*YOUR NAME*____

Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

6.012 Electronic Devices and Circuits

Exam No. 1

Wednesday, October 7, 2009

7:30 to 9:30 pm

Notes:

1. An effort has been made to make the various parts of these problems independent of each other so if you have difficulty with one item go on, and come back later.
2. Some questions ask for an explanation of your answer. No credit will be given for answers lacking this explanation.
3. Unless otherwise indicated, you should assume room temperature and that kT/q is 0.025 V. You should also approximate [(kT/q) ln 10] as 0.06 V.
4. Closed book; one sheet (2 pages) of notes permitted. Formula sheet provided.
5. All of your answers and any relevant work must appear on these pages. Any additional paper you hand in will not be graded.
6. Make reasonable approximations and assumptions. State and justify any such assumptions and approximations you do make.
7. Be careful to include the correct units with your answers when appropriate.
8. Be certain that you have all ten (10) pages of this exam booklet and the three (3) page formula sheet, 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 34)
	PROBLEM 2	__________	(out of a possible 32)
	PROBLEM 3	__________	(out of a possible 34)
	TOTAL		

Problem 1 - (34 points)

This problem contains 4 independent short problems that can be worked in any order.

a) [6 pts] You find a sample of silicon, but the accompanying data sheet has been partially destroyed so you only know that it is n-type, its resistivity is 100 Ohm-cm, and its electron mobility is 1600 cm^2/V-s. You also remember that $n_i(Si) = 10^{10}$ cm^{-3}.

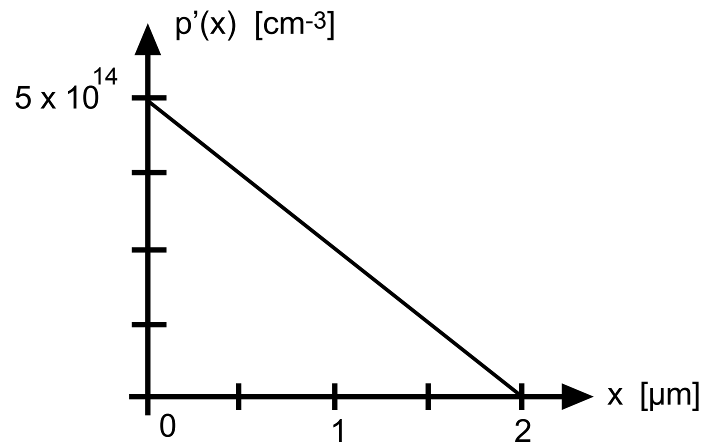
i) What is the approximate equilibrium electron concentration, n_o, in this sample?

n_o = _____________ cm^{-3}

ii) What is the approximate equilibrium hole concentration, p_o, in this sample?

p_o = _____________ cm^{-3}

b) [10 pts] The excess hole population illustrated on the right is established in an n-type silicon sample, $N_D = 10^{17}$ cm^{-3}. The minority carrier lifetime in this sample is 10^{-4} s, the hole mobility is 640 cm^2/V-s, and the cross-section of the sample is 10^{-4} cm^2.



Note: 1 $\mu m = 10^{-4}$ cm

i) What is the hole current, $i_h = A J_h$, in this sample?

i_h = ___________________ Amps

ii) What is the <u>total</u> number of excess holes in this sample?

Excess holes = ______________________

Problem 1 continues on the next page

Problem 1 continued

iii) What is the <u>total</u> rate at which excess holes are recombining with excess electrons in this sample, and what is the corresponding hole current, $i_{h,recomb}$?

Total recombination occurring in sample = ____________________ holes/s

Hole recombination current, $i_{h,recomb}$ = _________________________ Amps

c) [9 pts] Consider two p^+-n diodes which are identical except for the fact that in Diode A the minority carrier lifetime is infinite making $L_h >> w_N$, while in Diode B the minority carrier lifetime is finite and small enough that $L_h < w_N$. Note: w_N is the width of the n-type side, and L_h is the minority carrier diffusion length.

i) Which of these two diodes has the larger saturation current, I_S? Explain your answer.

Diode A ________ Diode B ________ They are similar ________

Explanation:

ii) Which of these two diodes has the larger total number of excess holes in the n-side quasi-neutral region when a forward biased V_{AB} is applied?

Diode A ________ Diode B ________ They are similar ________

Explanation:

iii) Which of these two diodes has the wider space charge layer (depletion region) in thermal equilibrium?

