Notes:

1. Unless otherwise indicated, assume room temperature and that kT/q is 0.025 V. You may also approximate [(kT/q) ln 10] as 0.06 V.

2. Open book; 6.012 text and any other notes permitted.

3. All of your answers and any relevant work must appear on these pages. Any additional paper you hand in will not be graded.

4. Make reasonable approximations and assumptions. State and justify any such assumptions and approximations you do make.

5. Be careful to include the correct units with your answers when appropriate.

6. Be certain that you have all nine (9) pages of this exam booklet and make certain that you write your name at the top of this page in the space provided.
Problem 1 (20 points)

a) Consider a silicon wafer which is doped throughout with $10^{16}$ cm$^{-3}$ arsenic atoms, and which in addition is doped with $10^{17}$ cm$^{-3}$ boron atoms to a depth of 4 µm and with $10^{18}$ cm$^{-3}$ phosphorous atoms to a depth of 2 µm. Taking the x-direction to be normal to the surface, what are the net doping type and concentration in the following three regions (6 pts. total):

i) $4 \mu m < x$

Type _______ Net doping _________

ii) $2 \mu m < x < 4 \mu m$

Type _______ Net doping _________

iii) $0 < x < 2 \mu m$

Type _______ Net doping _________

b) A uniform, n-type germanium bar ($N_D = 10^{15}$ cm$^{-3}$) in which the minority carrier lifetime is $10^{-6}$ s is excited with a constant illumination generating $10^{23}$ hole-electron pairs/cm$^3$.s throughout the sample. Does this illumination result in a large or a small change in the conductance of this sample, and why?

Large _______ Small _______ because

c) A certain p-type silicon bar is doped with a net acceptor concentration of $10^{17}$ cm$^{-3}$. If its temperature is increased from 300 K (room temperature) to 350 K, which quantity, the equilibrium hole concentration, $p_0$, the equilibrium electron concentration, $n_0$, or the intrinsic concentration, $n_i$, changes the most, and which changes the least, and why? (6 pts total)

i) Least changed: _________ because

ii) Most changed: _________ because

Problem 1 continues on the next page
Problem 1 continued

d) A polished sample of a certain semiconductor, call it Semiconductor A, is yellow and transparent, whereas a similar sample of another semiconductor, Semiconductor B, is gray and opaque. Which semiconductor has the larger energy gap? Explain your answer.

Semiconductor with largest energy gap: _____ because

End of Problem 1
Problem 2 (36 points)

The n-type silicon sample illustrated below has an ohmic contact on one end and a reflecting boundary on the other. It is doped with \( N_D = 5 \times 10^{16} \text{ cm}^{-3} \); the electron mobility, \( \mu_e \), is 1600 cm\(^2\)/V-s; the hole mobility, \( \mu_h \), is 600 cm\(^2\)/V-s; and the minority carrier diffusion length is 50 \( \mu\text{m} \).

![Diagram of n-type silicon sample with ohmic and reflecting contacts]

This sample is excited with constant, low-level illumination creating the excess minority carrier profile illustrated below:

![Excess minority carrier profile graph]

a) Use the information given above to calculate the minority carrier lifetime in this sample.

\[ \tau_{\text{min}} = \text{_________} \]

b) On the axes provided below sketch the current densities requested. Indicate the magnitude and sign of the current density at appropriate points on your sketches.

i) Total hole current density, \( J_h(x) \)

![Current density graph]

Problem 2 continues on the next page
Problem 2 continued

ii) Electron diffusion current density, $J_{e(x)}^{\text{diff}}$

\[ J_{e(x)}^{\text{diff}} \left[ \text{A/cm}^2 \right] \]

iii) Electron drift current density, $J_{e(x)}^{\text{drift}}$

\[ J_{e(x)}^{\text{drift}} \left[ \text{A/cm}^2 \right] \]

c) Derive an expression for the generation function, $g_l(x)$.

\[ g_l(x) = \text{expression} \]

d) i) What is the total rate of hole-electron recombination, $R$, per unit cross-sectional area in the bulk of the sample (i.e., excluding that occurring at the ohmic contact)?

\[ R(\text{in bulk}) = \text{expression} \text{ pairs/cm}^2\text{-s} \]

Problem 2 continues on the next page
Problem 2 continued

ii) Where do most of the optically generated hole-electron pairs recombine and what fraction of the total number of optically generated pairs recombine there?

