study notes, ECE 3386 solid state devices, Northeastern University, Boston

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Questions on semiconductor course

1 Questions

Q)how do we know we are dealing with low injection or high injection? so that we can use the correct approximations for low injection. equation (63) in book (page 51) in general case to find U, then the book assumed there is low injection, and did some approximations, I need to know when i can assume low injection in a problem.

A) when the injected minority carrier density is much lower than the majority carrier density, example $n_n \simeq n_{no}$

Q)what is difference between equation 66 page 52 and equation 61 page 94, since both are for low injection and equal capture corss section for holes and electron?

A)equation 61 page 94 is used when we have an applied external volatge?

Q)what is the difference between equation 64, page 51 and equation 67, page 52 since both are for low injection? it looks like equation 64 is when $E_t = E_i$ while equation 67 is not.

Q) about problem 1 set 2, where is the 1/cosh term in the I_{EP}calculation?

Q1) why is low injection in an n-type semiconductor $\Rightarrow n_n \gg p_n$

Q) how do you decide to use short base diode or long base diode for finding the diffusion capacitance?

for long base $C_d = \frac{AqL_p p_{no}}{KT} e^{\frac{V}{V_T}}$ while for short base $C_d = \frac{I}{V_T}\left(\frac{W^2}{2D_p}\right)$

example, the diffusion capacitance of the Emitter-Base junction is $\frac{I_E}{V_T}\left(\frac{W^2}{2D_p}\right)$ where $I_E = I_{En} + I_{En}$

where A the area of the junction

q electron charge

L_p the diffusion length $= \sqrt{D_p \tau_p}$

D_p the diffusion constant

$V_T = \frac{q}{KT} = 0.0259\ eV$ at room temp.

K is Blotzmann constant=$1.38066 \times 10^{-23} J/K$

$q = 1.60218 \times 10^{-19} C$

Q) how to find the electron effective mass m_n ?

Q)what is the transit time? $\tau_t ?and\ what\ is\ \frac{1}{\beta} = \frac{\tau_t}{\tau_p}$?

I think τ_p =time required by hole to traverse the base=$\frac{W^2}{2D_p}$

Q)is , under LOW level injection, the recombination life time τ_r the same thing as τ_p? is the difference is that τ_r is only when $\sigma_n = \sigma_n = \sigma_o$?

2 Defintions

•common-base current gain $\alpha_o = \frac{I_{CP}}{I_E}$

•emitter efficiency $\gamma = \frac{I_{EP}}{I_E}$, note: if $\frac{N_E}{N_B} \gg 1, like\ 5000, then\ \gamma = 1$

•base transport facotr $\alpha_T = \frac{I_{CP}}{I_{EP}}$

•α_F the forward common-base current gain (page 132)

•α_R the reverse commmon-base current gain=$\frac{\text{number of minority carries collected at emiiter}}{\text{number of minority carries injected into base at the forward-biased collector-base jun}}$

•$\alpha_o = \gamma\alpha_T$

•common-emitter current gain $\beta_o = \frac{\Delta I_C}{\Delta I_B} = \frac{\alpha_o}{1-\alpha_o}$ if γ very close to 1,$\beta_o = \frac{\gamma\alpha_T}{1-\gamma\alpha_T} \simeq \frac{\alpha_T}{1-\alpha_T} = \frac{2L_p^2}{W^2}$

• diffusion current

$$J_n = -q\,(carrie\ flow) = -q\left(-D_n\frac{dn}{dx}\right)$$

•Einstein relation relates mobility to diffusivity

$$D_n = \left(\frac{KT}{q}\right)\mu_n$$

• electron concentration in thermal equilibrium

$$n = n_i e^{\left(\frac{E_F-E_i}{KT}\right)}$$

• τ_g =the generation life time

• τ_p =the life time of the excess minority carriers

•τ_c = mean free time, the average time between collisions

•when there is no doping (i.e. $N_A = 0, N_D = 0$), then , assuming this is an n-type semiconductore, then

$$n_{no} = p_{no} = n_i$$

this means that

$$n_{no}p_{no} = n_i^2$$

when we have dopig added, then $n_n = n_{no} + N_D$ and $p_n = p_{no} + N_A$ and assuming full ionization, we have that

$$n_n p_n = n_i^2$$

and

$$n_n + N_A = p_n + N_D$$

• mobility $\mu = \frac{q\tau_c}{m_n}$

•m_n the electron effective mass

•resistivity $\rho \equiv \frac{1}{\sigma}$ where σ is the conductivity.

