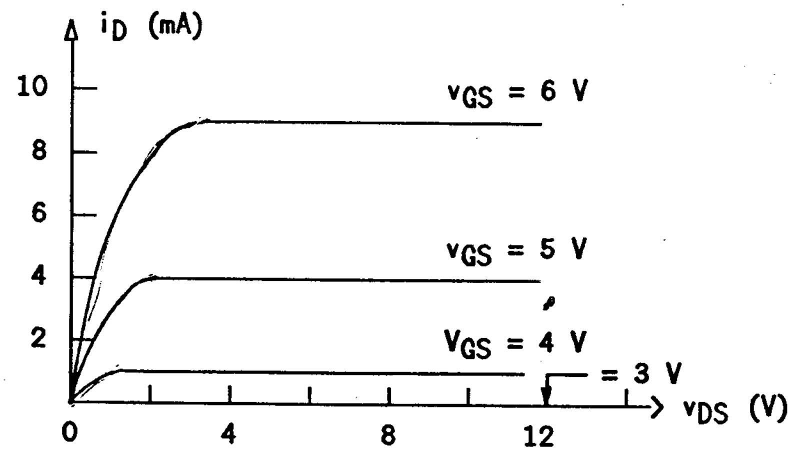
Chapter 5
Three-Terminal Devices

5.1 An n-channel MOSFET has the set of v-i characteristics shown below.



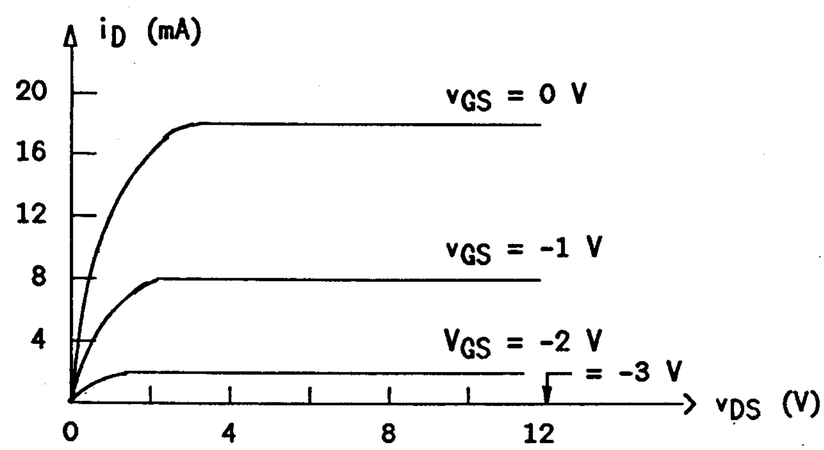
a) Is this an enhancement-mode or depletion-mode device?

b) What are the values of K and V_{TR}?

c) If v_{GS} = 5.5 V, what will the value of i_D be in the constant-current region?

d) What must be the minimum value of v_{DS} for constant-current region operation at v_{GS} = 5.5 V?

5.2 An n-channel MOSFET has the set of v-i characteristics shown below.



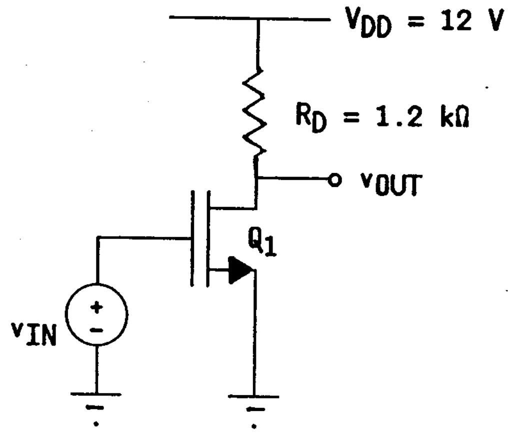
a) Is this an enhancement-mode or depletion-mode device?

b) What are the values of K and V_{TR}?

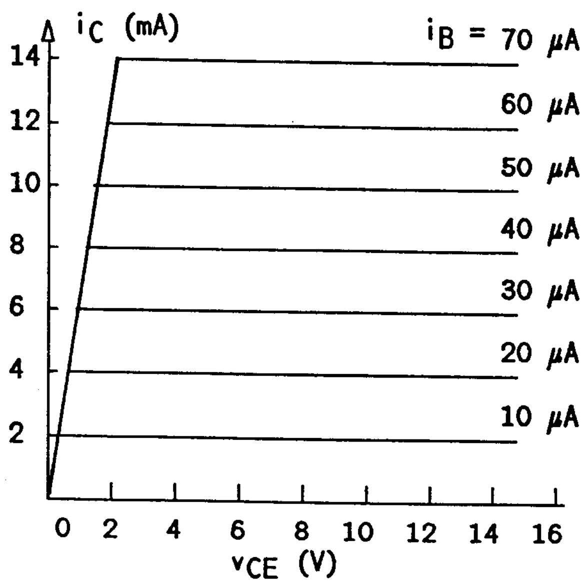
c) If the alternative representation is used for this FET, what are the values of I_{DSS} and V_P?

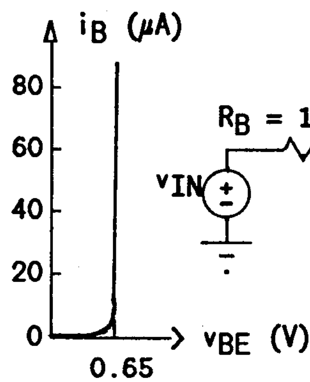
5.3 An n-channel enhancement-mode MOSFET has a threshold voltage of 0.8 V. At one operating point in the constant-current region, i_D = 2.5 mA when v_{GS} = 4 V. What will the value of i_D become if v_{GS} is increased to 7 V and the MOSFET continues to operate in the constant current region ?

