CLASS 4 & 5

Semiconductor parameters, Charge concentration in semiconductor, Fermi-Dirac function, Hall Effects, Currents in semiconductor, p-n junction

Ref: Donald A. Neamen, "Semiconductor Physics and Devices," Third Edition, McGraw Hill.

- <u>Current density, J (A/m^2)</u>

  $J = \sigma E$

  $\boxed{J = ne\mu_n E + pe\mu_p E}$

  J =electron current density + hole current density

  $J = neu_n + peu_p$

- <u>Drift current, I (A)</u>

  $I = Js$

  $\boxed{I = (ne\mu_n E + pe\mu_p E)s}$

  $= (neu_n + peu_p)s$

Charge concentration in semiconductor

The relationship between the electron and hole densities can be expressed by the following equations:

$\boxed{np = n_i^2}$

where n_i = intrinsic electron-hole pair concentration ($/m^3$)

$\boxed{N_D + p = N_A + n}$ (charge neutrality condition)

N_D = donor impurity concentration

N_A = acceptor impurity concentration

$N_D + p$ = total +ve charge density

$N_A + n$ = total -ve charge density

- <u>For intrinsic semiconductor:</u>

$\boxed{n = p = n_i}$

Conductivity, $\boxed{\sigma_i = n_i e(\mu_n + \mu_p)}$

Resistivity, $\boxed{\rho_i = 1/[n_i e(\mu_n + \mu_p)]}$

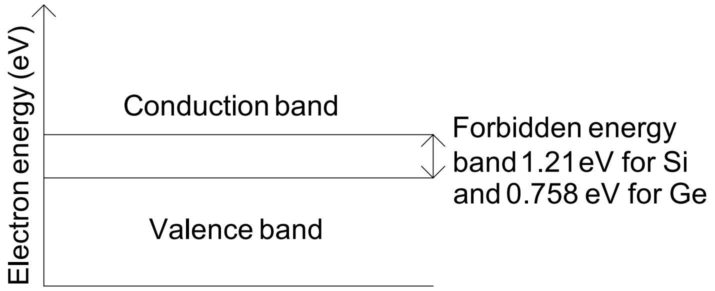
At room temperature,

$n_i = 2.4 \times 10^{19}$ for Ge

$= 1.5 \times 10^{16}$ for Si

Current density, $\boxed{J_i = n_i eE(\mu_n + \mu_p)}$

Current, $\boxed{I_i = n_i eEs(\mu_n + \mu_p)}$



- For extrinsic semiconductor , $\boxed{n \neq p}$

From $N_D + p = N_A + n$ and $np = n_i^2$,

Extrinsic-n: $n >> p$

$N_A = 0$

$\boxed{N_D \approx n}$, $p << N_D$

$\boxed{p \approx n_i^2 / N_D}$

Extrinsic-p: $p >> n$

$N_D = 0$

$\boxed{N_A \approx p}$, $n << N_A$

$\boxed{n \approx n_i^2 / N_A}$

- From, $\sigma = e(n\mu_n + p\mu_p)$ and $\rho = 1/[e(n\mu_n + p\mu_p)]$
- Extrinsic-n:

Conductivity, $\boxed{\sigma = e(N_D\mu_n + n_i^2\mu_p/N_D)}$

Resistivity, $\boxed{\rho = 1/[e(N_D\mu_n + n_i^2\mu_p/N_D)]}$

Since n >> p and for simplicity,

$\sigma \approx eN_D\mu_n$ and $\rho \approx 1/(eN_D\mu_n)$

$J = eN_D\mu_nE$

$I = eN_D\mu_nEs$

- From, $\sigma = e(n\mu_n + p\mu_p)$ and $\rho = 1/[e(n\mu_n + p\mu_p)]$
- <u>Extrinsic-p</u>:

Conductivity, $\boxed{\sigma = e(n_i^2\mu_n/N_A + N_A\mu_p)}$

Resistivity, $\boxed{\rho = 1/[e(n_i^2\mu_n/N_A + N_A\mu_p)]}$

Since p >> n and for simplicity,

$\sigma \approx e\, N_A\mu_p$ and $\rho \approx 1/(e\, N_A\mu_p)$

$J = eN_A\mu_pE$

$I = eN_A\mu_pEs$

Fermi-Dirac Function

- Not all of the electrons in a conducting material possess the same energy level. However, these electrons should be in one range of energy levels.
- f(E) = Fermi-Dirac probability function

  = the probability of an energy level, E, being occupied by an electron

$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}$$

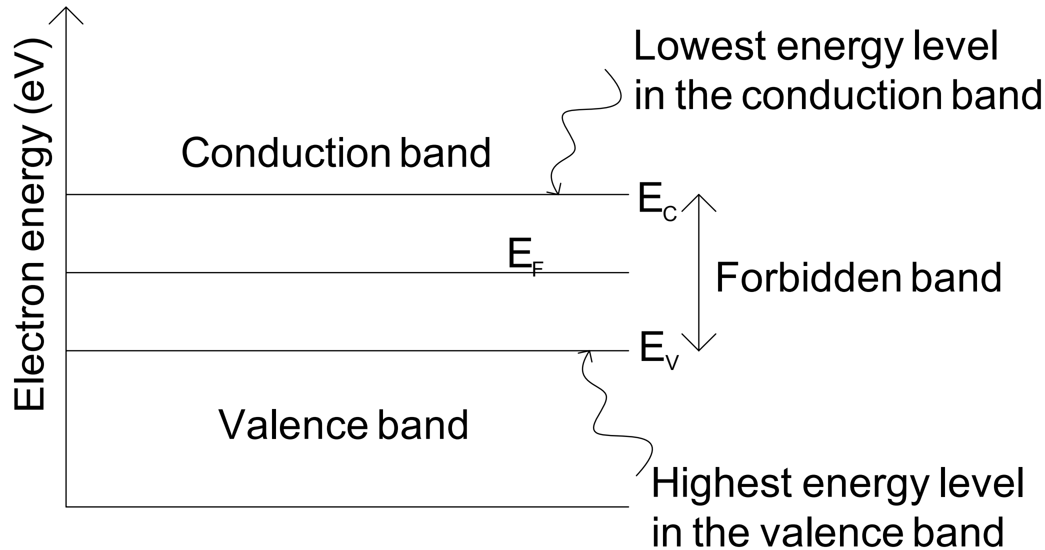
k = Boltzmann constant, 1.38×10^{-23} J/°K or 8.62×10^{-5} eV/°K

T = temperature (°K), 0°K = -273°C, 273°K = 0°C.

Room temperature is 300°K = 27°C

E_F = Fermi level

- E_F is purely a mathematical parameter and it may not be a permitted energy level. Nevertheless, it can be used as a reference when comparing with other energy levels.
- The Fermi level, E_F, is located between the conduction band and the valence band.



