Lecture 3:

Semiconductor Physics

Conductivity of intrinsic and extrinsic semiconductors

✓ Charged carriers in semiconductors: electrons and holes.

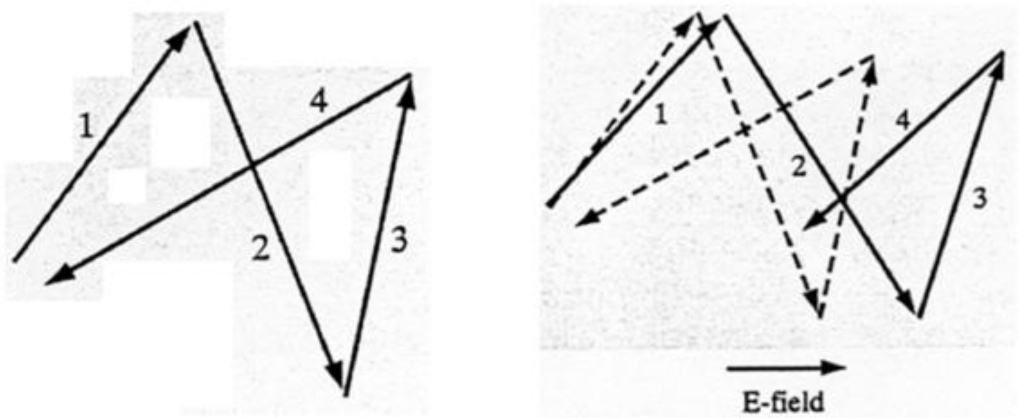
✓ Carrier transport: movement of electrons and holes.

Mechanisms of carrier transport
- Drift: charge movement due to electric field
- Diffusion: charge movement due to density gradient

➢ **Drift** → Movement of charged particles in response to an external field (typically an electric field)

The motion of a hole is related to an electric field by $F = m_p^* \dfrac{dv}{dt} = eE$

If we assume the initial drift velocity to be zero, then we have $v = \dfrac{eEt}{m_p^*}$



The hole undergoes random thermal motion under no applied electric field. In the presence of an electric field, **there will be a net drift of the hole in the direction of the electric field.**

If there is a mean time between collisions and this mean time is independent on the electric field, then the mean peak velocity just before a collision is:

$$v_{\mathrm{d|peak}} = \left(\frac{e\tau_{\mathrm{cp}}}{m_{\mathrm{p}}^{*}}\right)E$$

The average drift velocity will be:

$$\langle v_{\mathrm{d}} \rangle = \frac{1}{2}\left(\frac{e\tau_{\mathrm{cp}}}{m_{\mathrm{p}}^{*}}\right)E$$

If we consider the average collision time over the random thermal motion, the factor of ½ will be eliminated. The hole mobility is then given by:

$$\boxed{\mu_{\mathrm{p}} = \frac{v_{\mathrm{dp}}}{E} = \frac{e\tau_{\mathrm{cp}}}{m_{\mathrm{p}}^{*}}}$$

The same analysis applies for electrons:

$$\boxed{\mu_{\mathrm{n}} = \frac{e\tau_{\mathrm{cn}}}{m_{\mathrm{n}}^{*}}}$$

Carrier Drift

Observe that the text uses "*e*" instead of "q" as a symbol for a unit of charge

Drift current density $J_{drift} = \rho v_d$

- Current density due to the holes

Charge density: $\rho = ep$

Drift velocity of holes $v_{dp} = \mu_p E$

Current density due to the holes $J_{p|drift} = ep\mu_p E$

- Current density due to the electrons

Charge density: $\rho = -en$

Drift velocity of electrons $v_{dn} = -\mu_n E$

$$J_{n|drift} = en\mu_n E$$

- Total drift current density $J_{drift} = e(p\mu_p + n\mu_n)E$

Conductivity

$$J_{drift} = e(p\mu_p + n\mu_n)E = \sigma E$$

$$\Downarrow$$

Conductivity: $$\sigma = e(p\mu_p + n\mu_n)$$ Unit: (Ω.m)-1

Resistivity: $$\rho = \frac{1}{\sigma} = \frac{1}{e(p\mu_p + n\mu_n)}$$ Unit: (Ω.m)

