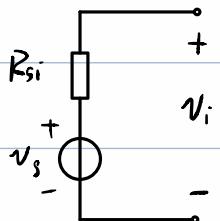


# § 1 谱论

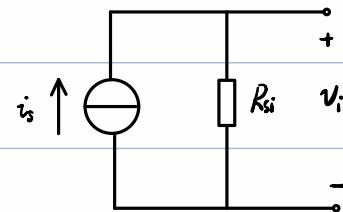
## 1 信号

传感器: 非电信号  $\rightarrow$  电信号 | 电压  
 $\downarrow$   
 信源

### ① 戴维宁等效电路



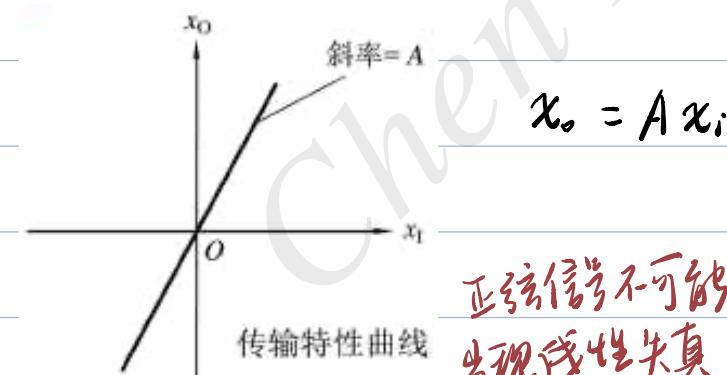
### ② 诺顿等效电路



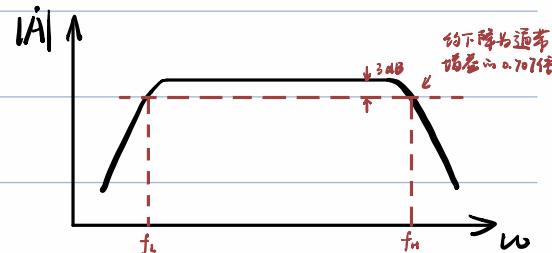
模拟信号  $\rightarrow$  连续函数

{ 时域: 平均值小, 直流分量小  
 { 频域

## 2 信号的线性放大



正弦信号不可能  
 出现线性失真



{ 频率失真 / 线性失真 { 中幅度失真 用幅频响应曲线描述  
 { 由线性寄生元件引起 相位失真 相频响应曲线  
 非线性失真

△ 区别: 频率失真不会产生输入信号没有的新频率分量  
 非线性失真会出现新的高次谐波分量

只有在一定的中值范围内和频率范围内，  
 A才能基本保持常数

### 3 放大电路模型

$$\text{电压增益 } A_v = \frac{v_o}{v_i}$$

$$20 \lg |A_v| \text{ dB}$$

$$\text{电流增益 } A_i = \frac{i_o}{i_i}$$

$$20 \lg |A_i| \text{ dB}$$

$$\text{互阻增益 } A_r = \frac{v_o}{i_i} \quad (r)$$

$$\text{互导增益 } A_g = \frac{i_o}{v_i} \quad (s)$$

$$\text{功率增益 } A_p = \frac{P_o}{P_i}$$

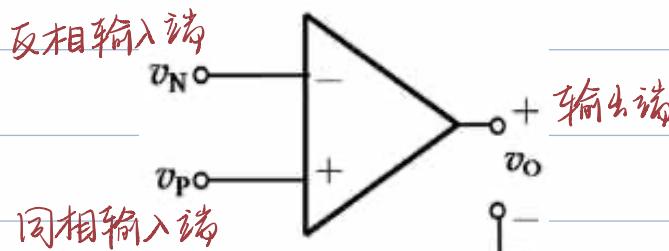
$$10 \lg A_p \text{ dB}$$

	电路模型	增益	对输入 电阻 要求	对输出 电阻 要求	适用 场合
电压放大		$A_v = \frac{v_o}{v_i} = A_m \frac{R_L}{R_L + R_o}$	$R_i$ 越大越好	$R_o$ 越小越好	电压信号源，电压驱动型负载
电流放大		$A_i = \frac{i_o}{i_i} = A_m \frac{R_o}{R_L + R_o}$	$R_i$ 越小越好	$R_o$ 越大越好	电流信号源，电流驱动型负载
互阻放大		$A_r = \frac{v_o}{i_i} = A_m \frac{R_L}{R_L + R_o}$	$R_i$ 越小越好	$R_o$ 越小越好	电流信号源，电压驱动型负载
互导放大		$A_g = \frac{i_o}{v_i} = A_m \frac{R_o}{R_L + R_o}$	$R_i$ 越大越好	$R_o$ 越大越好	电压信号源，电流驱动型负载

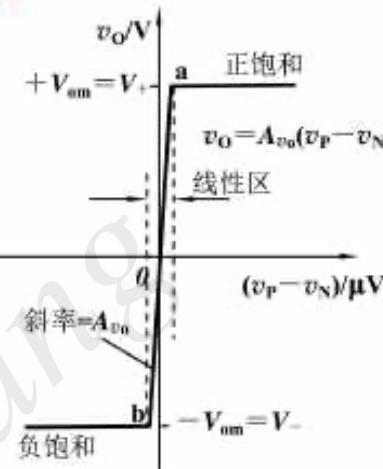
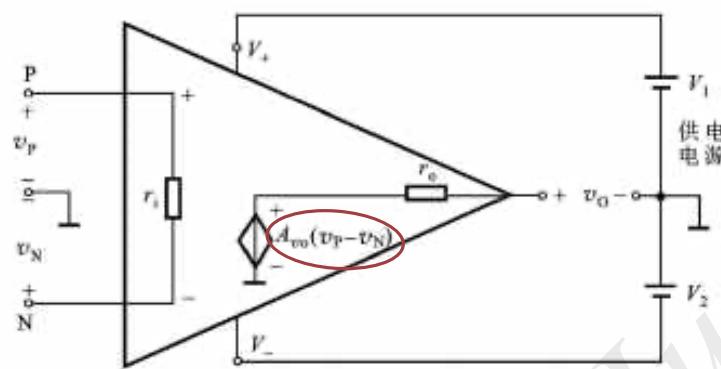
## §2 运算放大器

### I 运算放大器及其信号放大

#### (1) 运放的基本特性



同相 / 反相  
指输入端与输出端  
的相位关系



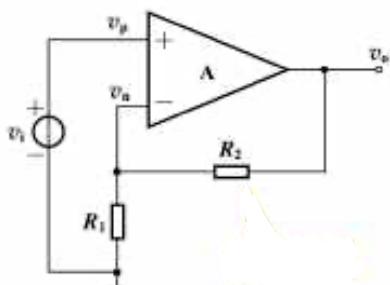
理想模型  $A_{vo} \rightarrow \infty$ ,  $r_i \rightarrow \infty$ ,  $r_o \rightarrow 0$ ,  $BW \rightarrow \infty$

在线性区  $v_P \approx v_N$  虚短

在线性区 / 饱和区  $r_i \rightarrow \infty \Rightarrow i_P \approx 0, i_N \approx 0$  虚断

#### (2) 基本应用

##### 同相放大电路

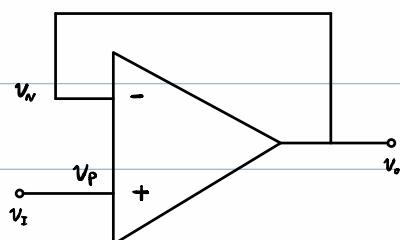


$$V_i = V_p = V_n = \frac{R_1}{R_1 + R_2} V_o$$

$$A_v = \frac{V_o}{V_i} = 1 + \frac{R_2}{R_1}$$

$$R_i \approx \infty \quad R_o \approx 0$$

##### EXP 电压跟随器

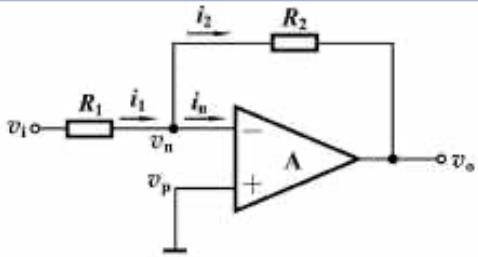


$$V_o = V_n \approx V_p = V_i$$

$$A_{vo} = \frac{V_o}{V_i} \approx 1$$

作用：隔离，缓冲

# 反相放大电路



$$v_N = v_p = 0$$

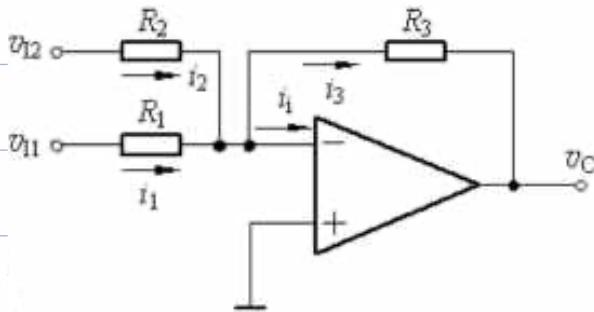
$$\frac{v_i - v_N}{R_1} = \frac{v_N - v_o}{R_2}$$

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

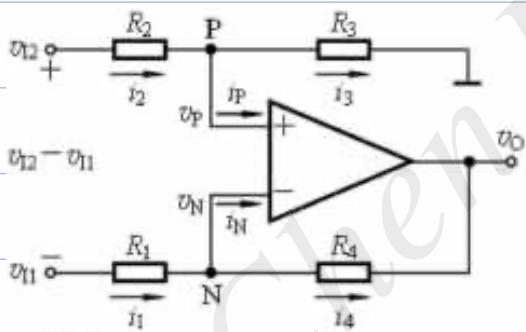
$$R_i = R_1 \quad R_o \approx 0$$

## 2 运算放大器其他应用

### (1) 加法电路



### (2) 反减法电路



$$v_p = \frac{R_3}{R_2 + R_3} v_{i2}$$

$$v_N = \frac{R_4}{R_1 + R_4} v_{i1} + \frac{R_1}{R_1 + R_4} v_o$$

$$v_p \approx v_N$$

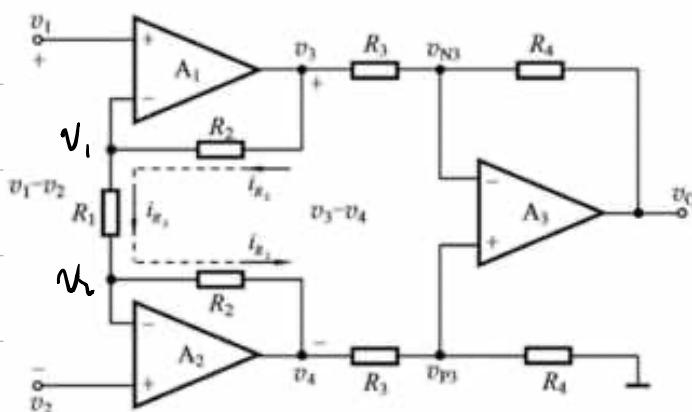
$$\Rightarrow v_o = \frac{R_1 + R_4}{R_1} \cdot \frac{R_3}{R_2 + R_3} v_{i2} - \frac{R_4}{R_1} v_{i1}$$

若  $\frac{R_3}{R_2} = \frac{R_4}{R_1}$ ,  $v_o = \frac{R_4}{R_1} (v_{i2} - v_{i1})$

$$A_v = \frac{v_o}{v_{i2} - v_{i1}} = \frac{R_4}{R_1}$$

$$R_{id} = \frac{v_{id}}{i_{id}} = R_1 + R_2$$

### (3) 仪用放大电路

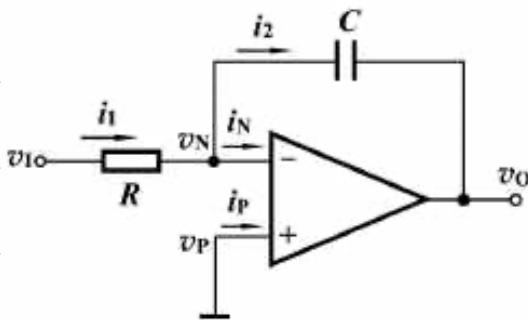


$$v_3 - v_4 = \frac{v_1 - v_2}{R_1} (R_1 + 2R_2)$$

$$v_o = -\frac{R_4}{R_3} (v_3 - v_4)$$

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

## (4) 积分电路



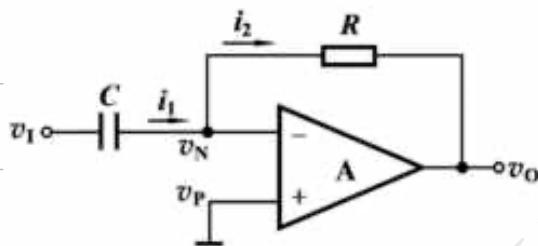
$$\begin{cases} v_p = v_n = 0 \\ i_n = i_p = 0 \\ i_2 = i_1 = \frac{v_i}{R} \end{cases}$$

设电容初始电压为0

$$v_n - v_o = \frac{1}{C} \int i_2 dt = \frac{1}{C} \int \frac{v_i}{R} dt = \frac{1}{RC} \int v_i dt$$

$$v_o = -\frac{1}{RC} \int v_i dt$$

## (5) 微分电路



$$v_o = -RC \frac{d v_i}{dt}$$

$$i_1 = i_2$$

$$i_1 = C \frac{d(v_2 - v_1)}{dt} = C \frac{d v_1}{dt}$$

$$i_2 = \frac{v_n - v_o}{R} = -\frac{v_o}{R}$$

虚断、虚短  
电路方程

分析设计方法

必须保证运放工作在线性区  
反馈电阻必须接在反相端和输出端之间

注意事项

## 运放线性应用电路



# 3 二极管及其基本电路

## 1. 半导体基本知识

空穴正负电荷对区别于导体的一个重要标志

本征半导体：+4 自由电子 & 空穴成对呈现（温度会影响）  
 杂质半导体：掺入 +3 多出一个空穴 P型半导体 (positive)  
 ↓ +5 多出一个电子 N型半导体 (negative)

