YOUR NAME

Department of Electrical Engineering and Computer Science
Massachusetts Institute of Technology

6.012 Electronic Devices and Circuits

Exam No. 1

Wednesday, March 12, 2008

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 <u>and</u> 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)

Parts a, b, and c of this question are each an independent mini-question.

(a) A short bar of p-type silicon, $N_A = 10^{17}$ cm^{-3}, is illuminated with light that uniformly generates 10^{20} hole-electron pairs/cm^3-s throughout it.

(i) [2 pts] The steady-state <u>excess</u> hole and electron populations, n' and p', in the illuminated bar are both 10^{14} cm^{-3}. What is the minority carrier lifetime in this sample?

$$\tau_{min} = \underline{\hspace{4cm}} \text{ s}$$

(ii) [4 pts] What are the approximate <u>total</u> hole and electron populations in the illuminated bar in the steady state?

$$n \approx \underline{\hspace{3cm}} \text{ cm}^{-3}$$

$$p \approx \underline{\hspace{3cm}} \text{ cm}^{-3}$$

(iii) [2 pts] After being on for a long time, the illumination is turned off at t = 0. Write an expression for n'(t) for t > 0. If you could not do Part (i) leave your answer in terms of τ_{min}.

$$n'(t) = \underline{\hspace{3cm}} \text{ cm}^{-3}$$

(iv) [2 pts] An ohmic contact is added to one end of the sample. How will the rate at which excess minority carrier populations decay when the light is turned off in the sample with a contact compare to the rate in your answer in (iii) above?

Faster _____ Slower _____ Negligibly different _____ because

Problem 1 continues on the next page

Problem 1 continued

b) This question deals with the MOS capacitor shown below. In this device $t_{ox} = 30$ nm, $\varepsilon_{ox} = 3.5 \times 10^{-13}$ Coul/V-cm, $\phi_m = 0.3$ V, and $\phi_p = -0.36$ V ($N_{Ap} = 10^{16}$ cm^{-3}).
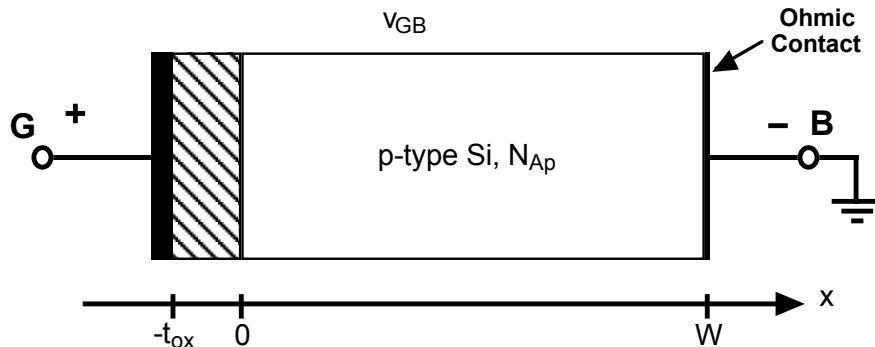
(i) [7 pts] Recall that the "flat-band" condition is defined by $\phi(0) = \phi_p$ (i.e., no change in potential between $x = 0$ and $x = w$) and occurs when $v_{GB} = V_{FB}$. On the axes below, sketch $\rho(x)$ and $\phi(0)$ at flat-band; also calculate the value of V_{FB}.
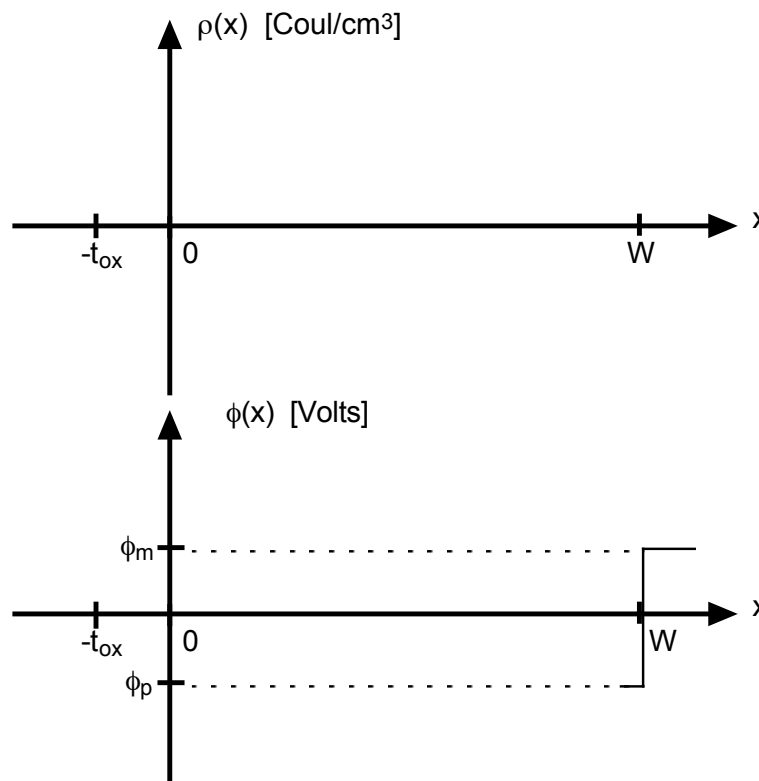

