

YOUR NAME _____

*Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology*

6.012 Electronic Devices and Circuits

Exam No. 1

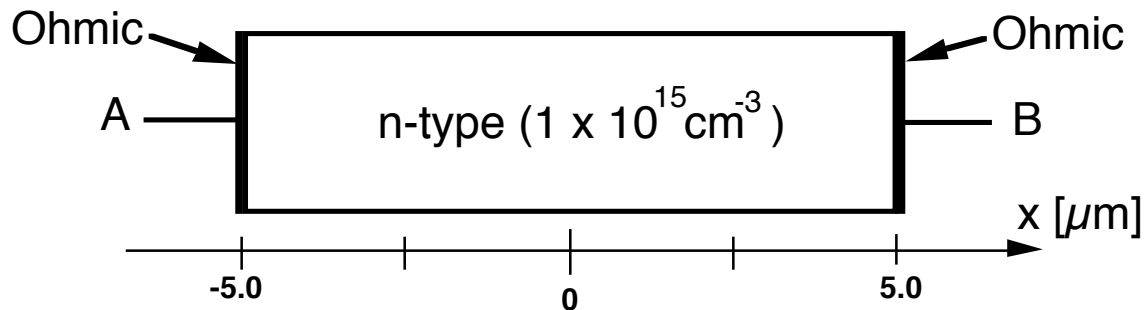
Notes:

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 one sheet of 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 ten (10) pages of this exam booklet and make certain that you write your name at the top of this page in the space provided.

6.012 Staff Use Only	PROBLEM 1	_____	(out of a possible 33)
	PROBLEM 2	_____	(out of a possible 33)
	PROBLEM 3	_____	(out of a possible 34)
	TOTAL		

Problem 1 - (33 points)

The n-type silicon sample illustrated below is 10 microns (μm) long and has metal ohmic contacts, A and B, on either end. The net donor concentration is $1 \times 10^{15} \text{ cm}^{-3}$; the electron mobility, μ_n is $1600 \text{ cm}^2/\text{V-s}$; and the hole mobility, μ_p is $600 \text{ cm}^2/\text{V-s}$. The electrostatic potential of the metal relative to intrinsic silicon is 0.2V , and the intrinsic carrier concentration at room temperature is 10^{10} cm^{-3} .



- a) What are the thermal equilibrium (i.e., no light, $v_{AB} = 0 \text{ V}$) hole and electron concentrations in this silicon? Show your work and/or explain your answer.

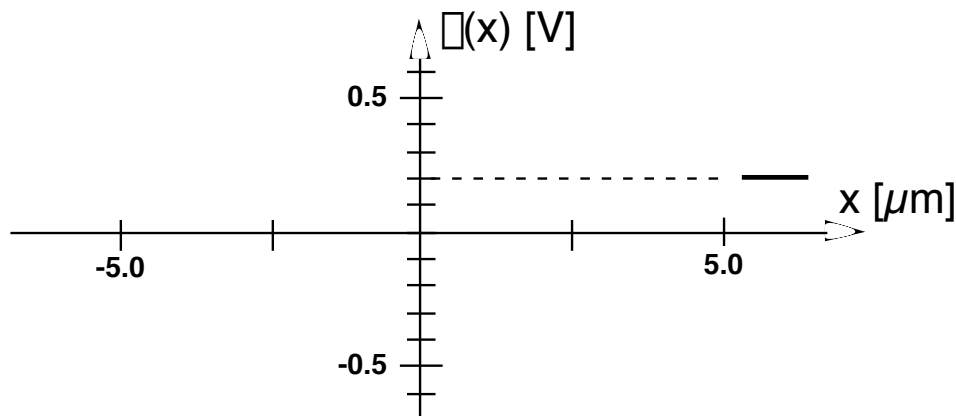
$$n_o = \text{_____} \text{ cm}^{-3}$$

$$p_o = \text{_____} \text{ cm}^{-3}$$

- b) What is the thermal equilibrium electrostatic potential, ϕ_n , of the silicon in this sample? Assume ϕ is zero in intrinsic silicon (our usual convention). Show your work and/or explain your answer.