Temperature effect on the Fermi-Dirac function

- <u>At 0°K</u>

1. For all energy levels < E_F:

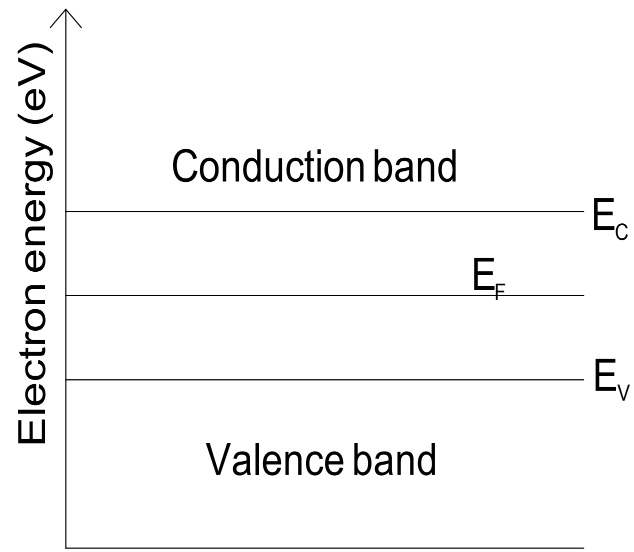
$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}=\frac{1}{1+e^{\frac{(E-E_F)}{0}}}=\frac{1}{1+e^{-\infty}}=1$$

2. For all energy levels > E_F:

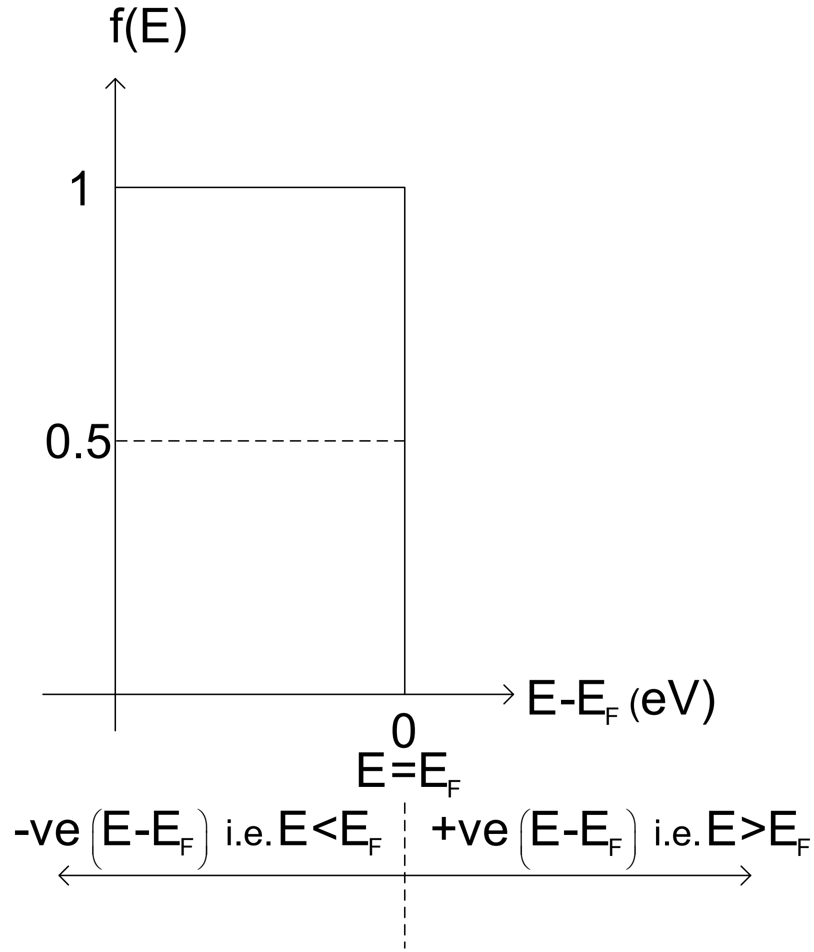
$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}=\frac{1}{1+e^{\frac{(E-E_F)}{0}}}=\frac{1}{1+e^{\infty}}=0$$

3. At $E = E_F$:

$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}=\frac{1}{1+e^{\frac{0}{kT}}}=\frac{1}{2}$$



- $f(E) = 1/2$, independent of the temperature.
- At 0°K, no electron will have an energy > E_F. $f(E>E_F) = 0$
- E_F is the maximum energy possessed by the electron at 0°K.
- $f(E<E_F) = 1$



At T = 300°K and setting $E - E_F$ = +0.1, -0.1 eV:

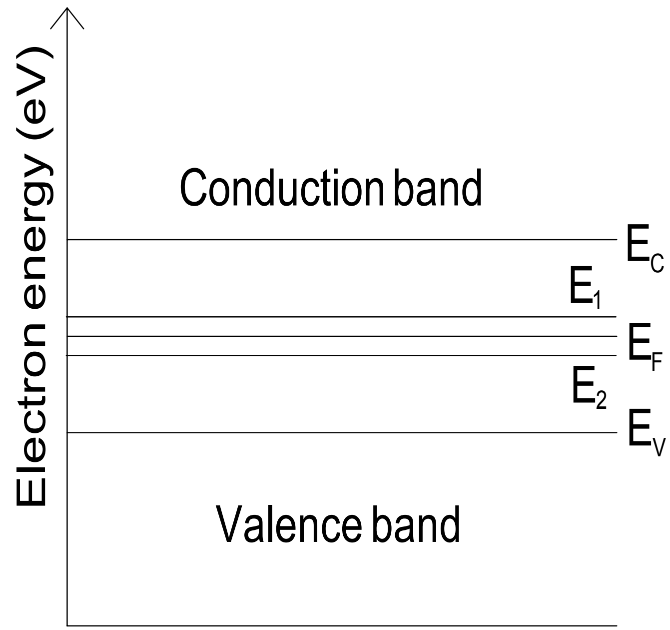
1. $E - E_F$ = +0.1 eV (at $E = E_1$)

$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}=\frac{1}{1+e^{\frac{0.1}{8.62\times10^{-5}\times300}}}=0.02$$

2. $E - E_F$ = -0.1 eV (at $E = E_2$)

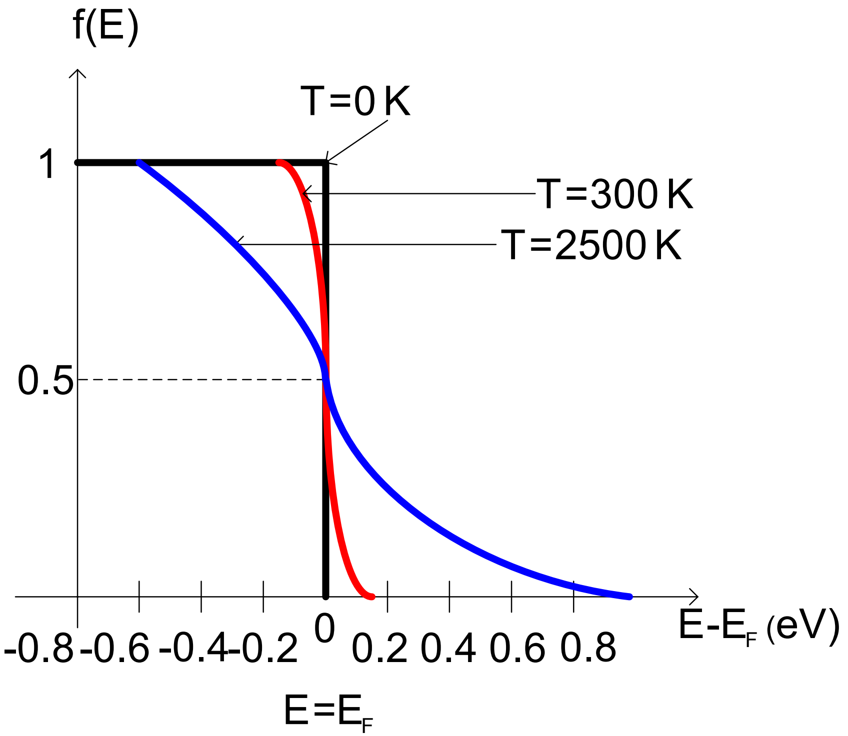
$$f(E)=\frac{1}{1+e^{\frac{(E-E_F)}{kT}}}=\frac{1}{1+e^{\frac{-0.1}{8.62\times10^{-5}\times300}}}=0.9795$$

When T↑, there is a probability that electron can be located at $E > E_F$. When T↑, the probability that electron can be located at $E < E_F$ is < 1. E_F is no longer the max. energy possessed by the electrons.

