Analogue Electronics

Xiping Hu

https://hxp.plus/

May 14, 2020

Contents

Chapter 1

Basics of Circuits

1.1 The direction of current and voltage

In complex problems, we can not always know the direction of currents or voltage. The usual solution is to assume a direction, and use it to solve problems. If the solution of current or voltage, is positive, then the position is just what we assumed, and vice versa.

1.2 How to determine whether a component is consuming or providing energy

For resistors, resistors are always consuming energy.

For power sources, if the direction of current is from the positive electrode to the negative electrode, then the power source is consuming energy, and vice versa.

1.3 Eletcronic Components

1.3.1 Resistors

$$U = -IR$$

1.3.2 Power Sources

(Controlled) Voltage Source

$$P = UI$$

The resistance of an ideal voltage source is : 0

Note that an ideal voltage source must not be short-circuited.

(Controlled) Current Source

The current through a current source is only decided by the source itself.

The resistance of an ideal current source is : ∞

Note that an ideal current source must not be open-circuited.

1.4 Kirchhoff's Laws

- branch
- node
- loop

- mesh

1.4.1 Kirchhoff's Current Law

For each node in the circuit, as the node can not accumulate charges, the sum of current is zero.

$$\sum I = 0$$

1.4.2 Kirchhoff's Voltage Law

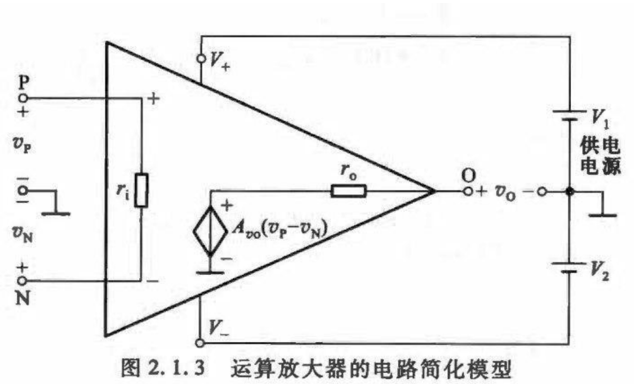
For each loop in circuit, the sum of the voltage in of all branches is zero.

$$\sum U = 0$$

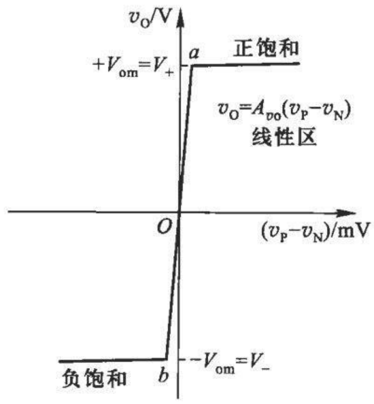
Chapter 2

Operational Amplifier

2.1 Operational Amplifier



(a) the model of an operational amplifier



(b) How the output voltage varies

Figure 2.1

We define r_i as the input impedance, r_o as the output impedance. v_p as the non-inverting input, v_n the inverting input.

Usually, we have $v_p \approx v_n$, $r_i \approx \infty$, $r_o \approx 0$.

Note that the output voltage of a operational amplifier has limits, called **Bandwidth**. When the input voltage exceeds the limits, it outputs the maximum or minimum value.

2.2 Ideal Operational Amplifier

For ideal operational amplifier:

- $v_p = v_n$, $i_i = 0$, $r_i = \infty$
- $r_o = 0$, $v_o = A_{vo}(v_p - v_n)$
- $bandwidth = \infty$

Here is a model which shows all the feature of an ideal operational comparator:

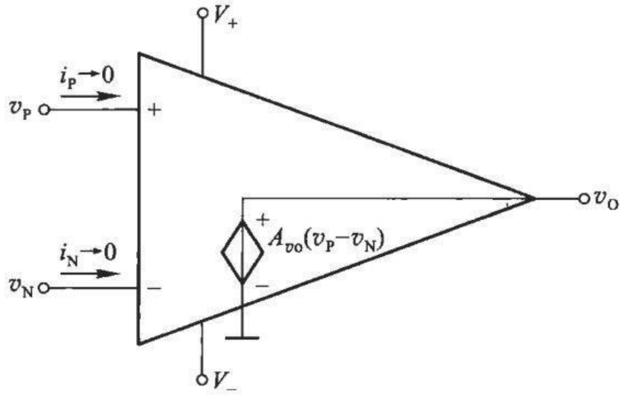


Figure 2.2: An ideal operational amplifier

2.3 Closed-looped Amplifier

Usually operational amplifiers are used with vegetative feedback to ensure its stability. We apply a portion of output voltage to input, reducing the gain of a circuit.

2.3.1 Non-inverting Operational Amplifier

If we connect the inverting input, to the ground, and use the non-inverting input, we get an non-inverting operational amplifier.

The gain of the amplifier is:

$$A_{vo} = \frac{R_2 + R_1}{R_1}$$

The picture below is a non-inverting amplifier.

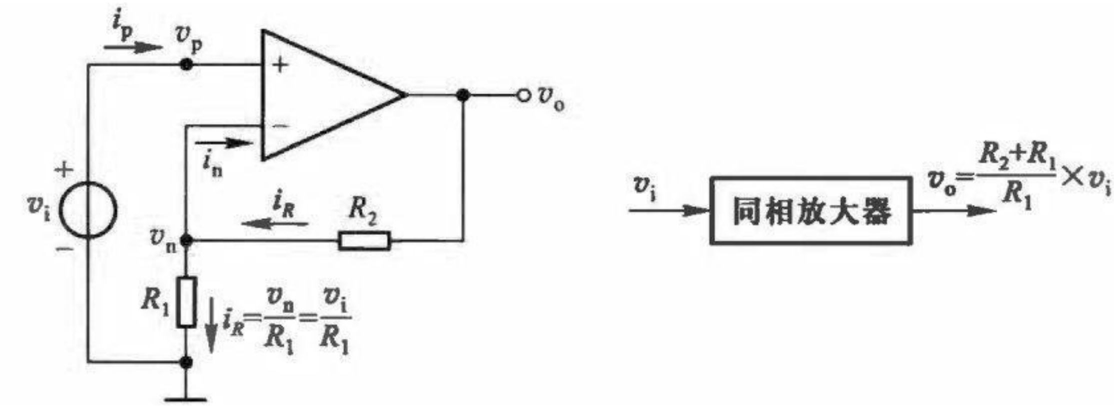


Figure 2.3: An non-inverting amplifier

$$\begin{cases} i_R = \dfrac{v_o - v_n}{R_2} = \dfrac{v_n}{R_1} \\ v_n = v_p = v_i \end{cases}$$

$$\frac{v_o - v_n}{R_2} = \frac{v_i}{R_1}$$

$$A_v = \frac{v_o}{v_i} = \frac{R_1 + R_2}{R_1}$$

Note that when $R_2 \ll R_1$, $A_{vo} = 1$, $v_i = v_o$.

2.3.2 Inverting Operational Amplifier

If we connect the non-inverting input, to the ground, and use the inverting input, we get an inverting operational amplifier.

The gain of this type of amplifier is:

$$A_{vo} = -\frac{R_2}{R_1}$$

The picture below shows as inverting operational amplifier:

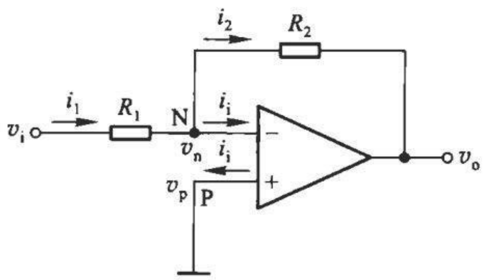


Figure 2.4: An inverting amplifier

$$\begin{cases} \dfrac{v_o - v_n}{R_2} = \dfrac{v_n - v_i}{R_1} \\ v_n = v_p = 0 \end{cases}$$

$$\frac{v_o}{R_2} = \frac{-v_i}{R_1}$$

$$A_v = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

2.4 Applications of operational amplifiers

2.4.1 Subtraction Circuit

An subtraction circuit can calculate the difference of inverting input and non-inverting input.

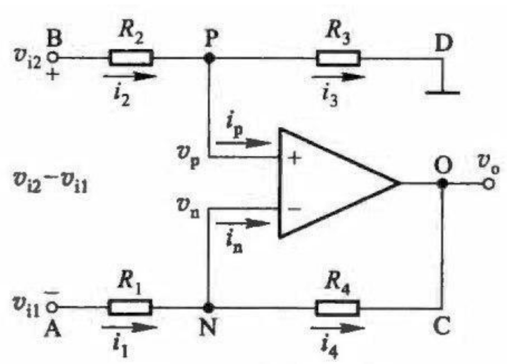


Figure 2.5: A subtraction circuit

$$\begin{cases} \dfrac{v_{i2} - v_p}{R_2} = \dfrac{v_p}{R_3} \\ \dfrac{v_{i1} - v_n}{R_1} = \dfrac{v_n - v_o}{R_4} \end{cases}$$

$$\begin{cases} R_3\left(v_{i2}-v_p\right)=R_2 v_p & \Rightarrow v_p=\dfrac{R_3}{R_2+R_3} v_{i2} \\ R_4\left(v_{i1}-v_n\right)=R_1\left(v_n-v_0\right) & \Rightarrow v_n=\dfrac{R_4 v_{i1}+R_1 v_o}{R_4+R_1} \end{cases}$$

$$\frac{R_3}{R_2+R_3} v_{i2}=\frac{R_4 v_{i1}+R_1 v_o}{R_4+R_1}$$

$$\frac{R_3\left(R_4+R_1\right)}{R_2+R_3} v_{i2}=R_4 v_{i1}+R_1 v_o$$

$\Rightarrow$

$$v_o=\frac{\frac{R_4}{R_1}+1}{\frac{R_2}{R_3}+1} v_{i2}-\frac{R_4}{R_1} v_{i1}=\left(1+\frac{R_4}{R_1}\right) \frac{\frac{R_3}{R_2}}{1+\frac{R_3}{R_2}} v_{i2}-\frac{R_4}{R_1} v_{i1}$$

If $R_4/R_1=R_3/R_2=r$, then

$$v_o=(1+r) \frac{r}{1+r} v_{i2}-r v_{i1}=r\left(v_{i2}-v_{i1}\right)$$

$$A_v=r=\frac{R_4}{R_1}=\frac{R_3}{R_2}$$

2.4.2 Sum Circuit

An sum circuit adds the inverting input and the non-inverting input.

