ECE 3040 Microelectronic Circuits

Exam 1

February 20, 2012

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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 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. A periodic table is supplied on the last page. 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:

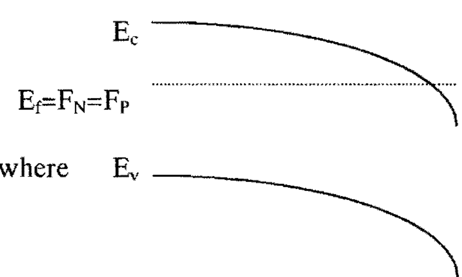
First 33% **Multiple Choice and True/False**
(Circle the letter of the most correct *answer or answers*)

1.) (3-points) True or False: The Pauli Exclusion Principle is the basis of the energy bandgap formation since each energy state in a crystal much split into a different energy thus, forming a band of states we call either the valance band or conduction band.
2.) (3-points) True or False: Atoms with large chemical bond strengths usually result in large energy bandgaps and low mobility (due to frequent collisions resulting from high atomic density).
3.) (3-points) True or False: The fermi distribution function predicts that for a non-degenerate doped semiconductor, the states in the conduction band will be mostly empty.
4.) (3-points) True or False: $In_{0.23}Ga_{0.47}N_{0.3}$ is a valid semiconductor formula in standard semiconductor notation.
5.) (3-points) True or False: The law of mass action for a wide bandgap semiconductor with a small intrinsic concentration can predict a negative electron concentration.
6.) (3-points) True or False: The density of states far away (in energy) from the band edges has a decreasing exponential form.
7.) (3-points) True or False: Impact ionization requires accelerating an electron to higher kinetic energy where it collides with other electrons forcing a recombination event between three particles (example – 2 electrons and 1 hole).

Select the **best** answer or answers for 8-10:

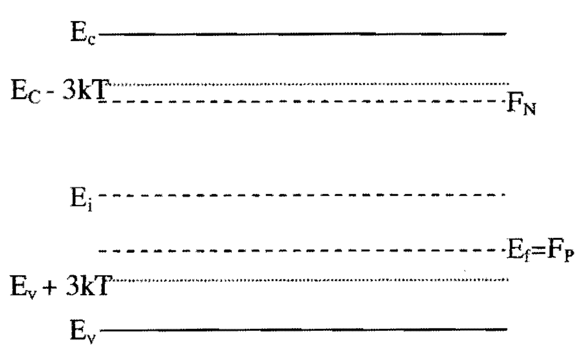
8.) (4-points) Which of the following are true about the drift velocity ...
a.) ... it depends on the current flowing in the material.
b.) ... it is proportional to electric field but only at low electric fields
c.) ...it plateaus to a constant value at high electric fields
d.) ... it determines the diffusion current through the use of the Einstein equation
e.) ... in some semiconductors, it can have a "peak value" at an intermediate electric field.

9.) (4-points) Select all of the following that are true.



a.) The material is in equilibrium
b.) The material is in steady state non-equilibrium
c.) The material has non-uniform doping
d.) The material has uniform doping
e.) The material has a non-zero electric field everywhere
f.) The material has zero electric field everywhere
g.) The material clearly has a net current flow
h.) The material clearly has no net current flow
i.) Something is wrong since the Fermi-level in above Ec in parts of the material
j.) There are too many choices in this problem for only 4 points.

10.) (4-points) The following energy band diagram indicates the material is:
a.) In equilibrium
b.) Degenerate and n-type
c.) Degenerate and p-type
d.) Non-degenerate n-type
e.) Non-degenerate p-type
f.) In low level injection
g.) In high level injection
h.) In steady state



Second 17% Short Answer ("Plug and Chug"):

For the following problems (11-12) use the following material parameters and <u>assuming total ionization</u>:

2.8e13

n_i=[redacted] cm^{-3} N_D=2e15 cm^{-3} donors N_A=1e15 cm^{-3} acceptors m_p^*=0.55m_o m_n^*=0.36m_o

E_G=0.66 eV Electron mobility, μ_n = 2200 cm^2/Vsec Hole mobility , μ_p = 500 cm^2/V-sec

Temperature=27 degrees C

* 11.)(7-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)?

