

**Exam No. 2, Fall 2001, Answers**

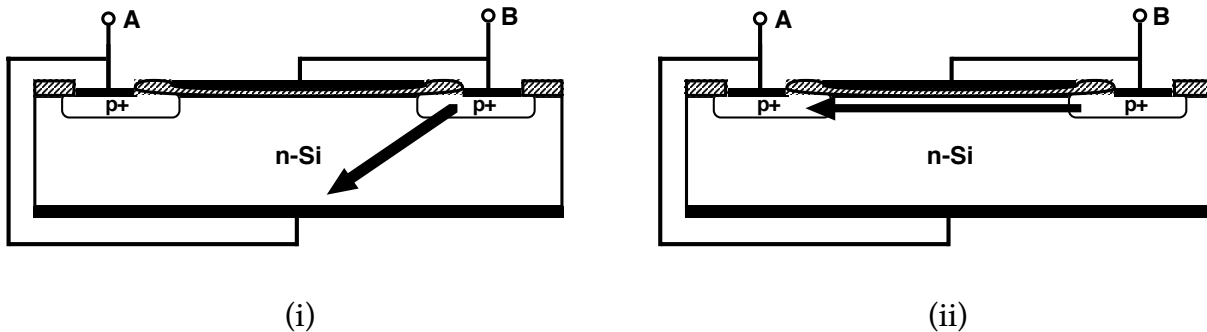
**Problem 1:**

- a) i) BJT A, the more heavily doped device because it will have the narrower depletion region and in it  $w_B^*$  will decrease more slowly with increasing  $v_{CB}$ .
- ii) BJT B, because it will have the smaller emitter defect, i.e., less injection from base to emitter, and more from emitter to base.
- iii) BJT A, because the junction depletion capacitance, which is what  $C_{\square}$  is, is larger in a more heavily doped junction.
- iv) Neither, because  $g_{\square}$  only depends on the bias current,  $I_C$ , not on the BJT structure.
- b) i) High, because both p-channel devices will be on and C will be at  $V_{DD}$ , i.e. high.
- ii) Low, because as long as one n-channel device is on and one p-channel off the output will be at ground, i.e. low.
- iii) Faster, because when both n-channel devices are on they will act in parallel to discharge the load twice as fast as when one alone is on.
- iv)  $4W_n$ , because the slowest discharge occurs when one n-channel device is on and it has a gate width  $W_n$  and a width-to-length ratio of  $W_n/L_{min}$ . To have the same charge speed the p-channel pull-up device must have a width-to-length ratio twice as large, or  $2W_n/L_{min}$ . Since it has an effective gate length of  $2L_{min}$ , it must have a width of  $4W_n$ .
- c) i) With 0.6 V dropped across the base-emitter junction of  $Q_1$ , there is  $3 - 0.6 = 2.4$  V across the resistor, so  $Q_1$  is approximately  $2.4/9.6 = 0.25$  mA.
- ii)  $Q_2$  is twice as large as  $Q_1$ , yet has the same base-emitter voltage, so its collector current is twice that of  $Q_1$ , or 0.5 mA.
- iii) The voltage on the collector of  $Q_2$  must stay above 0.2 V so the largest voltage drop we can have across R is 2.8 V. Since the collector current on  $Q_2$  is 0.5 mA, this tells us R must be less than  $2.8 \text{ V}/0.5 \text{ mA} = 5.6 \text{ k}\square$ . There is no maximum on the voltage across  $Q_2$  so R can be as small as 0. Thus  $0 < R < 5.6 \text{ k}\square$
- iv) The base currents are  $I_C/\beta$ , so  $I_B(Q_1) = 2.5 \text{ }\square\text{A}$ , and  $I_B(Q_2) = 1.25 \text{ }\square\text{A}$ .

