Print your name clearly and largely: Solution

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:
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![Graph showing test score distribution with categories ~F, ~D, ~C, ~B, and ~A]
**First 25% Multiple Choice and True/False (Circle the letter of the most correct answer)**

1.) (2-points) True or False: Ionized acceptors are positively charged
2.) (2-points) True or False: The energy bandgap is the energy required to break a valence electron away and have it conduct through the material
3.) (2-points) True or False: A metal has a much higher energy bandgap than an insulator, making it conduct better.
4.) (2-points) True or False: Indirect semiconductors are better at absorbing and emitting light than direct band gap materials.
5.) (2-points) True or False: Zincblende and diamond crystal structures are nearly the same, only the zincblende structure involves two or more elements while the diamond structure involves only one element.

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

6.) (3-points) A heavily doped n-type GaAs block \((n_d >> n_i)\) is connected to a battery. Which of the following is true:
   a.) The block is in equilibrium
   b.) The block has a flat fermi energy
   c.) Minority carriers carry most of the current
   d.) Holes carry most of the current
   e.) Electrons carry most of the current

7.) (3-points) Assuming only partial ionization (do not make this hard, it is not): If the fermi energy, \(E_F\), is located directly on an acceptor whose concentration is \(1e19 \text{ cm}^{-3}\), what is the hole concentration in the material?
   a.) \(1e19 \text{ cm}^{-3}\)
   b.) \(2e19 \text{ cm}^{-3}\)
   c.) \(3e18 \text{ cm}^{-3}\)
   d.) \(0 \text{ cm}^{-3}\)
   e.) This question is not fair!

8.) (3-points) The following energy band diagram indicates the material is:
   a.) Non-degenerate n-type
   b.) Degenerate n-type
   c.) intrinsic
   d.) Non-degenerate p-type
   e.) Degenerate p-type

9.) (3-points) For the electron and hole shown in the following band diagram circle all that are true.
   a.) The electron will move to the right
   b.) The hole will move to the right
   c.) The electron will move to the left
   d.) The hole will move to the left
   e.) There is no current flow in this device
   f.) The device has to be in equilibrium
10.) (3-points) In steady state:
   a.) The number of electrons equals the number of holes.
   b.) The number of electrons is greater than holes in a n-type material
   c.) No net current can flow
   d.) The time rate of change of the system is zero
   e.) The minority carrier concentration can not change from position to position.

Second 25% Short Answer ("Plug and Chug"): 
For the following problems (11-12) use the following material parameters:
\( n_0 = 5 \times 10^{12} \text{ cm}^{-3} \) \( N_D = 8 \times 10^{12} \text{ cm}^{-3} \) donors \( N_A = 6 \times 10^{12} \text{ cm}^{-3} \) acceptors.
Electron mobility, \( \mu_n = 1600 \text{ cm}^2/\text{Vsec} \) Hole mobility, \( \mu_p = 480 \text{ cm}^2/\text{Vsec} \)
Temperature=27 degrees C

11.) (10-points) Assuming total ionization, what is the electron and hole concentrations and is the material p or n-type?

\[
n = \frac{N_0 - N_A}{2} + \sqrt{\left(\frac{N_0 - N_A}{2}\right)^2 + n_i^2} \\
= \frac{8 \times 10^{12} - 6 \times 10^{12}}{2} + \sqrt{\left(\frac{8 \times 10^{12} - 6 \times 10^{12}}{2}\right)^2 + (5 \times 10^{12})^2} \\
n = 6.1 \times 10^{12} \text{ cm}^{-3}
\]

\[
p = \frac{n_i^2}{n} = \frac{(5 \times 10^{12})^2}{6.1 \times 10^{12}} = 4.1 \times 10^{12} \text{ cm}^{-3}
\]

\[
n > p \implies \text{n-type}
\]

12.) (15-points) A block of material is 5 mm long and has a cross-sectional area of 0.1 mm². If 9 Volts is placed across its length, what is the electron current density, and hole current density in the material when a.) it is in the dark and b.) when light generates an additional \( 1 \times 10^{11} \text{ cm}^{-3} \) electrons? You may assume the mobility is fixed in all cases.

