Semiconductors

Carrier concentrations representative of metals, semimetals, and semiconductors are shown in figure (1). Semiconductors are generally classified by their electrical resistivity at room temperature, with values in the range of 10^{-2} to 10^{9} Ω.cm, and strongly on temperature.

Devices based on semiconductors include transistors, switches, diodes, photovoltaic cell, and detectors. These may be used as single circuit elements or as components of integrated circuits.

A highly purified semiconductor exhibits intrinsic conductivity, as distinguished from the impurity conductivity of less pure specimens. The band gap is the difference in energy between the lowest point of ther conduction band and the highest point of the valence band. As the temperature is increased, electrons are thermally excited from the valence band to the conduction band (figure 2). Both the electrons in the conduction band and the holes left behind in the valence band contribute to the electrical conductivity.

The threshold of continuous optical absorption at frequency ω_g determines the band gap $E_g = \hbar\omega_g$. In the direct absorption process a photon is absorbed by the crystal with the creation of an electron and a hole.
In the indirect absorption process the minimum energy gap f the band structure involves electrons and holes separated by a substantial k_e. Here a direct photon transition at the energy of the minimum gap cannot satisfy the requirement of conservation of wavevector, because photon wavevector are negligible at the energy range of interest. But if a photon of wavevector k and frequency ω_{ph} is created in the process, then we can have

$$K(\text{photon}) = k_e + k$$
$$\hbar\omega = E_g + \hbar\omega_{ph}$$

As required by the conservation laws.

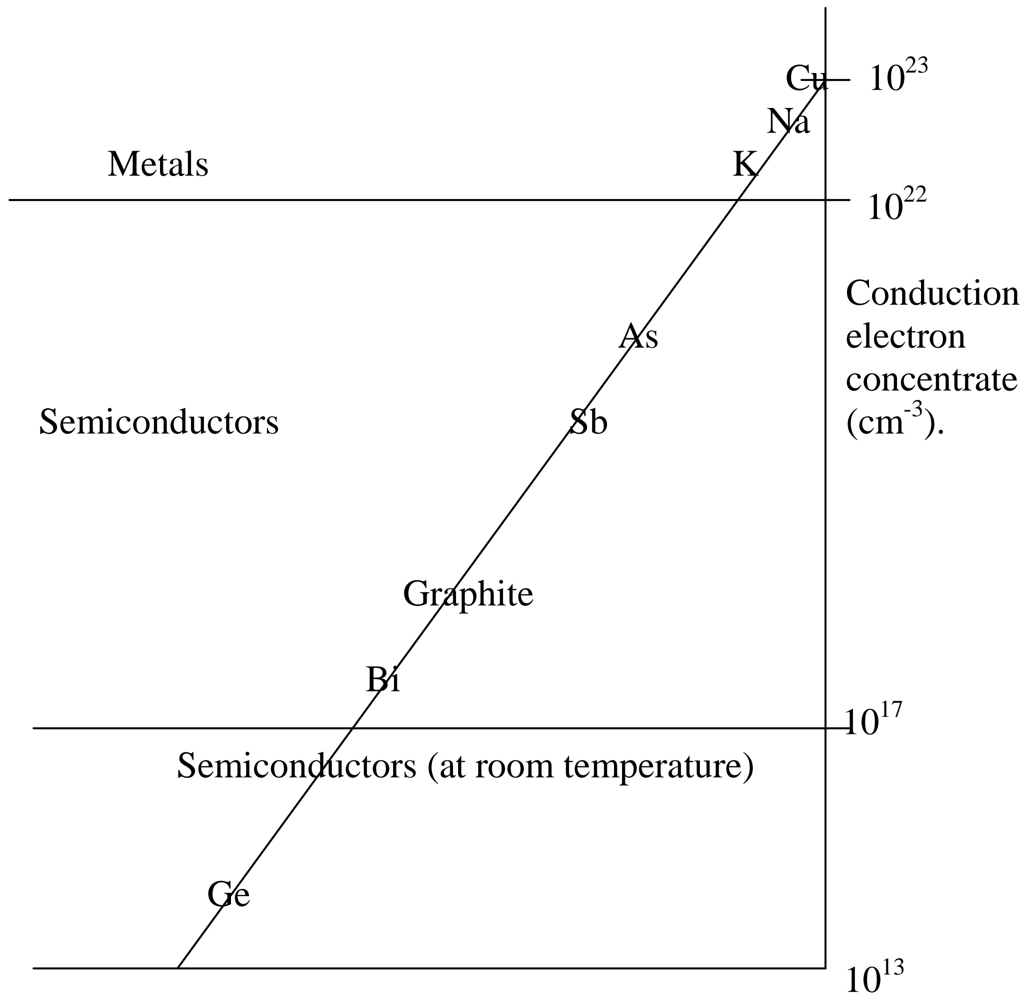


Figure (1) .

