Analogue Electronics

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https://hxp.plus/

June 20, 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.

$$\sum U = 0$$

1.5 Gain of an Amplifier Circuit

	Voltage	Current	Transresistance	Transconductance	Power
Gain	$A_v = \frac{v_o}{v_i}$	$A_i = \frac{i_o}{i_i}$	$A_r = \frac{v_o}{i_i}$	$A_g = \frac{i_o}{v_i}$	$A_p = \frac{P_o}{P_i}$
Gain in dB	$20 \lg \lvert A_v \rvert$	$20 \lg \lvert A_i \rvert$	$20 \lg \lvert A_r \rvert$	$20 \lg \lvert A_g \rvert$	$10 \lg A_p$

Chapter 2

Operational Amplifier

2.1 Operational Amplifier

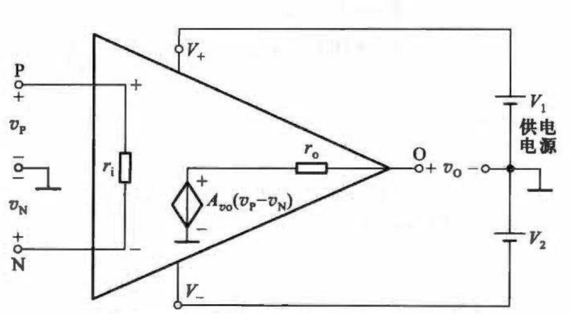
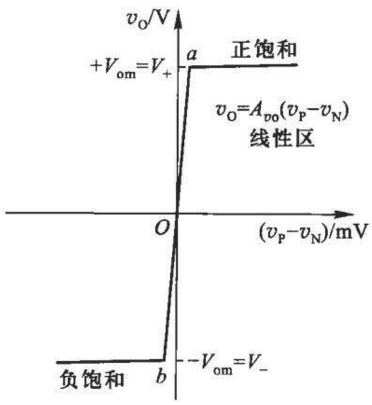


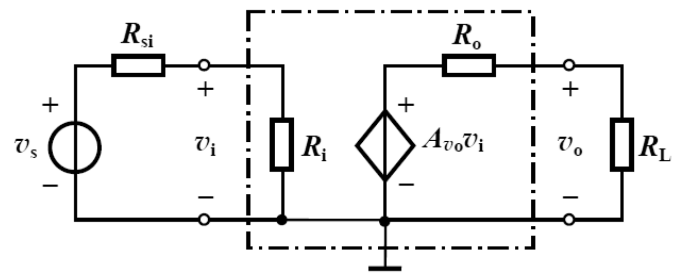
图 2.1.3 运算放大器的电路简化模型



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.



$$A_v = \frac{v_o}{v_i} = A_{vo} \cdot \frac{R_L}{R_o + R_L}$$

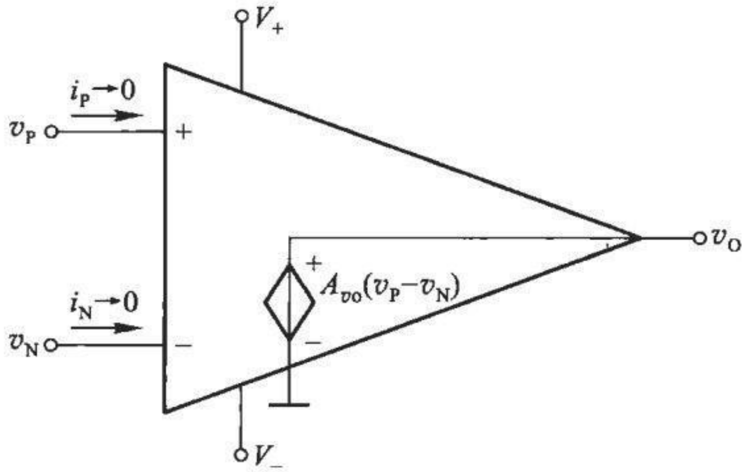
The output resistance may infect the gain of amplifier. The larger R_L is, the more A_v approaches A_{vo}, while the ideal case is when $R_o = 0$

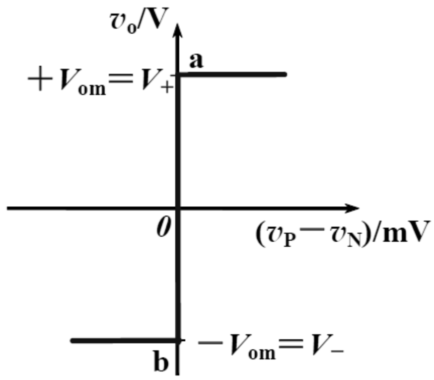
2.2 Ideal Operational Amplifier

For ideal operational amplifier:

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

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

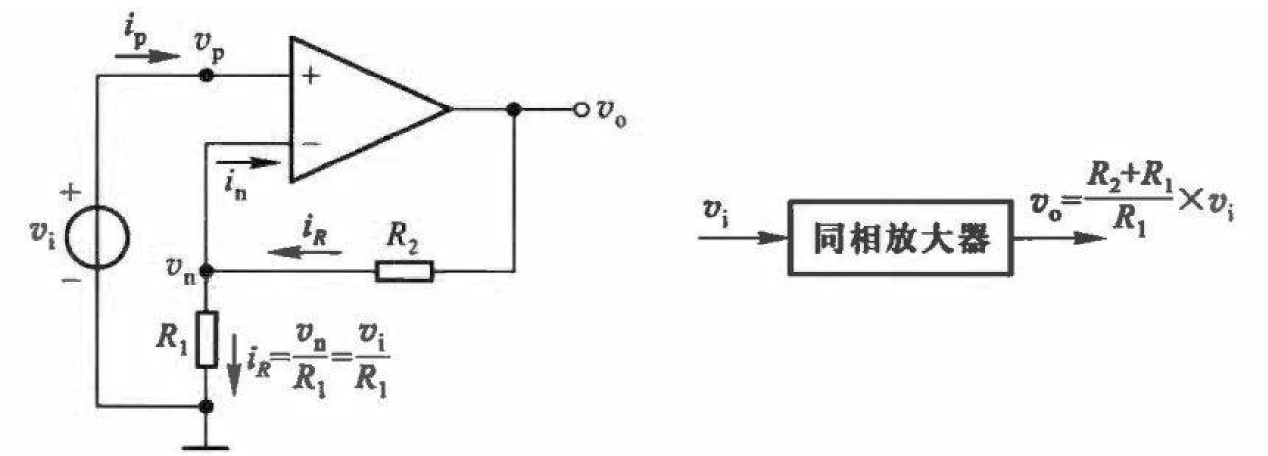




2.3 Closed-looped Amplifier

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.

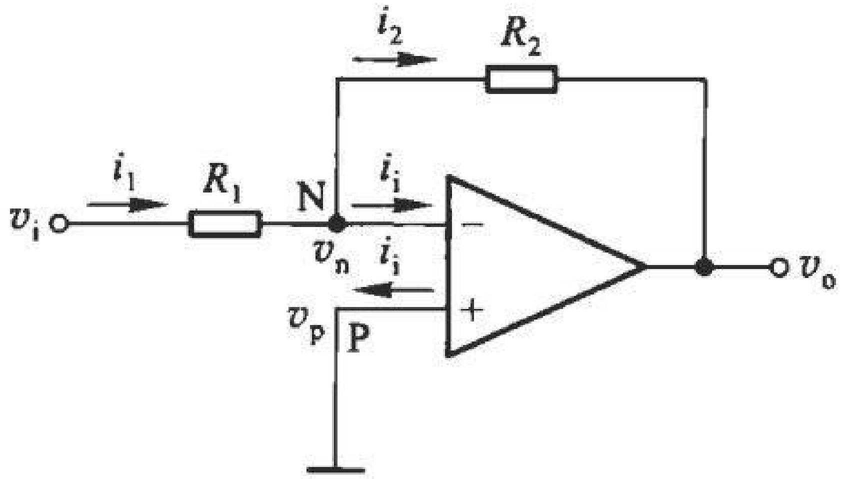
2.3.1 Non-inverting Operational Amplifier



$$A_{vo} = \frac{R_2 + R_1}{R_1} = 1 + \frac{R_2}{R_1}$$

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

2.3.2 Inverting Operational Amplifier

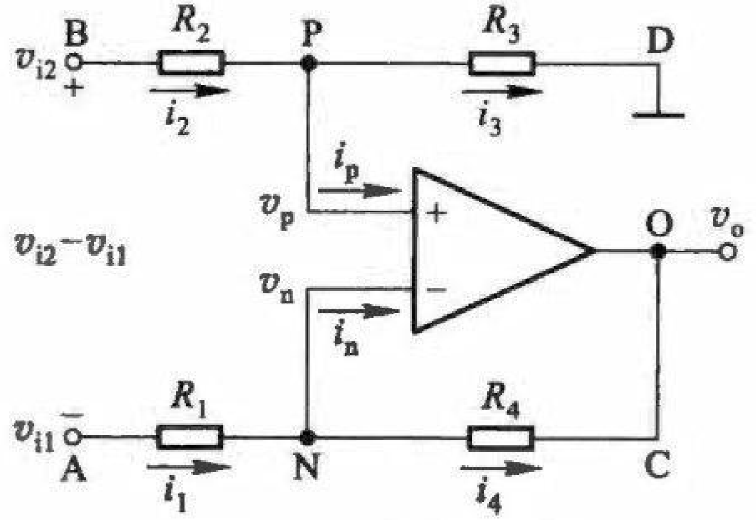


$$A_{vo} = -\frac{R_2}{R_1}$$

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.



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

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

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

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

$\Rightarrow$

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

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

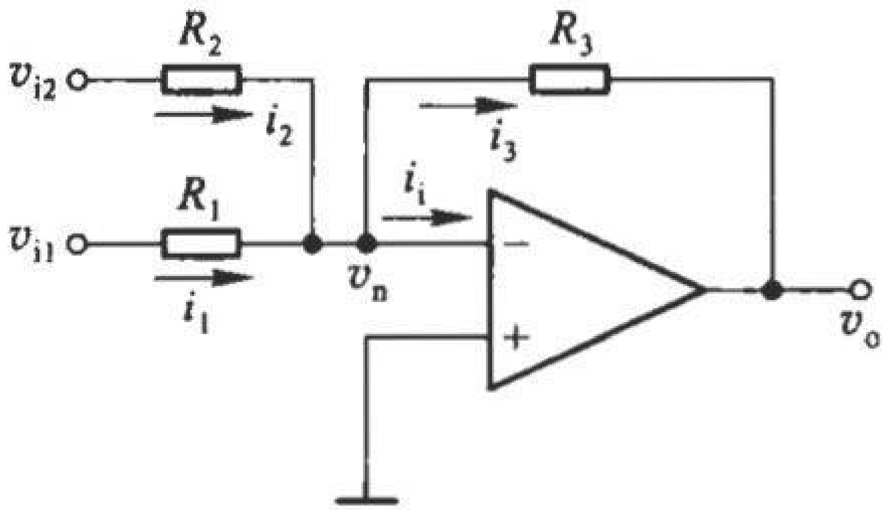
$$v_o = (1+r)\frac{r}{1+r}v_{i2} - r v_{i1} = r\left(v_{i2} - v_{i1}\right)$$

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

Input Resistance $R_{id} = R_1 + R_2$, When $v_{i2} = 0$, $R_{i1} = R_1$, When $v_{i1} = 0$, $R_{i2} = R_2 + R_3$.

2.4.2 Sum Circuit

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



Similarly, we have

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

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

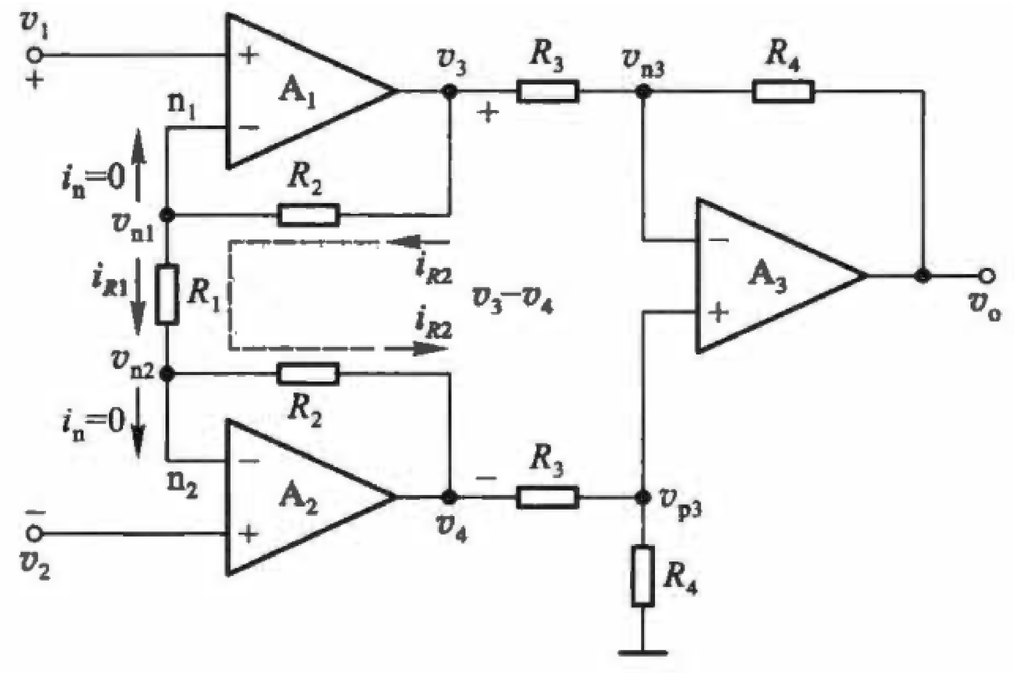
When we set

$$R_1 = R_2 = R_3$$

We have

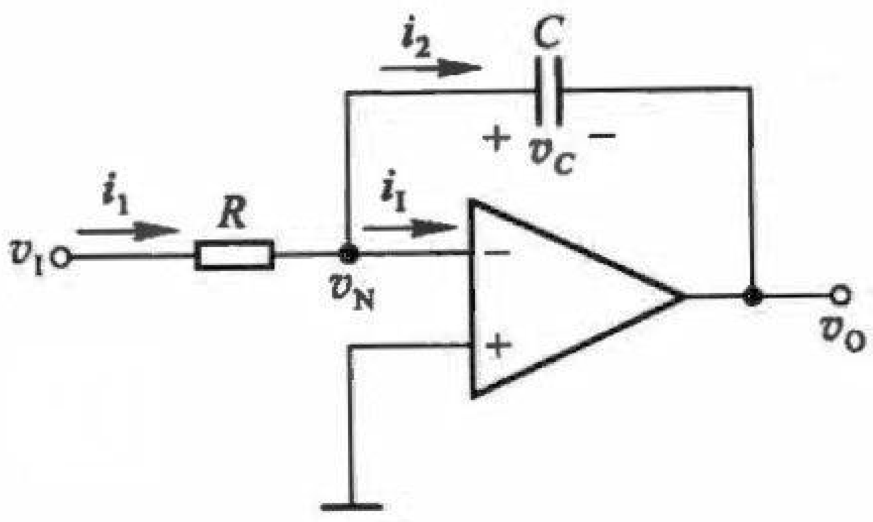
$$v_o = -\left(v_{i1} + v_{i2}\right)$$

2.4.3 Instrumentation Amplifier



$$A_{vd} = -\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right) \qquad v_o = A_{vd}\left(v_1 - v_2\right)$$

2.4.4 Integrating Circuit



Since

$$C = \frac{Q}{U}$$

⇒

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

$$0 - v_o = U$$

⇒

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

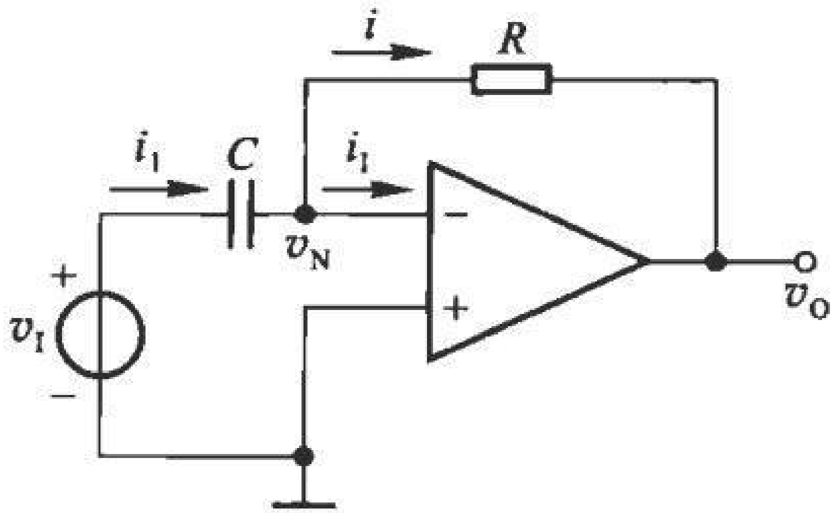
We define

$$\tau = RC$$

Then

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

2.4.5 Differential Circuit



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

⇒

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

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.