\[
E = \frac{9 \text{V}}{0.5 \text{cm}} = 18 \text{ V/cm}
\]

\[
J_p = \sigma_p E = (q \mu_p p), \quad J_n = \sigma_n E, \quad \sigma_n = (q \mu_n n)
\]

a.) \( J_p = (18 \text{ V/cm}) (1.6 \times 10^{-19}) (480) 4.1 \times 10^{12} \quad J_n = 18 (1.6 \times 10^{-19}) (600) (6.1 \times 10^{12}) \)

\[
J_p = 5.67 \text{ mA/cm}^2 \quad J_n = 28.1 \text{ mA/cm}^2
\]

b.) \( J_p = 18 (1.6 \times 10^{-19}) (480) (4.1 \times 10^{12} + 1 \times 10^{11}) \quad J_n = 18 (1.6 \times 10^{-19}) (1600) (6.1 \times 10^{12} + 1 \times 10^{11}) \)

\[
J_p = 5.8 \text{ mA/cm}^2 \quad J_n = 28.6 \text{ mA/cm}^2
\]
Third 25% Problems (3rd 25%)
13.) (25-points total)
A semiconductor at room temperature (27 degrees C) has the following parameters:
Hole Diffusion coefficient, \(D_p=11.86 \, \text{cm}^2/\text{Sec}\)
Electron Diffusion coefficient, \(D_n=33.625 \, \text{cm}^2/\text{Sec}\)
Substrate intrinsic concentration, \(n_i=1\times10^{10} \, \text{cm}^{-3}\)
Also, these conversion factors may help: Amp=Coulomb/Sec, and Coulomb=Joule/Volt

The sample is in non-equilibrium with the following energy band relationships

![Energy Band Diagram]  

\[ \begin{align*}
F_n &= E_{FN} \\
F_p &= E_{FP} \\
1.45 \, \text{eV} & \quad \text{Slope} = +10 \, \text{eV/\mu m} \\
1 \, \text{eV} & \quad \text{Slope} = -10 \, \text{eV/\mu m} \\
0.35 \, \text{eV} & \\
0 \, \text{eV}
\end{align*} \]

10 \, \mu m \quad 20 \, \mu m \quad x

a.) (7 points) What are the electron and hole current densities, \(J_n\) and \(J_p\) at position \(x=10 \, \mu m\)? Make sure you support your answer with equations or a discussion.

\[
\begin{align*}
J_p &= \mu_p p \nabla F_p, \quad \nabla F_p = 0 \Rightarrow J_p = 0 \, \text{A/cm}^2 \\
J_n &= \mu_n n \nabla F_n, \quad \nabla F_n = 0 \Rightarrow J_n = 0 \, \text{A/cm}^2
\end{align*}
\]

b.) (18 points) What are the electron and hole current densities, \(J_n\) and \(J_p\) at position \(x=20 \, \mu m\)? Make sure you support your answer with equations or a discussion.

@ 20 \mu m \quad F_n = F_p = E_i

Thus, \(p = n_i e^{(E_i-F_p)/kT} = n_i e^0 = n_i = 1\times10^{10} \, \text{cm}^{-3}\)

\[
\begin{align*}
h &= n_i e^{(F_n-E_i)/kT} = n_i e^0 = n_i = 1\times10^{10} \, \text{cm}^{-3}
\end{align*}
\]

see next page
\[ n_p = \frac{q D_p}{2T} = \frac{11.86 \text{ cm}^2/\text{sec}}{0.0259 V} = 458 \text{ cm}^2/\text{V-sec} \]

\[ n_n = \frac{33.625 \text{ cm}^2/\text{sec}}{0.0259} = 1298 \text{ cm}^2/\text{V-sec} \]

\[ \nabla F_p = 2eV/\mu_m \text{ or } \frac{2eV (1.6e-19 J/ev)}{1e-4 \text{ cm}} \]

\[ = 3.2 \times 10^{-15} \text{ J/cm} \]

\[ \therefore \ J_p = (n_p) \rho (\nabla F_p) \]

\[ = \left( \frac{458 \text{ cm}^2}{\text{V-sec}} \right) \left( 1e10 \text{ cm}^{-3} \right) \left( 3.2 \times 10^{-15} \frac{\text{J}}{\text{cm}} \right) \]

\[ = 0.0146 \left( \frac{\text{J}}{\text{V} \cdot \text{sec}} \right) \left( \frac{1}{\text{cm}^2} \right) \]

\[ J_p = 0.0146 \text{ coul} \frac{1}{\text{sec \ cm}^2} \]

\[ J_p = 0.0146 \text{ A/cm}^2 \]

