**Mobility with doping and temperature**

- For higher doping, the carrier mobilities systematically decrease with doping

- In the lowest doped samples, carrier mobility monotonically decreases with increase in temperature

Text

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**Dominant scattering mechanisms in doped materials:**

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**Holes**



**Drift velocity**

- When an electric field, E, is applied to a semiconductor

- carriers will not accelerate indefinitely due to scattering

- will have an averaged velocity called the drift velocity

**Carrier Scattering**

**Others**

- Deflection by ionized impurity atoms

**Carrier-carrier scattering**

- deflection due to coulombic force between carriers

- only significant at high carrier concentrations

**Lattice/phonon scattering**

- random thermal motion of electrons and atoms

- electrons frequently collides with vibrating atoms

- increases with increasing temperature

**Total Drift Current**

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**Holes**

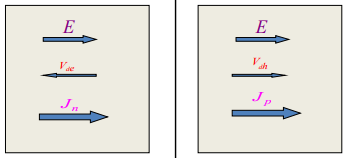




**Drift Current Density**

- current = charge per unit time

- current density = current per unit area



**Electrons**





**Electrons**



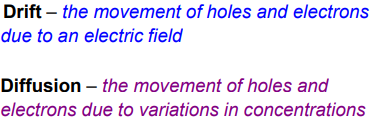
**-** Negative sign indicates electrons move in opposite direction to E

**Carrier drift**



Where E is the applied electric field

**Mechanisms**







**Einstein Relation**

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**Electrons & hole currents: Quasi Fermi Levels**

- Related to non-equilibrium carrier concentration the same way is to equilibrium carrier concentration

Text

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**Equilibrium conditions**

Graphical user interface, application

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**Non-equilibrium conditions**

Application

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Diffusion constant

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**Total Current: Steady State**

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**Total**

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**holes**

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**electrons**

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**Diffusion Current Density**

**Carrier Diffusion**

-> Thermally induced random motion

-> mobile carriers move from high concentration to low concentration

-> produce a flux of carriers

-> produce current

-> known as diffusion current

- Does not need external electric field

Timeline

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**n-type**

Chart

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**p-type**

Chart

Description automatically generated with low confidenceChart

Description automatically generated with medium confidence

**Resistivity**

Chart

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**Conductivity**

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**In both cases, force arises from a compositional gradient**

**Charge Separation**

- In crystalline semiconductors a junction between two electronically different materials provides electrostatic force

- In photosynthesis, excited electrons are driven across the photosynthetic membrane by differences in free energy of molecular acceptors

**Work Function (**

- work function of a material is the energy required to remove the least tightly bound electron from Fermi level too vacuum level



**Electron Affinity**

**-** electron affinity is the energy required to remove electron from CB

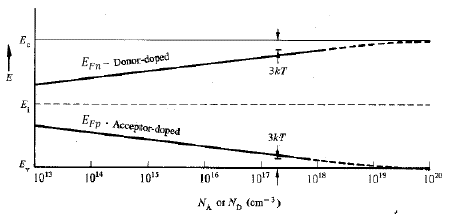


**Note**

- Work function of a material is strongly dependent on surface preparation

- Work function of metal is always equal to electron affinity, but semiconductor depends on doping

**Determination of (doped semiconductor)**



Fermi level systematically moves upward in energy from with increasing donor doping, and systematically downward in energy from with increasing acceptor doping

Figure above refers to exact positioning of in Si at room temperature as a function of doping concentration.