$$\phi_n = \text{_____} \text{ Volts}$$

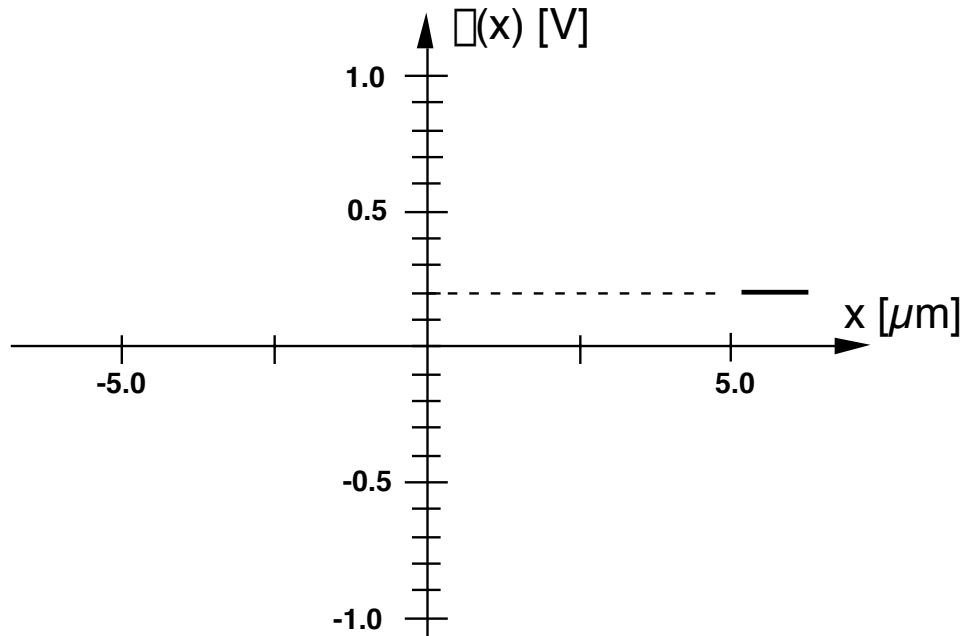
- c) On the axes provided below sketch the electrostatic potential, $\phi(x)$, with $v_{AB} = 0 \text{ V}$, going from the metal on the left, through the silicon, and into the metal on the right (where the value of ϕ is already indicated correctly). Dimension your sketch; label any significant features. **Note:** This is not a diode.



Problem 1 continues on the next page

Problem 1 continued

- d) Assume now that $v_{AB} = 0.5 \text{ V}$. On the axes provided below sketch the electrostatic potential, $\phi(x)$, going from the metal on the left, through the silicon, and into the metal on the right (where the value of ϕ is unchanged, as indicated), with $v_{AB} = 0.5 \text{ V}$. Dimension your sketch and label any significant features, including $\phi(0)$.

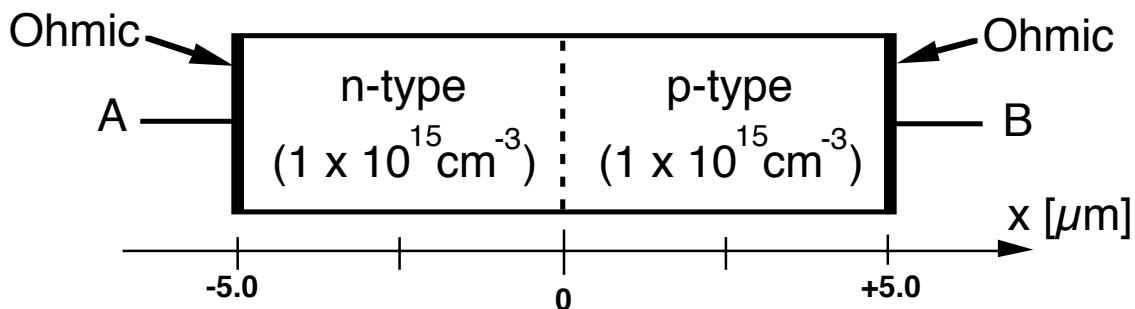


- e) When $v_{AB} = 0.5 \text{ V}$, what are the electron and hole drift current densities, J_e^{dr} and J_h^{dr} , respectively, at $x = 0 \text{ micrometers}$