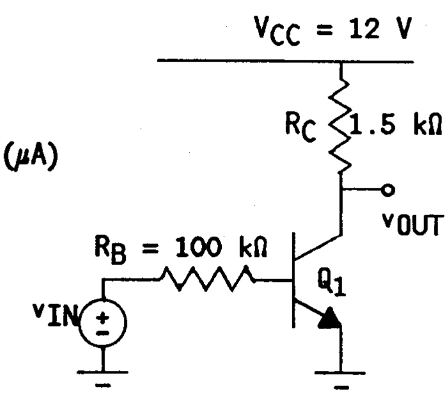
5.4 The MOSFET of Problem 5.1 is connected to the circuit shown below. Using graphical techniques, plot the v_{IN}-v_{OUT} transfer characteristic over the range -2 V < v_{IN} < 6 V.



5.5 A BJT with the indicated v-i characteristics is connected to the circuit shown. Using graphical techniques, plot the v_{IN}-v_{OUT} transfer characteristic.







5.6 a) An enhancement-mode MOSFET has parameters $V_{TR} = 1.5$ V and $K = 1$ mA/V^2. Is this transistor an n-channel or a p-channel device?

b) If $v_{GS} = 4$ V, how large must v_{DS} be for constant-current operation? What current flows in this case?

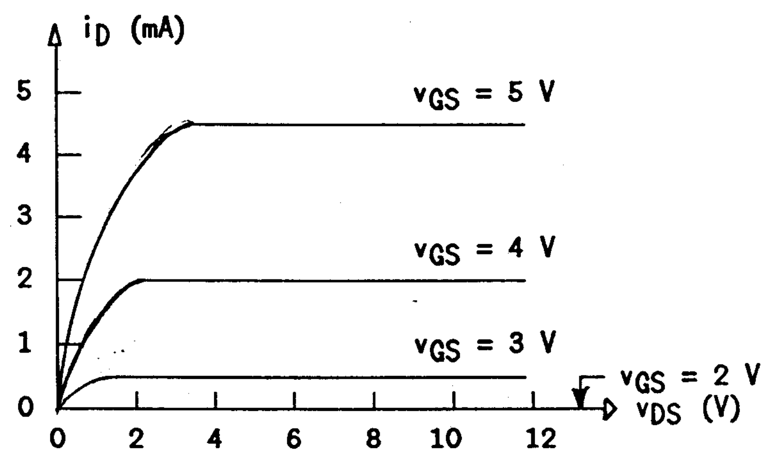
c) Repeat part b) for $v_{GS} = 2$ V; 5 V.

5.7 a) An n-channel MOSFET has parameters $V_{TR} = -1$ V and $K = 1$ mA/V^2. Is this transistor an enhancement-mode or depletion-mode device?

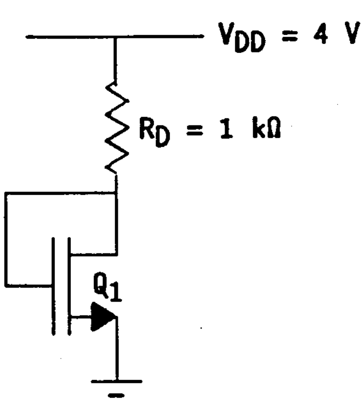
b) What is the minimum v_{DS} that will ensure constant-current operation when $v_{GS} = 1$ V? What current flows in this case?

c) Repeat part b) for $v_{GS} = 0$; 10 V.

5.8 An n-channel MOSFET has the set of v-i characteristics shown below. Plot i_D versus v_{GS} in the constant-current region.



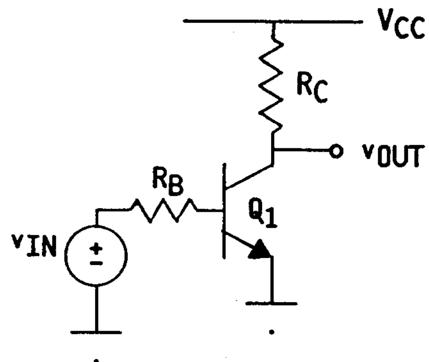
5.9 Use the plot of Prob. 5.8 to find the current in the circuit shown below.



5.10 A BJT with V_f = 0.7 V and V_{sat} ≃ 0.3 V is connected to the circuit shown below. As v_{IN} increases, v_{OUT} will decrease.

a) How small can v_{OUT} become before the BJT leaves the constant current region?

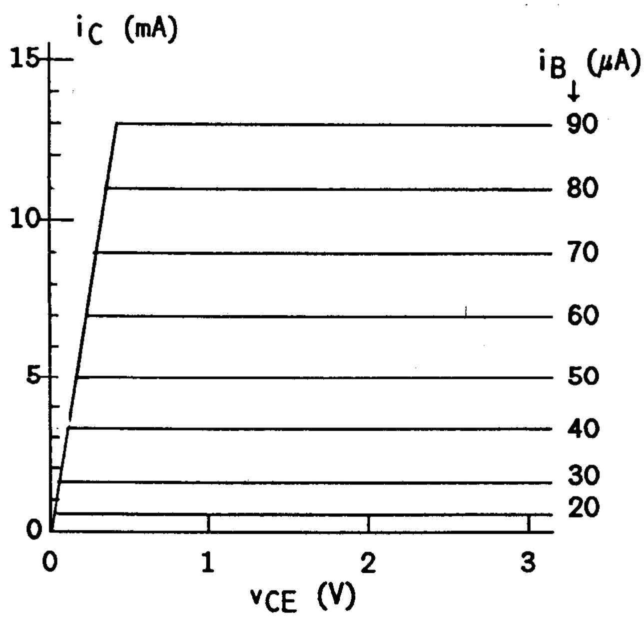
b) What will be the value of the collector-base voltage v_{CB} when v_{OUT} reaches this transition value?



