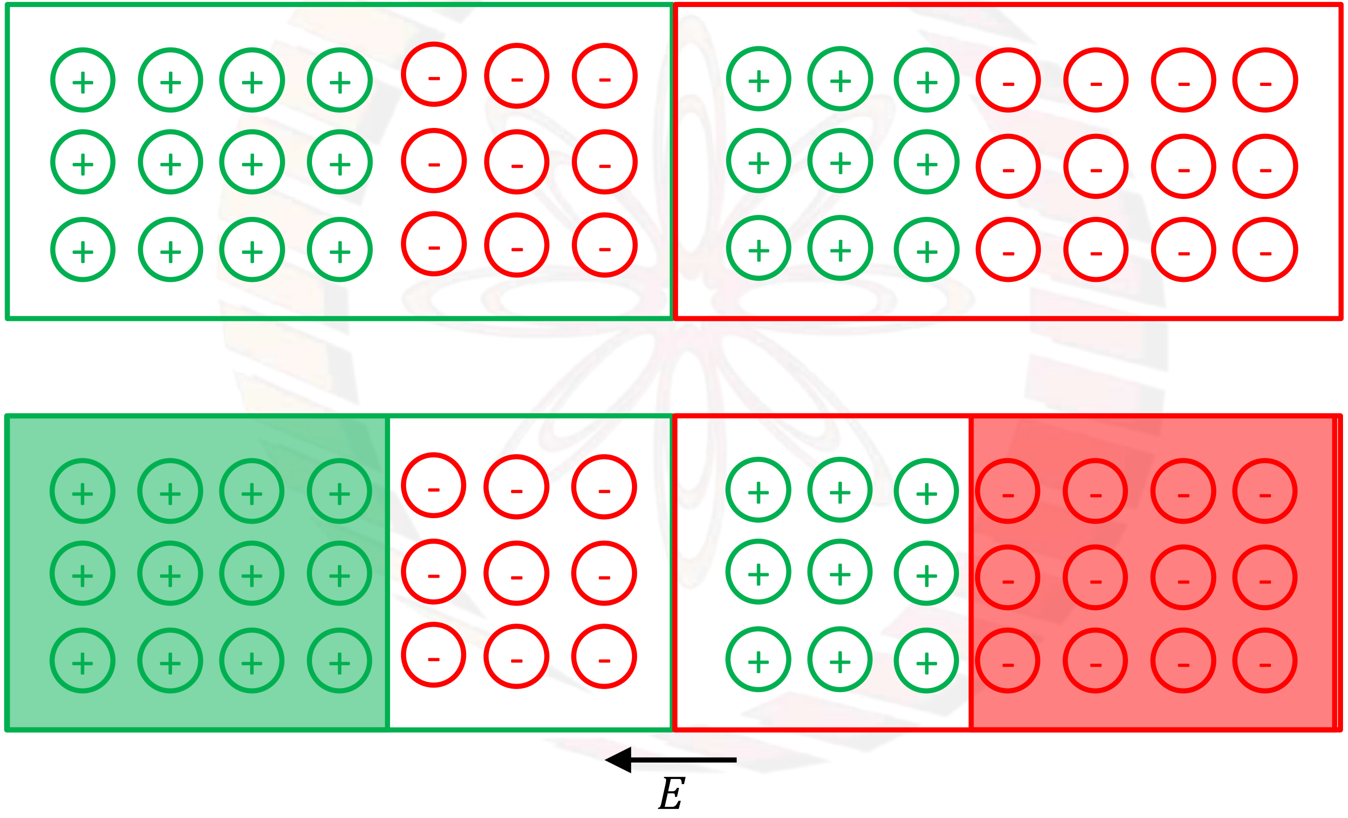


Si doped with B

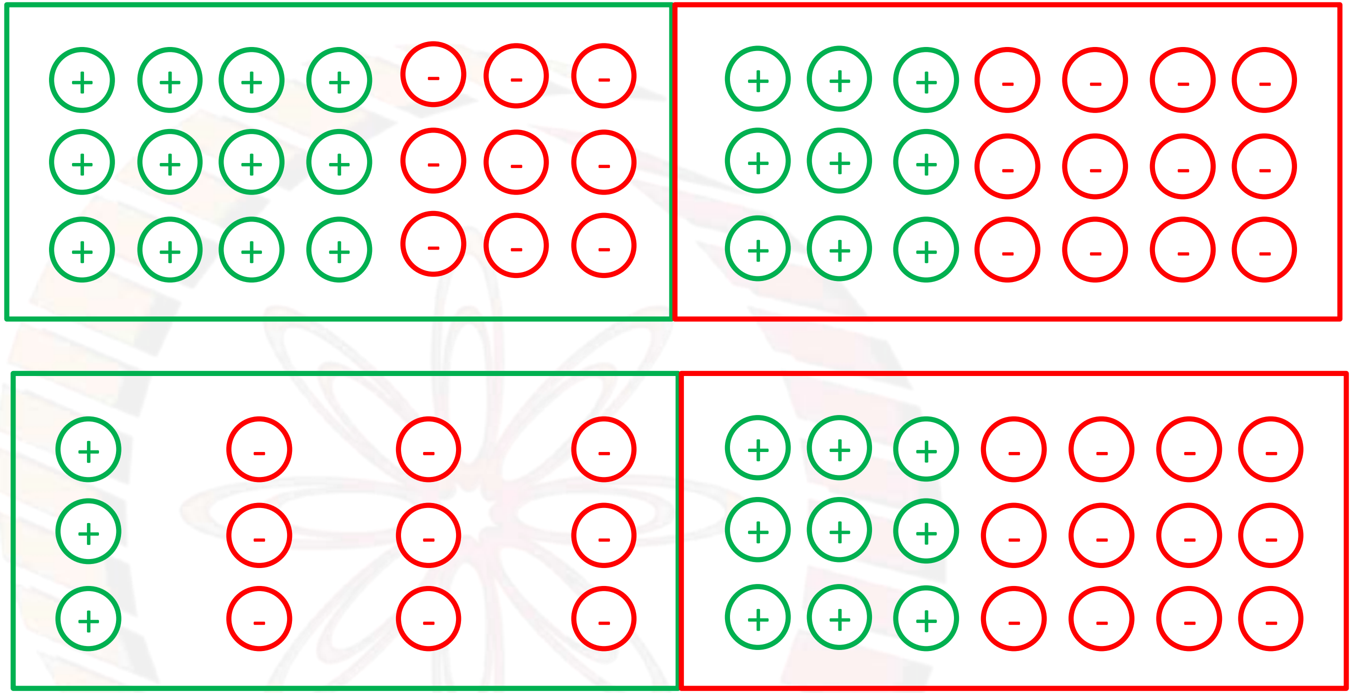
Si doped with P

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

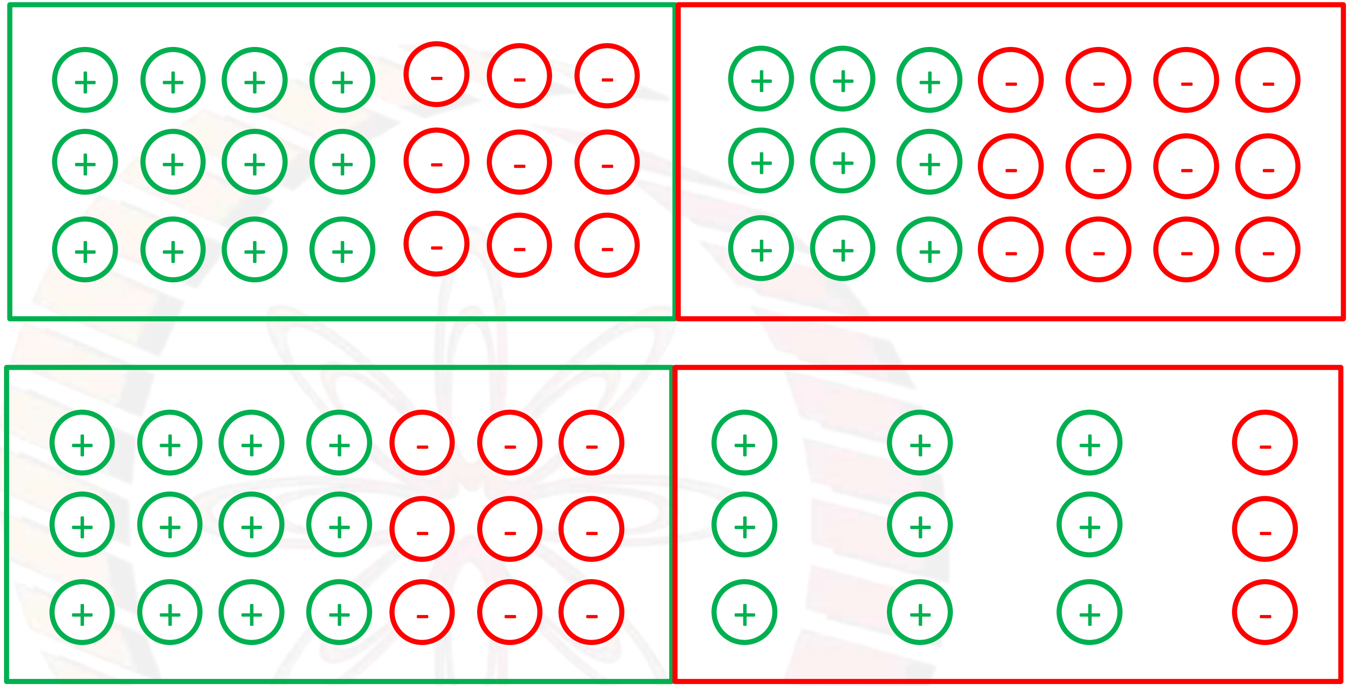
The space charge region
Depletion region