$$V_{FB} = \underline{\hspace{2cm}} \text{ Volts}$$

(ii) [7 pts] Now suppose that a sheet of charge, $Q_{ox} = 2 \times 10^{-8}$ Coul/cm^2, is added in the oxide side of the oxide-semiconductor interface at $x = 0-$.   On the axes on the next page complete the charge density plot and plot the electrostatic potential at flat-band in this new situation. Also, calculate the new value of the

Problem 1 continues on the next page

Problem 1 continued

flat-band voltage, V_{FB}. NOTE: Flat-band is still defined as when $\phi(0) = \phi_p$.
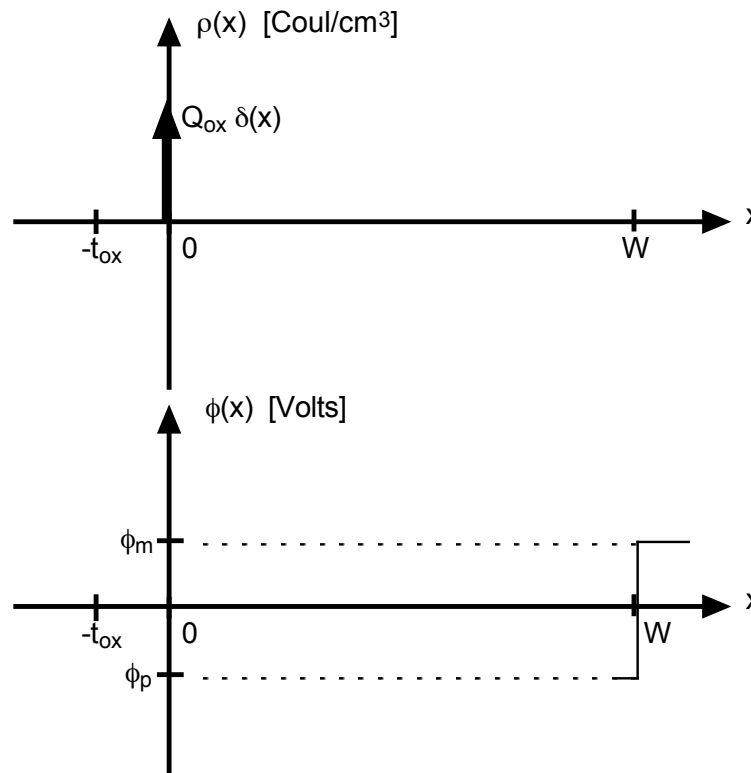
$V_{FB} =$ _____ Volts