$$J_e^{\text{dr}}(0 \text{ micrometers}) = \underline{\hspace{2cm}} \text{ A/cm}^2$$

$$J_h^{\text{dr}}(0 \text{ micrometers}) = \underline{\hspace{2cm}} \text{ A/cm}^2$$

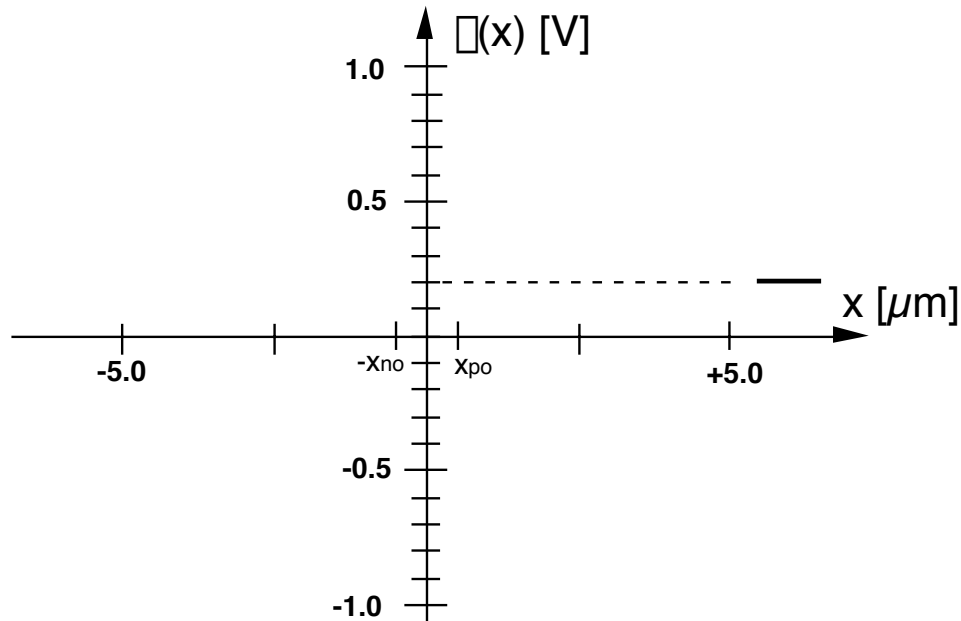
Next consider a sample similar to our original sample, except that it is doped p-type with a net acceptor concentration of $1 \times 10^{15} \text{ cm}^{-3}$ in the region from $x = 0 \text{ micrometers}$ to $x = +5 \text{ micrometers}$ as shown below. **Note:** This is a diode with the p-side to the right.