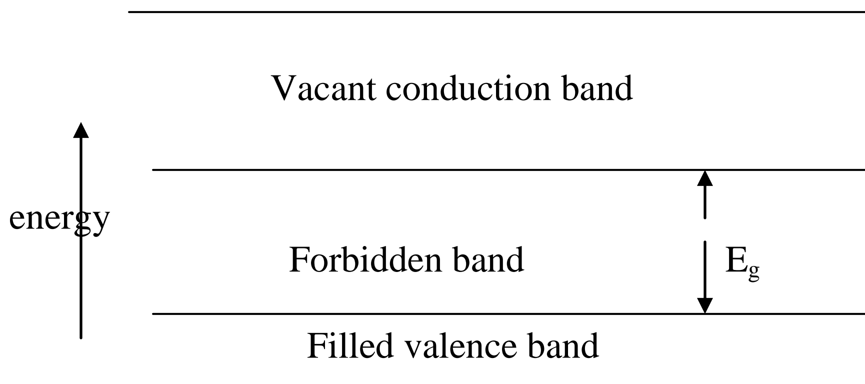


Figure (2) Band scheme for intrinsic conductivity in semiconductors.

Band theory of solids

The theory discussed in this chapter forms the basis for the modern theory of electrons in solids. It arises from the consideration of the periodicity of the crystal structure.

For traveling free electron wave, the wave function is given by

$$\nabla^2\psi(x,y,z)+\frac{2m}{\hbar^2}[E-V(x))\psi(x,y,z)=0$$

If wave function is independent on time and change with (x) only led to

$$\frac{\partial^2\psi(x)}{\partial x^2}+\frac{2m}{\hbar^2}[E-V(x)]\psi(x)=0$$

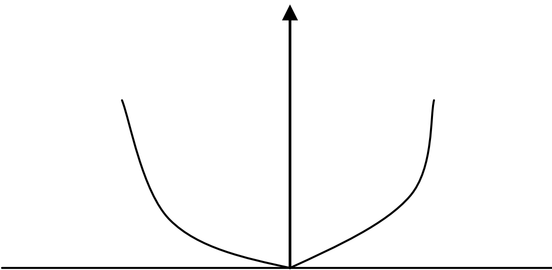
By solving last equation have two situations

i) $V(x)=0$ free electron

$$\frac{\partial^2\psi}{\partial x^2}+\frac{2m}{\hbar^2}E\psi(x)=0$$

The energies and k – values of the free electron in acube of side (L) are

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



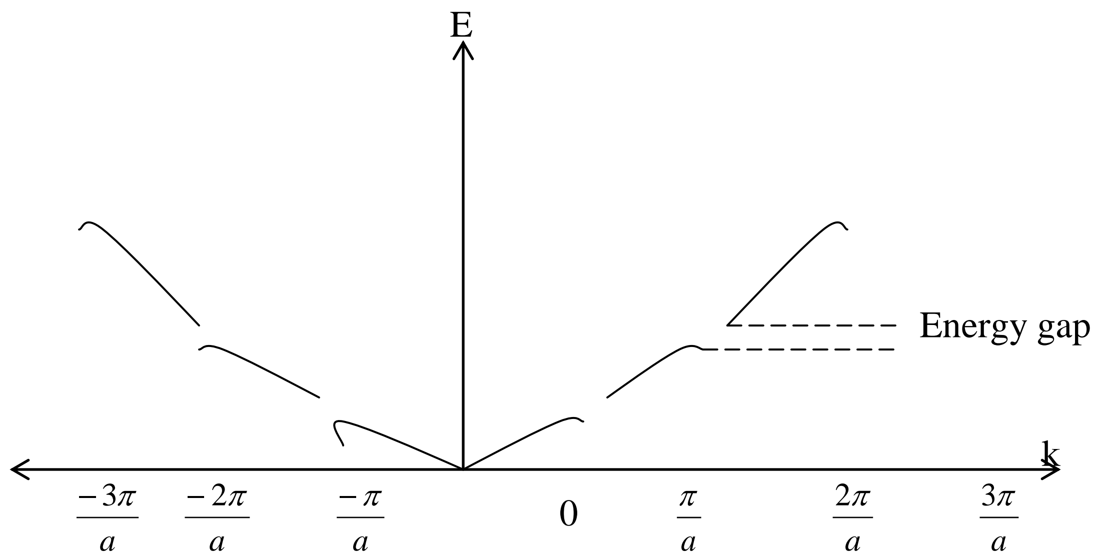
ii) if electron has periodic potential

electrons, besides acting as discrete particles, have wave like behavior. This property was used in considering the number of allowed states.