Location: ______________
Fraction: ______________

e) The sample is now damaged by proton (hydrogen ion) bombardment in order to reduce the minority carrier lifetime significantly; by doing this the minority carrier diffusion length is reduced to 1 µm.

i) Assuming that the optical generation function remains unchanged (i.e., is the same as it was previously) what would you expect the excess carrier profile to look like with this shorter minority carrier diffusion length? Answer by sketching the profile in this new situation on the axes provide below. You should be quantitative with regard to the x-axis variation, but you need only be qualitative about the magnitude of \( p' \), i.e. indicate if \( p'(5 \, \mu m) \) is larger or smaller than in the earlier situation.

\[
\begin{align*}
p'(x) \\
0 & \quad 10 & x (\mu m)
\end{align*}
\]

ii) On the axes provided below sketch and label the minority carrier current density along the length of the sample with this reduced minority carrier diffusion length.

\[
\begin{align*}
J_{h}(x) \, [A/cm^{2}] \\
0 & \quad 10 & x (\mu m)
\end{align*}
\]

End of Problem 2
Problem 3 (44 points)

This question concerns the silicon p-n junction diode illustrated below. Both sides of the diode are 10 µm long with a net acceptor concentration, $N_{Ap}$, of $10^{16}$ cm$^{-3}$ on the p-side and an net donor concentration, $N_{Dn}$, of $10^{17}$ cm$^{-3}$ on the n-side. Throughout the device the electron mobility is 1600 cm$^2$/V-s, and the hole mobility is 600 cm$^2$/V-s. The minority carrier diffusion lengths are both much larger than 10 µm. Neglect space charge layer generation and recombination when solving this problem.

![Diode Diagram]

a) What are the following electrostatic potentials, using intrinsic material as the zero reference for electrostatic potential?

i) Electrostatic potential, $\Phi_n$, in the quasineutral region on the n-side.

$$\Phi_n = \text{__________}$$

ii) Electrostatic potential, $\Phi_p$, in the quasineutral region on the p-side.

$$\Phi_p = \text{______}$$

iii) Built-in potential change, $\Phi_b$, across the junction.

$$\Phi_b = \text{__________}$$

b) If the zero-bias depletion width on the p-side of the junction, $x_{po}$, is 0.3 µm, what is it on the n-side?

$$x_{no} = \text{________________}$$

Problem 3 continues on the next page
Problem 3 continued

c) A bias is applied to the diode leading to an excess minority carrier population at the edge of the depletion region on the p-side of the junction, \( n'(-x_p) \) of \( 10^{14} \text{ cm}^{-3} \). Find the following quantities (you may assume \( x_n \) and \( x_p \) are much less than 10 \( \mu \text{m} \) in your calculations):

i) \( p'(x_n) \), the excess hole population at the edge of the depletion region on the n-side of the junction

\[
p'(x_n) = \phantom{0000000000} \]

ii) \( J_e(-x_p) \), the electron current density at the edge of the depletion region on the p-side of the junction.

\[
J_e(-x_p) = \phantom{0000000000} \]

iii) \( J_h(x_n) \), the hole current density at the edge of the depletion region on the n-side of the junction.

\[
J_h(x_n) = \phantom{0000000000} \]

iv) \( J_e(x_n) \), the electron current density at the edge of the depletion region on the n-side of the junction.

\[
J_e(x_n) = \phantom{0000000000} \]

d) With the bias as applied in Part (c), what is the corresponding voltage drop across the junction, \( v_J \)? That is, if the total change in the electrostatic potential in going from \(-x_p\) to \( x_n \) is written as \( (\Phi_b - v_J) \), what is \( v_J \)?

\[
v_J = \phantom{0000000000} \]

Problem 3 continues on the next page
Problem 3 continued

e) With the bias as applied in Part (c) there is a current through the diode and there are ohmic voltage drops in the quasineutral regions on either side of the junction which we normally neglect. This question concerns those voltage drops.

i) Which side of this junction has the higher resistivity, the n-side or the p-side and what is that resistivity?

______ p-side   ______ n-side

Resistivity, $\rho = \underline{}$

ii) Looking at the p-side of the junction and writing the resistance of the quasineutral region between $-w_p$ and $-x_p$ as $R_p$, which of the following is the correct expression for the ohmic voltage drop between $-w_p$ and $-x_p$? Check the correct answer and explain your answer in the space provided below.

______ The total current times the resistance, $A \times J_{tot} \times R_p$

______ The total hole current times the resistance, $A \times J_{h,tot} \times R_p$

______ The hole drift current times the resistance, $A \times J_{h,\text{drift}} \times R_p$

Explanation:

End of Problem 3

End of Exam