• capture cross section = σ_p or σ_n describes the effectiveness of the center to capture an electron and is a measure of how close the electron has come to the center to be captured. σ_n is in cm^2 , so it is an area.

• $v_{th}\sigma_n$ = this may be visualized as the volume swept out per unit time by an electron with cross section σ_n

•to find the built-in potional between 2 different doped materials, say $p - n$ use this

$$V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

• to find what is the width of the depletion region :

$$W = \sqrt{\frac{2\epsilon_s}{q}} \sqrt{\left(\frac{1}{N_D} + \frac{1}{N_A}\right)(V_{bi} - V_{external})}$$

$\epsilon_s = 1.0409 \times 10^{-12}$

$\frac{2\epsilon_s}{q} = \frac{2\times 1.0409\times 10^{-12}}{1.60218\times 10^{-19}} = 12993546$ $\sqrt{\frac{2\epsilon_s}{q}} = 3604.6$

note that when forward bias, $V_{external}$ is positive, and when revesrsed biased it is negative.

example, for $W_{EB} = \sqrt{\frac{2\epsilon_s}{q}} \sqrt{\left(\frac{1}{N_D} + \frac{1}{N_A}\right)(V_{bi} - V_{EB})}$ and $W_{CB} = \sqrt{\frac{2\epsilon_s}{q}} \sqrt{\left(\frac{1}{N_D} + \frac{1}{N_A}\right)(V_{bi} + V_{CB})}$

to find the extent of depletion region into only one side or the other use, example, given a base-collector juntion with W width, we want to find how far this W goes into the base, use:

$$W_{base'part} = \frac{N_C}{N_C + N_B} W$$

the length into the collector is

$$W_{collecter'part} = \frac{N_B}{N_C + N_B} W$$

• $n_i = 1.45 \times 10^{10} cm^{-2}$ where n_i is the intrinsic carrie density. it is the number of electrons per unit volume in the conduction band and equal to number of holes in the valence band. intrinsic semiconductor is one that contains relatively small amounts of impurities compared to the thermaly generated electrons and holes.

• Fermi distribution function $F(E) = \frac{1}{1+e^{\frac{(E-E_F)}{KT}}}$ where k is Blotzmann constant, T is abs. temp. in Kelvin and E_F is the fermi level energy. the fermi level is the energy at which the probability of occupation by electron is exactly .5

• about mobility, the KE energy of electron is given by

$$\frac{1}{2} m_n v_{th}^2 = \frac{3}{2} KT$$

where m_n is the electron effective mass=?, and v_{th} is the electron average thermal velocity.

•conductivity=$(qn\mu_n + qp\mu_p)$ where μ is the carrier mobility.

3 generation and recombination

when we have $\Delta n = \Delta p \ll N_D$ we call this low level injection

3.1 Direct

this means no recombination centers exist.

when the light is on, at steady state,

$$G_L = U = \frac{p_n - p_{no}}{\tau_p} \qquad (1)$$

when the light switched of, the excess carries die away at rate untill we get back to p_{no}

$$p_n(t) = p_{no} + \tau_p G_L e^{-\frac{t}{\tau_p}}$$

also we have

$$G = G_L + G_{th}$$

befor we reach steady state, i.e just after the light shine is on,

$$\frac{dp_n}{dt} = G - L = G_L + G_{th}$$

in steady state

$$G_L = R - G_{th} = U$$

3.2 indirect recombination

this means there are recomination centers N_t

under steady state, non-equilibrium (i.e. source that causes generation exist and is ON), we have

$$U = R_a - R_b = \frac{v_{th}\sigma_n\sigma_p N_t\left(p_n n_n - n_i^2\right)}{\sigma_p\left(p_n + n_i e^{\left(\frac{E_i - E_t}{KT}\right)}\right) + \sigma_n\left(n_n + n_i e^{\left(\frac{E_t - Ei}{KT}\right)}\right)} \qquad (2)$$

where

$$R_a = (\sigma_n v_{th})\, n N_t\,(1 - F(E_t))$$

$$R_b = e_n N_t F(E_t)$$

at thermal equilibrium, $R_a = R_b$

where e_n is called the emission probability.