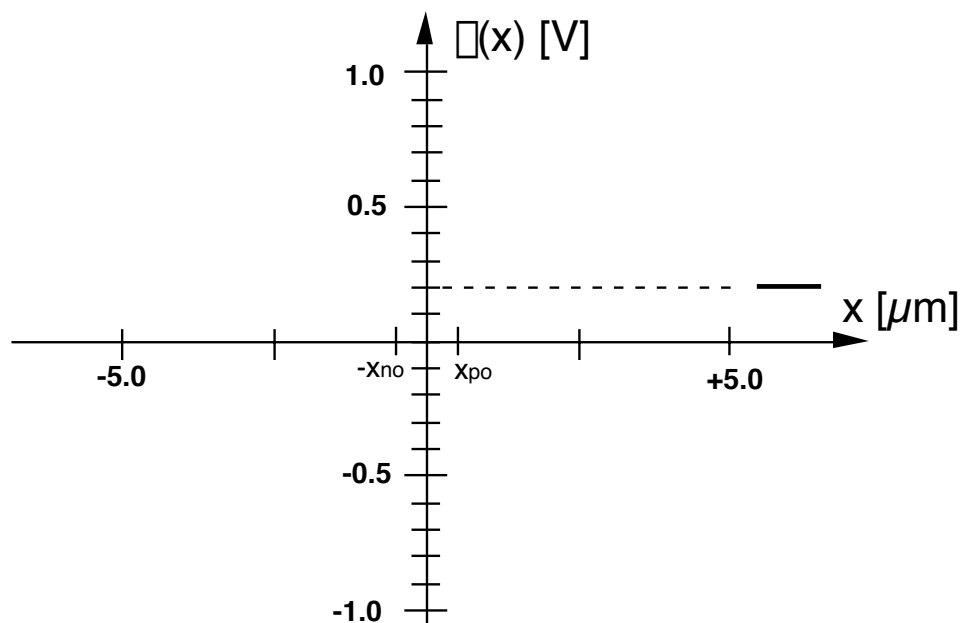
Problem 1 continues on the next page

Problem 1 continued

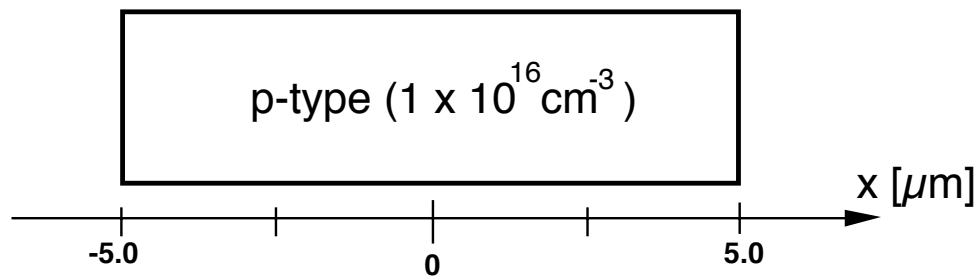
- f) On the axes provided below sketch the electrostatic potential, $\phi(x)$, going from the metal on the left, through the silicon, and into the metal on the right, with $v_{AB} = 0$ V. Dimension your sketch and label any significant features, including the shape of $\phi(x)$ in the depletion region and the value of $\phi(0)$. Use the x_{no} and x_{po} indicated on the horizontal axis.



- g) The diode is now reverse biased by $v_{AB} = 0.5$ V. On the axes provided below sketch the electrostatic potential, $\phi(x)$, now, going from the metal on the left, through the silicon, and into the metal on the right. Keep ϕ to the right of $x = 5 \mu\text{m}$ at the value it had in Part f. Dimension your sketch and label any significant features, including the shape of $\phi(x)$ in the depletion region and the value of $\phi(0)$.



End of Problem 1

Problem 2 (33 points)


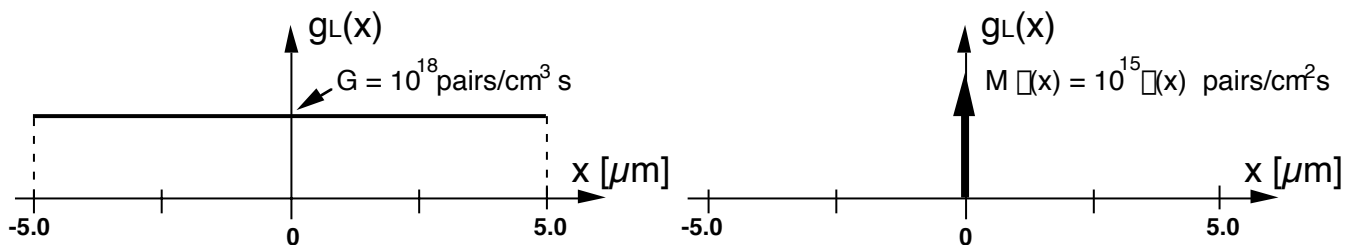
The p-type sample of silicon illustrated above is $10 \mu\text{m}$ long and uniformly doped with 10^{16} cm^{-3} acceptor atoms. The electron mobility, μ_e , is $1600 \text{ cm}^2/\text{V}\cdot\text{s}$ and the minority carrier lifetime, τ_e , is 10^{-5} s . Initially, the sample has reflecting boundaries on all surfaces.