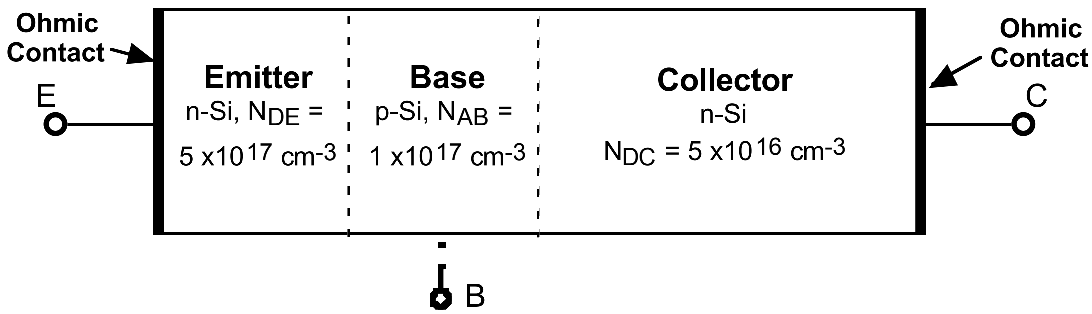
Diode A ________ Diode B ________ They are similar ________

Explanation:

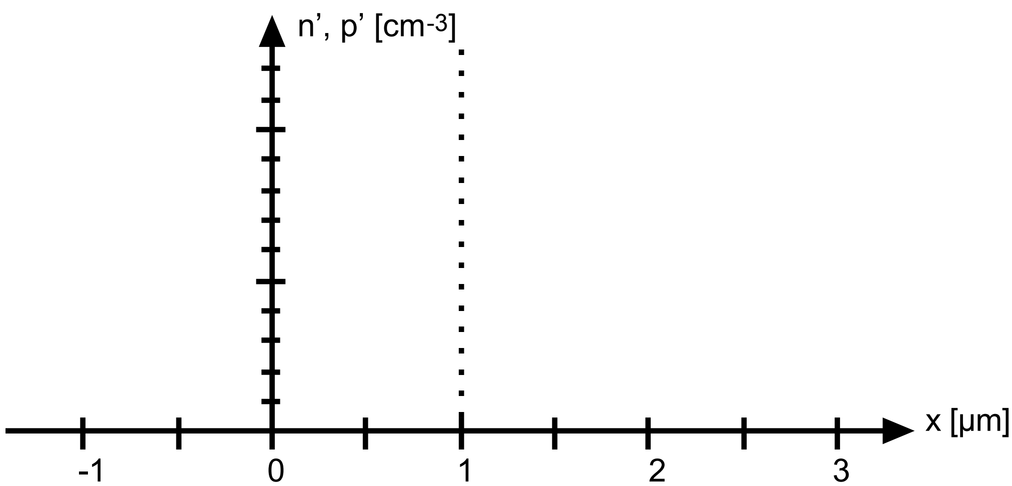
Problem 1 continues on the next page

Problem 1 continued

d) [9 pts] This question concerns the npn bipolar transistor shown below. There is negligible minority carrier recombination throughout except at the ohmic contacts.



i) On the axes provided, sketch and label the excess minority carrier profiles when both junctions are forward biased with $v_{BE} = v_{BC} = 0.6$ V. Notice that this is not a bias in the forward active region.



ii) Calculate the forward current gain, β_f ($\approx 1/\delta_E$), for this device when it is biased in the forward active region, i.e. $v_{BE} > 0$ and $v_{CE} \leq 0$. $D_e = 40$ cm^2/s, $D_h = 15$ cm^2/s.

β_f = ____________________

iii) Redesign this transistor to increase the forward current gain, β_f, to 100 by increasing the doping level of one of the three regions in this device. Indicate which region should be changed and to what the new doping level should be.