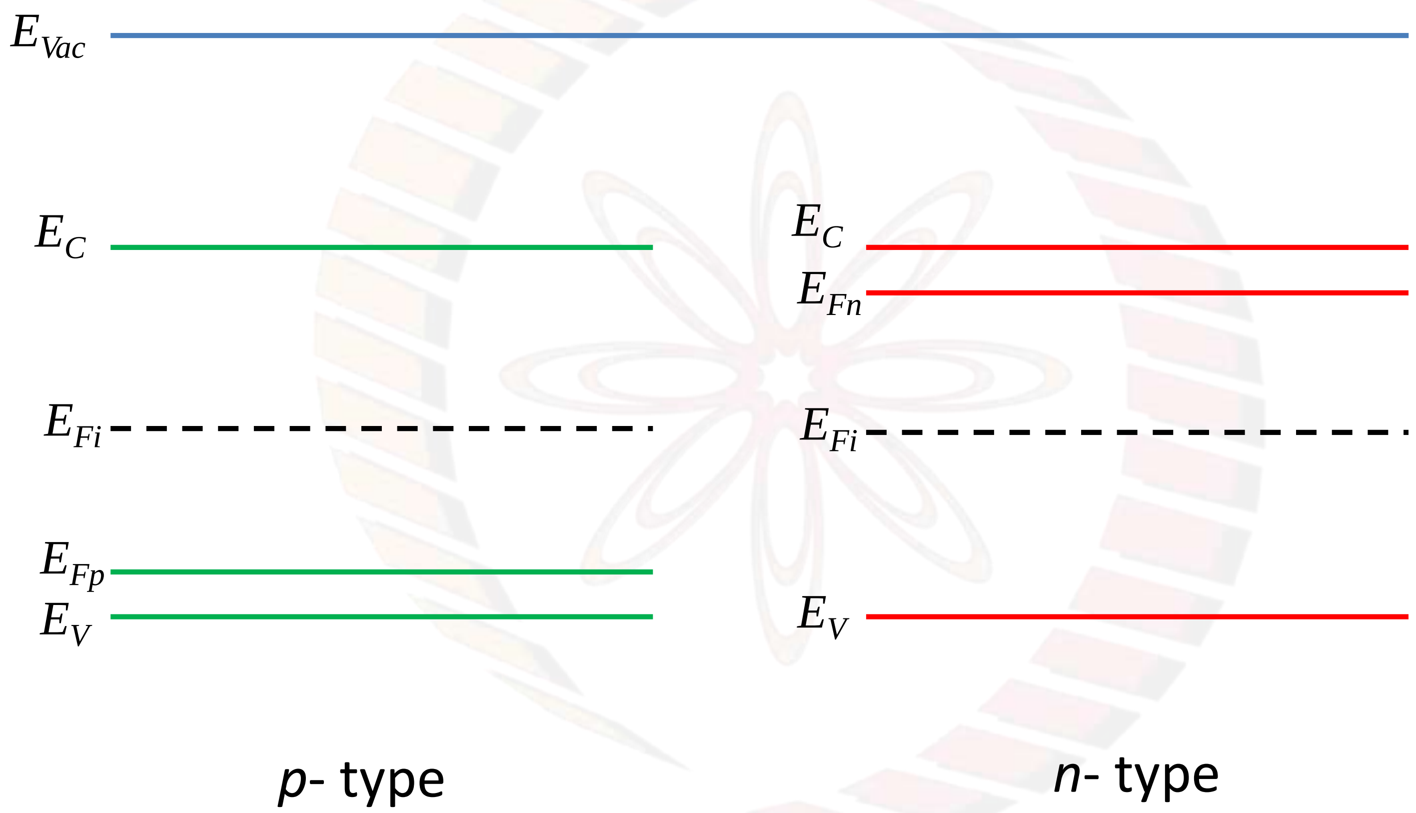


space charge region
depletion region

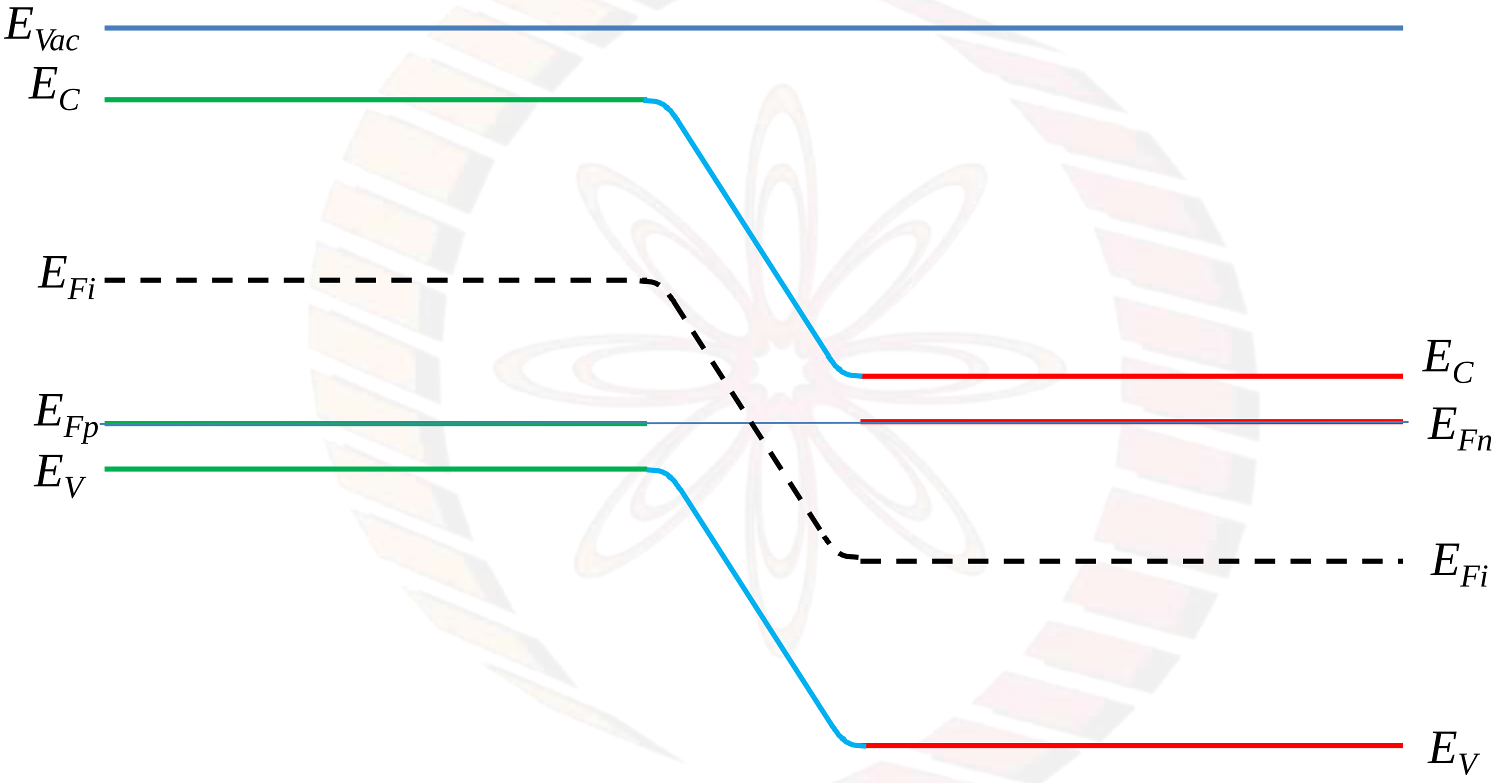


space charge region
depletion region

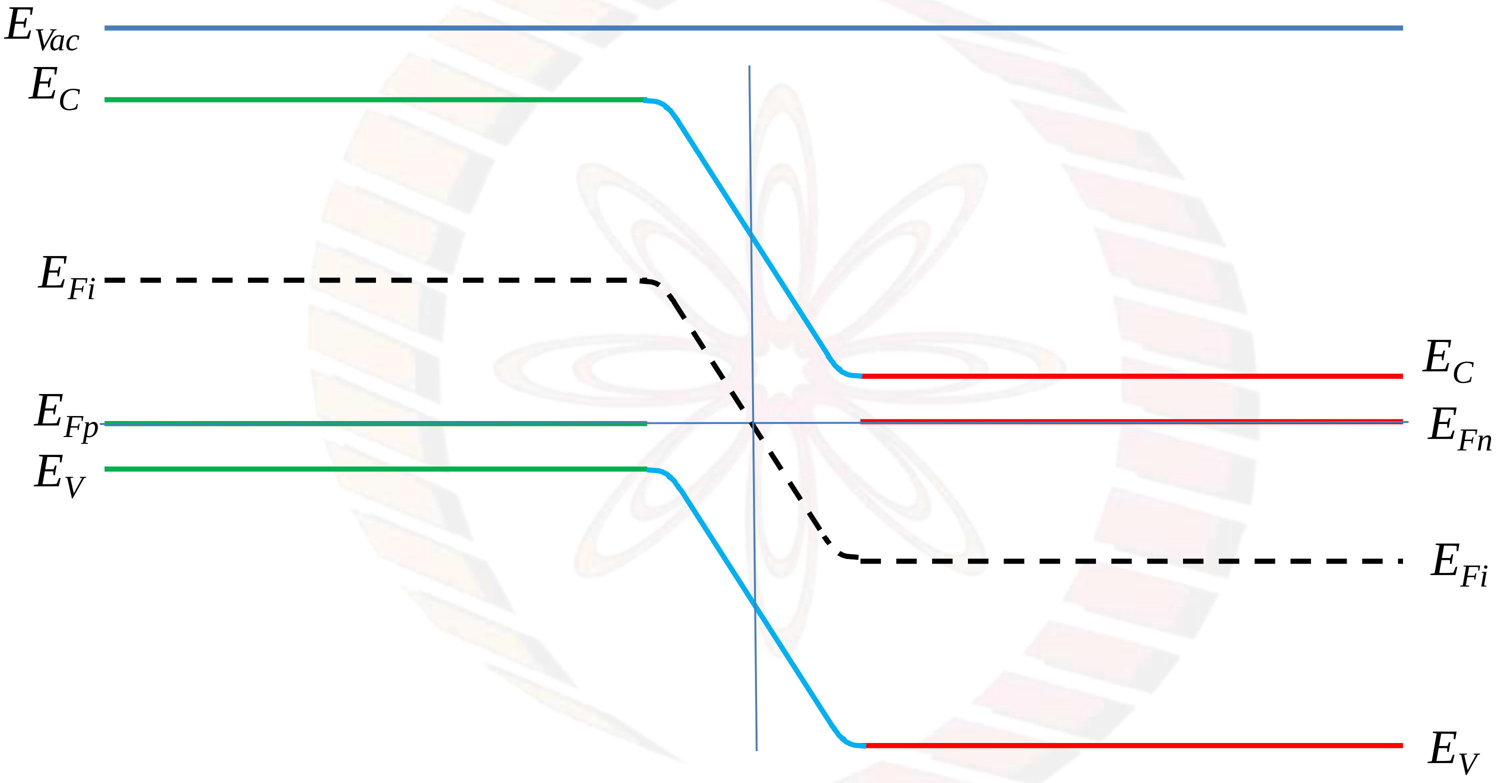




E_{Vac}
E_C
E_C
E_{Fn}
E_{Fi}
E_{Fi}
E_{Fp}
E_V
E_V
p- type
n- type

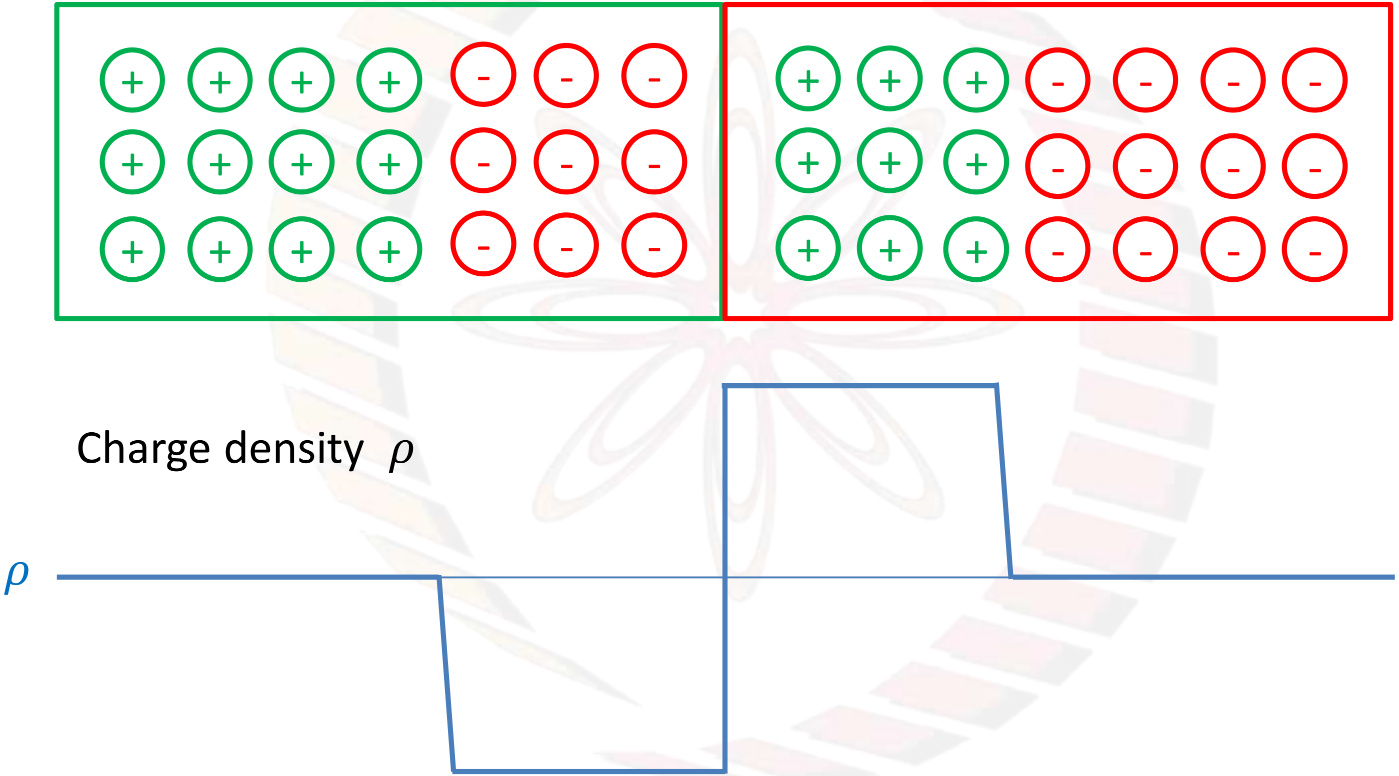


pn-junction

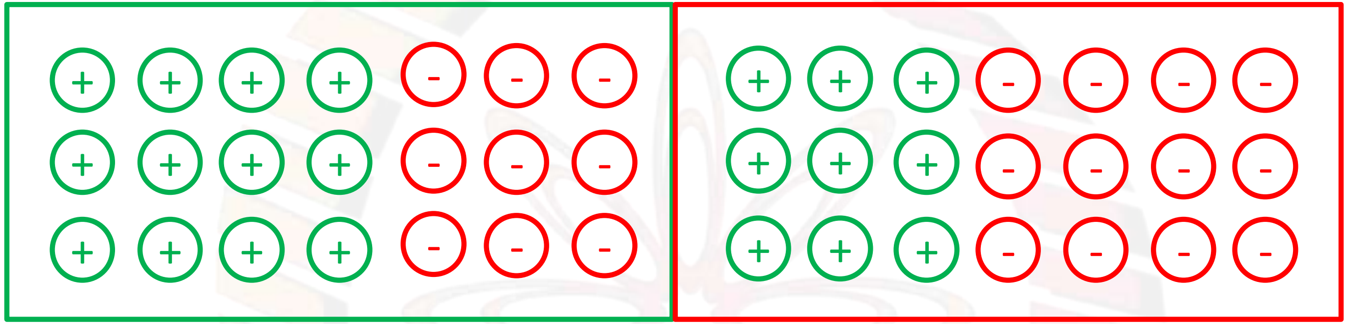


pn-junction

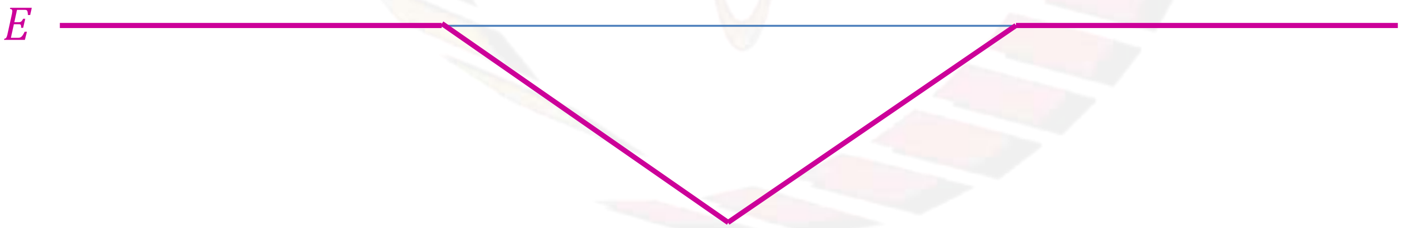
The space charge region



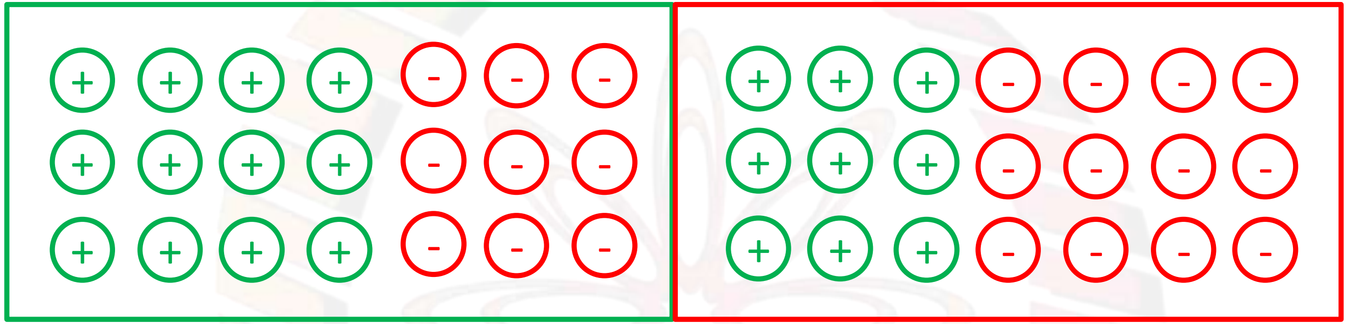
The space charge region



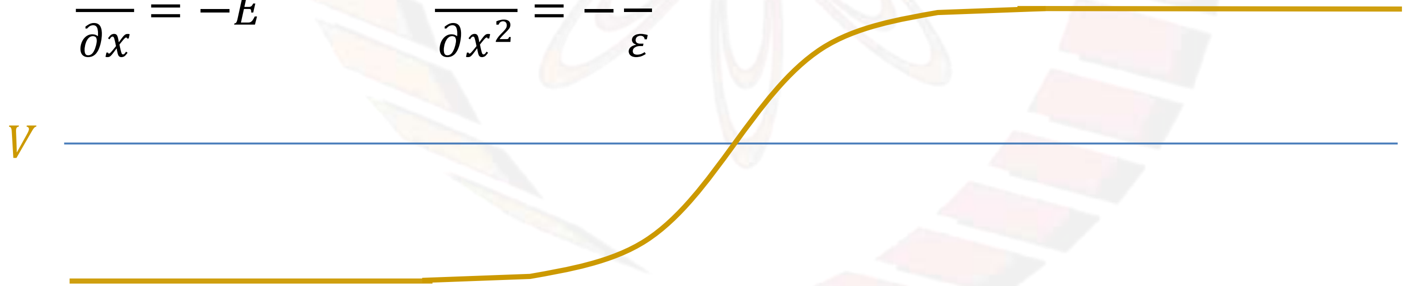
$$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$$

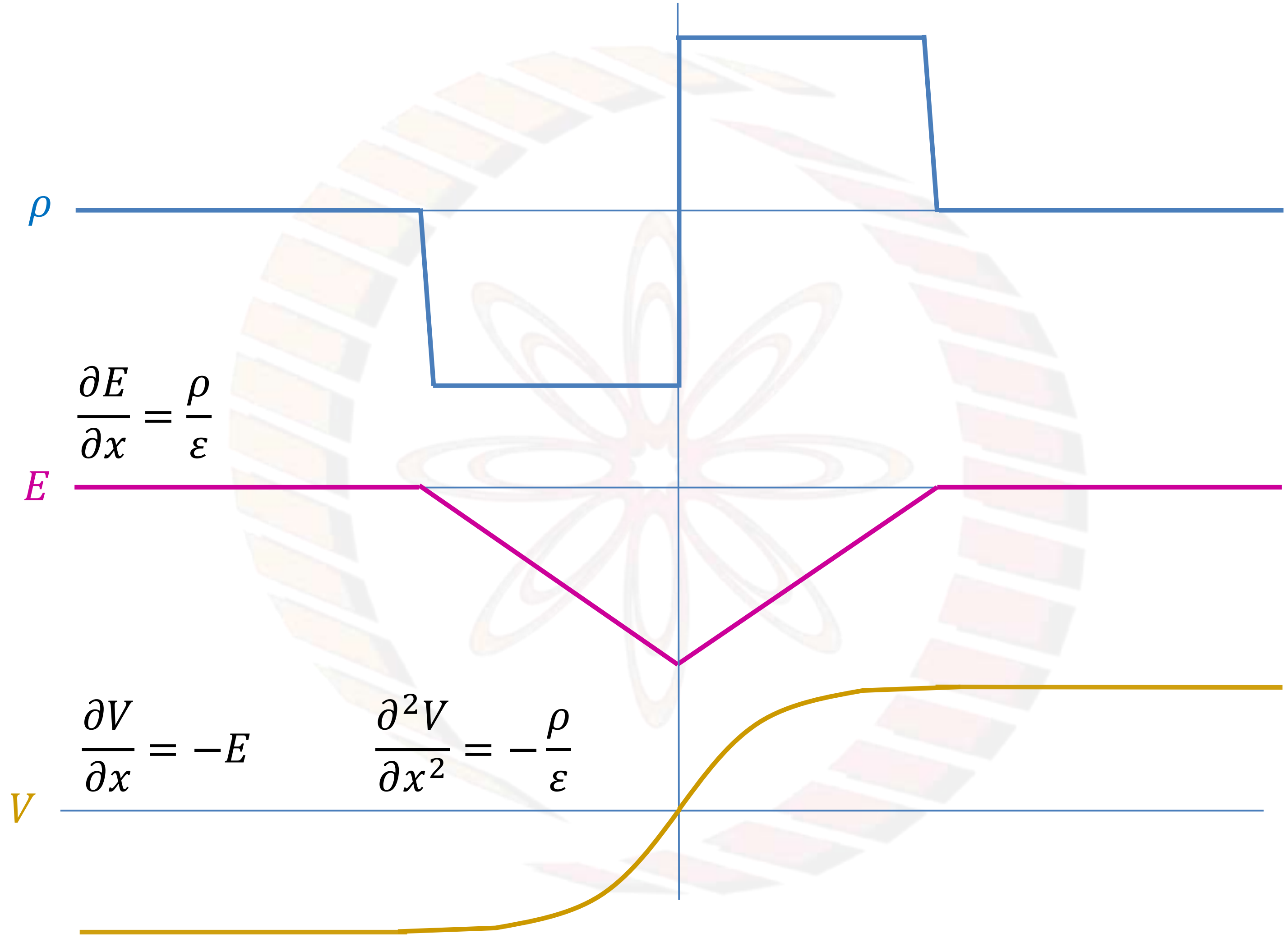


The space charge region

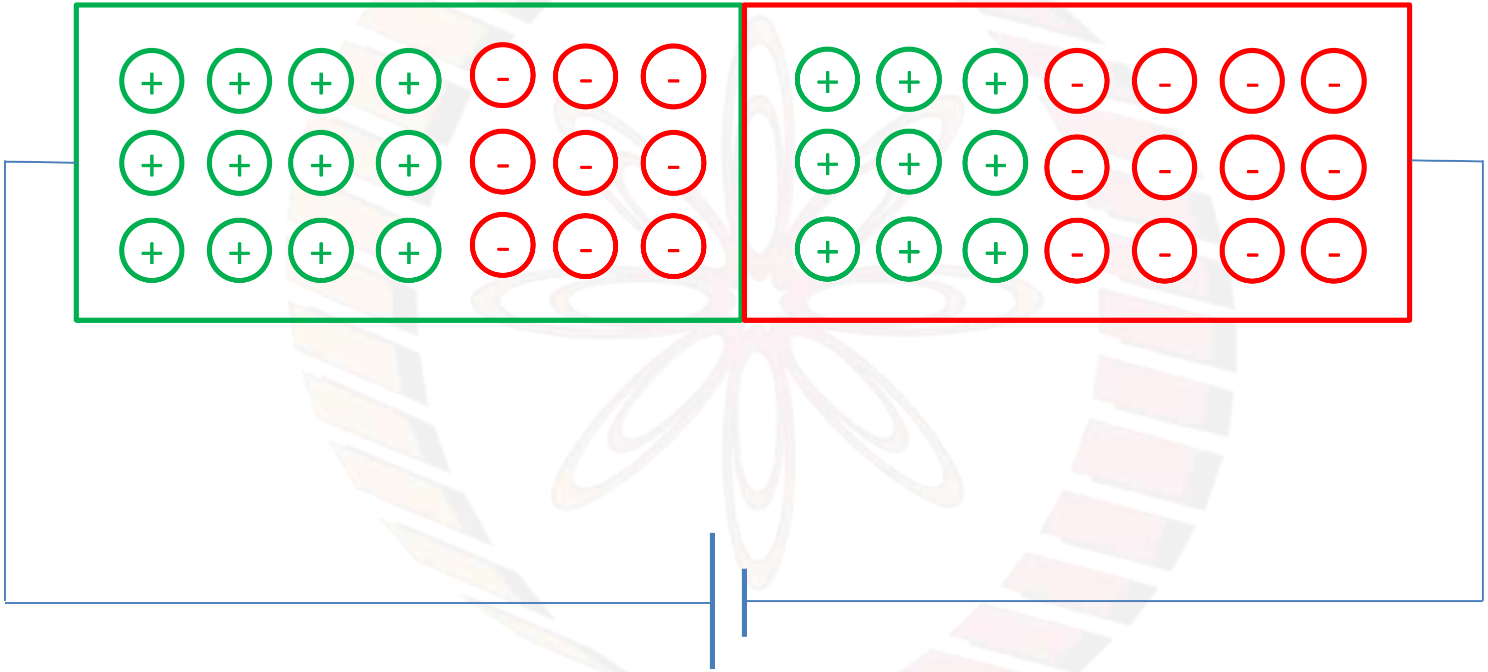


$$\frac{\partial V}{\partial x} = -E \qquad \frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon}$$

