ELEC4705 – Fall 2009

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LECTURE 10

Extrinsic Semiconductors
Carrier Flow

Contents

10.1. Extrinsic Semiconductors

To change the electrical properties of semiconductors we modify carrier concentrations by adding impurities to intrinsic material. This process is called doping. During doping, impurity atoms are introduced to an intrinsic semiconductor. Impurity atoms are atoms of a different element than the atoms of the intrinsic semiconductor. Impurity atoms act as either donors or acceptors to the intrinsic semiconductor, changing the electron and hole concentrations of the semiconductor. Impurity atoms are classified as donor or acceptor atoms based on the effect they have on the intrinsic semiconductor.

10.1.1. Donor Impurity

Donor impurity atoms have more valence electrons than the atoms they replace in the intrinsic semiconductor lattice. Donor impurities donate their extra valence electrons to a semiconductor's conduction band, providing excess electrons to the intrinsic semiconductor. Excess electrons increase the electron carrier concentration, n_0, of the semiconductor, making it n-type semiconductor. Consider figure 1. Suppose an Si atom is replaced with a phosphorus atom.

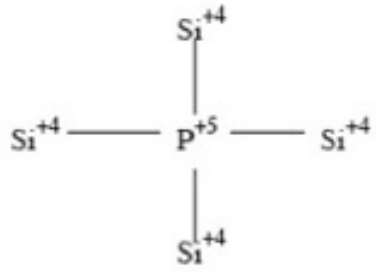

Figure 1. n-type semiconductor

We see that the phosphorus ion core has an extra +ve charge which means the periodic potential is disrupted and we get a localized energy level, E_D, see figure 2.
The phosphorus also provides an extra electron to fill this level We find that $E_c - E_D \approx 45meV$ which is very small. This electron is easily thermally donated to the conduction band at room temperature as $E_c - E_D$ is small compared with k_BT. This means that at room temperature $n \approx N_D$, which is called the complete ionization (only true if $n_i \ll N_D$). Therefore by doping Si crystal with phosphorus, we increase the free electron concentration, *n-type doping*.

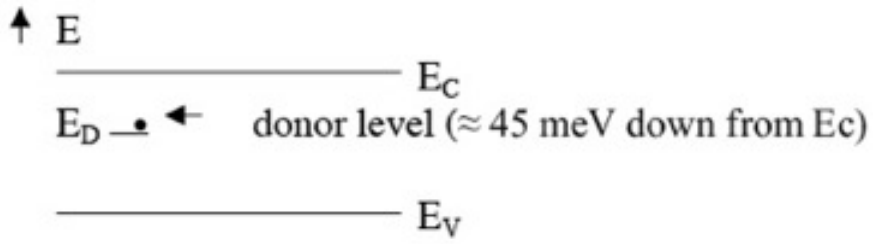

Figure 2. Localized Energy Level

By increasing E_D, E_F moves closer to E_c, see figure 3 and we have

$$n = N_c\, e^{-(E_c - E_F)/k_B T} \tag{10.1}$$

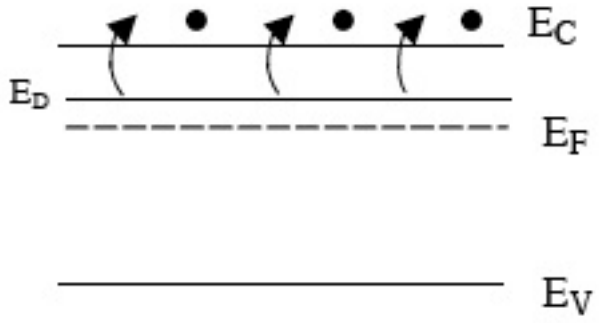

Figure 3. Energy Band Diagram of a n-type semiconductor

- As long as we don't have an applied voltage we still have the equation $np = n_i^2$. So at a constant temperature, p reduces as n increases.
- At low temperature, electrons return to donor levels; the dopant is frozen out.

10.1.2. Acceptor Impurity

Acceptor impurity atoms have less valence electrons than the atoms they replace in the intrinsic semiconductor. They accept electrons from the semiconductor's valence band. This provides excess holes to the intrinsic semiconductor. Excess holes increase the hole carrier concentration, p_0, of the semiconductor, creating a p-type semiconductor. Now suppose Si atom is replaced with Boron, again we have a perturbed lattice and a local E-level created as shown in figures 4 and

5.