- a) What are the minority carrier diffusion constant, D_e , and diffusion length, L_e , in this sample?

$$D_e = \underline{\hspace{2cm}}$$

$$L_e = \underline{\hspace{2cm}}$$

NOTE: From now on assume $L_e \gg 10 \mu\text{m}$ independent of what you found in Part a. Do not, however, assume that the minority carrier lifetime is infinite.



Illumination in Parts b, c, g, and h.

Illumination in Parts d, e, and f

- b) The sample is uniformly illuminated with light generating 10^{18} hole-electron pairs per second uniformly throughout it, as shown above (i.e., $g_L(x,t) = G = 10^{18} \text{ pairs}/\text{cm}^3\text{s}$). What is the excess electron population, $n'(x)$, after the illumination has been on for a long time?

$$n'(x) = \underline{\hspace{2cm}}$$

- c) If the illumination in Part b is extinguished at $t = 0$, after having been on for a long time, what is the excess minority carrier population as a function of time for $t > 0$?

$$n'(x, t) = \underline{\hspace{2cm}}$$

Problem 2 continues on the next page

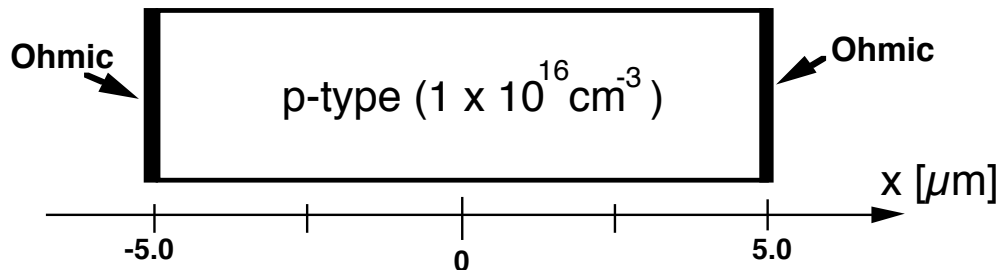
Problem 2 continued

d) Now consider that the illumination in Part b is not uniformly distributed, but is instead concentrated at a point as an impulse at the middle of the bar, $x = 0$, i.e., $g_L(x) = M \delta(x)$, where $\delta(x)$ is a spatial impulse at $x = 0$, and $M = 10^{15}$ pairs/cm²s. (See the illustration on the previous page.) What approximately is $n'(x)$ now, after the illumination has been on for a long time? Explain your answer.

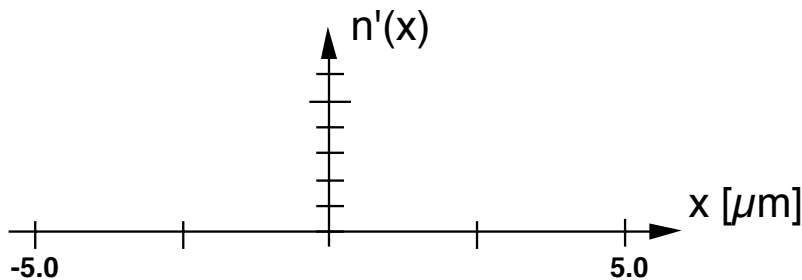
Suggestion: If you don't see the answer right away, come back to it later.