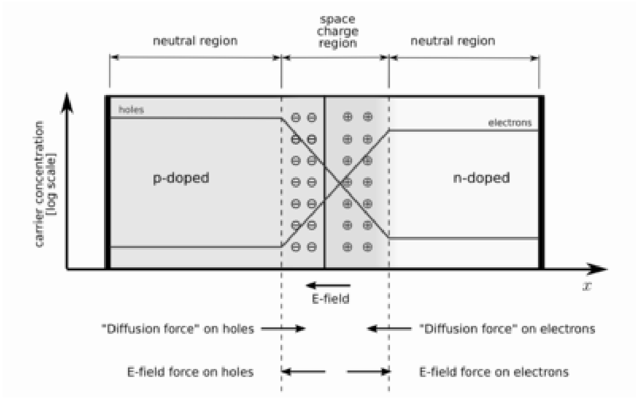


Figure 3.1: PN Junction at equilibrium state

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

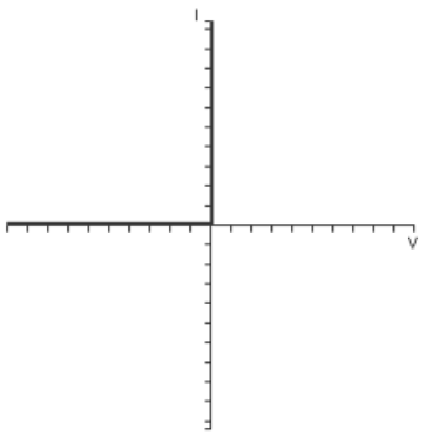
3.3 Diode modeling

3.3.1 Real Diode Modeling

$$i_d = I_S \left(\mathrm{e}^{v_D/(nV_T)} - 1 \right)$$

3.3.2 Mathematically idealized diode

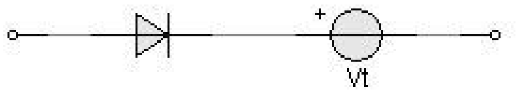
Firstly, consider a mathematically idealized diode. In such an ideal diode, if the diode is reverse biased, the current flowing through it is zero. This ideal diode starts conducting at 0 V and for any positive voltage an infinite current flows and the diode acts like a short circuit. The I-V characteristics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

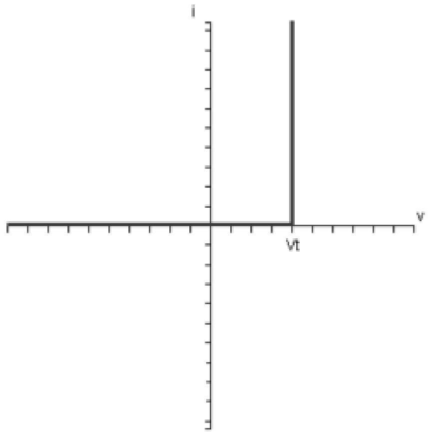


3.3.3 Ideal diode in series with voltage source

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

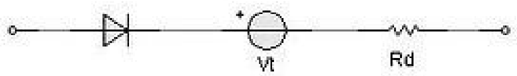
When forward biased, the ideal diode is simply a short circuit and when reverse biased, an open circuit.

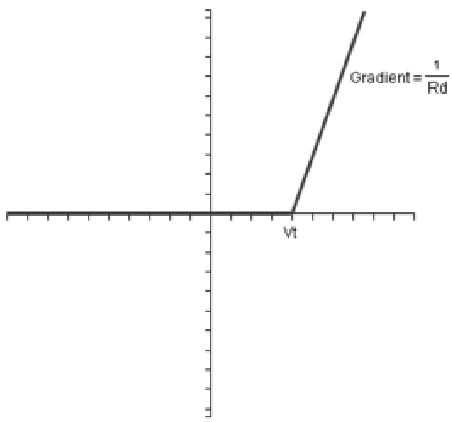




3.3.4 Diode with voltage source and current-limiting resistor

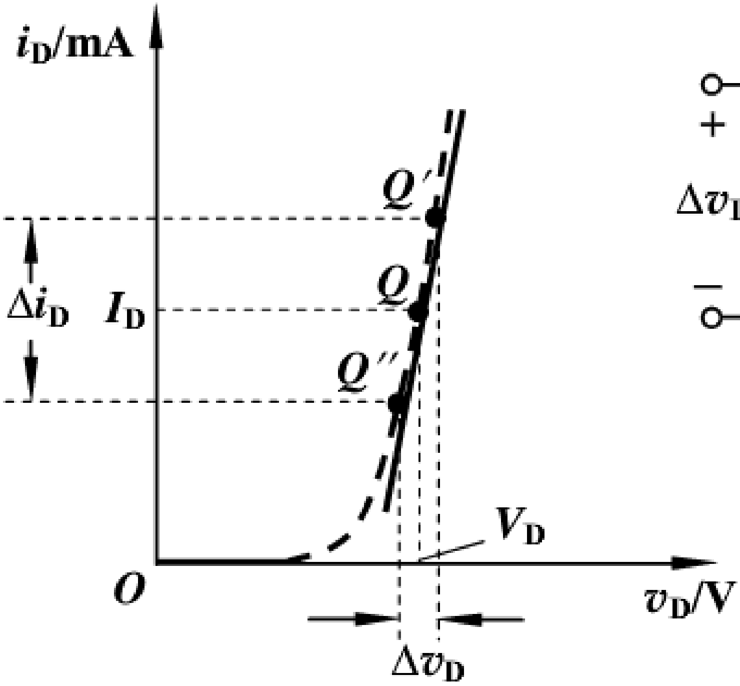
The last thing needed is a resistor to limit the current, as shown below:

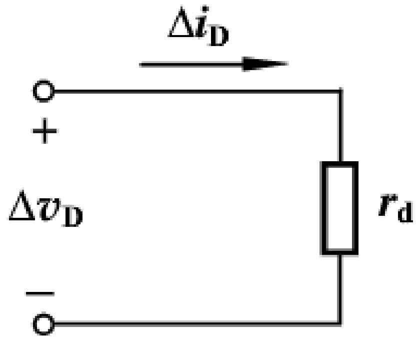




The real diode now can be replaced with the combined ideal diode, voltage source and resistor and the circuit then is modelled using just linear elements. If the sloped-line segment is tangent to the real diode curve at the Q-point, this approximate circuit has the same small-signal circuit at the Q-point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

3.3.5 Diode in Small Signal Circuits





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

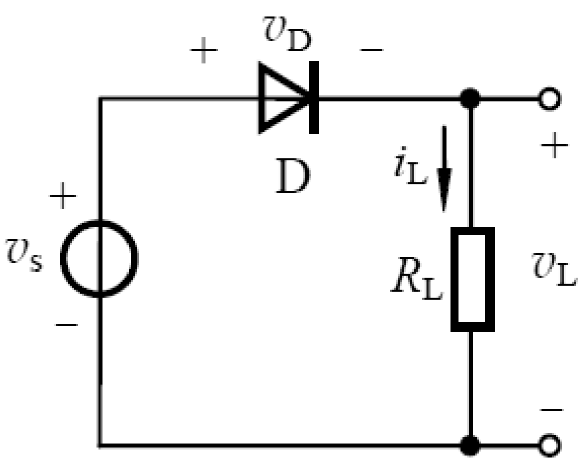
Where, in the condition of $T = 300$ K,

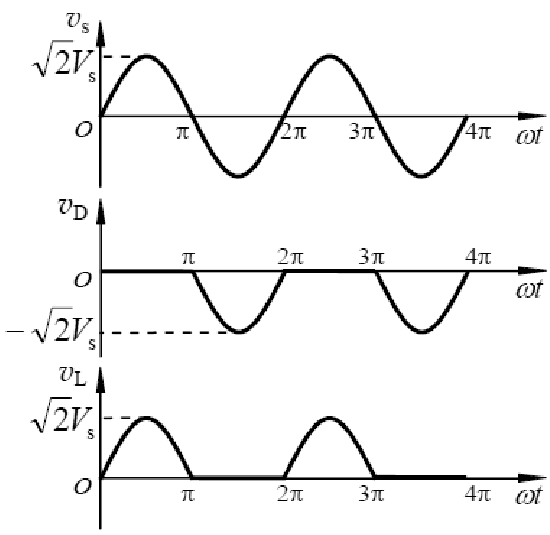
$$V_T = 26 \text{ mV}$$

3.4 Applications of Diodes

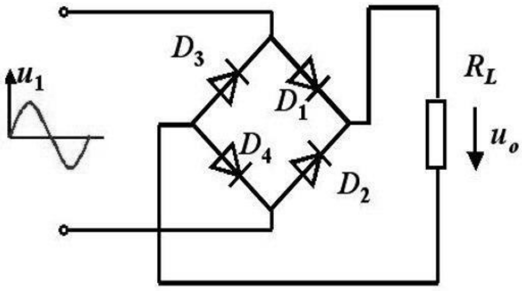
3.4.1 Rectifier Circuit

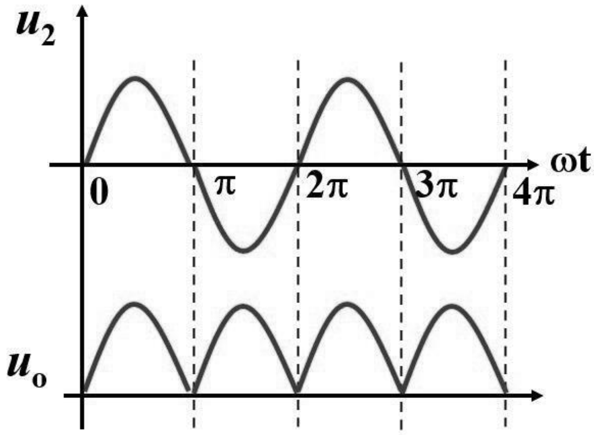
The Half-wave Rectifier





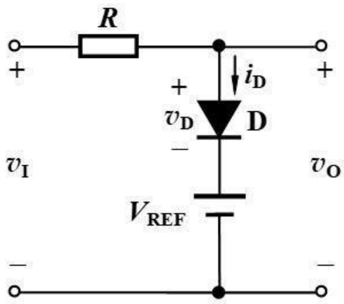
The Bridge Rectifier

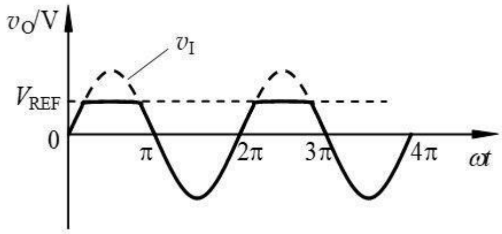




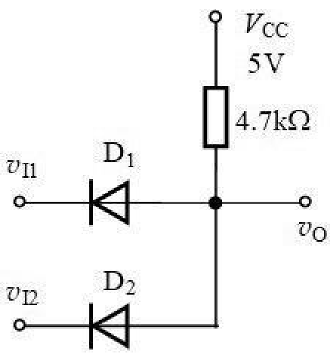
$$V_L \approx 0.9V_S \qquad I_{DI} = I_{D2} = I_{D3} = I_{D4} = \frac{0.45V_S}{R_L}$$

3.4.2 Limiting Circuit





3.4.3 Switching Circuit



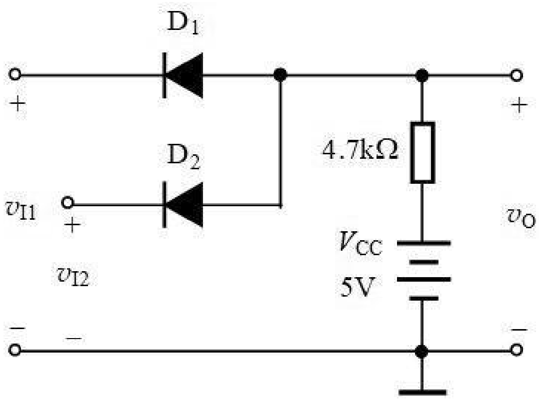
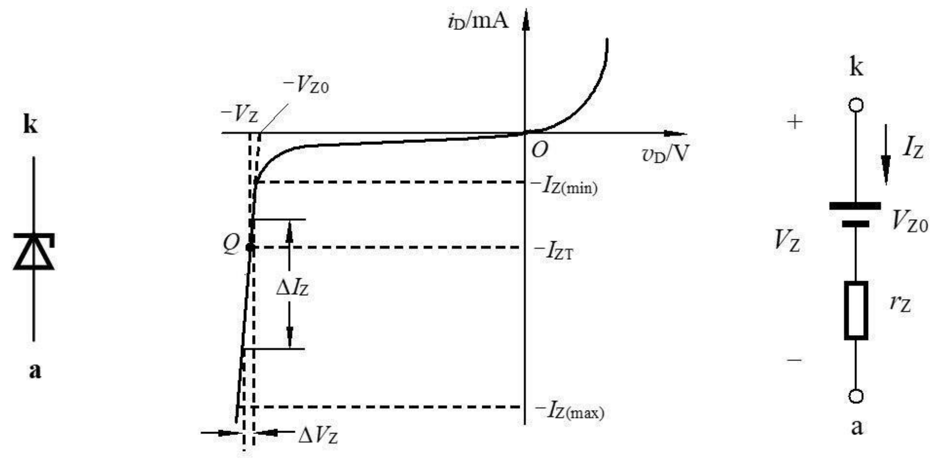


Figure 3.5: A Switching Circuit, $v_o = 5$ V holds only if all the input voltage is 5 V

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.



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.

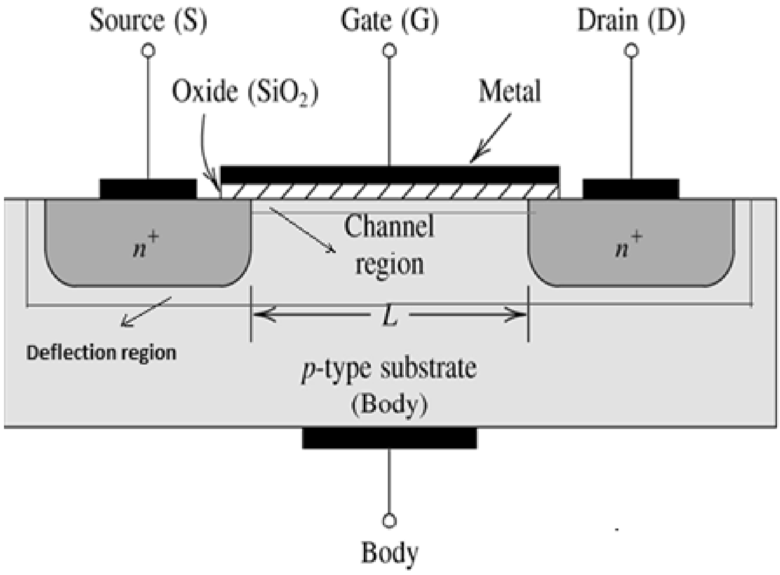
3.5.4 Schottky diode

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.

