Lecture 10

Carrier Action

Please use this power point as a guide to reading the textbook.

n and p

non-degenerate

$$n = N_c \exp(-\beta(E_c - E_F))$$
$$p = N_v \exp(-\beta(E_F - E_v))$$

$$np = n_i p_i$$

Law of mass action

$$n_i = p_i = N_c \exp(-\beta(E_c - E_i)) = N_v \exp(-\beta(E_i - E_v))$$

$$n_i = \sqrt{N_c N_v} e^{-E_G \beta/2}$$

$$N_c = n_i \exp(\beta(E_c - E_i))$$
$$N_v = n_i \exp(\beta(E_i - E_v))$$

E_F for intrinsic semicond.

$$n = n_i \exp(\beta(E_F - E_i))$$
$$p = p_i \exp(\beta(E_i - E_F))$$

!

$$N_c = 2\left(\frac{m_n^* kT}{2\pi\hbar^2}\right)^{3/2} \qquad N_v = 2\left(\frac{m_p^* kT}{2\pi\hbar^2}\right)^{3/2}$$

$\beta = 1/k_B T$

n and p

- Charge neutrality

$$p - n + N_D^+ - N_A^- = 0$$

ionized donor

At RT ≈ same

$$p - n + N_D - N_A = 0$$

total donor

acceptor densities

- Carrier concentration

$$\frac{n_i^2}{n} - n + N_D - N_A = 0$$

$$n = \frac{N_D - N_A}{2} + \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2}$$

For p swap N_D & N_A

n and p

- Important regime

$\approx RT$ or less

$$N_D \gg N_A, n_i \ (n\text{-type, moderate } T)$$

majority

$$n \approx N_D, \quad p \approx n_i^2/N_D$$

minority

$$N_A \gg N_D, n_i \ (p\text{-type, moderate } T)$$

$$p \approx N_A, \quad n \approx n_i^2/N_A$$

Si at RT $\quad n_i \approx 10^{10}/cm^3$

- majority carrier $\gtrsim 10^{14}/cm^3$

$\rightarrow$ minority carrier $\lesssim 10^6/cm^3$

Fermi level

$$n = n_i \exp(\beta(E_F - E_i))$$
$$p = p_i \exp(\beta(E_i - E_F))$$

$$E_i = \frac{E_c + E_v}{2} + \frac{3}{4} k_B T \ln\left(\frac{m_p^*}{m_n^*}\right)$$

$$E_F = E_i + k_B T \ \ln\left(\frac{n}{n_i}\right) = E_i - k_B T \ln\left(\frac{p}{p_i}\right) \qquad n_i = p_i$$

We know n, p (previous two slides), and so we know E_F completely!

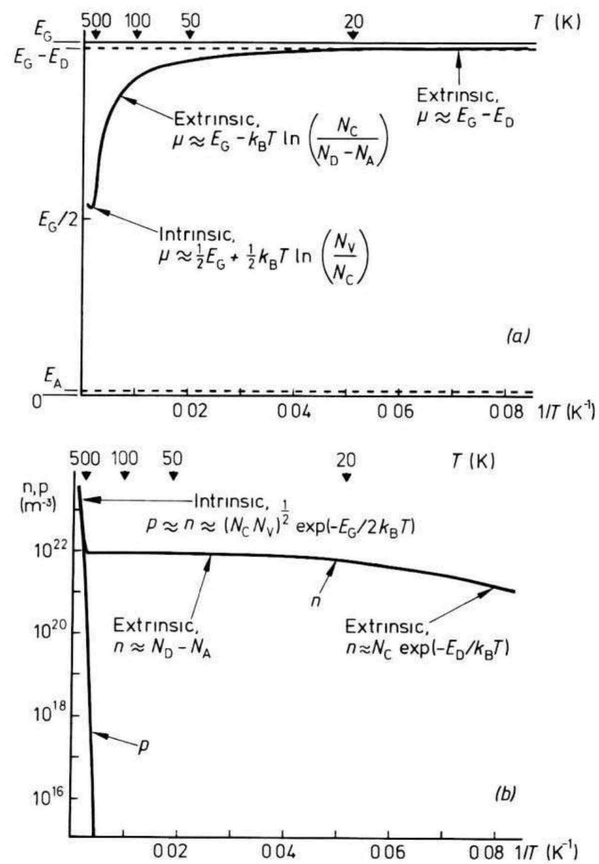
For example

n-type, moderate T: $E_F \approx E_i + k_B T \ln\left(\frac{N_D}{n_i}\right)$

p type, moderate T: $E_F \approx E_i - k_B T \ln\left(\frac{N_A}{n_i}\right)$

Example

n-type



← Fermi level

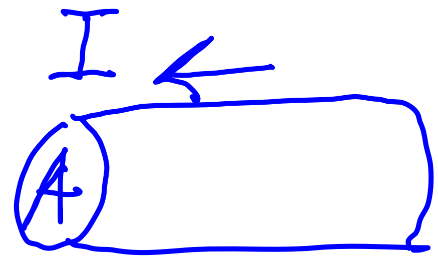
← n, p

Fig. 5.6 Variations of (*a*) the Fermi level μ and (*b*) the electron and hole concentrations (note the logarithmic scale) with $1/T$ for an n-type semiconductor containing a significant number of acceptor impurities. The figure was calculated for a germanium semiconductor with $N_D = 10^{22}\ \mathrm{m}^{-3}$, $E_D = 0.012$ eV, $N_A = 10^{21}\ \mathrm{m}^{-3}$ and $E_A = 0.010$ eV; the scale at the top shows temperature values for this case