Similarly,

\[ J_n = (n_n) n (\nabla F_n) \]

\[ = (1298) \left( 1e10 \right) \left( -\frac{10eV (1.6e-19 J/ev)}{1e-4 \text{ cm}} \right) \]

\[ J_n = -0.208 \text{ A/cm}^2 \]
14.) (25-points)
A thin SiC semiconductor material of thickness 2 μm with energy bandgap 3.2 eV is placed in a vacuum chamber and is bombarded with electrons at a rate equivalent to 1 nanoampere of current per square cm (1 nA/cm²). The extra electrons are absorbed in the material. Due to the high energy of the electrons used for this bombardment, valence electrons are “knocked” into the conduction band in a process analogous to light generation. Each high-energy bombarding electron has 10,000 eV of energy and thus, can generate multiple electron-hole pairs before all of its energy is dissipated. The wafer is p-type and is uniformly doped with $10^{18}$ cm⁻³ acceptors. The electron beam was turned on January 1, 2003 and is completely absorbed throughout the material uniformly. At 12 noon on February 6th 2003, a Clemson engineer knocked out power and the electron beam instantly shut off. Determine the excess electron concentration in the SiC for all positions AFTER the beam is turned off. Assume a minority carrier lifetime of 0.1 μS and a mobility of 30 cm²/V·sec.

NOTE: This is a real world example from a system known as an Electron Beam Induced Current (EBIC) system.

Given: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} \] General Solution is: \[ \Delta n_p(x) = A \exp{\frac{-x}{\lambda_n}} + B \exp{\frac{x}{\lambda_n}} \]

Given: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} + \frac{\Delta n_p}{\tau_n} + G_L \] General Solution is: \[ \Delta n_p(x) = A \exp{\frac{-x}{\lambda_n}} + B \exp{\frac{x}{\lambda_n}} + G_L \tau_n \]

Given: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_L \] 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: \[ \Delta n_p(x) = \left[ \frac{G_{LO}}{D_n} \int f(x) dx \right] + Bx + C \]

Given: \[ \frac{d\Delta n_p}{dt} = -\frac{\Delta n_p}{\tau_n} \] General Solution is: \[ \Delta n_p(t) = \Delta n_p(t=0) \exp{\frac{-t}{\tau_n}} \]

Given: \[ 0 = -\frac{\Delta n_p}{\tau_n} + G_L \] General Solution is: \[ \Delta n_p = G_L \tau_n \]
Pulling all the concepts together for a useful purpose: (4th 25%)

14.) (25-points)
A thin SiC semiconductor material of thickness 2 um with energy bandgap 3.2 eV is placed in a vacuum chamber and is bombarded with electrons at a rate equivalent to 1 nanoampere of current per square cm (1 nA/cm²). The extra electrons are absorbed in the material. Due to the high energy of the electrons used for this bombardment, valence electrons are “knocked” into the conduction band in a process analogous to light generation. Each high-energy bombarding electron has 10,000 eV of energy and thus, can generate multiple electron-hole pairs before all of its energy is dissipated. The wafer is p-type and is uniformly doped with $10^{18}$ cm⁻³ acceptors. The electron beam was turned on January 1, 2003 and is completely absorbed throughout the material uniformly. At 12 noon on February 6th, 2003, a Clemson engineer knocked out power and the electron beam instantly shut off. Determine the excess electron concentration in the SiC for all positions AFTER the beam is turned off. Assume a minority carrier lifetime of 0.1 μS and a mobility of 30 cm²/V·sec.