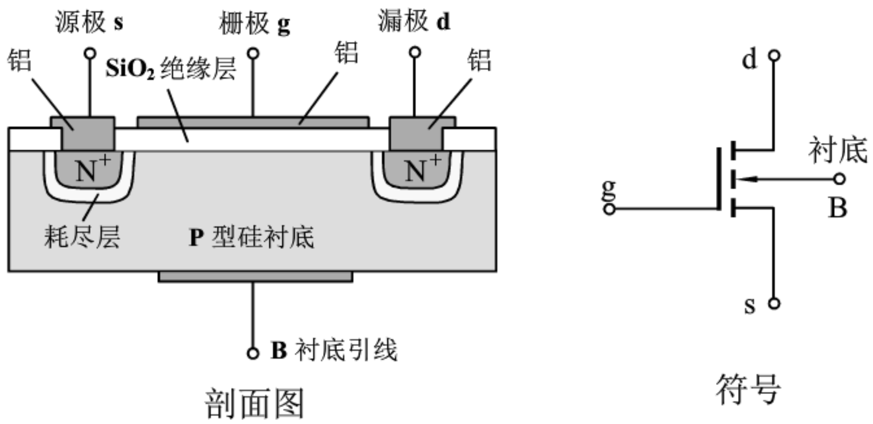
Chapter 4

MOSFET and Amplifying Circuit

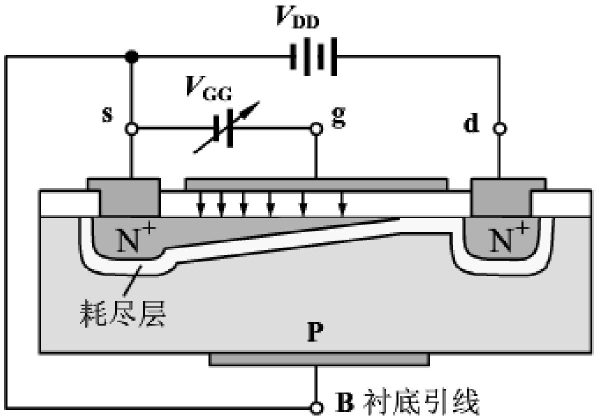
4.1 Classification of MOSFET

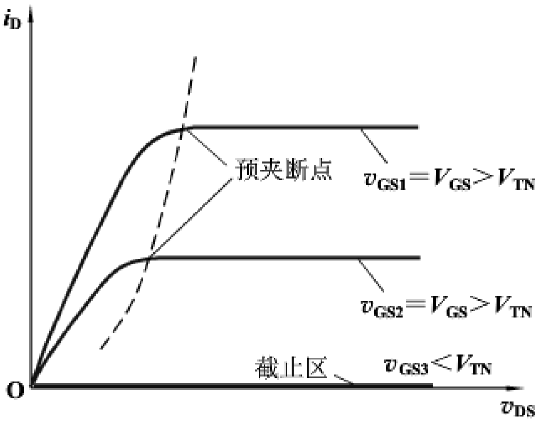


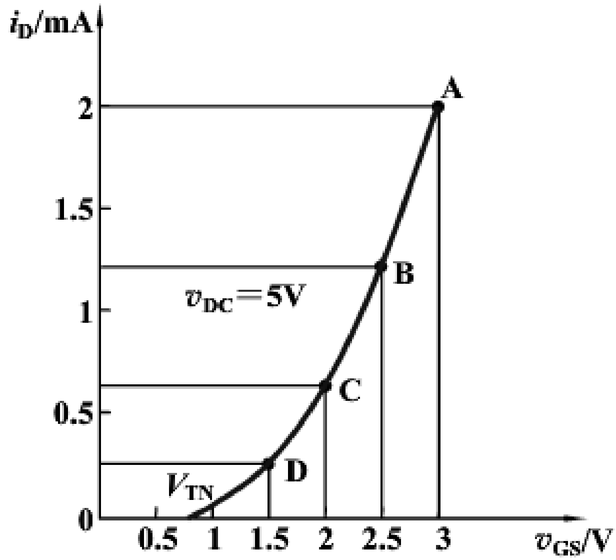
4.1.1 N-type Enhancement-mode MOSFET



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

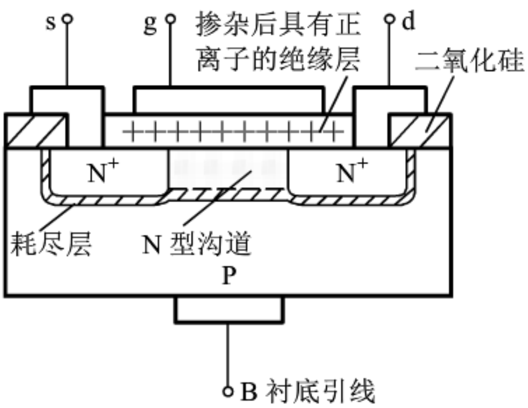


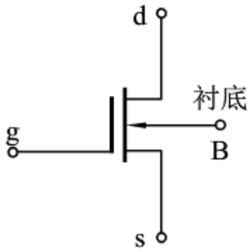


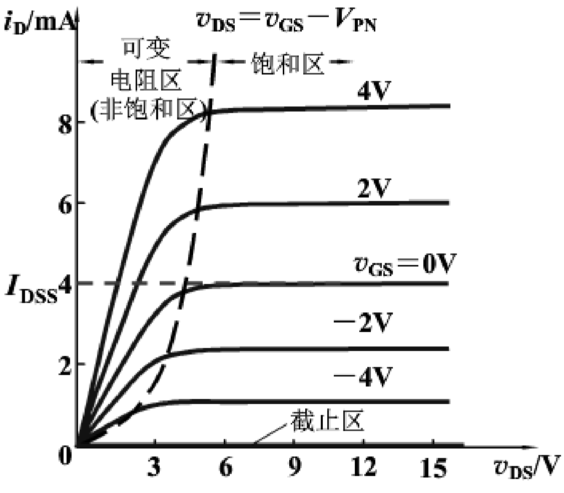


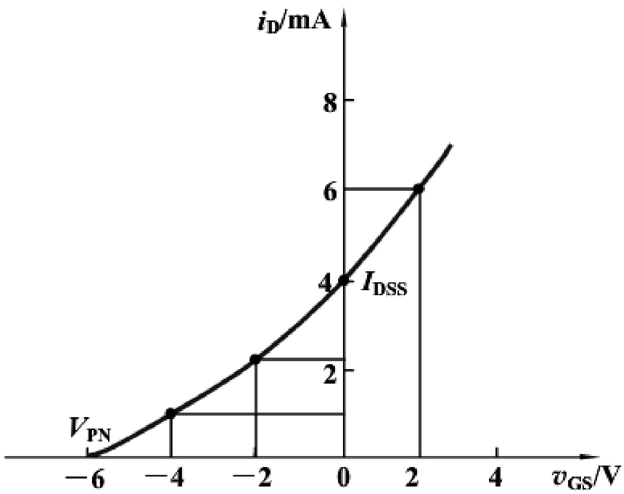
4.1.2 N-type Depletion-mode MOSFET

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

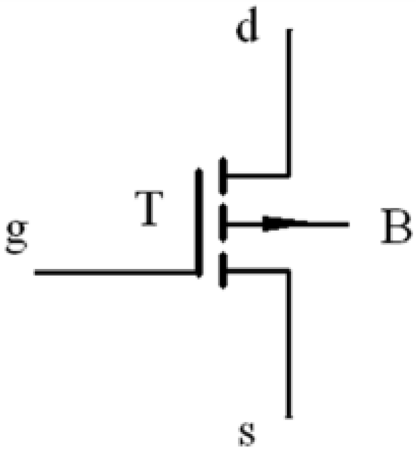




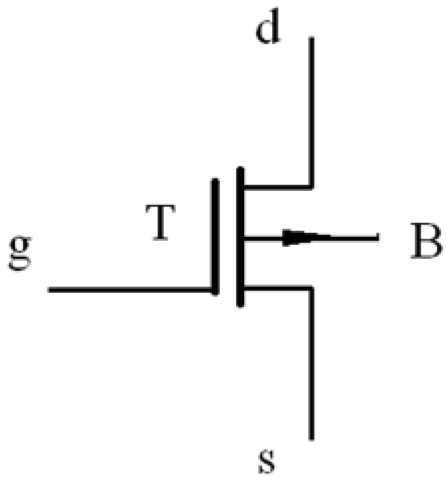




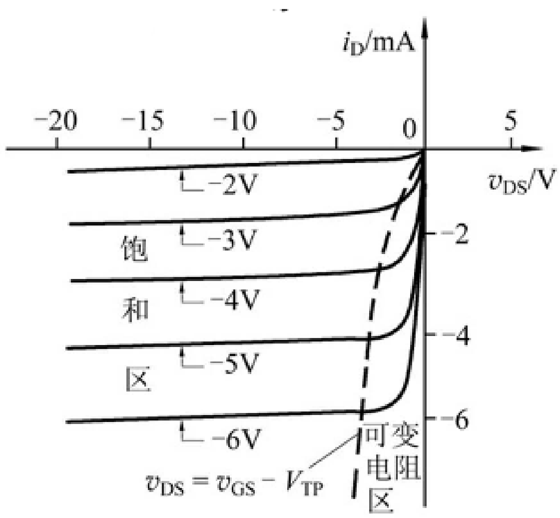
4.1.3 P-type MOSFET

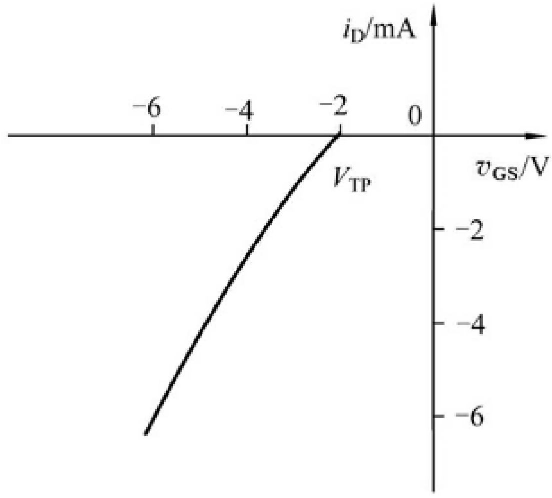


(a) Enhancement-mode

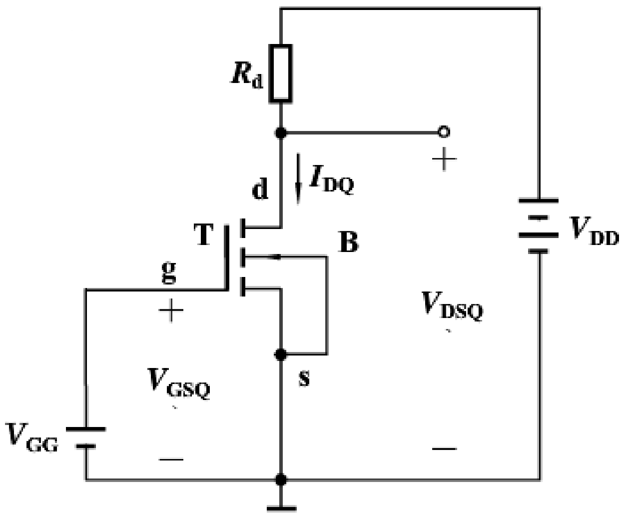


(b) Depletion-mode





4.2 Static Working Point



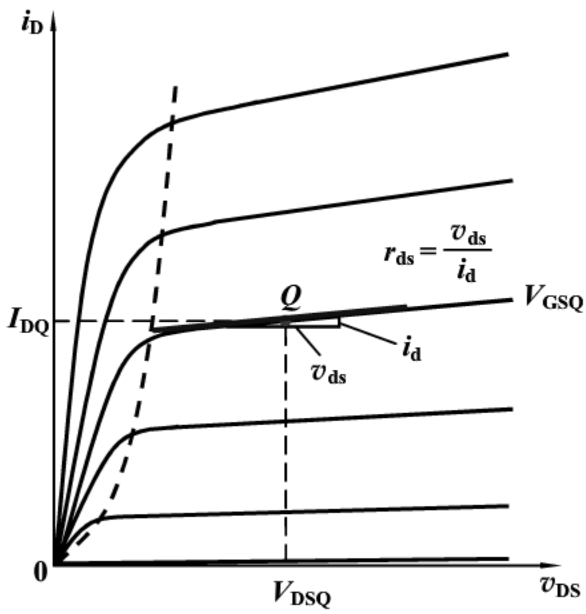
To calculate the DC bias point of a MOSFET

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

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



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

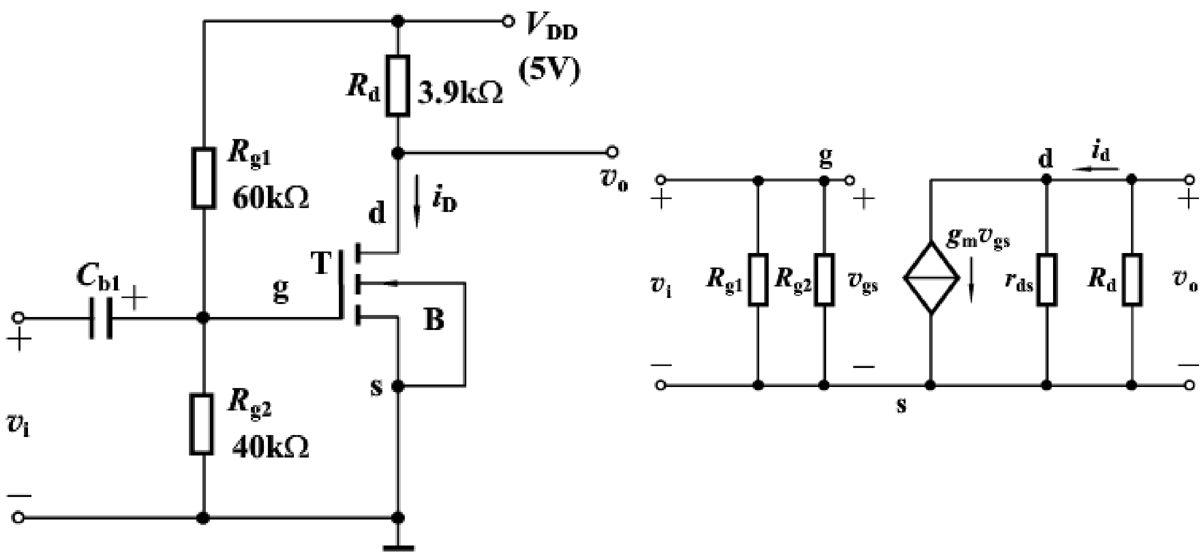
$$r_{ds} = \left.\frac{\partial v_{DS}}{\partial i_D}\right|_{V_{GSQ}} = \frac{1}{\lambda K_n \left(V_{GSQ} - V_{TN}\right)^2} \approx \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$$

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



DC bias point:

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

Transconductance:

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

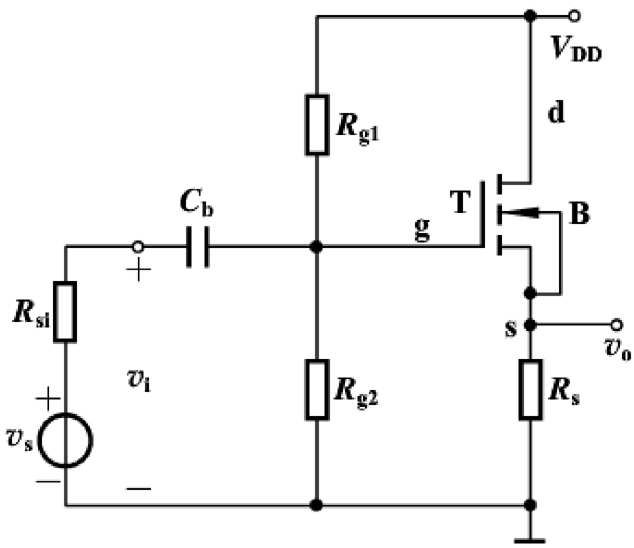
Gain:

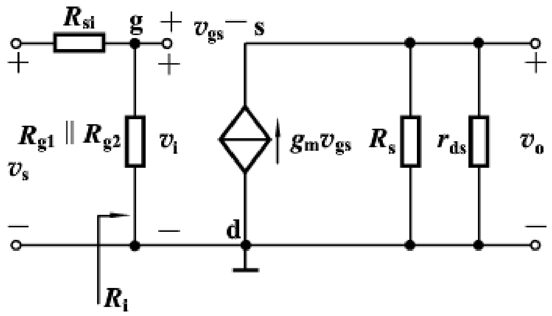
$$A_v = -g_m \left(r_{ds} \parallel R_d\right) \qquad A_{vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i} \cdot \frac{v_i}{v_s} = \frac{v_i}{v_s} A_v$$

Resistance:

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

4.4.2 Common Drain Amplifier Circuit





DC bias point:

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

Transconductance:

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

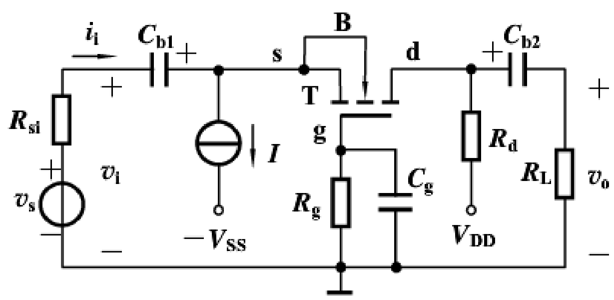
Gain:

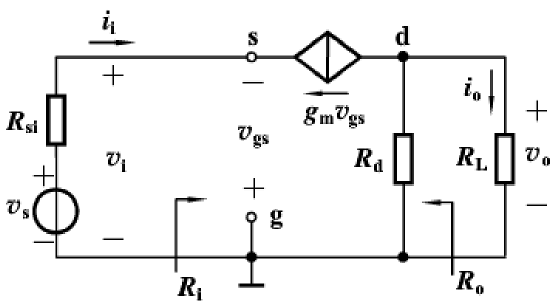
$$A_v = \frac{R_s \parallel r_{ds} \parallel R_L}{\dfrac{1}{g_m} + R_s \parallel r_{ds} \parallel R_L} \approx 1 \qquad A_{vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i} \cdot \frac{v_i}{v_s} = \frac{v_i}{v_s} A_v$$

Resistance:

$$R_i = R_{g1} \parallel R_{g2} \qquad R_o = R_s \parallel r_{ds} \parallel \frac{1}{g_m}$$

4.4.3 Common Gate Amplifier Circuit





DC bias point:

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

Transconductance:

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

Gain:

$$A_v = g_m \left(R_d \parallel R_L\right) \qquad A_{vs} = \frac{g_m \left(R_d \parallel R_L\right)}{1 + g_m R_{si}} \qquad A_{is} = \left(\frac{R_d}{R_d + R_L}\right)\left(\frac{g_m R_{si}}{1 + g_m R_{si}}\right)$$

Resistance:

$$R_i = \frac{1}{g_m} \qquad R_o \approx R_d$$

4.5 Summary

4.5.1 Features of Three Types of MOSFET Amplifing Circuits

Type	A_v	A_i	R_i	R_o
Common Source	high,inverse	-	high	-
Common Drain	1	-	high	low
Common Gate	high,non-inverse	1	low	-

4.5.2 Small Signal Model of MOSFET

$$I_{DQ} = K_n \left(V_{GSQ} - V_{TN}\right)^2 \qquad g_m = 2K_n \left(V_{GSQ} - V_{TN}\right) \qquad r_{ds} = \frac{1}{\lambda K_n \left(V_{GSQ} - V_{TN}\right)^2}$$

4.5.3 Saturation Mode of MOSFET

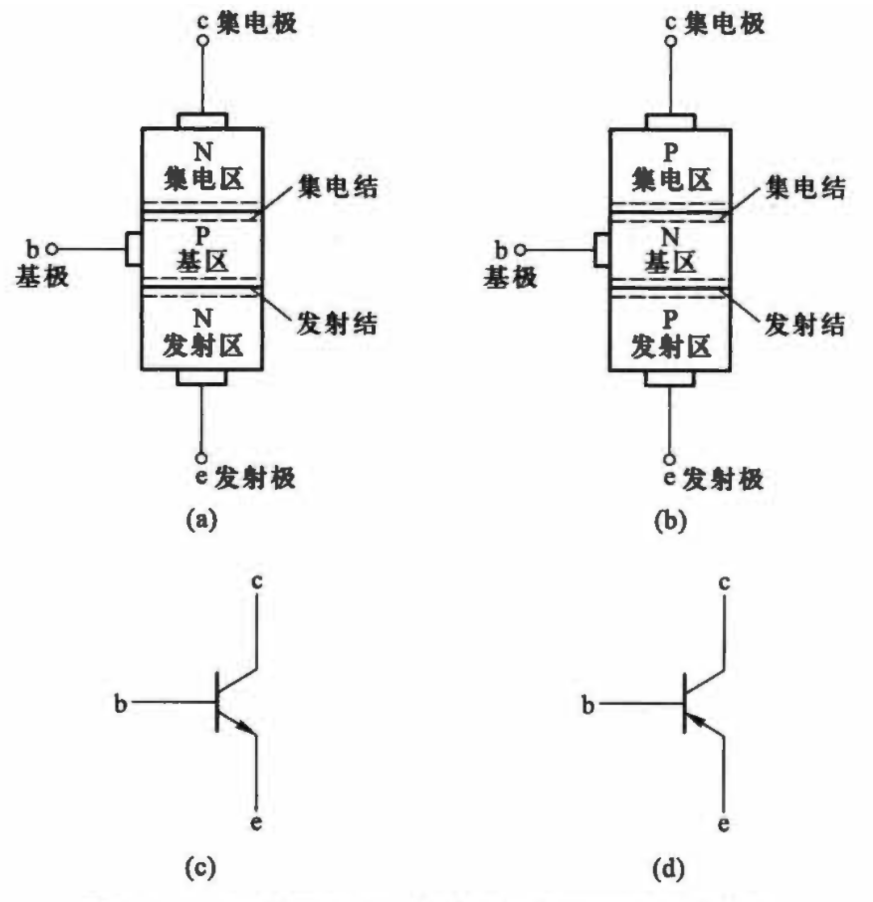
MOSFET Type	V_{GS}	V_{DS}
N-type enhancement	$V_{GS} > V_{TN}$	$V_{DS} > V_{GS} - V_{TN}$
N-type depletion	$V_{GS} > V_{PN}$	$V_{DS} > V_{GS} - V_{PN}$
P-type enhancement	$V_{GS} < V_{TP}$	$V_{DS} < V_{GS} - V_{TP}$
P-type depletion	$V_{GS} < V_{PP}$	$V_{DS} < V_{GS} - V_{PP}$