产生多数载流子；提高自由电子和空穴的复合几率

## 2. PN 结

← 内电场

P型	- -	++	N型
空穴	- -	++	自由电子
	- -	++	

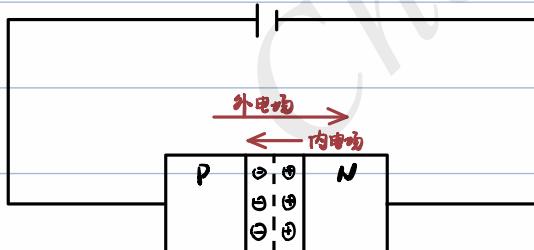
电阻  $\Rightarrow$  PN结

多子扩散 + 少子漂移

## 3. PN结特性

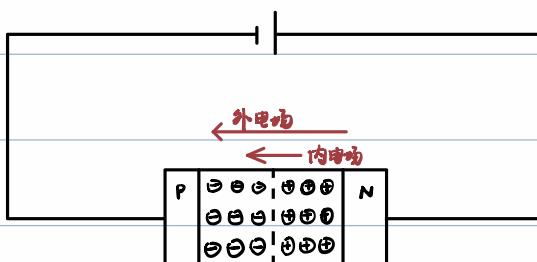
### (1) 单向导电性

#### 正向偏置



PN结变窄  $\Rightarrow$  阻值  $\downarrow$

#### 反向偏置 PN结截止



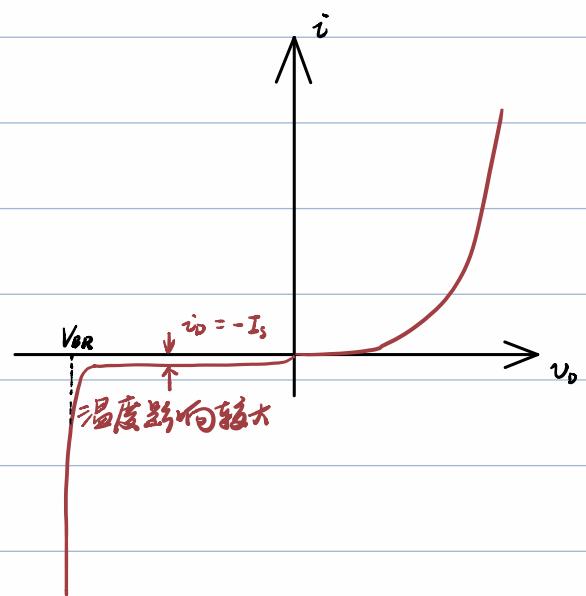
阻止多子扩散，促进少子漂移

$$i_D = I_s (e^{\frac{V_D}{V_T}} - 1)$$

$$I_s \text{ 反向饱和电流 } V_T = \frac{kT}{q}$$

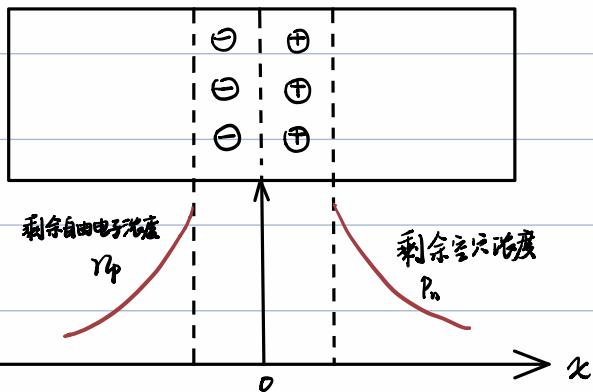
$$V_D \gg V_T \text{ 时, } i_D \approx I_s e^{\frac{V_D}{V_T}}$$

$$V_D < 0 \text{ 且 } |V_D| \gg V_T \text{ 时, } i_D \approx -I_s$$

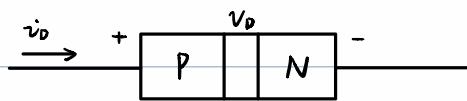


(2) 反向击穿 { 电击穿(可逆)  
热击穿(不可逆)

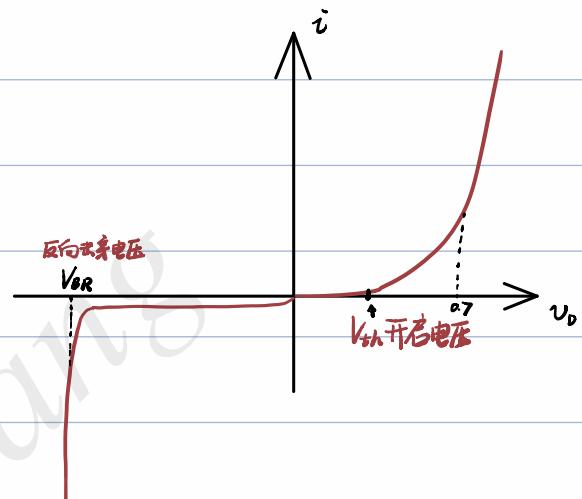
(3) 电容效应(扩散电容)



#### 4. 二极管 单向导电性



$\alpha_{阳极} \xrightarrow{i_D} + V_D - K_{阴极}$

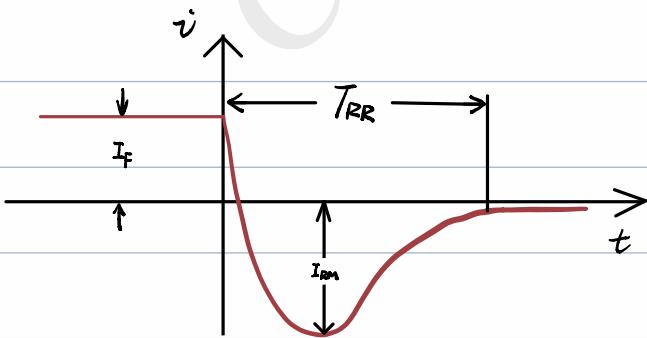


- 最大整流电流：长时间工作允许通过的最大正向平均电流

- 反向击穿电压

- 反向电流：工作在反向截止状态时的电流

- 极间电容  $\propto$  PN结面积

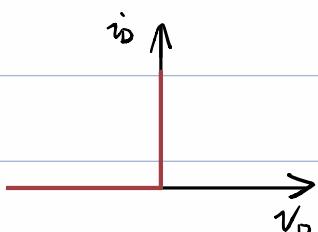


- $I_F$  正向电流

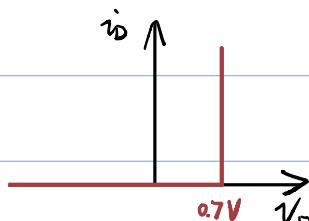
- $T_{RR}$  反向恢复时间

- $I_{RM}$  最大反向恢复电流

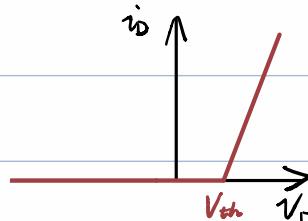
(1) 理想模型



(2) 恒压降模型



(3) 折线模型



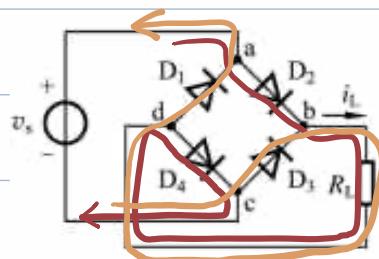
#### (4) 小信号模型 (小范围线性近似)

$$g_m = \frac{d i_o}{d v_o} = \frac{d}{d v_o} [I_s (e^{\frac{v_o}{V_T}} - 1)] = \frac{I_s}{V_T} e^{\frac{v_o}{V_T}} \Big|_a \approx \frac{i_o}{V_T} \Big|_a = \frac{I_o}{V_T}$$

$$r_d = \frac{1}{g_m} \quad \text{动态电阻 / 交流电阻}$$

### 5. 二极管基本电路

#### (1) 整流电路 { 半波整流 桥式整流 }

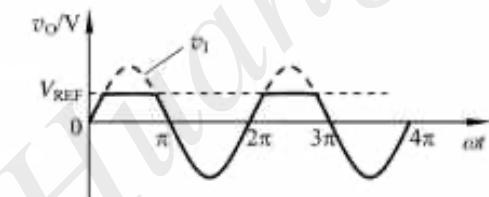
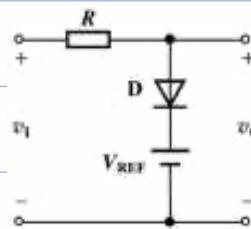


正半周  $v_a > v_b > v_d > v_c$   $D_2, D_4$  正偏;  $D_1, D_3$  反偏

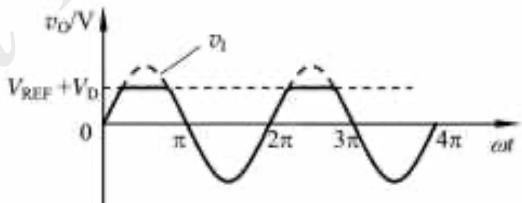
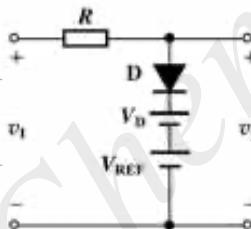
负半周  $v_c > v_b > v_d > v_a$   $D_1, D_3$  正偏;  $D_2, D_4$  反偏

#### (2) 限幅电路

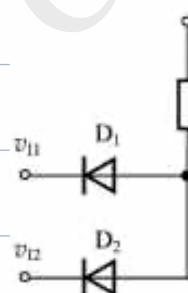
理想模型



恒压降模型



#### (3) 开关电路



$v_{H1}/V$	$v_{H2}/V$	二极管工作状态		$v_O/V$
		$D_1$	$D_2$	
0	0	导通	导通	0
0	5	导通	截止	0
5	0	截止	导通	0
5	5	截止	截止	5

#### (4) 小信号应用

{ 直流电源单独作用时 (静态) }

{ 交流电源单独作用时 (动态) }

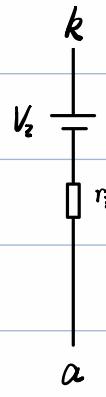
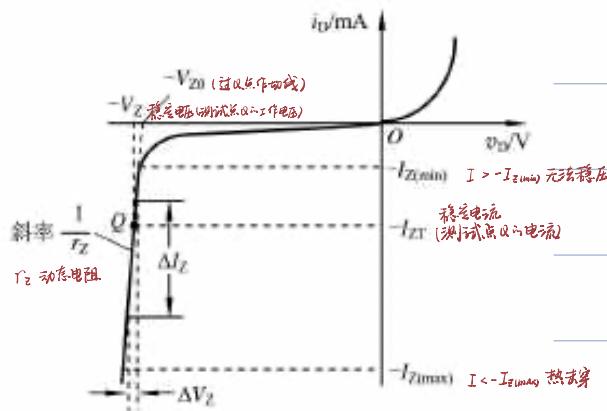
#### (5) 图解分析法 (前提: 已知二极管特性曲线)

## 6. 特殊二极管

### (1) 齐纳二极管

稳压二极管  
↑

可以在反向击穿下工作，电流反向迅速增加，电压变化很小。



$\Leftrightarrow$  反向击穿

$$V_z = 0 \Rightarrow V_z = V_{z0}$$

正常工作时处于反向击穿，电压及电流参考方向与普通二极管相反。  
使用时

① 电压  $V_I > V_z$ ，使齐纳二极管反向击穿

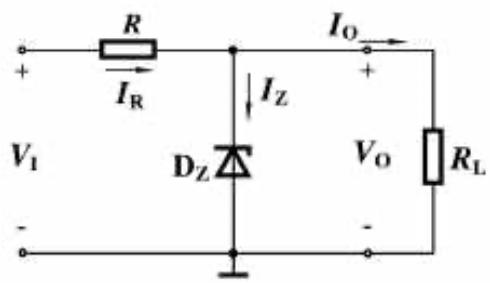
② 带入限流电阻  $R$ ，将电流  $I_z$  限制在  $[I_{z(min)}, I_{z(max)}]$

③ 负载电阻并联在二极管两端

● 输入电压  $[V_{I(min)}, V_{I(max)}]$

● 输出电压  $V_o$  ( $V_{I(min)} > V_o$ )

● 输出最大电流  $I_{o(max)}$



齐纳二极管的选择条件：

- 电压  $V_o = V_z$
- 电流  $I_z(max) > I_z(min) + I_{o(max)}$
- 最大耗散功率  $P_{zm} > V_z (I_{z(min)} + I_{o(max)})$
- 限流电阻  $R = \frac{V_I - V_z}{I_z + I_o}$