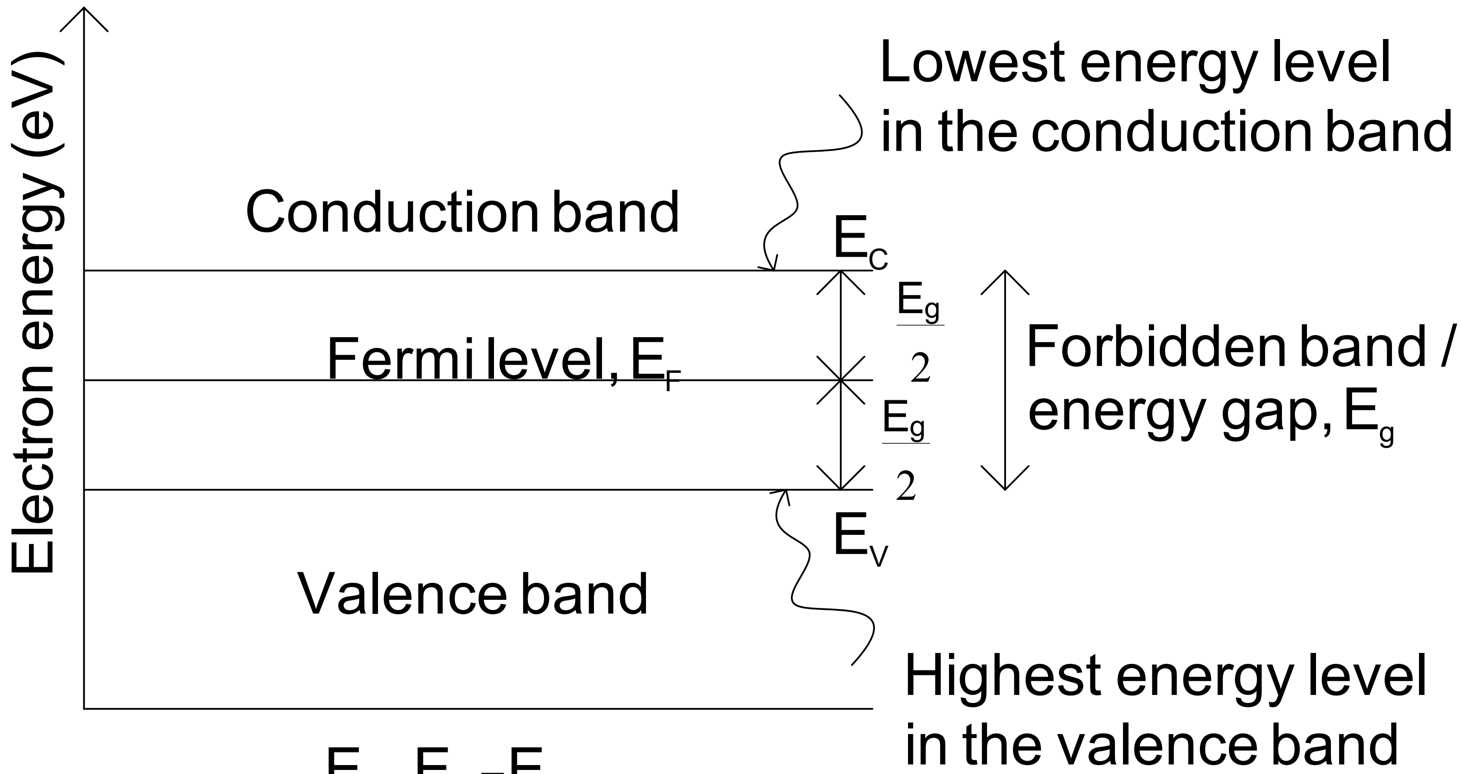


f(E)		Temperature (°K)		
		0	300	2500
$E - E_F$ (eV)	+0.1	0	0.02	0.3862
	0	0.5	0.5	0.5
	-0.1	1	0.9795	0.6139

- Observe that one ordinate will be passed at all temperatures which is at $E = E_F$ as $f(E_F) = ½$ for all temperatures.



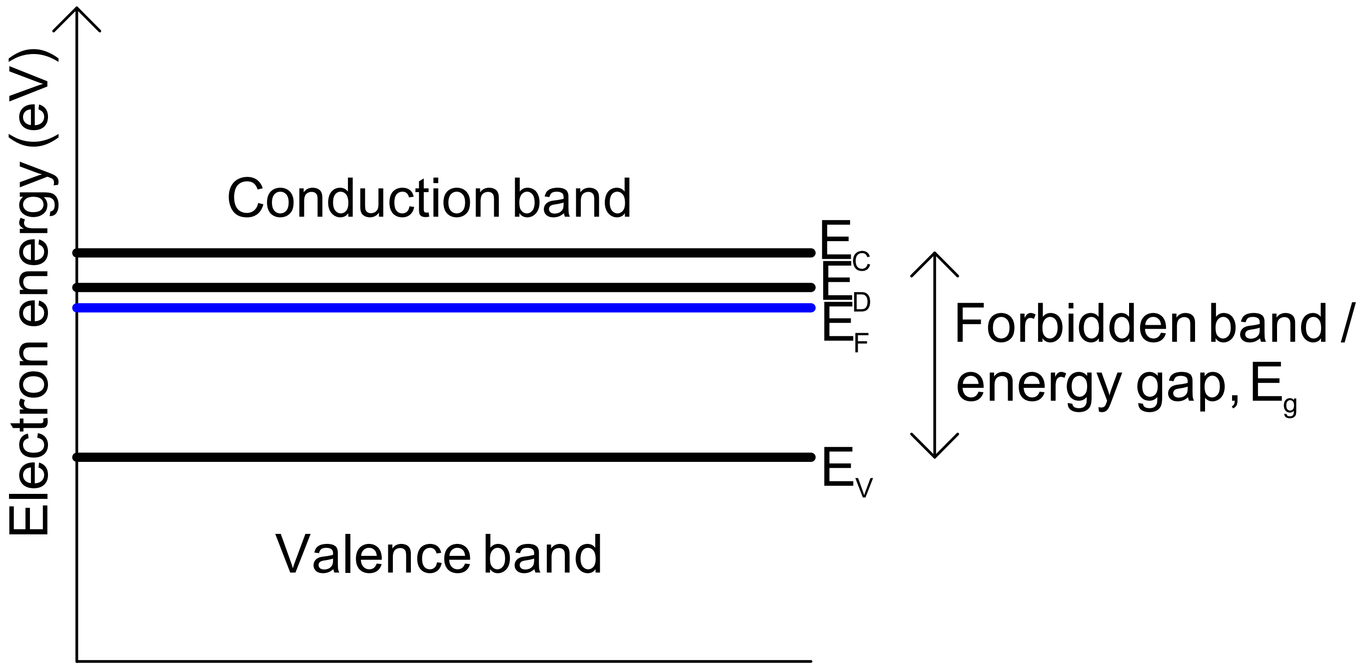
Fermi level in an intrinsic semiconductor