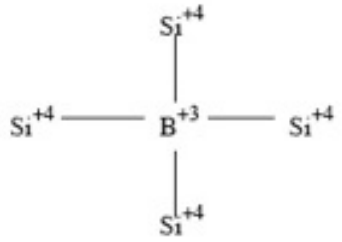

Figure 4. p-type semiconductor

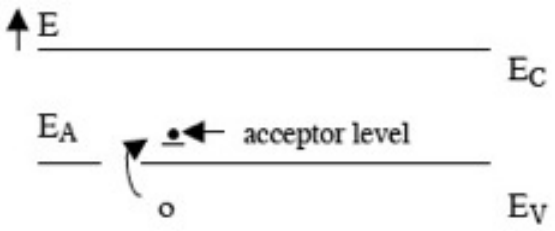

Figure 5. Localized Energy Level

- Boron is missing an electron and accepts an electron from valence band, creating a hole.
- The hole concentration is increased so the electron concentration is reduced. therefore $E_F$moves closer to E_v, as shown in figure 6.

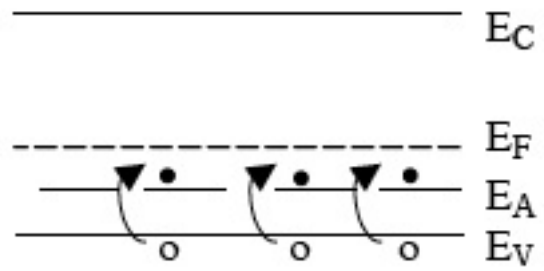

Figure 6. Energy Band Diagram of a p-type semiconductor

- At a reasonable temperature we have $p \approx N_A$ if $n_i \ll NA$.
- At low temperatures electrons return to valence band, holes are frozen out.

10.2. Carrier concentration and temperature dependency

Consider figure 7.