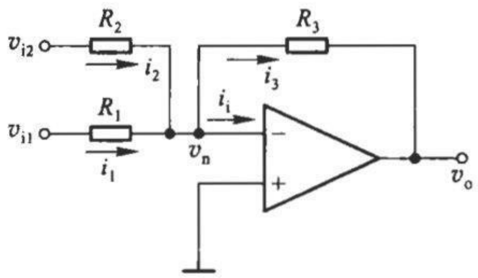


Figure 2.6: Sum Circuit

Similarly, we have

$$\begin{cases} \dfrac{v_{i1}-v_n}{R_1}+\dfrac{v_{i2}-v_n}{R_2}=\dfrac{v_n-v_o}{R_3} \\ v_n=v_p=0 \end{cases}$$

$\Rightarrow$

$$\frac{v_{i1}}{R_1}+\frac{v_{i2}}{R_2}=\frac{-v_o}{R_3}$$

$$v_o=-\left(\frac{R_3}{R_1} v_{i1}+\frac{R_3}{R_2} v_{i2}\right)$$

When we set

$$R_1=R_2=R_3$$

We have

$$v_o=-\left(v_{i1}+v_{i2}\right)$$

2.4.3 Integrating Circuit

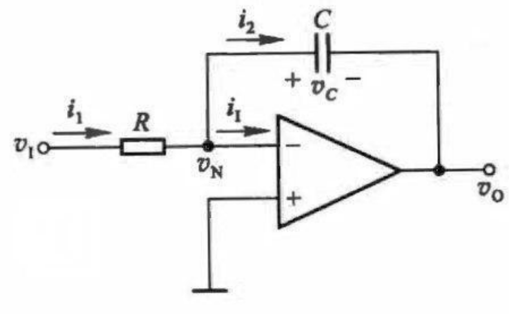


Figure 2.7: integrating circuit

$$C = \frac{Q}{U} \Rightarrow U = \frac{Q}{C} = \frac{1}{C}\int I \,\mathrm{d}t = \frac{1}{C}\int \frac{v_i}{R}\,\mathrm{d}t = \frac{1}{RC}\int v_i \,\mathrm{d}t$$

$$0 - v_o = U$$

$\Rightarrow$

$$v_o = -\frac{1}{RC}\int v_i \,\mathrm{d}t$$

We define

$$\tau = RC$$

Then

$$-v_o = \frac{1}{\tau}\int v_1 \mathrm{d}t$$

2.4.4 Differential Circuit

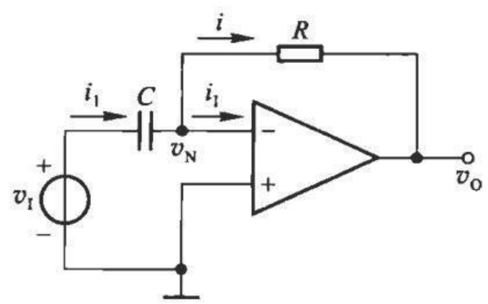


Figure 2.8: differential circuit

$$\begin{cases} i_i = \dfrac{\mathrm{d}Q}{\mathrm{d}t} = C\dfrac{\mathrm{d}v_i}{\mathrm{d}t} \\ i = \dfrac{v_o}{R} \\ i_i = i \end{cases}$$

$\Rightarrow$

$$-v_o = RC\frac{\mathrm{d}v_i}{\mathrm{d}t} = \tau\frac{\mathrm{d}v_i}{\mathrm{d}t}$$

Chapter 3

Diodes

3.1 Semiconductors

3.1.1 Intrinsic Semiconductor

An intrinsic semiconductor, also called as undoped semiconductor, is a pure semiconductor without and significant dopant species present. Two factors are responsible to the current pass through it:

- Excited electrons
- Holes

However, we seldom use intrinsic semiconductors.

3.1.2 Extrinsic Semiconductor

An extrinsic semiconductor is a semiconductor that has been doped, which has more features and provides more charge carriers.

P-type semiconductor

P-type semiconductors are created by doping some electron accepter elements during manufacture. It has more holes, holes are major carriers of the current.

N-type semiconductor

N-type semiconductors are created by doping some electron donor elements during manufacture. It has more electrons, electrons are major carriers of the current.

3.2 P-N Junction and Diode

When we combine the 2 types of extrinsic semiconductor together, we found some interesting features. As p-type semiconductors use holes to transmit currents, n-type semiconductors use electrons to transmit currents, and, to make life easier, we take holes as positive charges. When the two types of semiconductors are put together, at the contact surface, diffusion phenomenon occur.

Some holes traveled into the n-type semiconductor, some electrons traveled into the p-type semiconductor. And after that, an inner electric field formed, which hinders the p-n junction from carrying currents.

To ease the effect above, we need to add some positive voltage at p-type semiconductor, and also add some negative voltage at n-type semiconductor. And if we add negative voltage at n-type semiconductor, positive voltage at p-type semiconductor, the effect will be intensified.

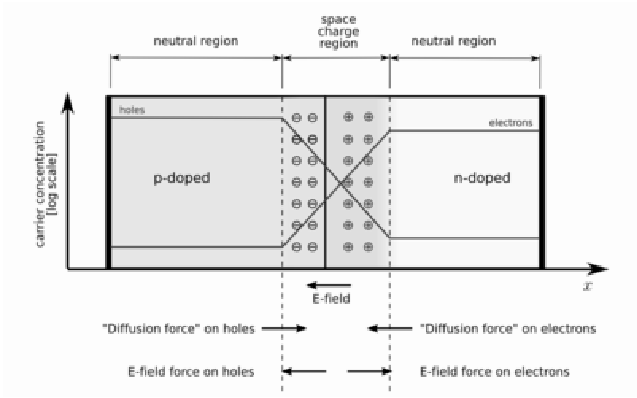


Figure 3.1: PN Junction at equilibrium state

In conclusion, if we add forward voltage (from p to n), the diode acts as a short circuit. If we add reversed voltage, the diode acts like an open circuit. And if the reversed voltage is big enough, it will cause the diode broken-through, and the current flow through it will increase tremendously.

3.2.1 Breakdown of P-N Junction

There are two types of breakdown

- electricity breakdown, which is invertible
- heat breakdown, which cause permanent damage

3.3 Diode modeling

3.3.1 Mathematically idealized diode

Firstly, consider a mathematically idealized diode. In such an ideal diode, if the diode is reverse biased, the current flowing through it is zero. This ideal diode starts conducting at 0 V and for any positive voltage an infinite current flows and the diode acts like a short circuit. The I-V characteristics of an ideal diode are shown below:

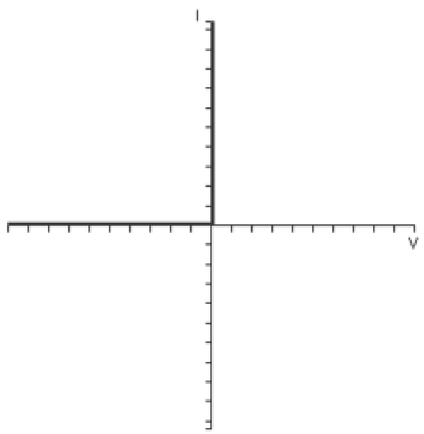
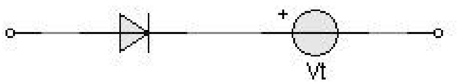


Figure 3.2: I-V characteristic of an ideal diode.

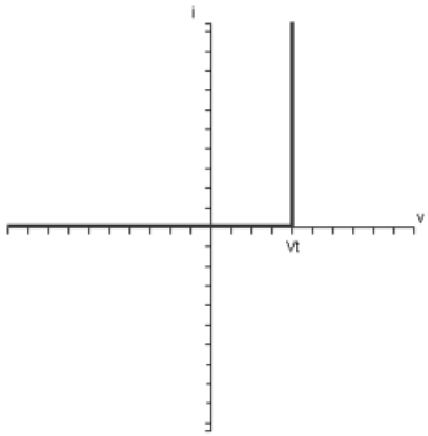
3.3.2 Ideal diode in series with voltage source

Now consider the case when we add a voltage source in series with the diode in the form shown below:

When forward biased, the ideal diode is simply a short circuit and when reverse biased, an open circuit.



(a) Ideal diode with a series voltage source.

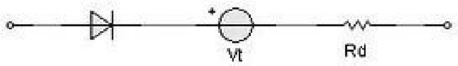


(b) I-V characteristic of an ideal diode with a series voltage source.

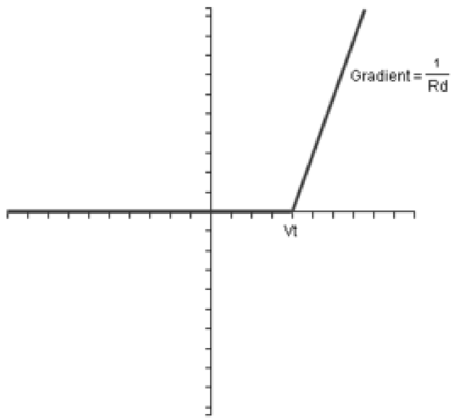
Figure 3.3: Ideal diode in series with voltage source

3.3.3 Diode with voltage source and current-limiting resistor

The last thing needed is a resistor to limit the current, as shown below:



(a) Ideal diode with a series voltage source and resistor.



(b) I-V characteristic of an ideal diode with a series voltage source and resistor.

Figure 3.4: Diode with voltage source and current-limiting resistor

The real diode now can be replaced with the combined ideal diode, voltage source and resistor and the circuit then is modelled using just linear elements. If the sloped-line segment is tangent to the real diode curve at the Q-point, this approximate circuit has the same small-signal circuit at the Q-point as the real diode.

3.3.4 Diode in Small Signal Circuits

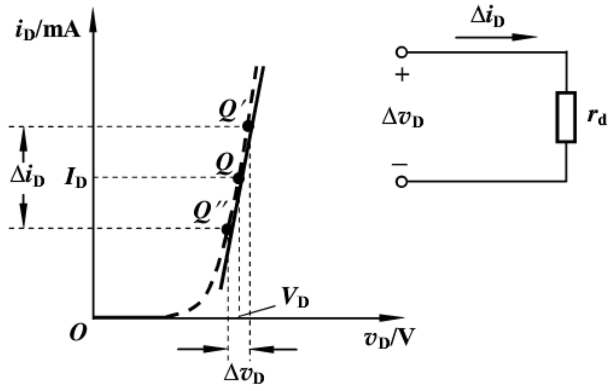


Figure 3.5: I-V Characteristic of Diode in Small Signal

$$r_d = \frac{1}{g_d} = \frac{V_T}{I_{DQ}}$$

Where, in the condition of $T = 300$ K,

$$V_T = 26 \text{ mV}$$

3.4 Applications of Diodes

3.4.1 Rectifier Circuit

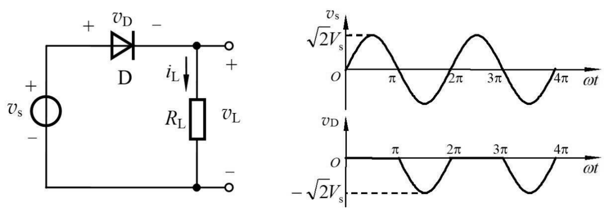


Figure 3.6: A Simple Rectifier Circuit

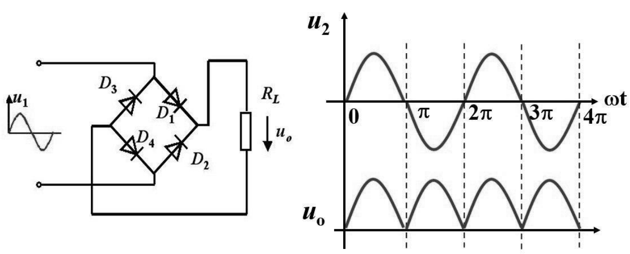


Figure 3.7: A Bridged Rectifier Circuit

3.4.2 Limiting Circuit

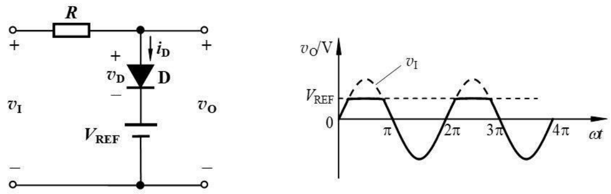


Figure 3.8: A Limiting Circuit

3.4.3 Switching Circuit

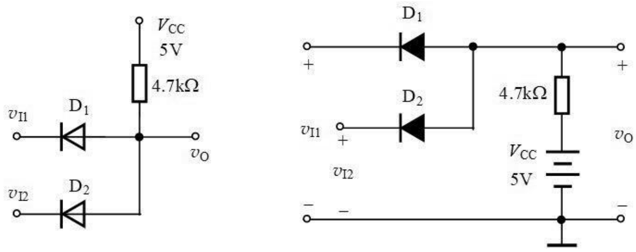


Figure 3.9: A Switching Circuit, $v_o = 5$ V holds only if all the input voltage is 5 V

3.5 Diodes for Special Usage

3.5.1 Zener diode

A Zener diode is manufactured to be broken-through. It is used to stabilize voltages. As we can know from the I-V characteristic of an diode, when the diode is broken-through, change in current only cause little change in voltage.