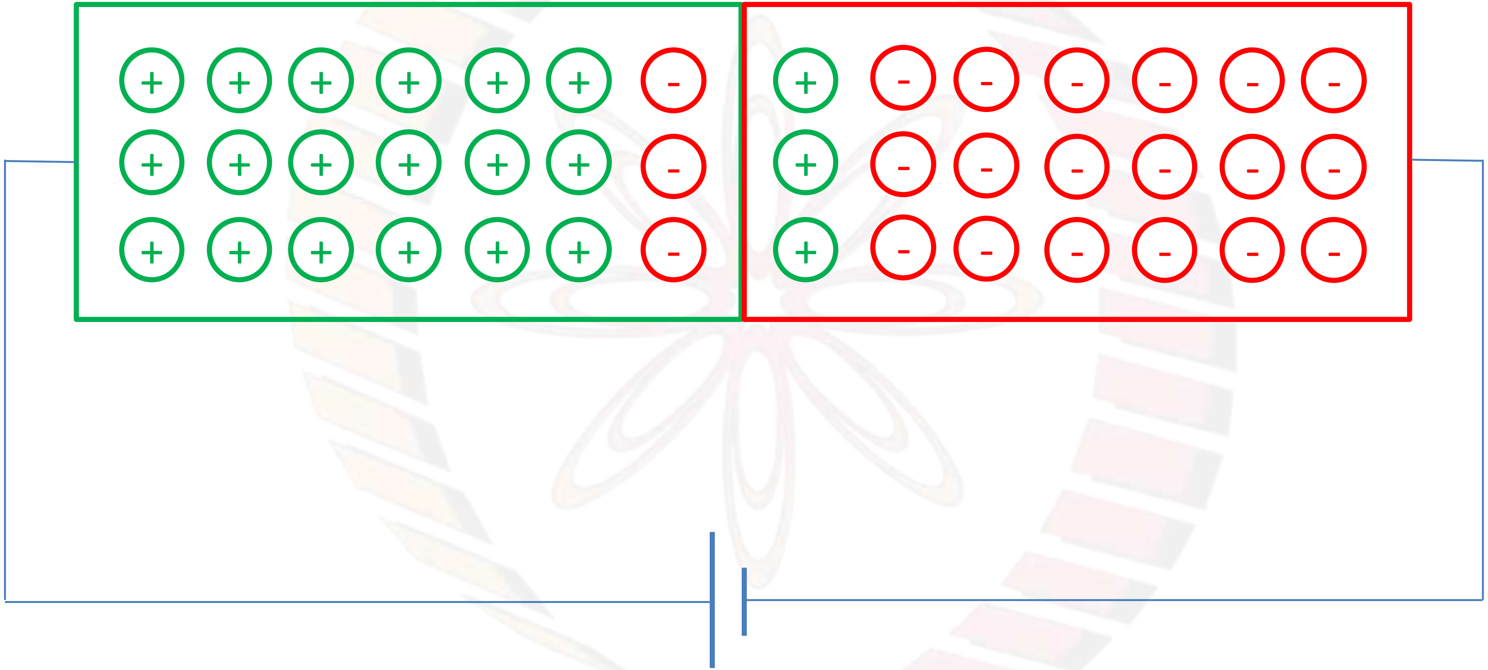



ρ
$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$
E
$\frac{\partial V}{\partial x} = -E$
$\frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon}$
V

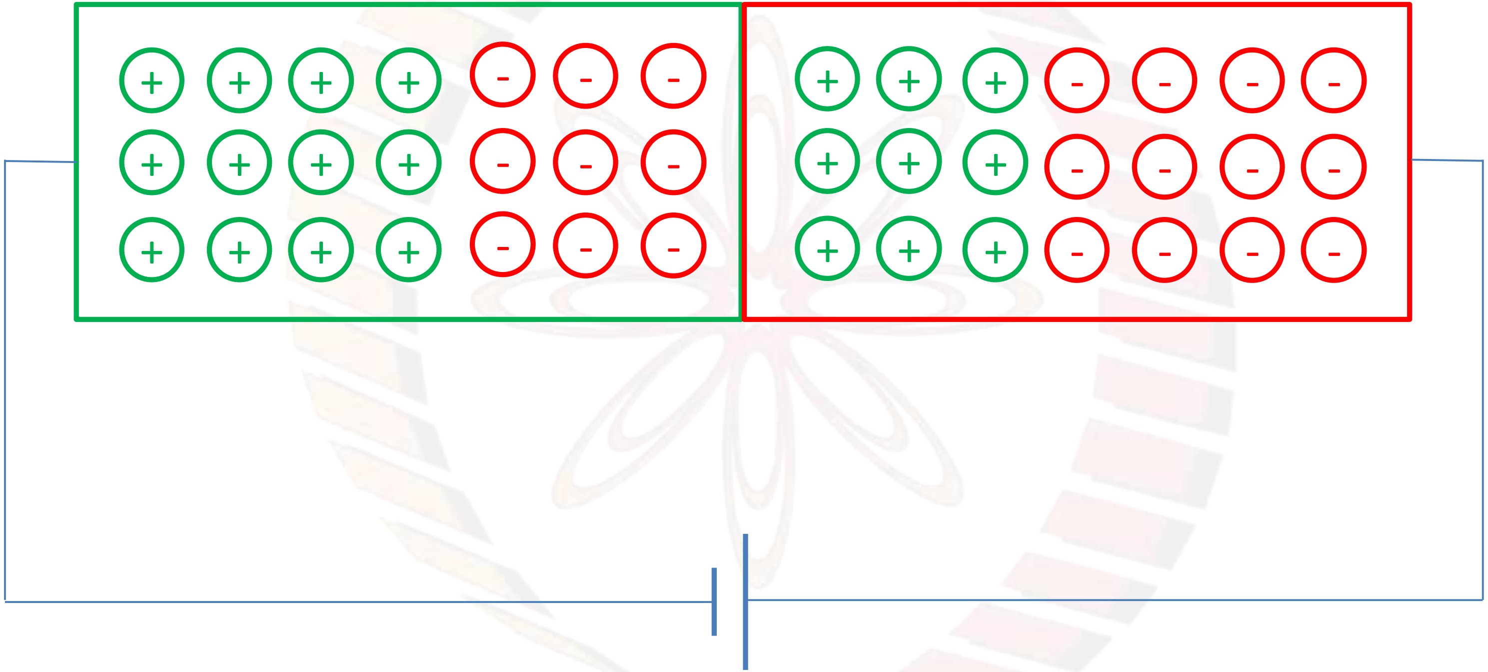
Forward bias



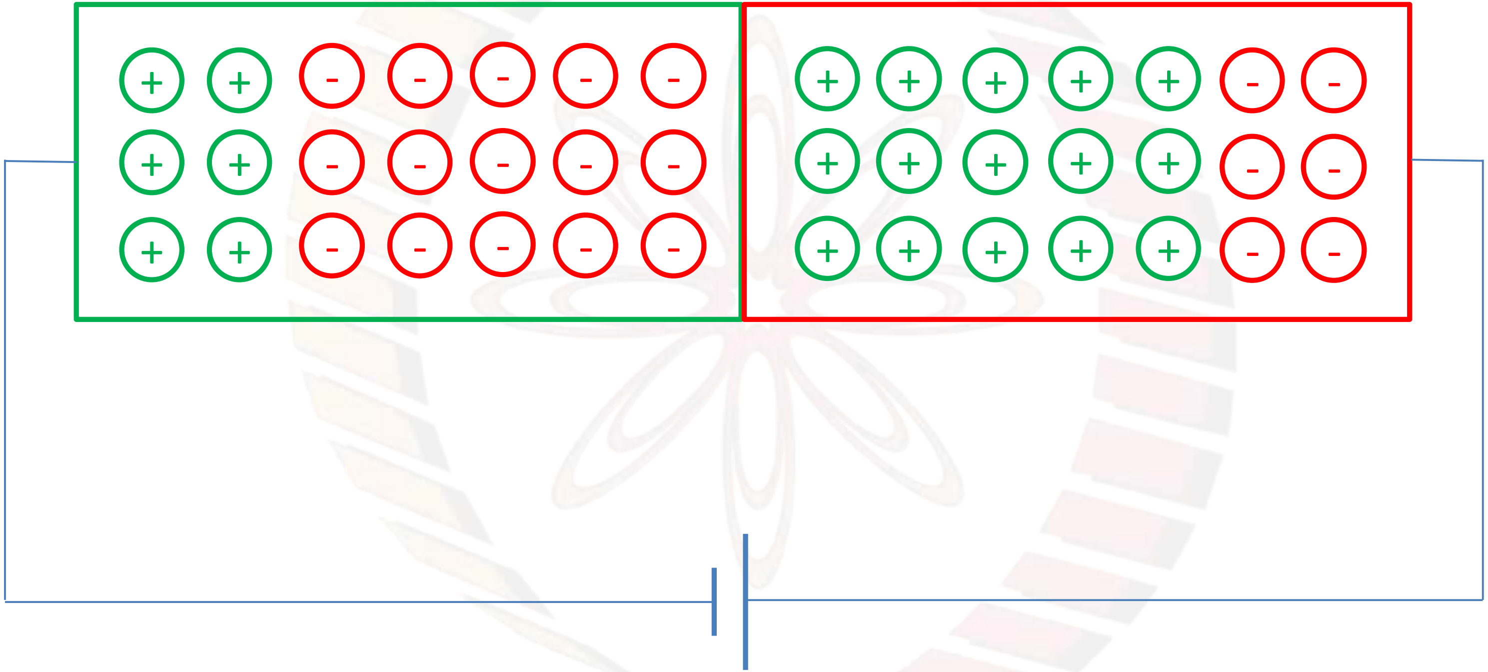
Forward bias



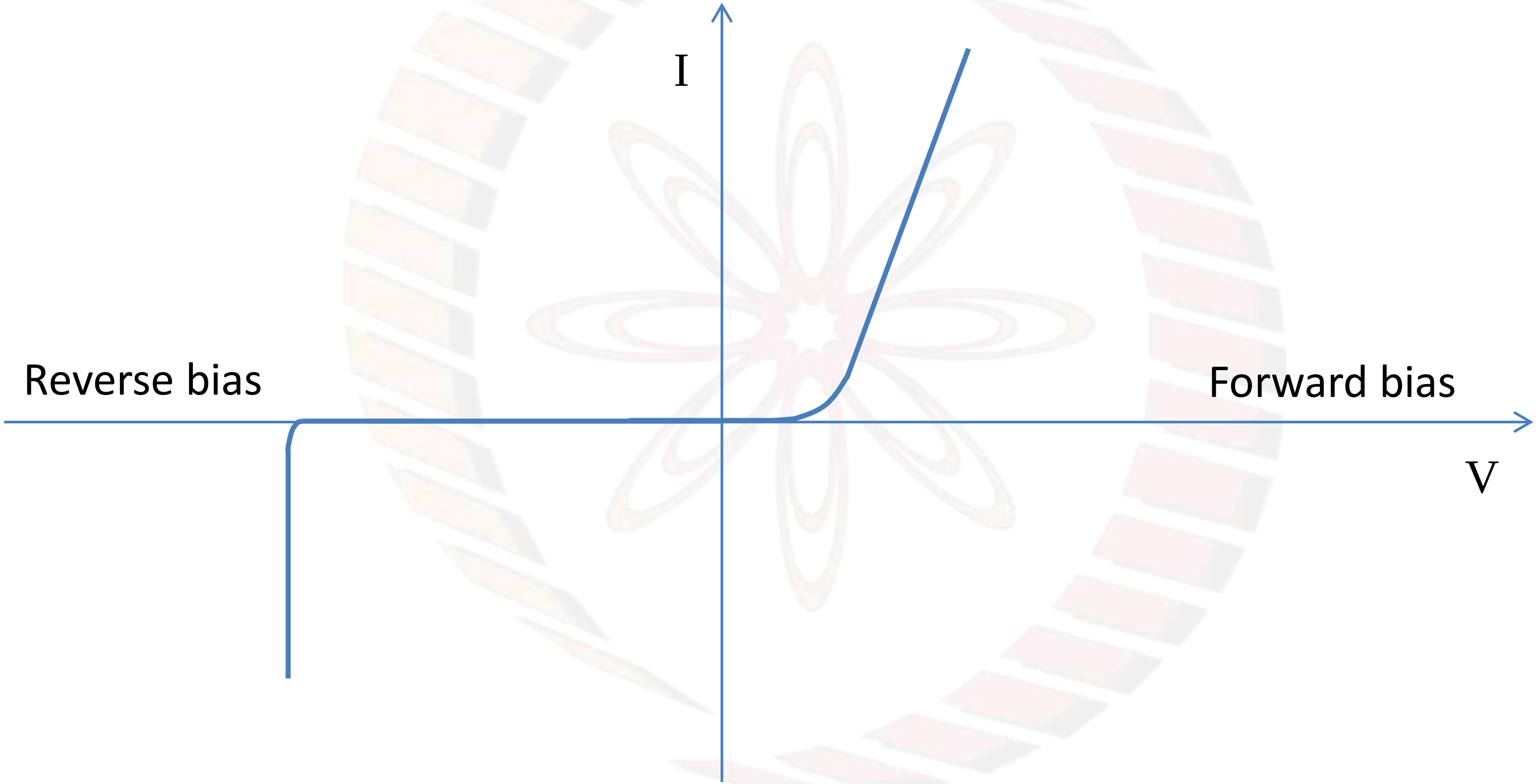
Reverse bias



Reverse bias



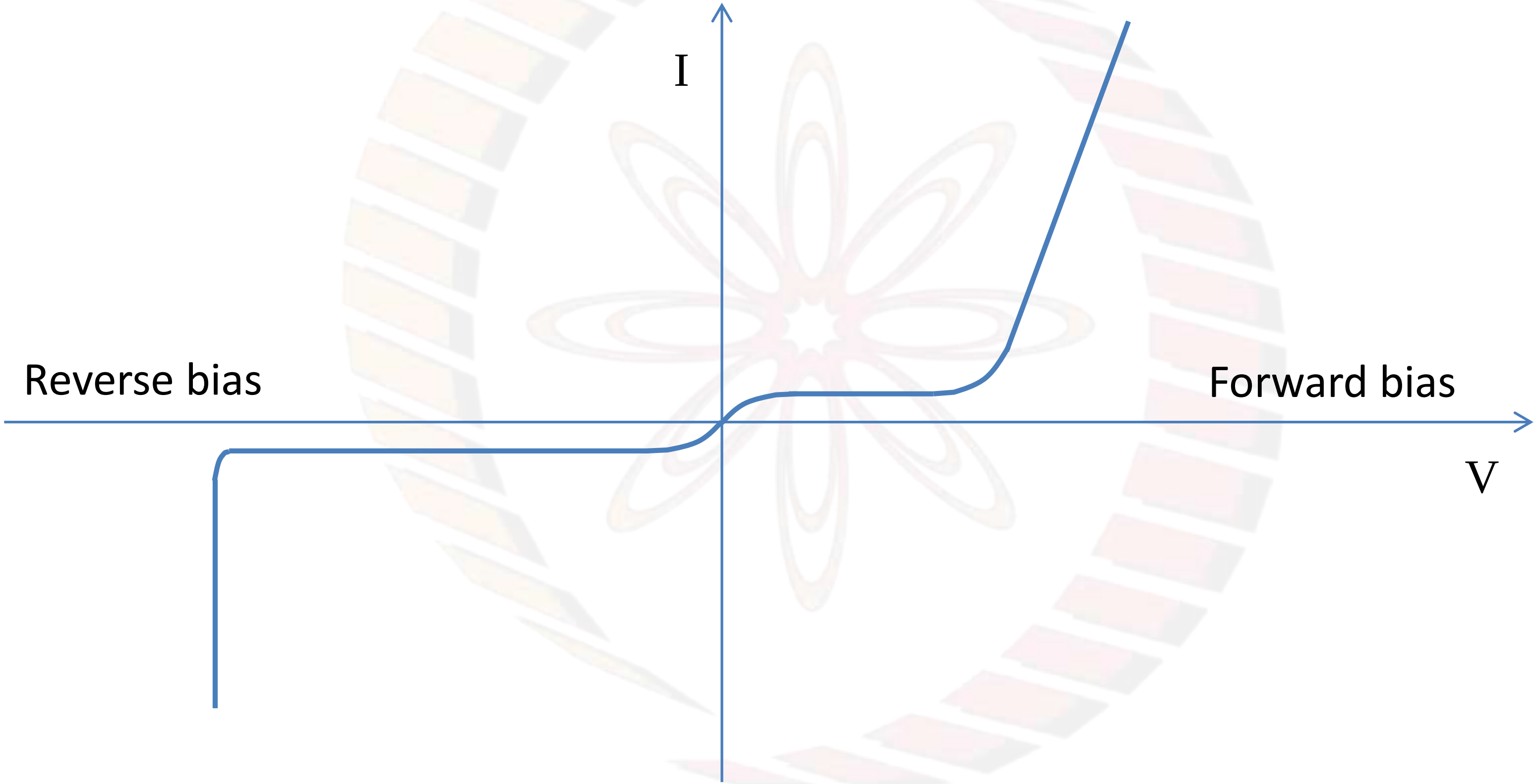
I-V characteristics



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



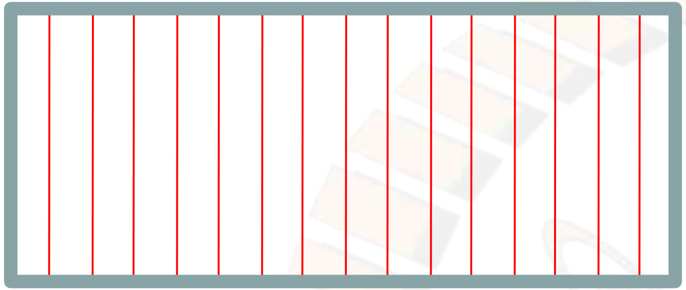
Solar Cell:
Growing the single crystal and making the p-n junction

Learning objectives:

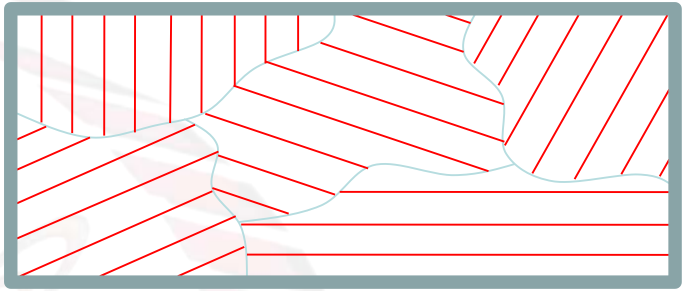
1) To become familiar with the techniques used to make single crystal as well as amorphous Si
2) To understand the method to manufacture the p-n junction

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

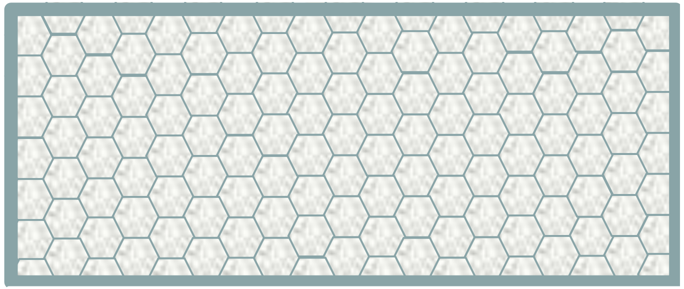
(a)



(b)



(c)



(d)

