*YOUR NAME*_____

Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

6.012 Electronic Devices and Circuits

Exam No. 1

Wednesday, March 15, 2006

7:30 to 9:30 pm

Notes:

1. 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.

2. Closed book; one sheet (2 pages) 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 the two (2) page formula sheet, and make certain that you write your name at the top of this page in the space provided.

7. 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.

6.012 Staff Use Only   **PROBLEM 1**   _____   (out of a possible 34)

PROBLEM 2   _____   (out of a possible 33)

PROBLEM 3   _____   (out of a possible 33)

TOTAL

Problem 1 - (34 points)

A silicon resistor is shown schematically below. The silicon is doped uniformly with a boron (B) concentration of 2×10^{16} cm^{-3}, and an arsenic (As) concentration of 1×10^{16} cm^{-3}. (Recall that boron is in Column III of the periodic table and As is in Column V.) There are ohmic contacts at each end of the silicon resistor. Assume the mobilities are $\mu_e = 1{,}600$ cm^2/V-s and $\mu_h = 600$ cm^2/V-s, and the minority carrier lifetimes are $\tau_e = \tau_h = 10^{-7}$ s.
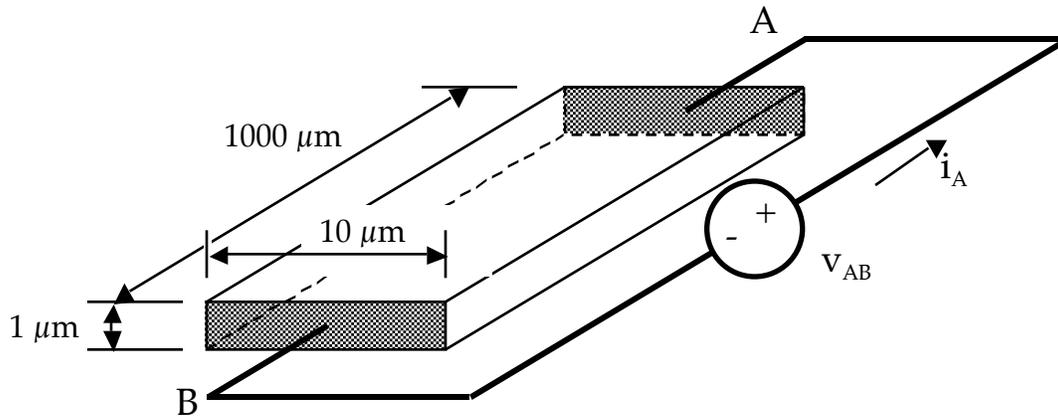
a) [18 pts] Assuming thermal equilibrium ($v_{AB} = 0$) at room temperature, find the following.

    i) The <u>total</u> acceptor concentration, N_a:

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

    ii) The <u>net</u> acceptor concentration, $N_A = (N_a - N_d)$:

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

    iii) The hole concentration, p_o:

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

Problem 1 continues on the next page

Problem 1 continued

    iv) The electron concentration, n_o:

$$n_o = \underline{\hspace{3cm}} \text{ cm}^{-3}$$

    v) The electrical conductivity, σ_o:

$$\sigma_o = \underline{\hspace{3cm}} \text{ S/cm}$$

    vi) The electrostatic potential relative to intrinsic silicon, ϕ_p:

$$\phi_o = \underline{\hspace{3cm}} \text{ V}$$

b) [9 pts] Let the applied voltage, v_{AB}, be 2 Volts. Find the following:

    i) The end-to-end resistance of the resistor.

$$R = \underline{\hspace{3cm}} \text{ } \Omega$$

    ii) The electric field, E, in the silicon.

$$E = \underline{\hspace{3cm}} \text{ V/cm}$$

Problem 1 continues on the next page

Problem 1 continued

    iii) The total drift current density, J^{dr}:

$$J^{dr} = \underline{\hspace{5cm}} \text{ A/cm}^2$$

c) [7 pts]   Assume the silicon is illuminated by a steady state light which generates electron-hole pairs uniformly throughout the bulk, with a rate $g_L = 10^{23} \text{ cm}^{-3}\text{s}^{-1}$. Find the following under illumination assuming steady state.

    i) The minority carrier diffusion length, L_{min}:

$$L_{min} = \underline{\hspace{5cm}} \text{ cm}$$

    ii) The excess minority carrier population and the conductivity, σ, in the <u>middle portion</u> of the resistor many minority diffusion lengths from the ohmic contacts:

$$n' = \underline{\hspace{5cm}} \text{ cm}^{-3}$$

$$\sigma = \underline{\hspace{5cm}} \text{ S/cm}$$

End of Problem 1

Problem 2 (33 points)