$$E_C - E_V = E_g$$
$$E_C - E_F = E_g/2$$
$$E_F - E_V = E_g/2$$

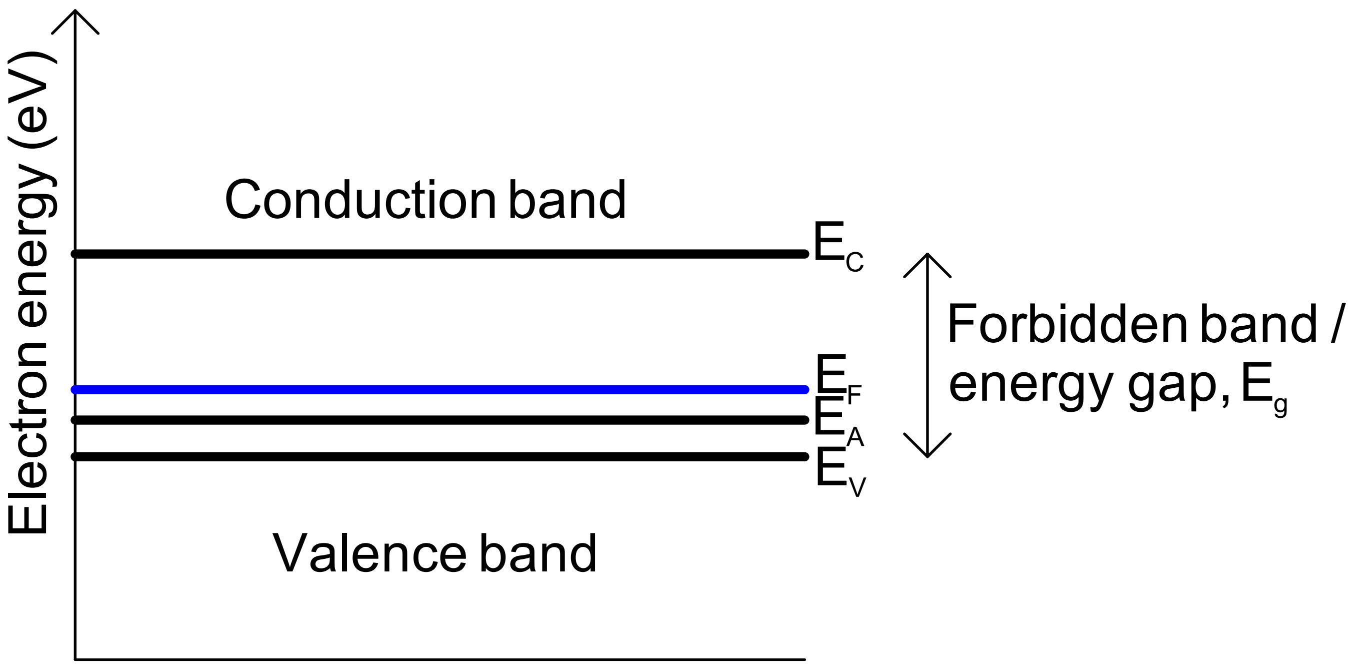
Fermi level in an extrinsic-n semiconductor

- For normal doping:



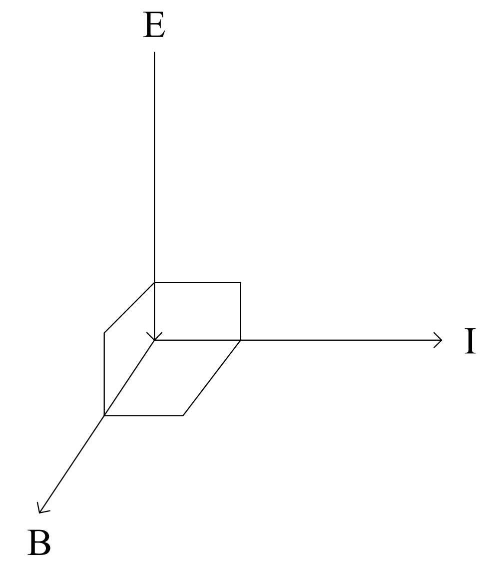
Fermi level in an extrinsic-p semiconductor

- For normal doping:



HALL EFFECT

- If a semiconductor with a current I is placed in a magnetic field B perpendicular to I, an electric field E will be induced perpendicular to both I and B. This phenomena is known as the Hall effect.
- Hall effect is used to determine:



1. type of semiconductor
2. carrier concentration
3. μ (from calculation) if σ can be measured

I is in the +ve x direction.

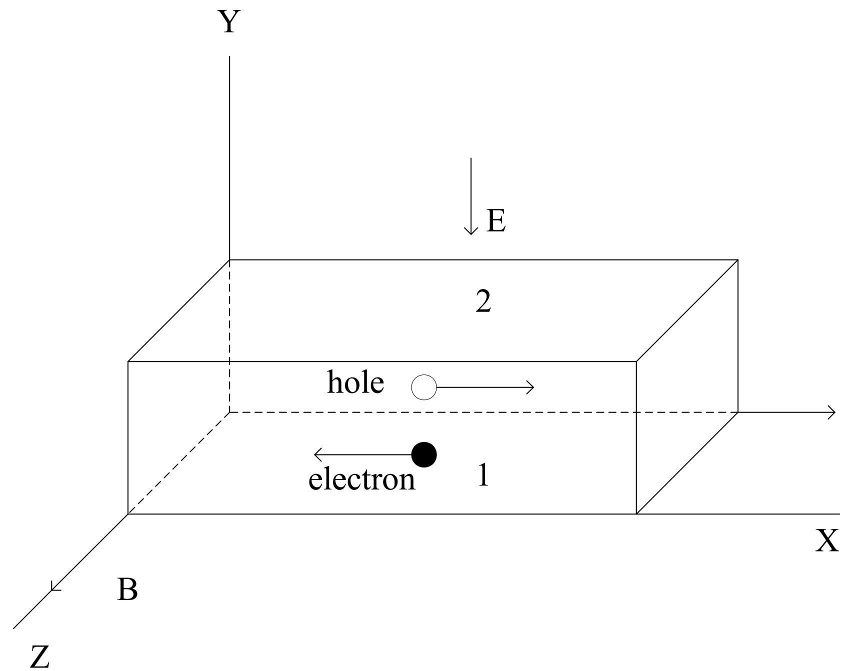
B is in the +ve z direction.

E is in the -ve y direction.

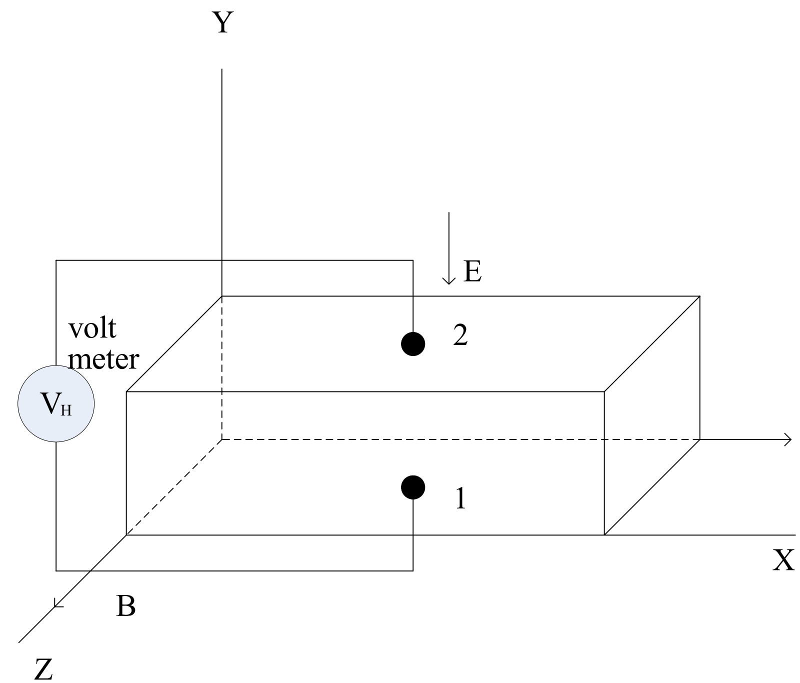
I is produced by:

- holes moving in the +ve x direction or
- electrons moving in the –ve x direction

  Because of E, carriers will be on surface 1 irrespective of whether they are holes or electrons.