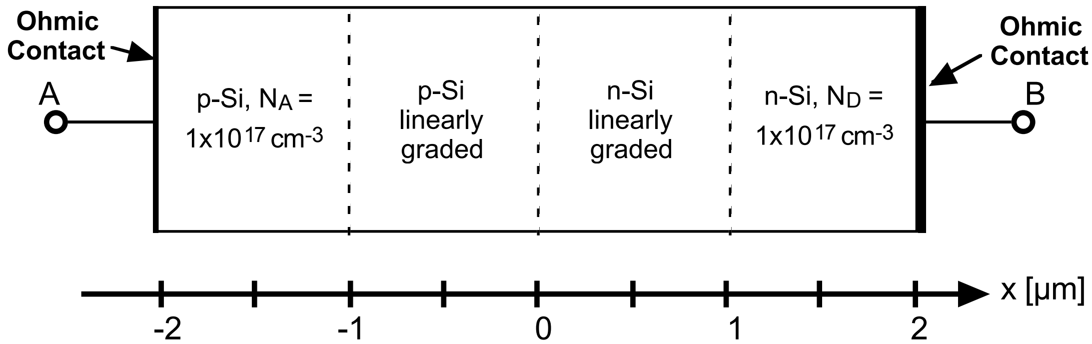
Region: ________________________

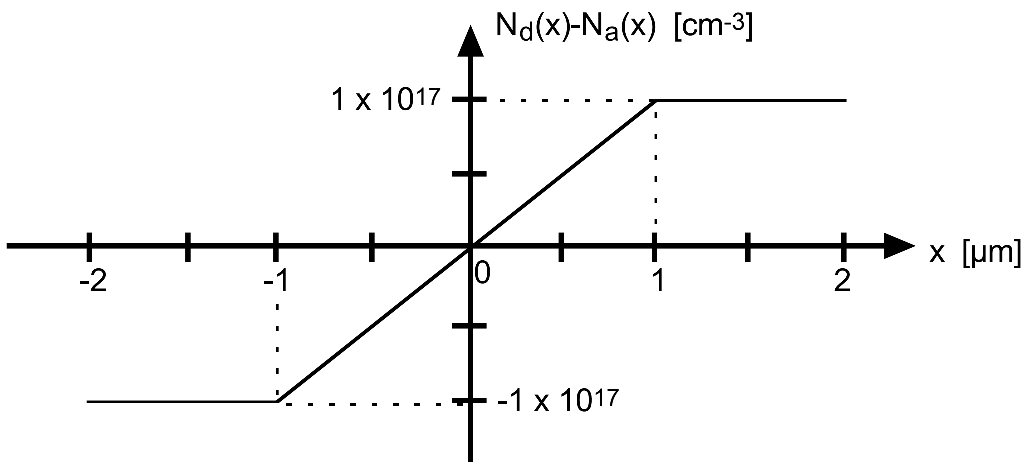
N = ______________________

End of Problem 1

Problem 2 - (32 points)

Consider the silicon diode pictured below. It is 4 μm long, with ohmic contacts at each end, and it is uniform p-type with $N_A = 1 \times 10^{17}$ cm^{-3} for 1 μm on its far left end and uniform n-type with $N_D = 1 \times 10^{17}$ cm^{-3} on its far right end. In between these two uniformly doped regions, the net concentration, $N_d(x) - N_a(x)$, slowly grades linearly over a distance of 2 μm from -1×10^{17} cm^{-3} on the left to 1×10^{17} cm^{-3} on the right, as shown in the lower figure.





Note: 1 μm = 10^{-4} cm

a) [6 pts] In thermal equilibrium, what is the electrostatic potential, $\phi(x)$, in the left-hand quasi-neutral region at x = -1.5 μm, and what is the electrostatic potential, $\phi(x)$, in the right-hand quasi-neutral region at x = +1.5 μm, and what is the built-in potential step, $\Delta\phi_b$, seen transiting from x = -1.5 μm to x = +1.5 μm? Use the 60 mV rule, and log 2 = 0.3.