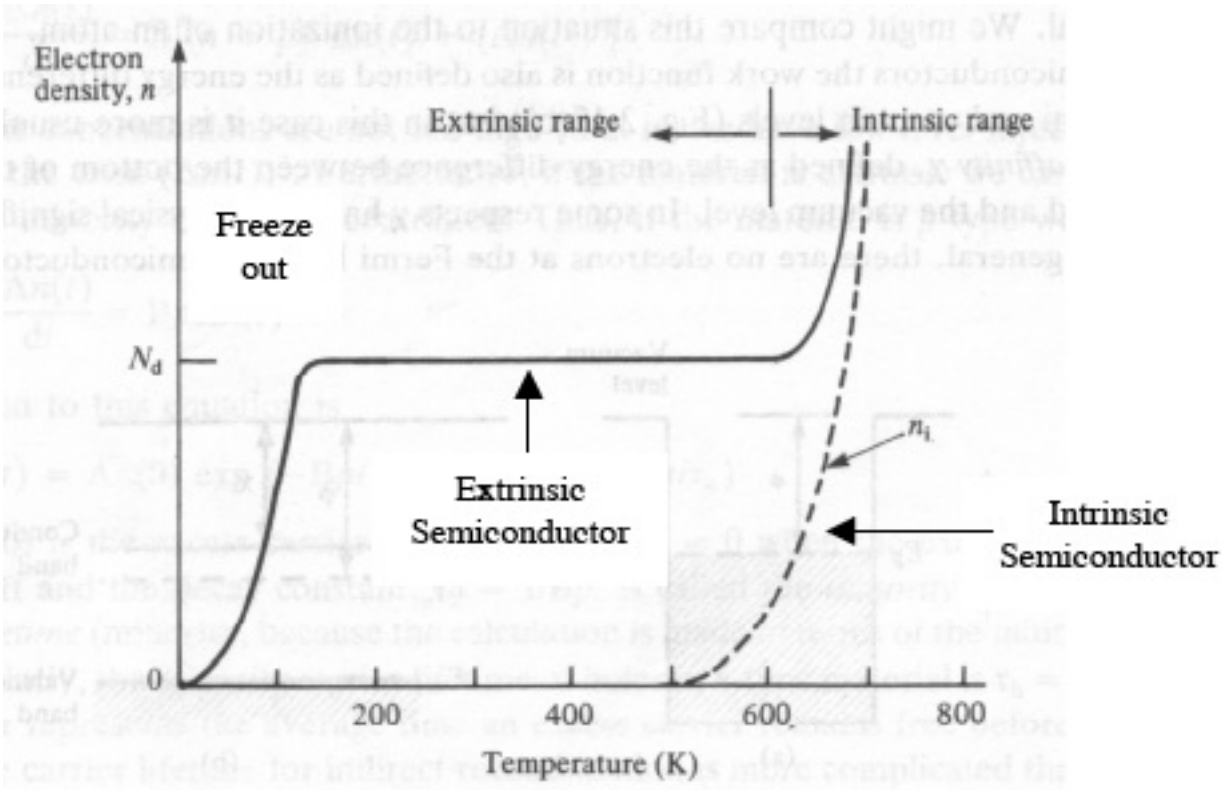

Figure 7. Electron density's temperature dependency

- At low temperature electrons drop to lowest E state.
- At medium temperature, donors/acceptors are activated.
- At high temperature large amount of excitation overs the bandgap.
- At lower T limit, impurities are frozen out ($n = N_D/2$).
- At upper T limit, intrinsic concentration take over ($n_i = N_D/2$).

Example 1. Lower Limit
Define useful activation at 50% of donor levels occupied when $E_F =$

ED.

We typically have:

$$E_c - E_D = E_c - E_F = 0.05\,eV$$
$$n = N_D/2 = N_C(\frac{T}{300})^{\frac{3}{2}}e^{-(E_c-E_F)/k_BT} \implies$$
$$5\times10^{15} = 5.4\times10^{15}(T)^{\frac{3}{2}}e^{-580.4/T} \implies$$
$$T = 86K$$

Example 2. Upper Limit

$$n_i = N_D/2 = \sqrt{N_cN_v(\frac{T}{300})^{\frac{3}{2}}e^{-E_G/2k_BT}} \implies$$
$$5\times10^{15} = 3.33\times10^{15}(T)^{\frac{3}{2}}e^{-1.6\times10^{-19}/2k_BT} \implies$$
$$T = 675K$$

10.3. Conductivity of Semiconductor

We know that Bloch waves (which describe electron flow) move freely through a perfect crystal. We also have the definition from classical physics:

Acceleration = Force/mass (Newton's law $F = ma$)

If the force is a constant, velocity goes to infinity ($F = \frac{d(mv)}{dt}$) and current will also. A few free electrons or holes would give infinite conductivity! What limits the velocity? We do know that certain materials (metals, ceramics) under certain conditions (usually low temperature) show zero resistivity, however, most materials at reasonable temperatures show significant resistance to electron flow.

It should be remembered that the material is at a temperature T. This temperature is a macroscopic reflection of the microscopic energy of the particles (nuclei, bound electrons and conduction electrons). For the free electrons this manifests itself as random motion (kinetic energy). For the nuclei and bound electrons it produces vibrations in the lattice of ionic cores which creates the material.

Therefore in practice, the crystal potential $V(r)$is not perfectly periodic because of:

- Lattice vibrates due to the thermal energy.
- Ion cores are displaced from their equilibrium positions.

- Lattice contains impurities(doping) and imperfections.

All of the above effects *scatter* the electron waves and limit the packet velocity. Also we know that the electron is in random thermal motion (with a drift due to the ε field) as shown in figure 8. The mean time between collisions is $\tau \sim 10^{-13}\, s$.

There are in fact two mechanisms of current flow that arise from the random motion of the electrons and any electric field that is present.

(a) **Drift** - due the electric field
(b) **Diffusion** - due to the random motion of a inhomogeneous distribution

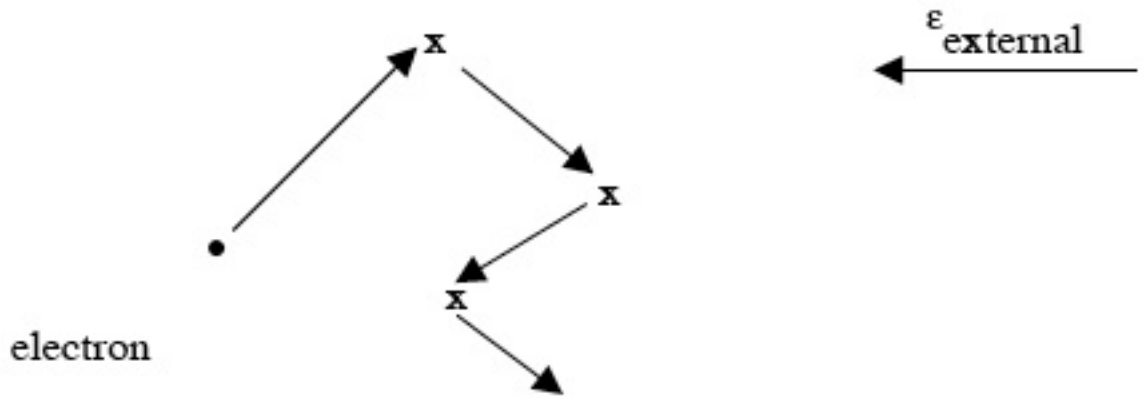

Figure 8. Motion of Electron

10.4. Drift Current

Consider first the drift current in figure 8 the random motion of an electron is presented. The presence of an external field, accelerates the electrons during time τ between scattering events this will perturb the trajectories of the electrons shown in figure 8 biasing them in one direction.