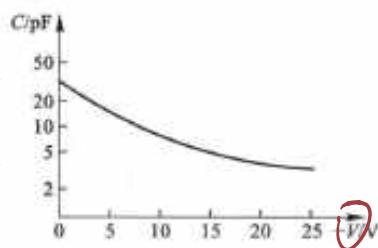
$$\textcircled{1} \quad V_I = V_{I(min)} \quad I_o = I_{o(max)} \quad I_z = I_{z(min)} \Rightarrow R_{max}$$

$$\textcircled{2} \quad V_I = V_{I(max)} \quad I_o = 0 \quad I_z = I_{z(max)} \Rightarrow R_{min}$$

$$\frac{V_{I(max)} - V_z}{I_{z(max)} + I_{o(min)}} < R < \frac{V_{I(max)} - V_z}{I_{z(min)} + I_{o(max)}}$$

$$P_R > \frac{(V_{I(max)} - V_z)^2}{R}$$

## (2) 变容二极管 (突出电容与电压的关系)



反偏电压

## (3) 肖特基二极管

- ① 电容效应小，工作速度快，适用于高频 / 开关状态应用
- ② 正向导通的正向压降和反向压降小。

## (4) 光电二极管 (光→电)

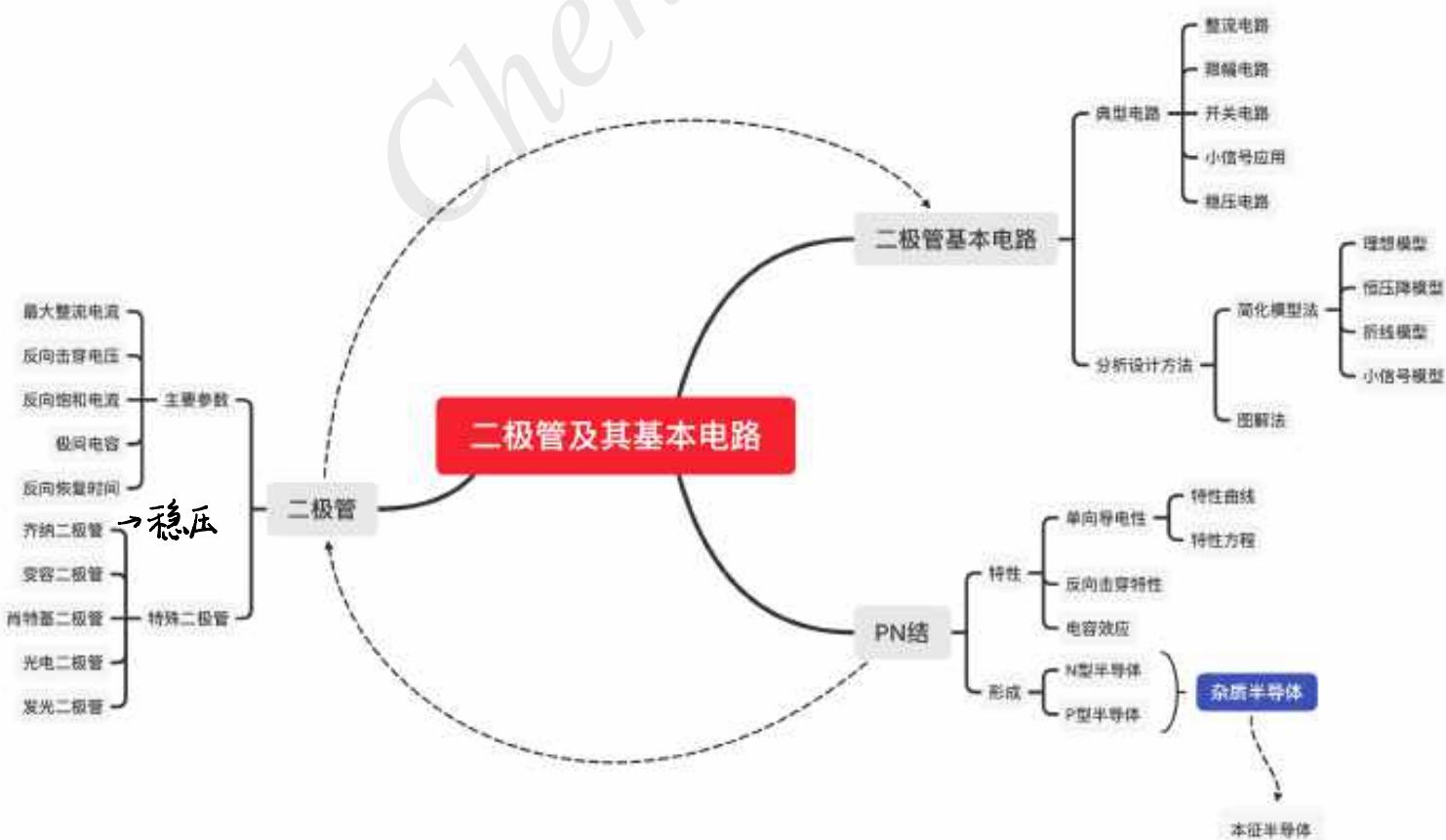
反偏电压

少子浓度与光照强度有关

## (5) 发光二极管 (电→光)

正偏电压

发光二极管必须施加正向偏置电压才能发光；光电二极管在不同的光照强度下，会有不同的反向饱和电流，所以应该加反向偏置电压；变容二极管正常工作时，也应该施加反向偏置电压。

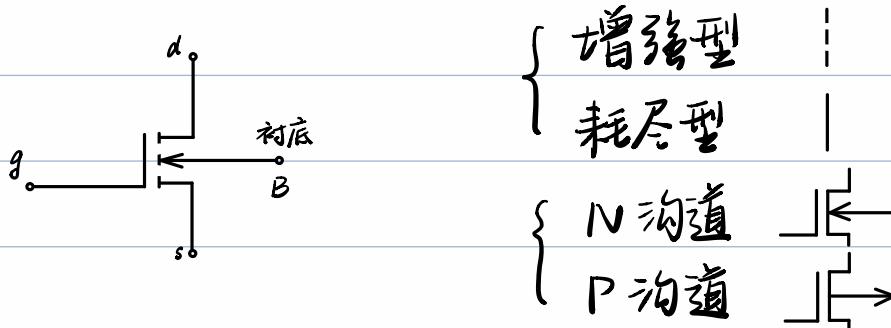


## § 4 场效应管及其放大电路

### 1 MOSFET 的结构及符号

金属 - 氧化物 - 半导体场效应管 MOSFET

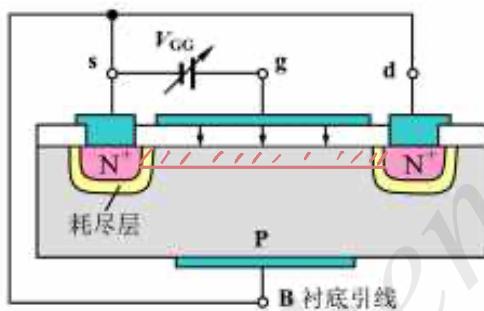
Metal - Oxide - Semiconductor Field Effect Transistor



### 2 MOSFET 的工作原理 (以 N 沟道增强型为例)

放大器件 → 控制关系

#### (1) 栅源电压对沟道的控制作用



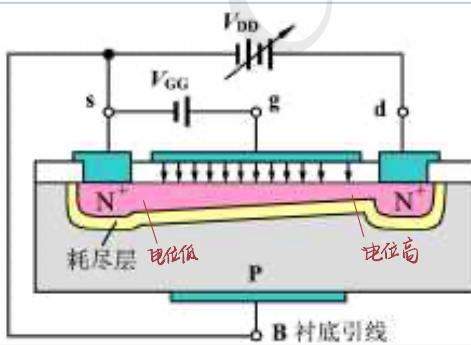
$$V_{GS} = V_{Gg} \quad (V_{GS} > V_{TN})$$

$V_{GS} \uparrow E \uparrow \Rightarrow$  产生导电沟道

$\left\{ \begin{array}{l} V_{GS} \uparrow E \uparrow \Rightarrow \text{沟道增厚}, R \downarrow \\ V_{GS} \downarrow E \downarrow \Rightarrow \text{沟道变薄}, R \uparrow \end{array} \right.$

$V_{GS} \downarrow E \downarrow \Rightarrow \text{沟道变薄}, R \uparrow$

#### (2) 漏源电压对沟道的控制作用 (此时已有 $V_{GS} > V_{TN}$ )

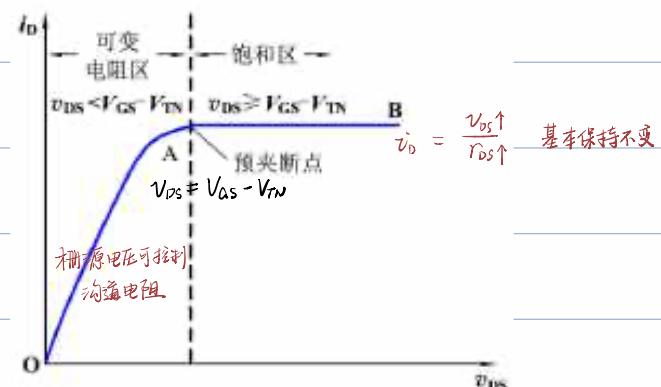
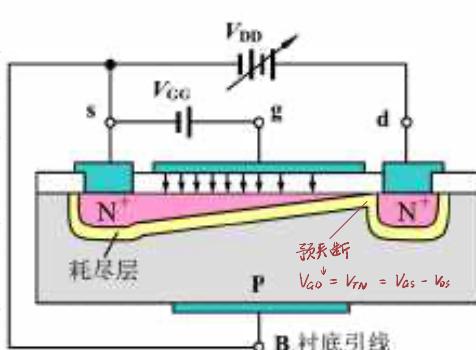


$$V_{DS} = V_{DD}$$

靠近漏极，压差减小，沟道变薄

靠近源极，压差不变，沟道厚度不变

$V_{DS}$  继续增大  $\Rightarrow$  预夹断  $V_{GD} = V_{GS} - V_{DS} = V_{TN}$



可变电阻区  $V_{GS} > V_{TN}$   $V_{DS} < V_{GS} - V_{TN}$

饱和区  $V_{GS} > V_{TN}$   $V_{DS} > V_{GS} - V_{TN}$

## N沟道增强型MOS管特点

- ① 沟道中只有一种载流子参与导电
- ② 棚极绝缘，输入电阻很高
- ③ 只有当  $V_{GS} > V_{TN}$  时，d,s 极才能导通
- ④ 可实现  $V_{GS}$  对  $i_D$  的控制（电压控制电流器件）

{ 预夹断前， $i_D$  与  $V_{DS}$  近似线性关系

预夹断后， $i_D$  趋于饱和

### 3 MOSFET的特性曲线及特性方程

双口网络  $V_{GS}$  控制  $i_D$

● 输出特性  $i_D = f(V_{DS}) \Big|_{V_{GS} = \text{const}}$

#### 输出特性曲线

① 截止区  $V_{GS} < V_{TN}$   $i_D = 0$

② 可变电阻区

$V_{GS} > V_{TN}$   $V_{DS} < V_{GS} - V_{TN}$

$$i_D = K_n [2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2]$$

$$K_n = \frac{k_n}{2} \frac{W}{L} = \frac{\mu_n C_{ox}}{2} \left( \frac{W}{L} \right) \frac{\text{宽度}}{\text{长度}} \left[ \frac{mA}{V^2} \right]$$

当  $V_{DS} \ll V_{GS} - V_{TN}$  时， $i_D = 2K_n(V_{GS} - V_{TN})V_{DS}$

等效电阻  $r_{ds0} = \left. \frac{dV_{DS}}{di_D} \right|_{V_{GS}=\text{const}} = \frac{1}{2K_n(V_{DS}-V_{TN})}$  等  $V_{GS}$  控制的可变电阻

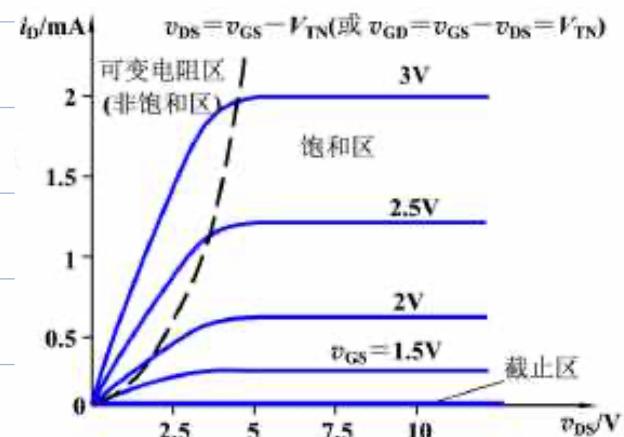
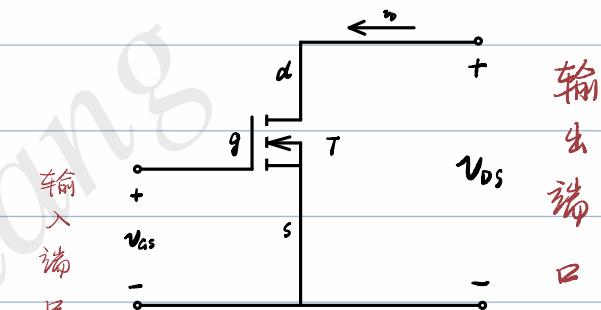
③ 饱和区（放大区）

$V_{GS} > V_{TN}$   $V_{DS} > V_{GS} - V_{TN}$

$$i_D = K_n (V_{GS} - V_{TN})^2$$

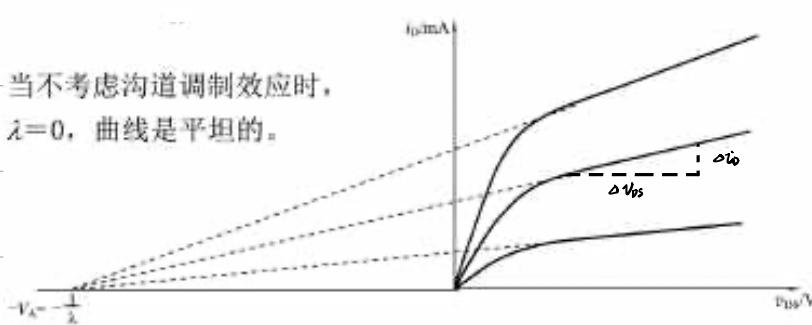
{ 理想情况：水平线

非理想： $L \downarrow \Rightarrow K_n \uparrow \Rightarrow$  向上倾斜（沟道卡度调制效应）



$V_A$  厄利电压

当不考虑沟道调制效应时,  
 $\lambda=0$ , 曲线是平坦的。



$$i_D = k_n (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$$

沟道调制系数  $\lambda = \frac{1}{V_A} \approx \frac{0.1}{L} V^{-1}$   $L [\mu m]$

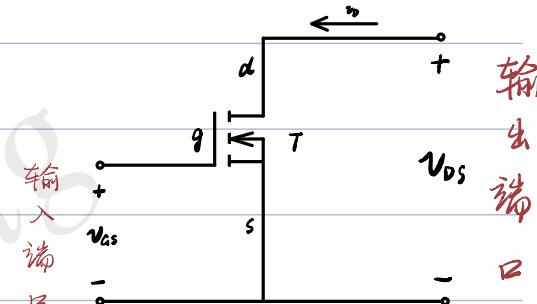
$$\text{动态电阻 } r_{ds} = \frac{1}{\lambda k_n (V_{GS} - V_{TN})^2} \approx \frac{1}{\lambda i_D} = \frac{V_A}{i_D}$$