From Hook & Hall

Current Density

- The Current Density



$$J = \frac{I}{A}$$

- Current can be large for large crossecton wire (large “gauge” wire).
- The intrinsic quantity to compare different materials with is then Current per crossection, i.e. the current density.
- Unit ? $\frac{C}{sm^2}$

Ohm's Law

Current and voltage

$G = \frac{1}{R}$

- $V = IR$ R = resistance (Ω)
- $I = V/R = GV$ G = conductance ($\frac{1}{\Omega} = S$)
- $J = \sigma E$ σ = conductivity (S / m)

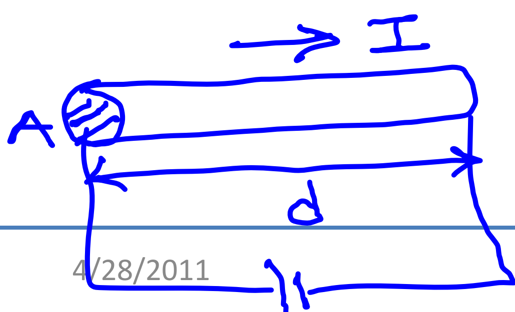
$R = \frac{1}{\sigma} \cdot \frac{d}{A}$

$E = V/d, \quad J = I/A$

$\sigma = \frac{1}{\rho}$

- $E = J/\sigma = \rho J$ ρ = resistivity (Ω m)

Common unit = $\mu\Omega$ cm, $m\Omega$ cm



Multiple Carriers

- If there are two types of carriers then

A. their resistivities add up
B. their conductivities add up

Mobility

- Conditions for a good conduction of current
  1. Each charge carrier is efficient.

     Mobility (μ_n or μ_p)
  2. Lots of charge carriers.

     Density of charge carriers (n or p)
  3. High electric field

→ intrinsic

affects conductivity

$$\boxed{\sigma = e\mu_n n + e\mu_p p}$$

- The current density

$$J = \left(e\mu_n n + e\mu_p p\right) E$$

$$\text{unit} = \frac{C}{m^2 s}\frac{m^3}{C}\frac{m}{V} = \frac{m^2}{Vs} \qquad \text{standard unit} = \frac{cm^2}{Vs}$$

Drift Velocity

- Drift velocity
  - The <u>average</u> velocity gain of charge carriers due to the electric field.
  - Quite smaller, usually, than the average speed of charge carriers at equilibrium.

- $J = nev_{d,n} + pev_{d,p}$
- Comparing with the last page

$$\mu = v_d / E$$

microscopic origin of μ

$$I = A v_d t\, ne / t$$

Drift Velocity

A. Is on the order of the actual average speed of each charge carrier in magnitude
B. Is much greater than the actual average speed of each charge carrier in magnitude
C. Is generally much less than the actual average speed of each charge carrier in magnitude

"Drude" Theory of Conduction

- Consider the carrier distribution as a entity whose drift velocity has a "decay time" of τ, like a radioactive particle that decays. $\tau =$ **relaxation time** due to scattering of the carrier by impurity, lattice vibration, other carriers etc.
- $\frac{dv_d}{dt} + \frac{v_d}{\tau} = 0$, if left alone $\rightarrow v_d(t) = v_d(0)e^{-t/\tau}$.
- If driven by a field, $m_n^* \left(\frac{dv_d}{dt} + \frac{v_d}{\tau}\right) = eE$.
- In steady state: $v_d = \frac{eE\tau}{m_n^*}$ and so $\mu_n = \frac{e\tau}{m_n^*}$.

Further microscopic origin of μ!

Mobility

- Mobility is due to the combination of two factors

$$\mu_n = \frac{e\tau_{n,r}}{m_n^*}$$

relaxation time

$$\mu_p = \frac{e\tau_{p,r}}{m_p^*}$$

effective mass

$e = \underbrace{q}_{\text{unusual notation}}$ of the book

Multiple Scattering Mechanisms

- If a carriers goes through multiple scattering channels (with impurity, phonons, or other carriers), then

A. their resistivities in different channels add up

B. their conductivities in different channels add up

Matthiessen's rule

- Probabilities add up **for a given carrier (e or h)**, if scattering processes are independent.

$$\frac{1}{\tau} = \left(\frac{1}{\tau}\right)_{impurity} + \left(\frac{1}{\tau}\right)_{lattice\ vibration} + \left(\frac{1}{\tau}\right)_{other\ carriers}$$

$$\frac{1}{\mu} = \frac{1}{\mu_{impurity}} + \frac{1}{\mu_{lattice\ vibration}} + \frac{1}{\mu_{other\ carriers}}$$

$\frac{dt}{\tau}$: probability of scattering event during dt

$$R = R_{impurity} + R_{lattice\ vibration} + R_{other\ carriers}$$

- It is a "*rule*" not a law – which means that it can and does break easily. Scattering processes are not independent.