Consider a one – dimensional lattice in which the energy of an electron is being slowly increased so that (k) increases.

$k = \frac{m\pi}{a}$ m = $\mp 1, \pm 2, \ldots\ldots\ldots$

When k becomes large enough (λ small enough) the electron wave will suffer a Bragg reflection. $2d\sin\theta = m\lambda$, for the one, dimensional case d=a.



Reduced mass

Acceleration $a = \frac{dV}{dt} = \frac{dV}{dk}\cdot\frac{dk}{dt}$……… (1)

$V = \frac{d\omega}{dk}$

$\because E = \hbar\omega, \qquad \omega = \frac{E}{\hbar} \qquad V = \frac{1}{\hbar}\cdot\frac{dE}{dk}$……..(2)

$\therefore \frac{dV}{dk} = \frac{1}{\hbar}\cdot\frac{d^2E}{dk^2}$………(3)

$\because E = F \cdot x \qquad \therefore dE = F \cdot dx$

$dE = F \cdot Vdt$

$\therefore \frac{dE}{dt} = F \cdot V$

$\frac{dE}{dk} \cdot \frac{dk}{dt} = F \cdot V \ldots\ldots\ldots(4)$

Substitute equation (2) in equation (4)

$\hbar \frac{dk}{dt} = F \ldots\ldots\ldots(5)$

By substitute equation (3) and (5) in equation (1)

$$a = \frac{dV}{dk} \cdot \frac{dk}{dt} = \frac{1}{\hbar} \cdot \frac{d^2E}{dk^2} \cdot \frac{F}{\hbar}$$

$\because a = \frac{F}{m} \qquad \therefore a = \frac{F}{m^*}$

$$\boxed{\therefore m^* = \frac{\hbar^2 dk^2}{d^2E}}$$

Intrinsic semiconductor

The semiconductors are defined as insulators with small forbidden gaps. At finite temperature some electrons are excited from the lower valence band to the upper, conduction one. So there are holes in the valence band and the electrons in the conduction one. Such semiconductor is called intrinsic.

For electron

Number of electron $n = \int_{E_c}^{\infty} f(E) \cdot g(E) dE$

$$n = \int_{E_c}^{\infty} \frac{1}{2\pi^2} (\frac{2m^*_e}{\hbar^2})^{3/2} (E - E_g)^{1/2} \cdot \frac{1}{1 + e^{\frac{E - E_F}{kT}}} \cdot dE$$

$$n = 2\left\{\frac{2\pi m^*{}_e kT}{\hbar^2}\right\}^{3/2} e^{\frac{E_{fi}-E_c}{kT}}$$

$$N_c = 2\left\{\frac{2\pi m^*{}_e kT}{h^2}\right\}^{3/2}$$ effective density of conduction band states

$$n = N_c e^{\frac{E_f - E_c}{kT}}$$

For hole

$$N_v = 2\left\{\frac{2\pi m^*{}_h kT}{h^2}\right\}^{3/2}$$ effective density of valence band states

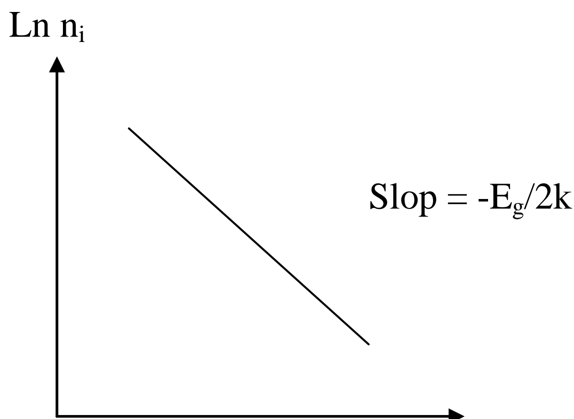
$$P = N_v e^{\frac{E_v - E_f}{kT}}$$

Normally electron excited from valence band leave hole.
In equilibrium n = P i.e. number of hole = number of electron.