● 转移特性  $i_D = f(V_{GS}) \Big|_{V_{DS} = \text{const}}$

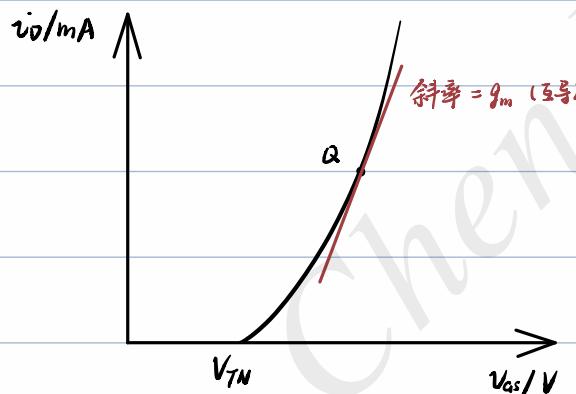
反映跨端口的电量关系

输入电压对输出电流的控制关系

转移特性曲线(饱和区)



$$i_D = k_n (V_{GS} - V_{TN})^2$$



$$g_m = \frac{di_D}{dV_{GS}} \Big|_a = \frac{d [k_n (V_{GS} - V_{TN})^2]}{dV_{GS}} \Big|_a \\ = 2 k_n (V_{GSa} - V_{TN})$$

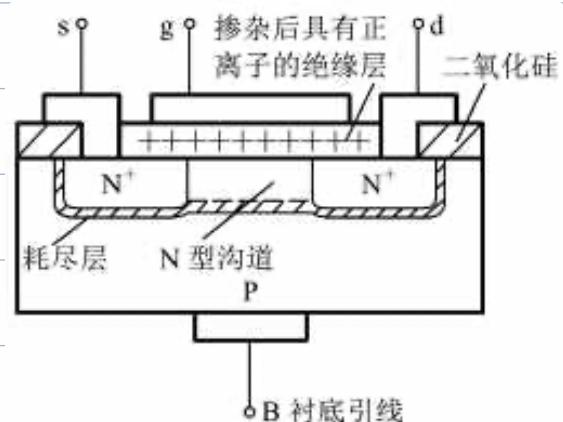
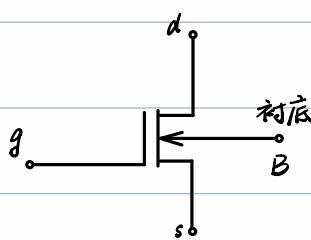
$$I_{DQ} = k_n (V_{GSQ} - V_{TN})^2$$

$$g_m = 2 \sqrt{k_n I_{DQ}}$$

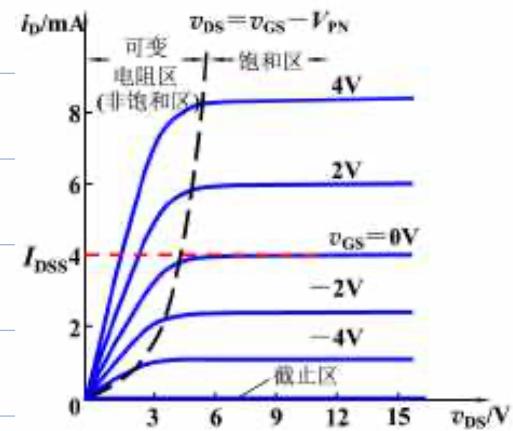
#### 4 其他几种MOS管

##### (1) N沟道耗尽型

绝缘层中掺入大量正离子



# 输出特性曲线



## ① 可变电阻区

$$V_{GS} > V_{PN} \text{ 且 } V_{DS} < V_{GS} - V_{PN}$$

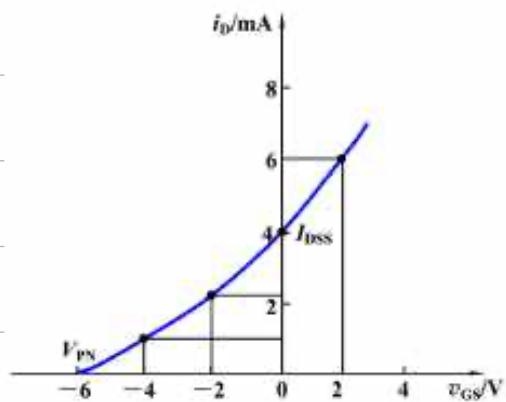
$$\text{特性方程 } i_D = K_n [2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2]$$

## ② 饱和区

$$V_{GS} > V_{PN} \text{ 且 } V_{DS} > V_{GS} - V_{PN}$$

$$i_D = K_n (V_{GS} - V_{PN})^2$$

# 转移特性曲线



$I_{DSS}$   $V_{GS} = 0$  时的漏极饱和电流

$$i_D = K_n (V_{GS} - V_{PN})^2$$

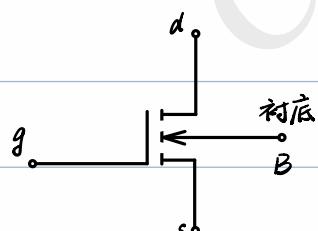
$$= K_n V_{PN} \left(1 - \frac{V_{GS}}{V_{PN}}\right)^2$$

$$= I_{DSS} \left(1 - \frac{V_{GS}}{V_{TN}}\right)^2$$

## (2) P沟道 MOSFET (反向)

## 5 MOSFET 基本放大电路构成及信号放大的实现

以 N 沟道增强型为例：



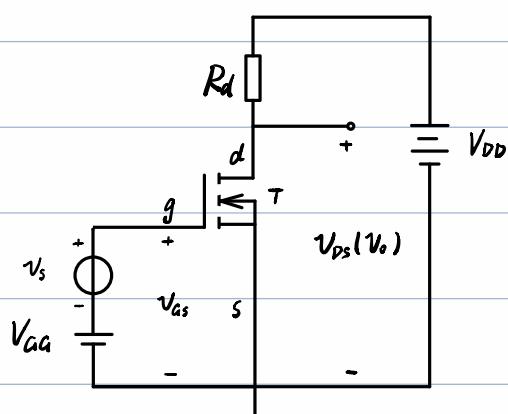
饱和区工作条件

$$V_{GS} > V_{TN} \text{ 且 } V_{DS} > V_{GS} - V_{TN}$$

$$V_{GS} = V_{GA} + V_s$$

$$\text{总量 } (i_D) = K_n (V_{GS} - V_{TN})^2 = (I_D) + (i_d)$$

$$V_{DS} = V_{DD} - i_D R_d \quad \begin{matrix} \text{直流量} & \text{交流量} \end{matrix}$$



$R_d$  ① 限流

② 把电流变化转化为电压变化

{ 静态 / 直流  
动态

$v_{DS}$  与  $v_{GS}$  相位反向

- 要点 ① MOSFET 工作在饱和区，并有合适的静态偏置  
 ② 信号叠加在静态电量上通过 MOSFET 的控制关系输出  
 ③ 输出信号的幅值受输出回路电源电压的限制  
 ④ 直流电源是 MOSFET 正常工作的前提；信号放大的能量供给者

### 6 MOSFET 放大电路的静态偏置和信号的输入输出

静态偏置：为三极管提供合适的静态工作点。

直流通路  $\Rightarrow$  静态工作点。

已知 MOSFET 的  $K_n$ ,  $V_{TN}$ , 以及  $V_{DD}$ ,  $V_{GS}$ ,  $R_d$

输入回路  $V_{GSQ} = V_{GS}$

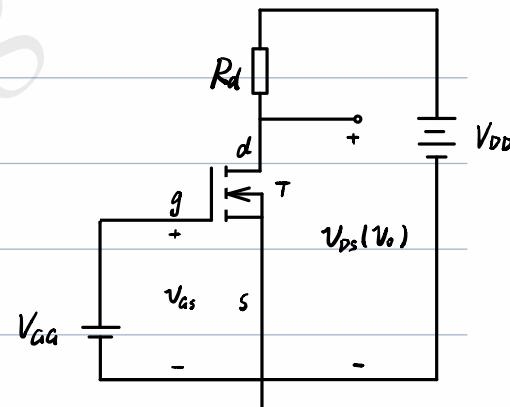
输出回路  $V_{DSQ} = V_{DD} - I_{DQ} R_d$

$$I_{DQ} = K_n (V_{GSQ} - V_{TN})^2$$

求得  $V_{GSQ}$ ,  $I_{DQ}$ ,  $V_{DSQ}$  (静态工作点)

检验是否满足饱和区工作条件  $V_{DSQ} > V_{GSQ} - V_{TN} > 0$

若不满足，改用可变电阻区的特性方程求解



EXP 1

$$V_{GSQ} = V_{GS} - I_{DQ} R_s$$

$R_s$  作用：

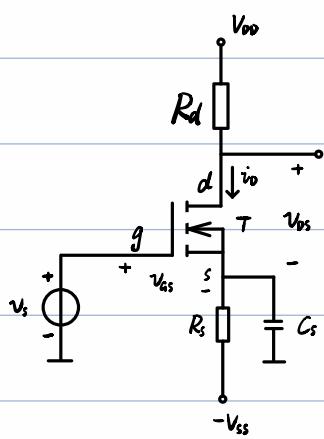
① 稳定静态工作点。

温度影响  $\Rightarrow (I_D \downarrow) \Rightarrow V_{RS} \downarrow \Rightarrow V_{GS} \uparrow \xrightarrow[\text{控制关系}]{\text{MOSFET}} I_D \uparrow$

② 影响放大倍数

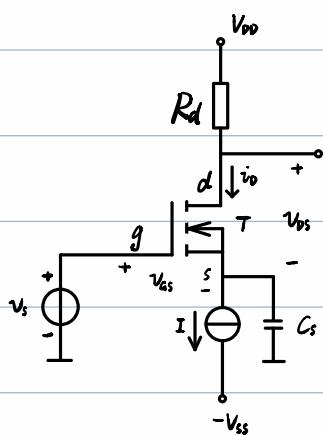
解决方法：并联大电容  $C_s$ ，隔直流通交流

交流旁路电容



## EXP 2 直流电流源为MOSFET提供静态工作点

假设MOSFET工作在静态饱和区



$$\text{由 } I_{DQ} = K_n (V_{GSQ} - V_{TN})^2 \Rightarrow V_{GSQ} = \pm \sqrt{\frac{I_{DQ}}{K_n}} + V_{TN}$$

$$\text{根据 } V_{GS} > V_{TN}, V_{GSQ} = \sqrt{\frac{I_{DQ}}{K_n}} + V_{TN}$$

$$V_{SD} = -V_{GSQ}$$

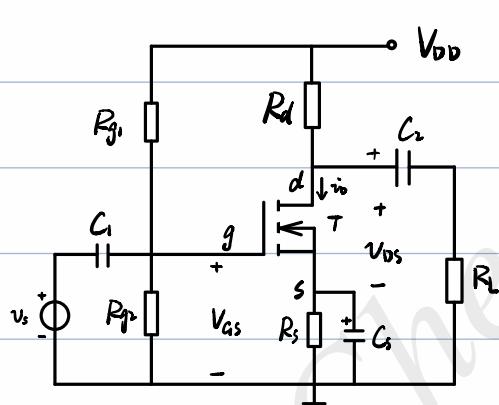
输出回路

$$\begin{aligned} V_{DSQ} &= V_{DD} - V_{GSQ} = (V_{DD} - I_{DQ} R_D) - (-V_{GSQ}) \\ &= V_{DD} - I_{DQ} R_D + V_{GSQ} \end{aligned}$$

求得Q点 ( $V_{GSQ}$ ,  $I_{DQ}$ ,  $V_{DSQ}$ )