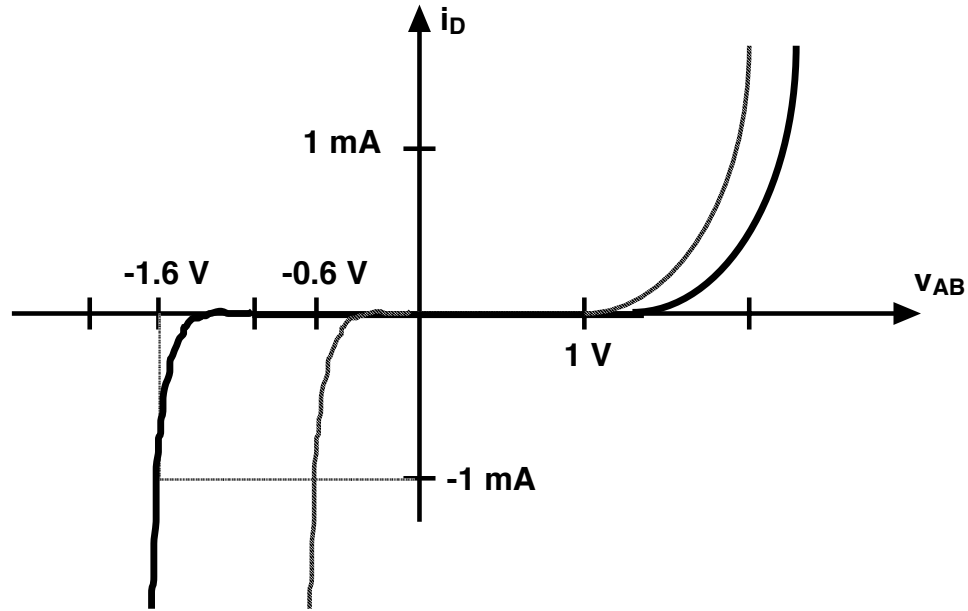
## Problem 2

a) Studying the curve we recognize that when  $v_{AB} < 0$  the drain-substrate diode can conduct, but when  $v_{AB} > 0$  it is reverse biased and the MOSFET controls the current between through this structure. With this understanding we can see that for  $0 < v_{AB} < 1$  V the MOSFET is cutoff, and for  $v_{AB} > 1$  V a channel must have formed. Thus  $|V_T| = 1$  V and in fact that  $V_T = -1$  V. We can figure out the minus sign by noting that  $v_{AB} = -v_{GS}$  in this example.

b) The current paths are shown as the thick lines in the figures below, and the explanations are given below the figures.