$\phi(-1.5\ \mu m)$ = ________________ V

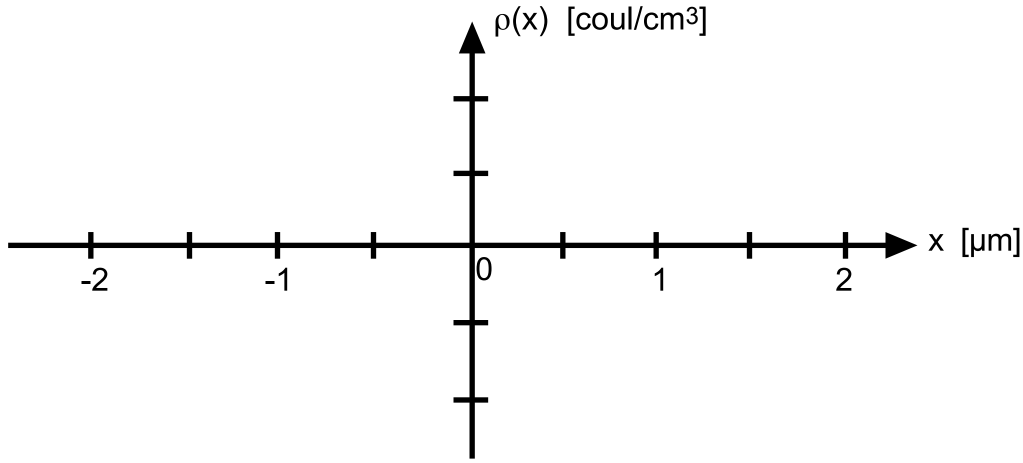
$\phi(1.5\ \mu m)$ = ________________ V

$\Delta\phi_b$ = ________________ V

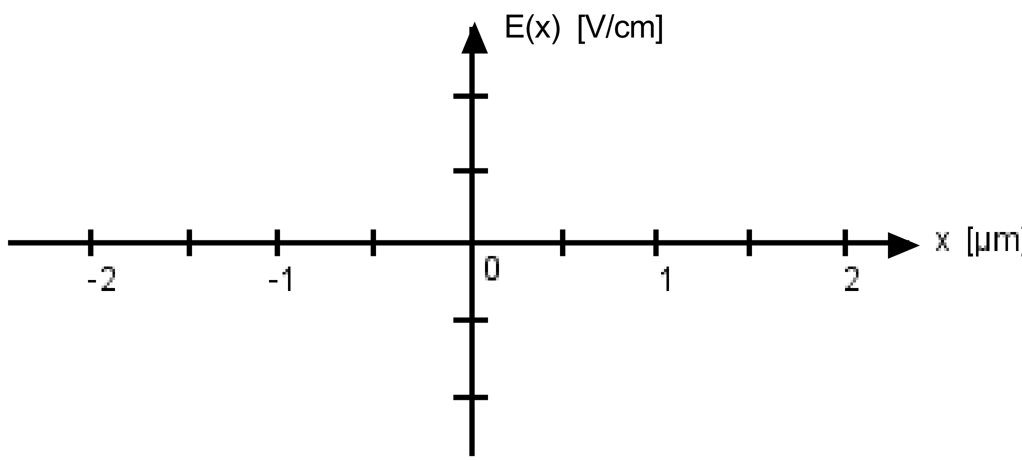
Problem 2 continues on the next page

Problem 2 continued

b) [4 pts] For the rest of this problem, a bias voltage, V_{AB}, is applied to this diode resulting in a total depletion region width of 1 μm, and $x_N = |x_P| = 0.5$ μm. On the axes provided below, plot and label the net charge density, $\rho(x)$, for x in the range - 2 μm < x < 2 μm with this bias voltage applied. Use the depletion approximation and assume that the regions outside the depletion region are quasi-neutral, i.e. $\rho(x) \approx 0$.



c) [4 pts] On the axes provided below, plot and label the electric field, E(x), for x in the range - 2 μm < x < 2 μm with the bias voltage V_{AB} applied.



d) [4 pts] What is the change in potential, $\Delta\phi$, transiting the depletion region when the bias is the same as in Part b, i.e. what is $\phi(0.5\ \mu m) - \phi(-0.5\ \mu m)$?

$\Delta\phi_{Depl.Reg.} = \phi(0.5\ \mu m) - \phi(-0.5\ \mu m) =$______________ Volts