$n_i = \sqrt{np}$ effective mass law

$$n_i = (N_c N_v)^{1/2} e^{\frac{E_v - E_c}{2kT}} = (N_c N_V)^{1/2} e^{-\frac{E_g}{2kT}}$$

$$n_i = 2\left(\frac{kT 2\pi}{h^2}\right)^{3/2} (m^*{}_e m^*{}_h)^{3/4} e^{-\frac{E_g}{2kT}}$$

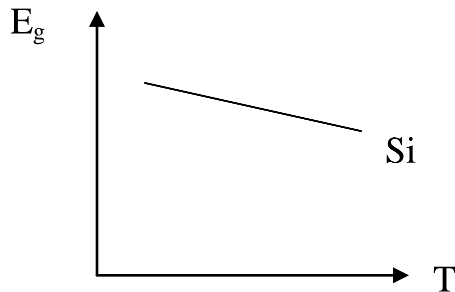


1/T

Variation of band (energy gap) with temperature

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

Material	Ge	Si	GaAs
$E_g(0)$	0.741	1.16	1.522
$\alpha(10^{-4})$	4.56	7.02	5.8
β	210	1108	300



Conductivity

$$\sigma = n_i e\mu = n_i e(\mu_h + \mu_e)$$

Intrinsic material has limited application careful chosen impurity alter electrical properties since conductivity in intrinsic

$$\sigma = n_i e\mu$$

Doped semiconductor

The semiconductors are defined as insulators with small forbidden gaps. At finite temperature some electrons are excited from the lower valence band to the upper, conduction one. So there are holes in the valence band and the electrons in the conduction one. Such semiconductor is called intrinsic. The modern way to produce materials for electronics is to “dope” semiconductor material with impurity atoms which introduce carriers in a controllable way.

The impurity level is usually situated in the forbidden gap. If the impurity level are situated near the bottom of conduction band the atom are

ionized at low enough temperatures and provide extra electrons to the band (such impurities are called donors). Contrary, if the levels are near the top of the valence band they take electrons from the band producing holes (they are called accepters). We will come back to this classification later to describe special features of different materials.
Adding small percentage of atom of other materials group we can control electrical properties.

- impurity atom should fit in crystal without crystal distortion.
- Doped atom produce electronic state E_D or E_A.

Impurity n- type (donor atoms

- Donor atom has one electron extra.

$$n_n = \frac{1}{\sqrt{2}}\{N_D N_C\}^{1/2} e^{-\frac{E_d}{2kT}} \qquad \text{if} \quad N_D \succ\succ \frac{1}{2} N_C e^{-\frac{E_d}{kT}}$$

Or $n_n = N_D$ if $N_D \prec\prec \frac{1}{2} N_C e^{-\frac{E_d}{kT}}$

- impurity states spreading : band width increase as impurity density increase i.e. gab between E_d, E_C decrease as impurity increase.
- Electron density = donor atom density. These electrons appears in conduction band and no corresponding hole in valance band.

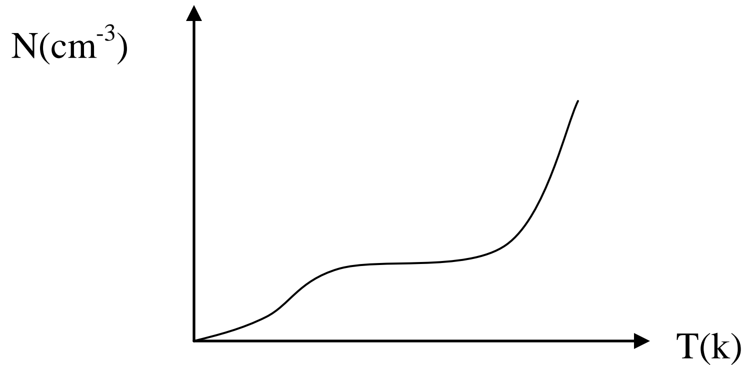
Impurity p- type (acceptor atoms)

- acceptor atom need one electron

$$P_P = \frac{1}{\sqrt{2}}\{N_V N_A\}^{1/2} e^{-\frac{E_A}{2kT}} \qquad \text{if} \quad N_A \succ\succ \frac{1}{2} N_V e^{-\frac{E_A}{kT}}$$

Or $P_P = N_A$ if $N_A \prec\prec \frac{1}{2} N_V e^{-\frac{E_A}{kT}}$

- energy transfer small from valence band, i.e. hole generated in valance band.
- Hole density = accepter atom density.
- Hole appears in valance band and no corresponding electron in conduction band.