$n'(x) \approx$ _____

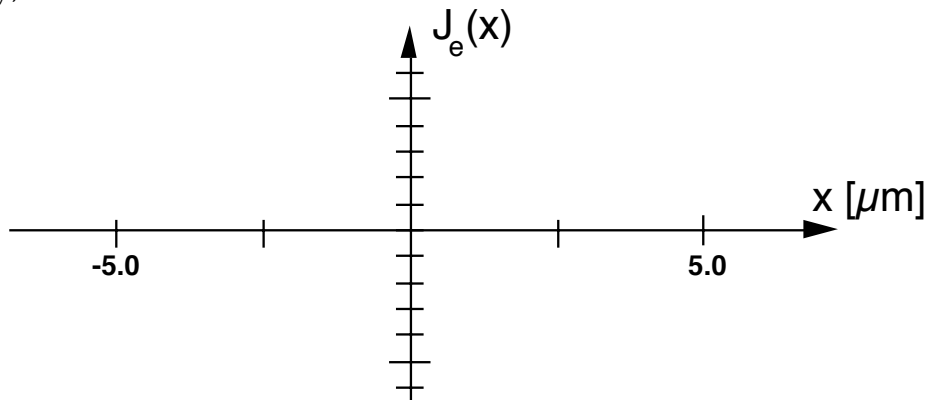
e) Ohmic contacts are now added to the ends of the sample, as illustrated below.



On the axes provided below sketch $n'(x)$ in this new sample with the same illumination as in Part d, i.e., $g_L(x) = M \delta(x) = 10^{15}$ pairs/cm²s $\delta(x)$. You may label $n'(0)$ as N' and you need not evaluate it.



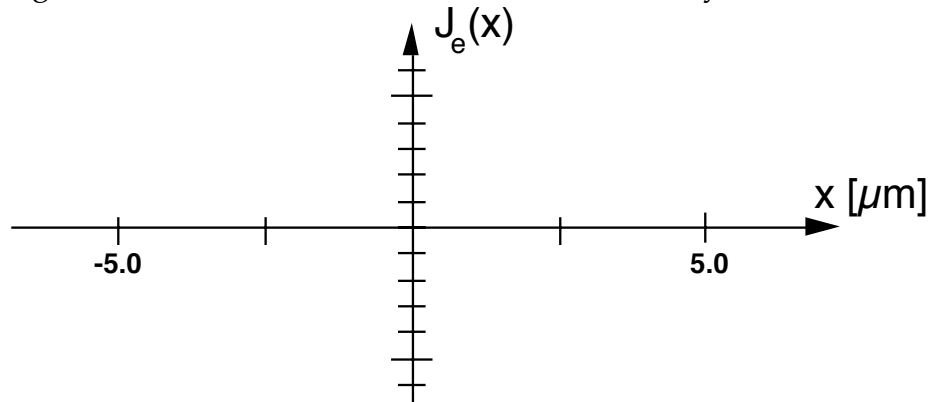
(f) On the axes below sketch and label the minority carrier current, $J_e(x)$, throughout the sample for the situation in Part e. You should be able to label the vertical axis numerically; do not label it in terms of N' .



Problem 2 continues on the next page.

Problem 2 continued

(g) Next consider changing the illumination on the sample with the ohmic contacts to the uniform illumination in Part b, i.e., $g_L(x) = G$. Sketch and label the minority carrier current, $J_e(x)$ throughout the sample on the axes provided below in this case. You should again be able to label the vertical axis numerically.



h) If the illumination on the sample in Part g is extinguished at $t = 0$ after having been on for a long time, how will the rate of decay of the excess population compare what you found in Part c? Explain your answer.