The p-type silicon sample illustrated below is made from silicon having a net acceptor concentration of 5×10^{17} cm^{-3}; minority carrier diffusion length, L_{min}, of 100 μm; electron mobility, μ_e, of 1600 cm^2/V-s; and hole mobility, μ_h, of 600 cm^2/V-s. The sample is 10 μm long (10 μm = 10^{-3} cm). All of the surfaces are reflecting boundaries except for the ohmic contact on the right end. The sample is illuminated with a constant light that generates 10^{19} hole-electron pairs/cm^3-s <u>uniformly</u> throughout the bulk.
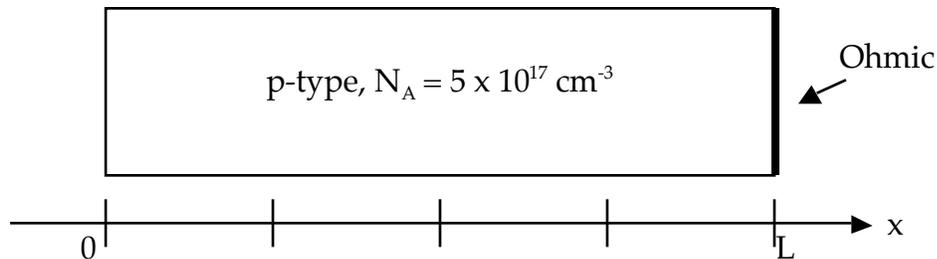
a) [8 pts] What is the boundary condition on the excess minority carrier concentration or its derivative at each end of the sample?

   i) Boundary condition at x = 0:

   ii) Boundary condition at x = L (= 10 μm):

b) [5pts] What is the minority carrier lifetime, τ_{min}, in this sample?

$$\tau_{min} = \text{_____} \text{ s}$$

c) [8 pts] The figures you need to answer this question are on the next page.

   i) From the six sketches on the next page, select the one which best illustrates the <u>magnitude</u> of the <u>minority carrier current</u> in this sample when it is uniformly illuminated as described above. Explain your answer.

   Sketch _____ because

Problem 2 continues on the next page

Problem 2 continued

A

B

C

D

E

F
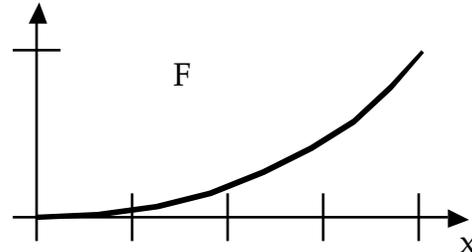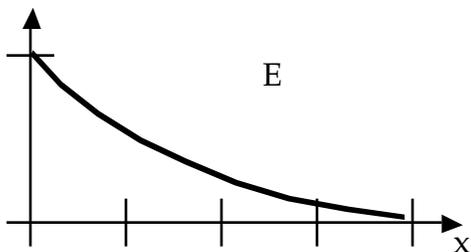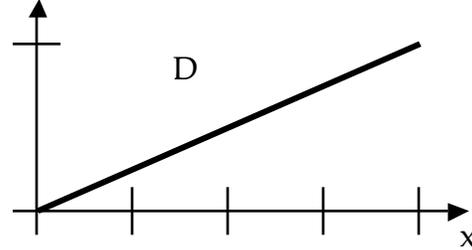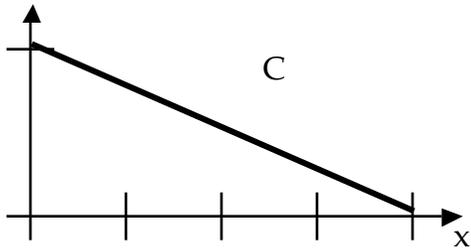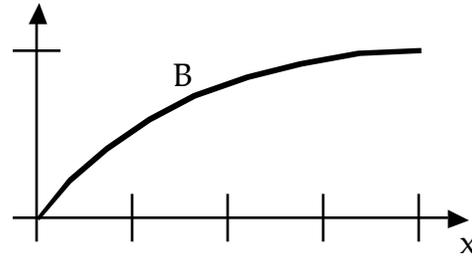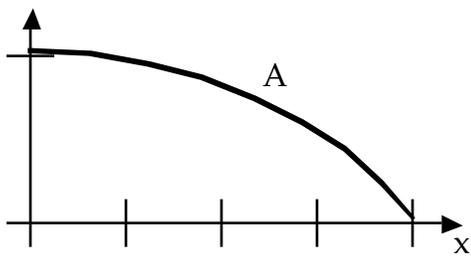
ii) From the six sketches above, select the one which best illustrates the profile of the excess minority carrier concentration in this sample when it is illuminated as described above. Explain your answer.