$$n = \frac{N_D - N_A}{2} \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + n_i^2} = 1e15\ cm^{-3}$$

$$p = \frac{n_i^2}{n} = \frac{(2.8e13)^2}{1e15} = 7.84e11$$

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

$$= 0.338eV$$

$$n = 1e15 = 2.8e13\, e^{(E_f - 0.338233)/kT}$$

$E_f = 0.43eV$

or $p = 7.84e11 = 2.8e13\, e^{(E_i - E_f)/kT}$

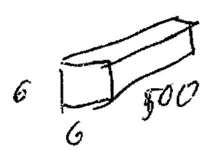
$E_f = 0.43\ eV$

or

$$n = N_c e^{(E_f - E_c)/kT} = 1e15 = 5.4\times10^{18} e^{(E_f - 0.66)/kT} \quad \text{or} \quad p = N_v e^{(E_v - E_f)/kT}$$

$n = 0.43(7)\ eV$ $\quad 7.84e11 = 1.02e19 e^{(-E_f/kT)}$ **$E_f = 0.424eV$**

* 12.) (10-points) A 6um x 6 um x ~~1mm~~ 500 um rectangular semiconductor resistor is made from the semiconductor from problem 11. It is biased on two opposing sides (longest dimension) with 9 volts. Determine <u>both</u> the electron and hole <u>current density</u> and <u>currents</u> flowing in the device.



$$A = (6e-4)^2 = 3.6e-7\ cm^2$$

$$L = 0.05cm$$

Electrons

$$J_n = \sigma_n E = q\mu_n n\,(9V/0.05cm)$$

$$= (1.6e-19)(2200\,cm^2/V\text{-}s)(1e15\,cm^{-3})(180\,V/cm)$$

$J_n = 63.36\ A/cm^2$ or $I = JA = 22.8\ \mu A$

Holes:

$$J_p(E) = (1.6e-19)(500)[redacted](180)(7.84e11)$$

J_p = 11.2[redacted] mA/cm²

$I_p = J_p A =$ [redacted]4 nA

10

Section 3 (more short answer)

13.) (10-points total) The material in problems 11 and 12 is exposed to a laser light that generates 2e16 cm^{-3} extra minority carriers.

a) (2 points) Is this low level or high level injection?

$\Delta n = \Delta p >> n_0 \Rightarrow$ High level injection

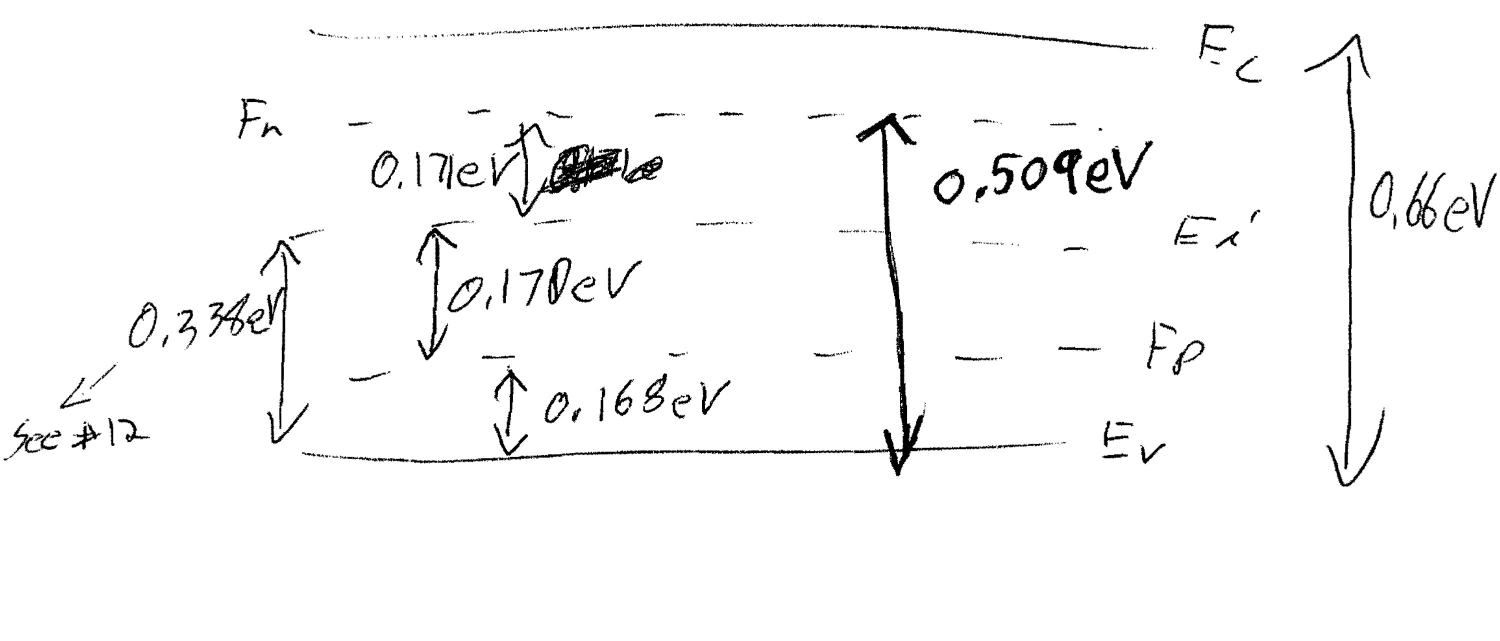
b) (8 points) Draw the 1 dimensional energy band diagram showing the placement of both the quasi-fermi levels (numeric answer).