Chapter 5

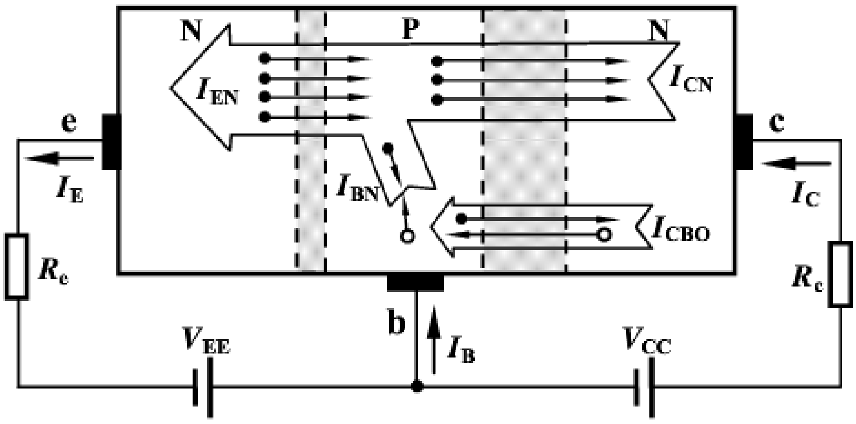
Bipolar Junction Transistor

5.1 Electronic Symbol

The arrow represents the direction of current.



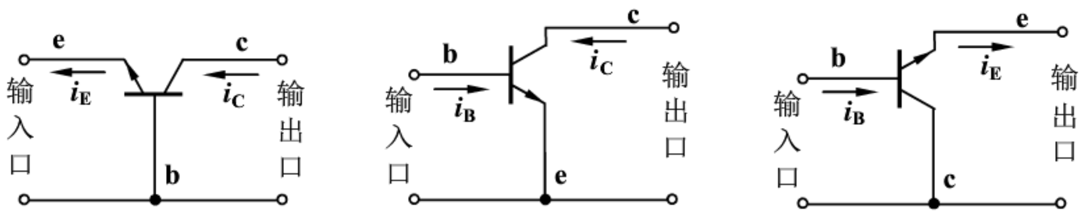
5.2 Control Principle



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

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

5.3 Three Types of Amplifier Circuit

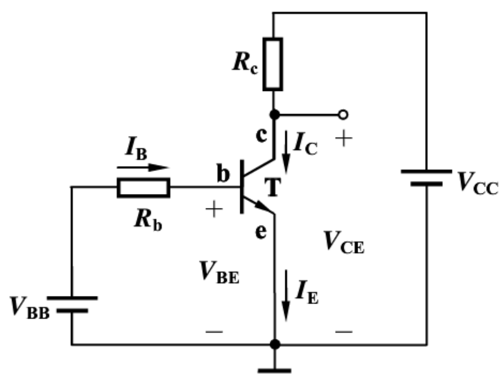


（a）共基极 $i_C = \alpha\, i_E$

（b）共发射极 $i_C = \beta\, i_B$

（c）共集电极 $i_E = (1+\beta)\, i_B$

5.4 Static Working Point

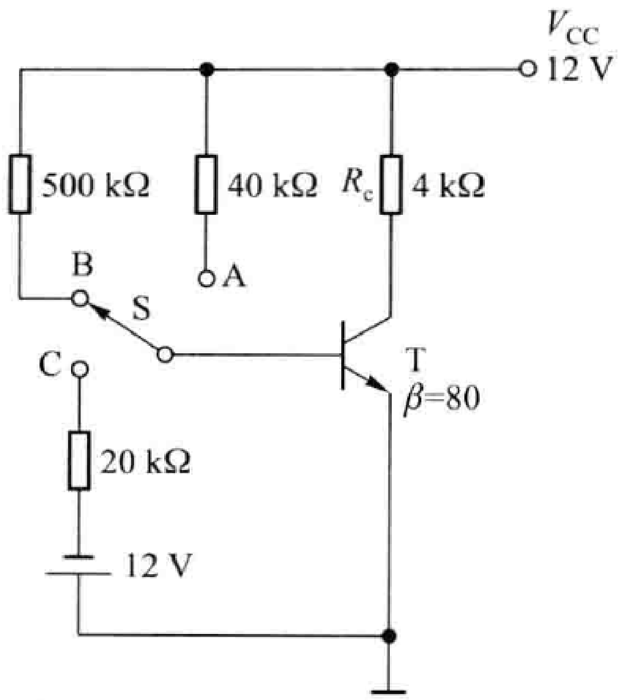


$$I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_b}$$
$$V_{BEQ} = 0.7 \text{ V}$$
$$I_{CQ} = \beta I_{BQ}$$
$$V_{CEQ} = V_{CC} - I_{CQ} R_C$$

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

5.5 Determine the working state of BJT

$\beta = 80, V_{BE} = 0.6$ V (Note that if the problem asks you to estimate, $V_{BE} = 0$ V)



$S \to A$

$$I_B = \frac{(12 - 0.6 \text{ V})}{40 \text{ k}\Omega} = 0.3 \text{ mA} \qquad I_{CS} = \frac{V_{CC}}{R_C} = 0.038 \text{ mA} \qquad I_{BS} = \frac{I_{CS}}{\beta} = 3 \text{ mA}$$

Since

$$I_B > I_{BS}$$

BJT works in **saturation** mode.

$S \to B$

$$I_B = \frac{(12 - 0.6 \text{ V})}{500 \text{ k}\Omega} = 0.023 \text{ mA} \qquad I_{CS} = \frac{V_{CC}}{R_C} = 0.038 \text{ mA} \qquad I_{BS} = \frac{I_{CS}}{\beta} = 3 \text{ mA}$$

Since

$$I_B < I_{BS}$$

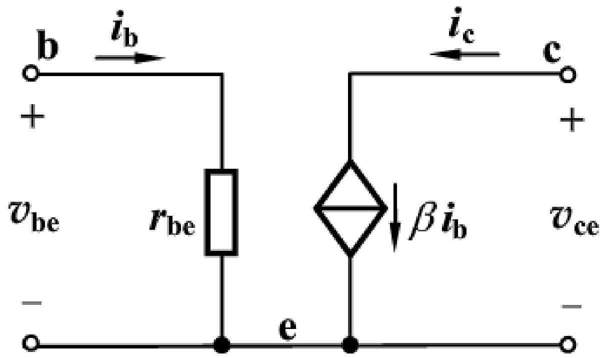
BJT works in **active** mode.

$S \to C$, since

$$V_B < V_E$$

The Emitter-Base Junction is reverse biased, BJT works in **cutoff** mode.

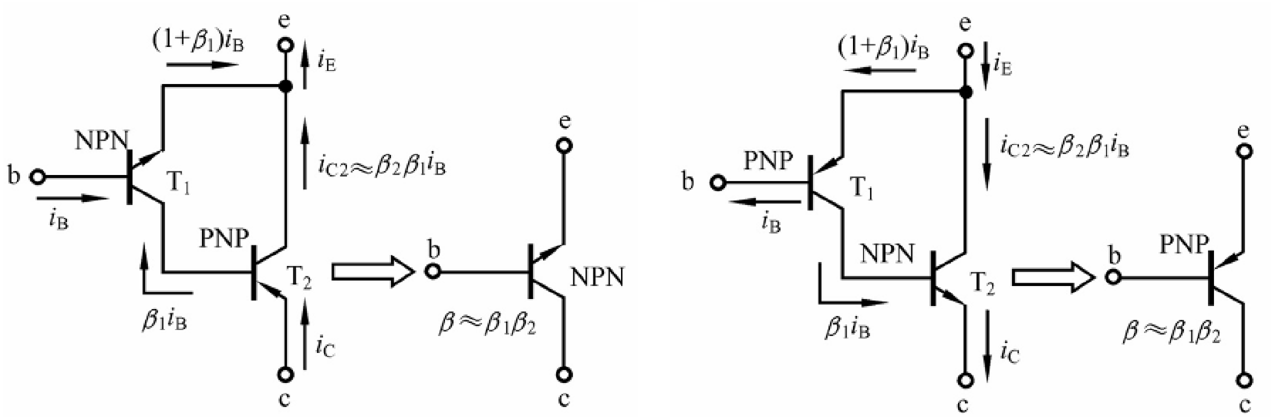
5.6 Model of Small Signal



When $T = 300$ K

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

5.7 Compound Transistor

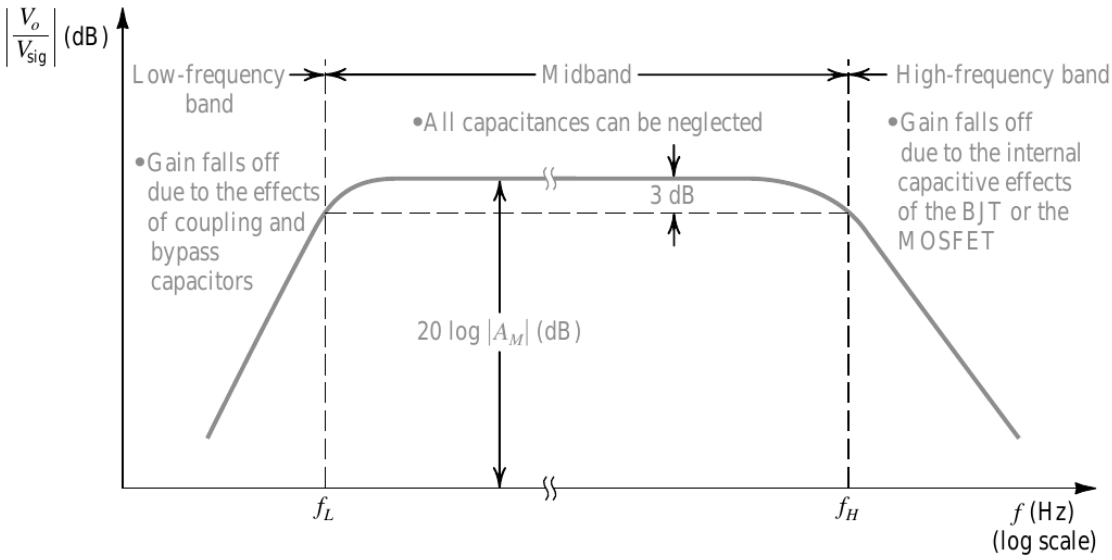


Noted that the emitter and base of compound transistor is exactly the same as the first transister's.

Chapter 6

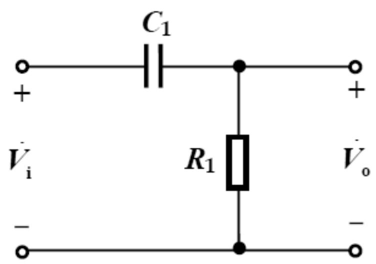
Frequency Response

6.1 Sketch of Gain vs Frequency of All Circuits



6.2 R-C Series Circuit

6.2.1 Low-Frequency Response of R-C High Pass Filter



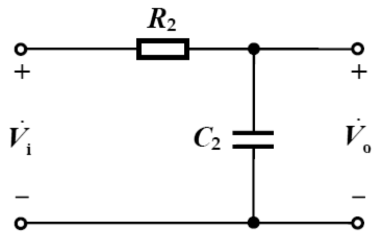
$$f_L = \frac{1}{2\pi R_1 C_1} \qquad |A_{vL}| = \frac{1}{\sqrt{1+(f_L/f)^2}} \qquad \varphi_L = \arctan{(f_L/f)}$$

6.2.2 Mid-Frequency

In mid-frequency, capacitors are equal to open circuit while only resistors remain in the circuit. Where

$$A_{vM} = 1 \qquad \varphi = 0$$

6.2.3 High-Frequency Response of R-C Low Pass Filter

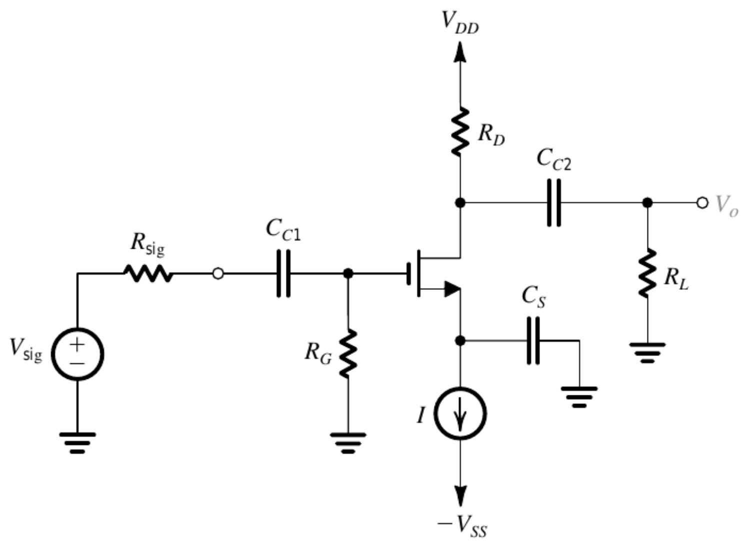


$$f_H = \frac{1}{2\pi R_1 C_1} \qquad |A_{vH}| = \frac{1}{\sqrt{1+(f_H/f)^2}} \qquad \varphi_H = -\arctan(f_H/f)$$

6.3 Frequency Response of Amplifiers

6.3.1 Low-Frequency

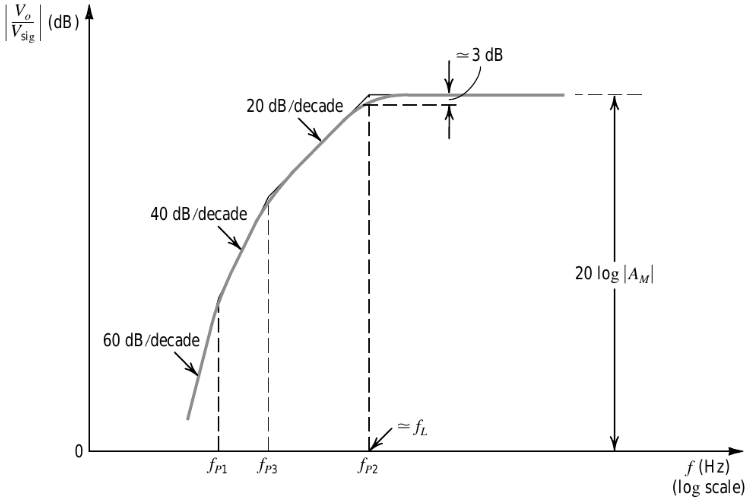
Common-Source Amplifier



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

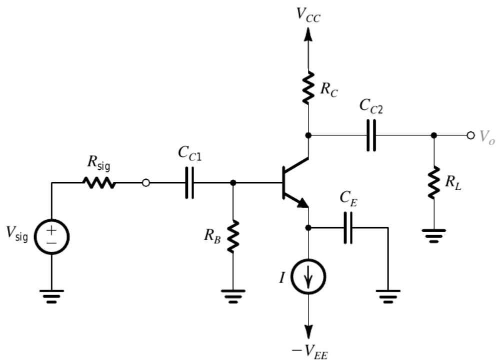
$$\omega_{p1} = \frac{1}{C_{C1}\left(R_G + R_{sig}\right)}$$
$$\omega_{p2} = \frac{g_m}{C_S}$$
$$\omega_{p3} = \frac{1}{C_{C2}\left(R_D + R_L\right)}$$

$$\frac{V_o}{V_{sig}} = A_M \left(\frac{s}{s+\omega_{p1}}\right)\left(\frac{s}{s+\omega_{p2}}\right)\left(\frac{s}{s+\omega_{p3}}\right)$$



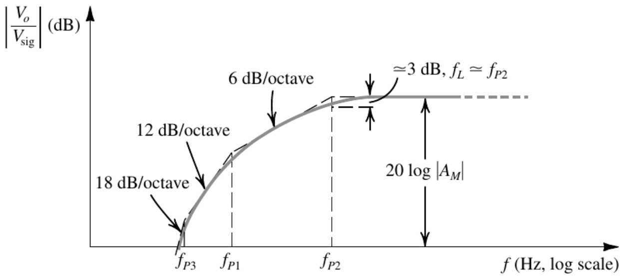
$$f_L \approx f_{p2} = \frac{\omega_{p2}}{2\pi} = \frac{1}{2\pi\left(C_S/g_m\right)}$$

