Basics of **extrinsic semiconductor**

An **extrinsic semiconductor** is a **semiconductor** doped by a specific impurity which is able to deeply modify its electrical properties, making it suitable for electronic applications (diodes, transistors, etc.) or optoelectronic applications (light emitters and detectors).

N-type semiconductors

When a small amount of pentavalent impurity such as arsenic is added to a pure germanium semiconductor crystal, the resulting crystal is called N-type semiconductor.

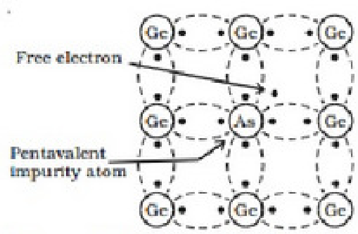


Fig -a N-type semiconductor

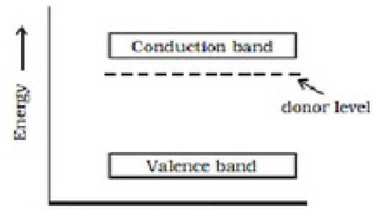


Fig b Energy band diagram of N-type semiconductor

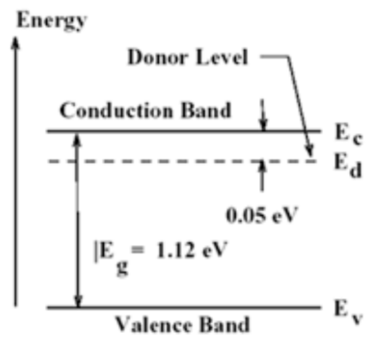


Fig a shows the crystal structure obtained when pentavalent arsenic impurity is added with pure germanium crystal. The four valence electrons of arsenic atom form covalent bonds with electrons of neighboring four germanium atoms. The fifth electron of arsenic atom is loosely bound. This electron can move about almost as freely as an electron in a conductor and hence it will be the carrier of current. In the energy band picture, the energy state corresponding to the fifth valence electron is in the forbidden gap and lies slightly below the conduction band (Figure-b). This level is known as the donor level.

When the fifth valence electron is transferred to the conduction band, the arsenic atom becomes positively charged immobile ion. Each impurity atom donates one free electron to the semiconductor. These impurity atoms are called donors.

In N-type semiconductor material, the number of electrons increases, compared to the available number of charge carriers in the intrinsic semiconductor. This is because; the available larger number of electrons increases the rate of recombination of electrons with holes. Hence, in N-type semiconductor, free electrons are the majority charge carriers and holes are the minority charge carriers.

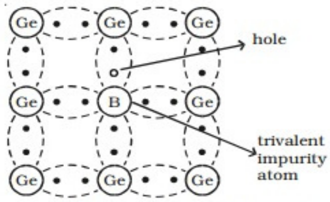


Fig a P-type semiconductor

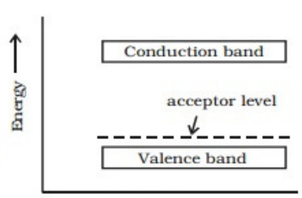


Fig b Energy band diagram of a P-type semiconductor

P-type semiconductor:

When a small amount of trivalent impurity (such as indium, boron or gallium) is added to a pure semiconductor crystal, the resulting semiconductor crystal is called P-type semiconductor.

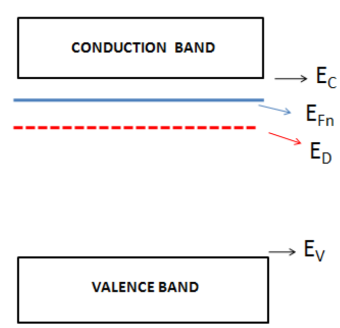
Fig a. shows the crystal structure obtained, when trivalent boron impurity is added with pure germanium crystal. The three valence electrons of the boron atom form covalent bonds with valence electrons of three neighborhood germanium atoms. In the fourth covalent bond, only one valence electron is available from germanium atom and there is deficiency of one electron which is called as a hole. Hence for each boron atom added, one hole is created. Since the holes can accept electrons from neighborhood, the impurity is called acceptor. The hole, may be filled by the electron from a neighboring atom, creating a hole in that position from where the electron moves. This process continues and the hole moves about in a random manner due to thermal effects. Since the hole is associated with a positive charge moving from one position to another, this is called as P-type semiconductor. In the P-type semiconductor, the acceptor impurity produces an energy level just above the valence band. (Fig.-b). Since, the energy difference between acceptor energy level and the valence band is much smaller, electrons from the valence band can easily jump into the acceptor level by thermal agitation.