Intrinsic semiconductor: $$\sigma = e(p\mu_p + n\mu_n) = en_i(\mu_p + \mu_n)$$

N-type semiconductor: $$\sigma = e(p\mu_p + n\mu_n) \approx en\mu_n \approx eN_d\mu_n$$

P-type semiconductor: $$\sigma = e(p\mu_p + n\mu_n) \approx ep\mu_p \approx eN_a\mu_p$$

- For intrinsic semiconductor, $n = p = n_i$

$$J = n_i e(\mu_n + \mu_p)E$$

- Comparing with current density, $J = \sigma E$, we can get the conductivity,

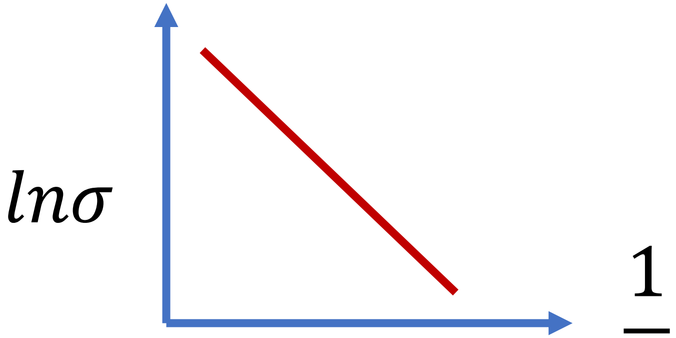
$$\sigma = n_i e(\mu_n + \mu_p) \Longrightarrow \sigma = (\sigma_n + \sigma_p)$$

where, $\sigma_n = n_i e \mu_n$ and $\sigma_p = n_i e \mu_p$. Using n_i expression,

$$\sigma = e(\mu_n + \mu_p)\frac{2(2\pi kT)^{3/2}}{h^3}(m_n^* m_p^*)^{3/4} exp\left(-\frac{E_g}{2kT}\right)$$

$$ln\sigma = -\frac{E_g}{2kT} + \frac{3}{2} lnT + C$$

Here C is a constant.

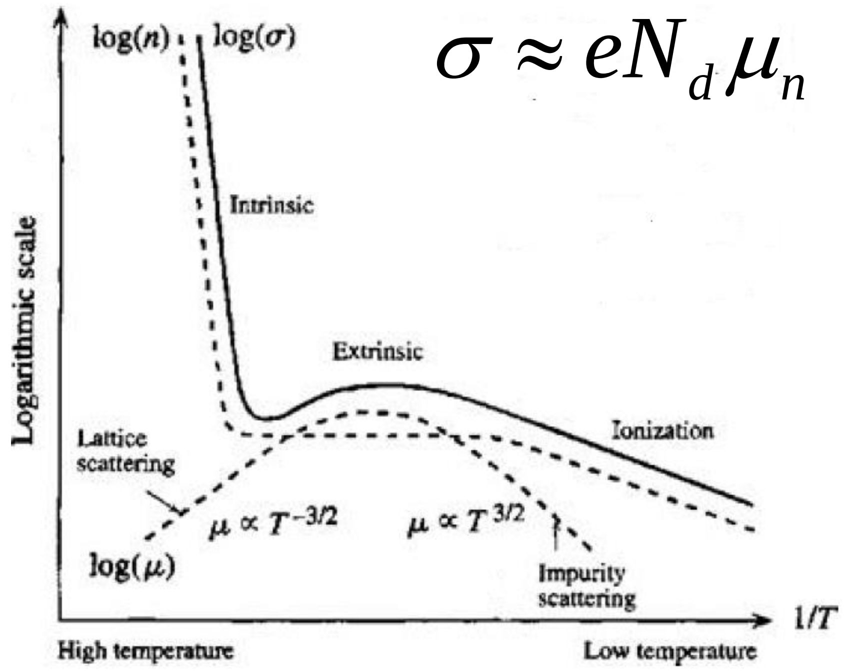


- The slop of the line gives an estimate of bandgap of a semiconductor.