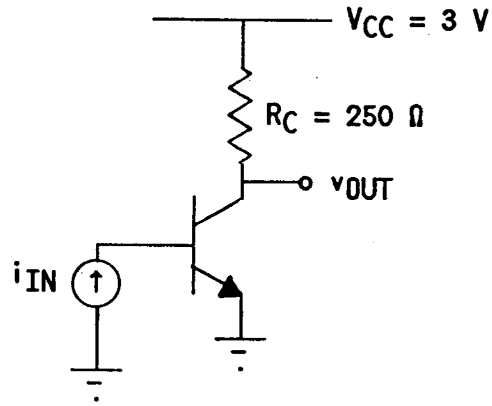
5.11 A non-ideal BJT has the set of v-i characteristics shown below.

a) Plot i_C as a function of i_B in the constant current region

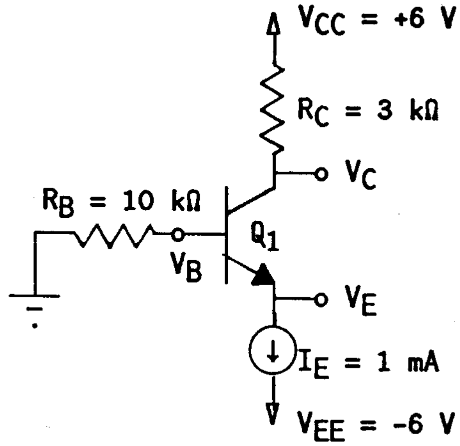
b) Plot β_F as a function of i_C.



5.12 The BJT of Prob. 5.11 is installed in the circuit shown below. Use the graphical technique to plot v_{OUT} versus i_{IN}.



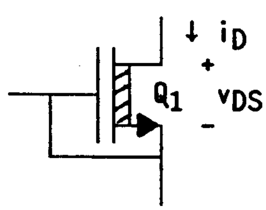
5.13 The BJT in the following circuit has a β_F of 100. Find V_B, V_C, and V_E.



5.14 An n-channel depletion mode MOSFET is connected as shown.

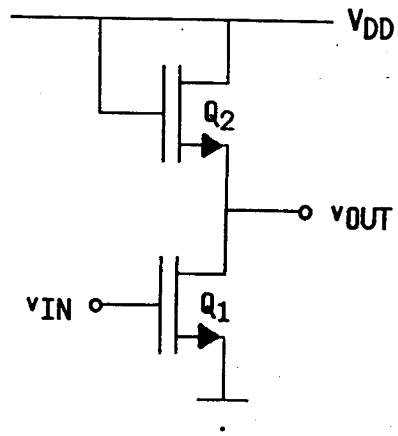
a) Show that Q_1 will never operate in cutoff.

b) For what values of v_{DS} will Q_1 operate in the constant-current region? Find a relationship between v_{DS} and i_D over this region.



5.15 Consider the depletion-mode MOSFET shown above. If K = 0.5 mA/V^2 and V_{TR} = -2 V, find the value of i_D in the constant-current region.

5.16 Two enhancement-mode MOSFETs are connected in the configuration shown below:

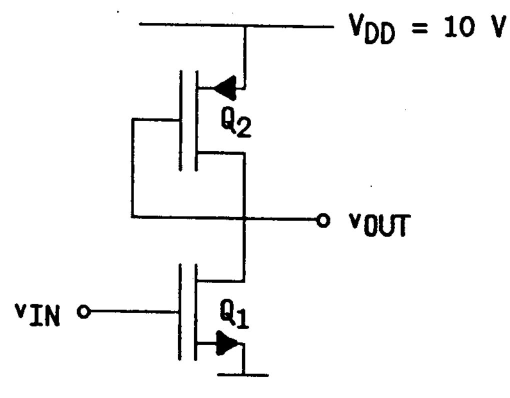


a) Prove that Q_2 always operates in the constant-current region.

b) Show that the v_{IN}-v_{OUT} transfer characteristic is a straight line as long as Q_1 operates in the constant current region.

c) Over what range of v_{IN} values will Q_1 operate in the constant-current region?

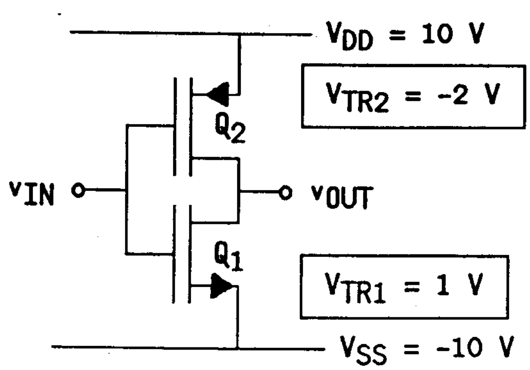
5.17 Repeat Prob. 5.16 for the CMOS circuit shown below.