In P-type semiconductors, holes are the majority charge carriers and free electrons are the minority charge carriers.

<u>Calculation of concentration of electrons in conduction band of n-type semiconductor:</u>

- N_D – Concentration of donors in the material
- E_D - Donor energy level close to conduction band lower edge E_C
- When the temperature of the material is raised above 0K, donor atoms get ionized and the liberated electrons are raised to conduction band because of thermal energy.
- So, number of positive donor ions (N_D^+) in the donor energy level (E_D) is equal to number of free electrons in the conduction band (n_n) of ‘n’ type semiconductor. $n_n = (N_D^+)$
- $(n_n) = (N_D^+) = N_D(\ 1 - f\ (E_D)\ )$; $(\ 1 - f\ (E_D)\ )$ is the probability of not finding electron in the donor energy level (E_D)

Energy level diagram of n-type semiconductor



- $1 - f(E_D) = 1 - \frac{1}{1+exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)} = \frac{1+exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)-1}{1+exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)}$
- $1 - f(E_D) = \frac{1}{1+exp\left(\frac{E_{Fn} - E_D}{K_B T}\right)} \approx exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)$
- $(E_{Fn} - E_D) \gg K_B T$. This means that thermal energy ($K_B T$) supplied to the material is less than $(E_{Fn} - E_D)$. Fermi level(E_{Fn}) lies between the donor energy level (E_D) and conduction band lower edge (E_C).
- $Therefore\ (n_n) = N_D \times exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)$
- The number of free electrons in the conduction band (n_n) of 'n' type semiconductor can also be given by $(n_n) = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_{Fn} - E_c}{K_B . T}\right)}$.
- $Thus, 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_{Fn} - E_c}{K_B . T}\right)} = N_D \times exp\left(\frac{E_D - E_{Fn}}{K_B T}\right)$
- $e^{\left(\frac{E_{Fn} - E_c - E_D + E_{Fn}}{K_B . T}\right)} = e^{\left(\frac{2E_{Fn} - (E_c + E_D)}{K_B . T}\right)} = \left(\frac{N_D}{2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}}\right)$
- Taking logarithm on both sides,

$$\left(\frac{2E_{Fn} - (E_c + E_D)}{K_B . T}\right) = log_e\left(\frac{N_D}{2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}}\right)$$

- $E_{Fn} = \left(\frac{E_c + E_D}{2}\right) + \frac{K_B . T}{2} log_e\left(\frac{N_D}{2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}}\right)$

- $E_{Fn} = \left(\frac{E_c+E_D}{2}\right) + K_B.T log_e \left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right)$

- When T=0K, $E_{Fn} = \left(\frac{E_c+E_D}{2}\right)$. This means that the Fermi energy level in n-type semiconductor (E_{Fn}) lies at the midpoint of conduction band lower edge and donor energy level.

- $\left(\frac{E_{Fn}-E_c}{K_B T}\right) = \left(\frac{E_c+E_D-2E_c}{2K_B T}\right) + log_e \left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right)$

- $\left(\frac{E_{Fn}-E_c}{K_B T}\right) = \left(\frac{E_{D-}E_c}{2K_B T}\right) + log_e \left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right)$

- $exp\left(\frac{E_{Fn}-E_c}{K_B T}\right) = exp\left(\left(\frac{E_{D-}E_c}{2K_B T}\right) + log_e \left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right) \right)$

$$exp\left(\frac{E_{Fn}-E_c}{K_B T}\right) = exp\left(\frac{E_{D-}E_c}{2K_B T}\right) \times \left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right)$$

$$Multiplying\ by\ 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2}\ on\ both\ sides,$$

$$2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2} exp\left(\frac{E_{Fn}-E_c}{K_B T}\right) = 2\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/2} exp\left(\frac{E_{D-}E_c}{2K_B T}\right)\left(\frac{N_D^{1/2}}{2^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4}} \right)$$

