NATIONAL UNIVERSITY OF SINGAPORE

Department of Electrical and Computer Engineering

EE2027 Electronic Circuits
Tutorial 3: Solution

- Unless otherwise stated, you may assume temperature, $T = 300$ K, thermal voltage, $V_T \approx 0.025$ V.
- All the symbols are as defined in lecture notes.

Homework 3:

Homework 3 has 2 questions, Questions 7 and 8 of Tutorial 3. You will need to submit a softcopy of your handwritten homework to Canvas>Homework Submissions>HW3 half an hour after class (i.e., latest by 4:30 pm) on Tuesday, 26 March 2024. Failing to do that will mean zero mark for homework.

The softcopy submission of your homework must be in PDF format (in a single file) and named using the convention "<Your Name>_HW3".

Homework questions will not be discussed in class.

Q1. The npn BJT in an amplifier circuit has the i_C versus v_{CE} characteristics shown in Fig. Q1, along with the load line of the amplifier circuit. As shown, the BJT operates at the DC bias point Q. The temperature is T = 300 K.

At the dc bias point Q, $v_{BE} = 0.69$ V, $v_{CE} = 12$ V, the small _change in i_C owing to the small change in v_{BE} is 48 mA/V, while the small change in i_C owing to the small change in v_{CE} is 0.013 mA/V.

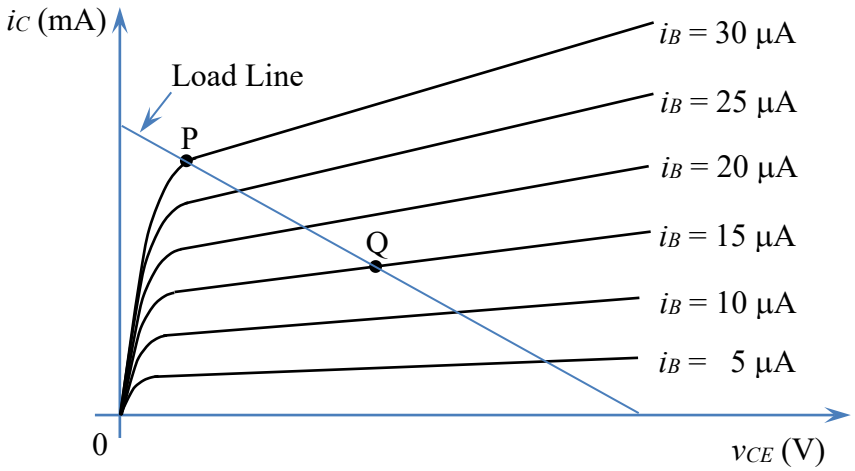


Fig. Q1

(a) Does the BJT amplifier circuit operate properly at the dc bias point Q? Explain your answer, and specify the biasing conditions and calculate the voltages of the two junctions in the BJT at Q.

(b) Determine the current gain (β), Early voltage (V_A), and saturation current (I_S) of the BJT. Do NOT ignore the Early effect, if present, in your calculation.

[Ans: $\beta = 80$, $V_A = 92.3$ V, $I_S = 1.1\times10^{-15}$ A]

(c) How will the amplifier circuit operation be affected, if the dc bias point is moved to P? You need to elaborate your answer briefly.

Q1. **Solution:**

BJT is of the npn type.

(a) Yes. As BJT operates well within the **forward active region** at the dc bias point Q.

At the dc bias point, Q, $v_{BE} = V_{BE} = 0.69$ V, $v_{CE} = V_{CE} = 12$ V -

- base-emitter junction is in **forward bias**: $V_{BE} = 0.69$ V (≈ 0.7 V) > 0
- base-collector junction is in **reverse bias**: $V_{BC} = V_{BE} - V_{CE} = 0.69 - 12 = -11.31 < 0$

(b) In forward active region, at the bias point Q -

- $g_m = I_C/V_T \approx$ small change in i_C owing to small change in $v_{BE} = 48$ mA/V
  So, $I_C = V_T \times 48 \approx 0.025 \times 48 = 1.2$ mA
- $I_B = 15$ μA (determined from the i_C versus v_{CE} characteristics),
  So, $\beta = I_C/I_B = 1.2\text{m}/15\mu = 80$

BJT experiences Early effect, as i_C depends on v_{CE} in the forward active region (as shown in the i_C versus v_{CE} characteristics)

- $r_o = V_A/I_C \approx$ reciprocal of small change in i_C owing to small change in $v_{CE} = 1/0.013\text{m}$
  So, $V_A = I_C/0.013\text{m} = 1.2\text{m}/0.013\text{m} = 92.3$ V

At the dc bias point Q, $V_{BE} = 0.69$ V, $V_{CE} = 12$ V, and $I_C = 1.2$ mA

$$I_C = I_S e^{V_{BE}/V_T}\left[1 + \frac{V_{CE}}{V_A}\right] \text{ (which includes Early Effect)}$$

$$1.2\text{m} = I_S e^{\frac{0.69}{0.025}}\left[1 + \frac{12}{92.3}\right]$$

$$I_S = 1.1 \times 10^{-15}\ \text{A}$$

(c) Point P is not within the forward active region, but at the verge of saturation, hence the small-signal ac i_c and v_{ce} will be distorted, and the amplifier will no longer work properly.