Mobility

Normally electron have thermal random velocity $V_T = \left(\frac{3kT}{m}\right)^{1/2} \approx 10^5 M/S$

And electron sufer random collision with lattice.

$\tau = \frac{l}{V_T}$: time interval between collision for electron or hole.

$$\frac{1}{\tau} = \frac{1}{\tau_{impurity}} + \frac{1}{\tau_{lattice}}$$

Where $\tau_{impurity}$: electron deflected when passes near charged particle (donor or acceptor) therefore scattering probability depend on total concentration.

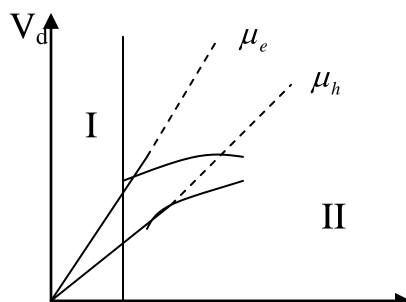
$\tau_{lattice}$: thermal vibration impedes the motion oh electros.

When E electric field applied, electron accelerate due to force by field

F = -Ee

$a = \frac{eE}{m}$ Acceleration during time (τ) and increase energy and when collision happen energy lost.

$$V_d = a\tau = \frac{e\tau}{m^*_e} E = \mu_e E \Rightarrow \mu_e = \frac{e\tau}{m^*_e} \propto \tau$$



E

Region I : E- small $\Rightarrow V_d \approx \frac{V_T}{30}$ i.e. ($V_d < V_T$) $\mu = f(E)$

At each collision electron return to lattice temperature.

Region II : E- high $V_d \geq V_T$

Electron velocity increased by field and electron temperature greater than lattice temperature i.e. not like metal.

Mobility can be measured by Hall effect or four probe technique.

$\mu_{imperuity} \propto T^{3/2}$ dominant at low temperature because lattice vibration concentration.

$\mu_{lattice} \propto \frac{1}{T^{3/2}}$ Dominate at high temperature.

Hall Effect in semiconductor

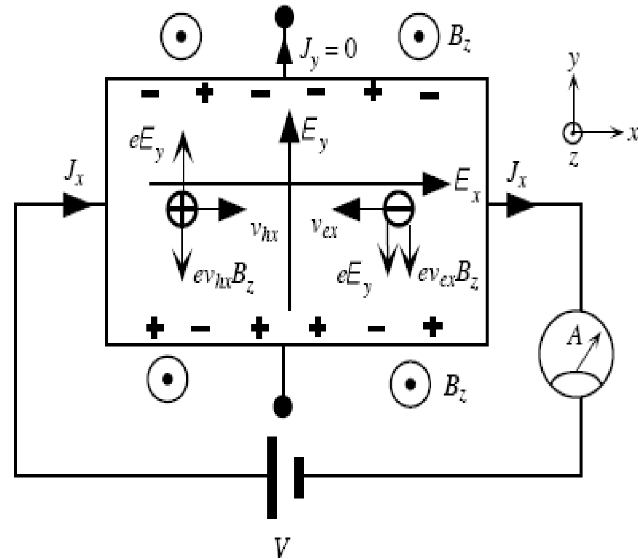
Hall effect in a sample where there are both negative and positive charge carriers, e.g. electrons and holes in a semiconductor, involves not only the concentrations of electrons and holes, n and p respectively, but also the electron and hole drift mobilities, μ_e and μ_h. We first have to reinterpret the relationship between the drift velocity and the electric field, E.

If μ_e is the drift mobility and v_e the drift velocity of the electrons, then we have already shown that $v_e = \mu_e E$. This has been derived by considering the *net electrostatic force*, eE, acting on a single electron and the imparted acceleration $a = eE/m_e$. The drift is therefore due to the net force, $F_{net} = eE$, experienced by a conduction electron. If we were to keep eE as the *net force* F_{net} acting on a single electron then we would have found

$$v_e = \frac{\mu_e}{e} F_{net} \qquad (1)$$

Equation (1) emphasizes the fact that drift is due to a net force, F_{net}, acting on an electron. A similar expression would also apply to the drift of a hole in a semiconductor.

When both electrons and holes are present as in a semiconductor sample, both charge carriers experience a Lorentz force in the same direction since they would be drifting in the opposite directions as illustrated in Figure 1.



