ECE 3040 Microelectronic Circuits

Exam 1

September 27, 2023

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25 minutes

Print your name clearly and largely: Solution

Instructions:
DO NOT REMOVE ANY SHEETS FROM THIS EXAM! 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 placed under your exam.*** 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 20%* Multiple Choice and True/False**
(Circle the letter of the most correct *answer or answers*)

1.) (2-points) True or False: The energy bandgap can be considered the energy required to rip an electron out of the material into the vacuum where it conducts electricity.

2.) (2-points) True or False: The mobility is the low electric field slope of the drift velocity, in the region where the drift velocity is linearly proportional to the electric field.

3.) (2-points) True or False: Electric fields are always applied from external sources like batteries and can never be created inside the device.

4.) (2-points) True or False: If both electrons and holes are exposed to a built in field, as in a solar cell, the charges both move to the same side of the device accumulating on the anode (p-side).

5.) (2-points) True or False: For a device with a high concentration of defect states or impurity states, the minority carrier lifetime will be very high.

6.) (2-points) True or False: In a degenerately doped semiconductor, more than one hole can occupy a given state.

7.) (2-points) True or False: Larger bond strength results in higher energy bandgaps.

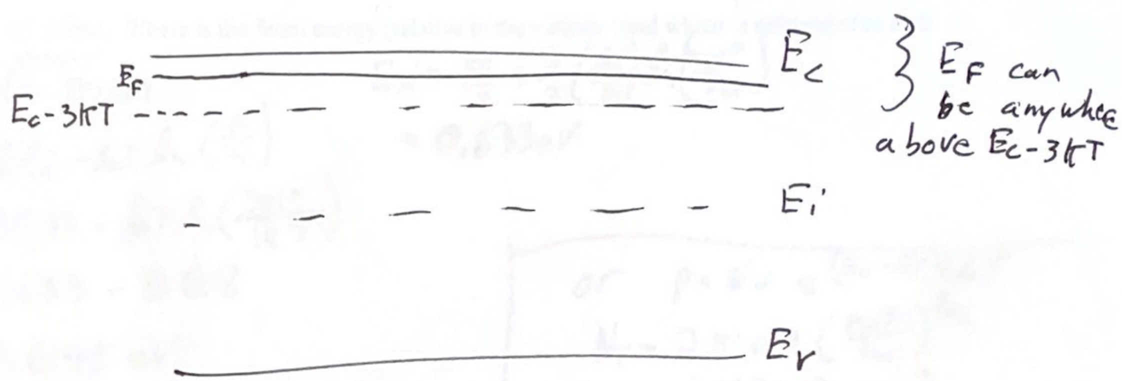
8.) (2-points) True or False: The Fermi-Dirac integral of order ½ , the Fermi distribution function and the Boltzmann distribution function are all ways of describing the probability that a state is filled with an electron.

9.) (2-points) True or False: Auger recombination is only important at low current density or at low optical injection (low optical power).

10.)(2-points) True or False: Impact ionization can increase a small current into a large current but is generally noisy current as the multiplication of charge is random and thus, stochastic.

Short Answer ("Plug and Chug"):

11.) (6-points) Sketch and label the energy band diagram of <u>any</u> degenerately doped n-type semiconductor indicating why the material is degenerately doped and where the fermi-energy is. Points deducted for lack of neatness, clarity and missing energy labels. No numeric values are needed – just symbolic labels.



For the following problems (12-13) use the following material parameters and assuming total ionization:

For InP:
n_i=1.3e7 cm^{-3} N_D=3e13 cm^{-3} donors N_A=3e17 cm^{-3} acceptors
$m_p^*=0.6m_o$ $m_n^*=0.08m_o$
E_G=1.344 eV Electron mobility, μ_n = 900 cm^2/Vsec Hole mobility , μ_p = 120 cm^2/V-sec
Temperature=27 degrees C

12.)(7-points) Where is the fermi energy (relative to the valence band which is referenced to zero energy)?