Q2. For the circuit shown in Fig. Q2, the diode D_1 has a breakdown voltage of 6 V, and the BJT Q_1 has a common-emitter current gain of 100 and saturation current of 7.6×10^{-15} A. Temperature T = 300 K.

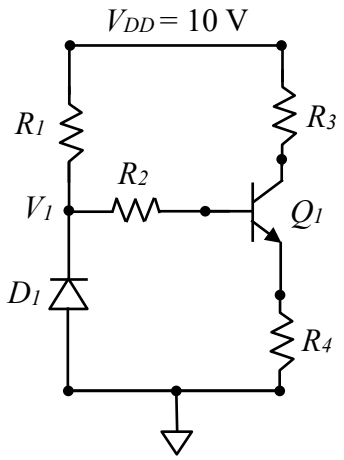


Fig. Q2

(a) Show with explanation that the voltage V_1 = 6 V.

(b) The base-emitter voltage of BJT Q_1 has a magnitude of 0.64 V. For R_2 = 0 Ω and R_3 = 2.2 kΩ, determine the collector current of BJT Q_1 and R_4. State the assumption(s) made and verify it (them).

[Ans: I_C = 1 mA, R_4 = 5.31 kΩ]

(c) For the collector current of BJT Q_1 to drop to 0.3 mA, what is the required value of R_2? Resistance of all other resistors remain unchanged from part (b).

[Ans: R_2 = 1.26 MΩ]

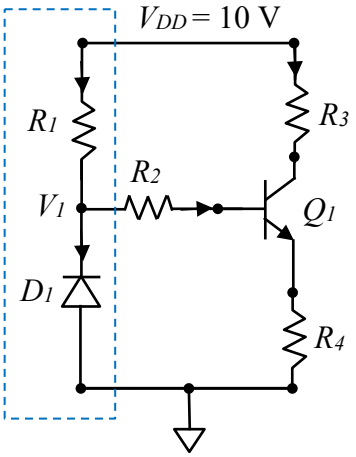
Q2. **Solution:**

- BJT Q_1: npn type, β = 100, $I_S = 7.6\times10^{-15}$ A
- Diode D_1: V_Z = 6 V

(a) Consider the sub-circuit comprising R_1, D_1 and V_{DD} (as shown below within the dashed box), where it can be seen that D_1 is in reverse bias by V_{DD} (as current flows through D_1 from n- to p-type side). Current flowing through R_2 is the base current of BJT and is expected to be small. Hence, the current flowing through R_1 and the diode are likely to be substantially larger than the base current of BJT, meaning current flowing through the diode is not negligible.

Since V_{DD} = 10 V > V_Z = 6 V, hence D_1 operates in the breakdown region, and $V_1 = V_Z$ = 6 V.

Note:
The above explanation is valid assuming that the circuit to the right of diode D_1 does not substantially load the circuit within the blue rectangular box.



(b) $R_2 = 0$ and $R_3 = 2.2$ kΩ

Assume BJT Q_1 is in the **forward active mode**.

Given that V_{BE} = 0.64 V for BJT Q_1 -

$$I_C = I_S e^{V_{BE}/V_T} = 7.6 \times 10^{-15} \times e^{0.64/0.025} = 1 \text{ mA}$$

$$V_B = V_1 - I_B R_2 = 6 \text{ V} \ (R_2 = 0)$$

$$V_E = V_B - V_{BE} = 6 - 0.64 = 5.36 \text{ V}$$

$$V_E = I_E R_4 = \frac{(1+\beta)}{\beta} I_C R_4 \Rightarrow R_4 = 5.31 \text{ k}\Omega \ [\text{Or, } R_4 = 5.36 \text{ k}\Omega, \text{assuming } I_E \approx I_C]$$

For Q_1:

$$V_C = V_{DD} - I_C R_3 = 10 - 1\text{m} \times 2.2\text{k} = 7.8 \text{ V}$$
$$V_B = 6 \text{ V}$$

So, $V_{BC} = V_B - V_C = 6 - 7.8 = -1.8 \text{ V} < 0$

BJT Q_1 is of the npn type, with $V_{BE} > 0$ and $V_{BC} < 0$, BJT is in forward active mode.