Sketch _____ because

d) [6 pts] Assuming infinite minority carrier lifetime (and thus no recombination in the bulk), what is the minority carrier current density, J_{emin}, flowing into, or out of, the ohmic contact, when the sample is illuminated as described?

$$J_{min}(x = L^-) = \underline{\hspace{3cm}} \ A/cm^2$$

Problem 2 continues on the next page

Problem 2 continued

e) [6 pts] We know that the minority carrier lifetime is not infinite, and there is some recombination in the bulk.

   i) What is the rate per unit area at which hole-electron pairs are <u>recombining</u> in the entire bulk of the sample away from the ohmic contact? First give a formula , and then a numerical value.

   Algebraic expression = _____

   Recombination = _____ pairs/cm²-s

   ii) Compare your answer above to your answer in Part d. How would you expect the excess carrier fluxes into the ohmic contact to compare with the rate of hole-electron recombination occurring in the bulk? Explain your answer.

   Much greater than _____   Much less than _____   Similar to _____

   because:

End of Problem 2

Problem 3 - (33 points)

You are given the following asymmetrical silicon (Si) n^+-p junction diode structure with $w_n = 1$ μm, $w_p = 4$ μm, and $\tau_e = \tau_h = \infty$. The n-region of this diode is heavily doped, $N_D = 10^{19}$ cm^{-3}. The p-region is composed of two sub-regions with doping N_{A1} and N_{A2} as shown. The width of the first sub-region, w_1, is 2 μm. Assume the mobilities are $\mu_e = 1,600$ cm^2/V-s and $\mu_h = 600$ cm^2/V-s.
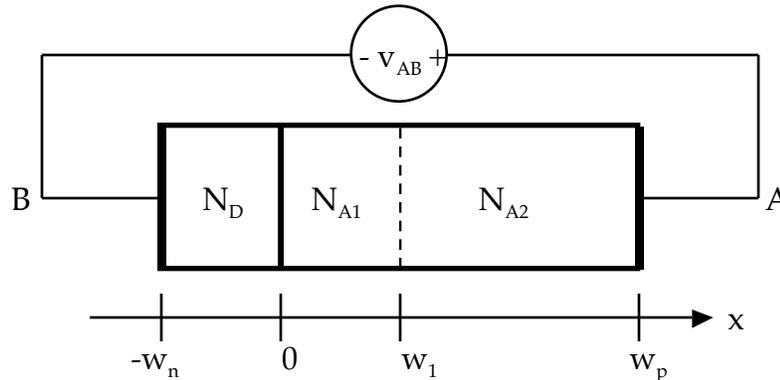
a) [15 pts] First consider a diode in which the two p-type sub-regions have the same doping level with $N_{A1} = N_{A2} = 10^{15}$ cm^{-3}. In Parts i) and ii) assume there is zero applied bias, $v_{AB} = 0$ V; in Part iii) assume forward bias, $v_{AB} > 0$. Calculate the following quantities:

i) The built-in potential of the junction, ϕ_b.

$\phi_b =$ _____V

ii) The width of the depletion region on the p-side of the junction, x_p.

$x_p =$ _____ μm

iii) The ratio of the electron to hole current density crossing the junction.

$J_e / J_h =$ _____

Problem 3 continues on the next page

Problem 3 continued

b) [18 pts] Next consider a device in which the second region is doped much more heavily p-type with $N_{A2} = 10^{18}$ cm^{-3}. The doping level in the first region is the same as before, i.e., $N_{A1} = 10^{15}$ cm^{-3}. The width of this first region is 2 μm.

i) Consider the situation with zero applied bias, i.e., $v_{AB} = 0$ V. What is the built-in potential, ϕ_b, of the junction?

$$\phi_b = \underline{\hspace{3cm}} \text{ V}$$

ii) A bias, $v_{AB} = V_1$, is applied so that the width depletion region on the p-side of this diode, x_p, is 2 μm, i.e. the first p-region is fully depleted.   What is V_1?

$$V_1 = v_{AB}(\text{such that } x_p = w_1) = \underline{\hspace{3cm}} \text{V}$$

iii) With a bias applied as in Part b) ii) so that $x_p = w_1 = 2$ μm, what is the small signal linear equivalent junction capacitance per unit area, $C_{ab}(V_1) \equiv \partial q_{AB}/\partial v_{AB}|_{vAB = V1}$?

