ECE 3040 Microelectronic Circuits

Exam 1

February 15, 2017 24 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 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. ***Turn in your notes sheet.*** 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 <u>*answer or answers*</u>)

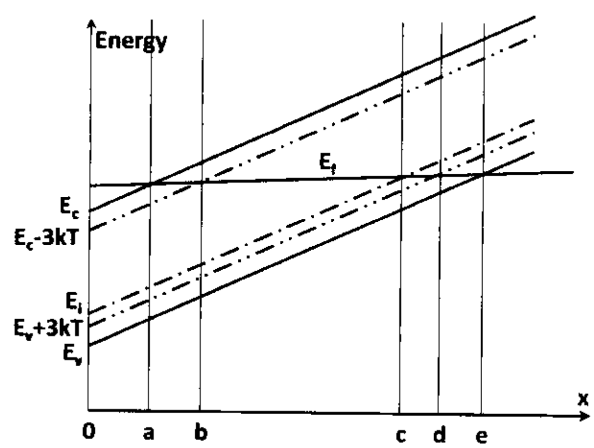
1.) (3-points) True or False: The energy bandgap is generally larger in materials with strong chemical bonds.
2.) (3-points) True or False: Metals are conductive because each atom prefers to not release its electrons to the electron cloud.
3.) (3-points) True or False: The density of states determines how likely the state is to be occupied.
4.) (3-points) True or False: $Al_{0.2}In_{0.50}Ga_{0.40}N_{0.4}P_{0.4}As_{0.4}$ is a valid semiconductor formula in standard semiconductor notation.
5.) (3-points) True or False: The fermi distribution function determines the probability of a hole existing in a state. $1-f(E)$
6.) (3-points) True or False: In a degenerately doped semiconductor, one must use partial ionization. Ambiguous question; either answer accepted
7.) (3-points) True or False: If a material is non-degenerately doped, we know the fermi energy is located inside the bandgap and is at least 3kT away from either the conduction or valence band.

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

8.) (4-points) Which of the following are true about drift currents ...
   a.) ... they only result from electric fields created by dopants ×
   b.) ... they are driven by electric field
   c.) ...they always result in diffusion currents that balance ×
   d.) ... they are the smaller of the three types of current flow ×
   e.) ... they are constant at high electric fields but vary linearly with electric field strength at low electric fields.

9.) (4-points) Which of the following are true about the fermi-distribution function.
   a.) The product of the fermi-distribution function and the density of states results in a distribution of electron concentrations as a function of energy.
   b.) The fermi-distribution function decays exponentially at higher energy
   c.) The fermi-distribution function is always equal to ½ at energy equal to the fermi-energy
   d.) The fermi-distribution function reduces to a simple exponential for energies far away from the fermi-energy

10.)(4-points) The following energy band diagram indicates the material is:
   a.) In equilibrium Ef Flat
   b.) In Steady State ×
   c.) Degenerate and n-type for x<b
   d.) Degenerate and p-type for x>d
   e.) Non-degenerate n-type for b<x<c
   f.) Non-degenerate p-type for c<x<d
   g.) In low level injection ×
   h.) In high level injection ×
   i.) $m_n^* > m_p^*$
   j.) $m_n^* < m_p^*$
   k.) Has zero electric field
   l.) Has a non-zero electric field everywhere



Short Answer ("Plug and Chug"):

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

For InP:

n_i=1.3e7 cm^{-3} N_D=1e17 cm^{-3} donors N_A=1.2e17 cm^{-3} acceptors m_p^*=0.6m_o m_n^*=0.08m_o

E_G=1.344 eV Electron mobility, μ_n = 5000 cm^2/Vsec Hole mobility, μ_p = 150 cm^2/V-sec

Temperature=27 degrees C

11.) (5-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)?

$$p_o = \frac{N_A - N_D}{2} + \sqrt{\frac{(N_A-N_D)^2}{4} + n_i^2} = 2e16\ cm^{-3} \quad n_o = \frac{n_i^2}{p_o} = \frac{(1.3e7)^2}{2e16} = 0.00845\ cm^{-3}$$

$$E_i = \frac{E_g}{2} + \frac{3}{4}kT \ln\left(\frac{m_p^*}{m_n^*}\right) = 0.711eV$$

Several Approaches:

1) $p = 2e16 = n_i\, e^{(E_i - E_f)/kT}$ $\Rightarrow E_f = 0.163eV$

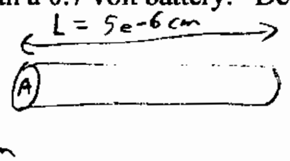
2) $n = 0.00845cm^{-3} = n_i\, e^{(E_f - E_i)/kT}$ $E_f = 0.163eV$

3) $N_C = 2.51\times10^{19}\left(\frac{m_n^*}{m_o}\right)^{3/2}$ $= 5.679e17cm^{-3}$

$n = 0.00845\ cm^{-3} = N_C\, e^{(E_f - E_c)/kT}$ (E_c = 1.344) $E_f = 0.161eV$

4) $N_V = 2.5?\times10^{19}\left(\frac{m_p^*}{m_o}\right)^{3/2}$ $p = N_V\, e^{(E_v - E_f)/kT}$ $E_f = 0.165eV$

12.) (8-points) A 12 nm (1 nm = 1e-9 m) ***diameter*** x 50 nm long cylindrical semiconductor resistor is made from the semiconductor from problem 11 for use in a microprocessor. It is biased on two opposing sides (longest dimension) with a 0.7 volt battery. Determine both the electron and hole currents flowing in the device.



