6.012 Electronic Devices and Circuits
Fall 1999

November 17, 1999
Quiz #2

-OPEN BOOK-

Problem #points

NAME SOLUTIONS

1__________

RECITATION TIME____________________

2__________

3__________

Total__________

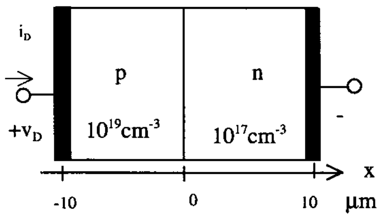
General guidelines (please read carefully before starting):

- Make sure to write your name on the space provided above.
- All answers should be given in the space provided. Please do not turn in any extra material. If you need more space, use the back page.
- You have 120 minutes to complete the quiz.
- Where required, make reasonable approximations and *state them.*
- Partial credit will be given for setting up problems without calculations. NO credit will be given for answers without reasons.
- Use the symbols utilized in class for the various physical parameters, i.e. N_d, n_o, etc.
- Every numerical answer must have the proper units next to it. Points will be subtracted for answers without units or with wrong units.
- Use the following fundamental constants and physical parameters for silicon at room temperature.

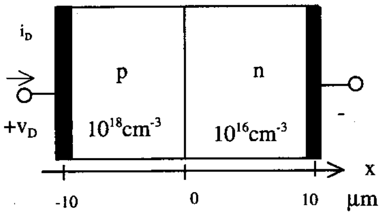
$n_i = 1.0 \times 10^{10} \text{cm}^{-3}$
$kT/q = 0.026\text{V}$
$q = 1.60 \times 10^{-19}\text{C}$
$\varepsilon_s = 1.04 \times 10^{-12}\text{F/cm}$
$\varepsilon_{ox} = 3.45 \times 10^{-13}\text{F/cm}$

Problem 1 – 32 Points

Diode A



Diode B



This problem concerns the two abrupt p-n diodes pictured above. These two diodes have identical dimensions and differ only in their doping levels. In Diode A, the p-side is doped with 10^{19} cm^{-3} acceptors and the n-side with 10^{17} cm^{-3} donors; in Diode B, the p-side is doped with 10^{18} cm^{-3} acceptors and the n-side with 10^{16} cm^{-3} donors (i.e., an order of magnitude less than that in Diode A on each side). You may assume for purposes of this problem that the widths of the depletion regions on either side of the junctions in these diodes are all negligible relative to 10 μm.

a) If forward biases are applied to the diodes and are adjusted so that the terminal current is the same in both, on which diode, if any, will the <u>bias</u> be larger, and why?

☑ Larger on Diode ☐ Larger on Diode B ☐ Similar on both

Because lower minority carrier conc ⇒ w/ same applied voltage ⇒ lower gradient.

b) With the same forward bias <u>current</u> through both diodes, as in Part a, in which diode, if any, will the magnitude of the <u>excess carrier charge stored</u> i.e., the diffusion charge stored be largest, and why?

☑ Larger in Diode A ☐ Larger in Diode B ☐ Similar in both

Because

D_n, D_p greater for B

c) The diode voltages are adjusted so the same forward bias voltage is applied to both diodes. In which diode, if any, will the magnitude of the excess carrier charge stored i.e., the diffusion charge stored be largest now, and why?

☐ Larger in Diode A ☑ Larger in Diode B ☐ Similar in both

Because

d) If the diodes are now reverse biased, each by the same amount, which diode, if any, will have the larger reverse bias current, and why?

☐ Larger in Diode A ☑ Larger in Diode B ☐ Similar in both

Because

$$I_0 \propto \frac{1}{N_{a,d}}$$

e) Which diode, if any, will have the larger reverse-bias breakdown voltage, and why? You may assume that reverse breakdown occurs when the magnitude of the peak electric field in the junction reaches a critical value, which is itself independent of doping level.

☐ Larger in Diode A ☑ Larger in Diode B ☐ Similar in both

Because

f) If both diodes are forward biased at the same current level, i_D, and a small signal current i_d, is added, which diode, if any, will have the larger incremental conductance, g_d, and why?

☐ Larger for Diode A ☐ Larger for Diode B ☑ Similar for both

Because

$$g_d = \frac{\partial I_D}{\partial V_D} = \frac{kT}{q} I_D = \frac{kT}{q} I_o e^{\frac{qV_D}{kT}}$$

g) With the diodes forward biased with I_D as in Part f, which diode, if any, has the larger small signal diffusion capacitance, C_{df}, and why?

☑ Larger for Diode A ☐ Larger for Diode B ☐ Similar for both

Because

$$C_{df} = \tau_T g_d$$

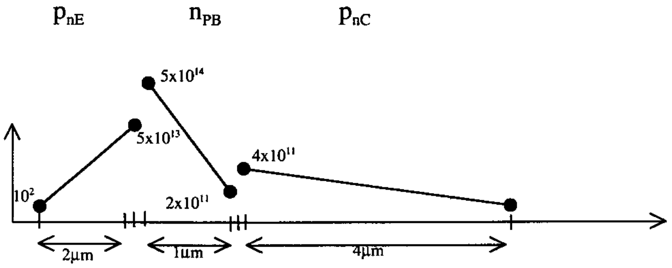
$$\tau_T = \frac{W_n^2}{2D_p}$$

$$g_d = \frac{q}{kT} I_D$$

B has greater μ_p, D_p, lower τ_T, and lower C_{df}.