检验是否满足饱和区工作条件

## EXP 3 阻容耦合放大电路



$$V_{GSQ} = \frac{R_{G2}}{R_{G1} + R_{G2}} V_{DD}$$

$$I_{DQ} = K_n (V_{GSQ} - V_{TN})^2$$

$$V_{DSQ} = V_{DD} - I_{DQ} R_D$$

$C_1$  耦合电容 使栅极电位不受信号源影响

$C_2$  避免负载电阻对静态工作点的影响

$R_S$ ,  $C_S$  稳定静态工作点

总结：根据特性方程和电路方程求解

改变信号输入/输出的电极，构成了3种

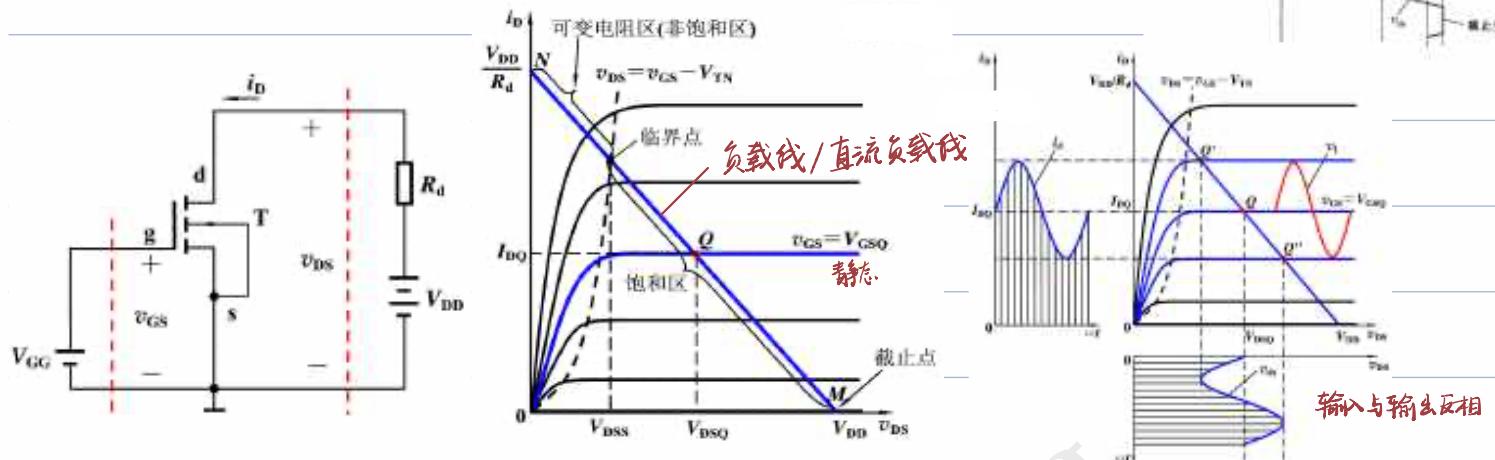
不同阻态的放大电路

{ 共源极  
共漏极  
共栅极

## 7 图解分析法

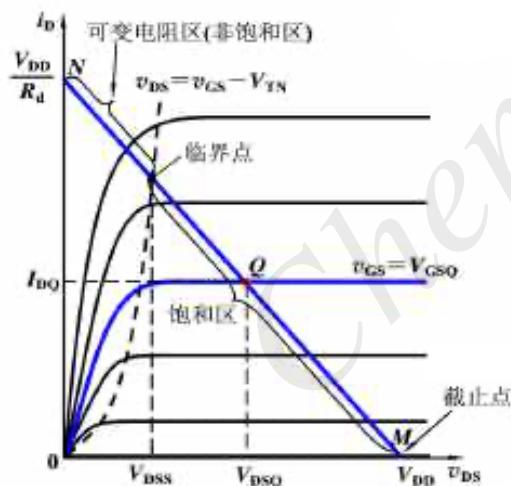
前提：已知三极管特性曲线

画负载线



{ 静态工作点太低  $\Rightarrow$  截止失真  
静态工作点太高  $\Rightarrow$  饱和失真

$\triangle$  如何设置静态工作点才能获得幅值最大的不失真输出幅度？



Q设置在临界点和截止点之间

截止点  $i_D = 0 \quad v_{DS} = V_{DD}$

临界点  $i_D = A$  代替  $V_{DSQ} = V_{GSQ} - V_{TN}$

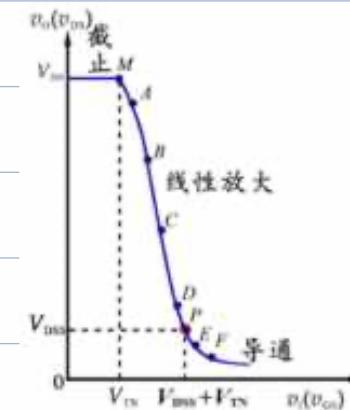
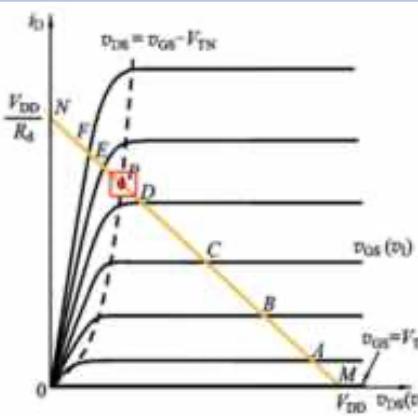
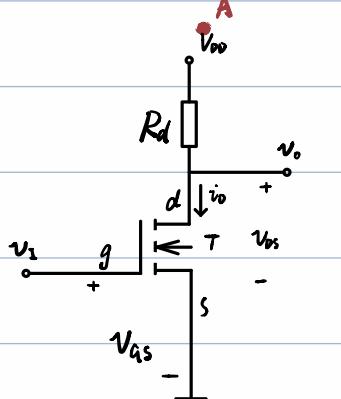
Q点  $V_{DSQ} = \frac{1}{2}(V_{DSs} + V_{DD})$

$$\Rightarrow V_{DSQ} - V_{DSs} = V_{DD} - V_{DSs}$$

$$\text{斜率 } I_{DQ}R_d = V_{DD} - V_{DSQ}$$

电压传输特性曲线

特性方程  $I_{DQ} = K_n(V_{GSQ} - V_{TN})^2$



输入低电平  $\Rightarrow$  输出高电平 (反相器)

## 8 小信号模型分析法

$$\text{饱和区特性方程 } i_d = K_n (V_{ds} - V_{TN})^2 \quad (\lambda = 0)$$

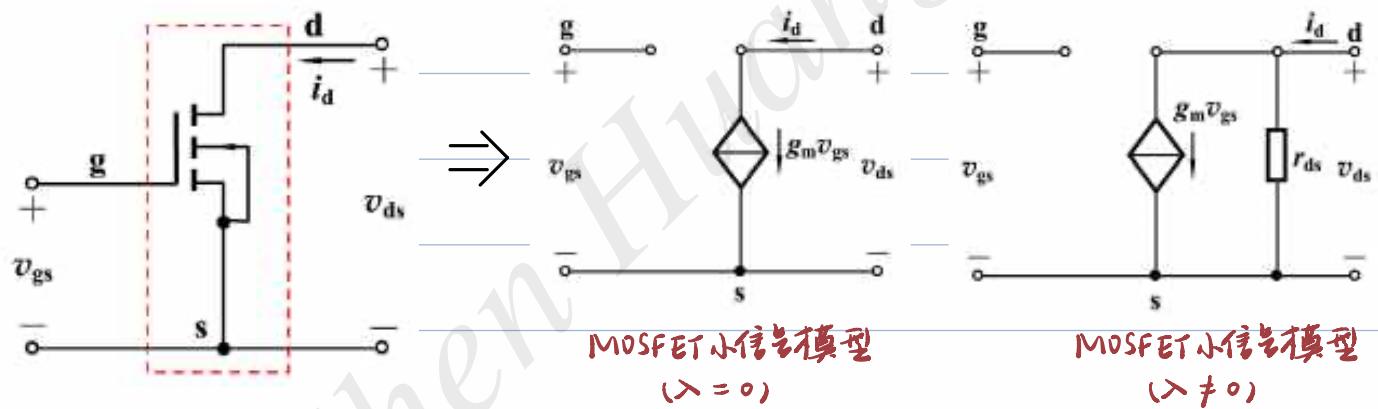
小范围近似  $\rightarrow$  线性

$$\begin{aligned} i_d &= K_n (V_{ds} - V_{TN})^2 = K_n (V_{dsQ} + v_{gs} - V_{TN})^2 \\ &= K_n [(V_{dsQ} - V_{TN}) + v_{gs}]^2 \\ &= K_n (V_{dsQ} - V_{TN})^2 + 2K_n (V_{dsQ} - V_{TN})v_{gs} + K_n v_{gs}^2 \\ &= I_{DQ} + g_m v_{gs} + K_n v_{gs}^2 \end{aligned}$$

静止值  
(直流)      动态值  
(交流)      非线性失真

当  $v_{gs} \ll 2K_n (V_{dsQ} - V_{TN})$  时

$$i_d \approx I_{DQ} + g_m v_{gs} = I_{DQ} + i_d$$

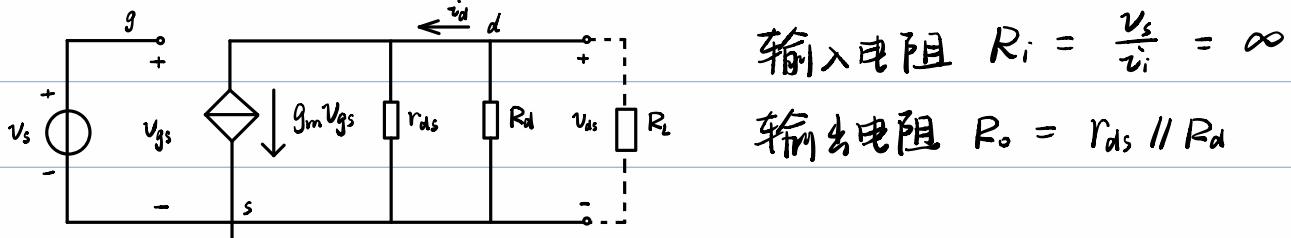


$$r_{ds} = \frac{1}{\lambda K_n (V_{dsQ} - V_{TN})^2} \approx \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$$

$$r_{ds} = \frac{dV_{ds}}{di_d}$$

$$g_m = \frac{di_d}{dv_{gs}} = 2K_n (V_{dsQ} - V_{TN}) = 2\sqrt{K_n I_{DQ}}$$

- 注意**
- ① MOSFET 必须工作在饱和区，并且在小信号情况下，模型才可用
  - ② 只适用于交流信号或变化量的分析，不能用来分析静态工作点
  - ③ 参数  $g_m$ 、 $r_{ds}$  与 Q 位置有关
  - ④ 受控源  $g_m v_{gs}$  的电流方向与控制电压  $v_{gs}$  极性无关



## 9 共源极、共漏极和共栅极放大电路

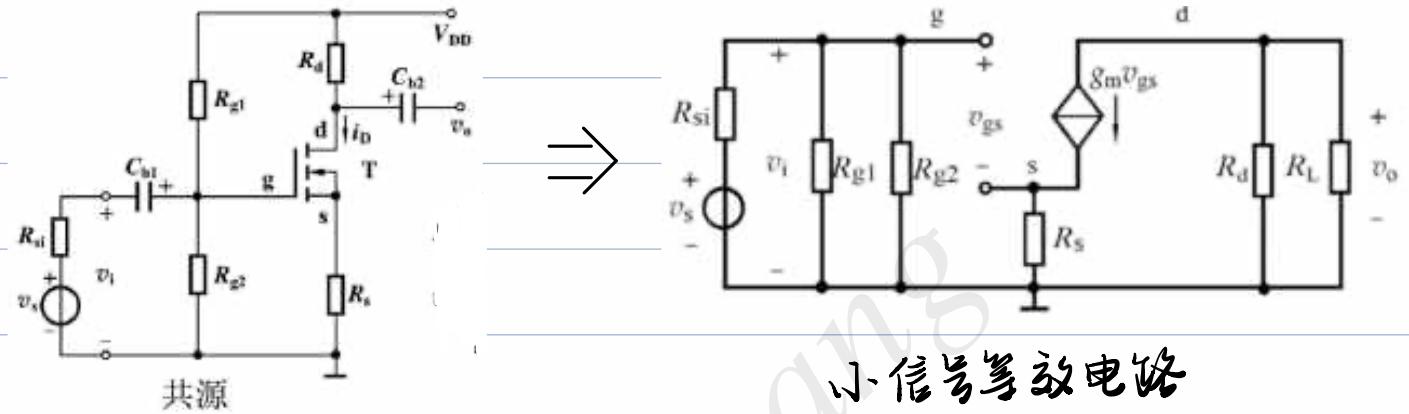
### 用小信号模型分析法

共源极：信号由栅极输入，漏极输出

共漏极：信号由栅极输入，源极输出

共栅极：信号由源极输入，漏极输出

#### (1) 共源极



小信号等效电路

$$\text{输入回路 } V_i = V_{gs} + (g_m V_{gs}) R_s$$

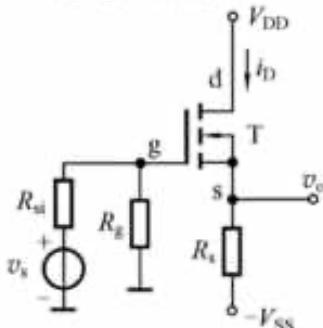
$$\text{输出回路 } V_o = -g_m V_{gs} (R_d // R_L)$$

$$\text{端口电压增益 } A_v = \frac{V_o}{V_i} = -\frac{g_m (R_d // R_L)}{1 + g_m R_s}$$

$$\text{输入电阻 } R_i = R_{g1} // R_{g2}$$

$$\text{源电压增益 } A_{Vs} = \frac{V_o}{V_s} = \frac{V_o}{V_i} \cdot \frac{V_i}{V_s} = -\frac{g_m (R_d // R_L)}{1 + g_m R_s} \cdot \frac{R_i}{R_i + R_{s1}}$$

#### (2) 共漏极

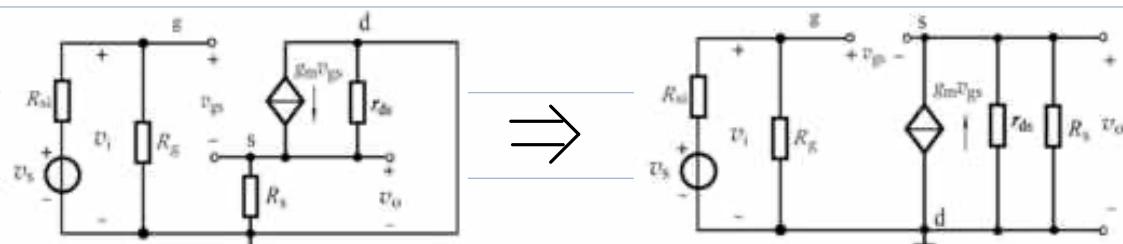


$$\text{静态: } V_{GQ} = 0$$

$$\begin{cases} V_{GSQ} + I_{DQ} R_s + (-V_{ss}) = 0 \\ I_{DQ} = k_n (V_{GSQ} - V_{TN})^2 \end{cases}$$

$$V_{DSQ} = V_{DD} - (-V_{ss}) - I_{DQ} R_s$$

#### 动态



$$g_m = 2k_n (V_{GSQ} - V_{TN}) = 2\sqrt{k_n I_{DQ}}$$

$$r_{ds} = \frac{1}{\lambda k_n (V_{GSQ} - V_{TN})^2} \approx \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$$

