Chapter 3

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Mobility

- $1/2m_nVth^2 = 3/2KT$ with tree degrees of freedom
- 0 Efield leads to random motion no net gain.
- Non Zero Efield leads to net motion.
- *v*=μE

$$\frac{1}{\tau_c} = \frac{1}{\tau_{c\_lattice}} + \frac{1}{\tau_{c\_impurity}} \qquad \frac{1}{\mu} = \frac{1}{\mu_L + \mu_I}$$

Resistivity

- Ntype
- If V left to right, Efield is left to right
- Band goes up right to left
- Electrons go from left to right down the hill
- Electron go left to right
- Holes go from right to left

$$\rho = \frac{1}{\sigma} = \frac{1}{q\cdot\left(n\cdot\mu_n + p\cdot\mu_P\right)}$$

Recombination

- Direct
- Indirect ntype
- Surface Dangling bonds ~#surface states
- Auger three particles $R=Bn^2p=Bnp^2$

Carrier concentrations

- Space charge neutrality
  - $p_o + N_d^+ = n_o + N_a^-$
  - $no = N_d^+ - N_a^-$, for strongly n-type
  - $po = N_a^- - N_d^+$, for strongly p-type

Drift of carriers in electric and magnetic fields

- The carriers are in constant random motion due to heat and there is no net motion.
- Under an electric field there is net motion.

$$J_x = -qn < \mathrm{v}_x >$$

$$J_x = \sigma E_x$$

$$\sigma = qn\mu_n$$

$$J_x = qn\mu_n E_x$$

$$J_x = q(n\mu_n + p\mu_p)E_x$$

Drift of carriers in electric and magnetic fields

- Mobility
  - Impurity scattering $T^{3/2}$ (affects highly doped samples more than lowly doped samples)
  - Lattice scattering $T^{-3/2}$ (affects can be seen in lowly doped samples)
  - Depends on effective mass as well
  - in Si the electron mobility is higher the the hole mobility, thus PMOS channel widths have to be twice that of NMOS channel widths

Drift of carriers in electric and magnetic fields

- Mobility
  - At high electric field the mobility can saturate or even become smaller.

Hall effect

1) Make sure that the contacts to the semiconductor are ohmic. Set up your voltage and current measurement and find the linear range.

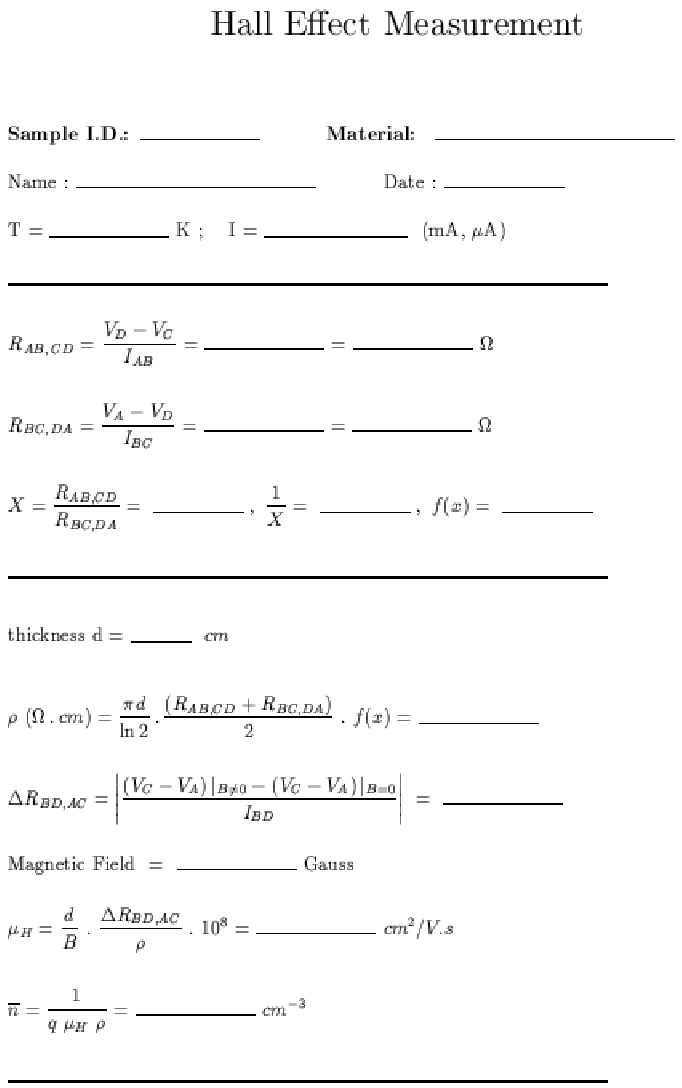
2) Take and record your I V measurements quickly. If the current is left on for to long the sample will heat up and this will affect your results.

3) Take the hall effect data. (for RHall the B-Field=2360 Gauss.)

    a. (VD-VC)/IAB=?
    b. (VA-VD)/IBC =?
    c. VC-VA @ 2360 Gauss=?, IBD=?
    d. VC-VA= @ 0 Gauss=?, IBD=?