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

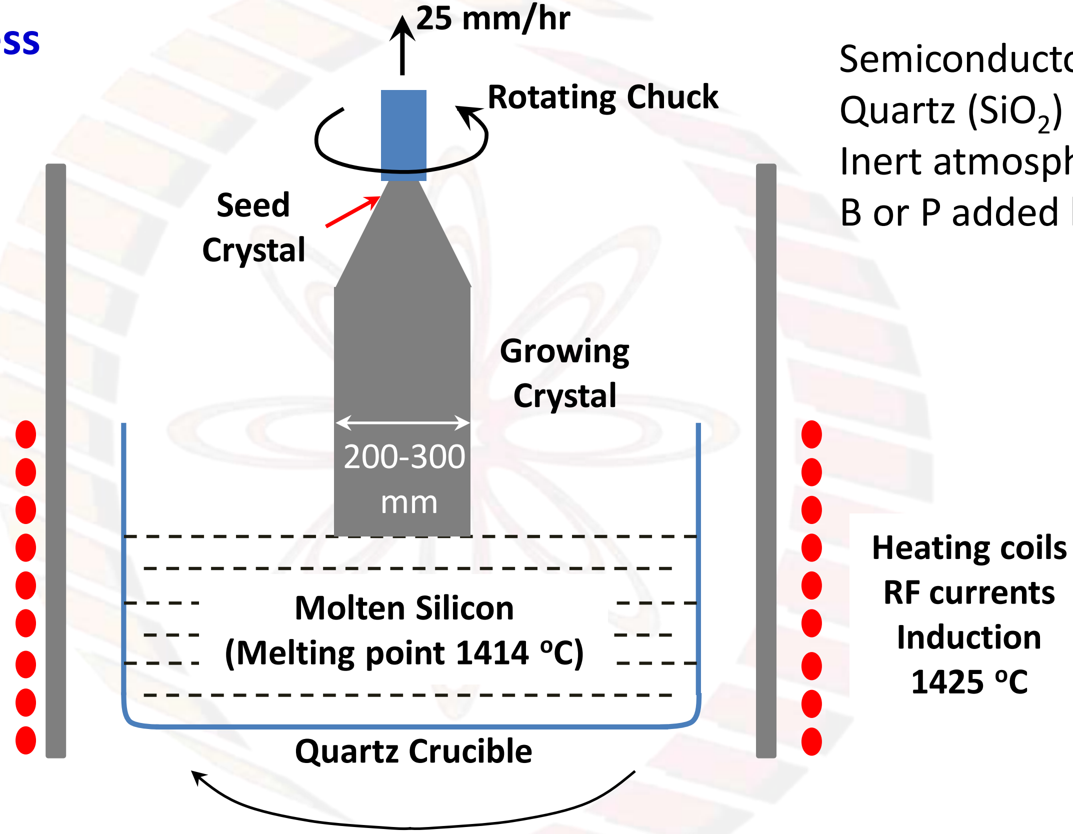
SiO_2 + Coke + Heat

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

$$Si\ (solid) + 3HCl \longrightarrow SiHCl_3\ (gas) + H_2$$

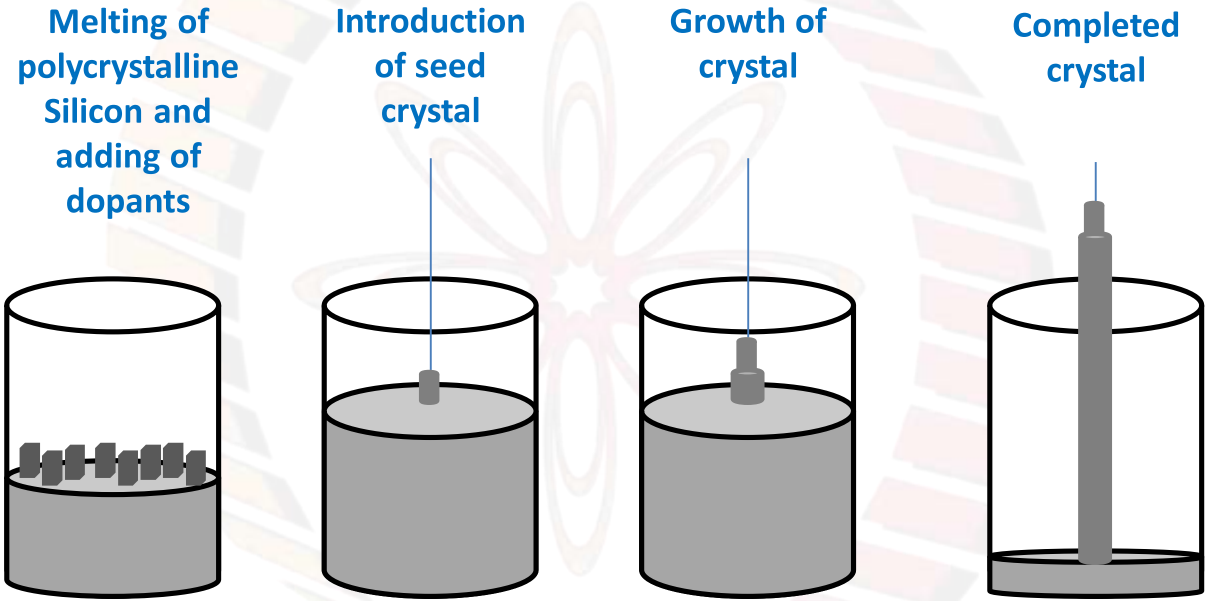
Si converted to Trichlorosilane, which is purified and reduced back to Si

Czochralski process



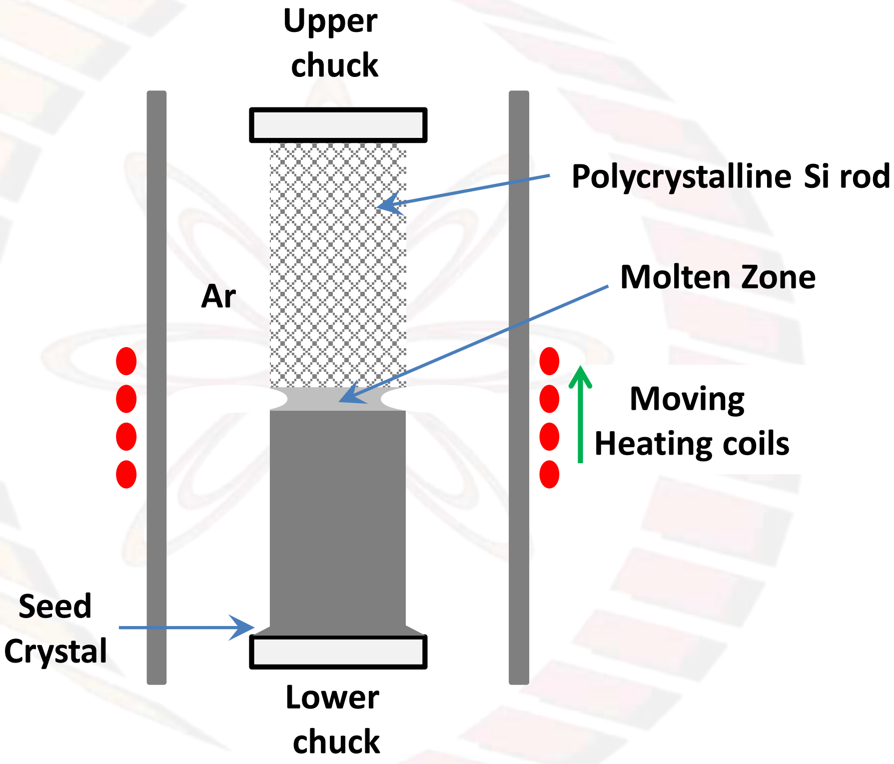
Semiconductor grade Silicon
Quartz (SiO_2) crucible (1670 °C)
Inert atmosphere of Ar
B or P added before melting

Czochralski process

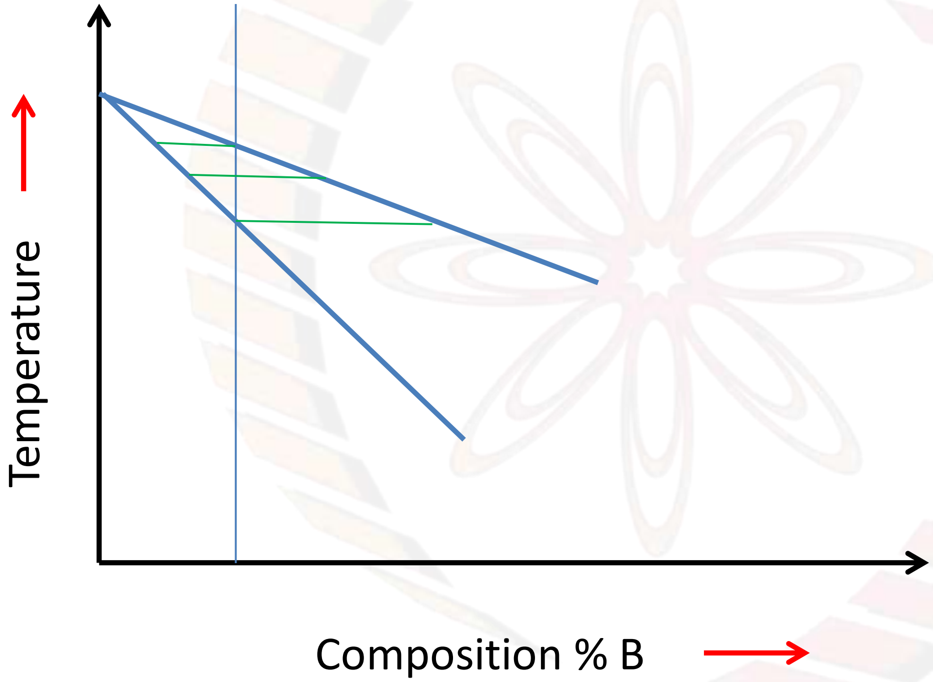


Float zone process

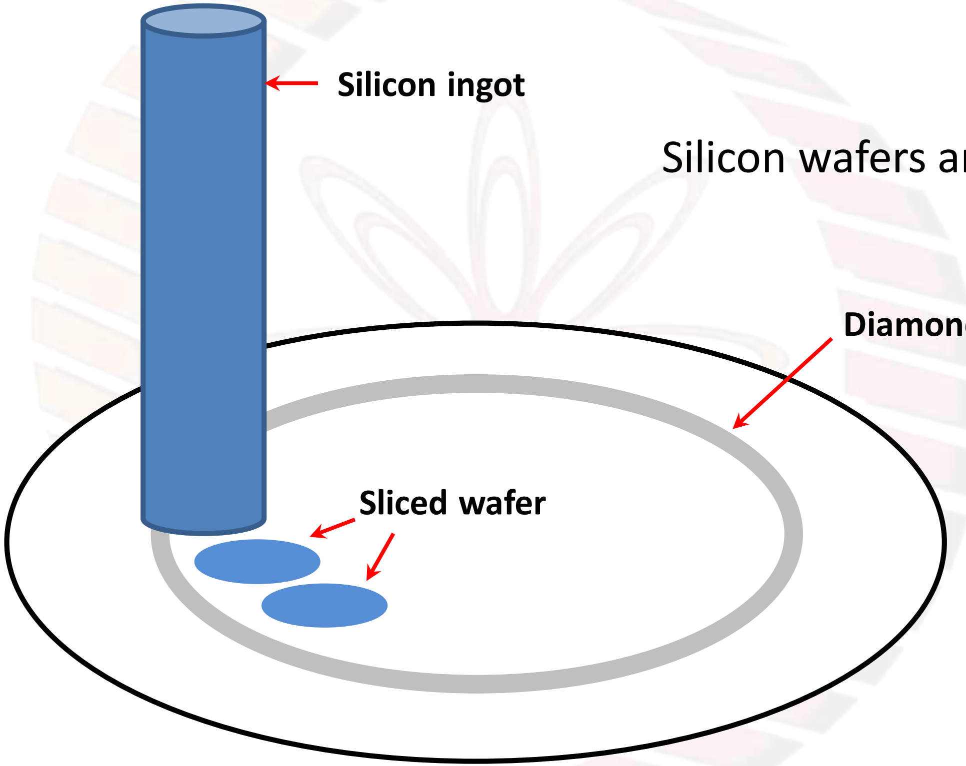
- Smaller diameter (150mm) due to surface tension
- Higher purity



Zone refining



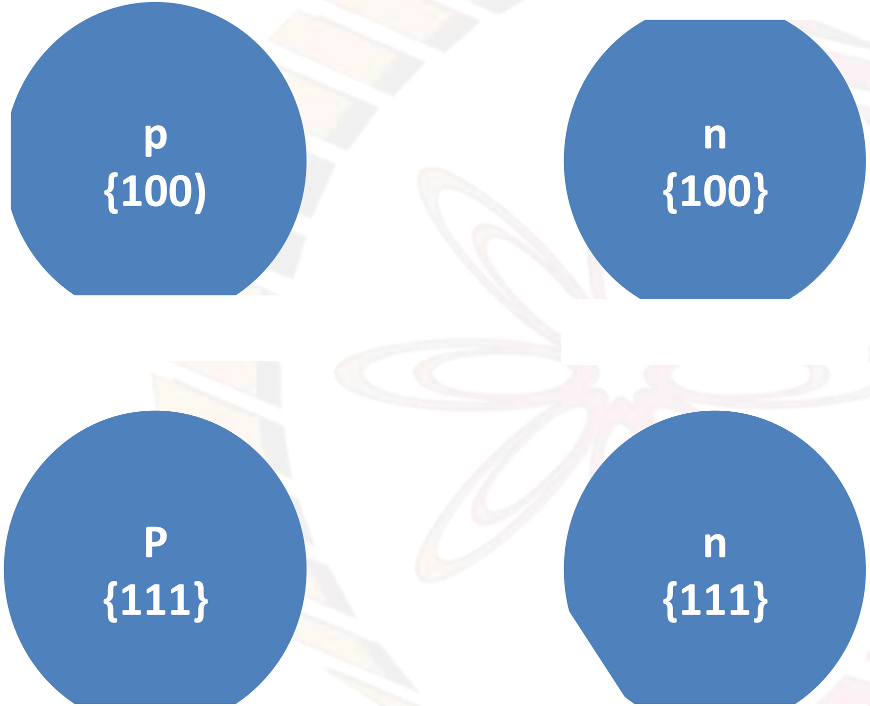
Inner diameter slicing of Si ingot



Silicon wafers are 0.2 to 0.75 mm thick

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:

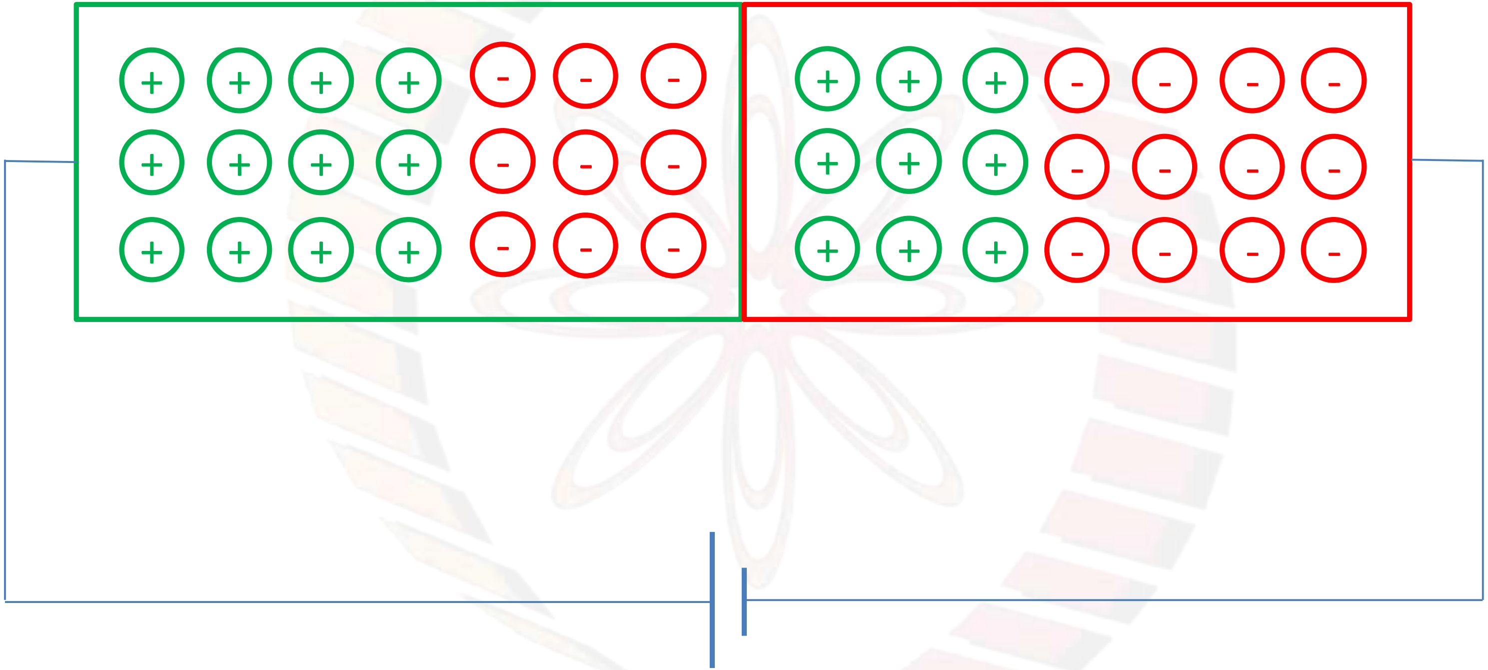
1) It is quite challenging to produce single crystal Si
2) Multiple process steps involved
3) Purity and dimensions can have significant impact on costs
4) Amorphous Si is an option