Hall effect for ambipolar conduction as in a semiconductor where there are both electrons and holes. The magnetic field B_z is out from the plane of the paper. Both electrons and holes are deflected toward the bottom surface of the conductor and consequently the Hall voltage depends on the relative mobilities and concentrations of electrons and holes.

Figure 1

Thus, both holes and electrons tend to pile near the bottom surface. The magnitude of the Lorentz force, however, will be different since the drift mobilities and hence drift velocities will be different. Once equilibrium is reached, there should be no current flowing in the y direction as we have an open circuit; the resistance of the voltmeter connected between the top and bottom surfaces is very large. Let us suppose that more holes have accumulated near the bottom surface so that there is a built-in electric field $\mathbf{E}_y$ along y as shown in Figure 1. In the y-direction there is no net current, therefore

$$J_y = J_h + J_e = epv_{hy} + env_{ey} = 0 \quad (2)$$

where v_{ey} and v_{hy} are the electron and hole drift velocities in the y-direction. From Equation (2) we obtain

$$pv_{hy} = -nv_{ey} \quad (3)$$

We note that the net force acting on the charge carriers cannot be zero. This is impossible when two types of carriers are involved and that both carriers are drifting along y to give a net current J_y that is zero. This is what Equation (2) represents. We therefore conclude that, along y, both the electron and the hole must experience a driving force to drift them. The net force experienced by the carriers, as shown in Figure 1, is

$$F_{hy} = e\mathbf{E}_y - ev_{hx}B_z \qquad \text{and} \qquad -F_{ey} = e\mathbf{E}_y + ev_{ex}B_z \quad (4)$$

where v_{hx} and v_{ex} are the hole and electron drift velocities along x. We know that, in general, the drift velocity is determined by the net force acting on a charge carrier, that is, from Equation (1),

$$F_{hy} = ev_{hy}/\mu_h \qquad \text{and} \qquad -F_{ey} = ev_{ey}/\mu_e$$

so that Equation (4) becomes,

$$\frac{ev_{hy}}{\mu_h} = e\mathbf{E}_y - ev_{hx}B_z \qquad \qquad \frac{ev_{ey}}{\mu_e} = e\mathbf{E}_y + ev_{ex}B_z$$

where v_{hy} and v_{ey} are the hole and electron drift velocities along y. Substituting $v_{hx} = \mu_h\mathbf{E}_x$ and $v_{ex} = \mu_e\mathbf{E}_x$, these become

$$\frac{v_{hy}}{\mu_h} = \mathbf{E}_y - \mu_h\mathbf{E}_xB_z \qquad \qquad \frac{v_{ey}}{\mu_e} = \mathbf{E}_y + \mu_e\mathbf{E}_xB_z \quad (5)$$

From Equation (5) we can substitute for v_{hy} and v_{ey} in Equation (3) to obtain

$$p\mu_h\mathbf{E}_y - p\mu_h^2\mathbf{E}_xB_z = -n\mu_e\mathbf{E}_y - n\mu_e^2\mathbf{E}_xB_z$$

or

$$\mathbf{E}_y(p\mu_h + n\mu_e) = B_z\mathbf{E}_x(p\mu_h^2 - n\mu_e^2) \quad (6)$$

We now consider what happens along the x-direction. The total current density is finite and is given by the usual expression,

$$J_x = epv_{hx} + env_{ex} = (p\mu_h + n\mu_e)e\boldsymbol{E}_x \qquad (7)$$

We can use Equation (7) to substitute for $\boldsymbol{E}_x$ in Equation (6), to obtain

$$e\boldsymbol{E}_y(n\mu_e + p\mu_h)^2 = B_z J_x(p\mu_h^2 - n\mu_e^2)$$

The Hall coefficient, by definition, is $R_H = \boldsymbol{E}_y/J_xB_z$ so that

$$R_H = \frac{p\mu_h^2 - n\mu_e^2}{e(p\mu_h + n\mu_e)^2} \qquad \textit{Hall Effect for ambipolar conduction} \qquad (8)$$

or

$$R_H = \frac{p - nb^2}{e(p + nb)^2} \qquad \textit{Hall Effect for ambipolar conduction} \qquad (9)$$

where $b = \mu_e/\mu_h$. It is clear that the Hall coefficient depends on both the drift mobility ratio and the concentrations of holes and electrons. For $p > nb^2$, R_H will be positive and for $p < nb^2$, it will be negative. We should note that when only one type of carrier is involved, e.g. electrons only, $J_y = 0$ requirement means that $J_y = env_{ey} = 0$, or $v_{ey} = 0$. The drift velocity along y can only be zero, if the net driving force, F_{ey}, along y is zero. This occurs when the Lorentz force just balances the force due to the built-in field.