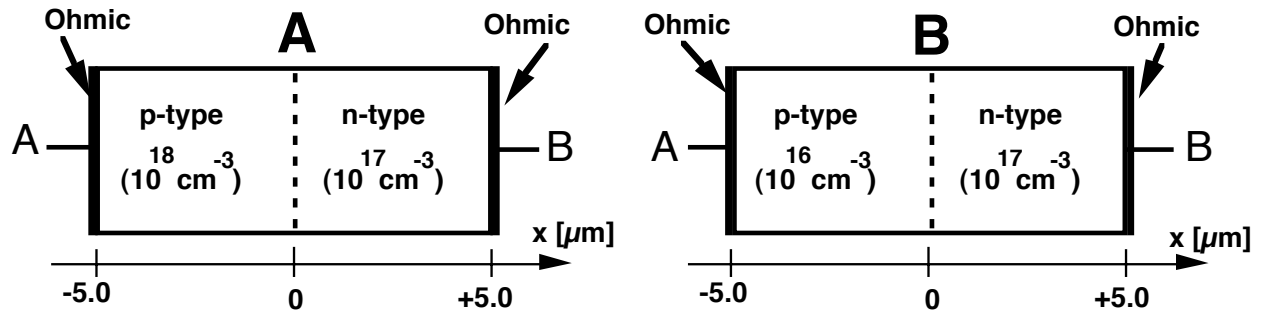
Faster now
because:

Slower now

Little difference

End of Problem 2

Problem 3 (34 points)



This problem concerns the two abrupt p-n diodes pictured above. These two diodes have identical dimensions and differ only in the doping levels on the p-sides. In both diodes the n-side is doped with 10^{17} cm^{-3} donors. In Diode A the p-side is doped with 10^{18} cm^{-3} acceptors and in Diode B it is doped with 10^{16} cm^{-3} acceptors. You may assume for purposes of this problem that:

- (1) the widths of the depletion regions on either side of the junctions in these diodes are all negligible relative to $5 \mu\text{m}$ when they are forward biased,
- (2) the hole mobility is $600 \text{ cm}^2/\text{V-s}$ and the electron mobility is $1600 \text{ cm}^2/\text{V-s}$ in all regions, and
- (3) the minority carrier diffusion lengths are much larger than $10 \mu\text{m}$.

a) Which diode has the wider zero-bias depletion region? Explain your answer.

- Diode A Diode B Little difference
 because:

b) With zero applied bias, in which diode is the magnitude of the peak electric field in the depletion region largest? Explain your answer.

- Diode A Diode B Little difference
 because:

c) For which diode will the magnitude of the reverse breakdown voltage be largest? Explain your answer.

- Diode A Diode B Little difference
 because:

Problem 3 continues on the next page

Problem 3 continued

d) A reverse bias is applied to both diodes so that the depletion region on the n-side in each diode is $0.2 \mu\text{m}$ wide.

i) What is the width of the depletion region on the p-side in each diode?

Diode A: $x_p =$ _____

Diode B: $x_p =$ _____

ii) On which diode is the magnitude of the reverse bias larger? Explain your answer.

Diode A
because:

Diode B

Little difference

e) A forward bias is applied to each diode so that the excess hole population on the n-side at x_n , $p'(x_n)$, is 10^{12} cm^{-3} in both diodes.

i) What are the excess electron populations at the edge of the depletion region on the p-side, i.e., $n'(-x_p)$, in each diode?

Diode A: $n'(-x_p) =$ _____

Diode B: $n'(-x_p) =$ _____

ii) What is the ratio of the total hole current to the total electron current through each diode at $x = 0$?

Diode A: $J_h(0)/J_e(0) =$ _____

Diode B: $J_h(0)/J_e(0) =$ _____

Problem 3 continues on the next page

Problem 3 continued

- iii) What is the total excess minority carrier charge per unit area in each diode at this bias level? Note: The integrals indicated in the answer lines below extend over the entire device, i.e., from $-5\mu\text{m}$ to $+5\mu\text{m}$.

$$\text{Diode A: } q \int p'(x) dx = q \int n'(x) dx = \text{_____ coul/cm}^2$$

$$\text{Diode B: } q \int p'(x) dx = q \int n'(x) dx = \text{_____ coul/cm}^2$$

- iv) What is the applied bias on each diode?

$$\text{Diode A: } V_{AB} = \text{_____}$$

$$\text{Diode B: } V_{AB} = \text{_____}$$

End of Problem 3

End of Exam