5.18 The complementary MOSFET (CMOS) circuit shown below contains both an n-channel and a p-channel device.

a) Over what ranges of v_{IN} will Q_1 and Q_2 operate out of cutoff?

b) Over what ranges of v_{OUT} will Q_1 and Q_2 operate in the constant current region?



Solutions

Chapter 5

5.1 a) The v_{GS} = 3 V curve lies on the v_{DS}-axis, hence V_{TR} = 3 V. An n-channel MOSFET with a positive value of V_{TR} is an enhancement-mode device.

b) As noted in part a), V_{TR} = 3 V. The value of K can be found by evaluating the v-i characteristics at one or more test points. On the constant-current portion of the v_{GS} = 5 V curve, for example, i_D = 4 mA. The constant-current v-i relation is $i_D = K(v_{GS} - V_{TR})^2$, hence K =

$$\frac{i_D}{(v_{GS} - V_{TR})^2} = \frac{4 \text{ mA}}{(5V - 3V)^2} = 1 \text{ mA/V}^2$$

Similarly, at v_{GS} = 6 V, K =

$$\frac{i_D}{(v_{GS} - V_{TR})^2} = \frac{9 \text{ mA}}{(6V - 3V)^2} = 1 \text{ mA/V}^2$$

c) For the computed value of K, i_D = $(1\text{mA/V}^2)(5.5 \text{ V} - 3 \text{ V})^2 = 6.25$ mA in the constant-current region.

d) The condition for constant-current operation is $v_{DS} > v_{GS} - V_{TR}$. For v_{GS} = 5.5 V, v_{DS} must be greater than 5.5 V - 3 V = 2.5 V.

5.2 a) The v_{GS} = -3 V curve lies on the v_{DS}-axis, hence V_{TR} = -3 V. An n-channel MOSFET with a negative value of V_{TR} is a depletion-mode device.

b) As noted in part b), V_{TR} = 3 V. The value of K can be found by evaluating the v-i characteristics at one or more test points. On the constant-current portion of the v_{GS} = 0 curve, for example, i_D = 18 mA. The constant-current v-i relation is $i_D = K(v_{GS} - V_{TR})^2$, hence K =

$$\frac{i_D}{(v_{GS} - V_{TR})^2} = \frac{18 \text{ mA}}{[0 -(-3V)]^2} = 2 \text{ mA/V}^2$$

Similarly, at v_{GS} = -2 V, i_D will be equal to 2 mA, and

$$K = \frac{2 \text{ mA}}{[-2V - (-3V)]^2} = 2 \text{ mA/V}^2$$

c) I_{DSS} is equal to the value of i_D on the constant-current region portion of the v_{GS} = 0 curve. In this case, I_{DSS} = 18 mA. V_P is equivalent to V_{TR}. For this device, V_P = -3 V.

5.3 In the constant-current region, the MOSFET v-i characteristic is

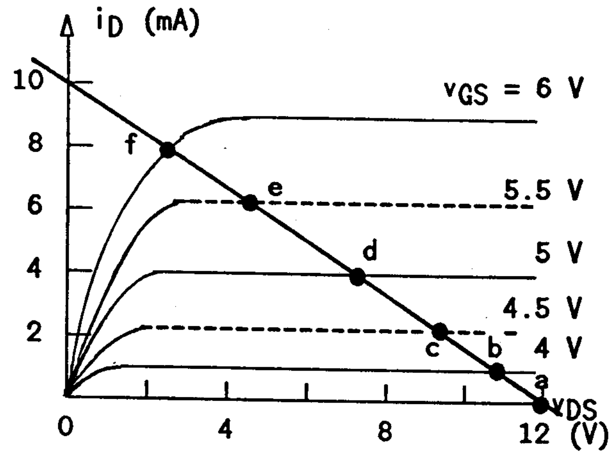
$$i_D = K(v_{GS} - V_{TR})^2$$

From the given data, the value of K can be found:

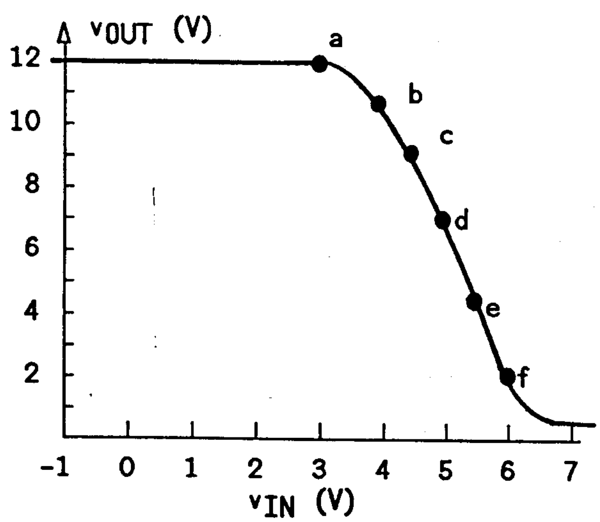
$$K = \frac{i_D}{(v_{GS} - V_{TR})^2} = \frac{2.5 \text{ mA}}{(4 \text{ V} - 0.8 \text{ V})^2}$$

= 0.24 mA/V^2. When v_{GS} = 7 V, i_D becomes $(0.24 \text{ mA/V}^2)(7 \text{ V} - 0.8 \text{ V})^2 \simeq$ 9.4 mA.

5.4 A load line consisting of V_{DD} = 12 V and R_D = 1.2 kΩ (i_{SC} = 10 mA) can be plotted over the device v-i characteristics, as shown below.



The resulting transfer characteristic can be found by plotting the points (a) - (f), as shown below. Note that for $v_{IN} < V_{TR}$ = 3 V, i_D = 0 and v_{OUT} = V_{DD} = 12 V.