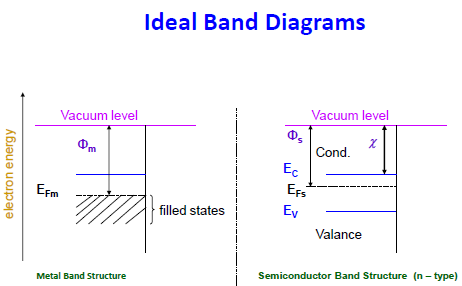
**Charge Separation: Types of Junctions**

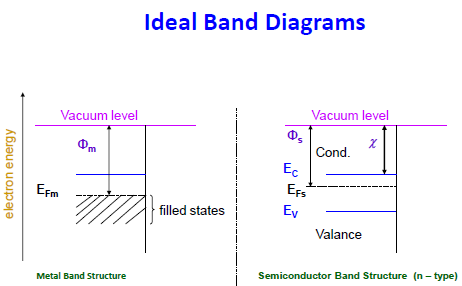
- key step in photovoltaic energy conversion

- requires some kind of driving force, which should be built in the device

- driving force is electric field which effectively separates charge carriers and drives them in opposite directions

- in solar cells, a junction between 2 electronically different materials provides necessary driving force





**Schottky Barrier (in dark)**

- When two materials isolated from each other, fermi levels are independent

- When brought into contact, electrons flow from semiconductor into the metal until Fermi energies of both solids are equal

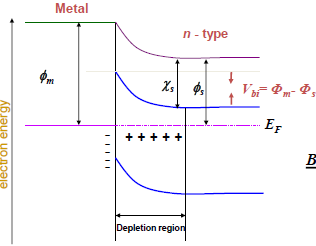
- Upon electrons leaving the semiconductor, a layer of fixed positive charge left behind and a negative surface charge layer on metal appear

- This creates depletion region in semiconductor and hence, a built-in electric field which prevents further electron flow

- Since electron affinity and band gap are invariant in semiconductor, hence, changes by a certain amount, so conduction and valence band energies must vary, by the same amount (band bending)

- Band bending energy, , is equal to gradient in vacuum level (or difference in work functions)

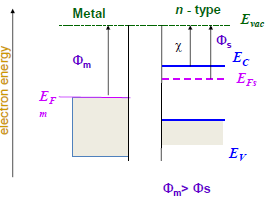
- The greater the difference in work functions, larger the bending and higher the



**Schottky Barrier**

- Formed between metal and a n- or p- semiconductor when are brough into contact

-



**Metal-Semiconductor Junction**

- Simple photovoltaic junction

- charge separating field is established due to difference in work functions of metal and semiconductor

**Types**

1. Schottky barrier

2. Ohmic contact

**Types of Junctions**

- Electrostatic field can be established at the junction between any two regions of different work functions due to vacuum level gradient

**Homo Junction**

- two layers of same semiconductor with different levels of doping

- most widely used technique in solar cells for establishing the charge separating field

**Hetero Junction**

- a semiconductor and a metal or

- two semiconductor of different work functions

**Origin of Photovoltaic Action**

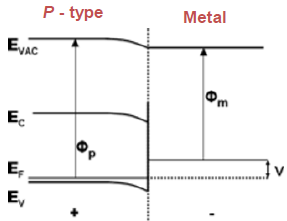
- In photovoltaic device, light produces a pair of charges which are then separated

- that charge separation then gives rise to a photocurrent (short circuit) or photo-voltage (open circuit)

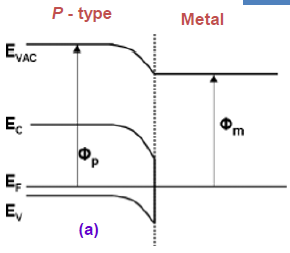
- photovoltaic action arises from the driving force separating charges

**Schottky Barrier (upon illumination)**

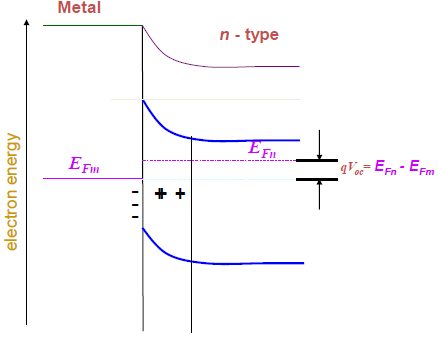
**Under illumination at open circuit**



**Equilibrium**



**Schottky Barrier (upon illumination)**



- When semiconductor is illuminated with photons of energy greater than band gap

-> built-in electric field will cause EHP generated in semiconductor to be separated