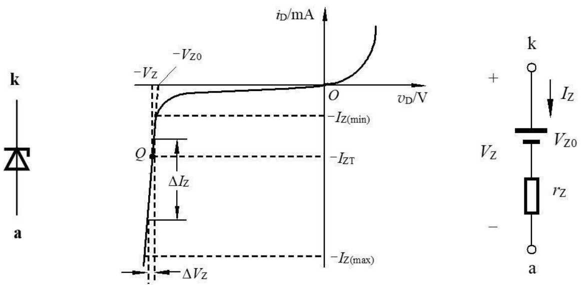


Figure 3.10: Zener Diode's electronic symbol and I-V characteristic

3.5.2 Photodiode

A photodiode is a semiconductor device that converts light into an electrical current. The current is generated when photons are absorbed in the photodiode.

3.5.3 Light-emitting diode

A light-emitting diode (LED) is a semiconductor light source that emits light when current flows through it.

3.5.4 Schottky diode

The Schottky diode (named after the German physicist Walter H. Schottky), also known as Schottky barrier diode or hot-carrier diode, is a semiconductor diode formed by the junction of a semiconductor with a metal. It has a low forward voltage drop and a very fast switching action.

Chapter 4

MOSFET and Amplifying Circuit

4.1 Classification of MOSFET

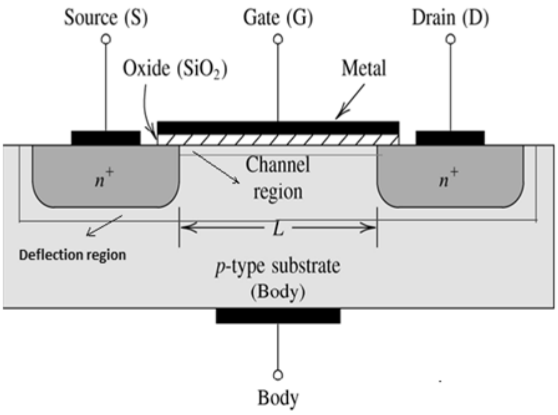
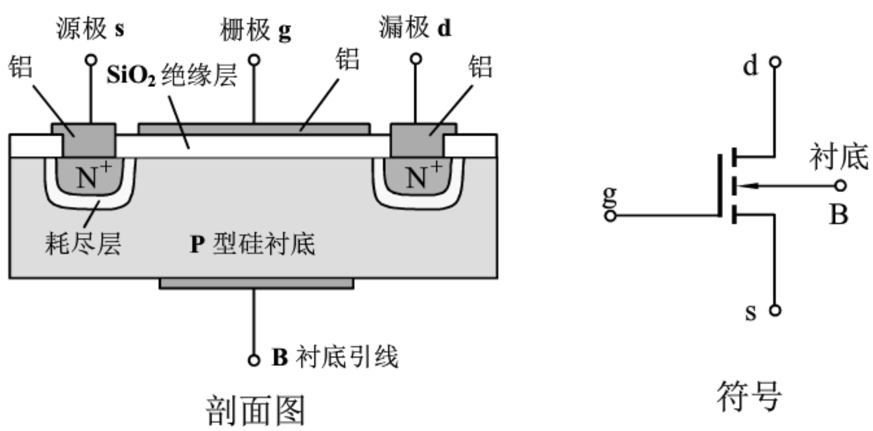


Figure 4.1: MOSFET Block diagram

4.1.1 N-type Enhancement-mode MOSFET



Only when $V_{GS} > V_{TN} > 0$, N-Channel will be formed, MOSFET is conductive. V_{TN} is called the Threshold Voltage.

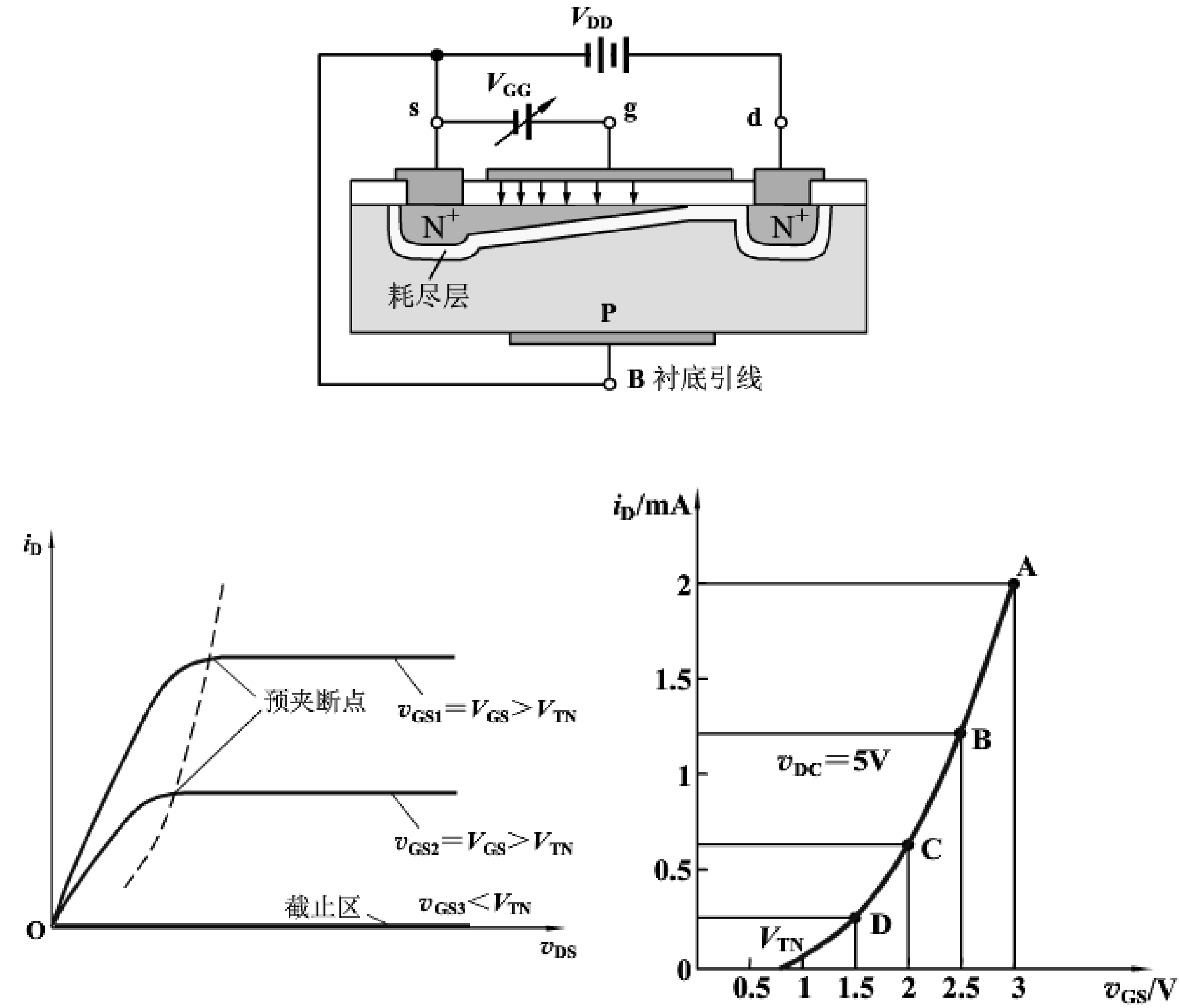
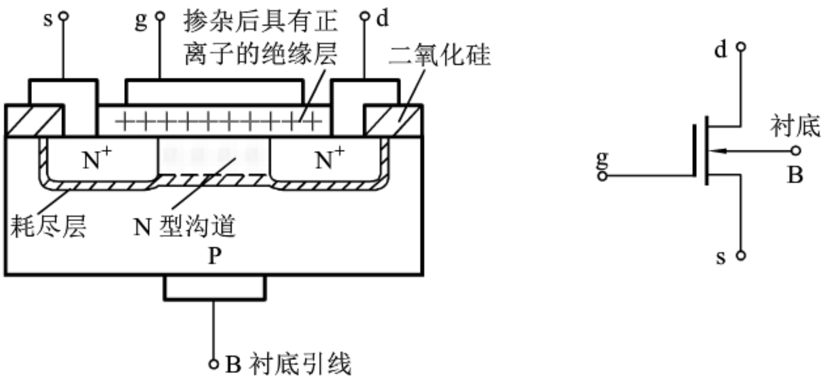


Figure 4.2: The I-V Characteristic of N-type Enhancement-mode MOSFET

4.1.2 N-type Depletion-mode MOSFET

The only difference between Enhancement-mode and Depletion-mode is the charges in oxide, which made $V_{TN} < 0$