- The Hall voltage, V_H, is measured across surface 1 and 2.
- If V_H is +ve at surface 2 and –ve at surface 1, the semiconductor is extrinsic-n. If the polarities of V_H are the opposite, the semiconductor is extrinsic-p.
- Hence, the polarities of V_H will enable us to determine the type of extrinsic semiconductor.



$V_H = Ed$

d = distance between surface 1 and 2

$\boxed{E = Bu}$

u = drift velocity of the current carriers

$V_H = Bud$

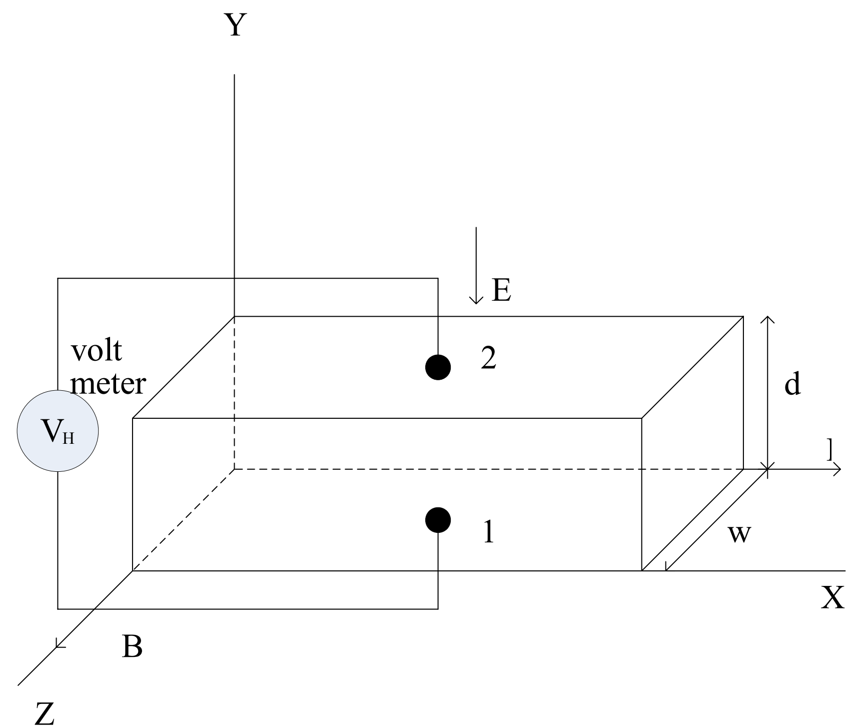
$J = neu_n + peu_p$

$J \approx neu_n$ if the semiconductor is n as n >> p

$J \approx peu_p$ if the semiconductor is p as p >> n

If the semiconductor is n:

$V_H = BJd / (ne)$



$V_H = BJd / (ne)$

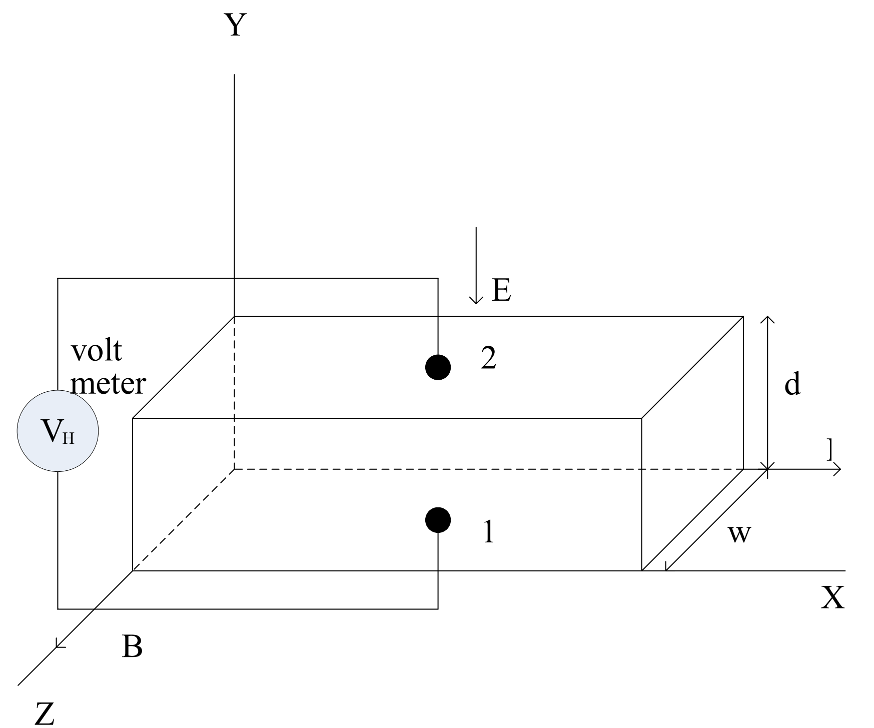
$I = Js$

$V_H = BId / (nes)$

$\boxed{V_H = BI / (new)}$

as the cross section area, $s = wd$.

If V_H, B, I and w are known, carriers concentration can be calculated.



Charge density = ne for electron carriers

= pe for hole carriers

n = electron density or concentration

p = hole density or concentration

For electron carriers (extrinsic-n):

$J = en\mu_n E$

$I = en\mu_n Es$

Conductivity, $\sigma = J / E = I / (Es)$

Since I, E and s can be measured, σ can be known.

$\sigma \approx en\mu_n Es / (Es)$

$\sigma \approx ne\mu_n$

For holes (extrinsic-p):

$\sigma \approx pe\mu_p$

If carrier density is known, μ can be calculated.

Hall coefficient, $\boxed{R_H \approx 1 / (ne)}$ if the current carriers are electrons.

n = electron density, ne = charge density

From $V_H = BI / (new)$

$V_H = R_H BI / w$

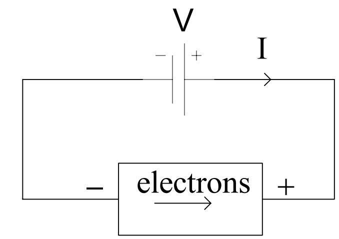
$$\boxed{R_H = wV_H / BI}$$

Since $\sigma = ne\mu_n = \mu_n / R_H$

Hence, $\boxed{R_H = \mu_n / \sigma}$

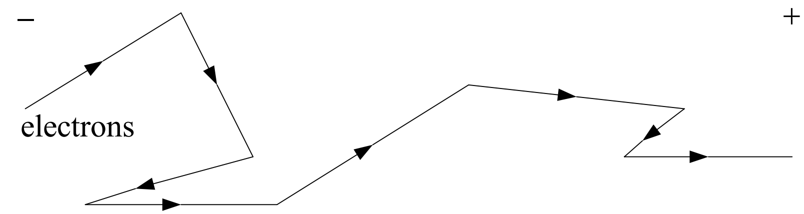
Take note that $R_H \neq R$ since R is resistance of the semiconductor.

