ECE 3040 Microelectronic Circuits

Exam 1

22 minutes

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Print your name clearly and largely: Solutions

Instructions:
Read all the problems carefully and thoroughly before you begin working. You are allowed to use 1 new sheet of notes (1 page front and back) as well as a calculator. There are 100 total points. Observe the point value of each problem and allocate your time accordingly. SHOW ALL WORK AND CIRCLE YOUR FINAL ANSWER WITH THE PROPER UNITS INDICATED. Write legibly. If I cannot read it, it will be considered a wrong answer. Do all work on the paper provided. Turn in all scratch paper, even if it did not lead to an answer. Report any and all ethics violations to the instructor. Good luck!

Sign your name on **ONE** of the two following cases:

I DID NOT observe any ethical violations during this exam:

I observed an ethical violation during this exam:

First 33% **Multiple Choice and True/False**
(Circle the letter of the most correct *answer or answers*)

1.) (3-points) True or False: The larger the interatomic bond length, the smaller the energy bandgap.

2.) (3-points) True or False: The energy bandgap can be thought of as the energy required to break an electron off the atom and allow it to conduct freely throughout the crystal.

3.) (3-points) True or False: The Fermi-energy describes the probability that a state is occupied or empty.
fermi-distribution

4.) (3-points) True or False: If Ga is a group 3, As is group 5, and Si is group 4, then Si would be a donor if it replaces As whereas Si would be an acceptor if it replaces Ga.

5.) (3-points) True or False: The Fermi-energy is lower in an acceptor doped material than in an n-type material.

6.) (3-points) True or False: The density of states multiplied by the fermi-distribution function predicts ~~that at~~ an exponentially fewer number of electrons can be found at higher energies compared to moderately high energies.

7.) (3-points) True or False: If a material is deficient in electrons compared to equilibrium, recombination is enhanced in an attempt to return the material back to equilibrium.
generation

Select the **best** answer or answers for 6-10:

8.) (4-points) Auger recombination ...
   a.) ... involves only 2 particles.
   b.) ... can amplify small drift currents.
   c.) ... is significant only at high carrier densities.
   d.) ... involves 3 particles, but only one remains afterwards.
   e.) ... is something I really do not understand and thus I might not pass this exam!

9.) (4-points) The probability of occupying a state at energy $E=2xE_f$ (where E_f is the fermi-energy) is...
   a.) ...essentially 1.
   b.) ...essentially 0.
   c.) ... equals 0.5.
   d.) ... not known without knowing the value of E_f.

10.) (4-points) The appropriate equation(s) to use for a n-type non-degenerate semiconductor to determine the electron concentration is:

a) $n = N_c e^{(E_f - E_c)/kT}$ b) $n = n_i e^{(E_f - E_i)/kT}$ c) $n = N_c \frac{2}{\sqrt{\pi}} F_{1/2}(\eta_c)$ d) $n = \frac{N^+_D - N^-_A}{2} + \sqrt{\left(\frac{N^+_D - N^-_A}{2}\right)^2 + n_i^2}$

Second 15% Short Answer ("Plug and Chug"):
For the following problems (11-12) use the following material parameters and <u>assuming total ionization</u>:

Germanium:
n_i=1e14 cm^{-3} (not a mistake) N_D=1e15 cm^{-3} acceptors N_A=5e14 cm^{-3} acceptors
m_p^*=0.36m_o m_n^*=0.55m_o
E_G=0.66 eV Electron mobility, μ_n = 1800 cm^2/Vsec Hole mobility , μ_p = 150 cm^2/Vsec
Temperature=27 degrees C

11.)(8-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)?