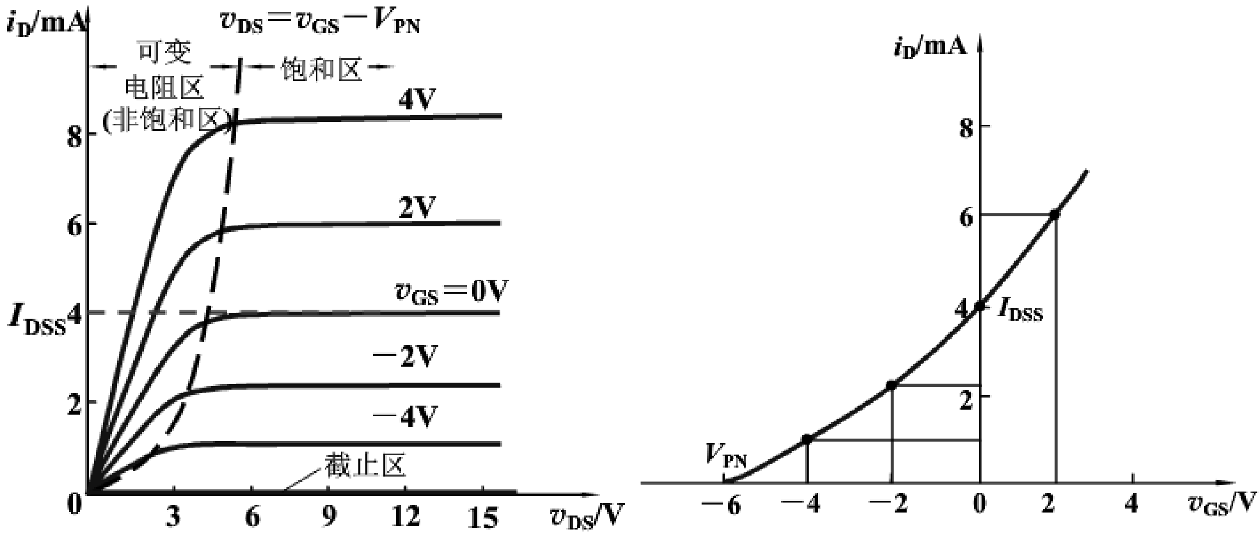
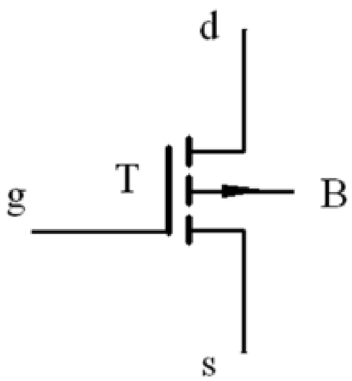
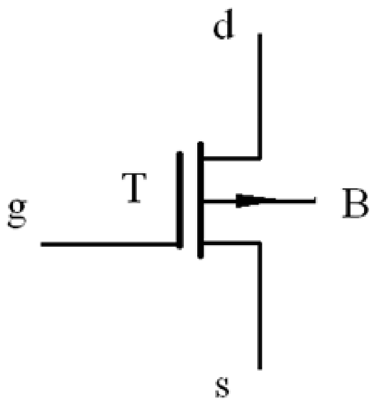


Figure 4.3: The I-V Characteristic of N-type Depletion-mode MOSFET

4.1.3 P-type MOSFET



(a) Enhancement-mode



(b) Depletion-mode

Figure 4.4: The Electronic Symbol of P-type MOSFET

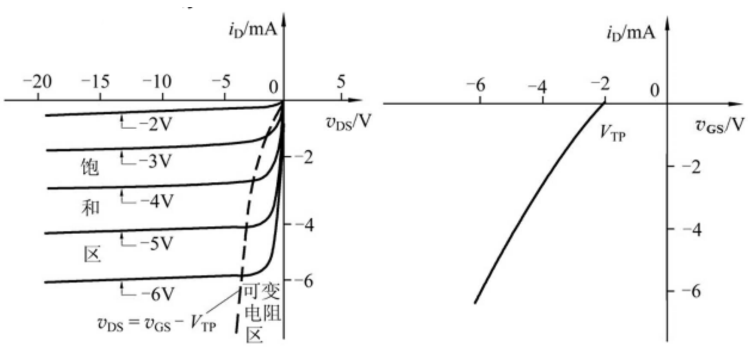
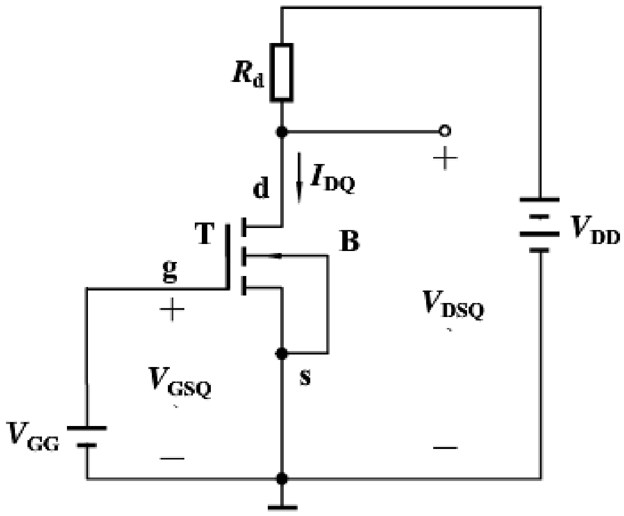


Figure 4.5: The I-V Characteristic of N-type Depletion-mode MOSFET

4.2 Static Working Point



To calculate the static working point of a MOSFET

$$\begin{cases} V_{GSQ} = V_{GG} \\ I_{DQ} = K_n \left(V_{GSQ} - V_{TN}\right)^2 \\ V_{DSQ} = V_{DD} - I_{DQ} R_d \end{cases}$$

Note that $V_{DSQ} > V_{GSQ} - V_{TN}$ must be verified to ensure that MOSFET is working in active mode. Then for small AC signal, the current at drain is

$$i_D = 2K_n \left(V_{GSQ} - V_{TN}\right) v_{GS} = g_m v_{GS}$$

4.3 Early Effect

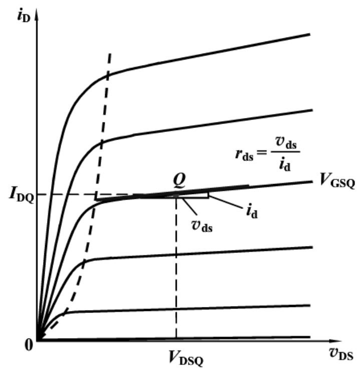


Figure 4.6: MOSFET-Early-Effect

$$i_D = K_n \left(v_{GS} - V_{TN}\right)^2 \left(1 + \lambda v_{DS}\right)$$

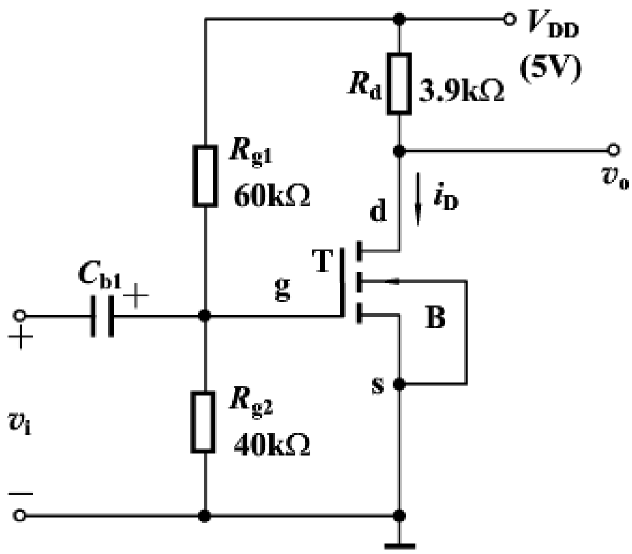
$$r_{ds} = \left.\frac{\partial v_{DS}}{\partial i_D}\right|_{V_{GSQ}} = \frac{1}{\lambda K_n \left(V_{GSQ} - V_{TN}\right)^2} \approx \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$$

Where V_A is called the Early Voltage

$$V_A = \frac{1}{\lambda}$$

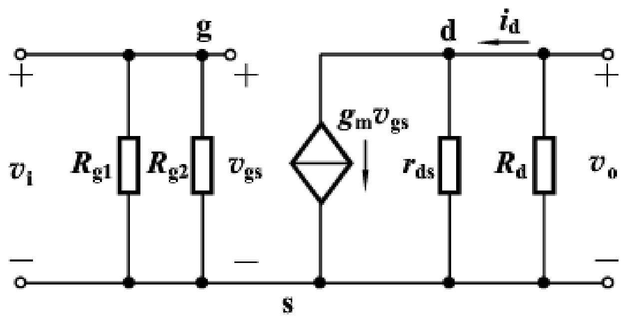
4.4 Three types of Amplifier Circuit

4.4.1 Common Source Amplifier Circuit



$$\begin{cases} V_{GSQ} = \left(\frac{R_{g2}}{R_{g1}+R_{g2}}\right) V_{DD} \\ I_{DQ} = K_n \left(V_{GSQ} - V_{TN}\right)^2 \\ V_{DSQ} = V_{DD} - I_{DQ} R_t I_d \end{cases}$$

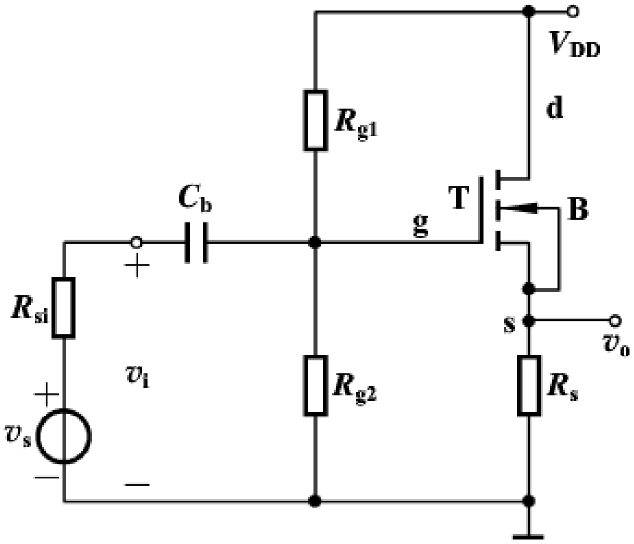
$$g_m = 2K_n \left(V_{GSQ} - V_{TN}\right)$$



$$A_v = -g_m \left(r_{ds} \parallel R_d\right)$$

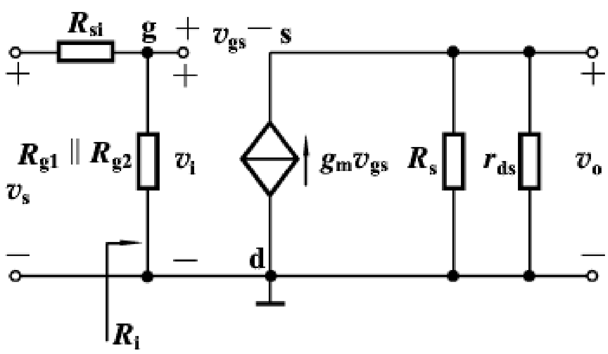
$$R_i = R_{gs1} \parallel R_{gs2}$$
$$R_o = R_d \parallel R_d \approx R_d$$