$$e_n = v_{th}\sigma_n n_i e^{\left(\frac{E_t - E_i}{KT}\right)}$$

this shows that as E_t goes away from E_i and closer to the conduction band, there is more probability of process R_b i.e. electron emmision from the center up to the conduction band.

see page 50 in book.

when we have low injection, so that $n_n \gg p_n$, and E_t close to the center of the gap, U simplifies to

$$U \simeq v_{th}\sigma_p N_t (p_n - p_{no})$$

compare this equation to equation (1) in the direct recombination, we see that

$$\tau_p = \text{ life time of holes in n-type } = \frac{1}{v_{th}\sigma_p N_t}$$

this is valid only under LOW LEVEL INJECTION and E_t close to center of gap.

back to the general case, now assume that $\sigma_n = \sigma_p = \sigma_o$ then U equation (2) becomes

$$\boxed{\mathrm{U}=\frac{v_t h\sigma_o N_t\left(p_n n_n - n_i^2\right)}{p_n + n_n + 2n_i \cosh\left(\frac{E_t - E_i}{KT}\right)}} \qquad (3)$$

now, if we have LOW INJECTION, U simplied to

$$\boxed{\mathrm{U}=\mathrm{v}_t h\sigma_o \mathrm{N}_t \frac{p_n n_no}{1+\left(\frac{2n_i}{n_no + p_no}\right)\cosh\left(\frac{E_t - E_i}{KT}\right)} = \frac{p_n - p_no}{\tau_r}}$$

where τ_r is the recombination life time

3.3 misc. notes about recombination and generation

1) when we have injection of excess carries, $pn > n_i^2$ this is called then RECOMBINATION, as in FORWARD biased juntions.

2)when we have $pn < n_i^2$ this is then called GENERATION. this is as in REVERSE BIASED junction

3)to find G let $p_n < n_i$ and $n_n < n_i$ in equation (3) we get

$$\boxed{\mathrm{G}=\text{-}\mathrm{U}=\frac{v_t h\sigma_o N_t n_i}{2\cosh\left(\frac{E_t - E_i}{KT}\right)} = \frac{n_i}{\tau_g}}$$

where τ_g is the generation life time. the above ASSUMES $\sigma_n = \sigma_p = \sigma_o$ only.

$$\frac{\tau_g}{\tau_p} = 2\cosh\left(\frac{E_t - E_i}{KT}\right)$$

4)when a $p^+ - n$ junction is forward biased, to find total current through it, we add the juntion current to the recombination current.

$$\begin{aligned} J &= J_p(x_n) + J_n(-x_p) \\ &= J_s\left(e^{\frac{V}{V_T}} - 1\right) \end{aligned}$$

where

$$J_s = \text{saturation current density}=\frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n}$$

the recombination current

$$J_{rec} = \int_0^w qU\,dx \simeq \frac{qWn_i}{2\tau_r} e^{\frac{V}{2V_T}}$$

where

$$\tau_r = \frac{1}{\sigma_o v_{th} N_t}$$

so, total forward current in forward biased p-n junction under High Injection is

$$J_F = J_s\left(e^{\frac{V}{V_T}} - 1\right) + J_{rec}$$

when the emitter is much more doped than teh base, ie. $p_{no} \gg n_{po}$and $V \gg \frac{3KT}{q}$ then we approixmate

$$J_F = q\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} e^{\frac{V}{V_T}} + \frac{qWn_i}{2\tau_r} e^{\frac{V}{V_T}} \sim e^{\frac{V}{\eta V_T}}$$

where η is called the ideality factor

5) in either generation or recombination, the most effective centers are those located near E_t

4 p-n junction

• diffusion current = $-qD_p \frac{dp}{dx}$

•drift current = $q\mu_p pE$