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

$$E_i = \frac{E_g}{2} + \frac{3}{2}\left(\frac{kT}{2}\right)\ln\left(\frac{m_p^*}{m_n^*}\right) = 0.633\,eV$$

$$E_f = E_i - kT\ln\left(\frac{p}{n_i}\right)$$

$$= 0.633 - kT\ln\left(\frac{3e17}{1e7}\right)$$

$$= 0.633 - 0.618$$

$$E_f = 0.0145\ eV$$

or $p = N_v e^{(E_v - E_f)/kT}$

$$N_v = 2.51e19\left(\frac{m_p^*}{m_o}\right)^{3/2} = 1.167e19\ cm^{-3}$$

$$3e17 = 1.167e19\, e^{(E_v - E_f)/kT}$$

$$E_f - \underset{E_v}{0} = 0.09482\ eV$$

13.) (10-points) A 52 nm (1 nm = 1e-9 m) ***diameter*** x 300 nm long cylindrical semiconductor resistor is made from the semiconductor from problem 12 is biased on two opposing sides (longest dimension) with 0.9 volts. Determine both the electron and hole currents flowing in the device.

$$A = \left[\frac{52e{-7}}{2}\right]^2 \pi = 2.12e{-11}\ cm^2 \qquad V = 0.9$$

$$p_o = N_A \quad (N_A \gg N_D + N_A \gg n_i) = 3e17\ cm^{-3}$$

$$n_o = \frac{n_i^2}{p_o} = \frac{(1.3e7)^2}{3e17} = 5.63e{-4}\ cm^{-3}$$

900 cm^2/V-s

$$\sigma_n = q\mu_n n_o = 8.11e{-20}\ 1/\Omega\text{-cm}$$

$$\sigma_p = q\mu_p p_o = 5.76\ 1/\Omega\text{-cm}$$

$$R_n = \frac{L}{\sigma_n A} = \frac{3e{-5}\,cm}{(2.12e{-11})(\ )} = 1.74e25\ \Omega$$

$$R_p = \frac{L}{\sigma_p A} = \frac{3e{-5}\,cm}{(2.12e{-11})(5.76)} = 2.45e5\ \Omega$$

$$I_n = \frac{V}{R_n} = \frac{0.9V}{1.74e25\,\Omega} = \boxed{5.2e{-26}\,A}$$

$$I_p = \frac{V}{R_p} = \frac{0.9\,V}{2.45e5\,\Omega} = \boxed{3.67\,\mu A}$$

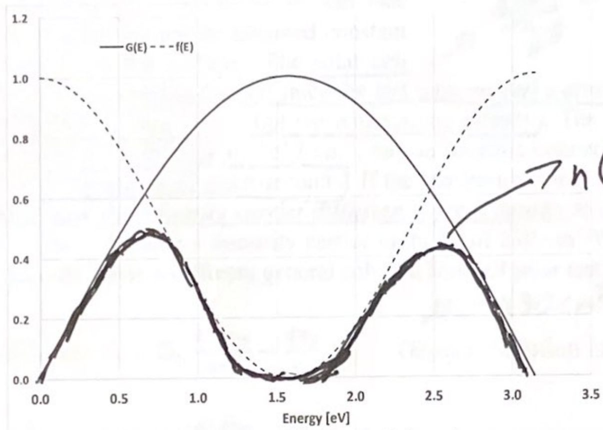
Section 3 (more short answer)

14.) (13 -points total) The brilliant and humble Professor Doolittle has found a semiconductor that obeys new "Doolittian Physics". It is found the density of states of this material follows the function:

$$G(E) = \begin{cases} sin(E) & \text{for } 0<E<\pi \\ 0 & \text{elsewhere} \end{cases}$$

and the fermi distribution function for this new physics is:

$$f(E) = \frac{1}{2}[1 + \cos(2E)] \text{ for } 0<E<\pi$$

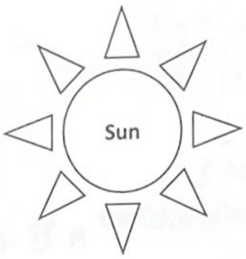


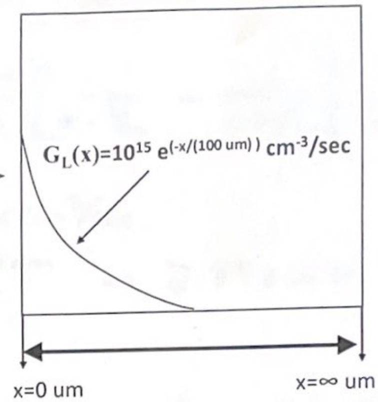
Sketch (do not label magnitudes) of the electron concentration versus energy function n(E) for 0<E<π.