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1. Example: Hall coefficient of intrinsic silicon

Intrinsic silicon has electron and hole concentrations, $n = p = n_i = 1.5 \times 10^{10}$ cm^{-3}, and electron and hole drift mobilities, $\mu_e = 1350$ cm^2 V^{-1} s^{-1}, $\mu_h = 450$ cm^2 V^{-1} s^{-1}. Calculate the Hall coefficient and compare it with a typical metal.

Solution

Given $n = p = n_i = 1.5 \times 10^{10}$ cm^{-3}, $\mu_e = 1350$ cm^2 V^{-1} s^{-1} and $\mu_h = 450$ cm^2 V^{-1} s^{-1} we have

$$b = \mu_e/\mu_h = 1350/450 = 3$$

then,

$$R_H = \frac{(1\times10^{16}\ \text{m}^{-3}) - (1\times10^{16}\ \text{m}^{-3})(3)^2}{(1.6\times10^{-19}\ \text{C})\left[(1\times10^{16}\ \text{m}^{-3}) + (1\times10^{16}\ \text{m}^{-3})(3)\right]^2}$$

or

$$R_H = -208\ \text{m}^3\ \text{A}^{-1}\ \text{s}^{-1}$$

Optical properties for semiconductor

1) Fundamental absorption process.
2) Absorption by impurities
3) Absorption by free carrier charge.
4) Absorption by exiton.
5) Absorption by lattice vibration.

1) Fundamental absorption process

Transition of electron from valence band to conduction band, have two conditions i) energy conserve. ii) Momentum conserves. Dependent on momentum conserve divided fundamental absorption process into a) direct fundamental absorption process and b) indirect fundamental absorption process.

a) Direct fundamental absorption process

Divided direct fundamental absorption process into allow direct fundamental absorption process and forbidden direct fundamental absorption process. The difference between them the wave function for electron in conduction band the same as in the valance band for allow direct fundamental absorption process, but the wave function for electron in conduction band different from the wave function in the valence band for forbidden direct fundamental absorption process. Give the absorption coefficient by the relation:

$\alpha_d = A(h\upsilon - E_g)^{1/2}$ Allow direct fundamental absorption process

When $h\upsilon \succ E_g$

$\alpha_d = 0$ if $h\upsilon \prec E_g$

$\alpha_d = B(h\upsilon - E_g)^{3/2}$ Forbidden direct fundamental absorption process

In this process generation electron – hole couple lead to change the conductivity.

b) Indirect fundamental absorption process.

In this transition the momentum is none conserved so that addition phonon.

$\alpha_i = \alpha_e + \alpha_a$

$\alpha_i = \alpha_e$ Emission phonon

$\alpha_i = \alpha_a$ Absorption phonon

2) Absorption by impurities

This process take place when the incident wave length has energy less than energy gap for semiconductor, with condition as below

i) $h\upsilon \succ E_d$ or E_A

ii) deionization of impurities

$\alpha_{imp} = N_t \delta$

Recombination process

i) **direct recombination**

take place in direct energy gap semiconductor and divided into

a) radiative recombination. B) Auger recombination.

a) **irradiative recombination**

when the electron returen from conduction band to the valence band radiate photon.

b) **Auger recombination**

Take place in generation semiconductor [Fermi level in conduction band or valence band, $N_d, N_E \succ 10^{20} cm^{-3}$]. The electron return from conduction band to the valance band and recombination with hole produce free hole.

ii) **recombination via recombination centers**

take place in indirect energy gap generally by recombination centre, structure distortion and deep impurity……

Examples

EXAMPLE 1) n – type silicon sample doped with two impurities, the first has ionization energy 0.045 ev and Nd=1016cm-3 , the second has ionization energy 0.35 ev and Nd =1016Cm-3. Calculate electrical conductivity if $\mu_e = 1500 cm^2/V \cdot \sec$, $\mu_h = 500 cm^2/V \cdot \sec$, $N_C = 2.8 \times 10^{19} cm^{-3}$, and $n_i = 1.2 \times 10^{10} cm^{-3}$.