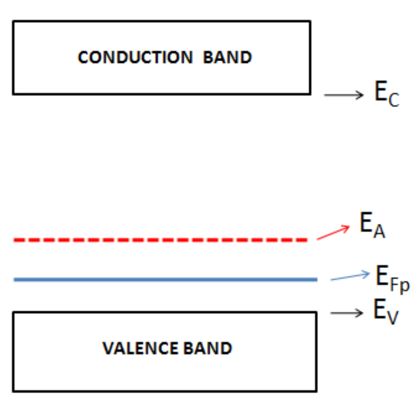
$$\boxed{(n_n) = (2N_D)^{1/2}\left(\frac{2\pi m_e^* K_B T}{h^2}\right)^{3/4} exp\left(\frac{E_D - E_c}{2K_B T}\right).}$$

$$Thus, (n_n) \propto (N_D)^{1/2}\ when\ 'T' is\ low$$

<u>Calculation of concentration of holes in valence band of p-type semiconductor:</u>

- N_A – Concentration of acceptors in the material
- E_A - Acceptor energy level close to conduction band lower edge E_V
- When the temperature of the material is raised above 0K, acceptor atoms accept electrons from covalent bonds and get ionized because of thermal energy. Thus holes are created in valence band.
- So, number of negative acceptor ions (N_A^-) in the acceptor energy level (E_A) is equal to number of free holes in the valence band (p_p) of 'p' type semiconductor. $p_p = (N_A^-)$
- (p_p) = (N_A^-) = N_A(f (E_A); f (E_A) is the probability of finding electron in the acceptor energy level (E_A)
- $f(E_A) = \frac{1}{1+exp\left(\frac{E_A - E_{Fp}}{K_B T}\right)} \approx exp\left(\frac{E_{Fp} - E_A}{K_B T}\right)$

Energy level diagram of p-type semiconductor



- $\left(E_A - E_{Fp}\right) \gg K_B T$. This means that thermal energy ($K_B T$) supplied to the material is less than $\left(E_A - E_{Fp}\right)$. Fermi level$\left(E_{Fp}\right)$ lies between the acceptor energy level (E_A) and valence band top edge (E_V).
- $Therefore\ (p_p) = N_A \times exp\left(\frac{E_{Fp}-E_A}{K_B T}\right)$
- The number of holes in the valence band (p_p) of 'p' type semiconductor can also be given by $(p_p) = 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_V - E_{Fp}}{K_{B.}T}\right)}$.
- $Thus, 2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2} e^{\left(\frac{E_V - E_{Fp}}{K_{B.}T}\right)} = N_A \times exp\left(\frac{E_{Fp}-E_A}{K_B T}\right)$
- $e^{\left(\frac{E_V - E_{Fp} - E_{Fp} + E_A}{K_{B.}T}\right)} = e^{\left(\frac{E_V + + E_A - 2E_{Fp}}{K_{B.}T}\right)} = \frac{N_A}{2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2}}$
- Taking logarithm on both sides,

$$\left(\frac{E_V + E_A - 2E_{Fp}}{K_{B.}T}\right) = log_e\left(\frac{N_A}{2\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/2}}\right)$$

- $\left(E_{Fp}\right) = \frac{E_V + E_A}{2} - K_{B.}T log_e\left(\frac{{N_A}^{1/2}}{2^{1/2}\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/4}}\right)$
- $\left(\frac{E_V - E_{Fp}}{K_B T}\right) = \frac{E_V - E_A}{2K_B T} + log_e\left(\frac{{N_A}^{1/2}}{2^{1/2}\left(\frac{2\pi m_h^* K_B T}{h^2}\right)^{3/4}}\right)$

- $exp\left(\frac{E_V - E_{Fp}}{K_BT}\right) = exp\left(\frac{E_V - E_A}{2K_BT} + log_e\left(\frac{{N_A}^{1/2}}{2^{1/2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/4}}\right)\right)$

- $exp\left(\frac{E_V - E_{Fp}}{K_BT}\right) = exp\left(\frac{E_V - E_A}{2K_BT}\right)\left(\frac{{N_A}^{1/2}}{2^{1/2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/4}}\right)$

- $Multiplying\ by\ 2\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/2}\ on\ both\ sides,$

$$\mathbf{2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/2} exp\left(\frac{E_V - E_{Fp}}{K_BT}\right) = \mathbf{2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/2} exp\left(\frac{E_V - E_A}{2K_BT}\right)\left(\frac{{N_A}^{1/2}}{2^{1/2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/4}}\right)$$

$$\boxed{(p_p) = (2N_A)^{1/2}\left(\frac{2\pi m_h^* K_BT}{h^2}\right)^{3/4} exp\left(\frac{E_V - E_A}{2K_BT}\right)}$$

$$Thus, (p_p) \propto (N_A)^{1/2}\ when\ 'T'\ is\ low.$$