Alternative Solution:

$E_i = \frac{E_g}{2} + \frac{3}{4}kT\left(\ln\left(\frac{m_p^*}{m_n^*}\right)\right)$

$= 0.322\,eV$

$n_o = 5.19e14\,cm^{-3}$

$n_o = n_i e^{(E_F - E_i)/kT}$

$E_F = E_i + kT\ln\left(\frac{n_o}{n_i}\right)$

$= 0.322 + 0.042$

$E_F = 0.364$

Note: Differs because n_i does not match m_n^* + m_p^*

$$n_o = \left(\frac{N_D^+ - N_A^-}{2}\right) + \sqrt{\left(\frac{N_D^+ - N_A^-}{2}\right)^2 + n_i^2} = \underline{5.19e14\,cm^{-3}}$$

$$p_o = \frac{n_i^2}{n_o} = \underline{1.93e13\,cm^{-3}}$$

$$p_o = N_v e^{(E_v - E_F)/kT}$$

$$1.93e13 = 2.51\times10^{19}\left(\text{[redacted]}\ 0.36\right)^{3/2} e^{(E_v - E_F)/0.0259}$$

$$E_F - E_v = -0.0259\ln\left(\frac{1.93e13}{2.51\times10^{19}\left(\text{[redacted]}\ 0.36\right)^{3/2}}\right)$$

0.321

$E_F - E_v =$ [redacted] eV

12.) (7-points) What is the resistance of the semiconductor if it has 10 um^2 area and 50 um length?

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} = \frac{1}{1.6e{-19}(1800 n_o + 150 p_o)}$$

$$\rho = 6.666\ \Omega\text{-cm}$$

$$R = \frac{\rho L}{A} = \frac{6.666\ \Omega\text{-cm}\ (50e{-4}\,cm)}{10\times10^{-8}\,cm^2}$$

$$\boxed{R = 333{,}300\ \Omega}$$

13.) (12-points total)

A semiconductor at room temperature (27 degrees C) has the following parameters:

Hole Diffusion coefficient, D_p=11.86 cm^2/Sec

Electron Diffusion coefficient, D_n=33.625 cm^2/Sec

N_d=1.07e15 cm^{-3}

Substrate intrinsic concentration, n_i=1e10 cm^{-3}

The sample is initially held in a dark room (no illumination)

a.) (9 points) Assuming total ionization and non-degenerate doping, what are the total electron and hole concentration under an illumination level that that results in a quasi-fermi level for electrons (F_N) that is 0.318 eV above the intrinsic energy level and a quasi-fermi level for holes (F_P) that is 0.3 eV below the intrinsic energy level.

b.) (3 points) Is the material under illumination in "low-level injection" or "high-level injection". Concisely explain your answer.

$N_D \gg N_A$ + $N_D \gg n_i$

a) $n_o = 1.07e15\ cm^{-3}$ $\quad p_o = \frac{n_i^2}{n_o} = \frac{1e20}{1.07e15} = 9.3e4\ cm^{-3}$

$F_n - E_i = 0.318eV \qquad E_i - F_p = 0.3eV$

$n = n_i e^{(F_n - E_i)/kT} = 1e10\, e^{0.318/0.0259}$

$n = 2.15e15\ cm^{-3}$

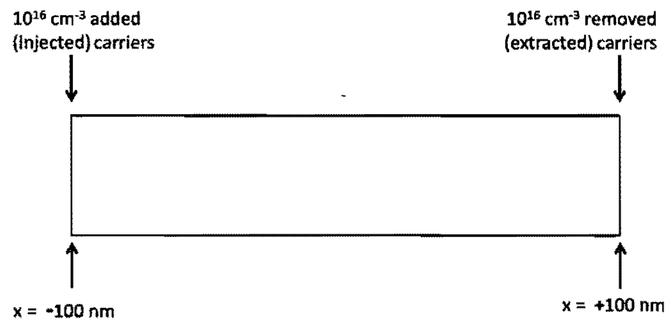
$p = n_i e^{(E_i - F_p)/kT} = 1e10\, e^{0.30/0.0259}$

$p = 1.07e15\ cm^{-3}$

b) Is high level injection since $n \gg n_o$

Pulling all the concepts together for a useful purpose:

14.) (40-points)