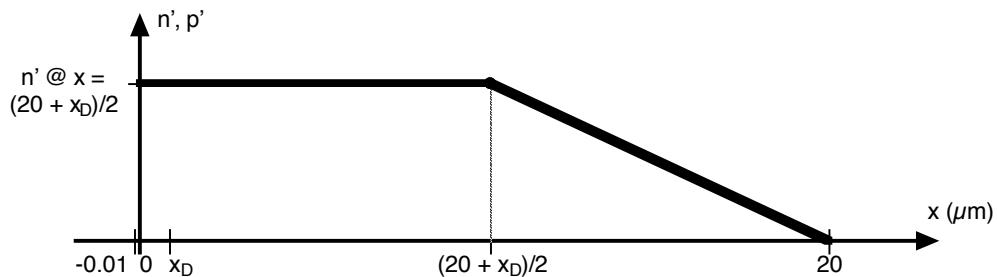


- i) As mentioned above, when  $v_{AB} < 0$  V the drain-substrate diode can conduct.
- ii) When  $v_{AB} > 1$  V the MOSFET channel is conducting.
- c) i) When  $v_{AB} < 0$  the diode is conducting and  $-i_D = I_S[\exp(-qv_{AB}/kT) - 1]$ . You have enough information on the figure to determine that  $I_S = 10^{-13}$  A because 0.6 V is  $10 \times 60$  mV, and thus 1 mA must be 10 orders of magnitude ( $10^{10}$ ) bigger than  $I_S$ .
- ii) When  $0 < v_{AB} < 1$  V the MOSFET is cut-off and  $I_D = 0$ . (You could also say  $I_S$ , but we usually approximate this as 0.)
- iii) When  $v_{AB} > 1$  V the MOSFET is conducting with  $v_{DS} = v_{GS}$ , so we have  $i_D = 1000 (v_{AB} - 1)^2 \mu\text{A}$ .
- d) The element we want is a resistor with conductance,  $g_d$ , equal to  $di_D/dv_{AB}|_Q$ .
- e) i) When  $i_D = 1$  mA the appropriate equation is  $i_D = 1000 (v_{AB} - 1)^2 \mu\text{A}$ , and thus  $g_d = 2000(v_{AB} - 1) \mu\text{S}$  evaluated at  $I_D = 1$  mA, or  $V_{AB} = 2$  V. Thus  $g_d = 2$  mS.
- ii) When  $v_{AB} = +0.5$  V the current is 0 so the incremental conductance,  $g_d$ , is 0.
- iii) When  $i_D = -1$  mA,  $v_{AB} = -0.6$  V, the diode is conducting and  $g_d = qI_D/kT = 40$  mS.
- f) Two things change: the magnitude of the threshold voltage increases so it is now greater than 1V (i.e.,  $V_T < -1$  V), and the diode does not turn on until the forward bias on it (which is  $-v_{AB}$ ) is 1 V larger. The characteristic is shown on the next page.



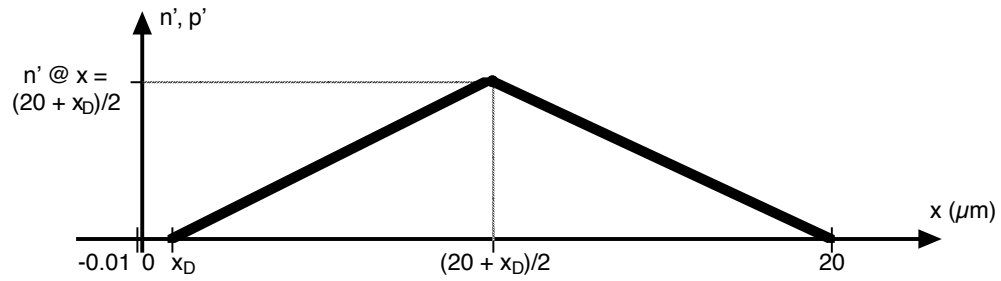
**Problem 3:**

- a) The flat-band voltage is  $-(\phi_m - \phi_{si})$ , and  $\phi_{si} = \phi_p = -(kT/q) \ln(N_A/n_i) = -0.42$  V. Thus  $V_{FB} = -[0.35 - (-0.42)] = -0.77$  V.
- b) At threshold the potential drop in the silicon is  $-2\phi_p$ , which is 0.84 V.
- c) i) With a reverse bias on the substrate the potential drop in the silicon is now  $(-2\phi_p - v_{BS})$  and since  $v_{BS} = -2$  V, the drop is 2.84 V.
- ii) With more potential drop in the silicon the magnitude of the threshold will be greater.
- d) i) The profile is flat to the left because the boundary at  $x = 0$  is a reflecting surface, and it slopes in a straight line to the ohmic contact at  $x = 20$   $\mu\text{m}$ .



- ii) The flow to the left is the current we are looking for and it is zero. The flow to the ohmic contact does not lead to current in the external circuit.

iii) Now the boundary at  $x = x_D$  is like a reverse biased p-n junction and the excess population is  $-n_i^2/N_{A'}$  which is effectively zero. Thus the profile slopes in straight lines from  $n'$  at  $x = (20 + x_D)/2$  to 0 at  $x = x_D$  and  $x = 0$ .



iv) The current to the "junction", i.e., to the channel, is half of the total injected excess charge, or  $qMA/2 = 48 \mu\text{A}$ .

| <b>Statistics:</b> | <b>Ave.</b>       | <b>St. Dev.</b>  |
|--------------------|-------------------|------------------|
| Problem 1          | 27.3 (72%)        | 9.0 (24%)        |
| Problem 2          | 17.9 (53%)        | 9.0 (27%)        |
| <u>Problem 3</u>   | <u>20.5</u> (73%) | <u>5.6</u> (20%) |
| Total Exam         | 65.8              | 16.9             |

**The grades distribution:** Can you find yourself in this picture?  
(3 late exams are not included in these statistics)