(c) $I_C = 0.3$ mA

As I_C has changed, so has V_{BE}: $V_{BE} = V_T ln\left(\frac{I_C}{I_S}\right) = 0.025 \times ln\left(\frac{0.3\text{m}}{7.6\times10^{-15}}\right) = 0.61 \text{ V}$

$$V_E = I_E R_4 = \frac{(1+\beta)}{\beta} I_C R_4 = 1.61 \text{ V}$$

$$V_1 = I_B R_2 + V_{BE} + V_E = \frac{I_C}{\beta} R_2 + V_{BE} + 1.61$$

$$6 = \frac{0.3\text{m}}{100} \times R_2 + 0.61 + 1.61$$

So, $R_2 = 1.26\ \text{M}\Omega$ [Or, $R_2 = 1.266\ \text{M}\Omega$, assuming $I_E \approx I_C$]

Q3. A BJT circuit is shown in Fig. Q3. The **pnp** transistor, Q_1, in the circuit has $\beta = 100$.

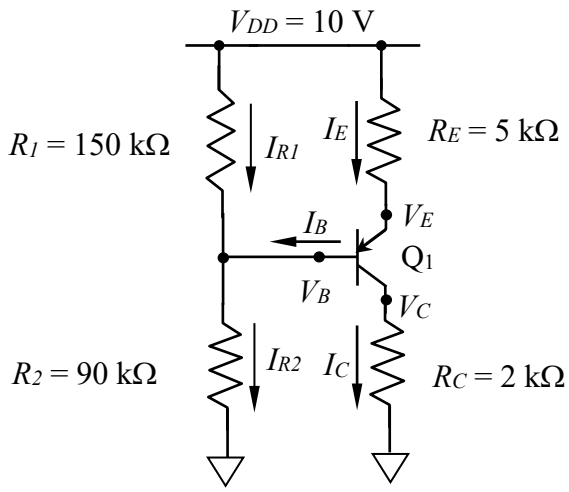


Fig. Q3

(a) Assuming that the base-emitter forward biased junction voltage is 0.7 V, determine the collector current, I_C, for the circuit shown in Fig. Q3 using the voltage divider method at the base terminal by assuming that $I_{R1} \approx I_{R2} >> I_B$.

[Ans: $I_C = 1.10\ \text{mA}$]

(b) Is the use of voltage divider assumptions valid? Explain.

(c) Based on the conclusions of part (b), determine the correct value of I_C. Also calculate V_E and V_C, and confirm that the BJT is operating in the forward active region.

[Ans: $I_C = 0.99\ \text{mA}$, $V_E = 5\ \text{V}$, $V_C = 1.98\ \text{V}$]

[Note: In order for a number A to be considered much larger than a number B, i.e., for $A >> B$, A must be 10 times or more than B.]

Q3. **Solution:**

(a) The BJT is of the pnp type. It is assumed that $V_{EB} \approx 0.7$ V.

Assuming $I_{R1} \approx I_{R2} >> I_B$, and using the voltage divider method,

$$V_B \approx \frac{R_2}{R_1+R_2} V_{DD} = \frac{90\text{k}}{90\text{k}+150\text{k}} \times 10 = 3.75\ \text{V}.$$

$V_E = V_B + V_{EB} \approx 3.75 + 0.7 = 4.45$ V.

$I_E = \frac{V_{DD} - V_E}{R_E} = \frac{10 - 4.45}{5\text{k}} = 1.11$ mA.

$I_C = \frac{\beta}{(\beta+1)} I_E = 1.10$ mA (or $I_C \approx I_E = 1.11$ mA is also acceptable).

(b) Using the value of I_C calculated above,

$I_B = \frac{I_E}{(\beta+1)} = 0.011$ mA $= 11\mu$A.