In a particular region of a "photo-transistor" similar to the "transistor" we will study in detail later, called the "base" region, there is a condition established where extra minority carriers are injected (added) at one side while the opposite side has extra minority carriers extracted (removed). If this region is 200 nm in length and the left end (x= -100) has a 1e16 cm^{-3} more minority carriers than found in equilibrium while the right end (x= +100 nanometers) has a 1e16 cm^{-3} fewer carriers than found in equilibrium. The light generates a uniform $G_L \longrightarrow$ $\boxed{\text{1.036e24 cm}^{-3}\text{ extra carriers per second.}}$ *What is the minority carrier diffusion current density in the region?* In this "base region", the minority carrier lifetime is $\boxed{9.65251\text{e-}10}$ $\rightarrow \tau_n$ seconds. $\frac{\partial \Delta n}{\partial t} \rightarrow$ The device has been operating since before democrats liked to tax the rich (ancient times ☺ -no worries, a republican joke will come next year – equal opportunity insulter). Assume a minority carrier mobility of 4.0 cm^2/Vsec.

$D_n = 4(0.0259) = 0.1036\ cm^2/sec$ Einstien Relationship

$G_L \tau_n = 1e15\ cm^{-3}$

$L_n = \sqrt{D_n \tau_n} = 1e\text{-}5\ cm = 100\ nm$

Given: $0 = D_n \dfrac{d^2 \Delta n_p}{dx^2} - \dfrac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n}$

Given: $0 = D_n \dfrac{d^2 \Delta n_p}{dx^2} - \dfrac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L \tau_n$

Given: $0 = D_n \dfrac{d^2 \Delta n_p}{dx^2}$ General Solution is: $\Delta n_p(x) = A + Bx$

Given: $0 = D_n \dfrac{d^2 \Delta n_p}{dx^2} + G_L$ General Solution is: $\Delta n_p(x) = Ax^2 + Bx + C$

Given: $0 = D_n \dfrac{d^2 \Delta n_p}{dx^2} + G_{LO} f(x)$ General Solution is: $\Delta n_p(x) = \left[-\dfrac{G_{LO}}{D_N} \iint f(x) dx \right] + Bx + C$

Given: $\dfrac{d\Delta n_p}{dt} = -\dfrac{\Delta n_p}{\tau_n}$ General Solution is: $\Delta n_p(t) = \Delta n_p(t=0) e^{-t/\tau_n}$

Given: $0 = -\dfrac{\Delta n_p}{\tau_n} + G_L$ General Solution is: $\Delta n_p = G_L \tau_n$

General: $\Delta n(x) = Ae^{-x/100nm} + Be^{+x/100nm} + 10^{15}\ cm^{-3}$

BC: $\Delta n(x=+100) = -10^{16} = Ae^{-1} + Be^{+1} + 10^{15}\ cm^{-3}$

$A = \dfrac{-1.1e16 - Be}{e^{-1}} = -1.1e16e - Be^2$

$\Delta n(x=-100) = +10^{16} = Ae^{1} + Be^{-1} + 10^{15}\ cm^{-3}$

Extra work can be done here, but clearly indicate which problem you are solving.

$$9E15 = (-1.1E16e - Be^2)e + \frac{B}{e}$$

$$(9E15 + 1.1E16e^2) = B\left(\frac{1}{e} - e^3\right)$$

$$B = -4.58E15 \text{ cm}^{-3}$$

$$A = -1.1E16e - Be^2$$

$$A = 3.93E15 \text{ cm}^{-3}$$

$$\Delta n(x) = 3.93E15\, e^{-x/100\text{nm}} - 4.58E15\, e^{+x/100\text{nm}} + 10^{15} \text{ cm}^{-3}$$

$$J_n(x) = q\, D_n \frac{\partial \Delta n}{\partial x}$$

$$= \frac{(1.6E-19)(0.1036 \text{ cm}^2/\text{s})}{1E-5 \text{ cm}} \Big[-3.93E15\, e^{-x/100\text{nm}} - \ldots$$

$$\ldots\ 4.58E15\, e^{x/100\text{nm}} \Big]$$

$$\boxed{J_n(x) = -6.514\, e^{-x/100\text{nm}} - 7.591\, e^{+x/100\text{nm}} \text{ A/cm}^2}$$