Drift and diffusion currents



- Two types of current flowing in a conducting material:

1. Drift current
2. Diffusion current

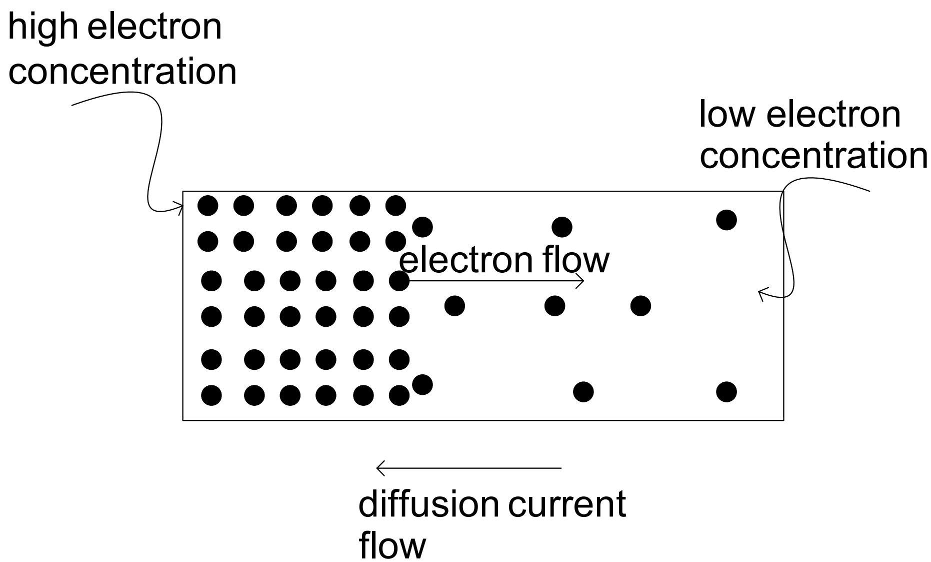


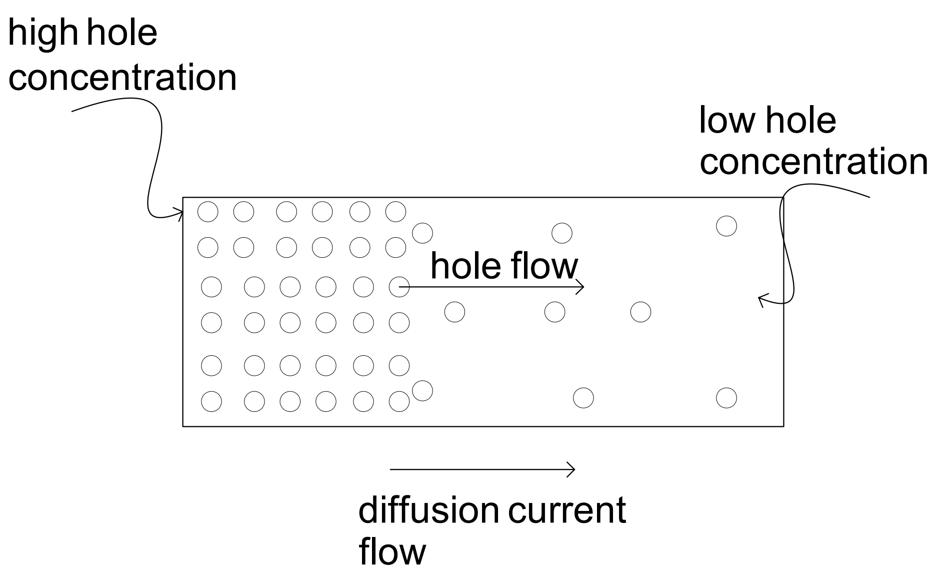
1. <u>Drift current</u>

   The diagram shows the current flow in a conducting material when there is a potential difference across the material. Free electrons will move towards the more positive potential. The flow of electrons is always opposite to the direction of the conventional current flow. The current generated from the flow of these electrons due to the potential difference is called the drift current. When a voltage is supplied to a wire or a resistor, the current produced is the drift current.

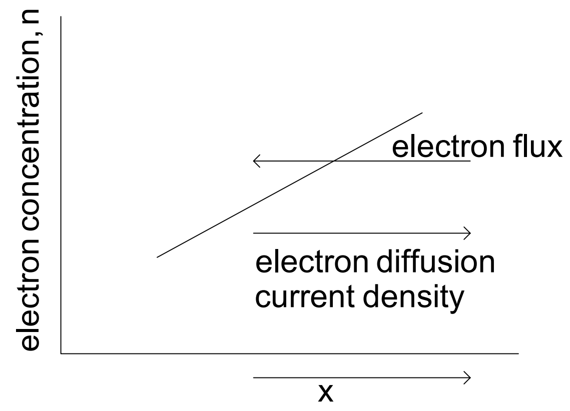
2. <u>Diffusion current</u>

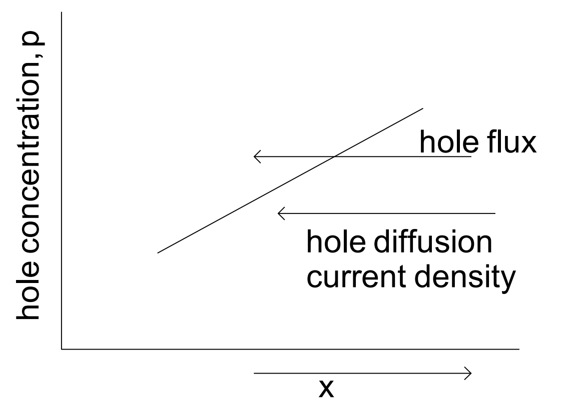
Current can still flow in a material even though there is no voltage supplied. This current is produced when there exist a concentration gradient in the material. Concentration gradient occurs if the charge concentration is higher at one end of the material if compared to another end. When concentration gradient of the charge carriers exists, charge carriers will move or diffuse from the higher concentration region to the lower concentration region. Current generated from this mechanism is called the diffusion current. The purpose of carrier diffusion is to achieve a balance condition where the charge concentration is uniform along the material. Diffusion current will always be in the same direction as the hole flow and opposite to the direction of the electron flow.


high electron
concentration
low electron
concentration
electron flow
diffusion current
flow


high hole
concentration
low hole
concentration
hole flow
diffusion current
flow

- Referring to the diagram, the diffusion of electrons from a region of high concentration to a region of low concentration produces a flux of electrons flowing in the –x direction. Since electrons have a –ve charge, the conventional current directional is in the +x direction. Electron diffusion current density is $J_n = eD_n(dn/dx)$ where D_n (in m^2/s) is the electron diffusion coefficient and is a positive quantity. If the electron density gradient becomes –ve, J_n will be in the –x direction.
- The diffusion of holes from a region of high concentration to a region of low concentration produces a flux of holes flowing in the –x direction. Since holes are +vely charged particles, the conventional diffusion current density is also in the -x direction. The hole diffusion current density is $J_p = -eD_p(dp/dx)$ where D_p (in m^2/s) is the hole diffusion coefficient and is a positive quantity. If the hole density gradient becomes –ve, J_p will be in the +x direction.





- Hole p density changes with distance x along a semiconductor and there is a concentration gradient dp/dx in the charge density. Diffusion current density for the hole, J_p (in A/m^2), is proportional to the concentration gradient and is given by the following expression:

  $J_p = -eD_p(dp/dx)$

  where D_p (in m^2/s) is the hole diffusion coefficient.

  $\boxed{D_p = kT\mu_p/e}$ ← Einstein Law for diffusion of charge particle.

  Diffusion current density for the negatively charged electron is

  $J_n = eD_n(dn/dx)$

  where D_n (in m^2/s) is the electron diffusion coefficient.

  $\boxed{D_n = kT\mu_n/e}$ ← Einstein Law for diffusion of charge particle.