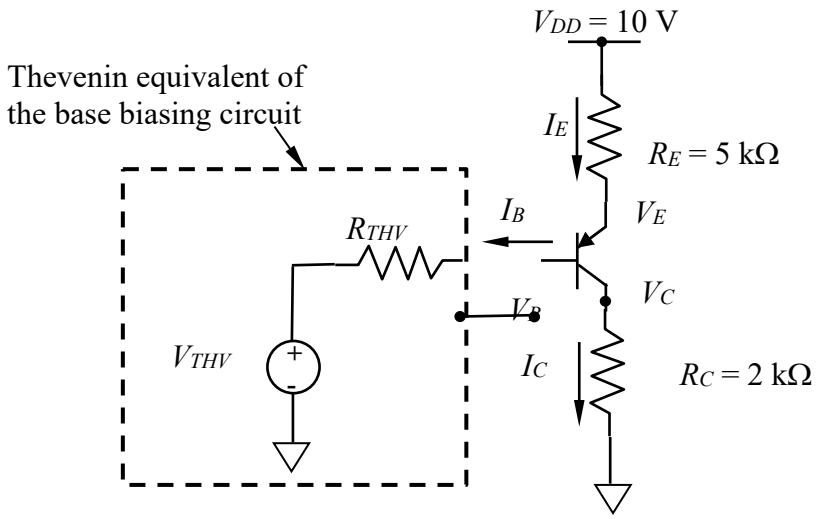
$I_{R1} \approx I_{R2} = \frac{V_{DD}}{R_1 + R_2} = \frac{10}{90k + 150k} = 0.042$ mA $= 42$ μA.

Since I_{R1} and I_{R2} are <u>not</u> at least 10 times more than I_B, the use of the voltage divider method is <u>not</u> valid.

(c) The Thevenin equivalent method needs to be used.

$V_{THV} = \frac{R_2}{R_1 + R_2} V_{DD} = \frac{90k}{90k + 150k} \times 10 = 3.75$ V.

$R_{THV} = R_1 // R_2 = 56.25$ kΩ.



By KVL, $V_{DD} = 10 = I_E R_E + V_{EB} + I_B R_{THV} + V_{THV}$

$= 101 I_B \times 5\text{k} + 0.7 + I_B \times 56.25\text{k} + 3.75$

$I_B = \frac{5.55}{561.25\text{ k}} = 0.0099$ mA, $I_E = (\beta + 1) I_B = 1$ mA, $I_C = \beta I_B = 0.99$ mA.

$V_E = V_{DD} - R_E I_E = 10 - 1 \times 5 = 5$ V.

$V_B = V_E - V_{EB} \approx V_E - 0.7 = 4.3$ V.

$V_C = R_C I_C = 0.99 \times 2 = 1.98$ V.

Since $V_{EB} \approx 0.7$ V > 0, and $V_{CB} = V_C - V_B = 1.98 - 4.3 = -2.32$ V < 0, the pnp BJT is confirmed to be operating in the forward active region.

Q4. In the circuit of Fig. Q4, the *p*-channel MOSFET has $\mu_p C_{ox} = 2\times10^{-5}$ AV^{-2}, $V_{TH} = -1$ V, $W/L = 5$, and $\lambda = 0.01$ V^{-1}.

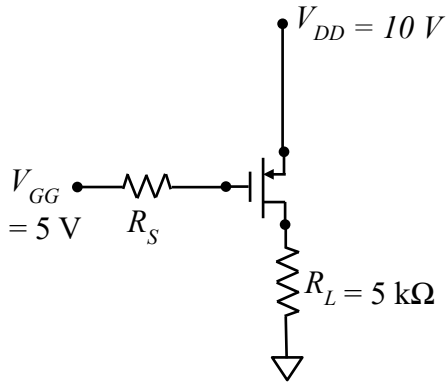


Fig. Q4

(a) What is the gate-to-source voltage, V_{GS}, of the MOSFET? Explain your answer.
[Ans: -5 V]

(b) Does the MOSFET has a channel formed between the source and drain? Explain your answer.

(c) Assuming the MOSFET is operating in the saturation region, estimate the value of the drain current, I_D, with and without Channel-Length Modulation effect. Compare the two values of I_D and discuss the implication.
[Ans: 0.846 mA; 0.8 mA]

(d) Verify if the MOSFET is operating in the saturation region.

Q4. **Solution:**

MOSFET is of the *p*-channel type: $\mu_p C_{ox} = 2\times10^{-5}$ AV^{-2}, $V_{TH} = -1$ V, $W/L = 5$, $\lambda = 0.01$ V^1

(a)

$V_G = V_{GG} = 5$ V (as gate current, $I_G = 0$, thus no voltage drop across R_S)

$V_S = V_{DD} = 10$ V (Source connected to the V_{DD})

$V_{GS} = V_G - V_S = 5 - 10 = -5$ V

(b)

Yes. As $V_{SG} = 5$ V > $|V_{TH}| = 1$ V.