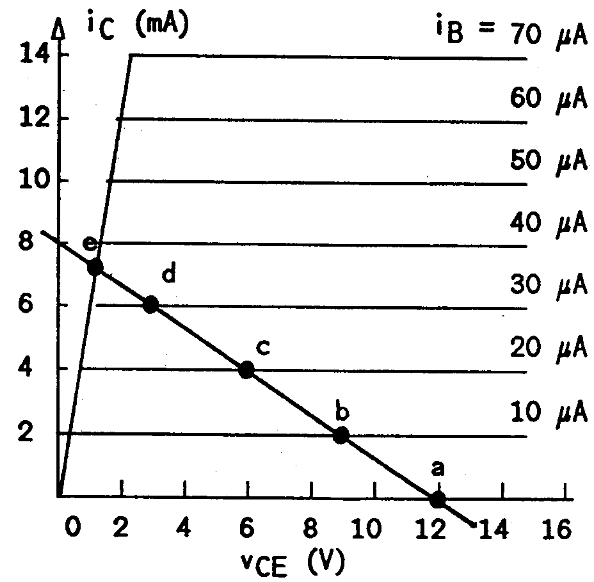


5.5 The load line imposed on the input port is determined by v_{IN} and R_B. Because the i_B-v_{BE} v-i characteristic is so steep, v_{BE} will essentially equal V_f = 0.65 V for all values of v_{IN} above V_f, so that

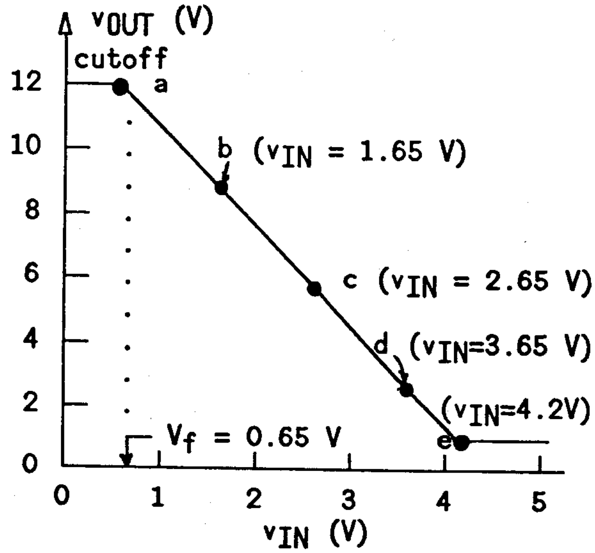
$$i_B = \frac{v_{IN} - V_f}{R_B} = (10\ \mu A/V)\,v_{IN} - 6.5\ \mu A$$

or $\quad v_{IN} = (100\ k\Omega)\,i_B + 0.65\ V$

The load line imposed on the output port of the BJT consists of V_{CC} = 12 V and $i_{SC} = V_{CC}/R_C$ = (12 V)/ (1.5 kΩ) = 8 mA. This load line is plotted below.



The transfer characteristic of the circuit, found by plotting the points (a) - (e), is shown below. For $v_{IN} < V_f$, i_B is zero (cutoff), so that i_C = 0 and $v_{OUT} = V_{CC}$ = 12 V. For $v_{IN} \simeq$ 4.2 V ($i_B \simeq$ 36 μA), the BJT enters saturation, and $v_{OUT} \simeq$ 1 V.



5.6 a) An enhancement-mode MOSFET with a positive V_{TR} is an n-channel device.

b) The condition for constant current region operation is $v_{DS} > v_{GS} - V_{TR}$. For $v_{GS} = 4$ V and $V_{TR} = 1.5$ V, v_{DS} must exceed 4 V - 1.5 V = 2.5 V. For $v_{GS} = 4$ V in the constant current region, $i_D = K(v_{GS} - V_{TR})^2 = (1 \text{ mA/V}^2)(4 \text{ V} - 1.5 \text{ V})^2 = 6.25$ mA.

c) Similarly, $v_{DS} > 0.5$ V; 3.5 V. $i_D = 0.25$ mA; 12.25 mA.

5.7 a) An n-channel MOSFET with a negative V_{TR} is a depletion-mode device.

b) The condition for constant-current region operation is $v_{DS} > v_{GS} - V_{TR}$. For $v_{GS} = 1$ V and $V_{TR} = -1$ V, v_{DS} must exceed [1 V - (-1 V)] = 2 V. For $v_{GS} = 1$ V in the constant-current region, $i_D = K(v_{GS} - V_{TR})^2 = (1 \text{ mA/V}^2)[1 \text{ V} - (-1 \text{ V})]^2 = 4$ mA.

c) Similarly, $v_{DS} > 1$ V; 11 V. $i_D = 1$ mA; 121 mA (large).