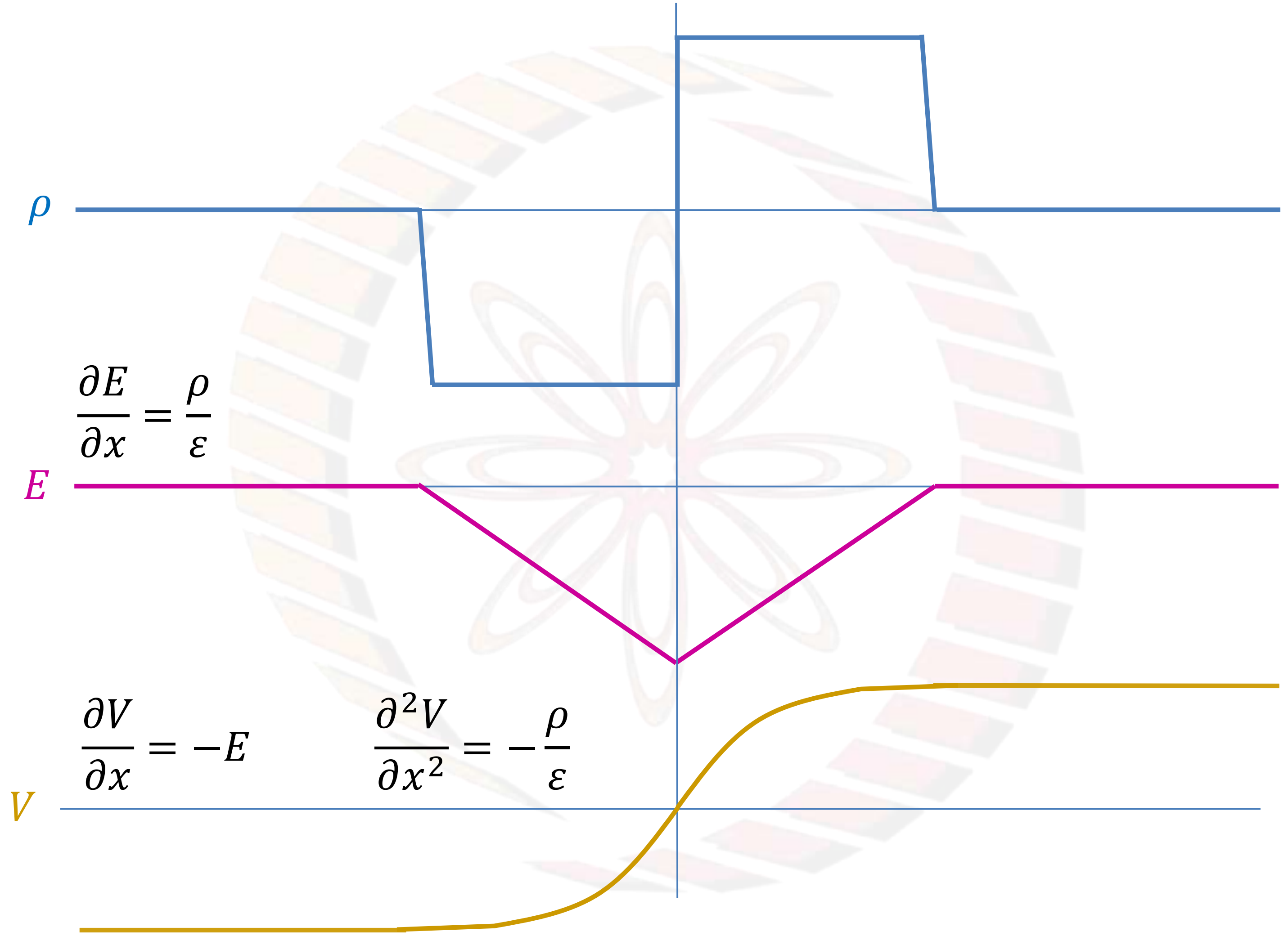
Solar Energy: Interaction of p-n junction with radiation

Learning objectives:

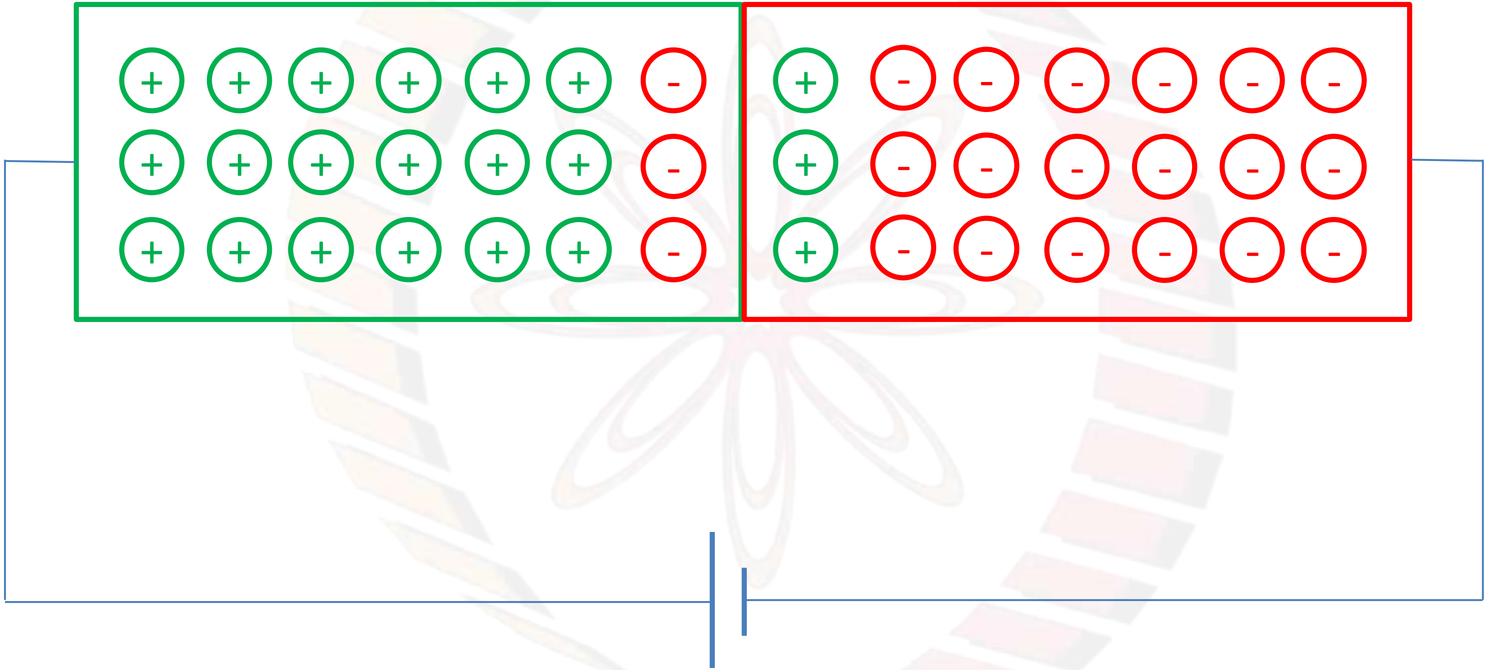
1) To describe the interaction of a p-n junction with radiation
2) To explain the functioning of the p-n junction solar cell

Forward bias

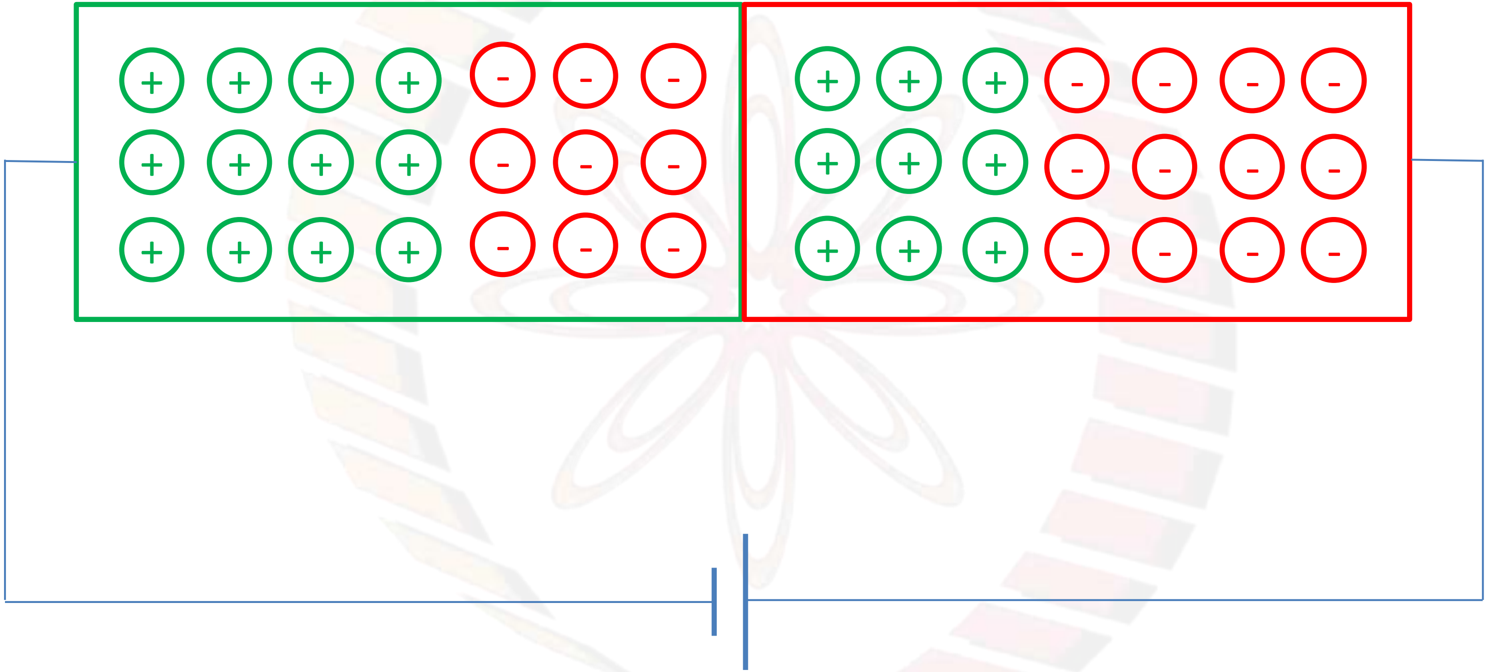



ρ
$\frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon}$
E
$\frac{\partial V}{\partial x} = -E$
$\frac{\partial^2 V}{\partial x^2} = -\frac{\rho}{\varepsilon}$
V