c) [10 pts] The p-type region of a silicon p-n diode has a net acceptor doping concentration, N_{Ap}, of 10^{17} cm^{-3}, and is 1 μm (10^{-4} cm) wide. Design the n-type region of this diode (i.e. specify its doping level and width) so that (1) the built-in potential at the junction is 0.78 V, and (2) the total diode current density is 1 mA/cm^2 when a forward bias of 0.4 V is applied. You may assume that the width of the depletion region is negligible in forward bias compared to the total width of the p and n regions. The minority carrier diffusion coefficients for electrons and holes are 40 cm^2/s and 15 cm^2/s, respectively; assume the minority carrier lifetime is infinite.
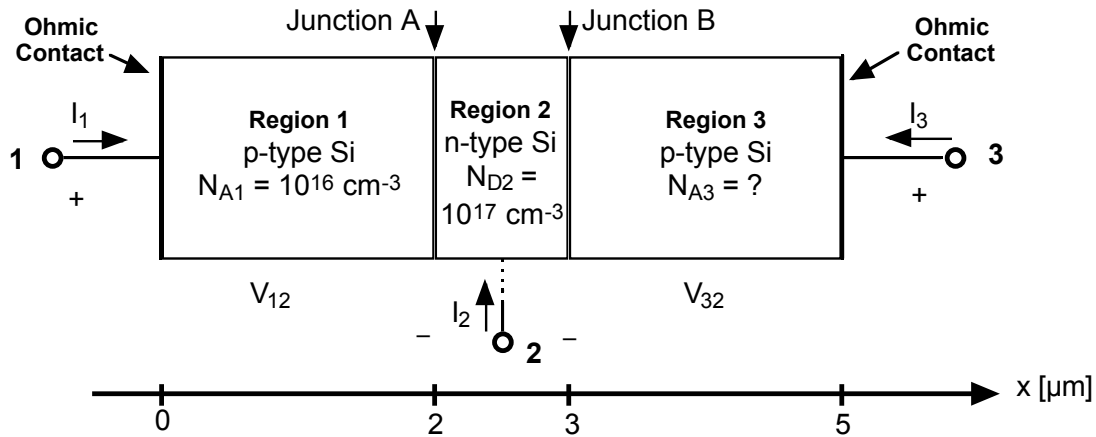
Doping level on n-side, $N_{Dn} =$ _____ cm^{-3}

Width of n-side, $w_n =$ _____ cm

End of Problem 1

Problem 2 - (32 points)

This question concerns the silicon sample illustrated below which has three uniformly doped regions: Regions 1 and 3 are p-type, and Region 2 is n-type. There are ohmic contacts on either end of the sample, and there is a contact to Region 2 off to the side (much as it is in a bipolar junction transistor). Throughout the sample the electron diffusion coefficient, D_e, is 40 cm^2/s, the hole diffusion coefficient, D_h, is 15 cm^2/s, and $\tau_{min} \approx \infty$. The cross-sectional area is 10^{-4} cm^2.

Ohmic Contact — Junction A ↓ — ↓ Junction B — Ohmic Contact

I_1 →
1 ○ +

| Region 1 p-type Si $N_{A1} = 10^{16}$ cm-3 | Region 2 n-type Si $N_{D2} = 10^{17}$ cm-3 | Region 3 p-type Si $N_{A3} = ?$ |

I_3 ← ○ 3 +

V_{12} V_{32}

I_2 ↑ ○ 2

→ x [µm]

0   2   3   5

When Terminal 2 is grounded and bias voltages, V_{12} and V_{32}, are applied to this device, the excess minority carrier profiles shown below result in Regions 2 and 3. (You have to figure out what happens in Region 1 yourself.)