(c)

With Channel Length Modulation Effect –

$$|I_D| = K_p[|V_{GS}| - |V_{TH}|]^2(1 + \lambda|V_{DS}|) = K_p[V_{SG} - |V_{TH}|]^2(1 + \lambda V_{SD}),$$

where $V_{SD} = V_{DD} - |I_D| \times R_L$ (by KVL)

$$|I_D| = \frac{1}{2}\mu_p C_{ox}\frac{w}{L}[5-1]^2(1 + 0.01[10 - |I_D| \times 5\text{k}])$$
$$|I_D| = \frac{1}{2}\times 2\times 10^{-5}\times 5\times 4^2(1 + 0.1 - |I_D| \times 50)$$
$$|I_D| = 0.846\ \text{mA}$$

Without Channel Length Modulation Effect –

$$|I_D| = K_p[|V_{GS}| - |V_{TH}|]^2 = \frac{1}{2}\mu_p C_{ox}\frac{w}{L}[5-1]^2 = 0.8\ \text{mA}$$

The difference between the above two $|I_D|$ values is only 5.75%.

Hence, it is acceptable to estimate I_D assuming no Channel Length Modulation effect as the percentage error is < 10%.

(d)

$V_{SG} = 5$ V > $|V_{TH}| = 1$ V.

- $V_{SD} = 10 - |I_D|R_L = 10 - 0.846\text{m} \times 5\text{k} = 5.77$ V
  [Or, $V_{SD} = 10 - |I_D|R_L = 10 - 0.8\text{m} \times 5\text{k} = 6$ V]
- $|V_{GS}| - |V_{TH}| = 4$ V

  $\therefore\ V_{SD} \geq |V_{GS}| - |V_{TH}|$, MOSFET is in saturation operation.

Q5. The n-MOSFET in the amplifier circuit shown in Fig. Q5 is operating in the saturation region and has the following device parameters: K_n = 1 mA V^{-2}, V_{TH} = 1 V. The source and body of the n-MOSFET are connected together, i.e., there is no body effect. The voltage supply V_{DD} = 5 V. The circuit designer decided that the drain current I_D is to be set at 1 mA and chose R_1 = 60 kΩ, and R_S = 1 kΩ. Complete the design of the circuit by following steps (a) to (d).

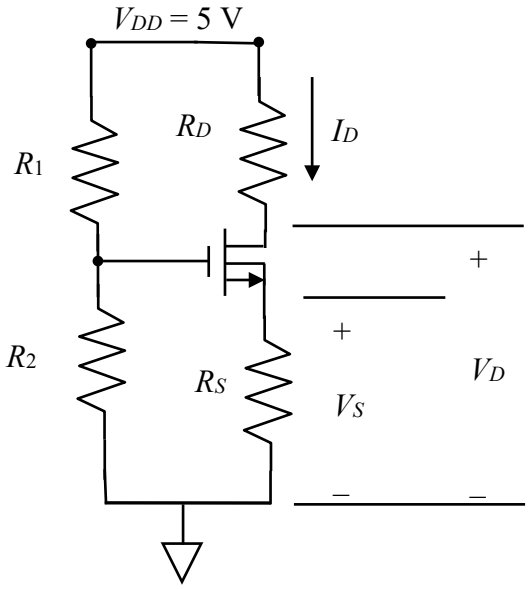


Fig. Q5

(a) Determine the value of V_G.

[Ans: V_G = 3 V]

(b) Determine the value of R_2.

[Ans: R_2 = 90 kΩ]

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

[Ans: Minimum V_D = 2 V]

(d) What is the maximum value of R_D for the n-MOSFET to be operating in the saturation region in this circuit?

[Ans: Maximum R_D = 3 kΩ]

Q5. **Solution:**

(a) n-MOSFET is operating in the saturation region: $I_D = K_n\left(V_{GS} - V_{TH}\right)^2$.

1 mA = 1 mA/V^2 × ($V_{GS} - V_{TH}$)^2.

$V_{GS} - V_{TH}$ = -1 V or + 1 V, i.e., V_{GS} = 0 V or 2 V.

From the above, $V_{GS} = V_G - V_S$ = 2 V; as V_{GS} = 0 (< V_{TH}) is not a valid solution as the MOSFET has no channel and is OFF.

$V_S = R_S I_D$ = 1 kΩ × 1 mA = 1 V.

Therefore, $V_G = V_{GS} + V_S$ = 2 + 1 = 3 V.

(b) $\dfrac{R_2}{R_1 + R_2} \times V_{DD} = V_G = 3$ V

$5R_2 = 3(R_1 + R_2) = 3 \times (60\ \text{k}\Omega + R_2)$

R_2 = 90 kΩ.

(c) For the MOSFET to operate in the saturation region:

$V_{DS} \geq (V_{GS} - V_{TH}) = (2 - 1)$ V $= 1$ V.

$V_{DS} = V_D - V_S \geq 1$ V, therefore $V_D \geq 2$ V.