➢ Variation of electrical conductivity of n-type semiconductor with temperature

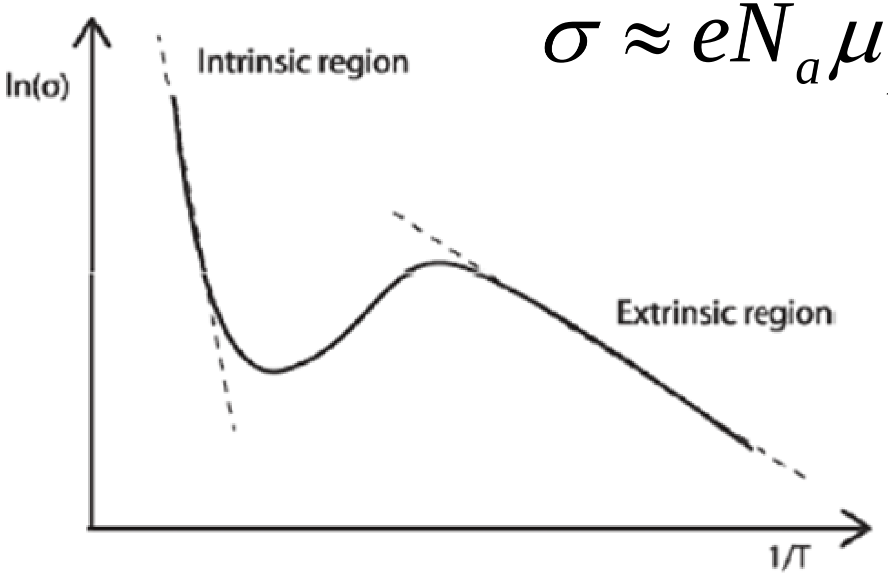
For a doped semiconductor, the temperature dependence of electron concentration can be seen in figure. At very low temperatures (large 1/T), negligible intrinsic electron hole pairs exist (n_i is very small), and the donor electrons are bound to the donor atoms. This is known as the ionization (or freeze out) region. As the temperature is raised, increased ionization occurs and at about 100 K all of the donor atoms are ionized, at which point the carrier concentration is determined by doping. The region where every available dopant has been ionized is called the extrinsic (or saturation) region. In this region, an increase in temperature produces no increase in carrier concentration. At high temperatures, the thermally generated intrinsic carriers outnumber the dopants. In this intrinsic region, carrier concentration increases with temperature.

$$\sigma \approx eN_d\mu_n$$



➢ Variation of electrical conductivity of p-type semiconductor with temperature

$$\sigma \approx eN_a\mu_p$$



Hall Effect

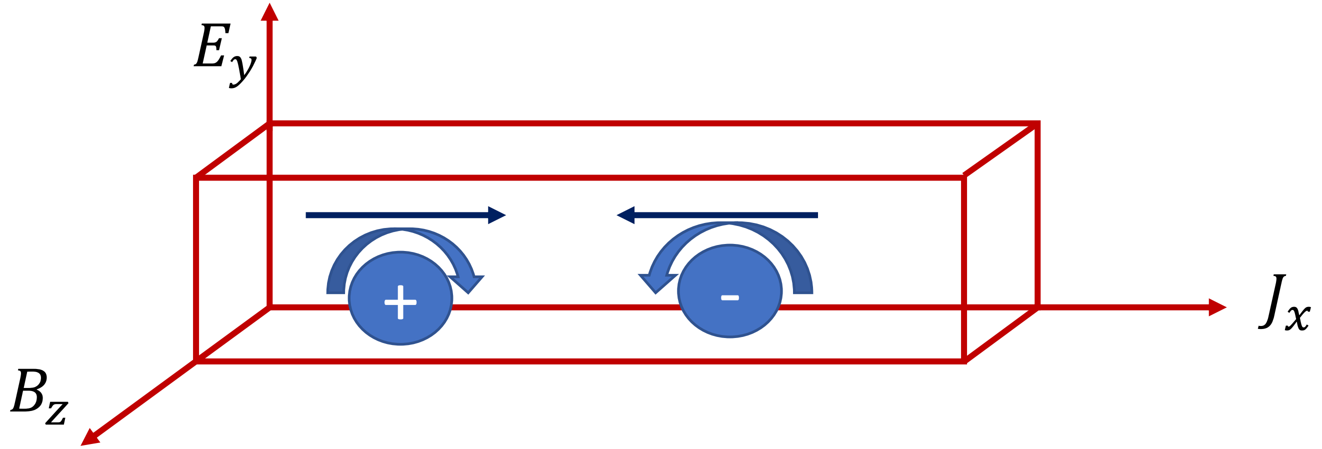
- When a material carrying current is subjected to a magnetic field in a direction perpendicular to direction of current, an electric field is developed across the material in a direction perpendicular to both the direction of magnetic field and current direction. This phenomenon is called “Hall-effect”.

