EE2021 Mid-Term Quiz (Time Allowed : 1 hour)

Name		Total
Matric. No.		

1. The paper consists of **5 (Five)** questions and **9 (NINE)** printed pages.
2. Answer all questions.
3. The questions DO NOT carry equal marks.
4. The MINIMUM mark for each question is ZERO.
5. Assume that $T = 300$ K, $V_T = kT/q = 0.025$ V, $q = 1.602 \times 10^{-19}$ C, $\varepsilon_0 = 8.854 \times 10^{-14}$ F cm^{-1}. For silicon, $n_i = 1.5 \times 10^{10}$ cm^{-3}, ε_r (silicon) =11.7.
6. A list of formulas are provided in a separate Appendix for your reference.

	Marks given

Q1 Consider a Si substrate with an initial doping of 3×10^{15} cm^{-3} of donors (Region 1). A pn junction is made in the Si substrate by doping a selected region (Region 2) with an additional 8×10^{15} cm^{-3} of acceptors, as shown in Fig. Q1. The temperature, $T = 300$ K, the intrinsic carrier concentration in Si, $n_i = 1.5\times10^{10}$ cm^{-3} and the thermal voltage, $V_T = 0.025$ V.

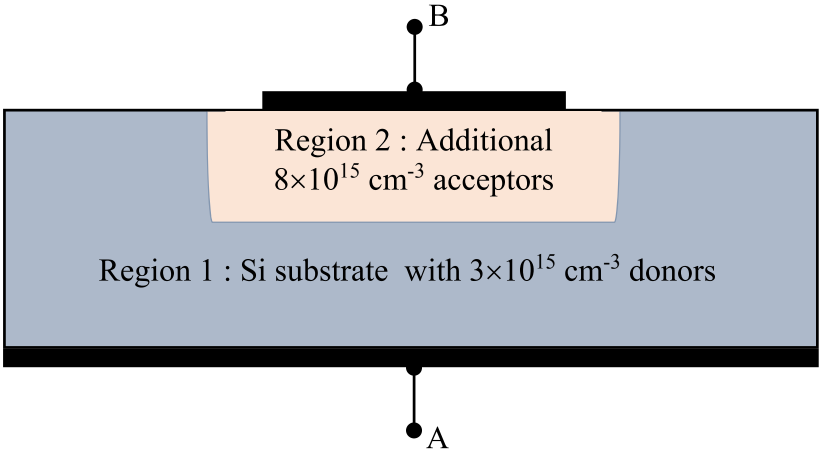


Fig. Q1

(a) What are the concentrations of the majority and minority carriers in the Si substrate (Region 1)?

[4 marks]

Substrate is doped only with donors ($N_D = 3\times10^{15}$ cm^{-3} >> n_i), which contribute to electrons, hence majority carriers in the substrate are electrons with concentration

$$\underline{n_0 \cong N_D = 3\times10^{15}\ \text{cm}^{-3}.}$$

Minority carriers are holes with concentration –

$$p_0 = n_i^2/n_0 \cong n_i^2/N_D = (1.5\times10^{10})^2/3\times10^{15} = \underline{7.5\times10^{4}\ \text{cm}^{-3}.}$$

(b) What is the majority carrier concentration of the selected region (Region 2)?

[2 marks]

Selected region is doped with additional acceptors ($N_A = 8\times10^{15}$ cm^{-3}), which is greater than $N_D = 3\times10^{15}$ cm^{-3}, hence the **net** doping concentration is **p-type**

$$N_p = N_A - N_D = 8\times10^{15} - 3\times10^{15} = 5\times10^{15}\text{ cm}^{-3},$$