Solution

$$\frac{1}{2}N_C e^{-\frac{E_{d1}}{kT}} = \frac{1}{2}\times 2.8\times 10^{19} e^{-\frac{0.045}{0.0258}} = 2.4\times 10^{18} cm^{-3}$$

$$10^{16} \prec\prec 2.4\times 1^{18}$$

$$\therefore n_n = 10^{16} cm^{-3}$$

$$\frac{1}{2}N_C e^{-\frac{E_{d2}}{kT}} = \frac{1}{2}\times 2.8\times 10^{19} e^{-\frac{0.35}{0.052}} = 1.7\times 10^{13} cm^{-3}$$

$$N_D \succ\succ 1.7\times 10^{13}$$

$$n_n = \frac{1}{\sqrt{2}}\left(2.8\times 10^{19}\times 10^{16}\right)^{1/2} e^{-\frac{0.35}{0.052}} = 3.87\times 10^{14} cm^{-3}$$

$$n_t = 10^{16} + 0.038\times 10^{16} = 1.038\times 10^{16} cm^{-3}$$

$$n_i^{\,2} = np$$

$$p = \frac{\left(1.2\times 10^{10}\right)^2}{10^{16}} = 1.44\times 10^{4} cm^{-3}$$

$$\delta = nq\mu_e + pq\mu_h$$

$$\delta = 10^{16}\times 1.6\times 10^{-19}\times 1500 + 1.44\times 10^{4}\times 1.6\times 10^{-19}\times 500$$

δ = (Ωcm)$^{-1}$

EXAMPLE 2) n – type Ge sample has resistivity 0.1 Ωcm in room temperature. Calculate electrical conductivity for hole if $\mu_e = 3900 cm^2 / V\cdot \sec$, $\mu_h = 1900 cm^2 / V\cdot \sec$, and $n_i = 2.4\times 10^{13} cm^{-3}$.

Solution

$$\delta = \frac{1}{\rho} = \frac{1}{0.1} = 10\left(\Omega\cdot cm\right)^{-1}$$

$$\delta = nq\mu_e$$

$$10 = n\times 1.6\times 10^{-19}\times 3900 = 1.6\times 10^{16} cm^{-3}$$

$$n_i^{\,2} = np$$

$$p=\frac{\left(2.4\times10^{13}\right)^{2}}{1.6\times10^{16}}=3.6\times1^{10}$$

$$\delta=pq\mu_{h}=3.6\times10^{10}\times1.6\times10^{-19}\times1900=1.1\times10^{-5}\left(\Omega\cdot cm\right)^{-1}$$

EXAMPLE 3) Intrinsic Ge sample with length 1 cm, width 2 mm, and thickness 1 mm has electrical resistance 2160 Ω in temperature 20 °C .Calculate electrons number if $\mu_{e}=3900cm^{2}/V\cdot\sec$,and $\mu_{h}=1900cm^{2}/V\cdot\sec$.

Solution

$$R=\rho\frac{l}{A}$$

$$\rho=\frac{AR}{l}=\frac{2\times10^{-1}\times10^{-1}\times2160}{1}=4320\times10^{-2}\,\Omega\cdot cm$$

$$\delta=\frac{1}{\rho}=0.0231=2.3\times10^{-2}\left(\Omega\cdot cm\right)^{-1}$$

$$\delta=n_{i}q\left(\mu_{e}+\mu_{h}\right)$$

$$2.3\times10^{-2}=n_{i}\times1.6\times10^{-19}\left(1900+3900\right)$$

$$n_{i}=\frac{2.3\times10^{-2}}{5800\times1.6\times10^{-19}}=2.4\times10^{13}cm^{-3}$$

EXAMPLE 4) Calculate Fermi level position in silicon doped with As ($N_d = 10^{15}$ cm^{-3}). If ionization energy for As 0.054 eV, and (Nc = 2.8*10^{19} cm^{-3}).

Solution

$$\frac{1}{2} N_C e^{-\frac{E_d}{kT}} = \frac{1}{2} \times 2.8 \times 10^{19} \times e^{-\frac{0.054}{0.0258}} = 1.6 \times 10^{17} cm^{-3}$$

$$N_d \prec\prec 1.6 \times 10^{17}$$

$$n_n = N_d = 10^{15} cm^{-3}$$

$$n = N_c \times e^{\frac{E_f - E_c}{kT}}$$

$$\frac{n}{N_c} = e^{\frac{E_f - E_c}{kT}}$$

$$\ln \frac{n}{N_c} = \frac{E_f - E_c}{kT}$$

$$E_f - E_c = kT \times \ln \frac{n}{N_c} = 0.0258 \ln \frac{10^{15}}{2.8 \times 10^{19}} = 0.19 eV$$