Problem 2 – 30 Points

Given a bipolar transistor that is biased such that the minority carrier concentration spatial distribution shown below results.



a) Determine the regime of operation for the BJT (forward, reverse, sat. or cutoff). Explain.

Sat.

B - E FB

B - C FB

b) Determine the doping concentration in the emitter, base and collector.

$N_{DE} = 10^{18}$

$N_{AB} = 10^{17}$

$N_{DC} = 5\times10^{16}$

Emitter:

$p_{n0} = 10^{2}\ cm^{-3} \Rightarrow n_{n0} = 10^{18}\ cm^{-3}$

$e^{\frac{qV_{BE}}{kT}} = \frac{5\times10^{13}}{100} = 5\times10^{11}$

Base:

$n_{PB0} = (5\times10^{14}) / \cancel{e^{\frac{qV_{BE}}{kT}}} = 1000$

$e^{\frac{qV_{BC}}{kT}} = \frac{2\times10^{11}}{1000} = 2\times10^{8}$

Collector:

$p_{nC0} = \frac{4\times10^{11}}{2\times10^{8}} = 2000$

c) Determine V_{BE} and V_{BC}.

$$V_{BE} = \frac{kT}{q} \ln\left(5 \times 10^{11}\right) = 0,70 \text{ V}$$

$$V_{BC} = \frac{kT}{q} \ln\left(2 \times 10^{8}\right) = 0.497 \text{ V}$$

d) Calculate the total base current.

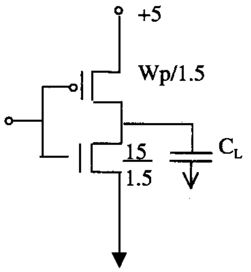
$$J_B = -q D_p \left.\frac{dp}{dx}\right|_{\text{Emitter}} - q D_p \left.\frac{dp}{dx}\right|_{\text{collector}}$$

e) Calculate the total collector current.

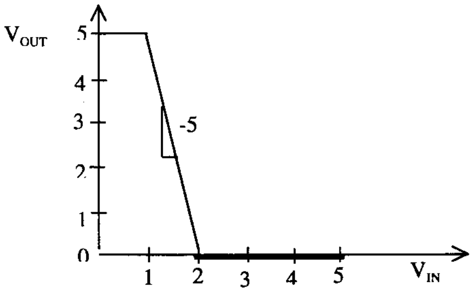
$$J_c = -q D_p \left.\frac{dp}{dx}\right|_{\text{Collector}} + q D_n \left.\frac{dn}{dx}\right|_{\text{Base}}$$

Problem 3 – 38 Points

You are given a CMOS inverter with a voltage transfer characteristic shown below.



$V_{TN} = 0.66V$
$V_{TP} = -1.33V$
$\mu_n C_{OX} = 50\mu A/V^2$
$\mu_p C_{OX} = 25\mu A/V^2$



a) What is V_{IL}, V_{IH}, V_{OL}, and V_{OH}?

$V_{OH} = 5$ V
$V_{OL} = 0$ V
$V_{IH} = 2$ V
$V_{IL} = 1$ V

b) What is NM_L and NM_H?

$NM_L = V_{IL} - V_{OL} = 1 V$
$NM_H = V_{OH} - V_{IH} = 3 V$

c) Calculate V_M.

$$V_M = \frac{V_{Tn} + \sqrt{\frac{k_p'}{k_n}}\left(V_{DD} + V_{Tp}\right)}{1 + \sqrt{\frac{k_p'}{k_n}}}$$

$$V_{OUT} = 5 - 5\left(V_{IN} - 1\right)$$

$$V_{OUT}(1) = 5V$$

$$V_{OUT}(2) = 0$$

$$V_{OUT} = V_{IN}$$

$$V_{OUT} = 5 - 5\left(V_{OUT} - 1\right)$$

$$6V_{OUT} = 10$$

$$V_{OUT} = 1.667$$

d) What is the value of W_P to yield this transfer characteristic?

$$V_M = \frac{V_{Tn} + \sqrt{\frac{k_p'}{k_n}}\left(V_{DD} + V_{Tp}\right)}{1 + \sqrt{\frac{k_p'}{k_n}}} = \frac{0.66 + \sqrt{\frac{k_p'}{k_n}}\left(5 - 1.33\right)}{1 + \sqrt{\frac{k_p'}{k_n}}} = 1.667$$

$$\sqrt{\frac{k_p'}{k_n}} = \frac{1}{2}$$

$$k_p = \frac{1}{4} k_n$$

$$W_p = \frac{W_n}{2}$$

$$W_p = 7.5\ \mu m$$

e) What is t_{PHL}? Assume the total load capacitance is 1pF.

$$t_{PHL} = \frac{C_L \Delta V}{I_{Dn}} = \frac{(1\times10^{-12})(2.5)}{\frac{1}{2}\frac{15}{1.5}(50\times10^{-6})(5-0.66)^2}$$

$$t_{PHL} = 531 \text{ psec.}$$

f) How much energy is dissipated in the n-channel transistor during this transition?

$$E = \frac{1}{2}CV^2 = \frac{1}{2}(1\times10^{-12})(2.5)^2$$

$$E = 3.125\times10^{-12}\ \text{J}$$