Consider a semiconductor (schematic diagram in next page), and current J_x passes along the X-axis and a magnetic field B_z is applied along the Z-direction, a field E_y is called the Hall field which is developed in the Y-direction.

Hall Effect in Semiconductors

- Consider a semiconductor, where both electrons and holes are present. Since there charges are different and they move in opposite directions in an electric field.

- Two charge carriers, electron and hole flow in $-x$ and $+x$ directions respectively, under the electric field E_x.



- The Lorentz force $F_L = q(\vec{v} \times \vec{B})$ deflects them in the same direction as shown in below figure.

- The current density along x −axis,

$$J_x = J_x(e) + J_x(h) = e(n\mu_e + p\mu_h)E_x \qquad (1)$$

- The current density along y −axis, the both charges will experience Lorentz field as well the Hall field, E_H,

$$J_y = J_y(e) + J_y(h)$$

$$J_y = ne\mu_e\left(E_y - v_{ex}B_z\right) + pe\mu_h\left(E_y - v_{hx}B_z\right)$$

where,

$$v_{ex} = -\mu_e E_x \qquad v_{hx} = \mu_h E_x$$

- In equilibrium, $J_y = 0$

$$0 = ne\mu_e\left(E_y + B_z\mu_e E_x\right) + pe\mu_h\left(E_y - \mu_e E_x B_z\right)$$

- Using v_{ex} and v_{hx}, above equation gives,

$$E_y = E_x B_z \frac{p\mu_h^2 - n\mu_e^2}{n\mu_e + p\mu_h} \qquad (2)$$

- Using E_x from equation (1) into equation (2),

$$E_y = \frac{J_x B_z}{e} \frac{p\mu_h^2 - n\mu_e^2}{(n\mu_e + p\mu_h)^2}$$

- It may write as,

$$\frac{E_y}{J_x B_z} = R_H = \frac{1}{e} \frac{p\mu_h^2 - n\mu_e^2}{(n\mu_e + p\mu_h)^2}$$

- It may write as,

$$\boxed{R_H = -\frac{1}{ne}}$$ For n-type semiconductor.

$$\boxed{R_H = \frac{1}{pe}}$$ For p-type semiconductor.

- Hall mobility,

$$\mu_H = \sigma R_H = \frac{p\mu_h^2 - n\mu_e^2}{(n\mu_e + p\mu_h)}$$ where, $\mu_e = \frac{\sigma}{ne}$ and $\mu_h = \frac{\sigma}{ne}$

Application of Hall Effect

1. Determination of the type of Semiconductors: The Hall coefficient R_H is -ve for an n-type semiconductor and +ve for *p*-type semiconductor. Thus the sign of Hall coefficient can be used to determine whether a given Semiconductor is n or p-type.

2. Calculation of carrier concentration.

$$\boxed{R_H = -\frac{1}{ne}}$$ For n-type semiconductor.

$$\boxed{R_H = \frac{1}{pe}}$$ For p-type semiconductor.

3. Determination of Mobility: If the conduction is due to one type carriers, ex: electrons

$$\sigma = \mathrm{ne}\mu_e$$

$$\mu_e = \frac{\sigma}{\mathrm{ne}} = \sigma\, R_H$$

$$\mu_e = \sigma\, R_H$$

4. Measurement of Magnetic Flux Density:

$$E_y = \frac{J_x B_z}{e} \frac{p\mu_h^2 - n\mu_e^2}{(n\mu_e + p\mu_h)^2}$$

Hall Voltage is proportional to the magnetic flux density B for a given current I. so, Hall Effect can be used as the basis for the design of a magnetic flux density metal.