and the majority carriers are holes with concentration

$$p_0 \cong N_p = \underline{5\times10^{15}\text{ cm}^{-3}.}$$

(c) What is the built-in voltage of the pn junction? **[2 marks]**

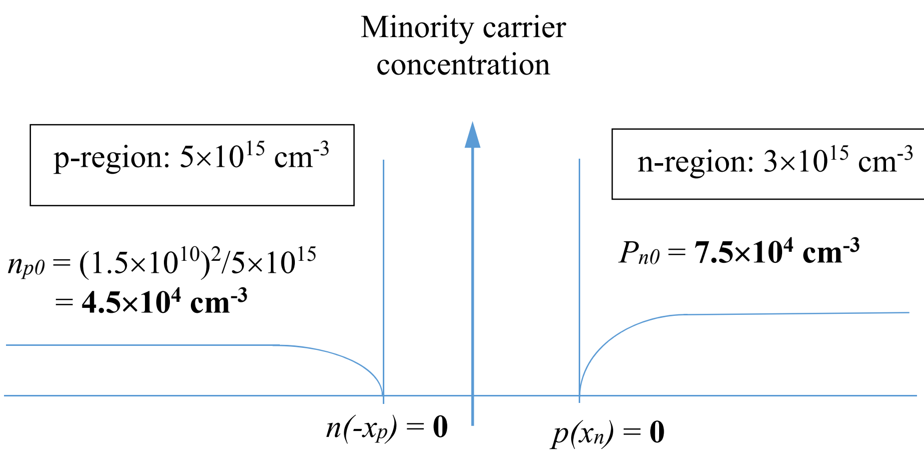
$$V_o = V_T \ln(N_P N_D / n_i^2) = 0.025 \times \ln[3\times10^{15} \times 5\times10^{15} / (1.5\times10^{10})^2] = \underline{0.62\text{ V.}}$$

(d) Under the condition of reverse bias, which of the two terminals (A and B) is at a higher voltage/potential with respect to the other?

In addition, sketch the minority carrier distribution in the neutral regions of the pn junction under a <u>reverse bias of 1 V</u> and indicate the carrier concentrations at the boundaries of the neutral regions. You can assume the neutral regions in the pn junction to be much longer than the respective minority carrier diffusion lengths.

[4 marks]

Under reverse bias, A has a higher voltage/potential w.r.t. B.



Q2 A diode circuit is shown in Fig. Q2. The exponential factor, n, of the diode is equal to 1. The voltage across R was measured and found to be 4.35 V.

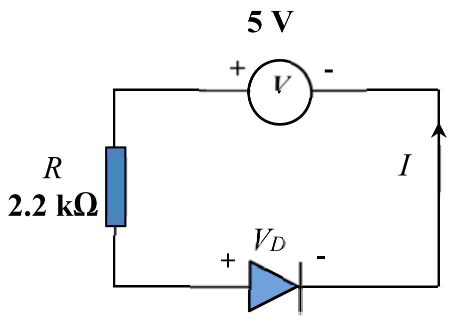


Fig. Q2

(a) Find the value of the current I flowing through the circuit.

[2 marks]

$I = 4.35\text{ V} / 2.2\text{ k}\Omega = 1.98\text{ mA}$.

(b) Find the value of the saturation current of the diode (I_s) in the circuit.

[3 marks]

$V_D = (5 - 4.35)\text{V} = 0.65\text{ V}$

$$I_s = \frac{I}{exp\left(\frac{0.65}{0.025}\right) - 1} = \frac{1.98\ 10^{-3}}{exp\left(\frac{0.65}{0.025}\right) - 1} = 1.01 \times 10^{-14}\text{ A}$$

(c) A diode has been partially designed to have the value of the saturation current I_s stated in part (b). In this unfinished design, the following diode parameters have been decided:

- Doping in the p-region $N_A = 10^{16}$ cm^{-3},
- Doping in the n-region $N_D = 10^{17}$ cm^{-3},
- Diffusion coefficient of holes in the n-region, $D_p = 1$ cm^2/s,
- Diffusion coefficient of electrons in the p-region, $D_n = 10$ cm^2/s,
- Diffusion length of holes in the n-region, $L_p =$ 0.300 µm
- Diffusion length of holes in the p-region, $L_n =$ 0.300 µm

Complete the design of the diode. **[7 marks]**

From $I_S = Aqn_i^2\left(\frac{D_p}{L_pN_D} + \frac{D_n}{L_nN_A}\right)$

All the parameters have been fixed except for the cross sectional area A. Therefore,

$$A = \frac{1.01\times10^{-14}}{1.602\times10^{-19}\times\left(1.5\times10^{10}\right)^2\left(\frac{1}{0.3\times10^{-4}\times10^{17}}+\frac{10}{0.3\times10^{-4}\times10^{16}}\right)}$$

$= 8.33 \times 10^{-6}$ cm^2

or $8.33 \times 10^2\ \mu m^2$

Q3 For each of the statements below, circle TRUE if the statement is correct, and FALSE if the statement is wrong.

(Marks will be deducted for each wrong answer you give. No mark will be deducted if you do not answer.)

(a) The following two statements refer to the bipolar transistor in the Fig. Q3 below. The diffusion length of holes in the base is 3µm.