-> electrons accumulate in semiconductor and holes in metal

-> electron quasi fermi level in semiconductor moves up

-> become higher than it was dark and higher than the fermi level in metal

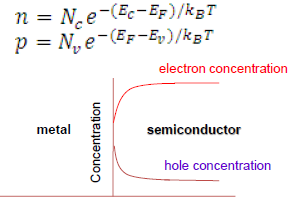
-> generates voltage called photo voltage

- Magnitude of phot voltage is equal to difference in fermi levels of semiconductor and metal

- Ability to sustain a difference in quasi fermi levels under illumination – key requirement in PV energy conversion

**Schottky Barrier**

Concentration profile



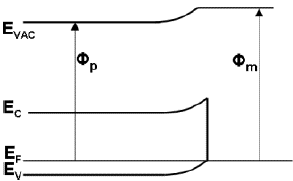
- When metal and semiconductor join -> electric field in layer close to interface

- Electric field drive electrons and holes in opposite direction – separation

- Contacts present lower resistance path for holes than electrons, from semiconductor to metals – this type of junction is an example for Schottky barrier

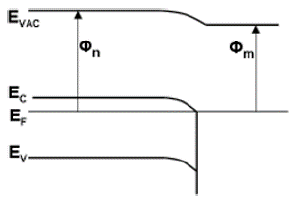
**p-type**

**-**



**n-type**

**-**



**p-n Junction**

- Formation:

-> p-n junction is established when layer of p-type semiconductor and layer of n-type material are brought together

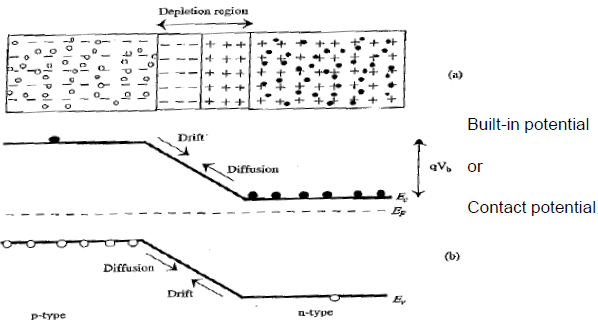
-> when p-n junction formed, majority carriers diffuse across junction

-> leave behind layer of fixed charge on either side due to ionized impurity atoms

-> this space charge sets up an electrostatic field which opposes further diffusion of carriers across junction

-> when diffusion of majority carriers across junction is balanced by drift of minority carriers back across junction in the built-in field, equilibrium is established

-> fermi levels of p-type and n-type semiconductors are now equal



**Ohmic contacts**

- When n-type semiconductor-metal are brought into contact

-> the semiconductor bands bend

-> such that it encourages transport of majority carriers across the junction and inhibits only flow of minority carriers

-> Majority carriers accumulate near interface to establish necessary potential difference and junction is rich with carriers

-> this means it can pass current easily in either direction

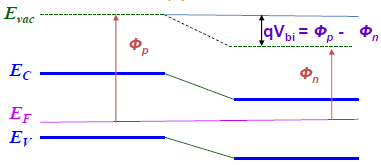
-> so have a low contact resistance for majority carriers usually an Ohmic contact.

-> the difference in work function between two layers causes build-up of majority carriers near the interface

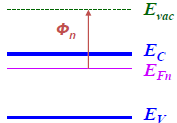
-> under illumination, the charges separated at the junction pass across the junction relatively easily

-> resultant photovoltage is negligible – mechanism which gives rise to photovoltage in a barrier junction – selective removal of minority carriers is absent

**p-n junction (in dark)**

**Band profile of p-n junction in equilibrium in the dark**

**Band profiles of p-type and n-type semiconductor in isolation**

**n-type**

**p-type**