Common-Emitter Amplifier



$$A_M = -\frac{(R_B \parallel r_\pi)}{(R_B \parallel r_\pi)\, R_{sig}} g_m \left(R_C \parallel R_L\right)$$

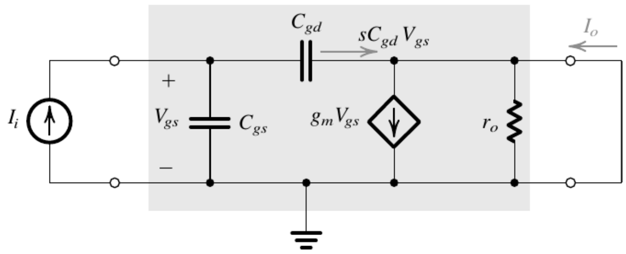
$$\omega_{p1} = \frac{1}{C_{C1}\left[(R_B \parallel r_\pi) + R_{sig}\right]}$$
$$\omega_{p2} = \frac{1}{C_E\left[r_e + \dfrac{R_B \parallel R_{sig}}{\beta+1}\right]}$$
$$\omega_{p3} = \frac{1}{C_{C2}\left(R_C + R_L\right)}$$



$$f_L \approx f_{p2}$$

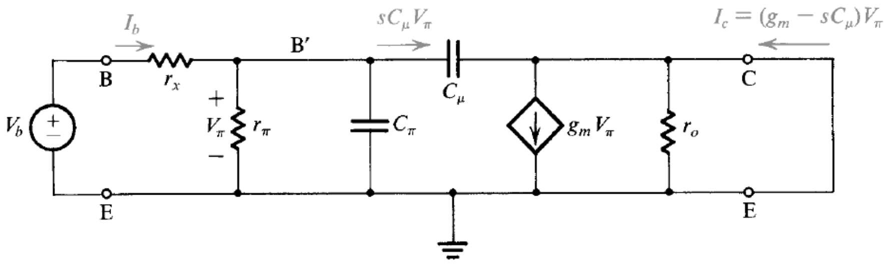
6.3.2 High-Frequency

Unity-Gain Frequency



MOSFET

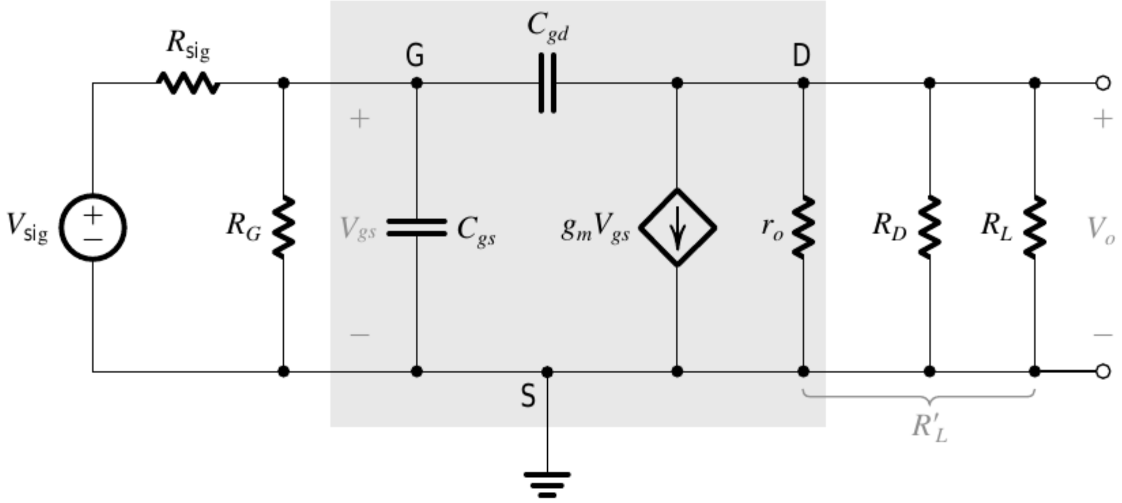
$$\frac{I_o}{I_i} = \frac{g_m}{s\left(C_{gs}+C_{gd}\right)} \qquad \omega_T = \frac{g_m}{\left(C_{gs}+C_{gd}\right)} \qquad f_T = \frac{g_m}{2\pi\left(C_{gs}+C_{gd}\right)}$$

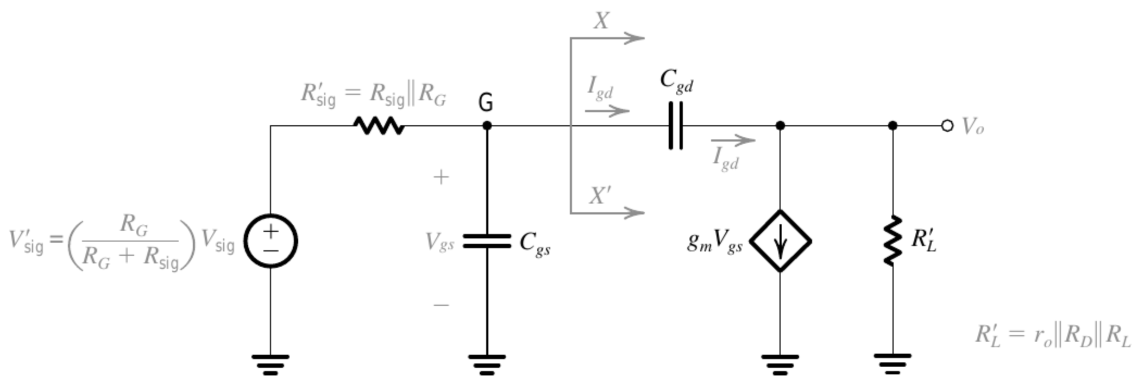


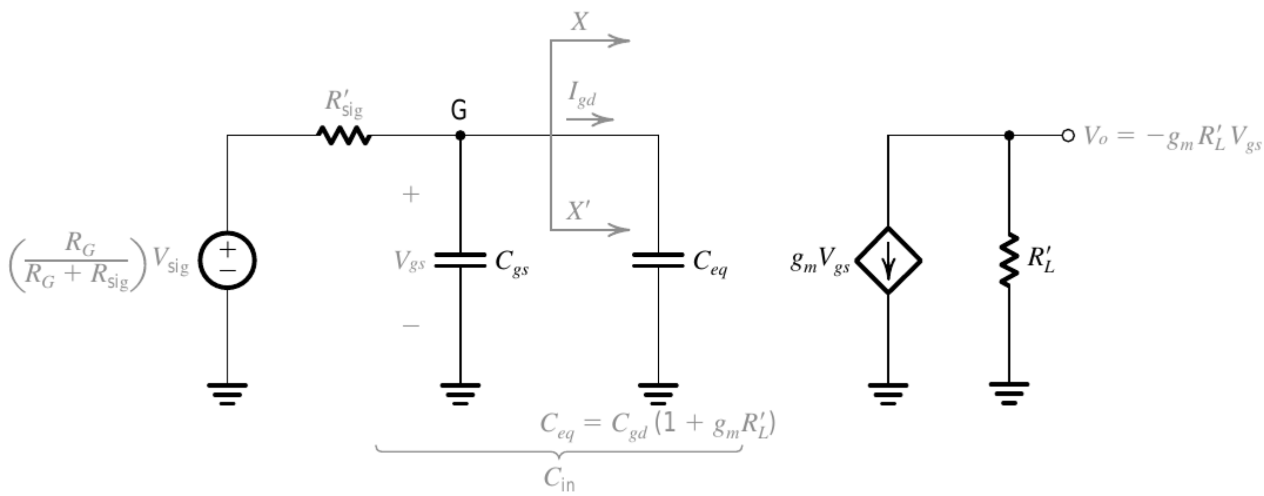
BJT

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

Common-Source Amplifier

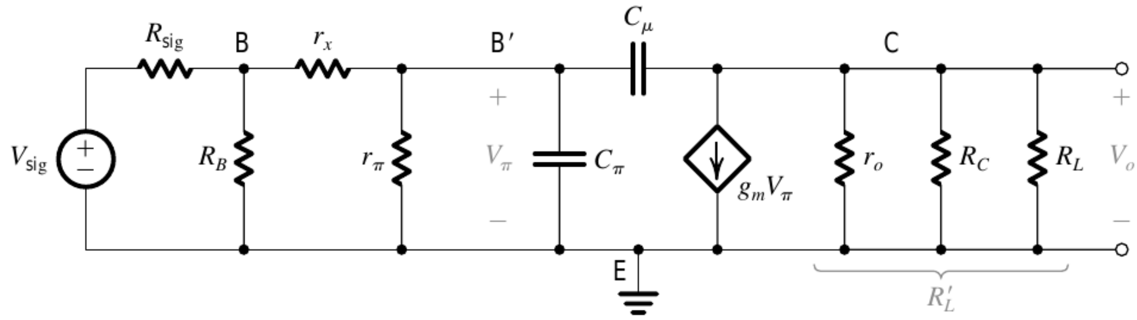


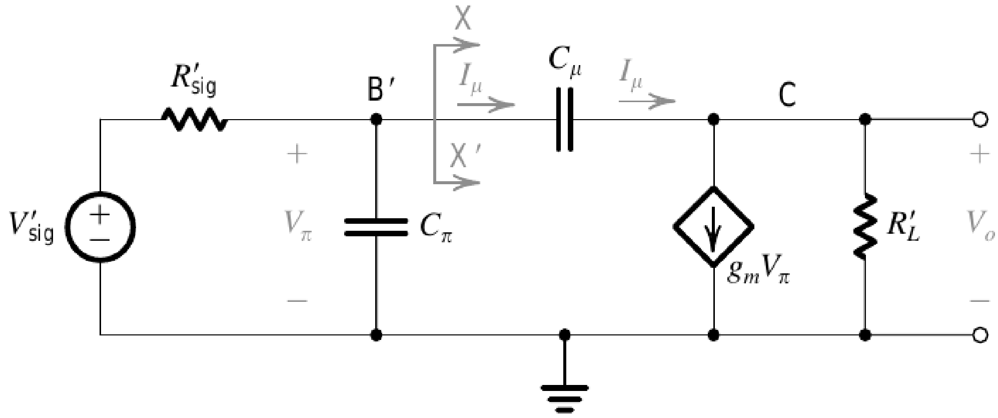




$$\omega_H = \frac{1}{C_{in} R'_{sig}} \qquad A_M = -\frac{R_G}{R_G + R_{sig}} g_m R'_L \qquad f_H = \frac{\omega_H}{2\pi} = \frac{1}{2\pi C_{in} R'_{sig}}$$

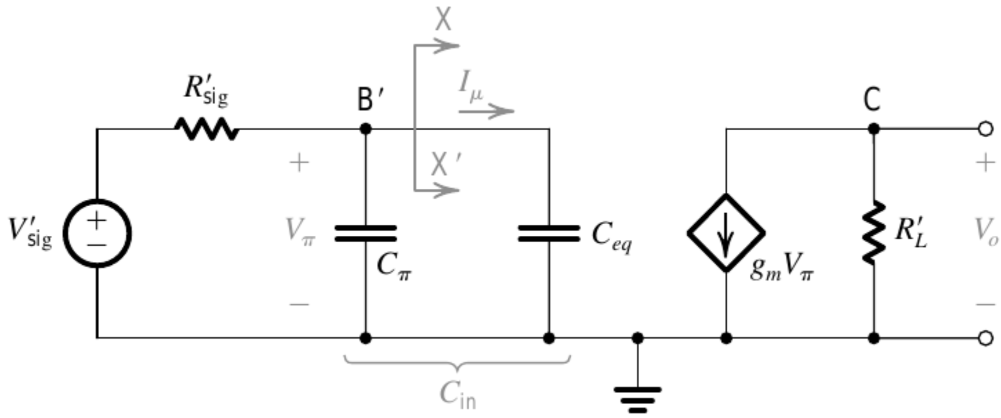
Common-Emitter Amplifier





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

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



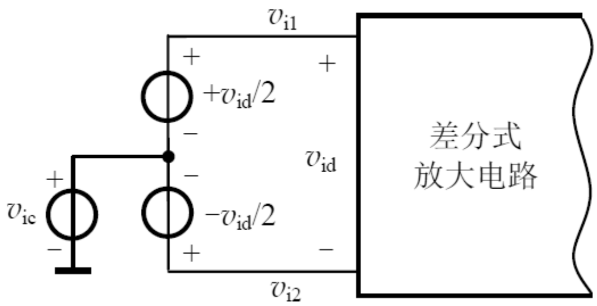
$$C_{in} = C_\pi + C_{eq} \qquad V_o = -g_m R'_L V_\pi$$
$$= C_\pi + C_\mu(1 + g_m R'_L)$$

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

Chapter 7

Analogue Integrated Circuits

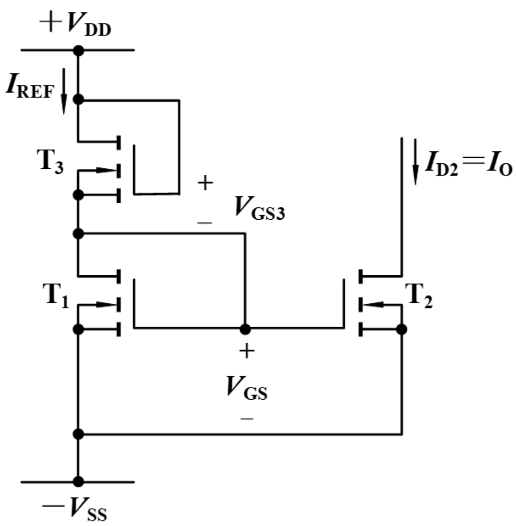
7.1 Differential Amplifier Circuit



$$v_{i1} = v_{ic} + \frac{v_{id}}{2} \qquad v_{i2} = v_{ic} - \frac{v_{id}}{2}$$

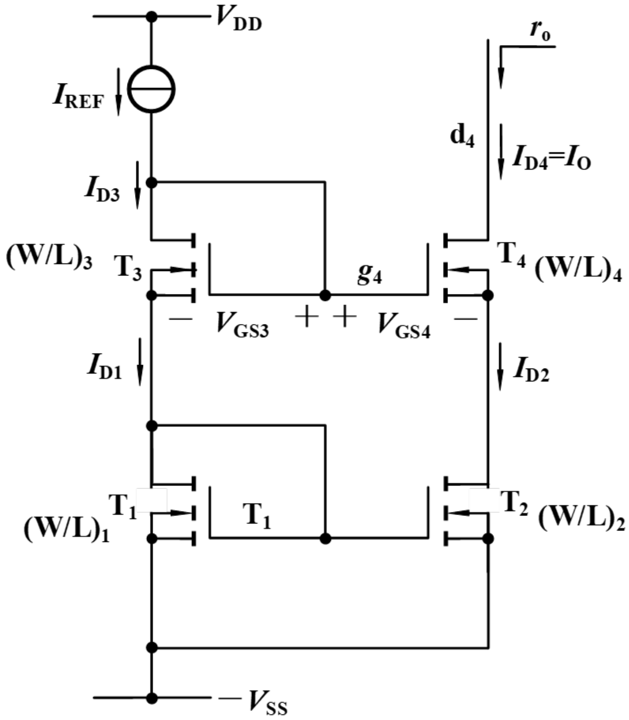
7.2 MOSFET Current Source

7.2.1 MOSFET Current Mirror



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

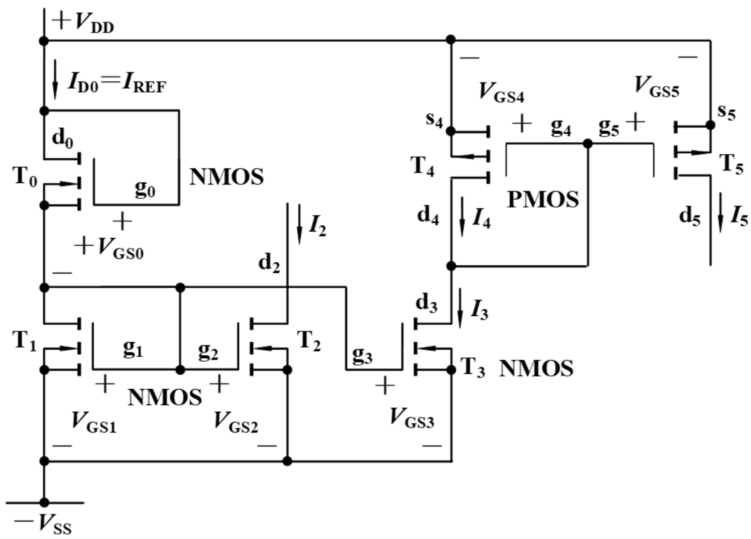
7.2.2 Cascade Current Mirror



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

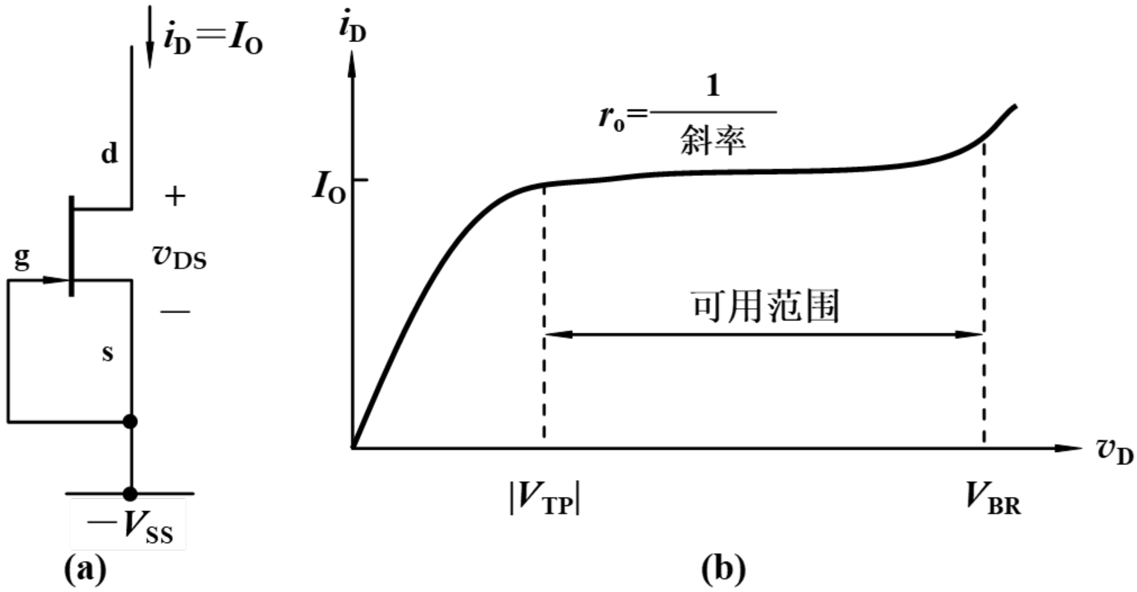
$$r_o = r_{ds4} + r_{ds2}\left(1 + g_m r_{ds4}\right) \approx g_m r_{ds4} r_{ds2}$$