Area $A = \pi(0.6\times10^{-6})^2$ $= 1.13e-12\ cm^2$

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)} \qquad R = \frac{\rho L}{A}$$

$$\rho_n = \frac{1}{q\mu_n n} \qquad \rho_p = \frac{1}{q\mu_p p}$$

$\rho_n = 1.47e17\ \Omega\text{-cm}$ $\rho_p = 2.08\ \Omega\text{-cm}$

$R_n = 6.54e23\ \Omega$ $R_p = 9.21e6$

$I_n = 1e-24\ Amps$ $I_p = 76\ nA$

Section 3 (more short answer)

13.)(14-points total) The material in problems 11 and 12 is exposed to the sun's light (like in a solar cell) that generates 1e19 cm^{-3} extra electron – hole pairs.

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

$p = \Delta p + p_0 = 1e19 + 2e16$

$\approx 1e19\ cm^{-3}$

High level injection

b) (8 points) Draw the 1 dimensional energy band diagram showing the placement of both the quasi-fermi levels (E_{fn} and E_{fp} – should be a numeric answer) relative to E_i, E_c, and E_v.

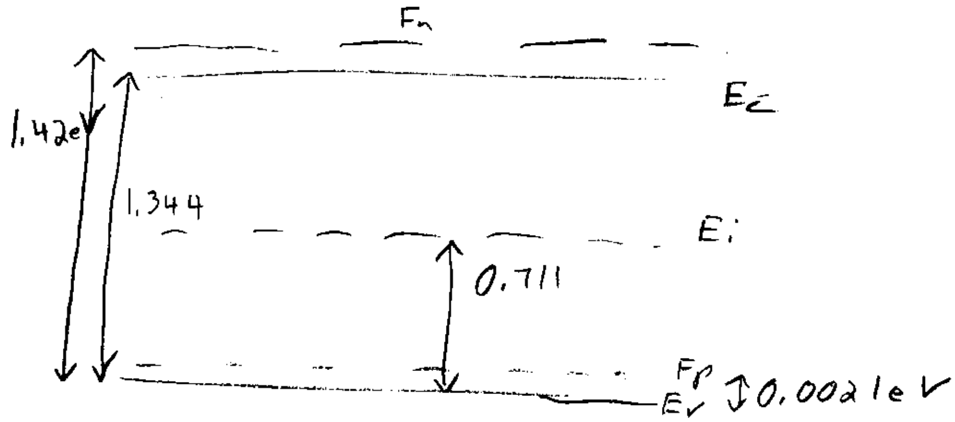
F_n: $n = n_i e^{(F_n - E_i)/kT}$

$F_n = 1.42\,eV$

F_p: $p = n_i e^{(E_i - F_p)/kT}$

$p_0 + \Delta p \approx 1.002\,e19\,cm^{-3}$

$F_p = 0.0021\,eV$



c) (4 – points) What is the total current flowing when light is present?

$\rho = \frac{1}{q(\mu_n n + \mu_p p)}$

$= \frac{1}{1.6e{-19}(5000 \times 1e19 + 150 \times 1e19)}$

$R = \frac{\rho L}{A}$

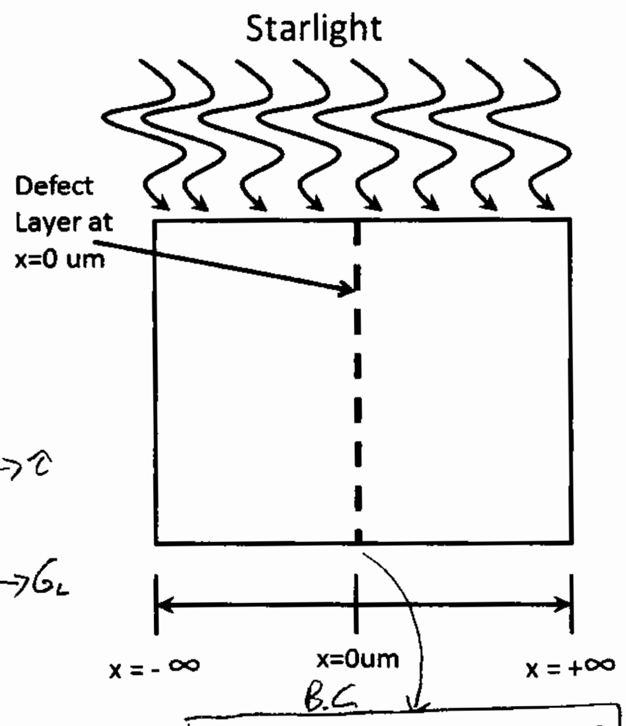
$R = 537\,\Omega$

$I = 1.3\,mA$

Pulling all the concepts together for a useful purpose:

14.) (40-points)

An infinite slab of semiconductor extends from positive to negative infinity. For a very long time, starlight has constantly illuminated the semiconductor and is absorbed uniformly with a very small absorption coefficient. The semiconductor is doped p-type with an acceptor concentration of 5e15 cm^{-3} and has a minority carrier lifetime of 2 microseconds. → τ The sunlight is absorbed uniformly in the semiconductor generating an excess minority carrier concentration rate of 10^{14} cm^{-3}/sec. → G_L At the center of the semiconductor at x=0, a defect layer exists which results in a lower excess minority carrier concentration than anywhere else in the semiconductor. Thus, at x=0, Δn(x=0)=1e8 cm^{-3}. If the semiconductor is held at room temperature (27 degrees C), determine the minority carrier diffusion current density at all positions in the semiconductor (-∞ ≥ x ≥ ∞). Assume a μ → minority carrier mobility of 2 cm^2/Vsec and the intrinsic concentration is 1e-14cm^{-3}.



Hint: It may be helpful to break this problem up into two symmetric problems.

$L_n = \sqrt{D_n \tau} = \sqrt{0.0518(2e-6)} = 3.219\ \mu m \qquad D_n = \frac{kT}{q}\mu_n = 0.0518\ cm^2/sec$

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

$-\infty < x < \infty$ 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: $\Delta n_p(x) = Ax^2 + Bx + C$

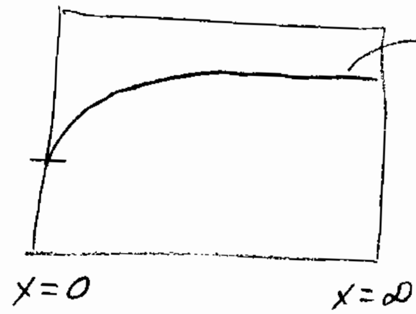
Given: $0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_{LO} f(x)$ General Solution is: $\Delta n_p(x) = \left[-\frac{G_{LO}}{D_N}\iint f(x)dx^2\right] + Bx + C$

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

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

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

Use $\infty > x \geq 0$: (Negative ½ is same due to symetry or you could solve it twice)



→ @ $x = +\infty$

$\Delta n(x=\infty) = G_L \tau_n$

=

Note: If you don't see this then see * below

$$\Delta n_p(x) = A e^{-x/L_n} + B e^{+x/L_n} + G_L \tau_n$$

B.C. 1: * $\Delta n_p(x=\infty) = A(0) + B(\infty) + G_L \tau_n$

$B \Rightarrow 0$ in order to have a physical meaning

$(\Delta n_p(x=\infty) = G_L \tau_n = 2e8 \text{ cm}^{-3}$

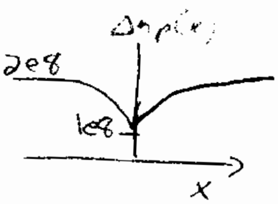
B.C. 2: $\Delta n(x=0) = 1e8 \text{ cm}^{-3} = A e^0 + 0 e^0 + G_L \tau_n$

$= A + 2e8 \text{ cm}^{-3}$

$A = -1e8 \text{ cm}^{-3}$

$x \geq 0$	$\Delta n(x) = 2e8 - 1e8\, e^{-x/3.219\,\mu m}$ [cm^{-3}]
$x \leq 0$	$\Delta n(x) = 2e8 - 1e8\, e^{+x/3.219\,\mu m}$ [cm^{-3}]

(by symetry, $A = 0$ + $B = -1e8 \text{ cm}^{-3}$)

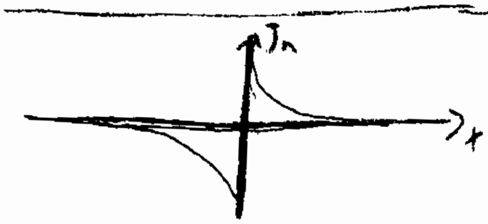


$$J_n = q D_n \frac{\partial \Delta n_p(x)}{\partial x}$$

$$= (1.6e-19)(0.0518) \frac{[1e8 \text{ cm}^{-3}]}{(3.219 \times 10^{-4} \text{cm})} e^{-x/3.219\,\mu m}$$

↑ note units ≡ cm

$x \geq 0$	$J_n = +\,2.57\,nA\, e^{-x/3.219\,\mu m}$ A/cm^2
$x \leq 0$	$J_n = -\,2.57\,nA\, e^{+x/3.219\,\mu m}$ A/cm^2



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