Setup: 11pts__________ B.C. : 11pts__________ Δn Solution: 11pts__________ Jn: 11pts__________

Pulling all the concepts together for a useful purpose:

15.) (44-points)





B.C. @ x = 0

$G_L(x=0)\tau_n = \Delta n(x=0)$

A semi-infinite length section of semiconductor is to be used as a solar cell. The sun's light is absorbed such that the surface (x=0) excess minority carrier concentration, Δn(x=0), always equals the surface generation rate times the minority carrier lifetime. The generation rate throughout the semiconductor is dependent on position as:

$G_L(x)=G_{LO}\,e^{-\alpha x} = 10^{15}\ e^{(-x/(100\ um))}\ cm^{-3}/sec$ for all x and cannot be assumed constant nor only on the surface. The solar cell has been exposed to the sun since the last time we had a presidential nominee that was competent for the office (a long time – but we will assume infinity). The semiconductor is doped p-type with an acceptor concentration of 1e17 cm^{-3}, has an intrinsic concentration of 1e10 cm^{-3} and has a minority carrier lifetime of 40 microseconds. If the semiconductor is held at room temperature (27 degrees C), ***determine the minority carrier diffusion current density*** at all positions in the semiconductor (0 ≥ x ≥ ∞ um). Assume a minority carrier mobility of 230 cm^2/Vsec. I note that this problem "may" or "may not" have a different general solution from all prior test problems but is given.

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

$\tau_n = 40\,\mu S$

$\mu_n = 230\,cm^2/V\text{-}s \rightarrow D_n = \frac{KT}{q}\mu = 5.957\ cm^2/sec$

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

$L_n = \sqrt{D_n \tau_n}$
$= 0.0154\ cm$ or
$\sim 154\ um$

b) Given: $0 = D_n\frac{d^2\Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_L$ ...

...General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} + G_L\tau_n$

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

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

e) Given: $0 = D_n\frac{d^2\Delta n_p}{dx^2} + G_{LO}f(x)$ …

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

f) Given: $0 = D_n\frac{d^2\Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} + G_{LO}e^{-\alpha x}$ …

… General Solution is: $\Delta n_p(x) = Ae^{-x/L_n} + Be^{+x/L_n} - \frac{L_n G_{LO} e^{-\alpha x}}{2D_n}\left[\frac{1}{\{\alpha-(\frac{1}{L_n})\}} - \frac{1}{\{\alpha+(\frac{1}{L_n})\}}\right]$

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

h) 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.

General Solution:

$$\Delta n(x) = Ae^{-x/L_n} + Be^{+x/L_n} - \frac{\overset{0.0154\,cm}{L_n}\,\overset{10^{15}\,cm^{-3}}{G_{L0}}}{2\underset{5.957\,cm^2/sec}{D_n}}\left[\frac{1}{\alpha - 1/L_n} - \frac{1}{\alpha + 1/L_n}\right]e^{-\overset{100\,cm^{-1}}{\alpha} x}$$

$$= Ae^{-x/0.0154cm} + Be^{+x/0.0154cm} - 2.89e10\, e^{-100x}$$

B.C.:

$\Delta n(x \rightarrow \infty) \Rightarrow B = 0$ to avoid unphysical results

$\Delta n(x=0) \equiv G_L(x=0)\,\tau_n = 4e10 = A - 2.89e10$

$A = 6.689e10\ cm^{-3}$

$$\boxed{\therefore\ \Delta n(x) = 6.689e10\, e^{-x/0.0154cm} - 2.89e10\, e^{-100x}}$$

$J_n = q D_n \nabla n_p(x)$ but $\nabla n_0 = 0$ so... $J_n = q D_n \nabla(\Delta n)$

$\cancel{J = q D_n \nabla \Delta n}$

$$J_n = (1.6e19)(5.957)\left[-\frac{6.689e10}{0.0154}e^{-x/L_n} + (100)\,2.89e10\, e^{-100x}\right]$$

$$\boxed{J_n = \left[-4.26\ \mu A/cm^2\right]e^{-x/0.0154cm} + \left[2.76\ \mu A/cm^2\right]e^{-100x}}$$