7.2.3 Combined Current Mirror



$$I_2 = \frac{(W/L)_2}{(W/L)_1} I_{REF} \qquad I_3 = \frac{(W/L)_3}{(W/L)_1} I_{REF} \qquad I_4 = I_3 \qquad I_5 = \frac{(W/L)_5}{(W/L)_4} I_4$$

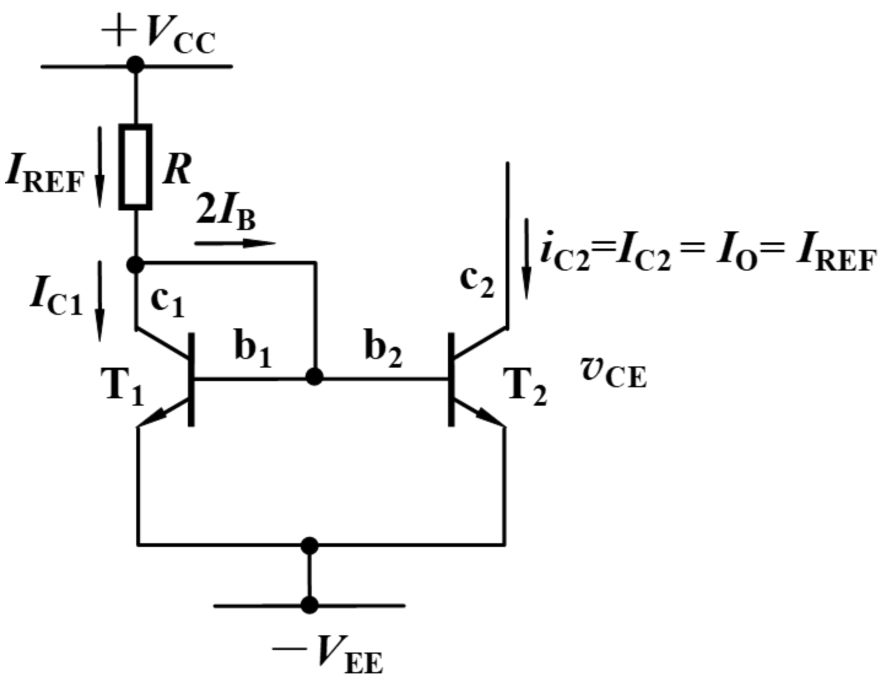
7.2.4 JFET Current Mirror



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

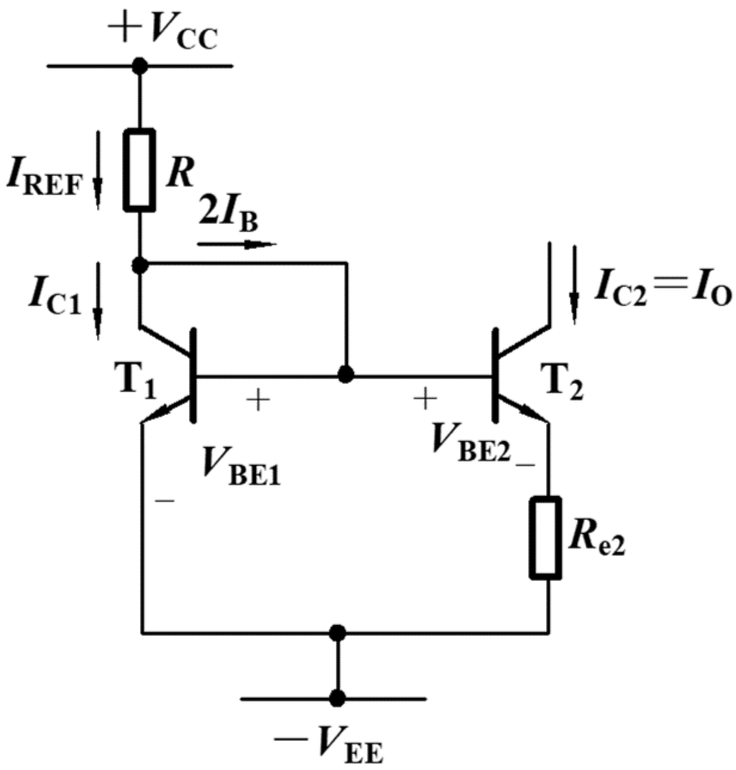
7.3 BJT Current Source

7.3.1 BJT Current Mirror



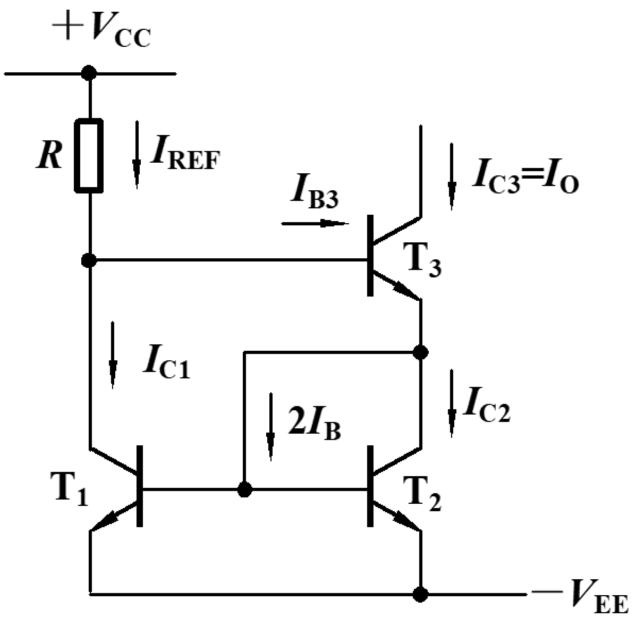
$$I_{C2} = I_{C1} \approx I_{REF} \approx \frac{V_{CC}}{R} \qquad r_o = r_{ce}$$

7.3.2 Micro Current Source



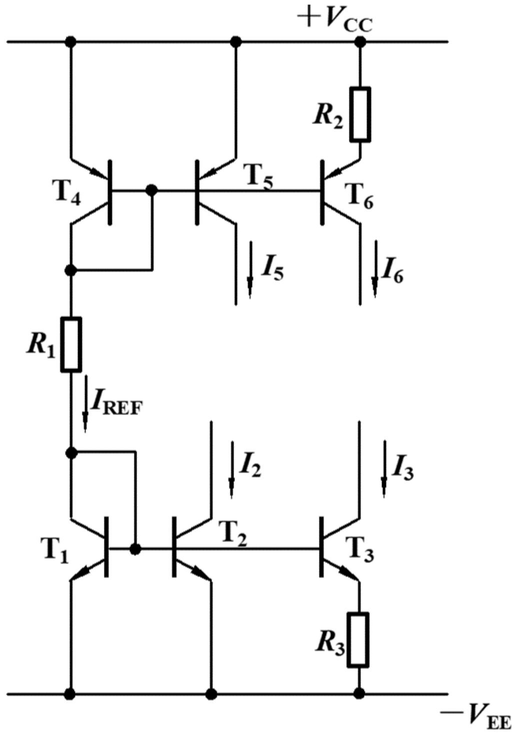
$$I_o = \frac{\Delta V_{BE}}{R_{e2}} \qquad r_o \approx r_{ce2} + \left(1 + \frac{\beta R_{e2}}{r_{be2} + R_{e2}}\right)$$

7.3.3 Current Source with High Output Resistance



$$I_{REF} = \frac{V_{CC} - V_{BE3} - V_{BE2} + V_{EE}}{R} \qquad I_o \approx I_{C2} = \frac{A_3}{A_1} \cdot I_{REF}$$

7.3.4 Combined Current Source

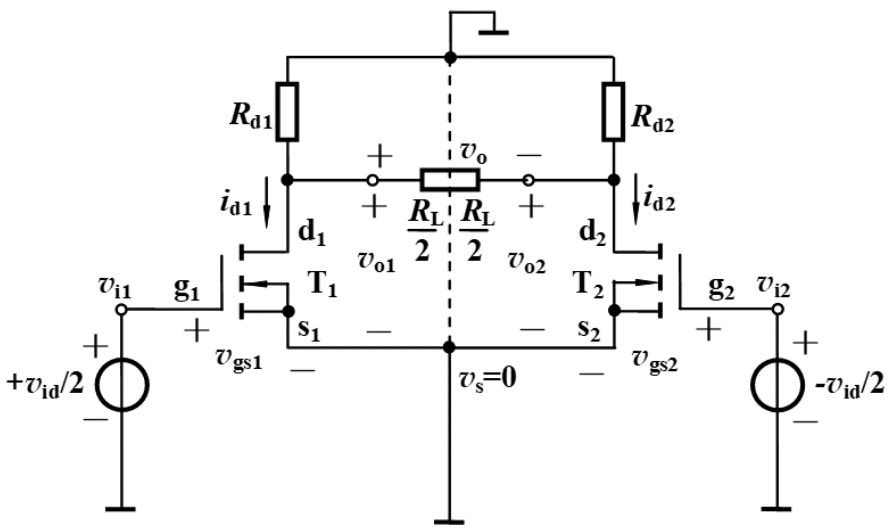


$$I_{REF} = \frac{V_{CC} + V_{EE} - V_{BE1} + V_{EB4}}{R_1}$$

7.4 Differential Amplifier

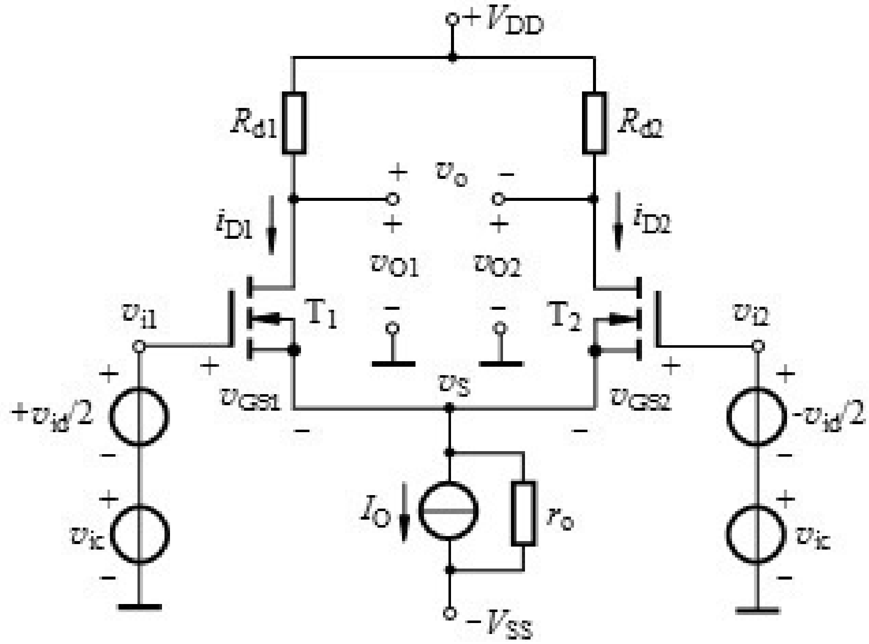
7.4.1 MOSFET

Two Output Terminals



$$i_{d1} = i_{d2} = I_D = \frac{1}{2} I_o \qquad g_m = \sqrt{2K_n I_o} \qquad A_{vd} = -g_m \left(r_{ds} \parallel R_d \parallel \frac{R_L}{2} \right) \qquad K_{CMR} = \infty \qquad R_o = 2R_d$$

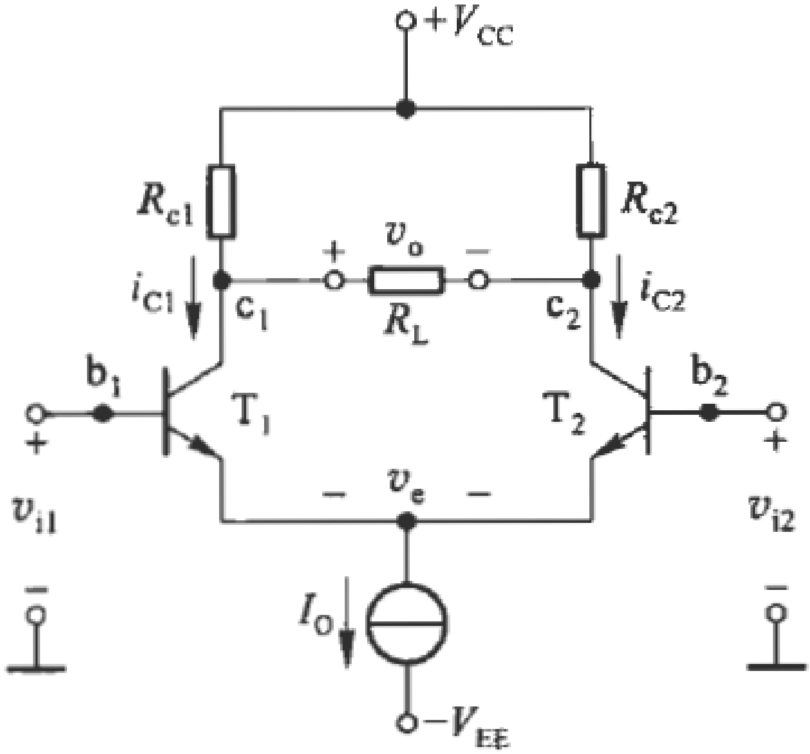
One Output Terminal



$$g_m = \sqrt{2K_nI_o} \qquad A_{vd1} = -A_{vd2} = -\frac{g_m\,(r_{ds} \parallel R_d \parallel R_L)}{2} \qquad K_{CMR} \approx g_m r_o \qquad R_o = R_d$$

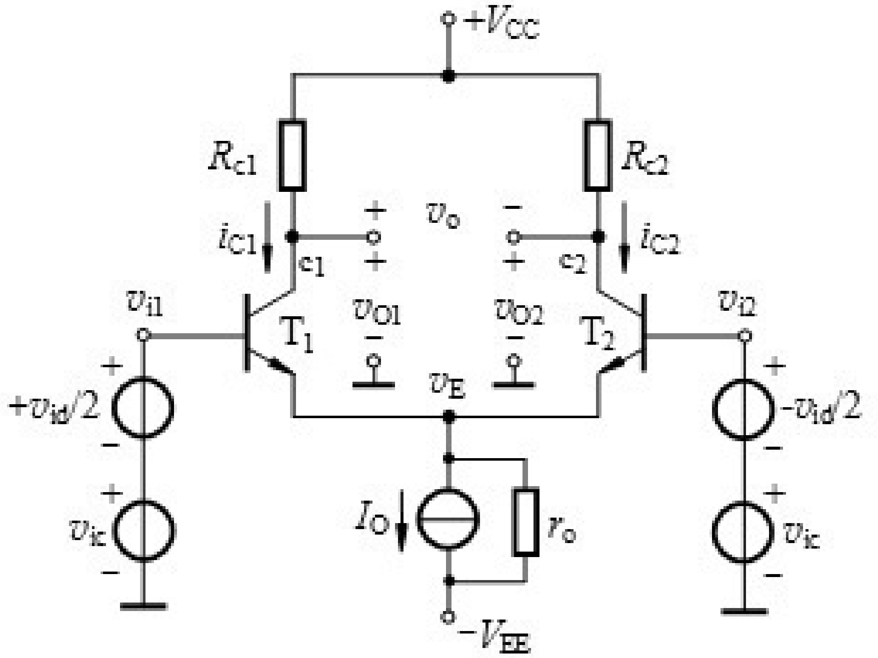
7.4.2 BJT

Two Output Terminals



$$A_{vd} = -\frac{\beta\left(R_c \parallel \dfrac{R_L}{2}\right)}{r_{be}} \qquad K_{CMR} = \infty \qquad R_{id} = 2r_{be} \qquad R_{ic} = \frac{1}{2}\left[r_{be} + (1+\beta)\,2r_o\right] \qquad R_o = 2R_c$$