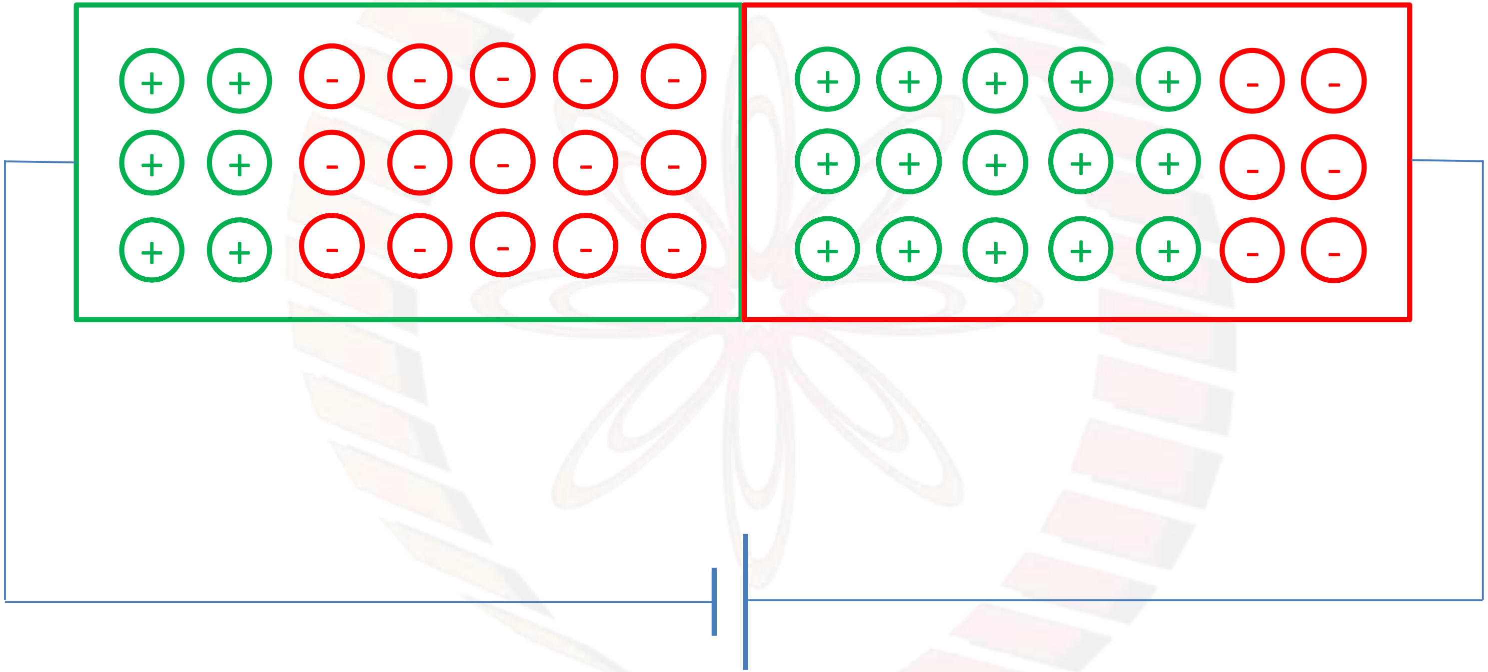
Forward bias



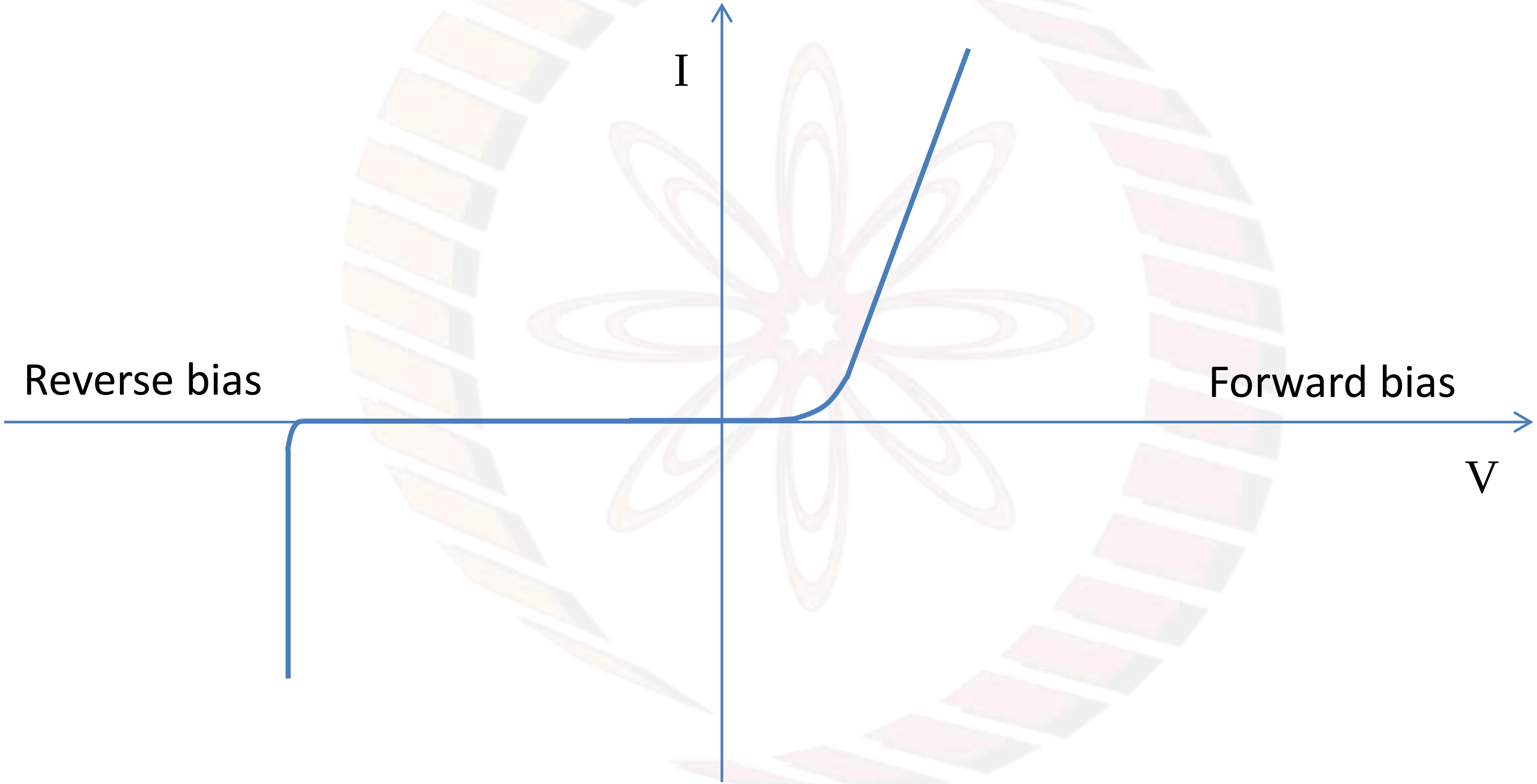
Reverse bias

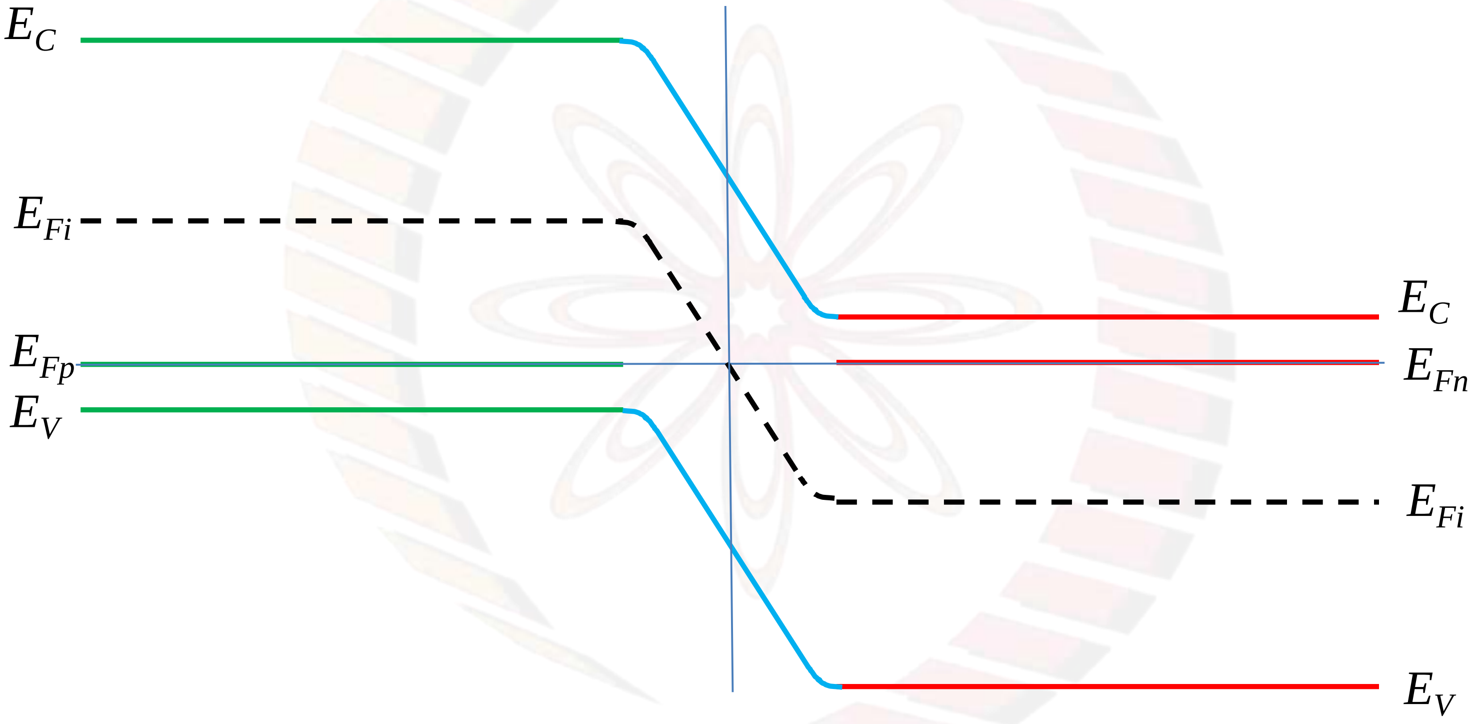


Reverse bias

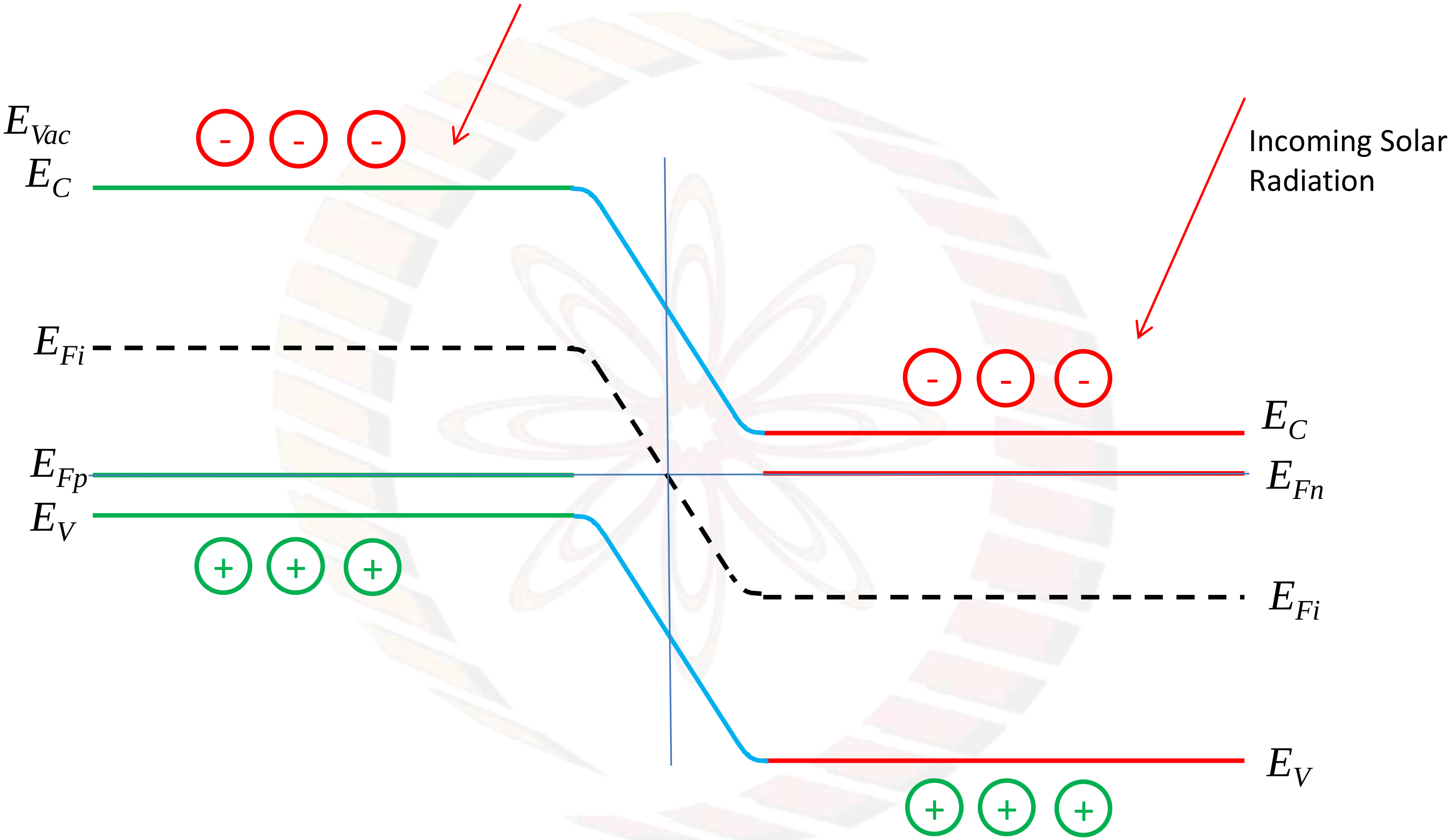


I-V characteristics

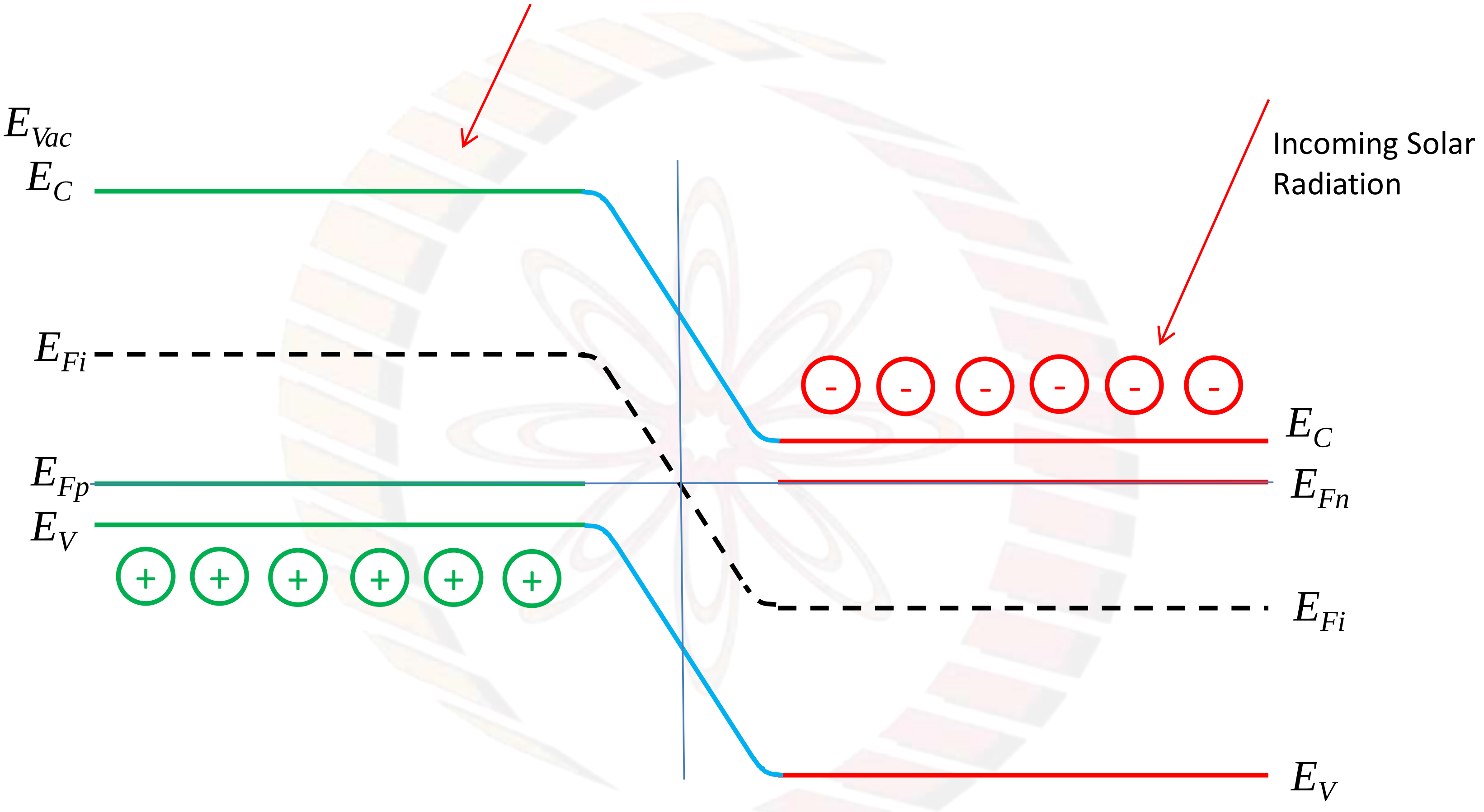




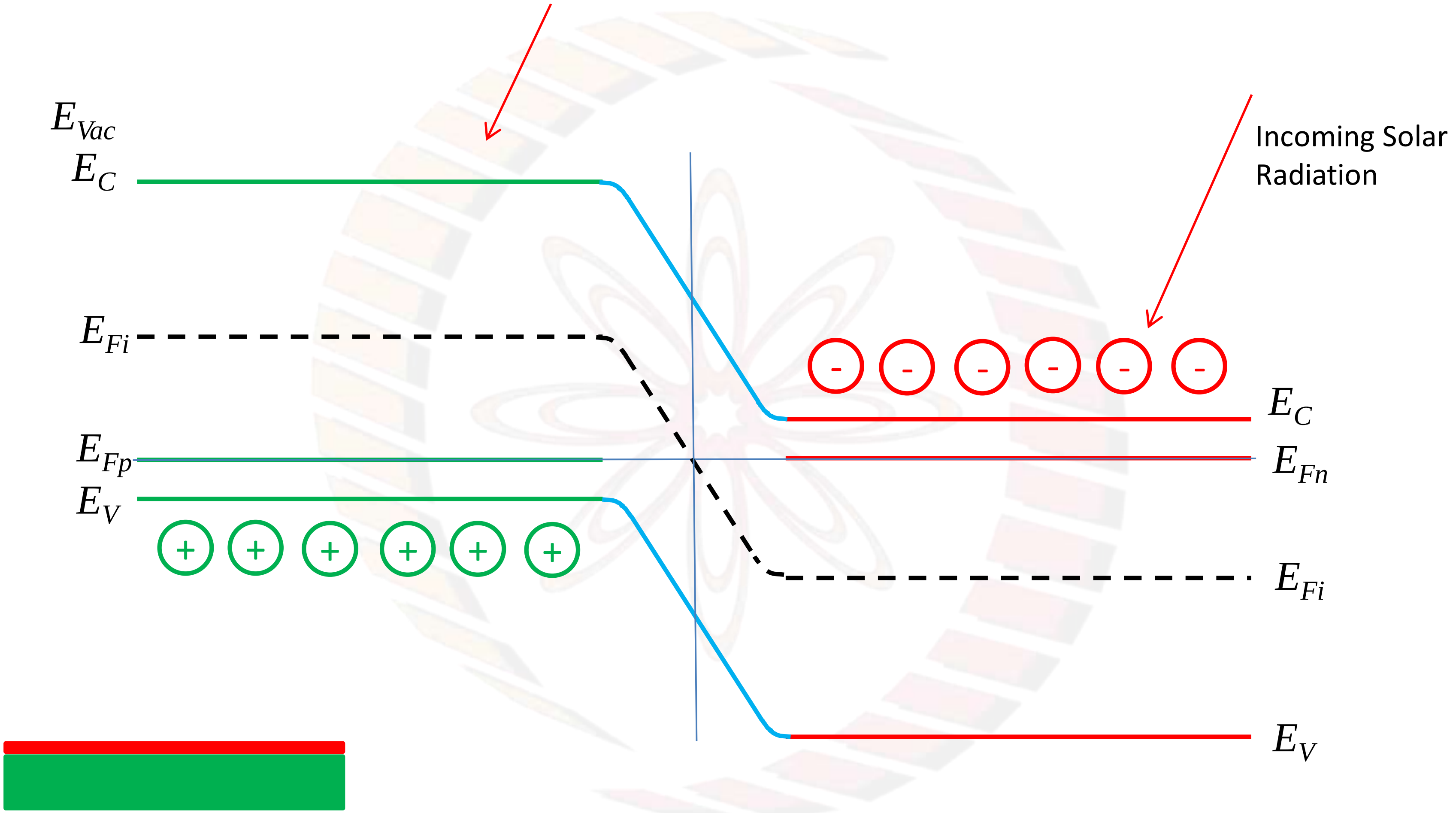
pn-junction



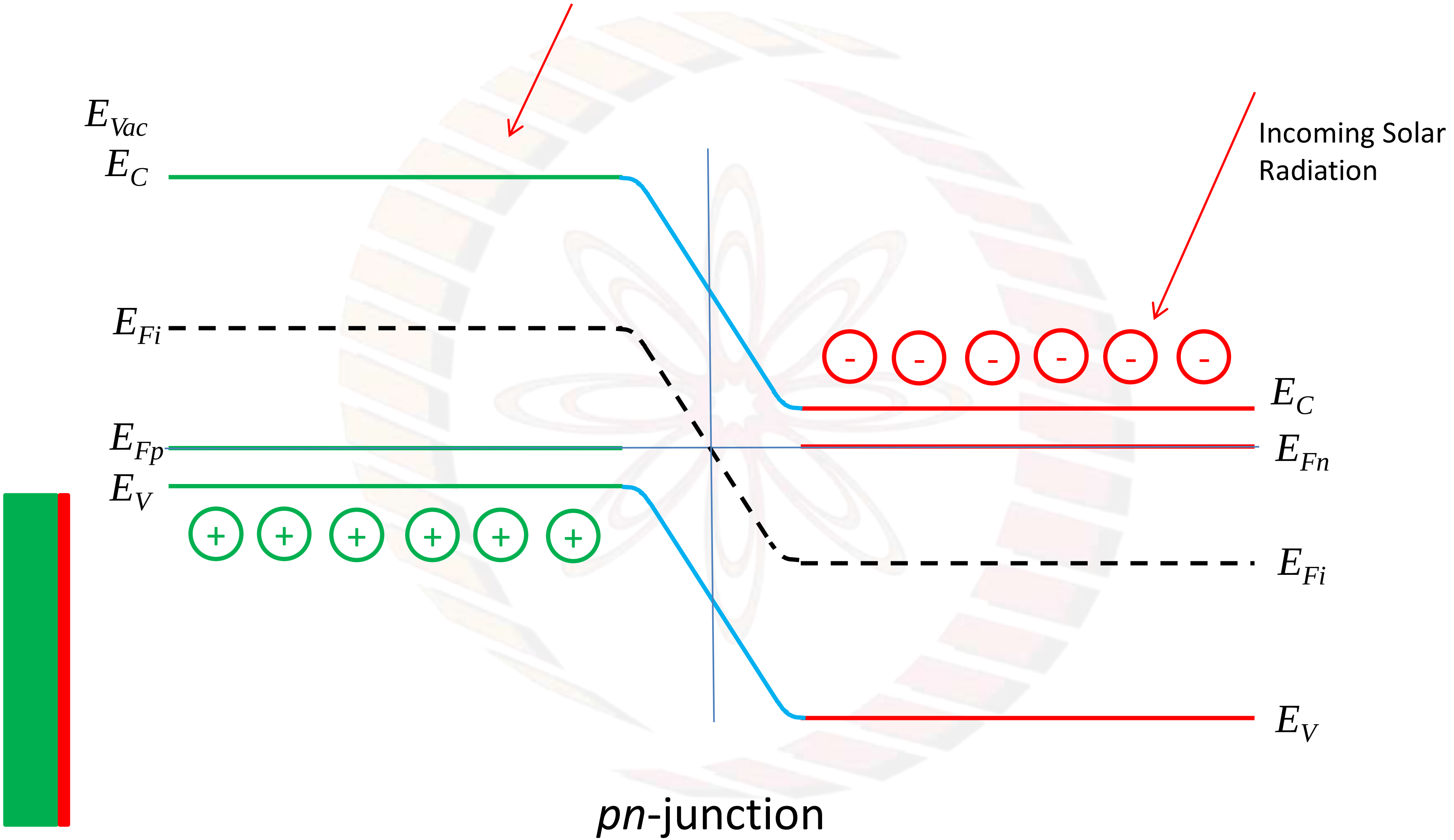
pn-junction



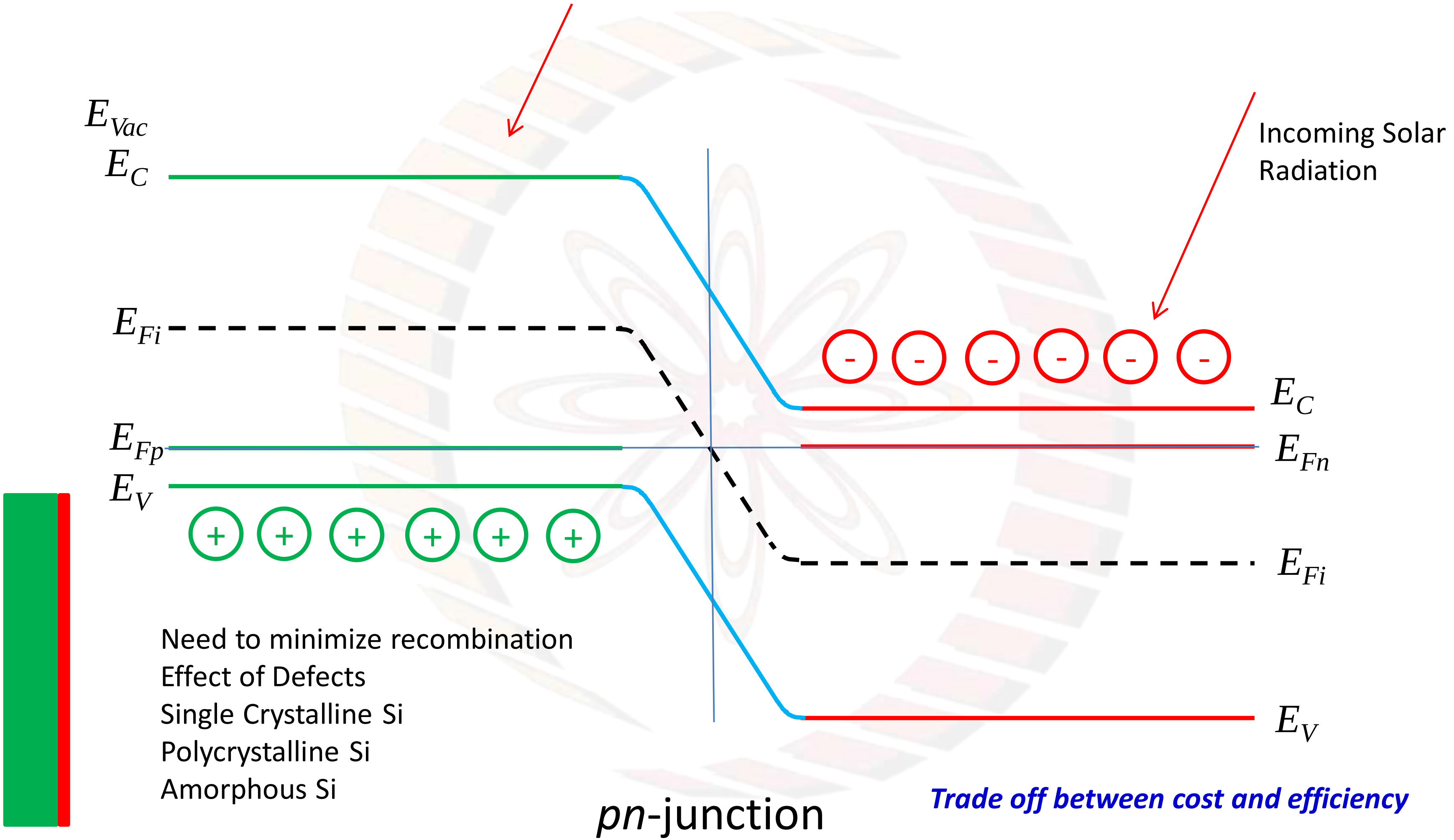
pn-junction



pn-junction



pn-junction



Need to minimize recombination
Effect of Defects
Single Crystalline Si
Polycrystalline Si
Amorphous Si