Hint: Think "depletion region width" rather than "complicated formula."

$$\text{Junction capacitance per unit area, } C_{ab}(V_1) = \underline{\hspace{3cm}} \text{ F/cm}^2$$

Problem 3 continues on the next page

Problem 3 continued

iv) The small signal linear equivalent capacitance of this junction in the reverse bias region, i.e. $V_{AB} < 0$ V, looks like one of the sketches below as the bias is changed. Chose the correct one and explain why. (Note that correct choice with no explanation receives no points.) <u>Hint</u>: See hint for Part (iii).
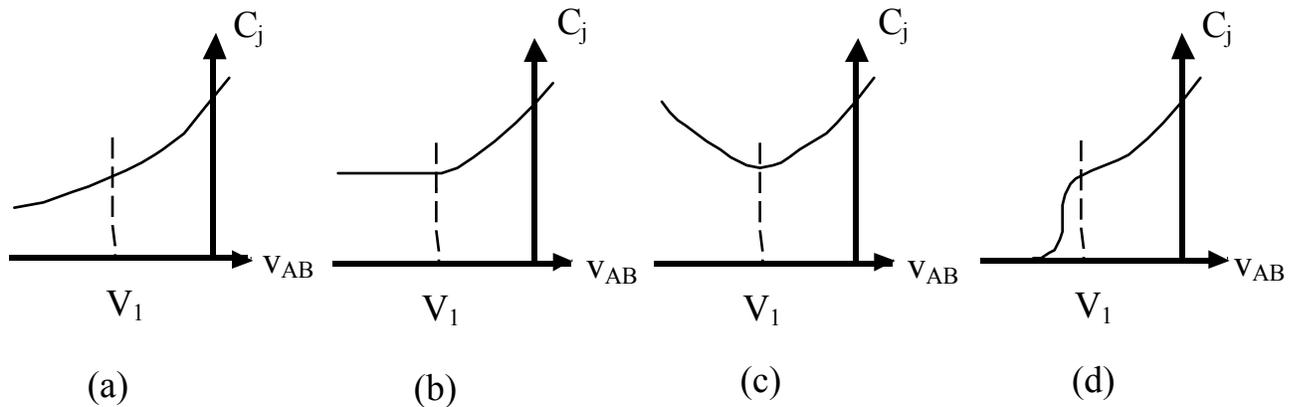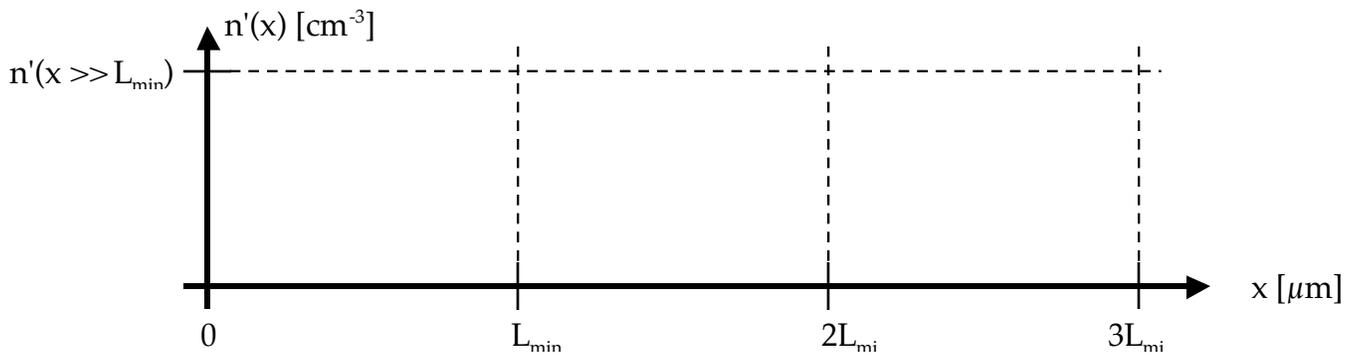
C_j	C_j	C_j	C_j
V_1	V_1	V_1	V_1
V_{AB}	V_{AB}	V_{AB}	V_{AB}
(a)	(b)	(c)	(d)

Figure _____ because

End of Problem 3; End of Exam

Extra pieces :

Problem 1:   Add to problem if use on future Problem Set

iii) On the axes provided below sketch and dimension the excess minority carrier population within 3 minority carrier diffusion lengths of the ohmic contact on the right end of the bar.

$n'(x) \, [cm^{-3}]$

$n'(x \gg L_{min})$

0 L_{min} $2L_{mi}$ $3L_{mi}$ $x \, [\mu m]$

Problem 3:   ditto

c) [8 pts] Finally consider a diode in which the first p-type sub-region is very thin, $w_1 = 10$ nm ($= 10^{-2} \, \mu m$), and is more heavily doped than the second p-type sub-region: $N_{A1} = 10^{16}$ cm^{-3}, $N_{A2} = 10^{15}$ cm^{-3}.   There is zero volts applied bias, $v_{AB} = 0$.   You may assume that $w_1 \ll x_p$ and treat the depletion charge in Sub-region 1 as a delta function at $x = 0^+$.

i) Calculate electrostatic potential step, ϕ_b, crossing the junction.

$$\phi_b = \text{_____} \ V$$

ii) Calculate width of the depletion region on the p-side, x_p.

$$x_p = \text{_____} \ \mu m$$

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