If this process is modeled in 1D the figure 9 presents the movement of the electron. Where each collision with the lattice is assumed to remove all of the electrons energy (setting the electron velocity to zero). Between collisions the electron is accelerated at rate determined by the field strength and the effective mass.

The average velocity acquired from field is given by equation 10.2.

$$v = \frac{q\varepsilon}{2m^*}.\tau = (\frac{q\tau}{2m^*}\varepsilon) = \mu_{n,p}\varepsilon. \tag{10.2}$$

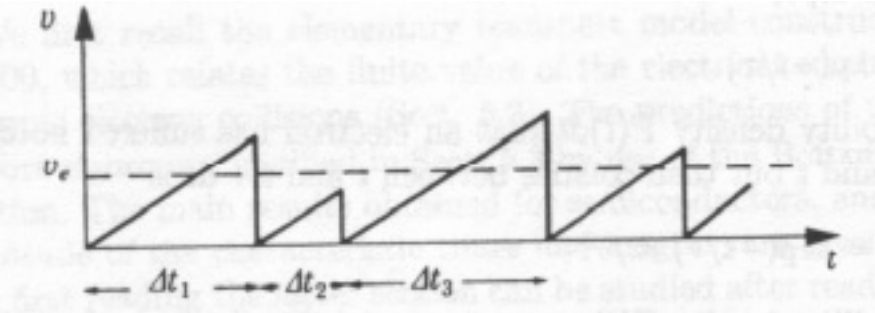

Figure 9. Motion of an Electron

Where $mu_{n,p}\varepsilon = \frac{q\tau}{2m^*}$ is defined as electron mobility units of $[cm^2V^{-1}s^{-1}]$ which relates field to velocity. This model shows that the electron velocity is linearly related to the field strength – which is the source of ohms law $V = IR$.

It is important to note that this model breaks down at high field, when the energy acquired by electrons between collisions becomes comparable to thermal energy. Then v is limited by v_{sat} which is the the *scatter limited velocity*, shown in figure 10.

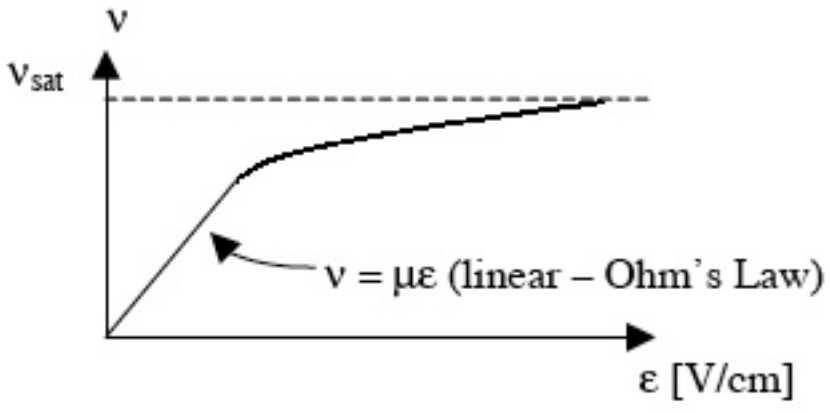

Figure 10. Velocity of Electron

Note: Many modern electronic devices work in the linear regime and it is important to have large τ as well as small m^*, for a high mobility μ. We must therefore must have clean material and a "good" band structure.

10.4.1. Calculating the drift current

To calculate a current from the analysis above consider figure 11.