The minimum value of V_D is 2 V.

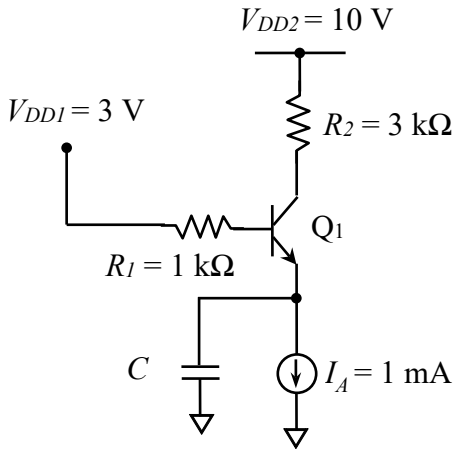
(d) $V_D \geq 2V \Rightarrow V_{DD} - V_D = V_{RD} = I_D R_D \leq 3$ V,

Since I_D = 1 mA, $R_D \leq 3$ kΩ.

The maximum value of R_D is 3 kΩ.

Q6. For part (a) and part (b) below, select the **correct** statement(s).

(a)



Consider the above circuit where BJT Q_1 has $\beta = 100$. Which of the following is(are) CORRECT?

(i) With only V_{DD2} changed to 7 V, BJT Q_1 still operates in forward active mode.

(ii) With only R_2 changed to 5 kΩ, BJT Q_1 no longer operates in forward active mode

(iii) With only V_{DD1} changed to 6 V and R_2 changed to 5 kΩ, BJT Q_1 no longer operates in forward active mode.

(iv) With I_A changed to 2.5 mA, BJT Q_1 still operates in forward active mode.

(b) Consider the following statements, indicate which is(are) CORRECT.

(i) When used in an amplifier circuit, a BJT should operate in the saturation region, while a MOSFET should not operate in the saturation region.

(ii) For a BJT operating in the forward active mode, its small-signal output resistance, r_o, decreases when the magnitude of the base-emitter voltage, $|V_{BE}|$, is increased.

(iii) For a MOSFET operating in the saturation mode, its transconductance, g_m, increases when the magnitude of its gate to source voltage, $|V_{GS}|$, is increased.

(iv) In a CMOS inverter, the sizing of the *N*-MOSFET is 2.5 times that of the *P*-MOSFET. It can be concluded that the ratio of propagation delays, t_{PHL}/t_{PLH} is 1.

Q7. The DC biasing circuit of a BJT amplifier circuit is shown in Fig. Q7. The BJT Q_1 has $\beta = 75$ and the collector voltage is required to be $V_C = 7$ V.

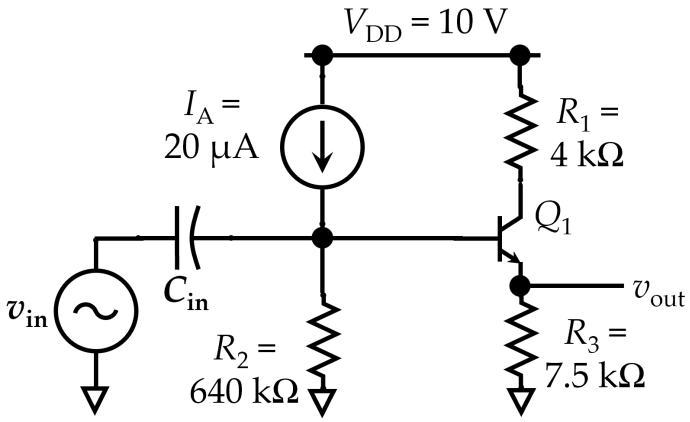


Fig. Q7

(a) What mode of operation should the BJT Q_1 be in for the circuit to work as an amplifier?

(1 mark)

(b) Assuming the Early effect is negligible, calculate the base, collector, and emitter currents of the BJT Q_1.

(6 marks)

(c) Calculate the voltages at the base and emitter terminals of the BJT Q_1 and show whether the BJT Q_1 is working in the desired operation mode.

(5 marks)

(d) Assuming the Early effect is negligible, calculate the small signal parameters g_m, r_π and r_o of the BJT Q_1.

(3 marks)

Q7. Solution:

(a) The BJT should operate in the forward active mode of operation for the circuit to work as an amplifier.