You can ignore the widths of the depletion regions for purposes of answering the questions below.

p',n' [cm-3]

5×10^{14}

10^{14}

10^{13}

→ x [µm]

0   2   3   5
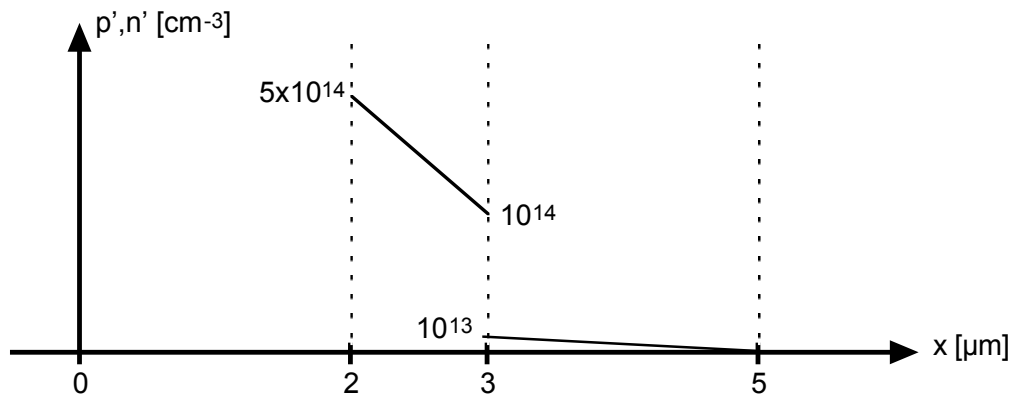
(a) Looking at Junction B:

(i) [4 pts] What is $J_{\text{Electron-B}}$, the <u>electron</u> current density crossing Junction B? Recall that this is the minority carrier diffusion current density in Region 3.

$$J_{\text{Electron-B}} = \underline{\hspace{3cm}} \text{A/cm}^2$$

Problem 2 continues on the next page

Problem 2 continued

    (ii) [4 pts] What is J_{Hole-B}, the <u>hole</u> current density crossing Junction B?

$$J_{Hole-B} = \underline{\hspace{3cm}} A/cm^2$$

    (iii) [4 pts] What is the terminal current I_3?

$$I_3 = \underline{\hspace{3cm}} A$$

    (iv) [4 pts] What is N_{A3}, the doping level in Region 3?

$$N_{A3} = \underline{\hspace{3cm}} cm^{-3}$$

  (b) Looking at Junction A:

    (i) [4 pts] What is $n'(2^-)$, the excess electron concentration at the edge of the quasi-neutral region on the p-side of this junction, i.e. just to the left of the edge of the depletion region at $x = 2^-$?

$$n'(2^-) = \underline{\hspace{3cm}} cm^{-3}$$

    (ii) [4 pts] What is V_{12}, the voltage bias on Junction A?

$$V_{12} = \underline{\hspace{3cm}} Volts$$

Problem 2 continued

(c) Looking now at the entire sample, removing the biases V_{12} and V_{32}, and thinking of the structure as a bipolar junction transistor:

(i) [4 pts] What is the best terminal to use as the emitter, and why?

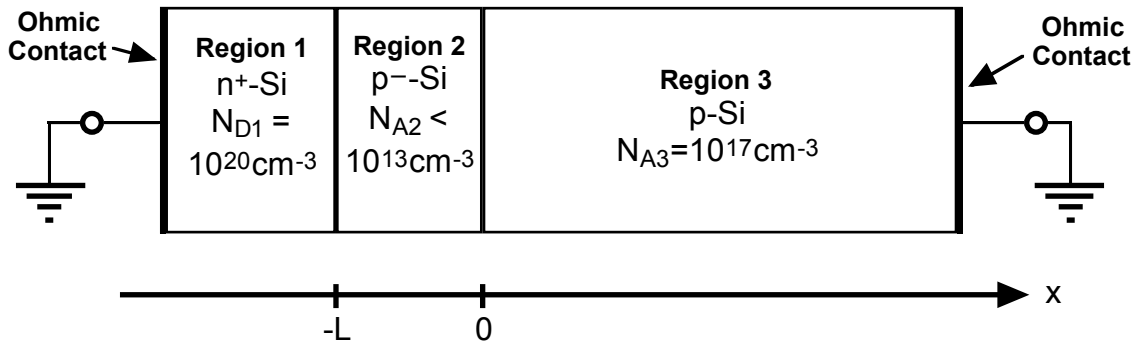Terminal 1 _____ Terminal 2 _____ Terminal 3 _____, because