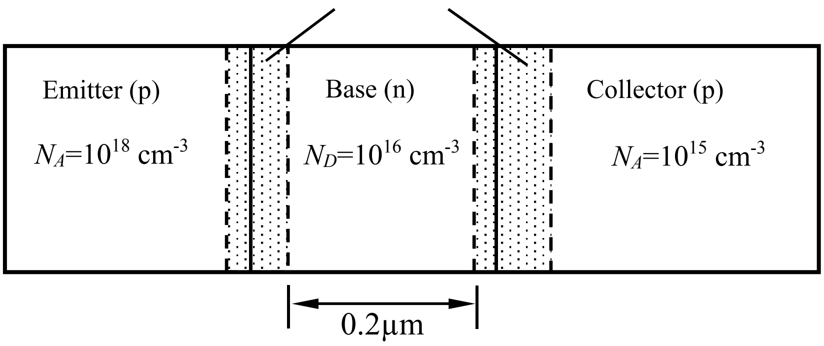


Fig. Q3

(i) The bipolar transistor in the diagram will have a reasonable value of β.

[1 mark]

TRUE/~~FALSE~~

(ii) The bipolar transistor will have a low value of β because the doping in the collector is too low.

[1 mark]

~~TRUE~~/FALSE

(b) A p-channel MOSFET is made on an n-type substrate material.

[1 mark]

TRUE/~~FALSE~~

(c) When a MOSFET is operating in the linear region, its channel is pinched off and the pinch off point is located near the drain.

[1 mark]

~~TRUE~~/FALSE

Q4 Consider the two BJT circuits shown in Figure Q4. You may assume the transistor, Q_1, in both circuits has $\beta = 100$ and $V_A = 100$ V. Also, you may assume $I_{R1} \approx I_{R2} >> I_B$.

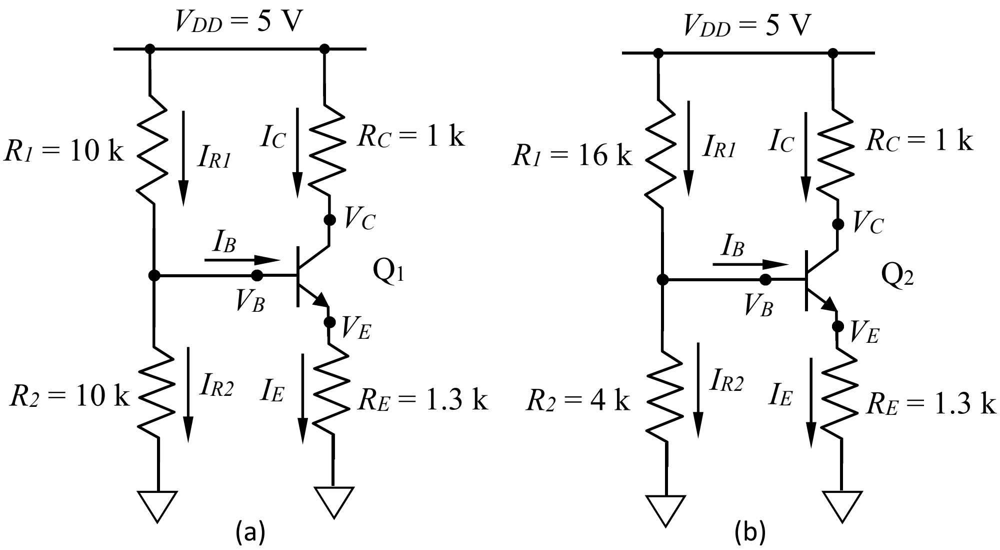


Figure Q4

(a) What is the typical assumed value of V_{BE} when the transistor is operating in the forward active region?

[1 mark]

$V_{BE} = 0.7$ V.

(b) Determine $I_{C,Q1}$ for the circuit in Fig. Q4(a).

[4 marks]

$$V_B = 2.5 \Rightarrow V_E = 1.8$$
$$I_C \approx I_E = \frac{1.8}{1.3k} = 1.38mA$$

(c) Determine $I_{C,Q2}$ for the circuit in Figure Q4(b).

[4 marks]

$$V_B = 1 \Rightarrow V_E = 0.3$$
$$I_C \approx I_E = \frac{0.3}{1.3k} = 0.23mA$$

(d) What would be the relative error on $I_{C,Q1}$ and $I_{C,Q2}$ in percentage terms if the actual value of V_{BE} deviates by +0.1V from your earlier assumed V_{BE} value?

[4 marks]

For Figure Q4(a), by assuming V_{BE}=0.7+0.1

$$V_B = 2.5 \Rightarrow V_E = 1.7 \Rightarrow error = \frac{0.1}{1.7} = 5.9\%$$

The error induced is small in estimating I_C and can be accepted.