(1 mark)

(b) BJT is of the npn type, and the dc bias point if $V_C = 7\ V$:

$$I_C = \frac{10 - V_C}{4k} = \frac{10 - 7}{4k} = 0.75\ \text{mA}$$

$$I_B = \frac{I_C}{\beta} = 10\ \mu\text{A}$$

$$I_E = 0.76\ \text{mA}$$

(6 marks)

(c)

$$V_B = (20 - 10) \times 10^{-6} \times 640 \times 10^3 = 6.4\ V$$

(1 mark)

$$V_E = 0.76 \times 10^{-3} \times 7.5 \times 10^3 = 5.7\ \text{V}$$

(1 mark)

$$V_{BE} = 6.4 - 5.7 = 0.7\ \text{V} > 0\ \text{V}$$

(1 mark)

$$V_{BC} = 6.4 - 7 = -0.6\ \text{V} < 0\ \text{V}$$

(1 mark)

Hence, BC junction is reverse biased and BE is forward biased and the BJT Q_1 is operating in the forward active mode of operation.

(1 mark)

(d)

$$g_m = \frac{I_C}{V_T} = \frac{0.75 \times 10^{-3}}{0.025} = 0.03\ \text{A/V}$$

(1 mark)

$$r_\pi = \frac{\beta}{g_m} = \frac{75}{0.03} = 2.5\ k\Omega$$

(1 mark)

$$r_o = \infty$$

(1 mark)

Q8. The DC biasing circuit of a MOSFET amplifier circuit is shown in Fig. Q8. The parameters of this circuit are V_{DD} = 6 V, R_1 = 100 kΩ, R_3 = 10 kΩ. The threshold voltage of the MOSFET M_1 is 1 V and its drain current is 0.16 mA. The temperature is 300 K.

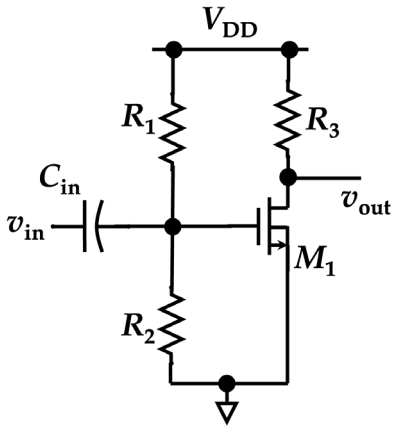


Fig. Q8

(a) Determine if the MOSFET in the circuit in Fig. Q8 is operating in the desired mode of operation if R_2 is 100 kΩ.

(5 marks)

(b) Determine the Channel Length Modulation parameter, λ, if the drain current of the MOSFET becomes 0.1616 mA when R_3 is 5 kΩ.

(6 marks)

(c) Calculate the small signal parameters, g_m and r_o , of the MOSFET if R_3 is 10 kΩ.

(4 marks)

Q8. Solution:

(a)

Since the circuit has to function as an amplifier, MOSFET M_1 is desired to operate in the saturation mode of operation.

(1 mark)

Voltage divider is applicable to the pair of resistors, R_1 and R_2, as $I_G = 0$ for MOSFET.

(1 mark)

$$V_{GS} = \left(\frac{R_2}{R_1 + R_2}\right) V_{DD} \geq V_{TH}$$

$$V_{GS} = \left(\frac{100\text{k}}{100\text{k} + 100\text{k}}\right) 6 = 3\ V\ \geq V_{TH} = 1\ V$$

(1 mark)

$$V_{DS} = V_{DD} - I_D R_3 = 6 - 0.16 \times 10^{-3} \times 10 \times 10^3 = 4.4\ V$$
$$V_{GS} - V_{TH} = 2\ V$$

(1 mark)

The MOSFET is operating in the saturation mode of operation since $V_{DS} \geq V_{GS} - V_{TH}$

(1 mark)

(b)

With channel length modulation,

$$I_D = K_n (V_{GS} - V_{TH})^2 (1 + \lambda_n V_{DS})$$

(1 mark)

$$\frac{I_{D1}}{I_{D2}} = \frac{(1 + \lambda_n V_{DS,1})}{(1 + \lambda_n V_{DS,2})} = \frac{0.1616}{0.16}$$

(1 mark)

From (a),

$$V_{DS,2} = 4.4\ V$$

$$V_{DS,1} = 6 - 0.1616 \times 10^{-3} \times 5 \times 10^3 = 5.192$$

$$\therefore \frac{0.1616}{0.16} = \frac{(1 + 5.192\lambda_n)}{(1 + 4.4\lambda_n)}$$

$$0.1616 + 0.711\lambda_n = 0.16 + 0.8307\lambda_n \rightarrow 0.0016 = 0.1197\lambda_n \rightarrow \lambda_n = 0.0134\ A/V$$

(4 marks)

(c)

If $R_3 = 10\ \text{k}\Omega$ and $I_D = 0.16\ \text{mA}$,

$$g_m = \frac{2I_D}{(V_{GS}-V_{TH})} = \frac{2\times 0.16\times 10^{-3}}{3-1} = 1.6\times 10^{-4} A/V$$

(2 marks)

$$r_o = \frac{1}{I_D \lambda_n} = \frac{1}{0.16\times 10^{-3}\times 0.0134} = 467.6\ \text{k}\Omega$$

(2 marks)

Q9. An n-channel MOSFET is connected as shown in the circuit in Fig. Q9, where V_{SS} provides a voltage across the source and body. The MOSFET drain current equations discussed in lecture are still applicable even when $V_{SS} < 0$ V, and the conductance parameter remains the same.