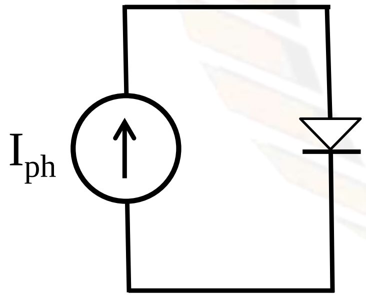
pn-junction

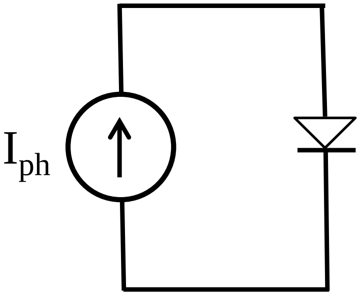
Trade off between cost and efficiency

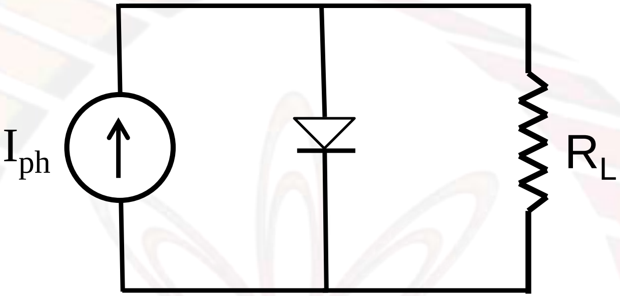
Solar Cell is a current source

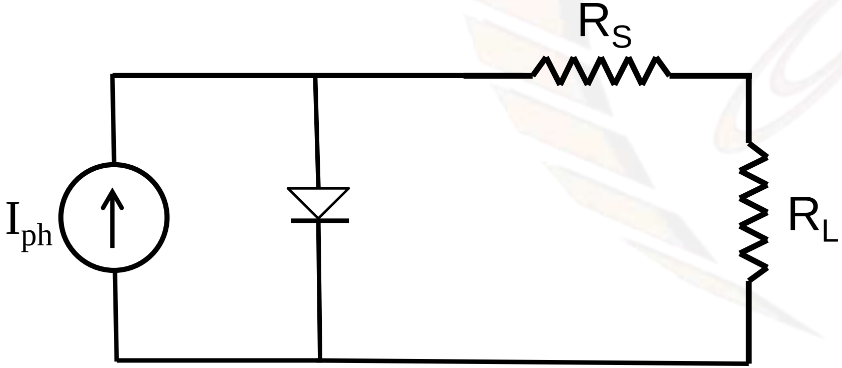
Charge carriers created by sunlight received: Photocurrent I_{ph}

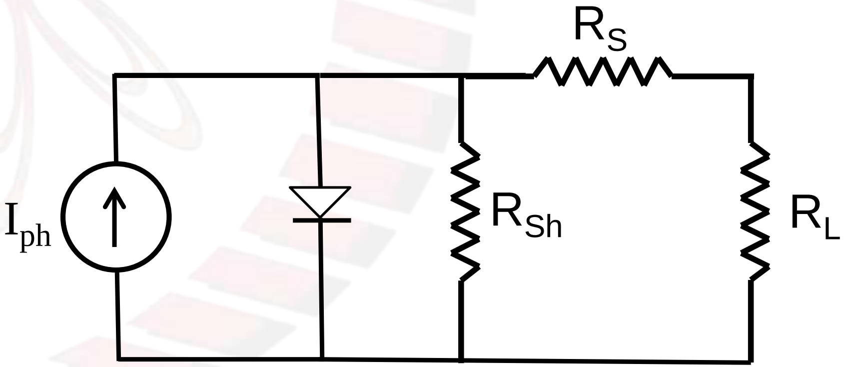
Without external load, the pn junction is forward biased, and internally shorts




I_{ph}


I_{ph}
R_L


R_S
I_{ph}
R_L


R_S
I_{ph}
R_{Sh}
R_L

Conclusions:

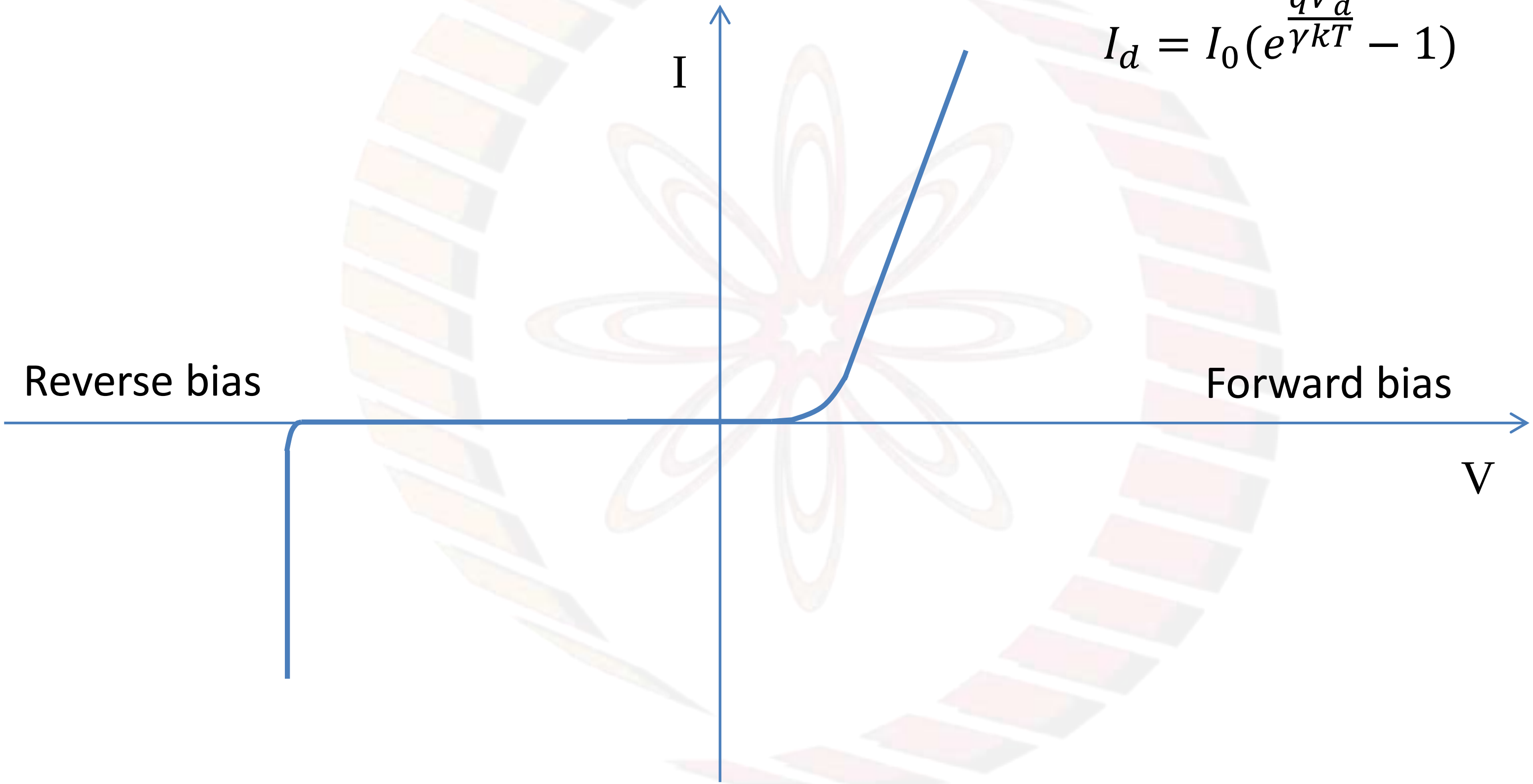
1) The p-n junction stabilizes the electron-hole pair
2) The p-n junction solar cell is a current source and has to be used accordingly

Solar Energy:
Solar cell characteristics and usage

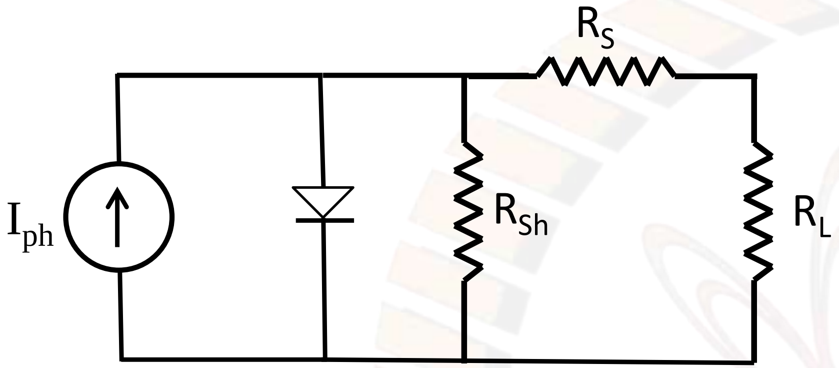
Learning objectives:

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



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



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

(Assuming recombination current is low)

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

$$V_d = V_L + I_L R_S$$

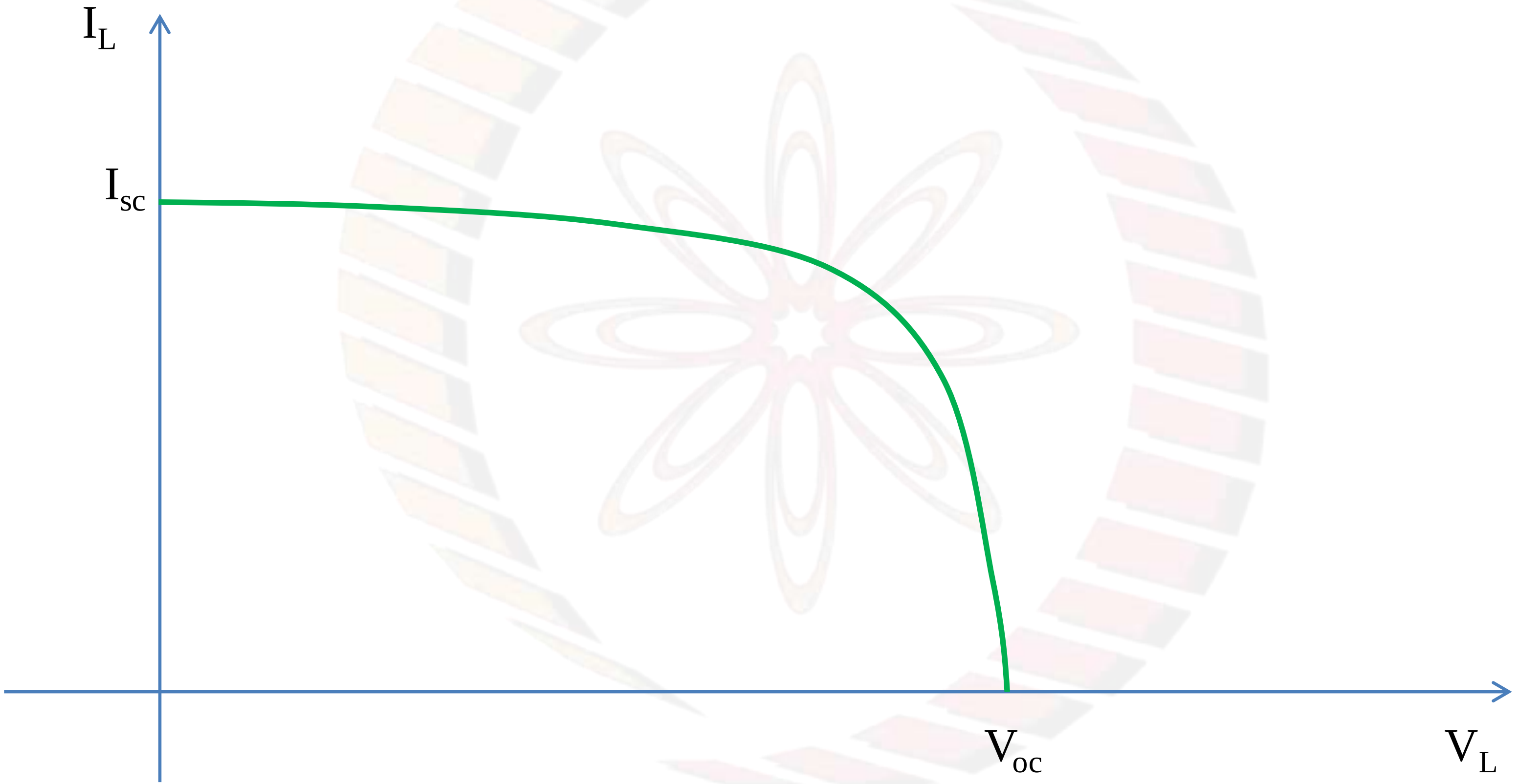
$$V_L = \frac{\gamma kT}{q} \ln\left\{\frac{I_{ph} - I_L}{I_0} + 1\right\} - I_L R_S$$