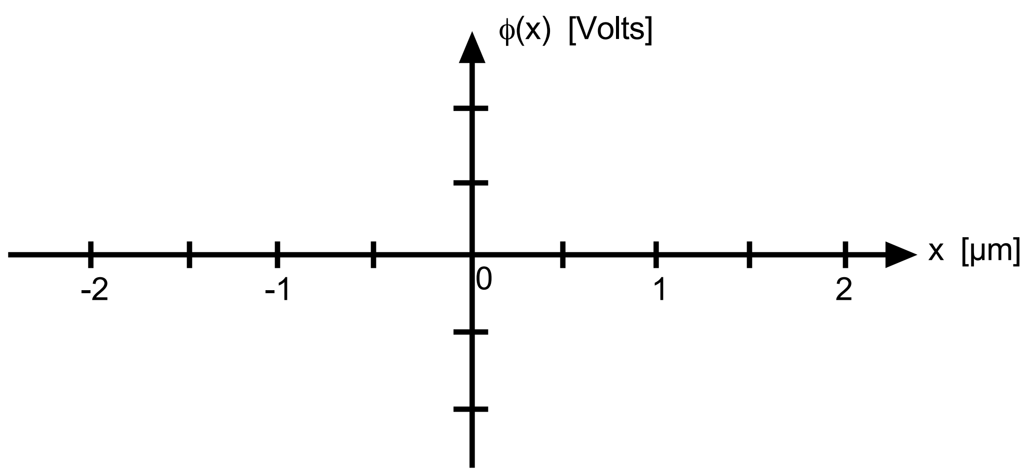
Problem 2 continues on the next page

Problem 2 continued

e) [4 pts] What is the change in potential, $\Delta\phi$, in transiting the quasi-neutral n-type graded region between $x = 0.5\ \mu m$ and $x = 1.0\ \mu m$, i.e. what is $\phi(1.0\ \mu m) - \phi(0.5\ \mu m)$?

$\Delta\phi_{nQNR.} = \phi(1.0\ \mu m) - \phi(0.5\ \mu m) =$ ________________ Volts

f) [4 pts] On the axes provided below, plot and label the electrostatic potential, $\phi(x)$, for x in the range $-2\ \mu m < x < 2\ \mu m$ with the same bias voltage applied as in Part c. Use the depletion approximation, and assume that the regions outside the depletion region are quasi-neutral. In your plot make $\phi(0) = 0$ Volts.



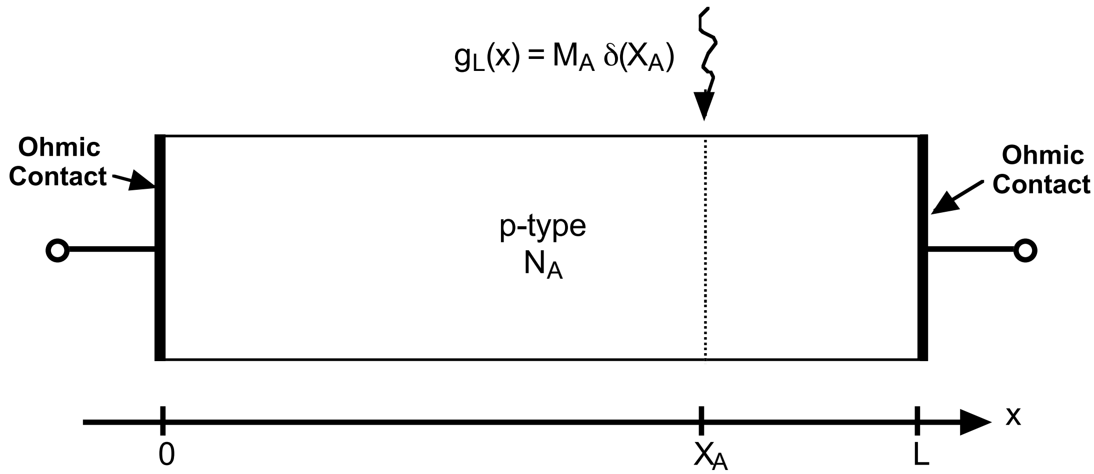
g) [2 pts] What is the applied bias voltage, V_{AB}?

$V_{AB} =$ ________________ Volts

End of Problem 2

Problem 3 (34 points)

A p-type semiconductor sample with acceptor concentration N_A and length L, illustrated below, has ohmic contacts at both its ends. A light source generates M_A electron-hole pairs/cm^2-s in the plane at $x = X_A$, i.e. $g_L(x) = M_A\delta(X_A)$. Assume low-level injection and quasi-neutrality everywhere in the bar.



The general equation governing the excess minority carriers in a uniformly doped material is

$$\frac{d^2n'(x)}{dx^2} - \frac{n'(x)}{L_e^2} = -\frac{1}{D_e} g_L(x)$$

a) [4 pts] What boundary condition is imposed on the excess minority carriers n′ at x = 0 and x = L ?

Boundary condition at x = 0: ______________________

Boundary condition at x = L: ______________________

b) [4 pts] We now make the assumption that the minority carrier lifetime is very long, which simplifies the general equation to:

$$\frac{d^2n'(x)}{dx^2} \approx -\frac{1}{D_e} g_L(x)$$

What quantitative restriction is placed on the minority carrier lifetime, τ_e, for this assumption to be valid?