$n = 1e15 + 2e16 = 2.8e13\, e^{(F_n - E_i)/kT}$

$(F_n - E_i) = 0.171$

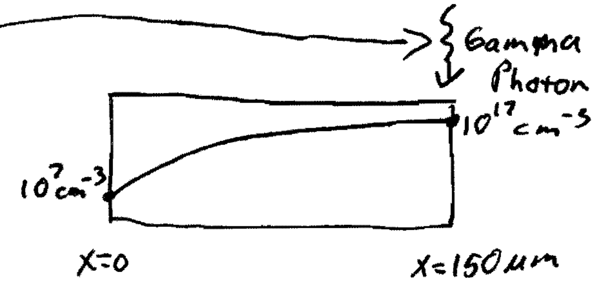
$p = (7.84e11 + 2e16) = 2.8e13\, e^{(E_i - F_p)/kT}$

$(E_i - F_p) = 0.170$



Set-10 B.C.-10 gd-10 J-10

Pulling all the concepts together for a useful purpose:



14.) (40-points)

$\tau = 10\,\mu s$

A 150 um length of super-secret semiconductor "X" is to be used in Peter Parker's Lab (Spiderman for the geek challenged) and will see cosmic radiation. The semiconductor is doped p-type with an acceptor concentration of 1e18 cm^{-3} and has a minority carrier lifetime, of 10 microseconds. A gamma photon is absorbed at the end of the semiconductor (at 150 um), generating 1e17 extra electron-hole pairs per cm^3 for a short period of time BUT long enough to bring the material to steady state. It is found that at x=0 the excess electron concentration is small, $\Delta n(x{=}0)=1e7\text{cm}^{-3}$. We want to analyze the diffusion current flowing during this pulse. If the semiconductor is held at room temperature (27 degrees C), determine the minority carrier diffusion current density at all positions in the semiconductor (150 um $\geq$ x $\geq$ 0 um). Assume a minority carrier mobility of 100 cm^2/Vsec and the intrinsic concentration is 1e10cm^{-3}.

$\frac{\partial \Delta n_p}{\partial t} = 0$

$D = \frac{kT}{q}\mu = 2.59\ \text{cm}^2/\text{sec}$

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

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

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

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

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

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

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

$L_n = \sqrt{D\tau} = \sqrt{2.59(1e\text{-}5)}$

$L_n = 50.89\ \mu m$

Note: other than @ x=150 um there is no generation

B.C. $\Delta n(x=0) = 1e7\ \text{cm}^{-3}$

$\Delta n(x=150\mu m) = 1e17\ \text{cm}^{-3}$

x=0

$1e7 = Ae^{-0} + Be^{+0}$

$A = (1e\text{-}7 - B)$

x = 150 um

$10^{17} = Ae^{-150/50.89} + Be^{150/50.89}$

$10^{17} = (10^7 - B)e^{-150/50.89} + Be^{150/50.89}$

$10^{17} - (524{,}751) = B(19.05 - 0.0524)$

$= 19B$

$B = 5.263\times10^{15}\ \text{cm}^{-3}$

$A = -5.263\times10^{15}\ \text{cm}^{-3}$

$\Delta n(x) = 5.263\times10^{15}\left(e^{x/50.89} - e^{-x/50.89}\right)\text{cm}^{-3}$

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

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

$$= (1.6e-19)(2.59)\left(\frac{5.26e15}{(50.89 \times 10^{-4})}\right)\left(e^{x/50.89} - e^{-x/50.89}\right)$$

$$\boxed{J_n = 0.428\left(e^{x/50.89\,\mu m} - e^{-x/50.89\,\mu m}\right) A/cm^2}$$

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