端口输入电压  $v_i = v_o + v_{gs}$

输出电压  $v_o = g_m v_{gs} (r_{ds} // R_d)$

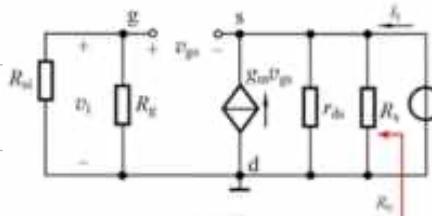
端口电压增益  $A_v = \frac{v_o}{v_i} = \frac{g_m (r_{ds} // R_d)}{1 + g_m (r_{ds} // R_d)}$  (不含负号, 同相)

当  $g_m (r_{ds} // R_d) \gg 1$  时,  $A_v \approx 0$ ,  $v_o \approx v_i$  电压跟随器

输入电阻  $R_i = R_g$

源电压增益  $A_{Vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i} \cdot \frac{v_i}{v_s} = \frac{g_m (r_{ds} // R_d)}{1 + g_m (r_{ds} // R_d)} \cdot \frac{R_i}{R_i + R_s}$

输出电阻 (将  $v_s$  置零, 保留内阻)



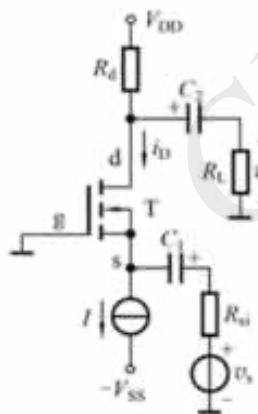
$$i_t = \frac{v_t}{R_s} + \frac{v_t}{r_{ds}} - g_m v_{gs}$$

$$v_{gs} = -v_t$$

$$R_o = \frac{v_t}{i_t} = \frac{1}{\frac{1}{R_s} + \frac{1}{r_{ds}} + g_m} = R_s // r_{ds} // \frac{1}{g_m}$$

$R_o$  较小

### (3) 共栅极



静态态:  $I_{DQ} = I$

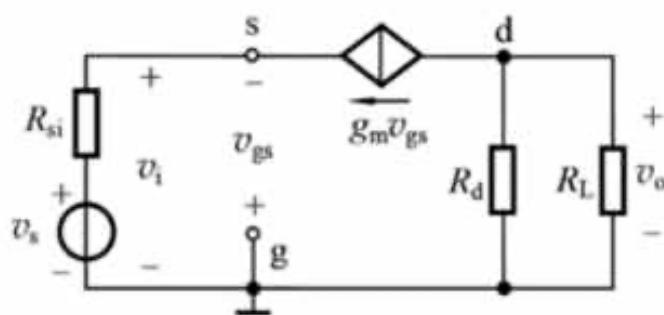
$$I_{DQ} = k_n (V_{GSQ} - V_{TN})^2 \Rightarrow V_{GSQ}$$

$$V_{SQ} = -V_{GSQ}$$

$$V_{DSQ} = V_{DQ} - V_{SQ} = V_{DD} - I_{DQ} R_d + V_{GSQ}$$

检验  $V_{GSQ} > V_{TN}$ ,  $V_{DSQ} > V_{GSQ} - V_{TN}$

动态:



$$g_m = 2\sqrt{k_n I_{DQ}}$$

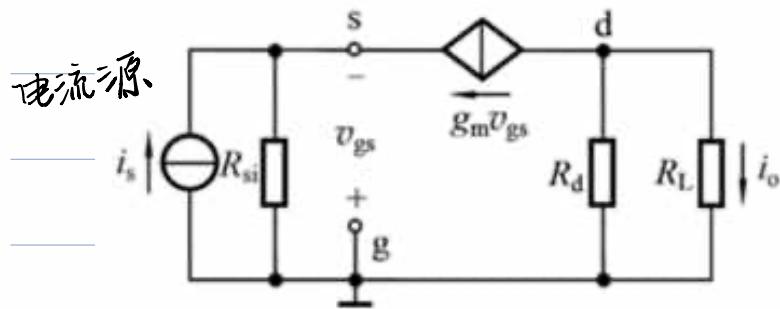
$$r_{dm} = \frac{1}{\lambda I_{DQ}}$$

端口输入电压  $v_i = -v_{gs}$

输出电压  $v_o = -g_m v_{gs} (R_d // R_L)$

端口电压增益  $A_v = \frac{v_o}{v_i} = g_m (R_d // R_L)$

忽略沟道调制效应



$$\text{源极节点 KCL: } i_s + g_m v_{gs} + \frac{v_{ds}}{R_{si}} = 0$$

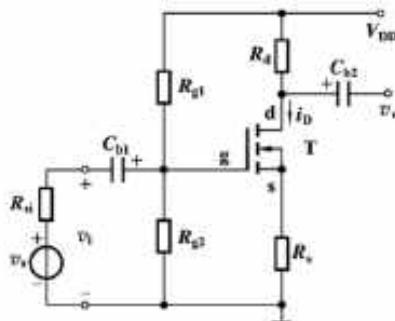
$$\text{输出电流 } i_o = \frac{R_d}{R_d + R_L} (1 - g_m v_{gs})$$

$$A_{is} = \frac{i_o}{i_s} = \frac{R_d}{R_d + R_L} \cdot \frac{g_m R_{si}}{1 + g_m R_{si}}$$

当  $g_m R_{si} \gg 1$  时,  $A_{is} \approx 1$  电流跟随器

## 小结

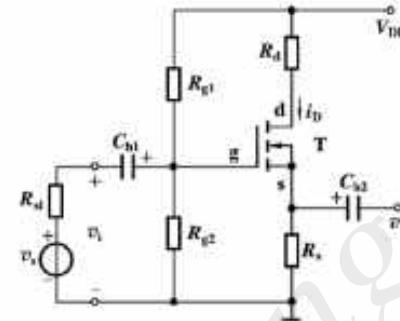
共源



电压增益

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

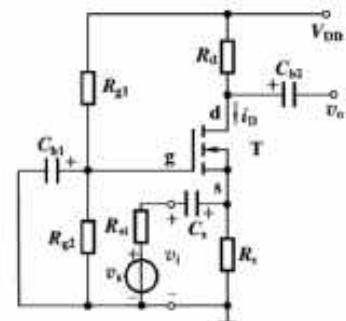
共漏



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

“电压跟随器”

共栅



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

“电流跟随器”

输入电阻

很高

很高

$$R_i \approx \frac{1}{g_m}$$
 最小

输出电阻

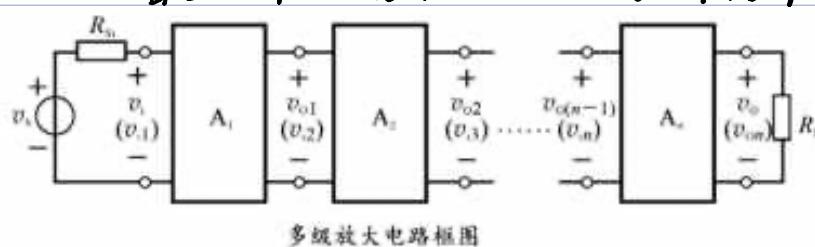
$$R_o \approx R_d$$

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

$$R_o \approx R_d$$

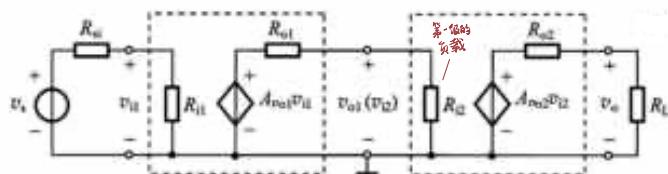
## 10 多级放大电路

△ 如何借助单级放大电路的分析结果分析多级放大电路



多级放大电路框图

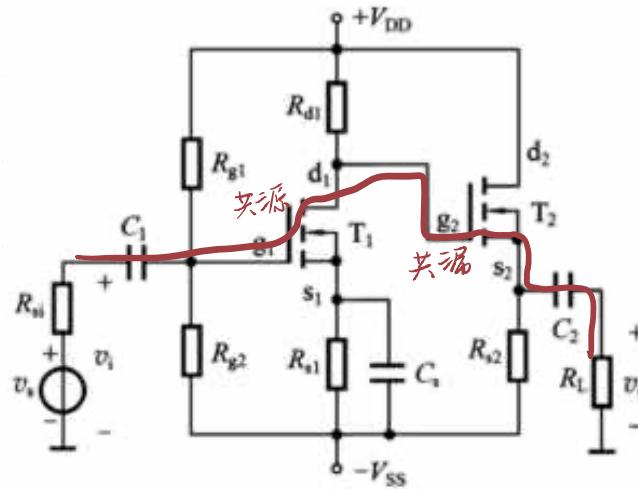
$$A_V = \frac{V_o}{V_i} = \frac{V_{o1}}{V_i} \cdot \frac{V_{o2}}{V_{o1}} \cdots \frac{V_o}{V_{on-1}} = A_{v1} \cdot A_{v2} \cdots A_{vn}$$



两级放大电路模型

- 级间关系 ① 后级的输入电阻是前级的负载  
 ② 前级的开路电压是后级的信号源电压  
 ③ 前级的输出电阻是后级的信号源内阻  
 ④ 第一级的输入电阻是放大电路的输入电阻  
 ⑤ 最后一级的输出电阻是放大电路的输出电阻

## EXP 1 共源-共漏放大电路



静态：设  $T_1, T_2$  均工作在饱和区

$$T_1 \left\{ \begin{array}{l} V_{ASQ1} = \frac{R_{g2}}{R_{g1} + R_{g2}} (V_{DD} + V_{SS}) - I_{DQ1} R_{S1} \\ I_{DQ1} = K_n (V_{ASQ1} - V_{TN1})^2 \end{array} \right.$$

$$V_{DSQ1} = V_{DD} + V_{SS} - I_{DQ1} (R_{d1} + R_{s1})$$

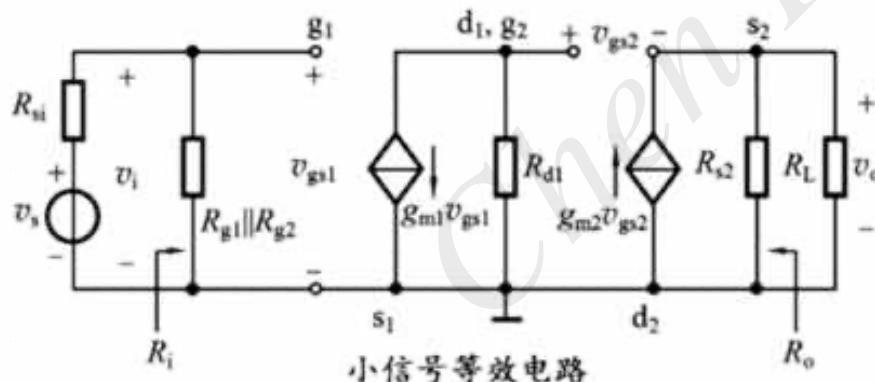
$$T_2 \left\{ \begin{array}{l} V_{ASQ2} = V_{DD} + V_{SS} - I_{DQ1} R_{d1} - I_{DQ2} R_{s2} \\ I_{DQ2} = K_n (V_{ASQ2} - V_{TN2})^2 \end{array} \right.$$

$$V_{DSQ2} = V_{DD} + V_{SS} - I_{DQ2} R_{s2}$$

$$g_{m1} = 2K_n (V_{ASQ1} - V_{TN1})$$

$$g_{m2} = 2K_n (V_{ASQ2} - V_{TN2})$$

$$\left\{ \begin{array}{l} v_i = v_{gs1} \\ v_o = g_{m2} v_{gs2} (R_{s2} // R_L) \\ v_o + v_{gs2} = -g_{m1} v_{gs1} R_{d1} \end{array} \right.$$



$$\text{第一级 } A_{v1} = \frac{v_o}{v_i} = -g_{m1} R_{d1}$$

$$\text{第二级 } A_{v2} = \frac{v_o}{v_{o1}} = \frac{g_{m2} (R_{s2} // R_L)}{1 + g_{m2} (R_{s2} // R_L)}$$

$$\text{总增益 } A_v = A_{v1} \cdot A_{v2}$$

$$\text{输入电阻 } R_i = R_{g1} // R_{g2}$$

$$\text{源电压增益 } A_{vs} = \frac{v_o}{v_s} = A_v \cdot \frac{R_i}{R_{s1} + R_i}$$

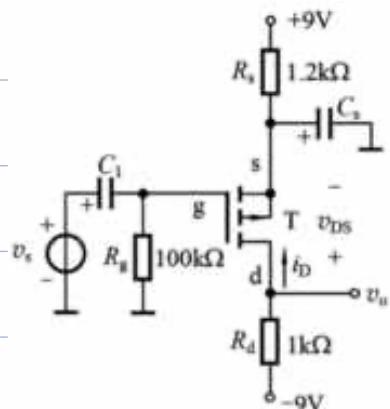
$$\text{输出电阻 } R_o = R_{s2} // \frac{1}{g_{m2}}$$

总增益

$$A_v = \frac{v_o}{v_i} = - \frac{g_{m1} g_{m2} R_{d1} (R_{s2} // R_L)}{1 + g_{m2} (R_{s2} // R_L)}$$