4.4.2 Common Drain Amplifier Circuit



$$\begin{cases} V_{GSQ} = \dfrac{R_{g2}}{R_{g1}+R_{g2}} \cdot V_{DD} - I_{DQ}R_s \\ I_{DQ} = K_n\left(V_{GSQ}-V_{TN}\right)^2 \\ V_{DSQ} = V_{DD} - I_{DQ}R_s \end{cases}$$

$$g_m = 2K_n\left(V_{GSQ}-V_{TN}\right)$$

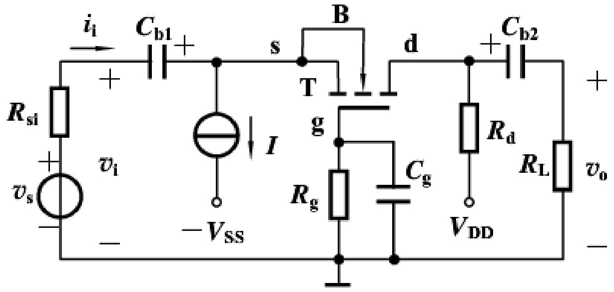


$$A_v = \frac{g_m\left(R_s \parallel r_{ds}\right)}{1+g_m\left(R_s \parallel r_{ds}\right)} \approx 1$$

$$R_i = R_{g1} \parallel R_{g2}$$

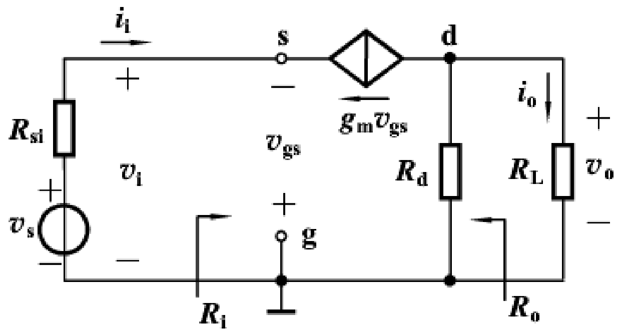
$$R_o = R_s \parallel r_{ds} \parallel \frac{1}{g_m}$$

4.4.3 Common Gate Amplifier Circuit



$$\begin{cases} I_{DQ} = K_n\left(V_{GSQ} - V_{TN}\right)^2 = I \\ V_{DSQ} = V_{DD} - I_{DQ}R_d + V_{GSQ} \end{cases}$$

$$g_m = 2K_n\left(V_{GSQ} - V_{TN}\right)$$



$$A_v = g_m\left(R_d \parallel R_L\right)$$

$$R_i \approx \frac{1}{g_m}$$

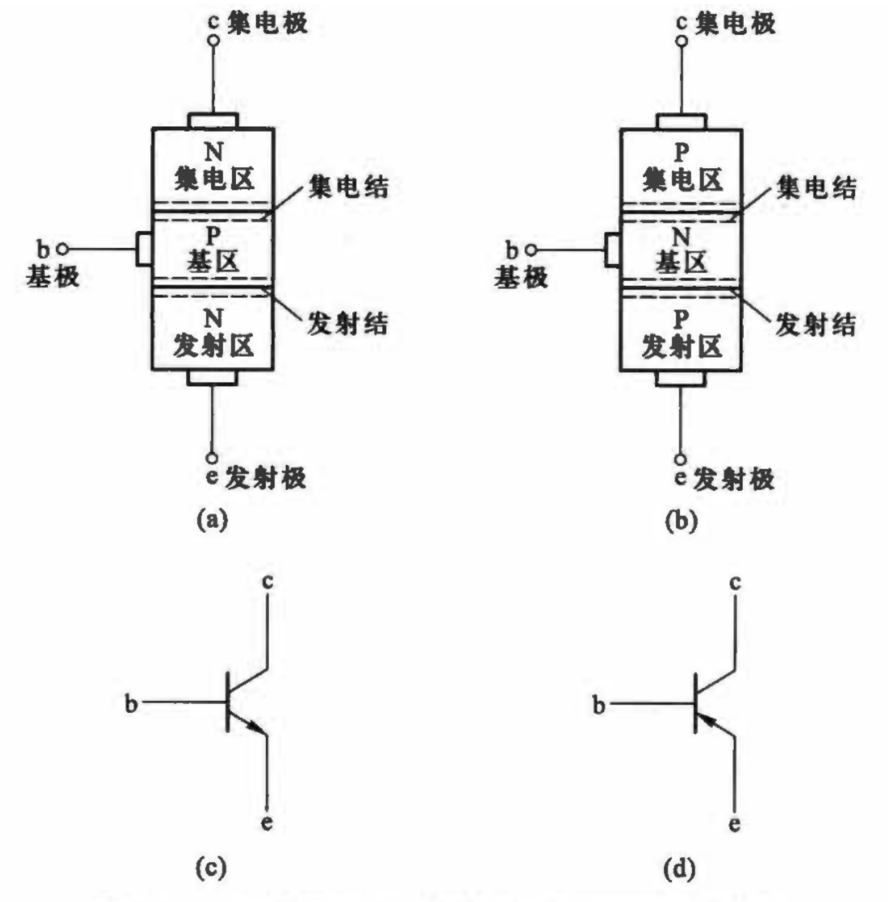
$$R_o \approx R_d$$

Chapter 5

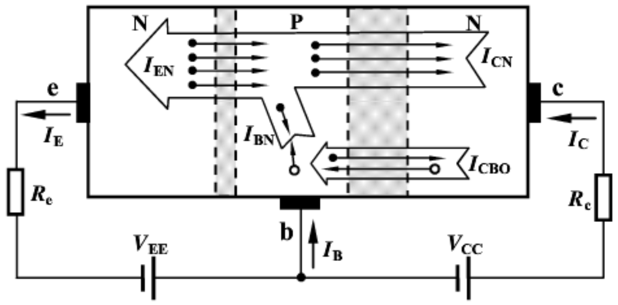
Bipolar Junction Transistor

5.1 Electronic Symbol

The arrow represents the direction of current.



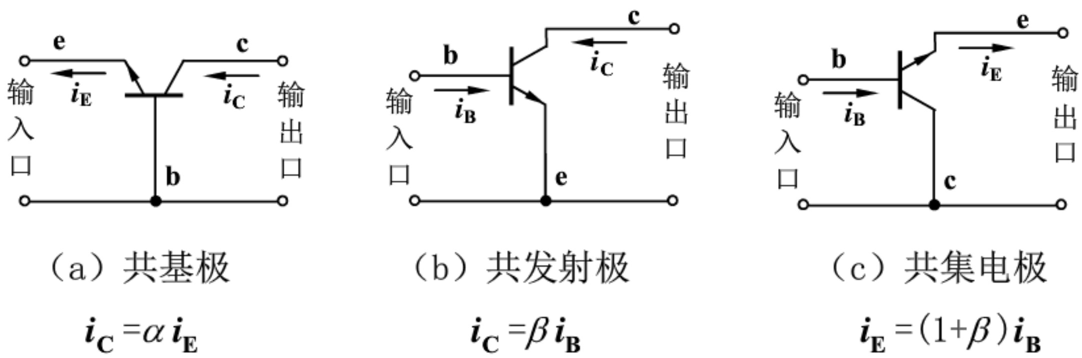
5.2 Control Principle



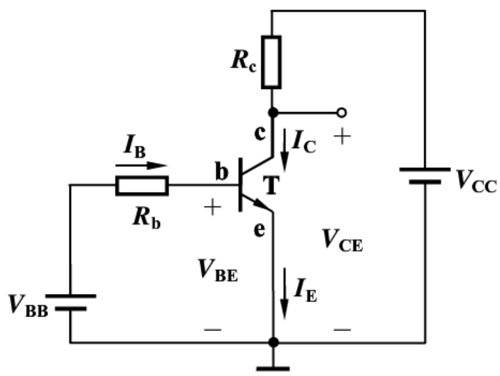
$$\alpha = \frac{I_c}{I_e} \qquad \beta = \frac{I_c}{I_b} \qquad \alpha = \frac{\beta}{1+\beta} \qquad I_e = (1+\beta) I_b$$

$$I_E = I_{ES} \exp\left(V_{BE}/V_T\right) \qquad V_T = 26 \text{ mV}$$

5.3 Three Types of Amplifier Circuit



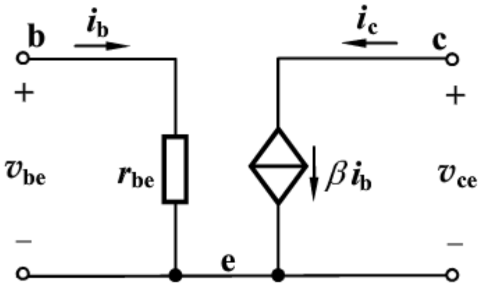
5.4 Static Working Point



$$
\begin{aligned}
I_{BQ} &= \frac{V_{BB} - V_{BEQ}}{R_b} \\
V_{BEQ} &= 0.7 \text{ V} \\
I_{CQ} &= \beta I_{BQ} \\
V_{CEQ} &= V_{CC} - I_{CQ} R_C
\end{aligned}
$$

Note that the static working point is not associated with small signals discussed below.

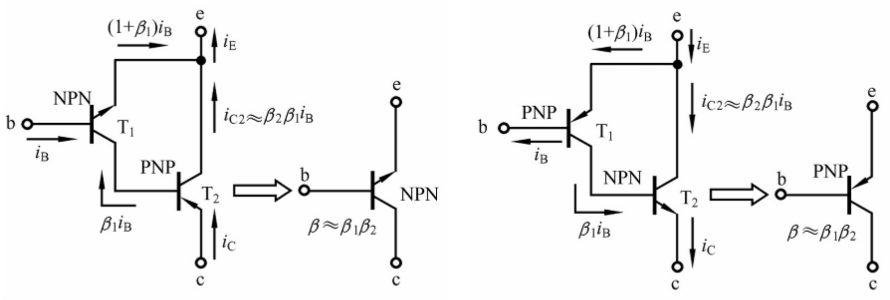
5.5 Model of Small Signal



When $T = 300$ K

$$r_{be} = 200\ \Omega + (1+\beta)\,\frac{26 \text{ mV}}{I_{CQ}\,(\text{mA})}$$

5.6 Compound Transistor



Chapter 6

Frequency Response

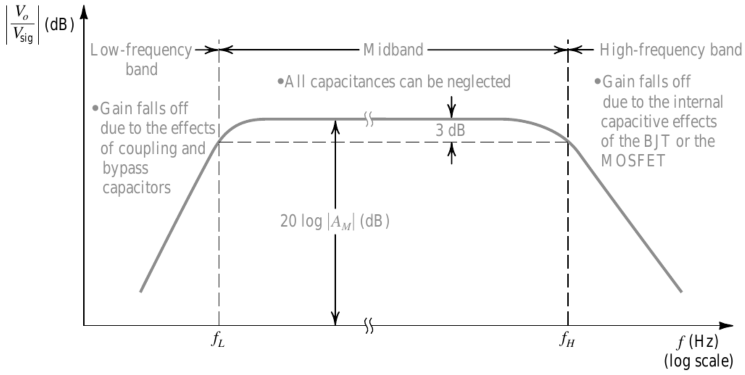
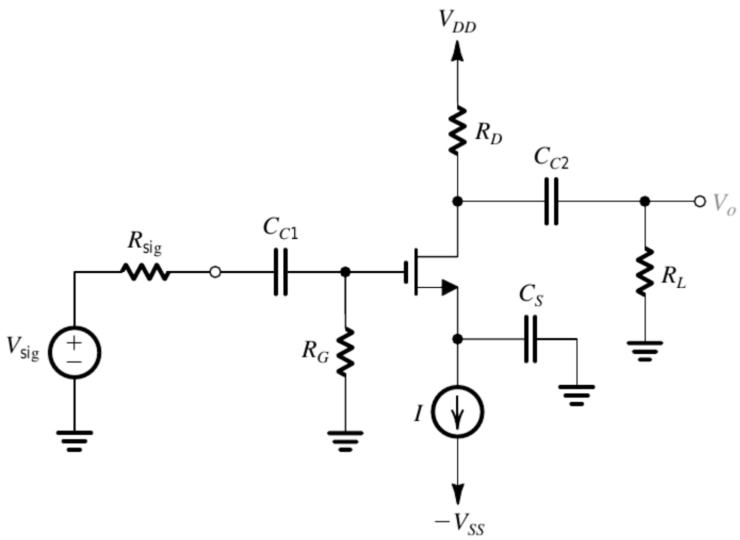