- At room temperature:

  $kT/e \approx 0.025$ V

  $\mu_n = 0.15\ m^2/Vs$

  $\mu_p = 0.05\ m^2/Vs$

  Hence,

  $D_n = 3.75 \times 10^{-3}\ m^2/s$

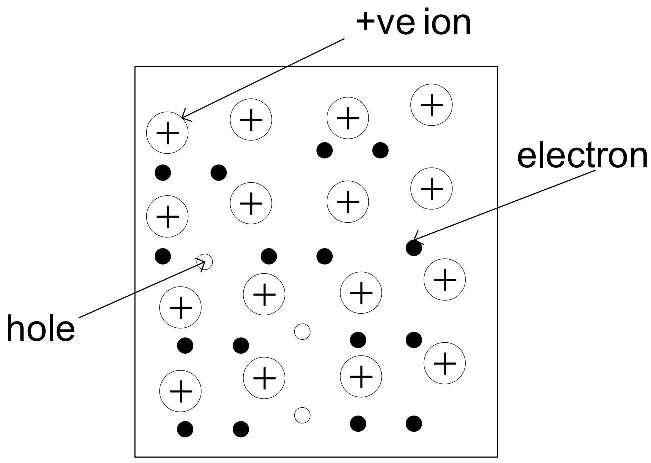
  $D_p = 1.25 \times 10^{-3}\ m^2/s$

p-n junction

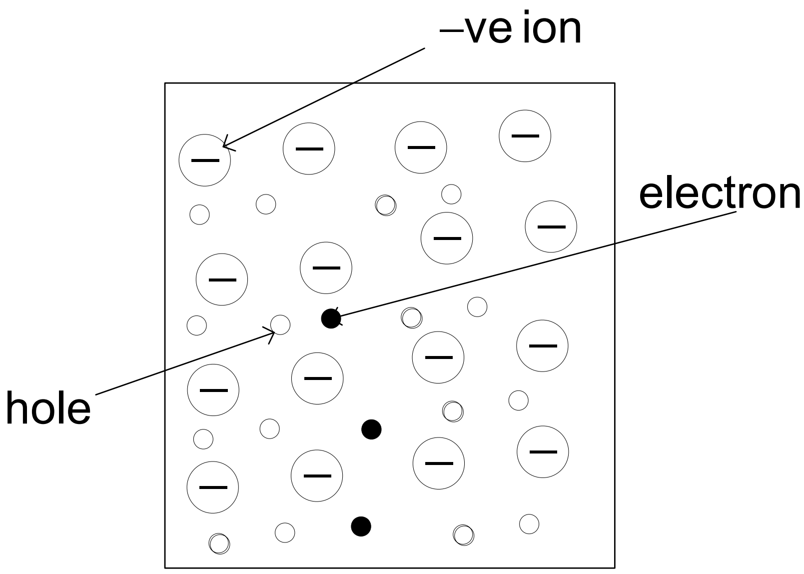
- When a p type semiconductor is connected to an n-type semiconductor, a p-n junction will be formed.
- Most of the semiconductor devices have at least 1 p-n junction. Hence, knowledge in the p-n junction is fundamental in understanding the characteristics of semiconductor devices.
- The most important characteristic of the p-n junction is its ability to let current flow in only one direction

p-type and n-type semiconductors

- **n-type**: consisted of mostly Si atoms, some donor impurity atoms, free electrons (majority carriers) and a few holes from thermal generation (minority carriers). In the diagram, Si atoms are not shown for simplicity. Donor impurity atoms are shown as +ve ions since 1 of their 5 valence electrons will be free at room temperature.These +ve ions are fixed in the crystal structure and do not contribute to the generation of current. The no. of majority carriers (electrons) are dependent on the no. of donor atoms. The no. of minority carriers (holes) are dependent on the temperature.



- **p-type**:consisted of mostly Si atoms, some acceptor impurity atoms, holes (majority carriers) and a few free electrons from thermal generation (minority carriers). In the diagram, Si atoms are not shown for simplicity. Acceptor impurity atoms are shown as -ve ions since each of them accepts 1 valence electron from its neighbouring Si atom at room temperature. -ve ions are fixed in the crystal structure and do not contribute to the generation of current. The no. of majority carriers (holes) are dependent on the no. of acceptor atoms. The no. of minority carriers (electrons) are dependent on the temperature.

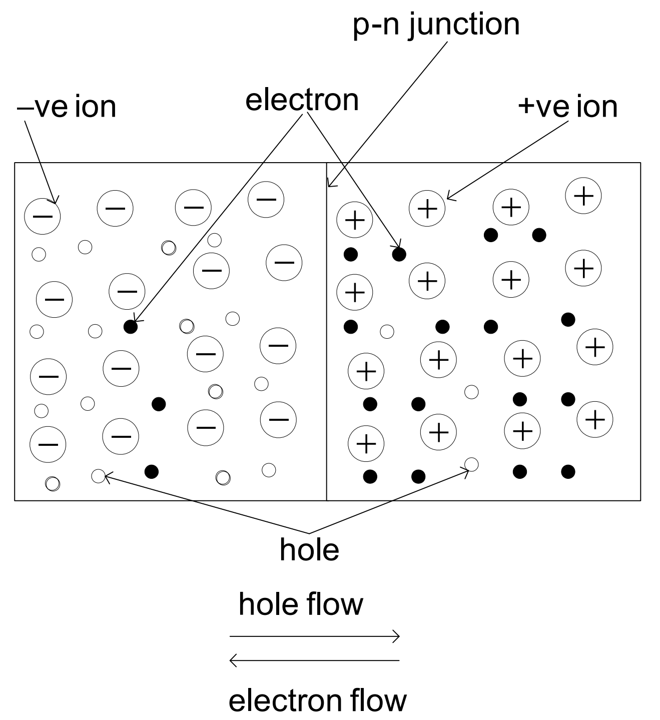


diffusion and drift currents

- **<u>When the p-type and n-type semiconductors are connected:</u>**

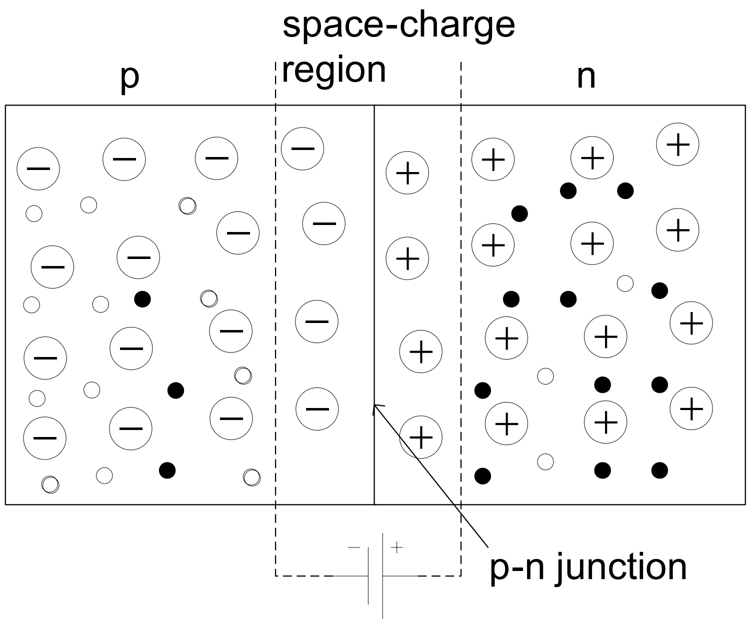
  The p has high hole density (hole – majority carrier). The n has low hole density (hole – minority carrier). The difference in the hole density will generate diffusion current. Holes in the p will diffuse to the n (diffusion is from a higher density to a lower density) crossing the p-n junction in the process.