One Output Terminal

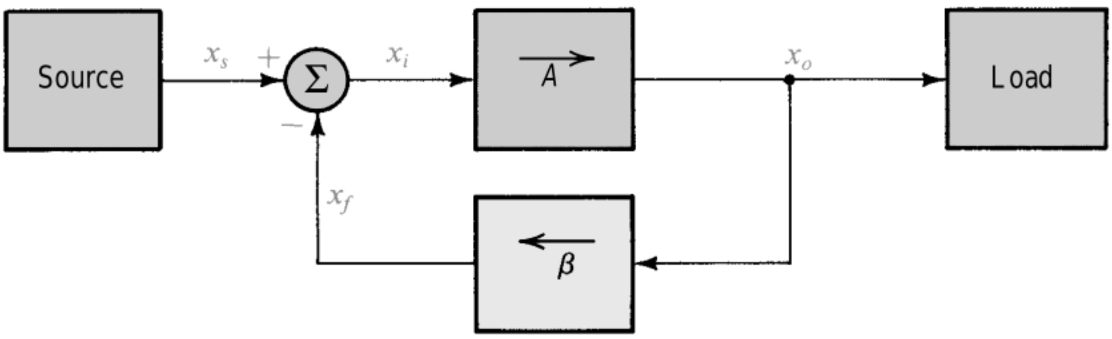


$$A_{vd1} = -A_{vd2} = -\frac{\beta\left(R_c \parallel R_L\right)}{2r_{be}} \qquad K_{CMR} \approx \frac{\beta r_o}{r_{be}} \qquad R_{id} = 2r_{be} \qquad R_{ic} = \frac{1}{2}\left[r_{be} + (1+\beta)\,2r_o\right] \qquad R_o = R_c$$

Chapter 8

Feedback

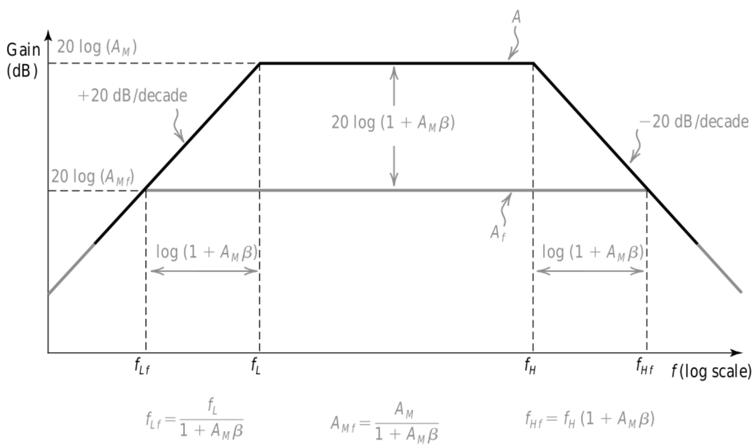
8.1 Basic Feedback Structure



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

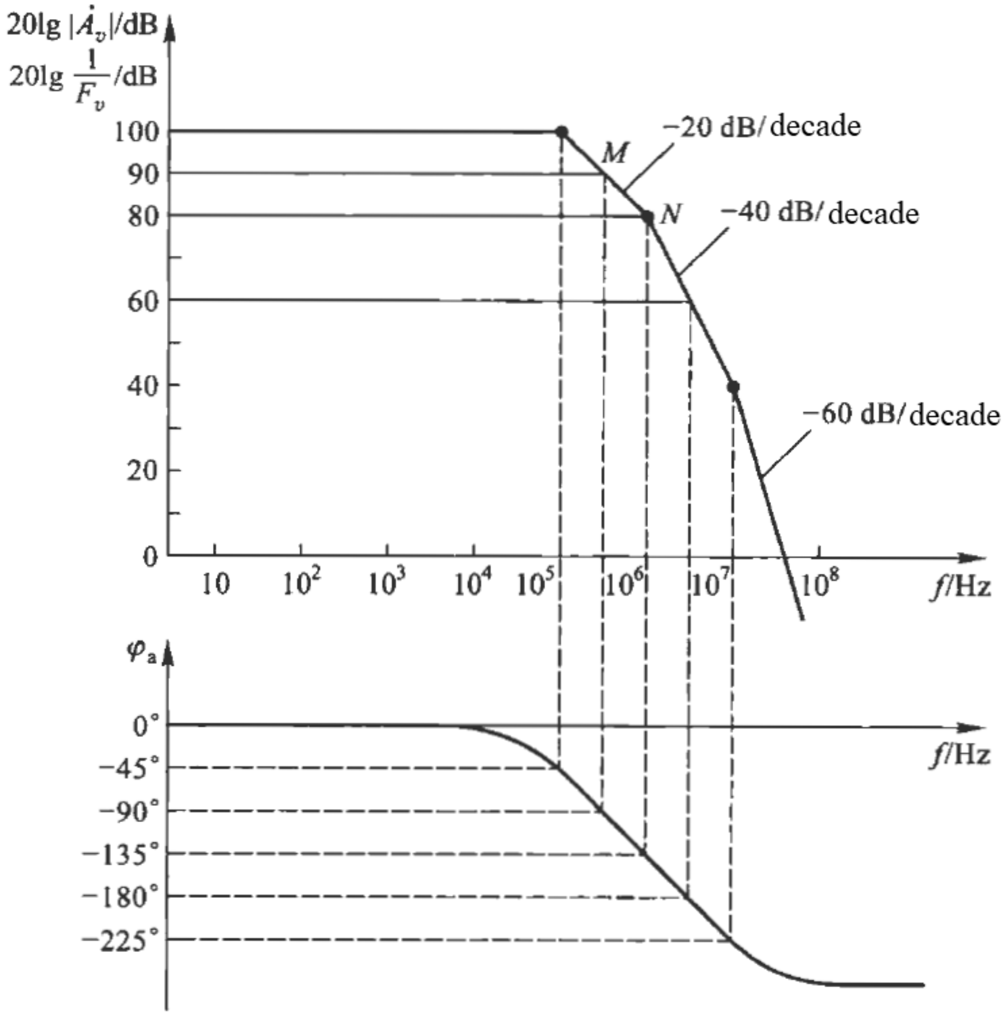
$$A_f = \frac{x_0}{x_s} = \frac{Ax_i}{x_i + \beta A x_i} = \frac{A}{1 + A\beta} \approx \frac{1}{\beta} \qquad (A\beta \gg 1)$$

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 Stability Problem of Feedback



$$\varphi_a = -135^\circ \qquad AF < 1$$

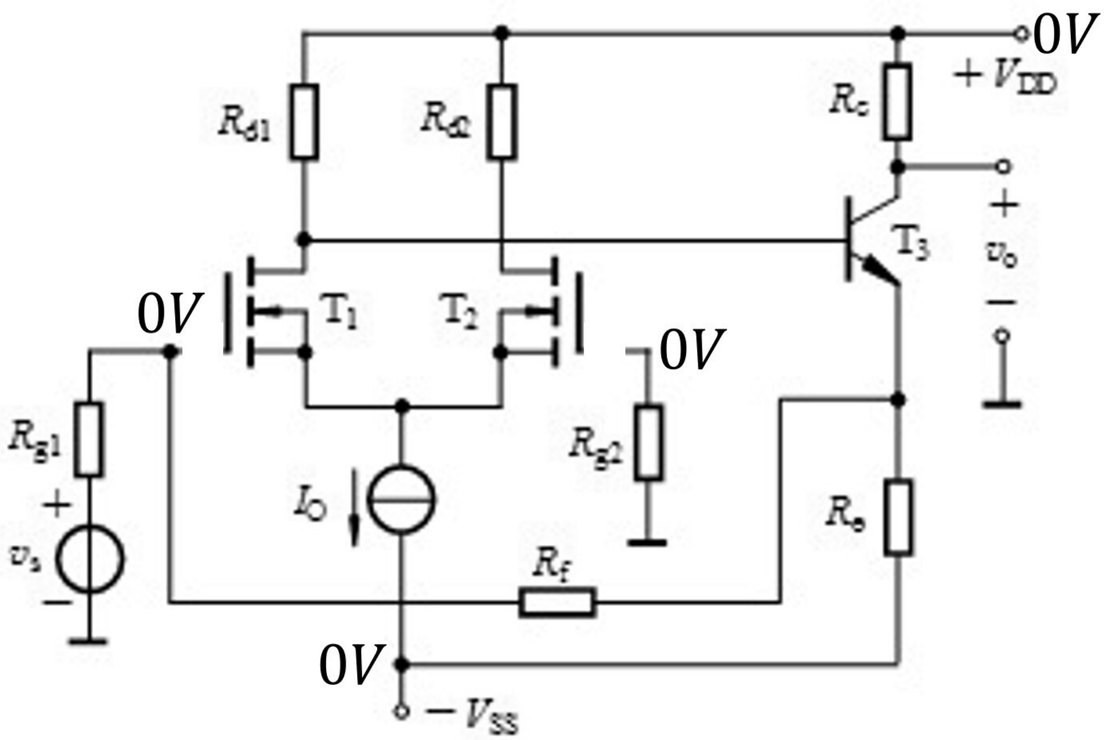
8.4 Four Basic Feedback Topologies

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	$A_f = \dfrac{A}{1+A\beta}$	$R_{if} = \dfrac{R_i}{1+A\beta}R_i$	$R_{of} = \dfrac{R_o}{1+A\beta}$

8.5 Positive or Negative

Amplifier Type	Common S	Common G	Common D	Common E	Common B	Common C
Sign of A_v	−	+	+	−	+	−

8.6 Virtual Short and Open Circuit of Amplifier in the State of Deep Negative Feedback

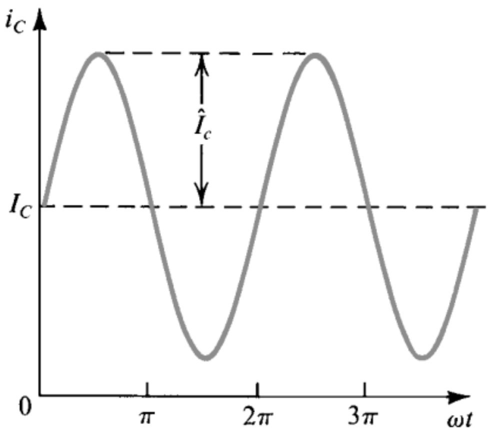


Chapter 9

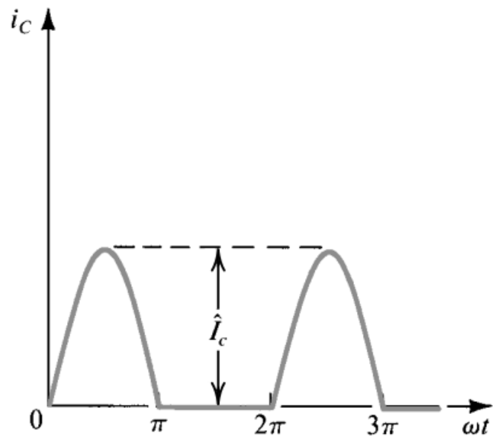
Power Amplifiers

9.1 Classfication of Power Amplifiers

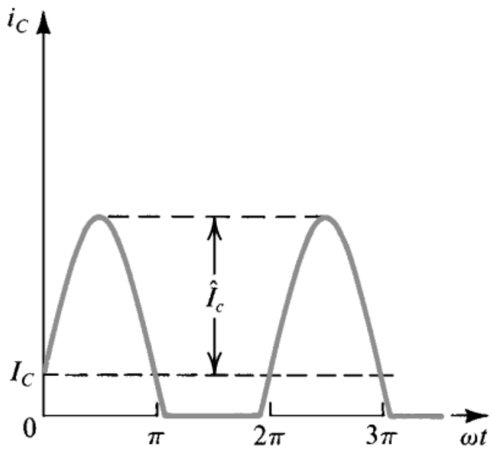
Output stages are classified according to the collector current waveform that results when an input signal is applied.



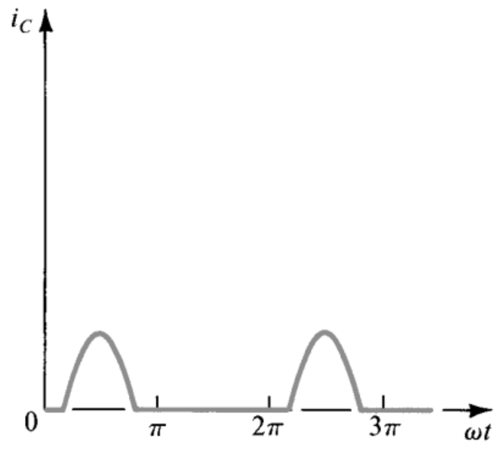
(a) Class A



(b) Class B

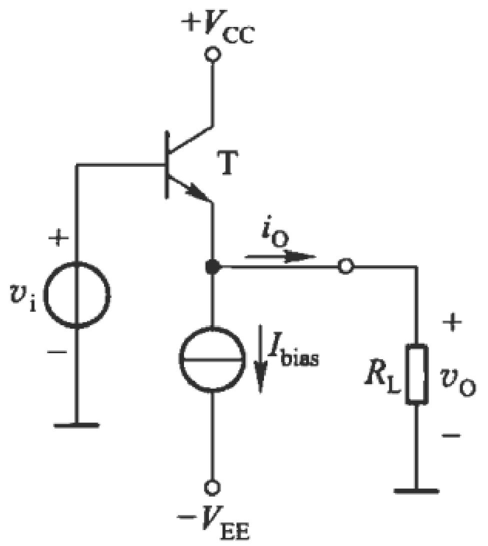


(a) Class AB

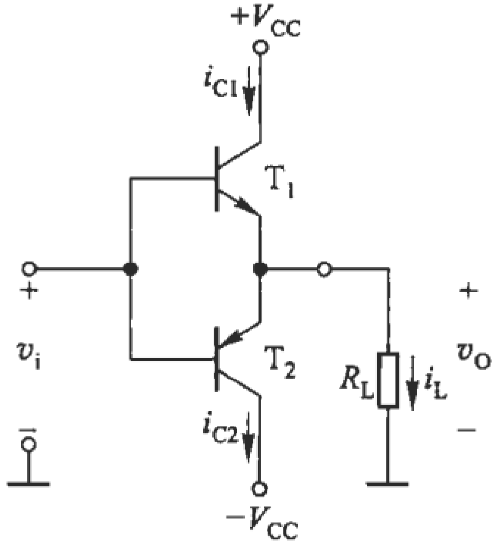


(b) Class C

9.2 Some Example Circuits



(a) Class A Output Stage



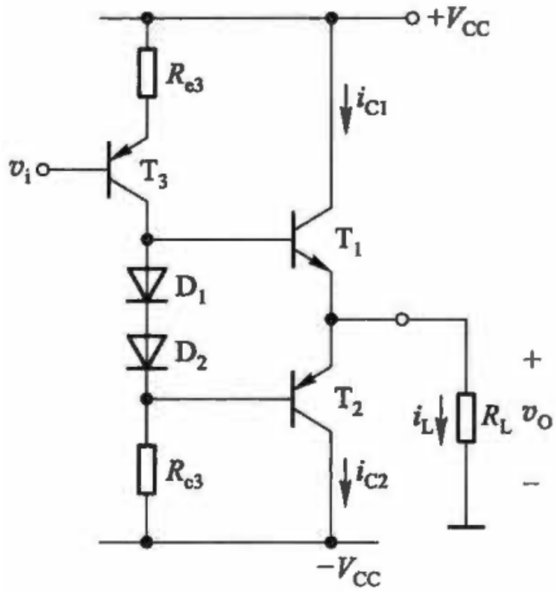
(b) Class B Output Stage

9.3 Power Output

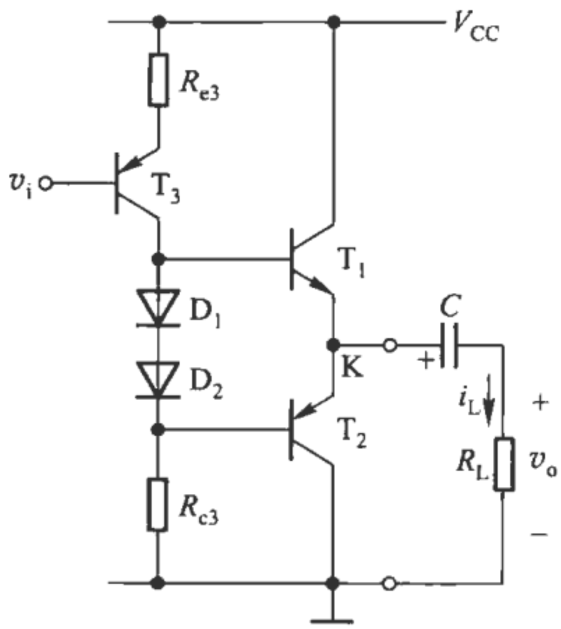
$$V_{om} = \frac{V_{om+} + V_{om-}}{2}$$

$$P_{om} = \left(\frac{V_{om}}{\sqrt{2}}\right)^2 \cdot \frac{1}{R_L}$$

9.4 Crossover Distortion Avoiding



(a) Class AB Output Stage with Double Source

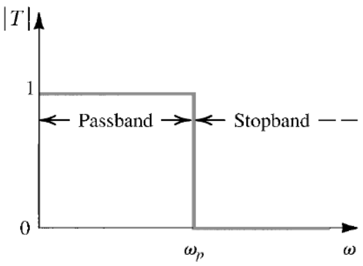


(b) Class AB Output Stage with Single Source

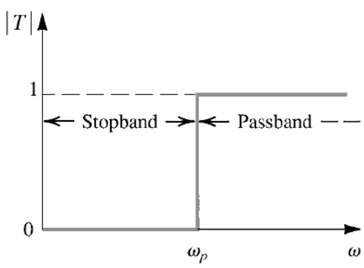
Chapter 10

Filters and Signal Generators

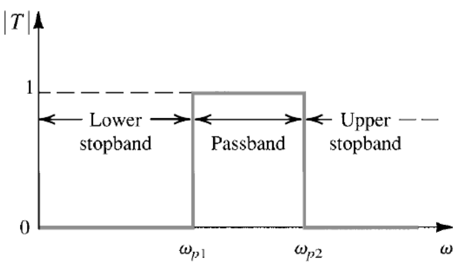
10.1 Four Types of Filters



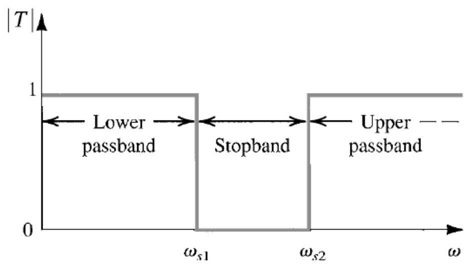
(a) Low-pass (LP)