5.Determine resistivity, mobility, carrier concentration, and carrier type for each sample.

Hall effect



Hall Effect Measurement

Sample I.D.: ________ **Material:** ________________

Name : ________________ Date : ________

T = ________ K ; I = __________ (mA, μA)

$R_{AB,CD} = \frac{V_D - V_C}{I_{AB}} =$ ________ $=$ ________ Ω

$R_{BC,DA} = \frac{V_A - V_D}{I_{BC}} =$ ________ $=$ ________ Ω

$X = \frac{R_{AB,CD}}{R_{BC,DA}} =$ ________ , $\frac{1}{X} =$ ________ , $f(x) =$ ________

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thickness d = _____ cm

$\rho\ (\Omega\,.\,cm) = \frac{\pi\,d}{\ln 2} \cdot \frac{(R_{AB,CD} + R_{BC,DA})}{2}\ .\ f(x) =$ ________

$\Delta R_{BD,AC} = \left| \frac{(V_C - V_A)\,|_{B\neq 0} - (V_C - V_A)\,|_{B=0}}{I_{BD}} \right| =$ ________

Magnetic Field = ________ Gauss

$\mu_H = \frac{d}{B} \cdot \frac{\Delta R_{BD,AC}}{\rho}\ .\ 10^8 =$ ________ $cm^2/V.s$

$\overline{n} = \frac{1}{q\ \mu_H\ \rho} =$ ________ cm^{-3}

Hall effect PE

- Calculate resistivity(ohm-cm), mobility (cm2/V.s), carrier concentration (cm-3), and carrier type (n or p) for the following case:
- (VD-VC)/IAB=200mV/2.5mA
- (VA-VD)/IBC=300mV/2.5mA
- d=430 microns
- VC-VA=86mV @ 2360 Gauss, IBD=2mA
- VC-VA=97mV @ 0 Gauss, IBD=2mA

Fermi level

- Qualitatively
  - At thermal equilibrium there can be no discontinuity or gradient in the Fermi level.
  - Assume two dissimilar semiconductors
    - There can be no net charge transport at thermal equilibrium, therefor no net charge transfer
    - The charges must balance each other. This leads to:

$$\frac{dE_F}{dx} = 0$$

Quiz #2

- InP is an important III-V Semiconductor.
- Show whether the group II, IV, and VI atoms will be donors, acceptors, or amphoteric (either a donor or acceptor) based on replacing an In atom or a P atom

II	III	IV	V	VI
	B	C		
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In		Sb	Te

Optical absorption

- Photons with $hv > E_g$ will excite EHP and the excess energy ($hv - E_g$) will be absorbed as heat. EHPs increase conductivity.
- Photons with $hv < E_g$ will pass through unabsorbed.
- One can measure E_g in this fashion.
- CdSe will pass all IR while GaP will pass green light and all longer wavelengths.

Luminescense

- Light may be given off as EHPs recombine and shed the excess energy.
- You can create EHPs (that will recombine) in three ways
  - Photoluminescense
  - Cathodeluminescense
  - Electroeluminescense

Luminescense

- Photoluminescense
  - – Shine monochromatic light larger than the bandgap of the material and measure frequency spectrum of emitted photons. Characterization tool.
- Cathodeluminescense
  - – Excite material with accelerated electrons. The electrons beam can be pointed to various parts of the structure. Characterization tool. (Except for ZnS on light bulbs and TV screens.)

Luminescense

- Electroeluminescense
  - – Excess electrons and holes that are supplied by a current or voltage source recombine to produce light.
  - – LEDs, LASERS
  - – While the other methods are characterization tools this method of creating luminescence is used in end use devices.

Carrier lifetime and photo-conductivity

- Direct recombination of Electrons and hole
  - – Electron drops from conduction band to the valence band and recombines with a hole without any change in momentum (E vs K) .
  - – The energy difference is used up in an emitted photon.
  - – This process occurs at a certain rate in the form of how long does a free electron or hole remain free before it recombines (τ_n or τ_n)

Carrier lifetime and photo-conductivity

- Direct recombination of Electrons and hole
  - τ_n or τ_n are dependant on doping level, crystal quality and temperature.
- Indirect recombination; Trapping
  - The probability of a direct recombination is small in Si and Ge.
  - A trapping level is needed. No photons generated just phonons (lattice vibrations)
  - Minority carrier lifetime dominates recombination process.