  The n has high electron density (electron – majority carrier). The p has low electron density (electron – minority carrier). The difference in the electron density will generate diffusion current. Electrons in the n will diffuse to the p (diffusion is from a higher density to a lower density) crossing the p-n junction in the process.

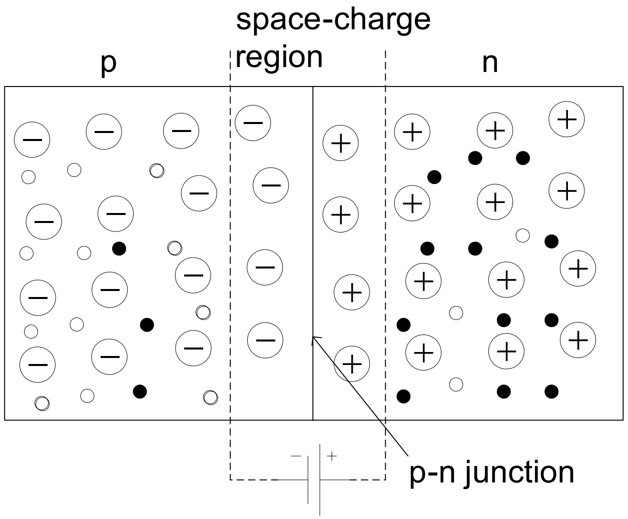


Space-charge region

- Holes from the p will diffuse to the n, crossing the p-n junction in the process. In the n (near the p-n junction), the holes will meet with the electrons and recombination occur.
- Electrons from the n will diffuse to the p, crossing the p-n junction in the process. In the p (near the p-n junction), the electrons will meet with the holes and recombination occur.
- The region near the p-n junction in the n- and p-semiconductors will have very few mobile carriers (due to the recombination). Only +ve fixed ions (in the n) and –ve fixed ions (in the p) exist in this region. These fixed charge regions with very few mobile carriers near the p-n junction is called the space-charge region.



- Only fixed ions will be in the space-charge region, +ve ions in the n and –ve ions in the p.
- The fixed charges near the junction will prevent future diffusion. If the holes in the p try to cross the junction and diffuse to the n, they will be repelled by the fixed +ve ions in the n near the junction.
- If the electrons in the n try to cross the junction and diffuse to the p, they will be repelled by the fixed -ve ions in the p near the junction.
- The repelling force of the fixed charges is initially small but will become larger with increased diffusion. When the repelling force becomes large enough, no more diffusion will occur.
- The space-charge region is also known as the depletion region as this fixed ion region near the p-n junction is depleted of majority carriers.

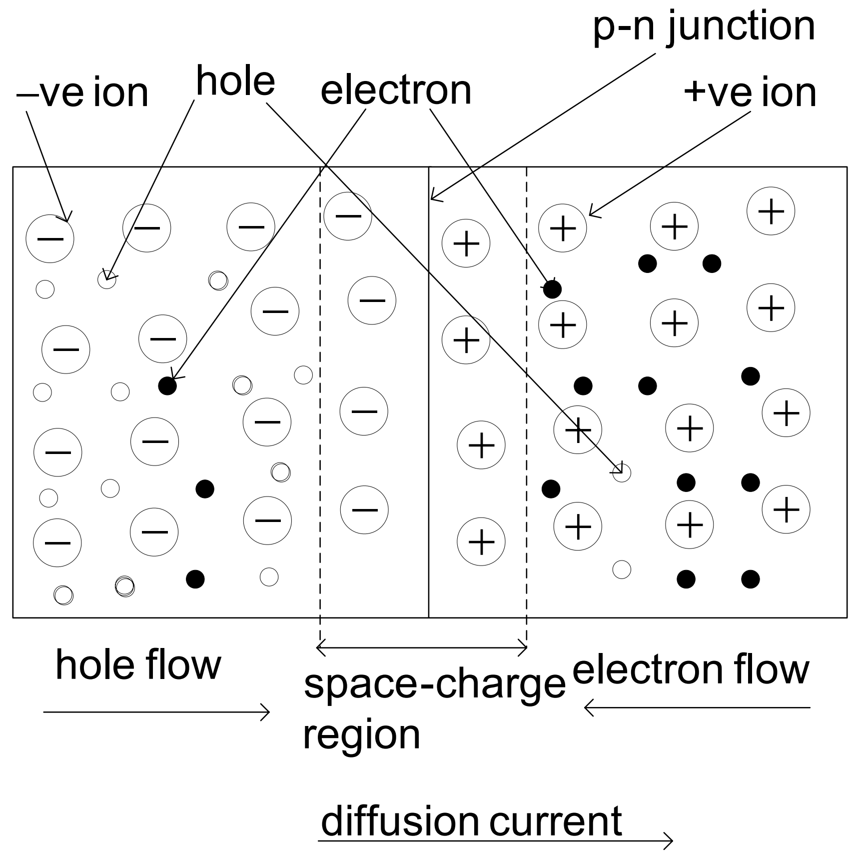


Potential barrier

- Repelling force of the space-charge region is an electrical force. Fixed charges in the opposite boundaries of the junction produce a potential barrier, similar to that of a battery. If a voltmeter can be placed across the space charge region, a voltage equivalent to the potential barrier can be measured. The value is ≈ 0.7 V for the Si and 0.3 V for the Ge.

- The space-charge region at the p-n junction is the potential barrier to the majority carriers trying to diffuse across the junction. If the free electrons from the n-region try to diffuse to the p-region, they need to possess sufficient energy to overcome the potential barrier. The same condition applies to the holes trying to diffuse to the n-region.

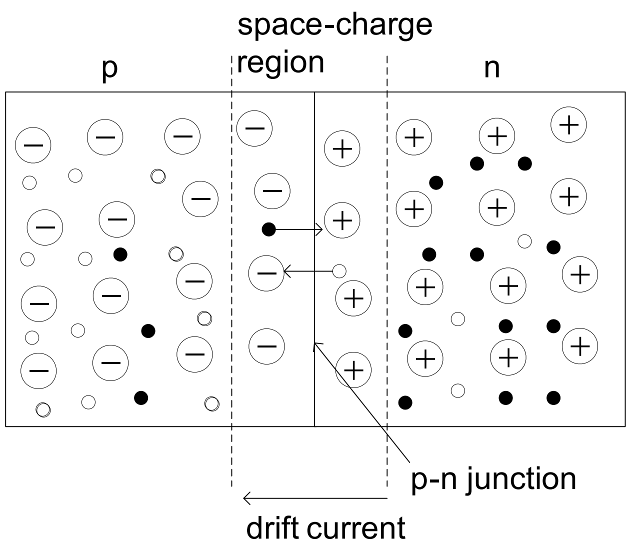
- At room temperature, additional thermal energy are given to the carriers. Some of the majority carriers (holes in p and electrons in n) are able to overcome the potential barrier and move across the p-n junction. This action generates majority carriers’ diffusion current.



Another type of current is produced by the minority carriers moving across the p-n junction due to the attraction by the fixed ions in the space-charge region. If an electron-hole pair is generated in the space-charge region due to thermal excitation:

1. Electrons in the p space-charge region will be attracted to the fixed +ve ions in the n space-charge region.
2. Holes in the n space-charge region will be attracted to the fixed -ve ions in the p space-charge region.

The resultant current generated from the movement of these minority carriers across the p-n junction is called the minority carriers' drift current.



- When there is no external voltage supplied to the p-n material, the majority carriers' diffusion current is cancelled off by the minority carriers' drift current. The p-n junction nett current is 0.
- A p-n junction with an external voltage supplied across its terminals is said to be biased; the voltage supplied is called the biasing voltage.