Figure 6.1: Sketch of the gain of amplifier versus frequency

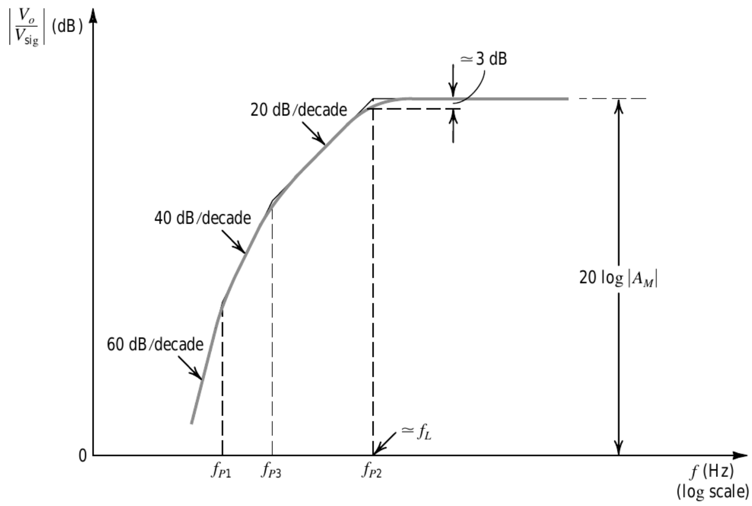
6.1 Low-Frequency

6.1.1 Common-Source Amplifier



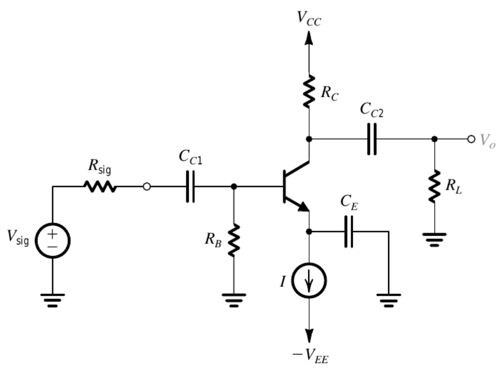
$$A_M = -\frac{R_G}{R_G + R_{sig}} \left[g_m \left(R_D \parallel R_L \right) \right]$$

$$\omega_{p1} = \frac{1}{C_{C1}\left(R_G + R_{sig}\right)}$$
$$\omega_{p2} = \frac{g_m}{C_S}$$
$$\omega_{p3} = \frac{1}{C_{C2}\left(R_D + R_L\right)}$$
$$\frac{V_o}{V_{sig}} = A_M\left(\frac{s}{s+\omega_{p1}}\right)\left(\frac{s}{s+\omega_{p2}}\right)\left(\frac{s}{s+\omega_{p3}}\right)$$

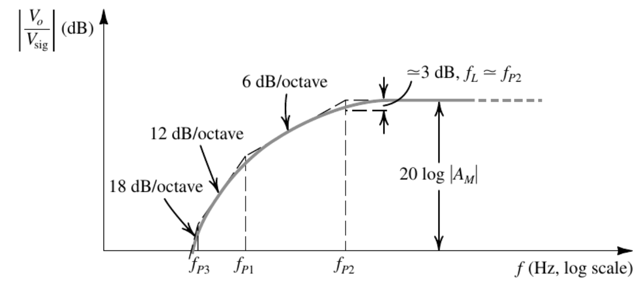


$$f_L \approx f_{p2} = \frac{\omega_{p2}}{2\pi} = \frac{1}{2\pi\left(C_s/g_m\right)}$$

6.1.2 Common-Emitter Amplifier



$$A_M = -\frac{\left(R_B \parallel r_\pi\right)}{\left(R_B \parallel r_\pi\right) R_{sig}} g_m\left(R_C \parallel R_L\right)$$
$$\omega_{p1} = \frac{1}{C_{C1}\left[\left(R_B \parallel r_\pi\right) + R_{sig}\right]}$$
$$\omega_{p2} = \frac{1}{C_E\left[r_e + \dfrac{R_B \parallel R_{sig}}{\beta+1}\right]}$$
$$\omega_{p3} = \frac{1}{C_{C2}\left(R_C + R_L\right)}$$

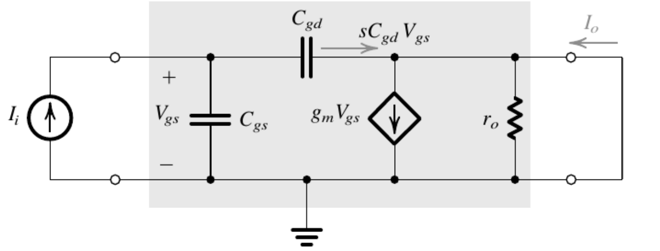


$$f_L \approx f_{p2}$$

6.2 High-Frequency

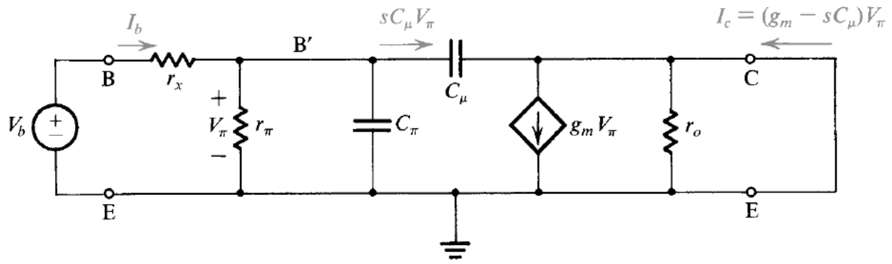
6.2.1 Unity-Gain Frequency

MOSFET



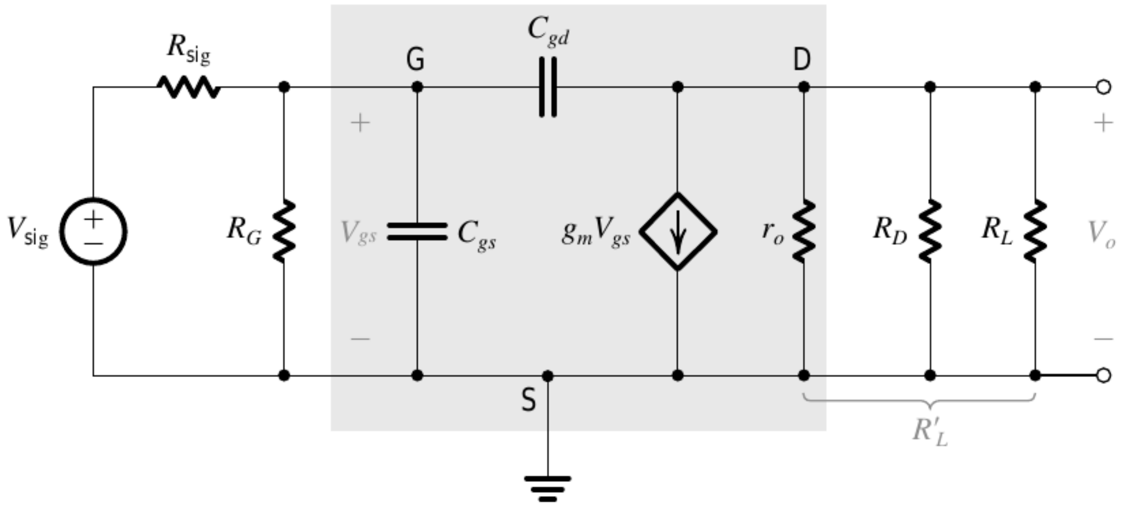
$$\frac{I_o}{I_i} = \frac{g_m}{s\,(C_{gs}+C_{gd})} \qquad \omega_T = \frac{g_m}{(C_{gs}+C_{gd})} \qquad f_T = \frac{g_m}{2\pi\,(C_{gs}+C_{gd})}$$

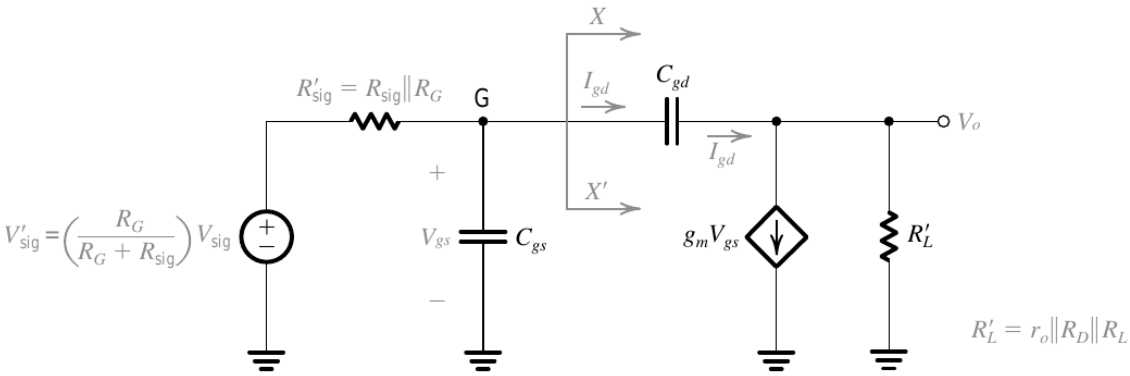
BJT

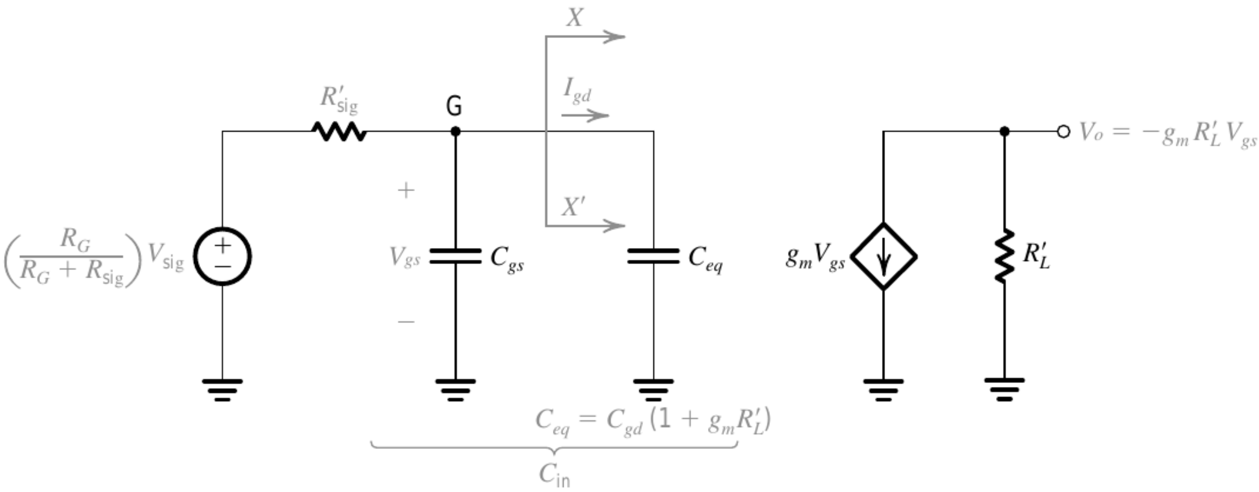


$$\frac{I_c}{I_b} = \frac{g_m r_\pi}{1+s\,(C_\pi+C_\mu)\,r_\pi} = \frac{\beta_0}{1+s\,(C_\pi+C_\mu)\,r_\pi} \qquad \omega_\beta = \frac{1}{(C_\pi+C_\mu)\,r_\pi} \qquad \omega_T = \beta_0\omega_\beta = \frac{g_m}{C_\pi+C_\mu}$$