## 11 MOSFET 放大电路分析设计举例

EXP 1 P-沟道增强型. 已知  $V_{TP} = -2V$ ,  $k_p = 2mA/V^2$ ,  $\lambda = 0.01V^{-1}$



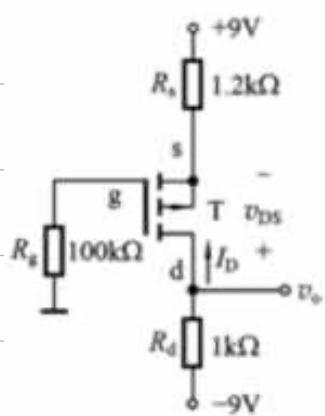
(1) 求  $I_{DQ}$  和  $V_{DSQ}$

(2) 试求小信号电压增益、

输入电阻和输出电阻

(1) 静态

设 MOSFET 工作在饱和区



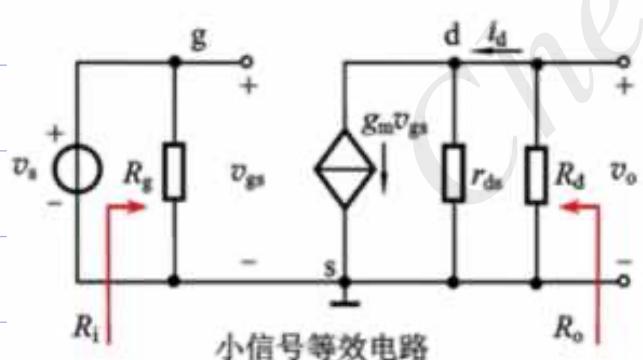
$$\begin{cases} I_{DQ} = -k_p (V_{GSQ} - V_{TP})^2 \\ 9V + I_{DQ} R_s + V_{GSQ} = 0 \end{cases}$$

$$\Rightarrow V_{GSQ} = -3.5V \quad I_{DQ} = -4.5mA$$

$$V_{DSQ} = -9V + (-9V) - I_{DQ}(R_s + R_d) = -8.1V$$

$V_{DSQ} < V_{GSQ} - V_{TN} < 0$  MOSFET 工作在饱和区

(2) 动态



$$g_m = -2k_p(V_{GSQ} - V_{TP}) = 6mA/V$$

$$r_{ds} \approx -\frac{1}{\lambda I_{DQ}} = 22.2k\Omega$$

$$v_o = -g_m v_{gs} (r_{ds} \parallel R_d)$$

$$v_i = v_{gs}$$

$$A_V = -g_m (r_{ds} \parallel R_d) = -5.7$$

输入电阻  $R_i = R_g = 100k\Omega$

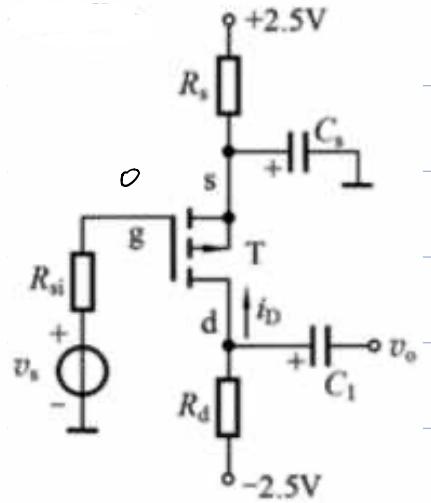
输出电阻  $R_o = r_{ds} \parallel R_d = 0.96k\Omega$

EXP 2 P-沟道增强型 已知  $V_{TP} = -0.7V$ ,  $\lambda = 0$

(1) 当 MOSFET 的  $I_{DQ} = -0.3mA$  和  $V_{GSQ} - V_{TP} = -0.3V$  时, 求电阻  $R_s$

(2) 当  $A_V = -10$  时, 求电阻  $R_d$

(1) 静态：设 MOSFET 工作在饱和区



$$\left\{ \begin{array}{l} V_{ASQ} = 2.5V + I_{DQ}R_s \\ I_{DQ} = -K_p(V_{ASQ} - V_{TP})^2 \end{array} \right.$$

$$\Rightarrow V_{ASQ} = -1V \quad R_s = 5k\Omega \quad K_p = \frac{10}{3} \text{ mA/V}^2$$

$$V_{DSQ} = -2.5V - 2.5V - I_{DQ}(R_s + R_d) < -5V$$

$V_{DSQ} < V_{ASQ} - V_{TP} < 0$  工作在饱和区

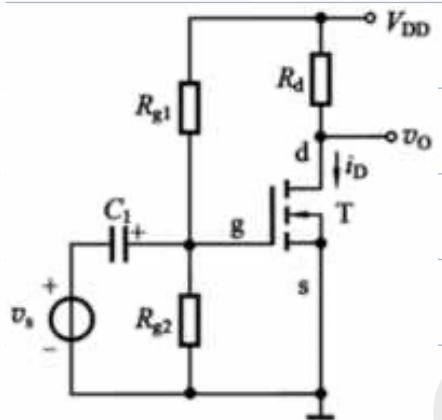
(2) 动态

$$g_m = -2K_p(V_{ASQ} - V_{TP}) = -\frac{20}{3} \times (-0.3) = 2 \text{ mA/V}$$

$$v_i = v_{gs} \quad v_o = -g_m v_{gs} R_d$$

$$A_v = -g_m R_d \Rightarrow R_d = \frac{A_v}{-g_m} = \frac{-10}{-2} = 5k\Omega$$

### EXP 3 N沟道增强型



提供20倍的电压增益和对称的电压输出振幅

已知  $V_{DD} = 5V$ ,  $V_{TN} = 0.8V$ ,  $K_n' = 40 \text{ mA/V}^2$ ,

$\lambda = 0.01 \text{ V}^{-1}$ , 当  $I_{DQ} = 0.1 \text{ mA}$  时, 求

(1) 满足条件的  $\frac{W}{L}$  和  $R_d$

(2) 求  $R_{g1}$  与  $R_{g2}$  的比值

(1) 对称输出时, 临界点漏极电流为  $2I_{DQ}$

$$\text{此时漏源电压 } V_{DSS} = V_{AS} - V_{TN} = \sqrt{\frac{2I_{DQ}}{K_n}} \quad \left. \right\}$$

$$\text{临界点输出回路 } V_{DSS} = V_{DD} - 2I_{DQ}R_d$$

$$\Rightarrow \sqrt{K_n} = \frac{\sqrt{2}I_{DQ}}{V_{DD} - 2I_{DQ}R_d} = \frac{\sqrt{0.2}}{5 - 0.2R_d}$$

$$g_m = 2K_n(V_{ASQ} - V_{TN}) = 2\sqrt{K_n I_{DQ}} = \frac{2\sqrt{2}I_{DQ}}{V_{DD} - 2I_{DQ}R_d} = \frac{0.2\sqrt{2}}{5 - 0.2R_d}$$

$$r_{ds} = \frac{1}{\lambda I_{DQ}} = 1000 \text{ k}\Omega$$

$$v_i = v_{gs} \quad v_o = -g_m v_{gs} (r_{ds} \parallel R_d)$$

$$A_v = \frac{v_o}{v_i} = -g_m (r_{ds} \parallel R_d)$$

$$\frac{0.2\sqrt{2}}{5 - 0.2R_d} \cdot \frac{1000R_d}{1000 + R_d} = 20 \Rightarrow R_d = 23.4 \text{ k}\Omega$$

$$K_n = \frac{0.2}{(5 - 0.2R_d)^2} = 1.95 \text{ mA/V}^2$$

$$\frac{W}{L} = 2 \frac{K_n}{V_{TH}} = 97.5$$

$$(2) I_{DQ} = K_n (V_{ASQ} - V_{TN})^2 \Rightarrow V_{ASQ} = \pm \sqrt{\frac{I_{DQ}}{K_n}} + V_{TN}$$

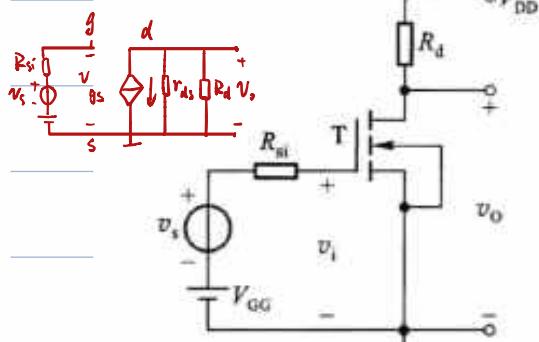
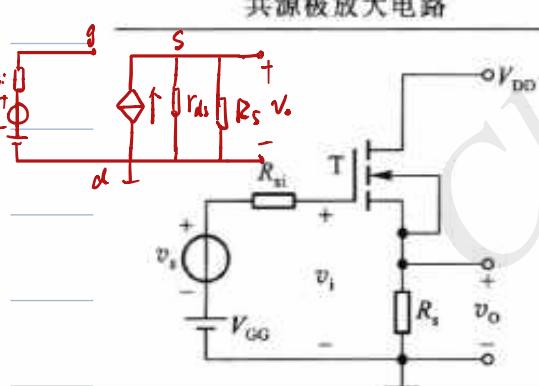
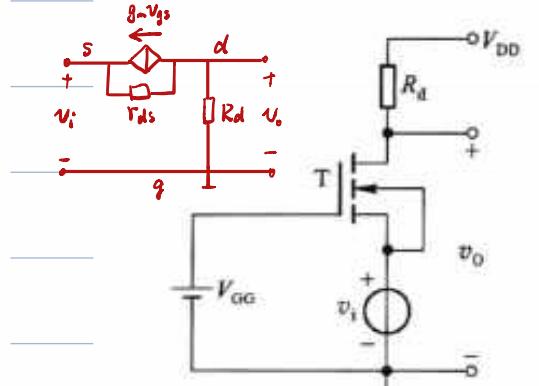
饱和区  $V_{ASQ} > V_{TN}$

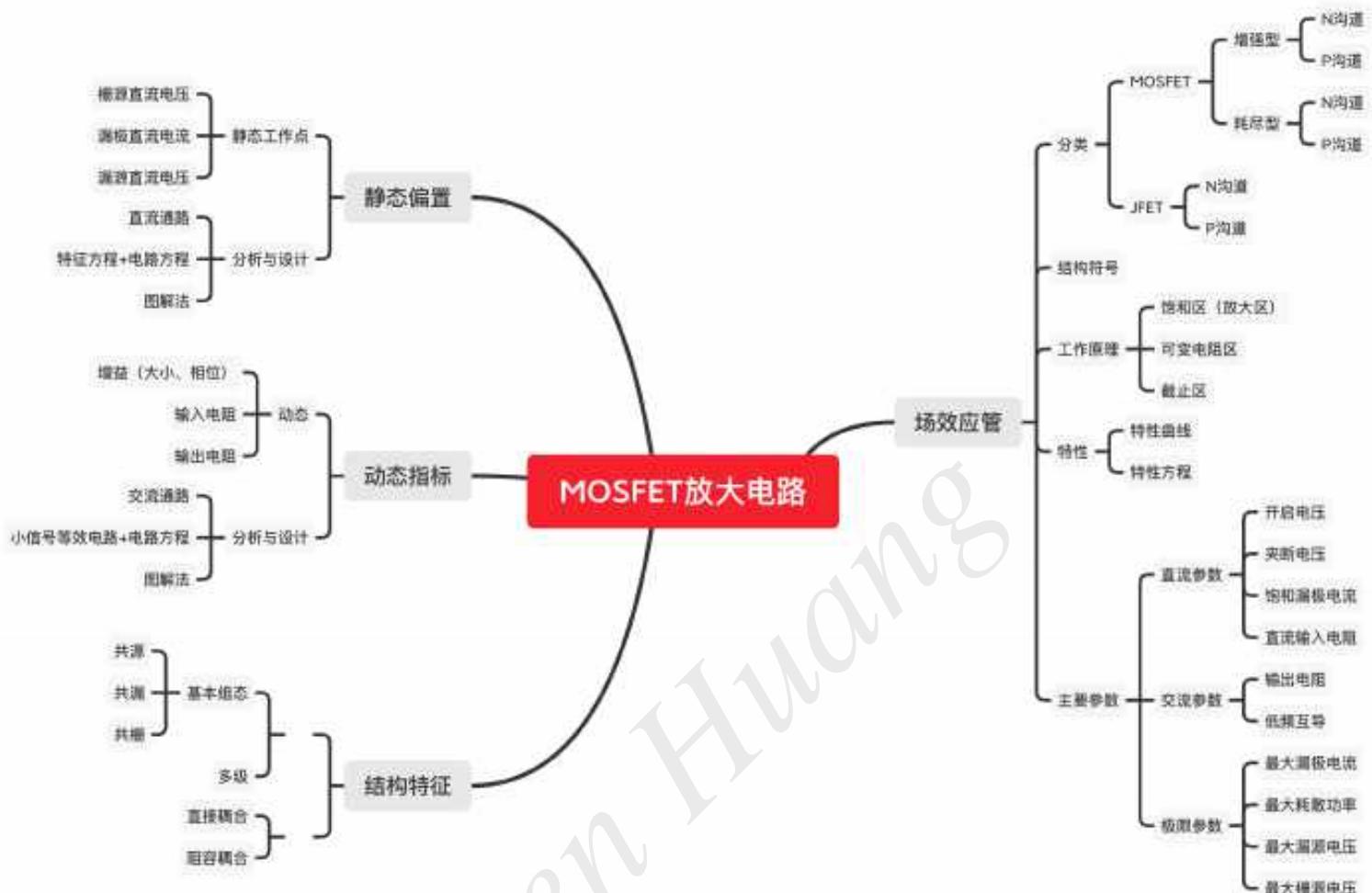
$$V_{ASQ} = \sqrt{\frac{I_{DQ}}{K_n}} + V_{TN} = \sqrt{\frac{0.1}{1.95}} + 0.8 \approx 1 \text{ V}$$

$$V_{ASQ} = \frac{R_{g2}}{R_{g1} + R_{g2}} V_{DD}$$

$$\frac{R_{g1}}{R_{g2}} = \frac{V_{DD}}{V_{ASQ}} - 1 = 4$$

表 4.5.1 MOSFET 三种基本放大电路的比较

电路形式(原理电路)	电压增益 $A_v = v_o/v_i$	输入电阻 $R_i$	输出电阻 $R_o$	基本特点
 共源极放大电路	$A_v = -g_m (R_d // r_{ds})$	很高	$R_o = R_d // r_{ds}$	电压增益高，输入输出电压反相，输入电阻大，输出电阻主要由 $R_d$ 决定
 共漏极放大电路(源极输出器)	$A_v = \frac{g_m (R_o // r_{ds})}{1 + g_m (R_o // r_{ds})}$	很高	$R_o = \frac{1}{g_m} // R_s // r_{ds}$ $R_i = \frac{v_i}{v_o} \text{ 很小}$	电压增益小于 1 但接近于 1，输出电压同相，有电压跟随作用。输入电阻高，输出电阻低，可作阻抗变换用
 共栅极放大电路	$A_v = \frac{(g_m + \frac{1}{r_{ds}}) R_d}{1 + (R_d / r_{ds})}$ $= g_m R_d (\text{当 } r_{ds} \gg R_d)$	$R_i = \frac{v_i}{v_o} = -\frac{v_i}{g_m v_{gs}}$ $= \frac{1}{g_m}$	$R_o = R_d // r_{ds}$	电压增益高，输入输出电压同相，电流增益小于 1 但接近 1，有电流跟随作用。输入电阻小，输出电阻主要由 $R_d$ 决定，常用于高频和宽带放大