For Figure Q4(b), by assuming V_{BE}=0.7±0.1

$$V_B = 1 \Rightarrow V_E = 0.2 \Rightarrow error = \frac{0.1}{0.2} = 50\%$$

The error induced in estimating I_C is much bigger and cannot be accepted.

(e) Discuss the implication of the V_{BE} assumption based on the results on (d). Would the Thevenin equivalent method help to resolve this issue?

[3 marks]

The assumption of V_{BE}=0.7 V is only acceptable provided V_E is large. Otherwise, small error of V_{BE} will induce huge error in V_E and thus I_C. Thevenin method would not help resolve this issue as it will still subject to V_{BE} error.

Q5 Figure Q5 shows a MOSFET amplifier circuit. The source and body of the n-MOSFET are connected together, i.e., there is no body effect. It has the following device parameters : $K_n = 1$ mA V^{-2}, $V_{TH} = 1$ V.

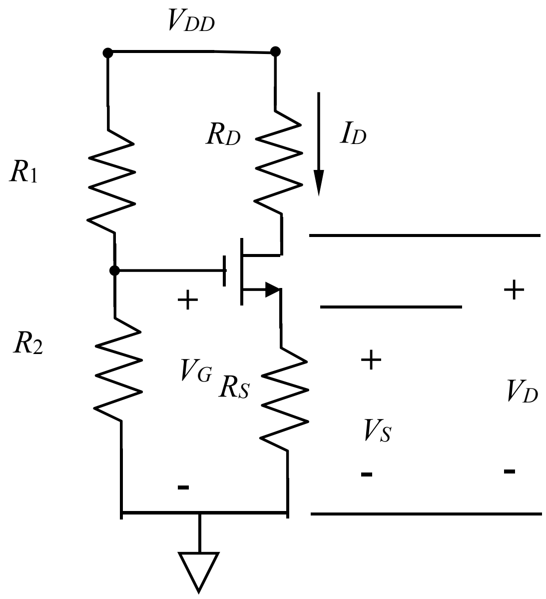


Figure Q5

It is given that V_{DD}= 10 V, I_D = 1 mA, R_1 = 60 kΩ, R_S = 3 kΩ, and that the MOSFET is operating in the saturation region.

(a) What is the gate voltage V_G?

[6 marks]

$$I_D = K_n (V_{GS} - V_{TH})^2$$

$$(V_{GS} - V_{TH}) = \sqrt{I_D / K_n} = \sqrt{1} = \pm 1\, V$$

$V_{GS} = V_{TH} \pm 1 = 0\, V$ or $2\, V$. $V_{GS} = 0\, V$ is not applicable as $V_{GS} < V_{TH}$.

$$V_S = I_D R_S = 1\, mA \times 3\, k = 3\, V$$

$$V_G = V_{GS} + V_S = 2 + 3 = 5\, V$$

(b) Determine the value of R_2.

[2 marks]

$$V_G = V_{DD} \times \frac{R_2}{R_1 + R_2} = 5\, V$$

$R_2 = R_1 = 60$ k.

(c) What is the **minimum** value of the drain voltage, V_D, such that the MOSFET is operating in the saturation region, under the given conditions?

[4 marks]

For the n-MOSFET to operate in the saturation region,

$V_{DS} \geq V_{GS} - V_{TH}$. Therefore,

Minimum $V_{DS} = V_{GS} - V_{TH} = 2 - 1 = 1$ V.

$V_D = V_S + V_{DS} = 3 + 1 = 4$ V.

(d) What is the **maximum** value of R_D in order that the MOSFET is operating in the saturation region, for the given conditions?

[2 marks]

Maximum, $R_D = \dfrac{V_{DD} - V_D}{I_D} = \dfrac{(10-4)\,\text{V}}{1\,\text{mA}} = 6\ \text{k}\Omega.$

(e) The channel length modulation factor of the MOSFET, $\lambda = 0.002\ \text{V}^{-1}$. Calculate the small signal parameters of the MOSFET, g_m and r_0, under the given d.c. bias condition.

[2 marks]

$$g_m = 2\sqrt{K_n I_D} = 2\sqrt{1\,\text{mA}\,\text{V}^{-2} \times 1\,\text{mA}} = 2\ \text{mA}\,\text{V}^{-1}$$

$$r_0 = \frac{1}{\lambda I_D} = \frac{1}{0.002\,\text{V}^{-1} \times 0.001\,\text{A}} = 500\ \text{k}\Omega.$$

END OF QUESTIONS