6.2.2 Common-Source Amplifier

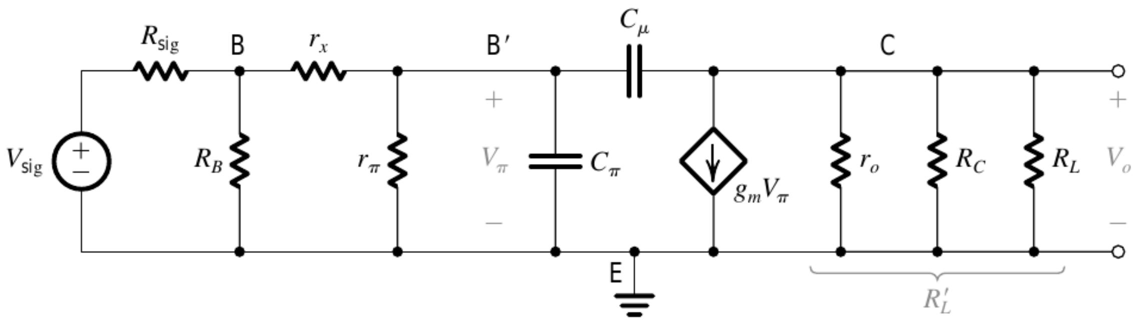


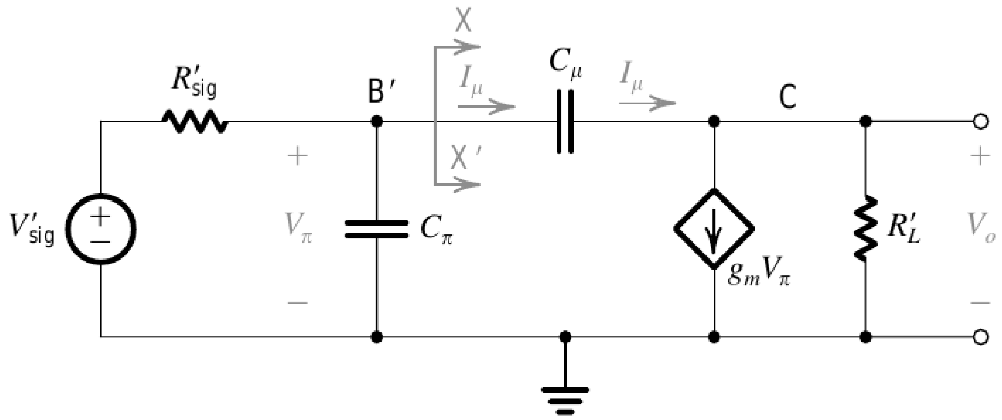




$$\omega_H = \frac{1}{C_{in} R'_{sig}} \qquad A_M = -\frac{R_G}{R_G + R_{sig}} g_m R'_L \qquad f_H = \frac{\omega_H}{2\pi} = \frac{1}{2\pi C_{in} R'_{sig}}$$

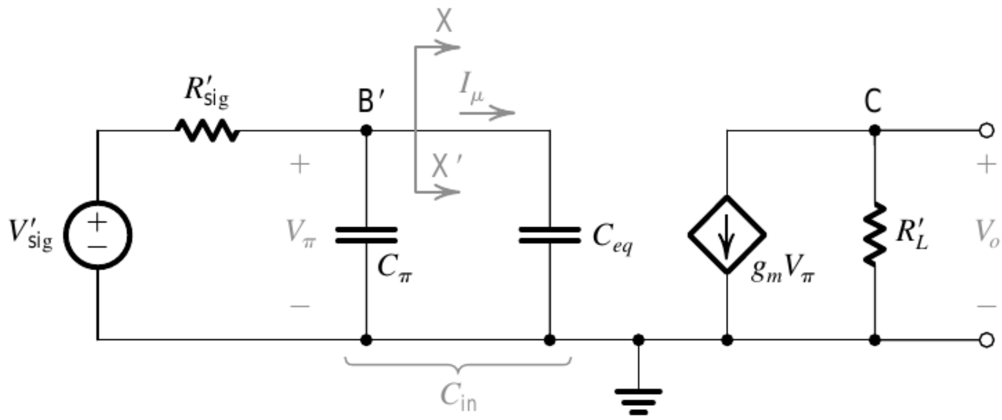
6.2.3 Common-Emitter Amplifier





$$V'_{\text{sig}} = V_{\text{sig}} \frac{R_B}{R_B + R_{\text{sig}}} \frac{r_\pi}{r_\pi + r_x + (R_{\text{sig}} \| R_B)} \qquad R'_L = r_o \| R_C \| R_L$$

$$R'_{\text{sig}} = r_\pi \| [r_x + (R_B \| R_{\text{sig}})]$$



$$\begin{aligned} C_{\text{in}} &= C_\pi + C_{eq} \\ &= C_\pi + C_\mu (1 + g_m R'_L) \end{aligned} \qquad V_o = -g_m R'_L V_\pi$$

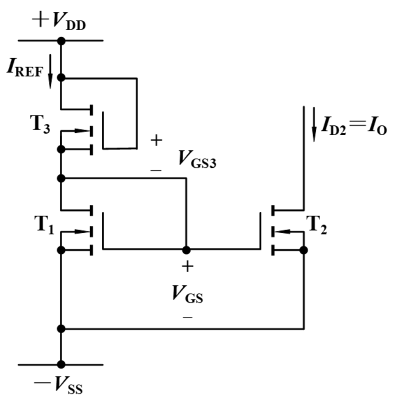
$$A_M = -\frac{R_B}{R_B + R_{sig}} \frac{r_\pi}{r_\pi + r_x + (R_{sig} \parallel R_B)} (g_m R'_L) \qquad f_H = \frac{\omega_H}{2\pi} = \frac{1}{2\pi C_{in} R'_{sig}}$$

Chapter 7

Analogue Integrated Circuits

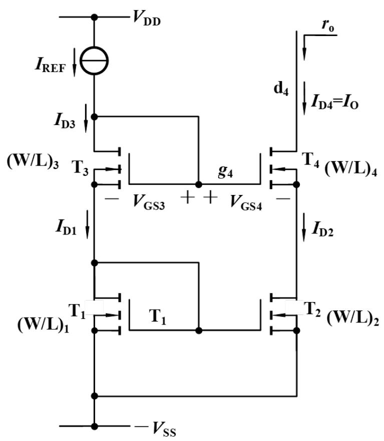
7.1 MOSFET Current Source

7.1.1 MOSFET Current Mirror



$$I_o = I_{D2} = K_n \left(V_{GS} - V_{TN}\right)^2$$

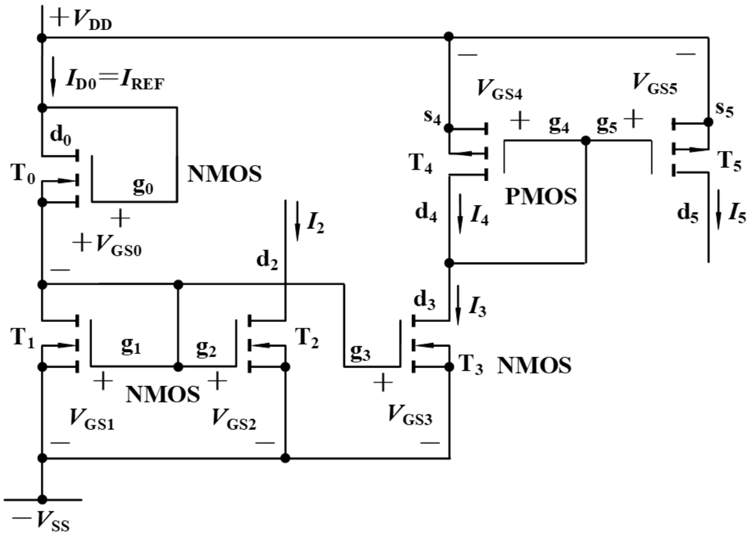
7.1.2 Cascade Current Mirror



The larger output resistance, the more stability of output current.

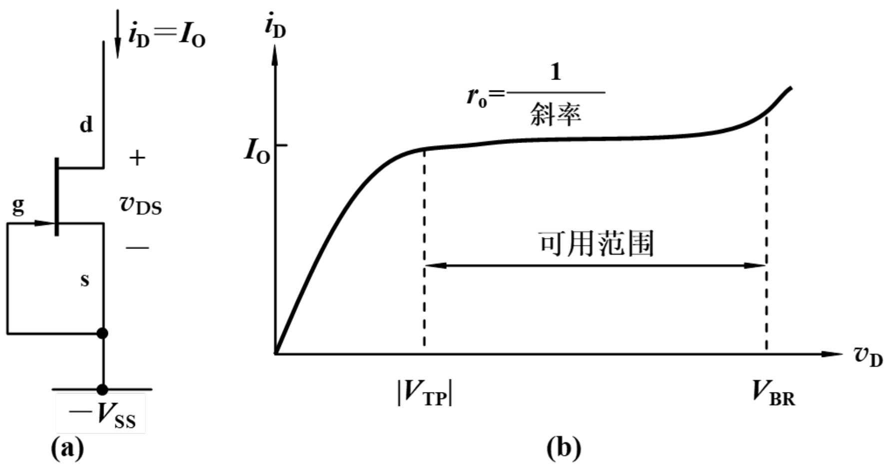
$$r_o = r_{ds4} + r_{ds2}\left(1 + g_m r_{ds4}\right) \approx g_m r_{ds4} r_{ds2}$$

7.1.3 Combined Current Mirror



$$
\begin{cases}
I_2 = \dfrac{(W/L)_2}{(W/L)_1} I_{REF} \\
I_3 = \dfrac{(W/L)_3}{(W/L)_1} I_{REF} \\
I_4 = I_3 \\
I_5 = \dfrac{(W/L)_5}{(W/L)_4} I_4
\end{cases}
$$