NOTE: This is a real world example from a system known as an Electron Beam Induced Current (EBIC) system.

\[
\frac{\frac{d^2 \Delta n_p}{dx^2}}{\Delta n_p} = 0 \quad \text{for case A}
\]

\[
\frac{\Delta n_p}{\Delta t} = 0 \quad \text{for case B}
\]

Given: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} - \frac{\Delta n_p}{\tau_n} \]

General Solution is: \[ \Delta n_p(x) = Ae^{-\frac{x}{\tau_n}} + Be^{\frac{x}{\tau_n}} \]

Given: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_L \]

General Solution is: \[ \Delta n_p(x) = Ae^{-\frac{x}{\tau_n}} + Be^{\frac{x}{\tau_n}} + G_L \tau_n \]

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: \[ 0 = D_n \frac{d^2 \Delta n_p}{dx^2} + G_L f(x) \]

General Solution is: \[ \Delta n_p(x) = \frac{G_L}{D_n} \int f(x) dx + Bx + C \]

Given: \[ \frac{\Delta n_p}{\Delta t} = -\frac{\Delta n_p}{\tau_n} \]

General Solution is: \[ \Delta n_p(t) = \Delta n_p(t = 0) e^{-\frac{t}{\tau_n}} \]

\[ \frac{d\Delta n_p}{dt} = \frac{\Delta n_p}{\tau_n} \]

Given: \[ 0 = -\frac{\Delta n_p}{\tau_n} + G_L \]

General Solution is: \[ \Delta n_p = G_L \tau_n \]

\[ \Delta n_p = G_L \Delta n \]

\[ G_L = ? \]

= electrons bombarding + generated electrons

\[ see \ next \ page\]
1 mA/cm² is absorbed into 2e-4 cm thick sample.

\[
\text{\# electrons/cm}^2/\text{sec} = \frac{1 \text{ mA/cm}^2}{1.6e-19 \text{ coul/electron}} = \frac{1e-9 \text{ Coul/sec/cm}^2}{1.6e-19 \text{ coul/elec}}
\]

\[
= 6.25e9 \frac{\text{electrons}}{\text{cm}^2/\text{sec}}
\]

\[
\text{\# electrons/cm}^3/\text{sec} = \frac{6.25e9}{2e-4 \text{cm}} = 3.125e13 \frac{\text{cm}^{-3}}{\text{sec}}
\]

Each electron has 10,000 eV but only needs 3.2 eV to generate a hole-electron pair. Thus, each electron generates an additional \(10,000/3.2 = 3125\) electron-hole pairs.

\[
G_L = 3.125e13 \frac{\text{cm}^{-3}}{\text{sec}} + 3.125e13 (3125) \frac{\text{cm}^{-3}}{\text{sec}}
\]

\[
G_L = 9.77e16 \frac{\text{cm}^{-3}}{\text{sec}}
\]

\[
\Delta n_p = G_L T_n = (9.77e16 \text{cm}^{-3/\text{sec}})(0.1 \mu\text{s})
\]

\[
\Delta n_p = 9.77e9 \text{ cm}^{-3}
\]

Now shut off the beam!
Extra work can be done here, but clearly indicate which problem you are solving.

Case B:
Beam off:

\[
\frac{2}{dx} \Delta N_p = \Delta N_p \frac{\partial^2 N_p}{\partial x^2} - \frac{\Delta N_p}{\tau_n} + \gamma_0
\]

General Solution

\[
\Delta N_p(x) = \Delta N_p(x=0) e^{-x/\tau_n}
\]

\[
\Delta N_p(x) = 9.77e9 cm^{-3} from before
\]

\[
\Delta N_p(x) = 9.77e9 cm^{-3} e^{-x/0.1 \mu s} cm^{-3}
\]

In a real EBIC system, the beam is not uniformly absorbed making the solution 3-dimensional including the diffusion term. Additionally, each electron creates \[\frac{1}{3}\] of its energy (i.e. \[\frac{10000}{3}\]) in this example) with the remaining energy wasted as heat. See EBIC image on the next page to see a map of "defects" lowering the minority carrier lifetime.
The following is an actual EBIC image of a SiC material containing 2 types of defects that will reduce the minority carrier diffusion length, lowering the current collected in the measurements. The small dots are dislocations (missing rows of atoms) while the large dark image is an inclusion (basically a trashed region of the crystal). The source of the current is from excess electron-hole pairs generated by a high energy electron beam (25 KV in this case) formed in a scanning electron microscope.