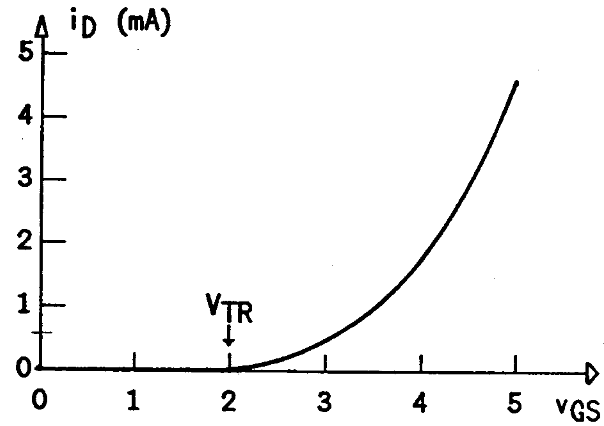
5.8 In the constant-current region, i_D varies as the square of the excess gate voltage $v_{GS} - V_{TR}$. For the v-i characteristics shown, V_{TR} is equal to 2 V. Here are two representative points on the i_D-v_{GS} curve:

$$i_D = 2 \text{ mA at } v_{GS} = 4 \text{ V}$$
$$i_D = 4.5 \text{ mA at } v_{GS} = 5 \text{ V}$$

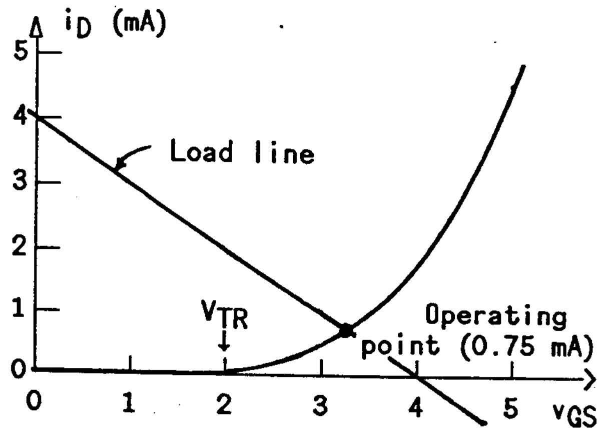
From either of these two representative points,

$$K = \frac{i_D}{(v_{GS} - V_{TR})^2} = 0.5 \text{ mA/V}^2$$

A plot of i_D versus v_{GS} for the complete range of v_{GS} is shown below.



5.9 To find the current i_D in the indicated circuit, plot the load line imposed by V_{DD} and R_D on the v_{DS}-i_D v-i characteristic of Q_1. The v_{GS}-i_D plot found in Prob. 5.8 can be used because the gate of Q_1 is connected to its drain, so that $v_{GS} = v_{DS}$. In essence, Q_1 functions as a two-terminal square-law device. From the plot shown, $i_D \simeq 0.75$ mA; $v_{GS} \simeq 3.2$ V.



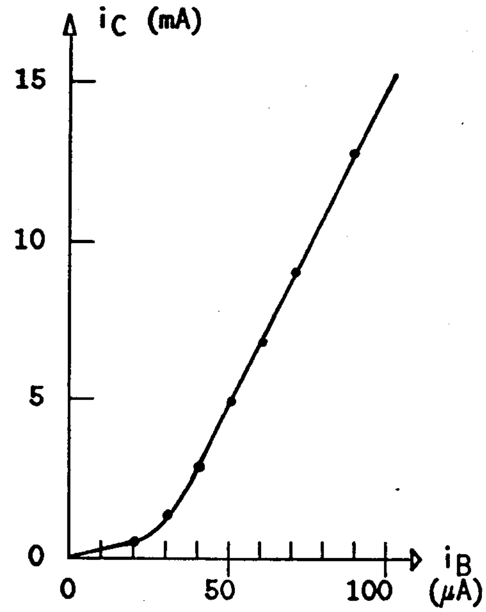
5.10 a) When $i_B > 0$, the BJT will operate in the constant-current region for $v_{CE} > V_{sat}$, where v_{CE} is identical to v_{OUT}. The latter voltage is measured relative to ground. The BJT will thus operate in the constant current region for $v_{OUT} > V_{sat} = 0.3$ V.

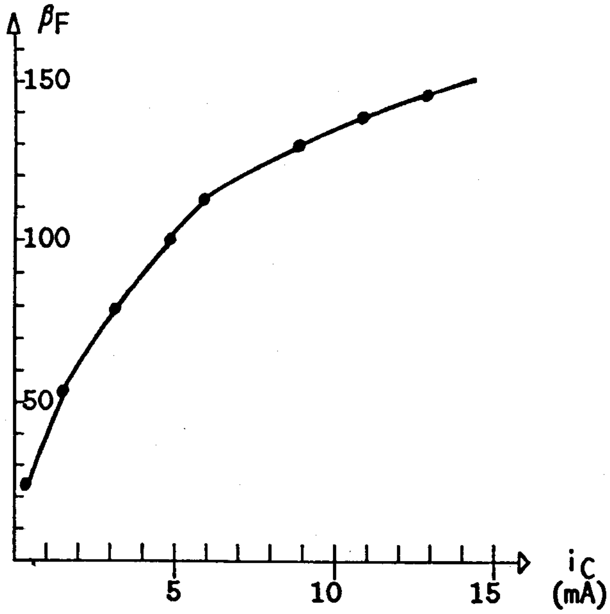
b) When $v_{IN} > V_f$, current will flow into the base of the BJT, so that $v_{BE} = V_f$. Since the emitter is grounded, the voltage to ground at the base of the BJT will be fixed at $V_f \simeq 0.7$ V for all values of $v_{IN} > V_f$. This statement assumes the v-i characteristic of the BJT base-emitter port to be so steep that $v_{BE} \simeq V_f$ whenever $i_B > 0$. When the BJT leaves the constant current region, the collector voltage v_C (to ground), which is identical to v_{OUT}, will equal V_{sat}. Thus v_{CB} will equal $v_C - v_B = V_{sat} - V_f = 0.3\text{ V} - 0.7\text{ V} = -0.4$ V. Note that v_{CB} is negative when the BJT leaves the constant current region.