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

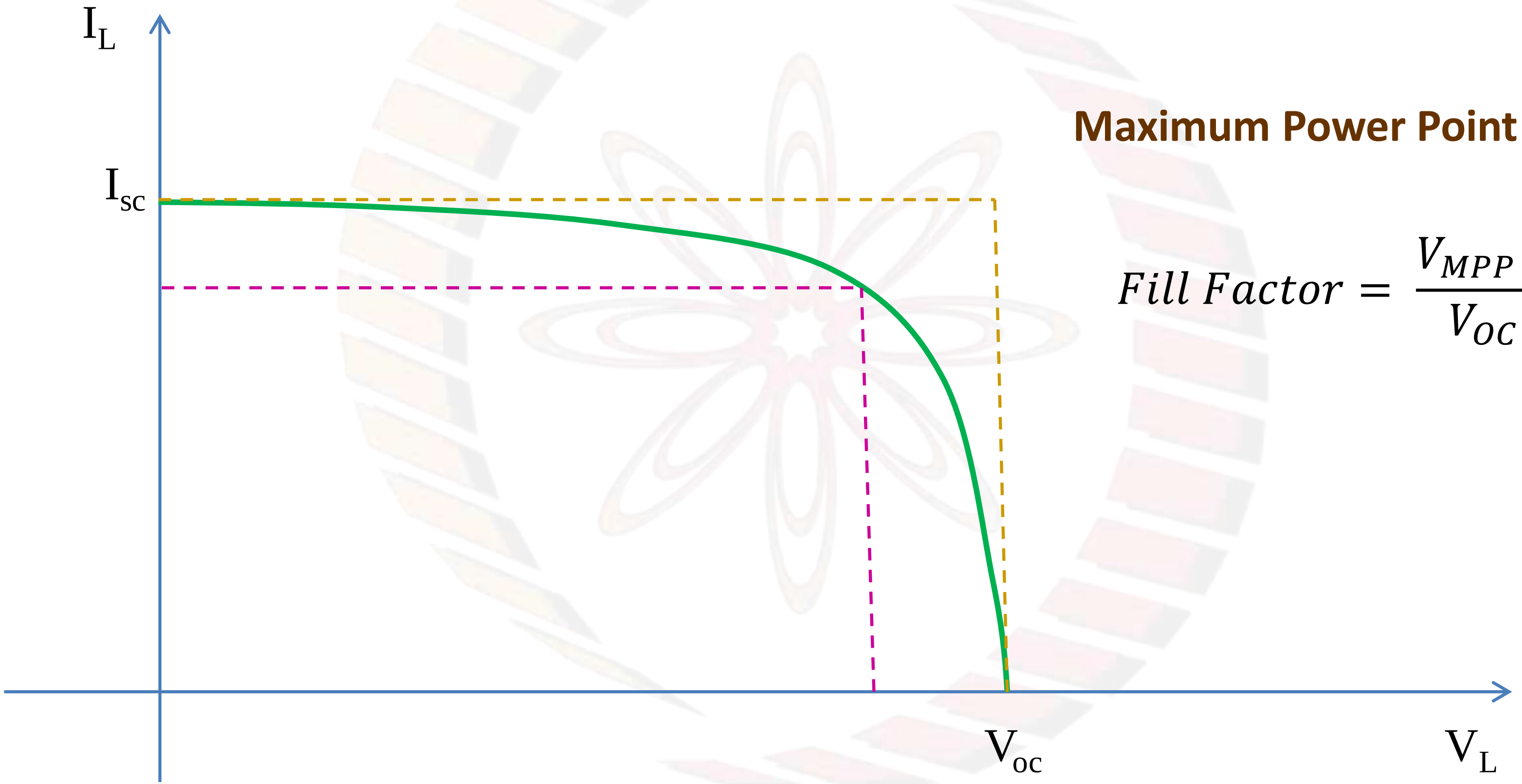
$$I_{ph} - I_d - I_{Sh} = I_L$$

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

I-V characteristics



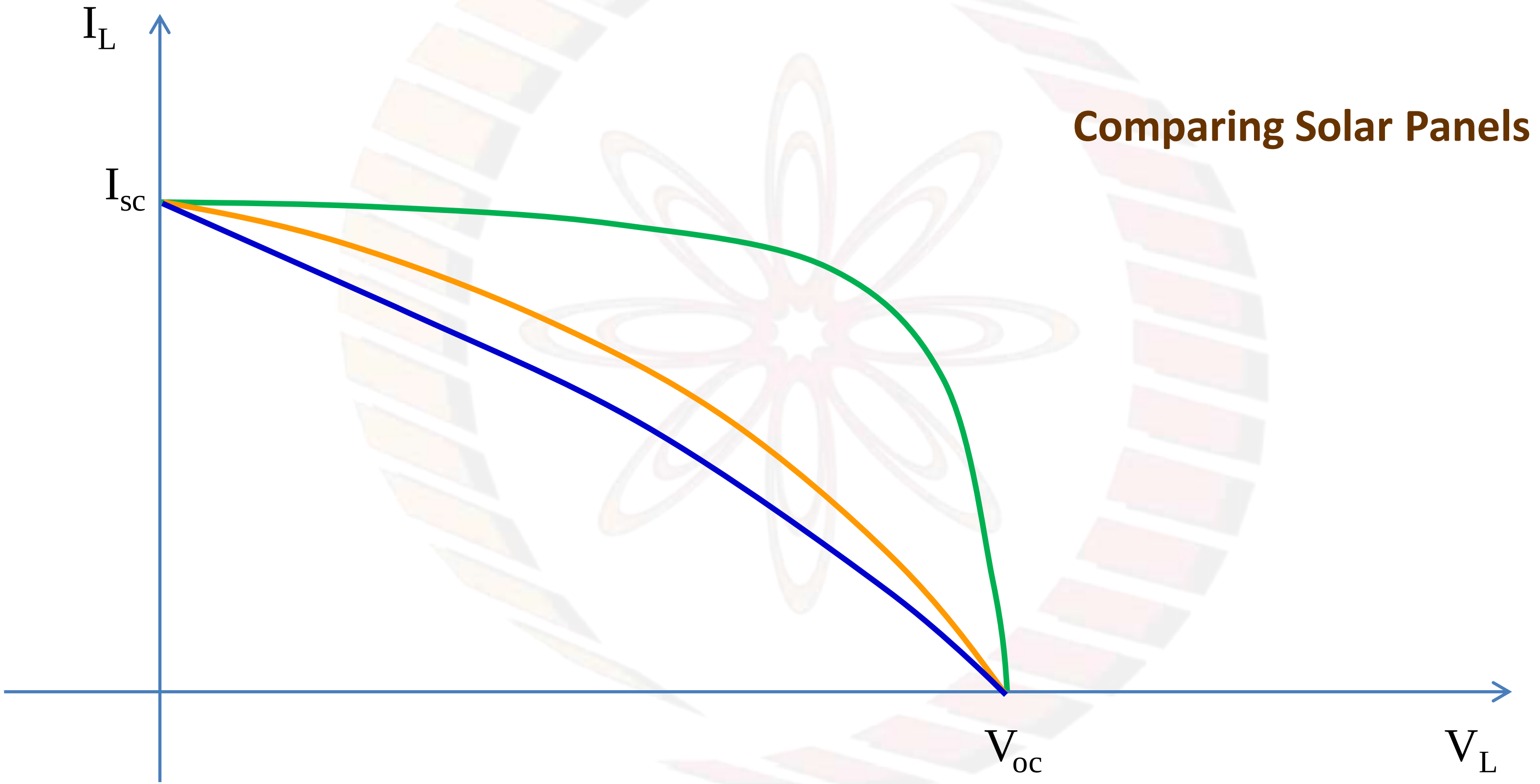
I-V characteristics



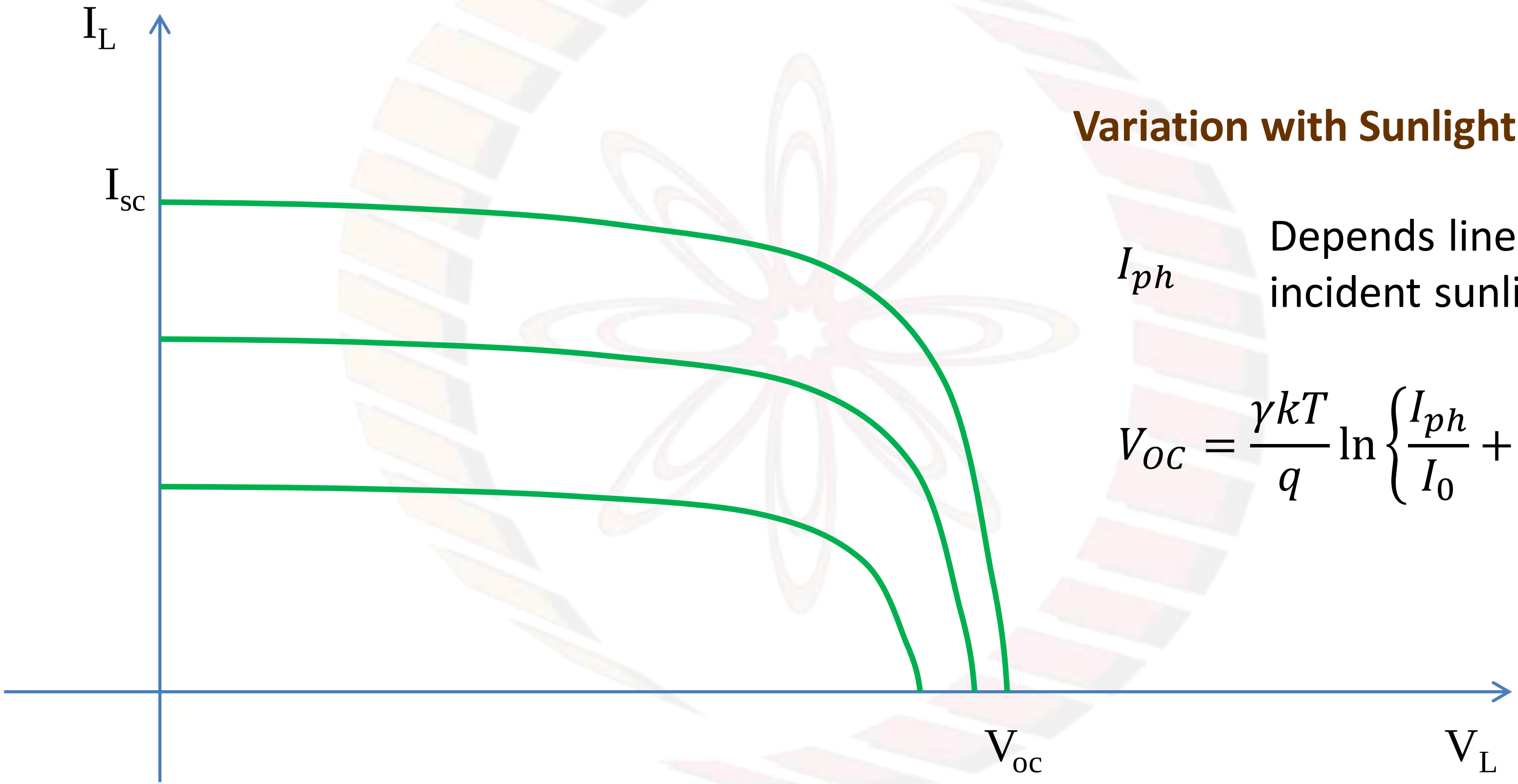
Maximum Power Point

$$Fill\ Factor = \frac{V_{MPP} \times I_{MPP}}{V_{OC} \times I_{SC}}$$

I-V characteristics



I-V characteristics

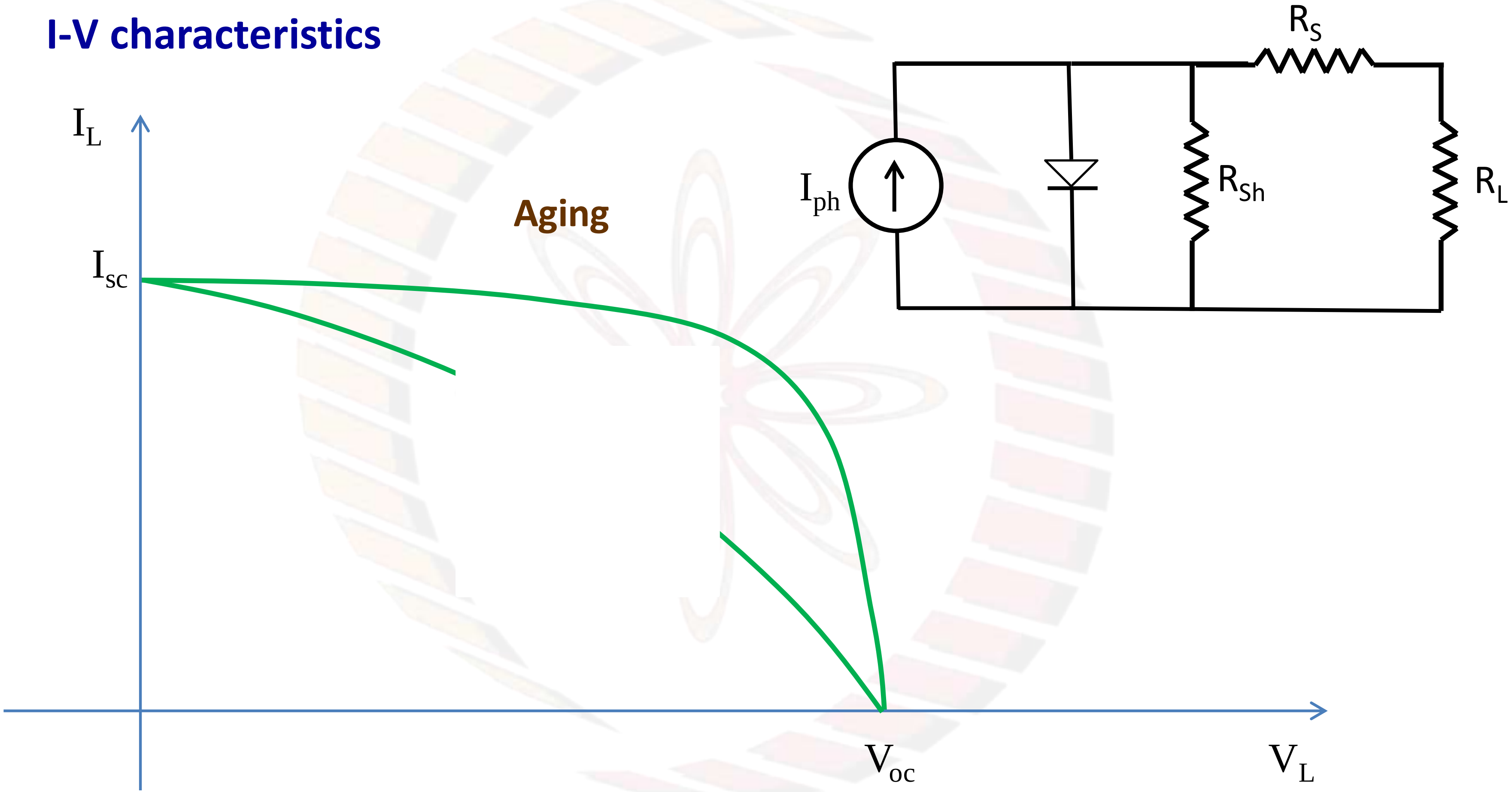


Variation with Sunlight

I_{ph} Depends linearly on incident sunlight

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

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

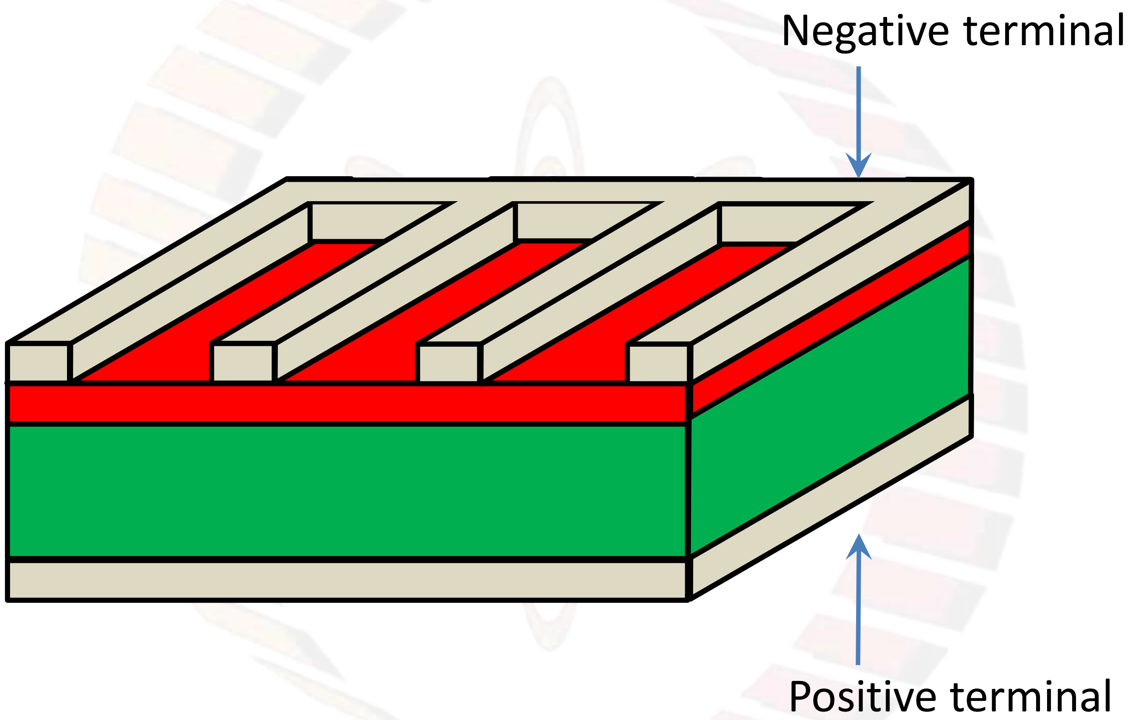
Shockley-Quiesser limit

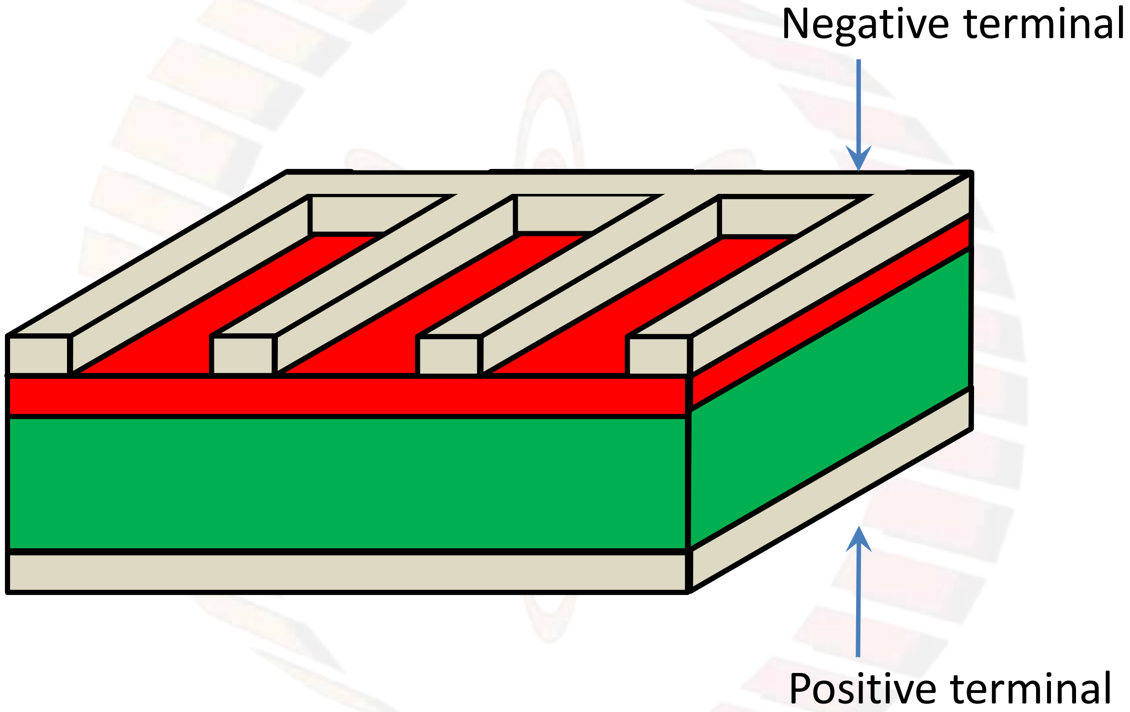
In unconcentrated, AM 1.5 Solar radiation with a band gap of 1.34 eV, 33.4 % efficiency is obtained

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

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

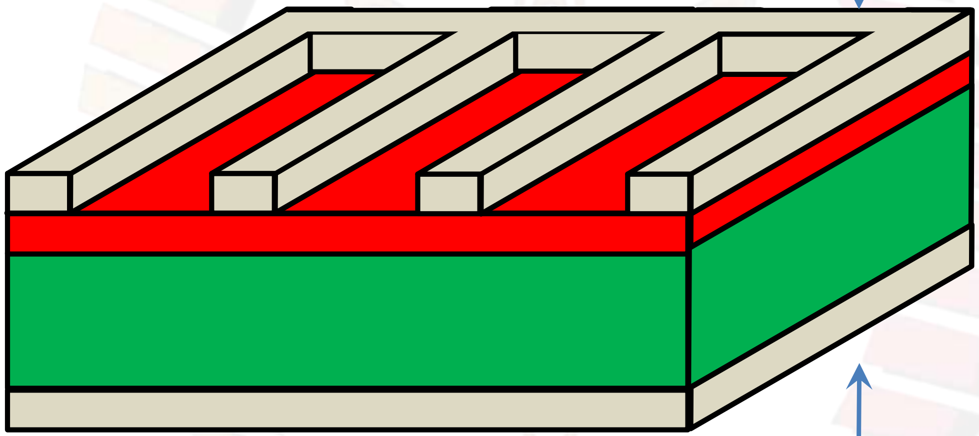
Blackbody radiation	7% (At room T, actual T~ 75 ^{o}C)
Recombination losses	10%
Spectrum losses	19% unabsorbed, 33% excess ν, total 52%


Negative terminal
Positive terminal

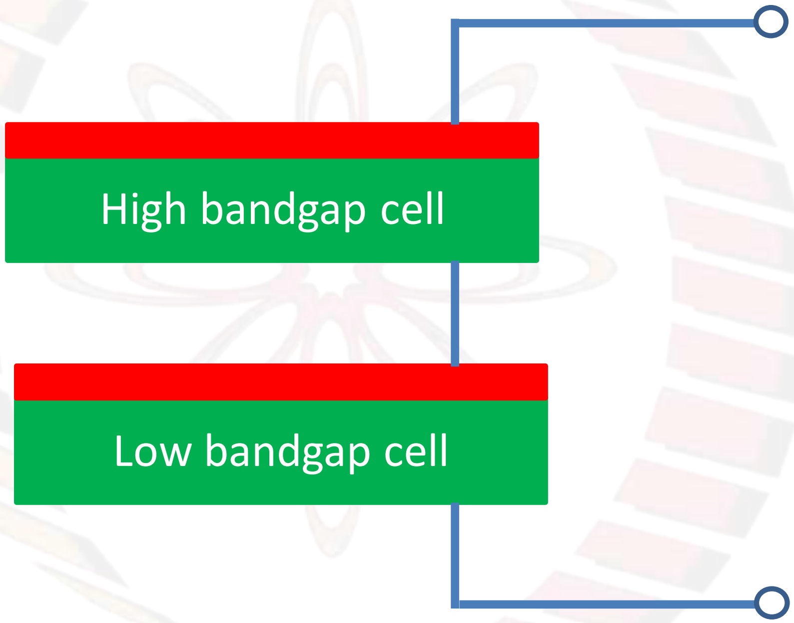


Anti-reflective coatings necessary

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



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-Quiesser limit indicates the limitation of a single junction solar cell
3) Tandem solar cells can overcome these limitations