(ii) [4 pts] For your choice of emitter above, what is the forward current gain, β_F, of this transistor?

$$\beta_F = \underline{\hspace{3cm}}$$

End of Problem 2

Problem 3 (34 points)

Consider the n^+-p diode shown below in thermal equilibrium. The n^+ doping in Region 1 is high enough that it is degenerate, with $\phi_{n+} = 0.55$ V. Assume that the depletion region on the n+ side of the junction is negligibly small so that you may also assume negligible change in potential across it. Note too that Region 2, the p^- Si region, is very lightly doped (i.e. $N_{A2} < 10^{13}$ cm^{-3}). Finally, $L = 0.2$ μm $(= 2 \times 10^{-5}$ cm).

Ohmic Contact → | **Region 1** n^+-Si $N_{D1} = 10^{20}$cm-3 | **Region 2** p^--Si $N_{A2} < 10^{13}$cm-3 | **Region 3** p-Si $N_{A3} = 10^{17}$cm-3 | ← **Ohmic Contact**

x-axis marked at -L and 0.

(a) [5 pts] Calculate $\Delta\phi_{13}$, the built-in potential difference between the QNR (quasi-neutral region) in Region 1 (i.e. where x << -L) and the QNR in Region 3 (where x >> 0).

$$\Delta\phi_{13} = \underline{\hspace{4cm}} \text{ Volts}$$

(b) [6 pts] Using the Depletion Approximation, sketch and label $\rho(x)$, the net charge density in this structure. You should label the depletion region width in Region 3 x_D (you are not expect to find a value for x_D). You may assume that the width of the depletion region in Region 1 is negligibly small (so that there is essentially an impulse of charge at x = -L).
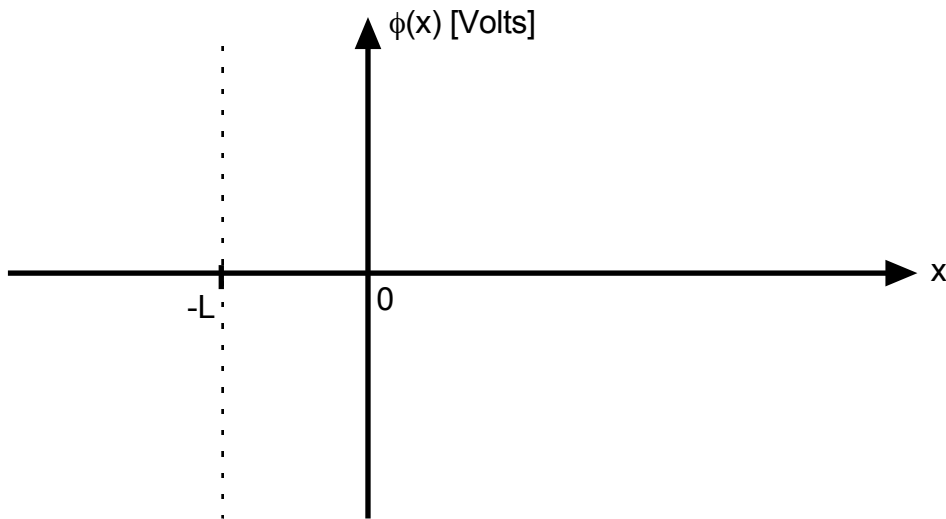
$\rho(x)$ [Coul/cm3]