5.11 a) Since the BJT v-i characteristics are horizontal in the constant current region, the simplified plot of i_C versus i_B can be made at any representative value of v_{CE}. A table of i_B and i_C values, as obtained from the graph, is given below. The value of β_F is found from the ratio i_C/i_B.

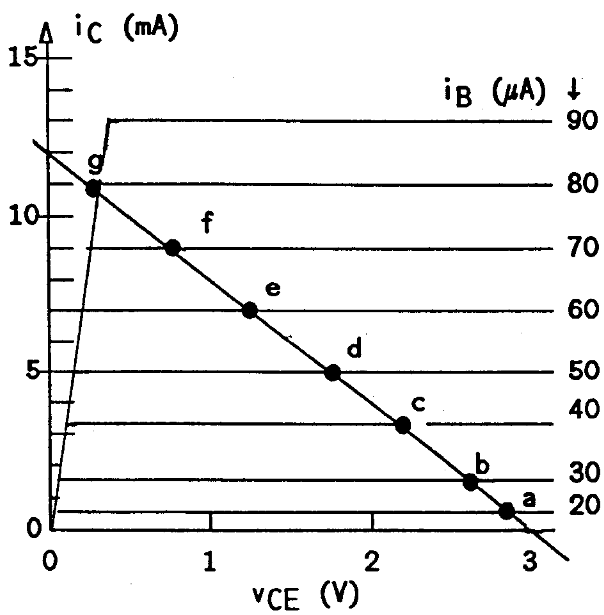
i_B(μA)	i_C(mA)	β_F	i_B(μA)	i_C(mA)	β_F
20	0.5	25	60	7	117
30	1.6	53	70	9	129
40	3.2	80	80	11	138
50	5	100	90	13	144

Here is a plot of i_C versus i_B; a plot of β_F versus i_C follows:

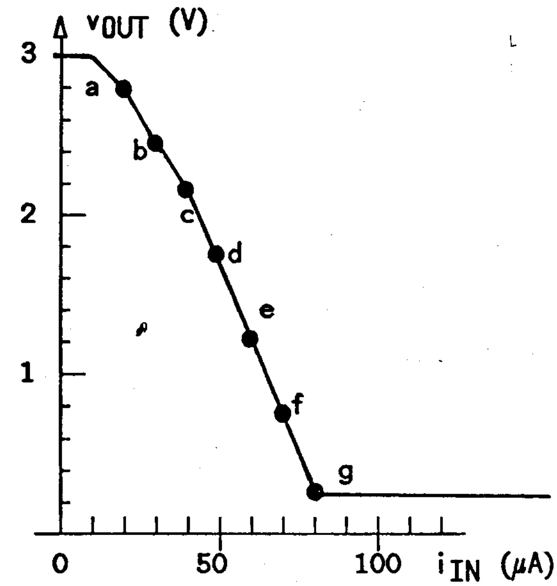




5.12 The output port of the BJT is connected to a Thevenin circuit consisting of V_{CC} = 3 V and R_C = 250 Ω. The load line corresponding to these element values [v_{OC} = 3 V; i_{SC} = (3 V)/(250 Ω) = 12 mA] can be superimposed over the BJT v-i characteristics:



The base current i_B corresponds to the input current i_{IN}. The points of intersection of the load line with the various BJT v-i curves can thus be used to plot v_{OUT} versus i_{IN}:



5.13 The emitter current I_E is fixed at the value 1 mA by the independent current source. If Q_1 operates in the constant-current region, the following must be true:

$I_E = I_B + I_C = I_B + \beta_F I_B = (\beta_F + 1) I_B$

For β_F = 100, I_B must thus equal

$$\frac{I_E}{\beta_F + 1} = \frac{1 \text{ mA}}{101} = 9.9\ \mu\text{A}$$

so that, via KVL, $V_B = 0 - I_B R_B =$ $-(9.9\ \mu\text{A})(10\text{k}\Omega) = -0.099\text{ V} \simeq -0.1\text{ V}$

For V_f = 0.7 V, V_E becomes $V_B - V_f = 0.1\text{ V} - 0.7\text{ V} = -0.8$ V.

Finally, V_C becomes $V_{CC} - I_C R_C$, where

$I_C = \beta_F I_B = 100(9.9\mu\text{A}) = 0.99$ mA

$\Longrightarrow V_C = 6\text{V} - (0.99\text{mA})(3\text{k}\Omega) = 3.03$ V

5.14 a) An n-channel depletion-mode MOSFET has a negative threshold voltage. The device is connected so that $v_{GS} = 0$, hence the conduction condition $v_{GS} > V_{TR}$ is always met.

b) Constant-current region operation requires that v_{DS} be larger than $v_{GS} - V_{TR}$. When $v_{GS} = 0$, this condition reduces to $v_{DS} > -V_{TR}$. As long as v_{DS} is large enough, i_D will be constant and equal to KV_{TR}^2.