A drain current (I_D) of 3.2 mA is measured with $V_{SS} = 0$ V. When V_{SS} is changed to -1 V, the threshold voltage of the MOSFET increases by 0.258 V compared to that with $V_{SS} = 0$ V, and this results in a reduced drain current at 2.8 mA.

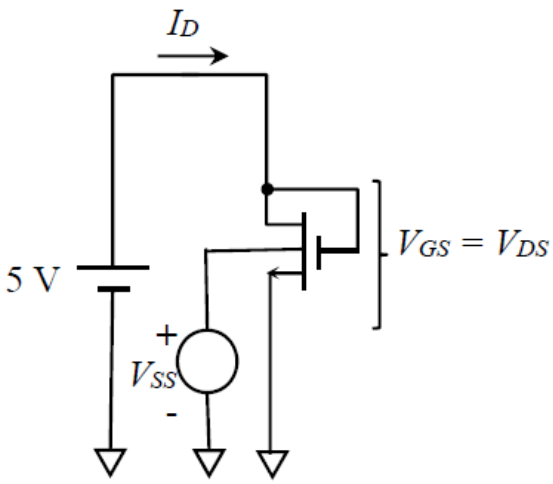


Fig. Q9

(a) When $V_{SS} = -1$ V, does the MOSFET experience body effect? Why?

(b) For both cases with $V_{SS} = 0$ and $V_{SS} = -1$ V, it can be concluded that the gate-to-source voltage, V_{GS}, of the MOSFET is greater than the respective threshold voltage. Explain the reason.

(c) For both cases with $V_{SS} = 0$ and $V_{SS} = -1$ V, which region is the MOSFET operating in? Why?

(d) Calculate the threshold voltage (V_{TH1}) of the MOSFET when $V_{SS} = -1$ V. Neglect channel length modulation.

[Ans: $V_{TH1} = 1.268$ V]

Q9. **Solution:**

(a) Yes, the MOSFET experiences body effect. The source and body terminal are not at the same potential (i.e., $V_{SB} \neq 0$) when V_{SS} = -1 V.

(b) As there is drain current flow for both $V_{SS} = 0$ and V_{SS} = -1 V, meaning a channel exists for both cases, which in turn means V_{GS} > threshold voltage for both cases.

(c) As the gate and drain are shorted together, $V_{DG} = 0$ V and $V_{GS} = V_{DS}$

- $V_{DS} = V_{GS} > (V_{GS} - V_{TH})$, since V_{TH} is positive for n-channel MOSFET.
- V_{GS} > threshold voltage for both $V_{SS} = 0$ and V_{SS} = -1 (From part (b)).

So, MOSFET is operating in the saturation region for both $V_{SS} = 0$ and V_{SS} = -1.

(d) As MOSFET operates in the saturation region for both $V_{SS} = 0$ and V_{SS} = -1, and neglecting channel length modulation effect -

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

- When $V_{SS} = 0$ V, I_D = 3.2 mA -

$$3.2\text{m} = K_n (5 - V_{TH0})^2, \quad (1)$$

where V_{TH0} is the threshold voltage at $V_{SS} = 0$ V.

- When V_{SS} = -1 V, I_D = 2.8 mA –

$$2.8\text{m} = K_n [5 - V_{TH1}]^2 = K_n [5 - (V_{TH0} + 0.258)]^2, \quad (2)$$

where V_{TH1} is the threshold voltage at $V_{SS} = 0$ V,

Dividing Eq. (2) by Eq. (1) and solving,

$$(4.742 - V_{TH0}) / (5 - V_{TH0}) = \pm 0.9354$$

Therefore, V_{TH0} = 1.01 V (or) 4.87 V

When V_{SS} = -1 V, threshold voltage, $V_{TH1} = V_{TH0} + 0.258$ = 1.268 V (or) 5.128 V

Threshold voltage, V_{TH1} = 5.128 V is not valid as the MOSFET will be in cut-off region since V_{GS} = 5 V < V_{TH1}.

Hence, when V_{SS} = -1 V, V_{TH1} = 1.268 V