(b) High-pass (HP)

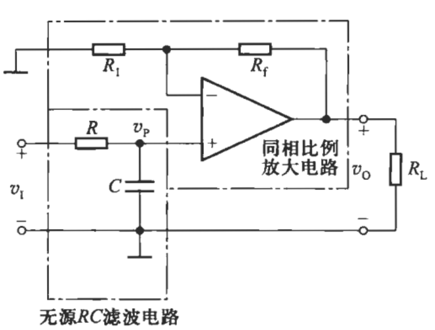


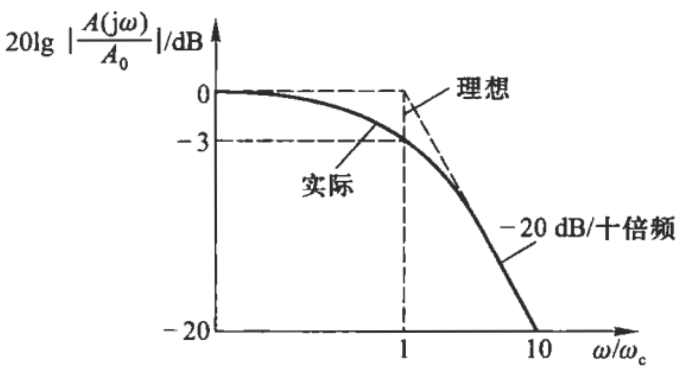
(c) Bandpass (BP)



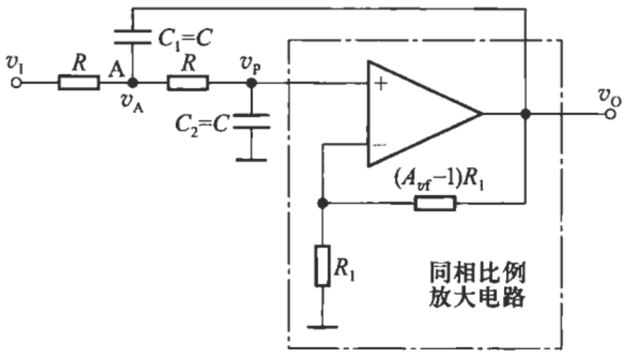
(d) Bandstop (BS)

10.2 Filter with source

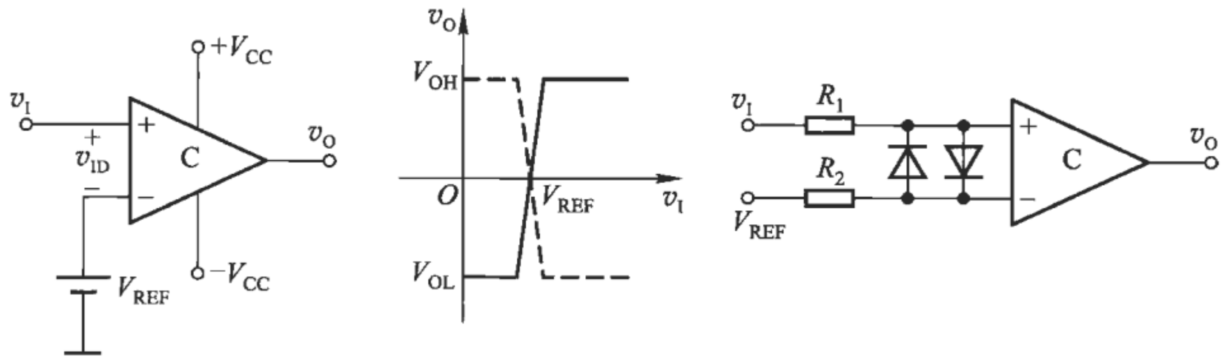




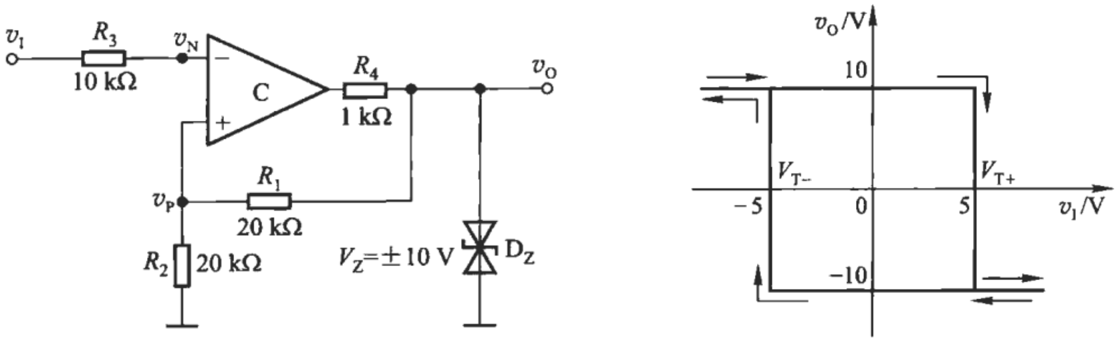
10.3 Sallen-Key Filtering Circuit



10.4 Voltage Comparator

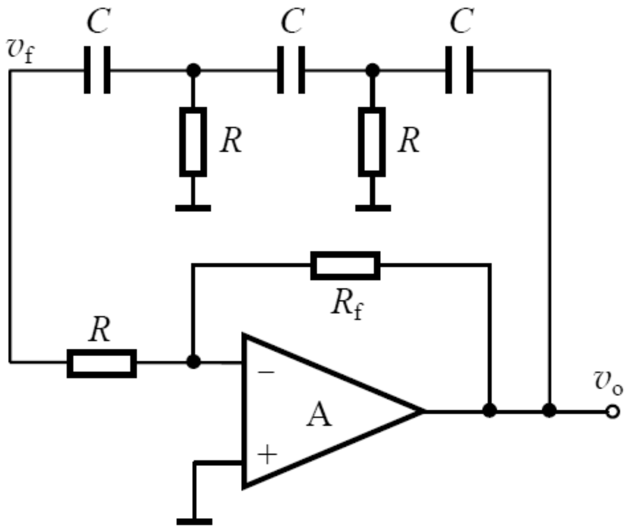


10.5 Inverting Schmitt Trigger

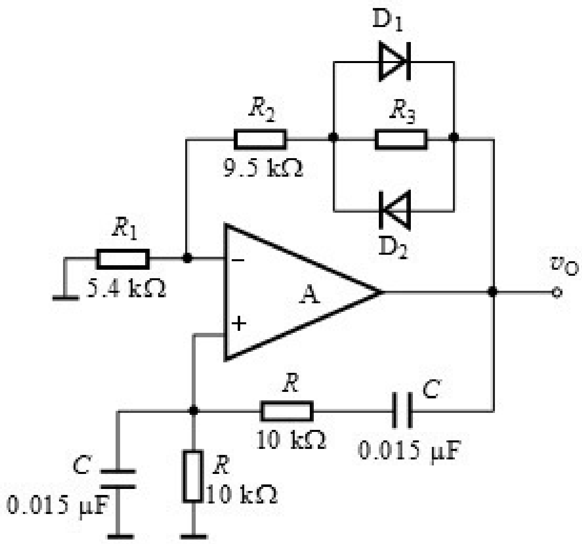


10.6 RC Phase Shifting Network

There are 3 this kind of network below, each may generate up to 90° phase shift.

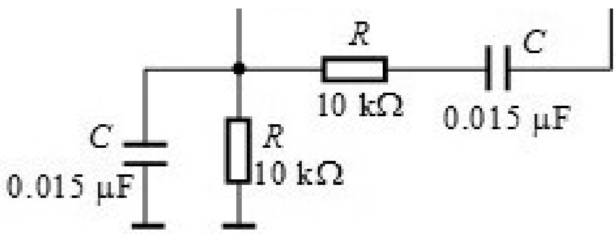


10.7 Stability of RC Oscillator



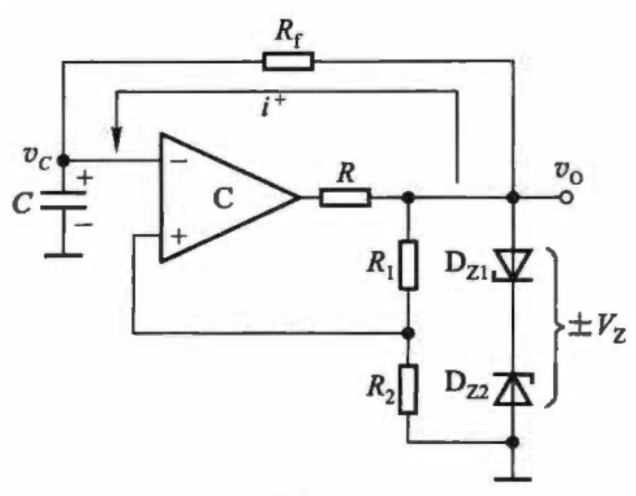
$$A_V = 1 + \frac{R_2 + R_3}{R_1} > 3$$

10.8 RC Phase Selecting Network

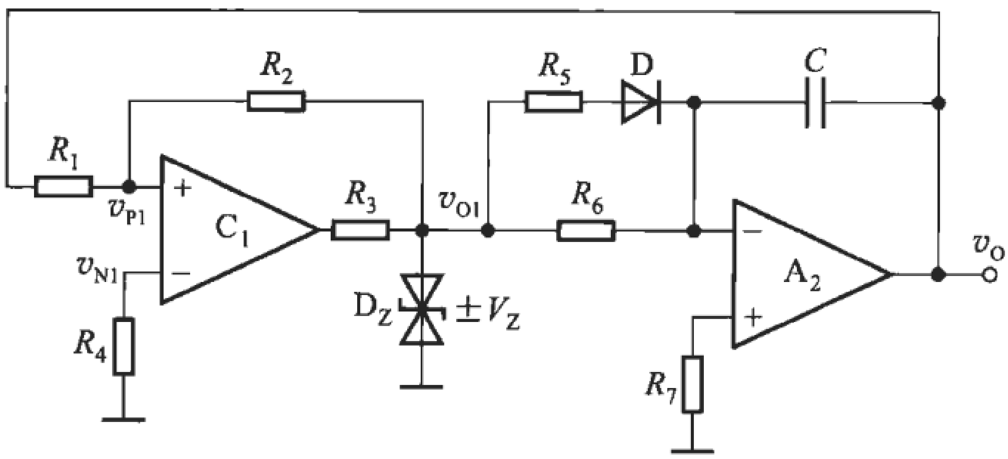


$$f = \frac{1}{2\pi RC}$$

10.9 Generation of Square Waveforms



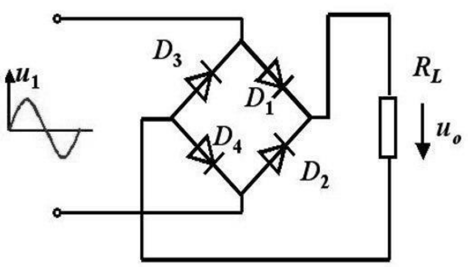
10.10 Generation of Triangle Waveforms

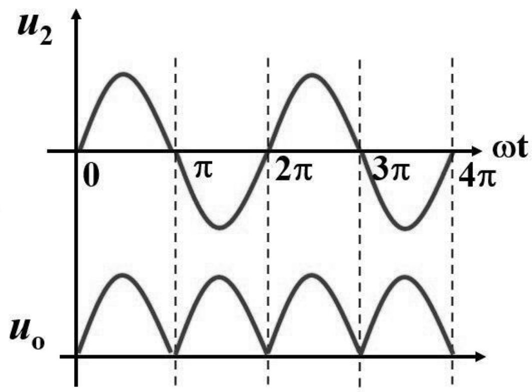


Chapter 11

Stability Problem of DC Source

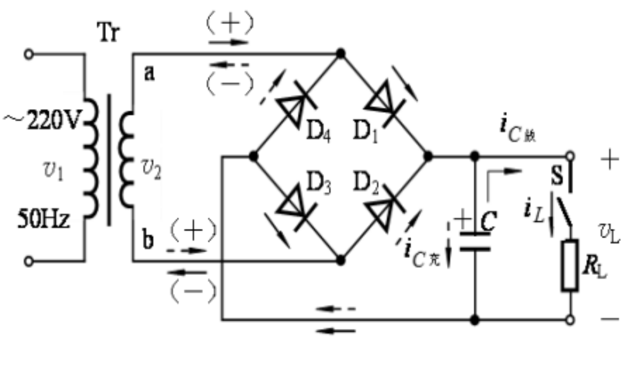
11.1 The Bridge Rectifier

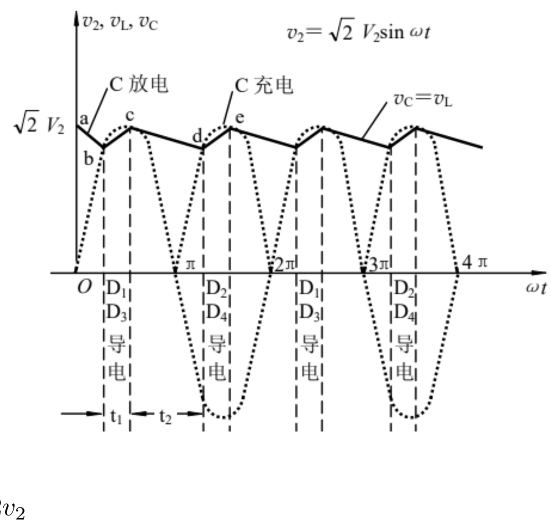




$$V_L \approx 0.9V_S \qquad\qquad I_{DI} = I_{D2} = I_{D3} = I_{D4} = \frac{0.45V_S}{R_L}$$

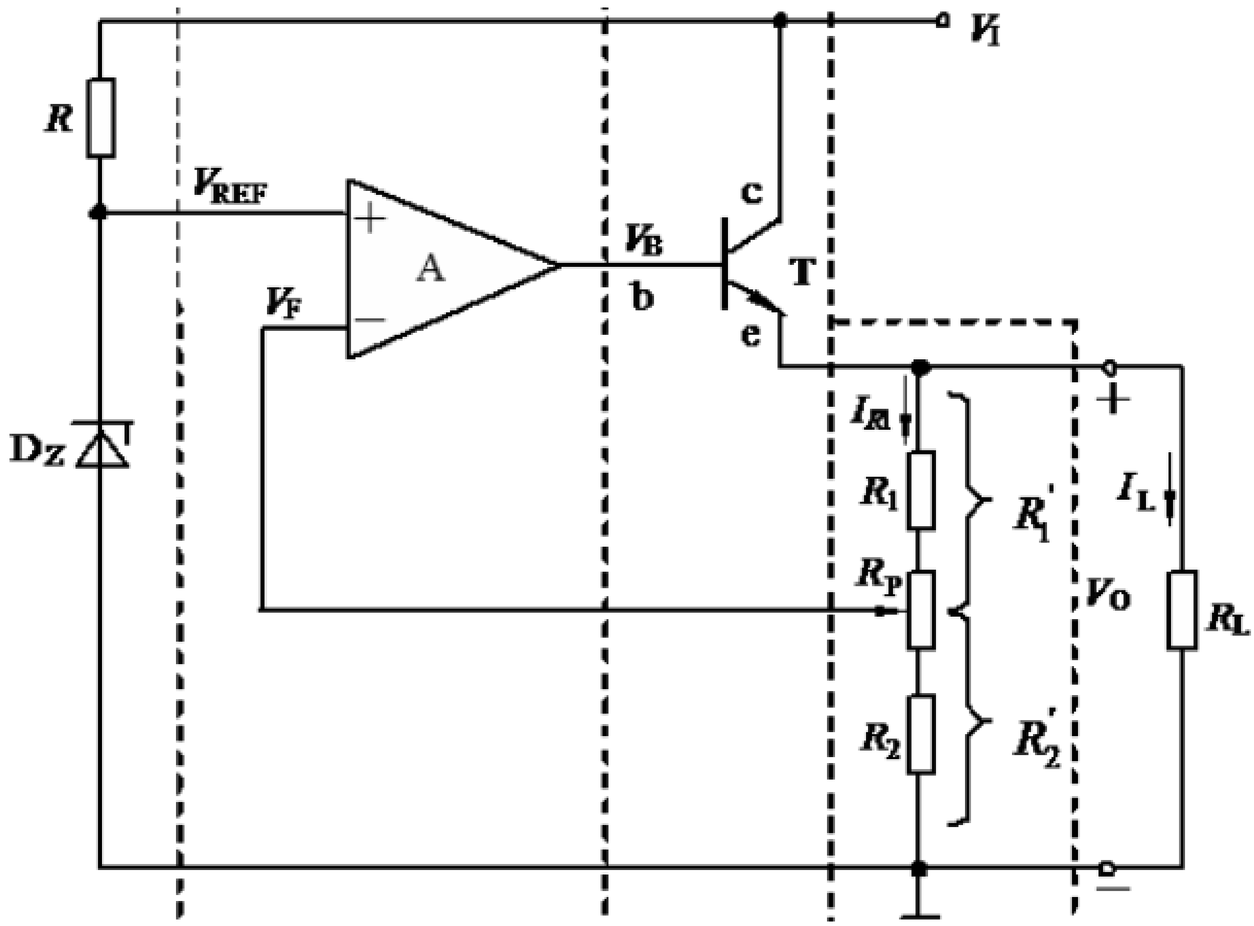
11.2 Single Phase Bridge Rectifier





$$v_L = 1.2v_2$$

11.3 Series Feedback Voltage Regulator



$$V_O = V_{REF}\left(1 + \frac{R_1}{R_2}\right)$$

11.4 Integrated Voltage Regulator