5.15 In the constant current region with $v_{GS} = 0$, $i_D = K(v_{GS} - V_{TR})^2 = KV_{TR}^2$. For the parameters given,

$$i_D = (0.5 \text{ mA/V}^2)(2 \text{ V})^2 = 2 \text{ mA}.$$

5.16 a) The condition for constant-current region operation of an n-channel MOSFET is $v_{DS} > v_{GS} - V_{TR}$. In the circuit shown, Q_2 is connected in such a way that $v_{DS2} = v_{GS2}$. Thus for Q_2, the constant-current region condition becomes

$$v_{GS2} > v_{GS2} - V_{TR2}$$

For an enhancement-mode, n-channel MOSFET, V_{TR} is a positive voltage, hence the above constant-current region condition is met for all values of v_{GS2}.

b) The current i_D through both devices is the same, hence if Q_1 operates in the constant current region, the following condition must be met:

$$K_1(v_{GS1} - V_{TR1})^2 = K_2(v_{GS2} - V_{TR2})^2$$

In this case, $v_{GS1} = v_{IN}$ and $v_{GS2} = V_{DD} - v_{OUT}$. Thus the above becomes

$$K_1(v_{IN} - V_{TR1})^2 = K_2(V_{DD} - v_{OUT} - V_{TR2})^2$$

Solving for v_{OUT} as a function of v_{IN} results in

$$v_{OUT} = V_{DD} - V_{TR2} - \sqrt{\frac{K_1}{K_2}}\,(v_{IN} - V_{TR1})$$

or

$$v_{OUT} = -\sqrt{\frac{K_1}{K_2}}v_{IN} + \sqrt{\frac{K_1}{K_2}}V_{TR1} - V_{TR2} + V_{DD}$$

The terms on the right containing V_{TR1}, V_{TR2}, and V_{DD} are constant, hence the graphical plot of v_{OUT} versus v_{IN} will be a straight line with constant slope

$$\frac{dv_{OUT}}{dv_{IN}} = -\sqrt{\frac{K_1}{K_2}}$$

c) Q_1 will operate in the constant-current region as long as

$$v_{DS1} > v_{GS1} - V_{TR1},$$

i.e.

$$v_{OUT} > v_{IN} - V_{TR1}$$

or

$$v_{IN} < v_{OUT} + V_{TR1}$$

In light of the above v_{IN}–v_{OUT} relation, this condition becomes $v_{IN} <$

$$-\sqrt{\frac{K_1}{K_2}}v_{IN} + \left[\sqrt{\frac{K_1}{K_2}} + 1\right]V_{TR1} - V_{TR2} + V_{DD}$$

or

$$v_{IN} < \frac{(\sqrt{K_1/K_2} + 1)V_{TR1} - V_{TR2} + V_{DD}}{\sqrt{K_1/K_2} + 1}$$

5.17 a) The condition for constant-current region operation of a p-channel MOSFET is $v_{DS} < v_{GS} - V_{TR}$. In the circuit shown, Q_2 is connected with gate to drain, so that the above condition becomes

$$v_{GS2} < v_{GS2} - V_{TR}$$

For an enhancement-mode p-channel device, V_{TR} is negative, hence the right-hand side of this inequality will always be greater than the left-hand side. The constant-current condition is always met for Q_2.

b) The current through both devices is the same, with $i_{D2} = -i_{D1}$ (the current i_{D2} is defined as positive *into* the drain of Q_2, i.e. "up"). If Q_1 operates in the constant-current region, then

$$K_1(v_{GS1} - V_{TR1})^2 = K_2(-v_{GS2} + V_{TR2})^2$$

where $v_{GS1} = v_{IN}$, V_{TR2} is negative, and $v_{GS2} = v_{OUT} - V_{DD}$. The above equation then becomes

$$K_1(v_{IN} - V_{TR1})^2 = K_2(V_{DD} - v_{OUT} + V_{TR2})^2$$

Solving for v_{OUT} results in

$$v_{OUT} = V_{DD} + V_{TR2} - \sqrt{\frac{K_1}{K_2}}(v_{IN} - V_{TR1})$$

This equation is similar to that derived in Prob. 5.16. It has a constant slope given by

$$\frac{dv_{OUT}}{dv_{IN}} = -\sqrt{\frac{K_1}{K_2}}$$

c) The answer to Prob. 5.16, part c) also applies here if V_{TR2} is replaced with $(-V_{TR2})$.

5.18 a) In each device, operation above cutoff requires that v_{GS} exceed V_{TR}. The source of Q_1 is connected to $V_{SS} = -10$ V, hence the condition $v_{GS1} > V_{TR1} = 1$ V will be met for $v_{IN} > -9$ V. Similarly, the source of Q_2 is connected to $V_{DD} = 10$ V. The p-channel device condition $v_{GS2} < V_{TR2}$ (v_{GS} more negative than V_{TR}) will be met for $v_{IN} < 8$ V.

The range of v_{IN} over which both devices will conduct is thus

$$-9 \text{ V} < v_{IN} < 8 \text{ V}$$

b) Operation of an n-channel device in the constant-current region requires that v_{DS} exceed $v_{GS} - V_{TR}$. This condition will be met in Q_1 for $v_{DS1} > v_{GS1} - V_{TR1}$, or

$$v_{OUT} - V_{SS} > v_{IN} - V_{SS} - V_{TR1}$$

This condition can be simplified to

$$v_{OUT} > v_{IN} - V_{TR1} = v_{IN} - 1 \text{ V}.$$

For the p-channel device Q_2, the constant-current condition becomes

$$v_{DS2} < v_{GS2} - V_{TR2}$$

where v_{DS2}, v_{GS2}, and V_{TR2} are all negative voltages. With the source of Q_2 connected to V_{DD}, this condition becomes

$$v_{OUT} - V_{DD} < v_{IN} - V_{DD} - V_{TR2}$$

This condition can be simplified to

$$v_{OUT} < v_{IN} - V_{TR2} = v_{IN} + 2 \text{ V}$$

For a given v_{IN}, the range of v_{OUT} over which both devices will operate in the constant-current region thus becomes $v_{IN} - 1 \text{ V} < v_{OUT} < v_{IN} + 2$ V.