7.1.4 JFET Current Mirror

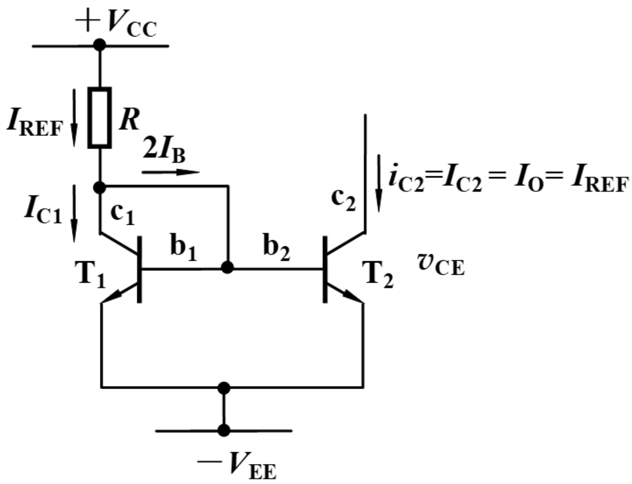


$$i_D = I_o = I_{DSS}\left(1 + \lambda v_{DS}\right)$$

$$r_o = \frac{1}{\lambda I_{DSS}}$$

7.2 BJT Current Source

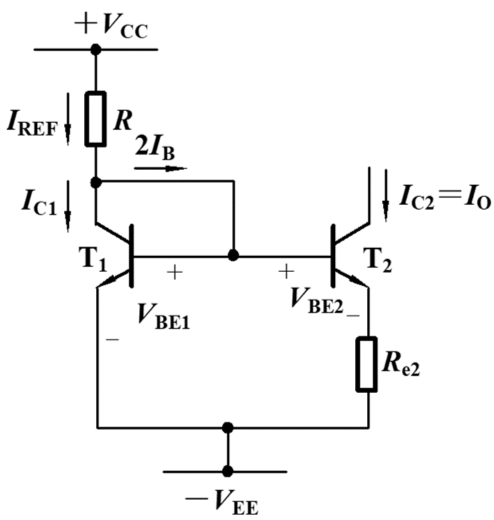
7.2.1 BJT Current Mirror



$$I_{C2} = I_{C1} \approx I_{REF} \approx \frac{V_{CC}}{R}$$

$$r_o = r_{ce}$$

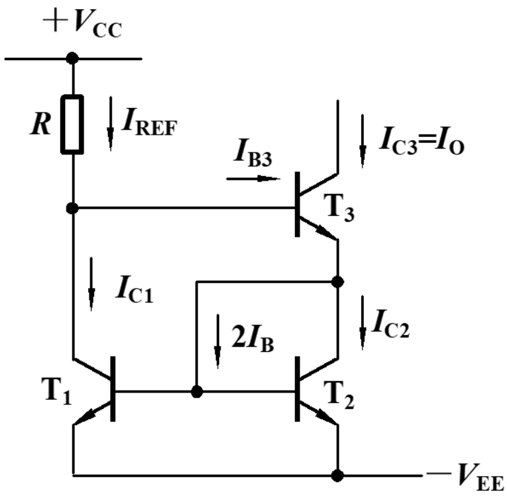
7.2.2 Micro Current Source



$$I_o = \frac{\Delta V_{BE}}{R_{e2}}$$

$$r_o \approx r_{ce2} + \left(1 + \frac{\beta R_{e2}}{r_{be2} + R_{e2}}\right)$$

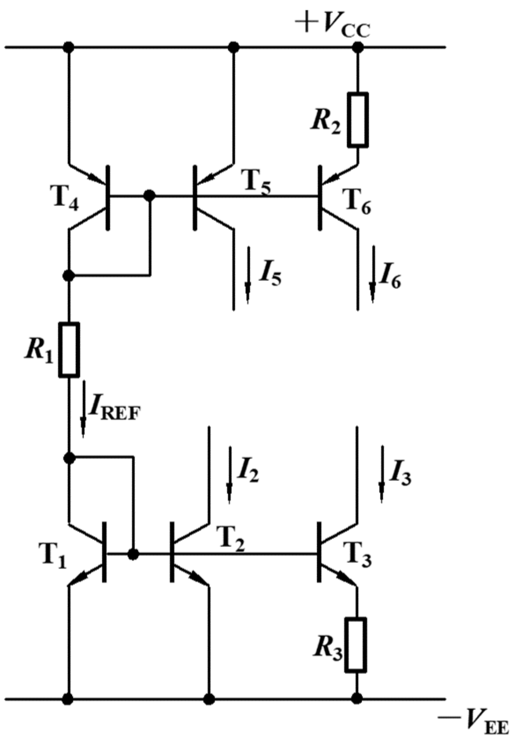
7.2.3 Current Source with High Output Resistance



$$I_{REF} = \frac{V_{CC} - V_{BE3} - V_{BE2} + V_{EE}}{R}$$

$$I_o \approx I_{C2} = \frac{A_3}{A_1} \cdot I_{REF}$$

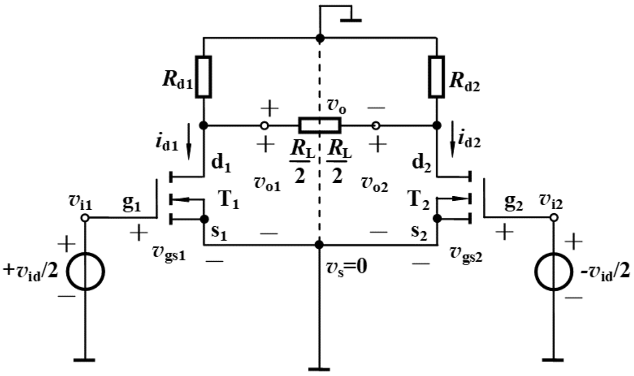
7.2.4 Combined Current Source

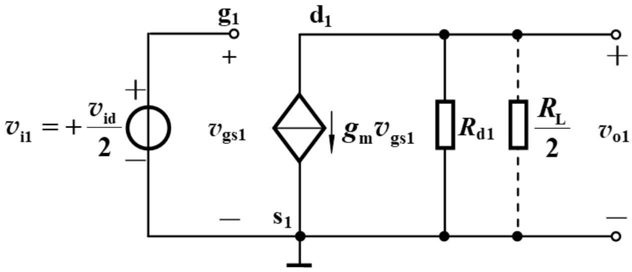


$$I_{REF} = \frac{V_{CC} + V_{EE} - V_{BE1} + V_{EB4}}{R_1}$$

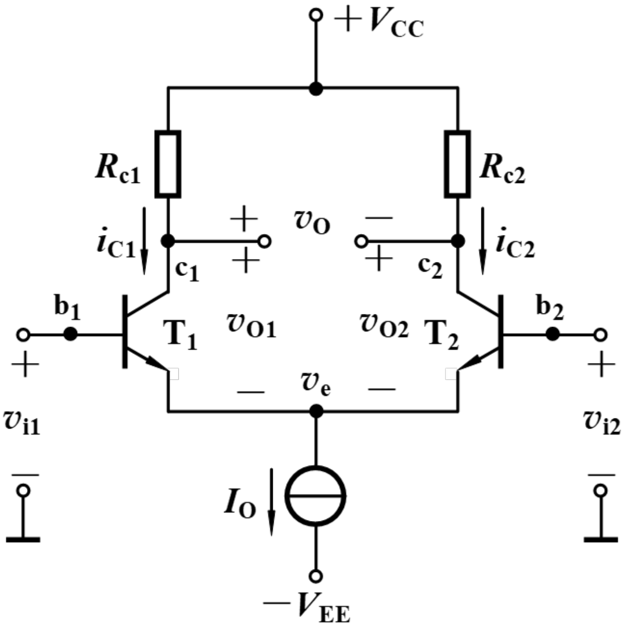
7.3 Differential Amplifier

7.3.1 MOSFET





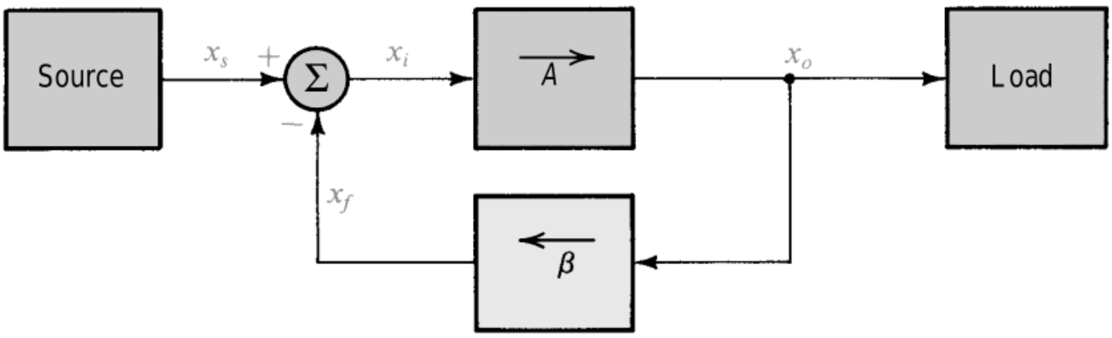
7.3.2 BJT



Chapter 8

Feedback

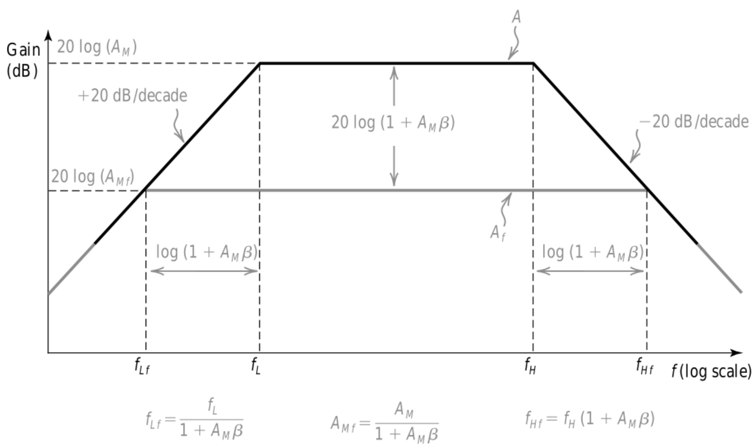
8.1 Basic Feedback Structure



$$x_o = Ax_i \qquad x_f = \beta x_o \qquad x_i = x_s - x_f$$

$$A_f = \frac{x_0}{x_s} = \frac{Ax_i}{x_i + \beta A x_i} = \frac{A}{1 + A\beta} \approx \frac{1}{\beta} \qquad (A\beta \gg 1)$$

8.2 Bandwidth and Gain



$$\omega_{Hf} = \omega_H \cdot (1 + A_M\beta) \qquad \omega_{Lf} = \omega_L / (1 + A_M\beta)$$

8.3 Four Basic Feedback Topologies

Feedback Type	Usage	Gain	Input Resistance	Output Resistance
Series-Shunt	Voltage → Voltage	$A_f = \dfrac{A}{1+A\beta}$	$R_{if} = (1+A\beta)\,R_i$	$R_{of} = \dfrac{R_o}{1+A\beta}$
Shunt-Series	Current → Current	$A_f = \dfrac{A}{1+A\beta}$	$R_{if} = \dfrac{R_i}{1+A\beta}$	$R_{of} = (1+A\beta)\,R_o$
Series-Series	Voltage → Current	$A_f = \dfrac{A}{1+A\beta}$	$R_{if} = (1+A\beta)\,R_i$	$R_{of} = (1+A\beta)\,R_o$
Shunt-Shunt	Current → Voltage	$A_f = \dfrac{A}{1+A\beta}$	$R_{if} = \dfrac{R_i}{1+A\beta}R_i$	$R_{of} = \dfrac{R_o}{1+A\beta}$