Carrier lifetime and photo-conductivity

- The Fermi level (EF) is only meaningful at thermal equilibrium.
- Under excitation we use the quasi Fermi level to denote excess hole and electron concentrations.

$$n = n_i e^{(F_n - E_i)/kT}, n = n_0 + \delta n, \delta n = \tau_n g_{op}$$

$$p = n_i e^{(E_i - F_p)/KT}, p = p_0 + \delta p, \delta p = \tau_p g_{op}$$

Diffusion of carriers

- Diffusion process
  - The random motion of similar particles from a volume with high particle density to volumes with lower particle density
  - A gradient in the doping level will cause electron or hole flow, which causes an electric field to build up until the force from the gradient equals the force of the electric field.
    - no current will flow at equilibrium

Diffusion of carriers

- Diffusion process
  - **t** is the mean free time that 1/2 of the particle will enter the next dx segment.
  - **l** is the mean free path of a particle between collisions.

$$\phi_n(x) = \frac{-\bar{l}^2}{2\bar{t}} \frac{dn(x)}{dx} = -D_n \frac{dn(x)}{dx}, \; Jn(diff.) = -(-q)D_n \frac{dn(x)}{dx} = +qD_n \frac{dn(x)}{dx}$$

$$\phi_p(x) = \frac{-\bar{l}^2}{2\bar{t}} \frac{dp(x)}{dx} = -D_p \frac{dp(x)}{dx}, \; Jp(diff.) = -(+q)D_p \frac{dp(x)}{dx} = +qD_p \frac{dp(x)}{dx}$$

Diffusion and drift of carriers

- Drift diffusion equations
  - The hole drift and diffusion current densities are in the same direction.
  - The electron drift and diffusion current densities are in the opposite direction.

$$J(x) = J_n(x) + J_p(x)$$

Diffusion and drift of carriers

- Drift diffusion equations
  - – Minority current flow is primarily diffusion.
  - – Majority current flow is primarily drift.
- An applied electric field will cause a positive slope in E_i (Ev and Ec as well)
- This can be used to derive the ***Einstein relation.***

$$\frac{D}{\mu} = \frac{kT}{q}$$

Continuity equation

- Rate of hole build up = increase of hole concentration in the volume - the recombination rate

$$\frac{\partial \delta p}{\partial t} = -\frac{1}{q}\frac{\partial Jp}{\partial x} - \frac{\delta p}{\tau_p}$$

$$\frac{\partial \delta n}{\partial t} = \frac{1}{q}\frac{\partial Jn}{\partial x} - \frac{\delta n}{\tau_n}$$

Diffusion length

- L_p is the average distance a hole will move before recombining.
- L_n is the average distance an electron will move before recombining.

$$L_n \equiv \sqrt{D_n \tau_n}$$

$$L_p \equiv \sqrt{D_p \tau_p}$$

Thermionic Emission

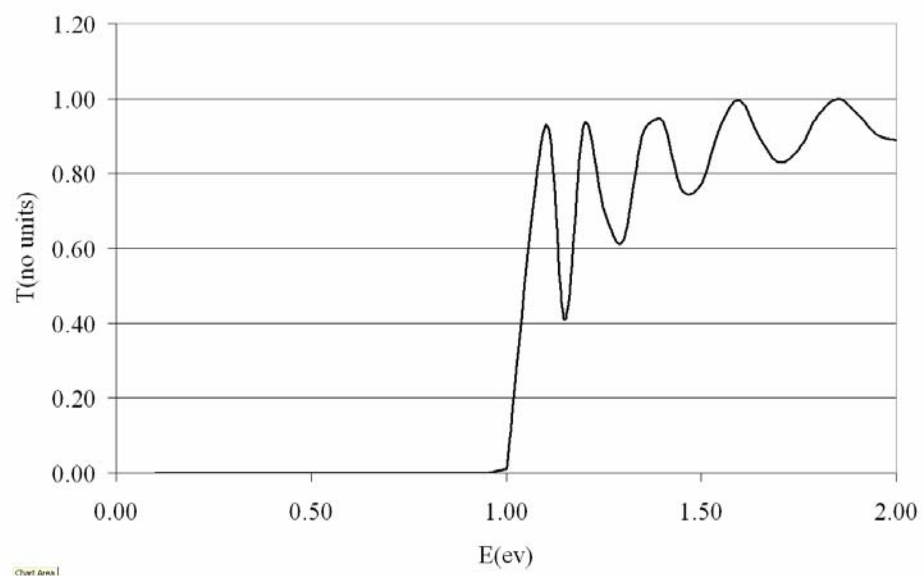
- Surface effect
  - Recombine with dangling bonds
  - Emitted into the vacuum

Metal/semiconductor Contacts

$$n_{th} = e^{\frac{-q\left(\chi + V_n\right)}{kT}}$$

Tunneling

- Tunnel Diodes
- Breakdown voltages less than .5 V
- Small Barrier height, and width
- Small Effective mass



High Field Effects

- Low E-Fields t_c is independent of electric field
- High E-Fields the interval is reduces, mobility goes down.
- This effects has to be taken into account when modeling CMOS logic gates.
  - RC ladder

$$\upsilon_n = \frac{\upsilon_s}{\left[1 + \left(\frac{\varepsilon_0}{\varepsilon}\right)^{\gamma}\right]^{\frac{1}{\gamma}}}$$

Gunn Effect

- Electrons with enough energy are promoted into a band with a different effective mass.
- Mobility is reduced
- Gunn Diode
- Negative differential resistance.

Avalanche Process

- Electron hits lattice with enough energy to break a bond.
- Sometimes the electrons that are created from this impact have enough energy to break other bonds.

$$G_A = \frac{1}{q\left(\alpha_n \left|J_n\right| + \alpha_p \cdot \left|J_p\right|\right)}$$