x-axis marked at -L and 0.
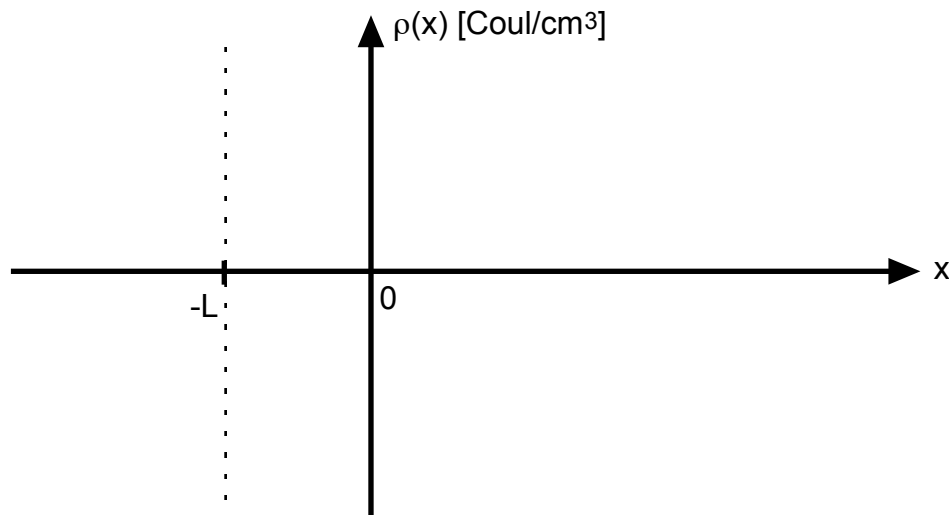
Problem 3 continues on the next page

Problem 3 continued

(b) [6 pts] Sketch E(x), the electric field, in the structure <u>assuming you can ignore the charge in Region 2</u>. You do not need to calculate numerical values, but you should label your sketch in the various regions with expressions for E(x) .
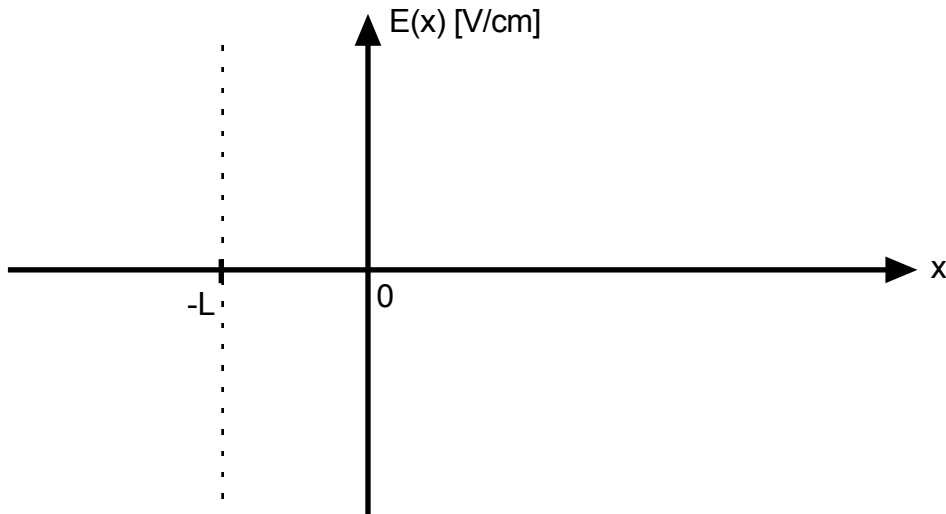
(c) [6 pts] Sketch $\phi(x)$, the electrostatic potential, through the structure. Label your sketch with the values of ϕ_{n+} and ϕ_p.   Also indicate and give expressions for $\Delta\phi_2$, the change in the electrostatic potential across Region 2, and for $\Delta\phi_3$, the change in the electrostatic potential across Region 3.

Problem 3 continued

(d) [6 pts] Set up an equation with x_D, the width of the depletion layer in Region 3, being the only unknown, that you could use to find x_D. DO NOT solve your equation to find x_D.

Equation with x_D being the only unknown: _____

(e) [5 pts] Give an expression for C^*_{dp}, the depletion capacitance per unit area of this device at zero bias, $V = 0$ Volts. x_D can appear as a parameter in your expression.

Expression for C^*_{dp} : _____

End of Problem 3

End of Exam One

6.012 Microelectronic Devices and Circuits
Fall 2009