τ_e >> ≈ << ______________________

(circle one) (fill in the blank)

Problem 3 continues on the next page

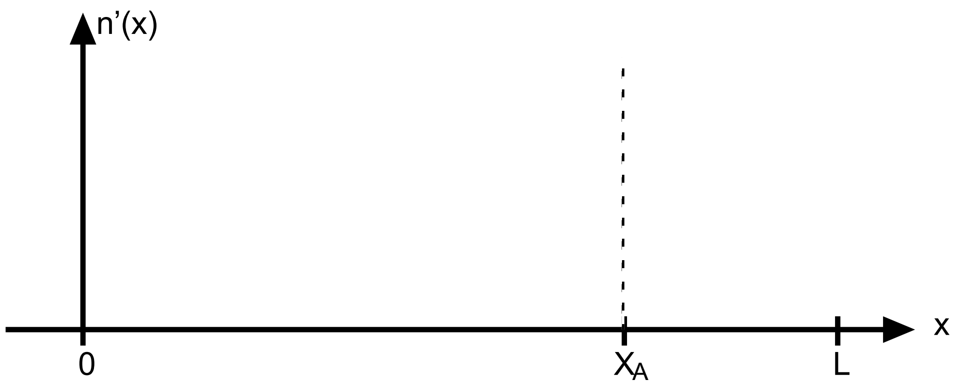
Problem 3 continued

c) [6 pts] Using the long-lifetime approximation in part (b), determine two constraints (i.e. boundary conditions) on the excess minority carriers at $x = X_A$, i.e. relating $n'(X_A^-)$ to $n'(X_A^+)$.

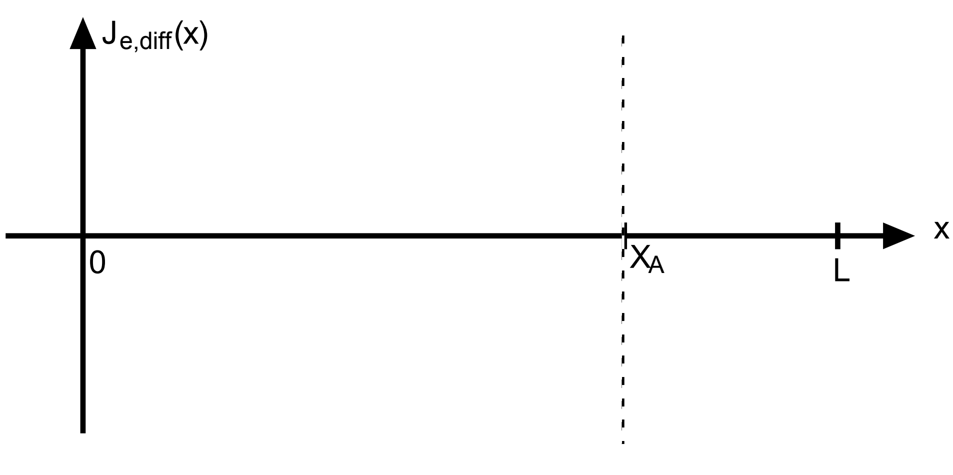
Constraint on n' at $x = X_A$: ______________________________
(Hint: Finite currents imply finite dn'/dx.)

Constraint on dn'/dx in the vicinity of $x = X_A$: ______________________________
(Hint: What goes in must come out.)

d) [6 pts] On the axes provided sketch the excess minority carrier concentration, $n'(x)$, everywhere inside the semiconductor. Label your sketch with the relevant equations for $n'(x)$.



e) [6 pts] On the axes provided sketch the minority carrier diffusion current, $J_{e,diff}(x)$, everywhere inside the semiconductor. Label your sketch with the relevant equations for $J_{e,diff}(x)$.



Problem 3 continues on the next page

Problem 3 continued

f) [4 pts] In the space below, briefly explain (approx. 25 words or less) why the minority carrier diffusion is the dominant minority carrier current.

g) [4 pts] A second light source is added illuminating a single spot along the semiconductor at $x = X_B$, where $x_B > X_A$, and generating electron-hole pairs at a rate M_B, so that $g_L(x)$ is now

$$g_L(x) = M_A \, \delta(X_A) + M_B \, \delta(X_B) \, .$$

Find $n'(x)$ and $J_{e,diff}(x)$ everywhere inside the semiconductor under this new illumination condition. If you could not do Parts d and e, indicate how you would use the results of those parts to answer this question.

$n'(x) =$ ____

$J_{e,diff}(x) =$ ____

End of Problem 3

End of Exam One