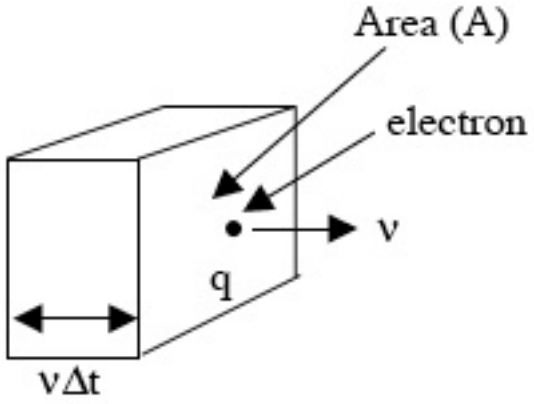

Figure 11. Calculation of the Drift Current

Assume electron's velocity is v and n is the electron density (cm^{-3}). Then at time Δt all electrons are within distance $v\Delta t$ with A being the cross-sectional area. Then for charge flowing in this time we will have,

$$\Delta Q = nv\Delta tAq \tag{10.3}$$

According to the definition of current density we have:

$$J = \frac{\Delta Q}{\Delta t.A} = qnv \tag{10.4}$$

Therefore for the drift currents we will have:

$$J_{n_{drift}} = q\mu_n n\varepsilon \quad \textbf{electrons} \tag{10.5}$$

$$J_{p_{drift}} = q\mu_p p\varepsilon \quad \textbf{holes} \tag{10.6}$$

$$J_{n,p_{drift}} = (q\mu_n n + q\mu_p p)\varepsilon \quad \textbf{total current} \tag{10.7}$$

$$J = \sigma\varepsilon \qquad \textbf{where} \qquad \sigma = q\mu_n n + q\mu_p p \tag{10.8}$$

$$I = J \times A = \sigma A\varepsilon \quad \textbf{total current} \tag{10.9}$$

$$\varepsilon = \frac{V}{L} \tag{10.10}$$

$$I = = \sigma A\frac{V}{L} \tag{10.11}$$

$$\rho = \frac{1}{\sigma} \quad \rho \textbf{ is the resistivity} \tag{10.12}$$

- in a n-type material we have $\sigma = q\mu_n n$ (p is very small)
- in a p-type material we have $\sigma = q\mu_p n$ (n is very small)

10.5. Diffusion of Electrons and Holes

The random thermal motion of electrons causes a net flow of electrons from a region of high concentration to region of low concentration as shown in figure 12.

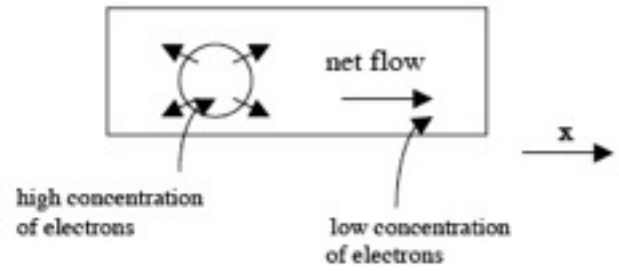

Figure 12. Flow of electrons

For the diffusion currents we have:

$$\begin{aligned} J_{n_{diff}} &= qD_n\frac{dn}{dx} \\ J_{p_{diff}} &= -qD_p\frac{dp}{dx} \end{aligned} \tag{10.13}$$

where $D_{n,p}$ is the diffusion coefficient which are related to mobilites according to *Einstein relation* as in equation 10.14, so from kinetic theory both diffusion and drift depend on μ.

$$D = \frac{k_B T}{q}\mu \tag{10.14}$$

Consider figure 13 as an example of a linear drop in concentration.

$$J_{n_{diff}} = qD_n\frac{dn}{dx} = qD_n\frac{\Delta_n}{L} \tag{10.15}$$

Note: The total current is sum of diffusion and drift in any situation.

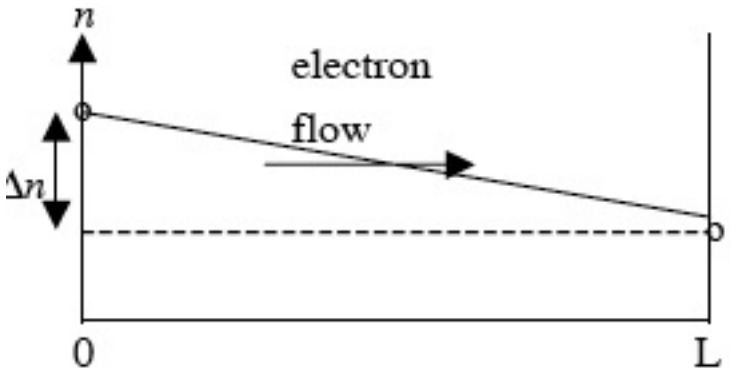

Figure 13. Electron Concentration Drop