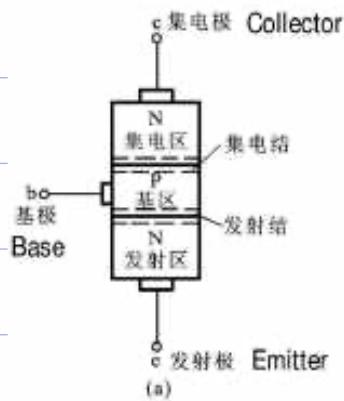


# §5 双极结型三极管及其放大电路

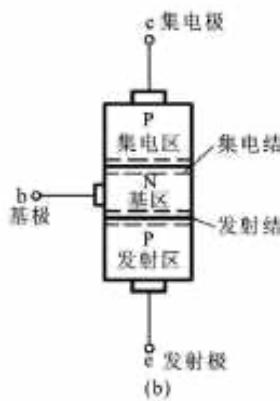
## 1 双极结型三极管的结构及工作原理

Bipolar Junction Transistor

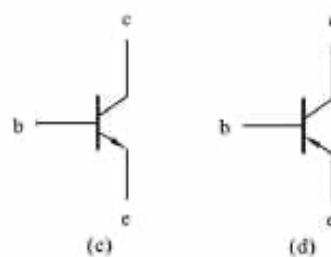
BJT



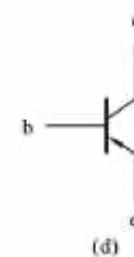
NPN型管结构示意图



PNP型管结构示意图



NPN型管  
电路符号



PNP型管  
电路符号

箭头方向：  
发射结方向  $P \rightarrow N$

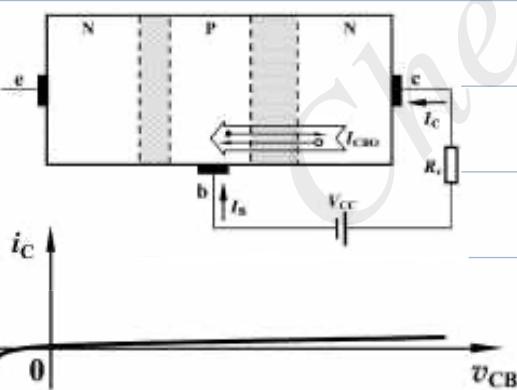
### 结构特点

① 发射区的掺杂浓度最高

② 集电区掺杂浓度最低，且面积大

③ 基区很薄，一般在几微米至几十个微米，且掺杂浓度低于发射区

### 工作原理

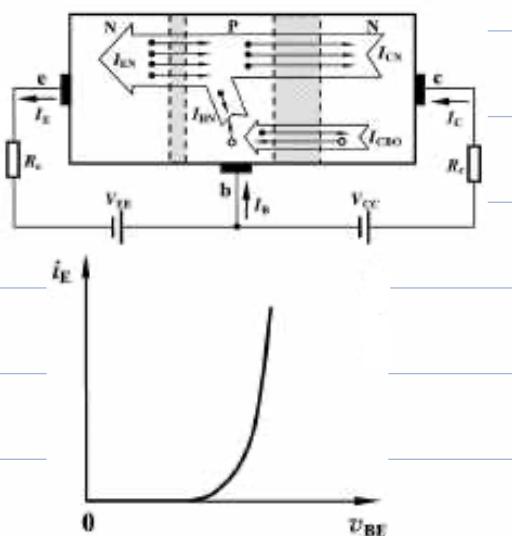


$V_{CC}$  使集电结反向偏置

促进少子漂移（少子由本征激发产生）

少子形成漂移电流  $I_{CBO}$

$I_{CBO}$  集电结反向饱和电流



$V_{EE}$  使发射结正向偏置

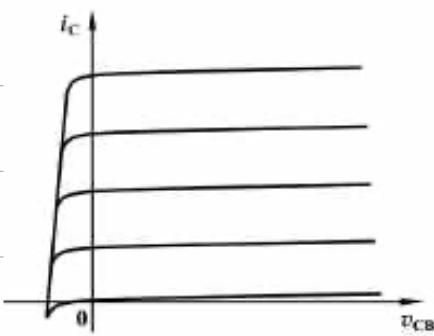
促进多子扩散，产生发射结电流  $I_{EN}$

（多子是掺杂引起的，不受温度影响）

基区复合电流  $I_{BN}$

$$I_E = I_{EN} \quad I_B = I_{BN} \quad I_c = I_{CN} + I_{CBO}$$

$$I_E = I_{ES} (e^{\frac{V_{BE}}{V_T}} - 1)$$



发射极电流  $I_E$  可以控制集电极电流  $I_c$   
控制关系：

$$V_{BE} \rightarrow i_E \rightarrow i_c$$

## 电流放大系数

$$\alpha = \frac{\text{传输到集电极的电流}}{\text{发射极注入电流}} = \frac{I_{CN}}{I_E} \approx \frac{I_c}{I_E} \quad I_c = \alpha I_E$$

$$\beta = \frac{I_c}{I_B} = \frac{I_c}{I_E - I_c} = \frac{\alpha}{1-\alpha}$$

反映载流子在基区的复合比例， $\alpha/\beta$  越大，复合比例越低。

## BJT 控制关系 $\Rightarrow$ 电流控制器件

$$I_c = \alpha I_E \quad I_c = \beta I_B \quad I_E = (1+\beta) I_B$$

工作条件：发射结正偏，集电结反偏

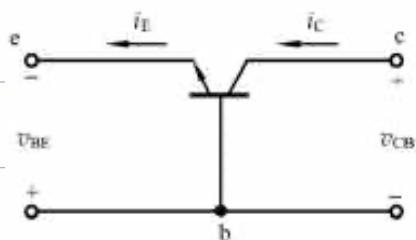
输入：发射极电流  $I_E$  / 基极电流  $I_B$

输出：集电极电流  $I_c$

组态：共基极、共射极、共集电极

## 2 BJT 的特性曲线

### (1) 共基极

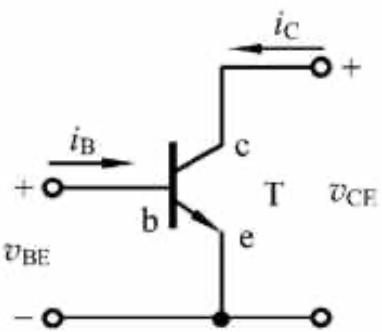


输入特性  $i_E = f(V_{BE}) \Big|_{V_{CB} = \text{const}}$

基本关系  $i_E = I_{ES} (e^{\frac{V_{BE}}{V_t}} - 1)$

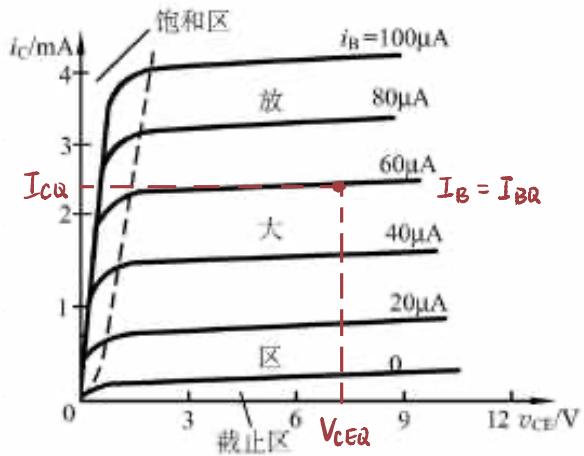
输出特性  $i_c = f(V_{CB}) \Big|_{V_{BE} = \text{const}}$

## (2) 共发射极



输入特性  $i_B = f(V_{BE}) \mid V_{CE} = \text{const}$

输出特性  $i_C = f(V_{CE}) \mid V_{BE} = \text{const}$



截止区  $i_C = 0$

饱和区  $i_C$  随  $V_{CE}$  增大迅速上升, 通常  $V_{CE} < 0.7V$  (硅)

无法区分不同  $i_B$  产生的影响

发射结正偏, 集电结正偏或反偏电压很小

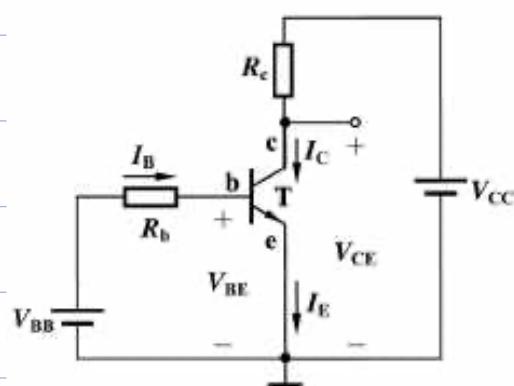
放大区  $i_C = \beta i_B$   $i_C$  与  $V_{CE}$  无关 (理想)

发射结正偏, 集电结反偏

静态工作点 Q 点:  $I_{BQ}$ ,  $I_{CQ}$ ,  $V_{CEQ}$

## 3 BJT 的静态偏置和放大电路构成

BJT 的偏置满足: 发射结有合适正偏, 集电结有合适反偏



$V_{BB}$  提供正向偏置

选择合适的  $R_B$ ,  $R_C$ , 使  $V_C > V_B$ , 集电结反偏

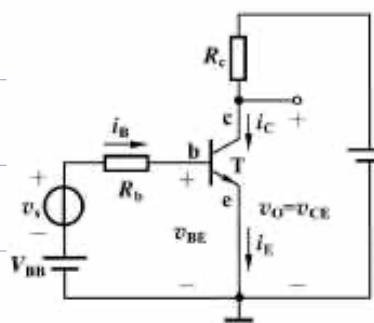
求静态工作点.

$$\text{输入回路 } I_{BQ} = \frac{V_{BB} - V_{BEQ}}{R_B}$$

$$\text{BJT 电流关系 } I_{CQ} = \beta I_{BQ}$$

$$\text{输出回路 } V_{CEQ} = V_{CC} - I_{CQ} R_C$$

其中, 一般硅管  $V_{BEQ} = 0.7V$ , 锗管  $V_{BEQ} = 0.2V$



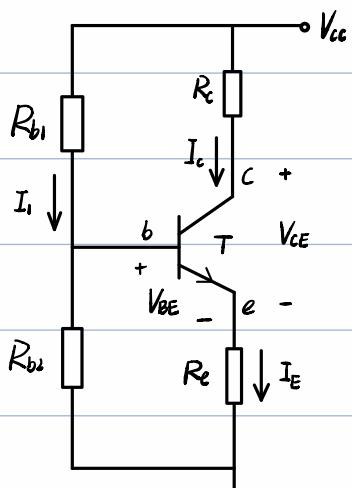
$$\text{输入信号后 } V_{BE} = V_{BB} + V_s - i_b R_b$$

$$i_B = I_{BO} + i_b$$

$$i_C = \beta i_B$$

$$V_o = V_{CE} = V_{cc} - i_C R_b$$

## EXP 基极分压射极偏置电路



当满足  $I_1 \gg I_B$  时

$$V_{BQ} = \frac{R_{b2}}{R_{b1} + R_{b2}} V_{cc}$$

$$I_{CQ} \approx I_{EQ} = \frac{V_{BQ} - V_{BEQ}}{R_c}$$

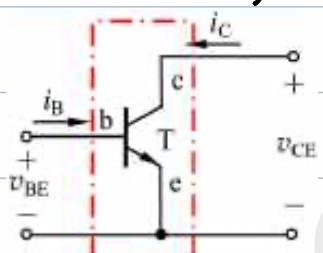
$$V_{CQE} = V_{cc} - I_c R_c - I_E R_E \approx V_{cc} - I_{CQ} (R_c + R_E)$$

$$I_{BQ} = \frac{I_{CQ}}{\beta}$$

检验是否满足  $I_1 \gg I_B$

## ④ BJT 放大电路的小信号模型分析法

### (一) H参数及小信号模型



$$\text{输入特性 } i_B = f(V_{BE}) \mid V_{CE} = \text{const}$$

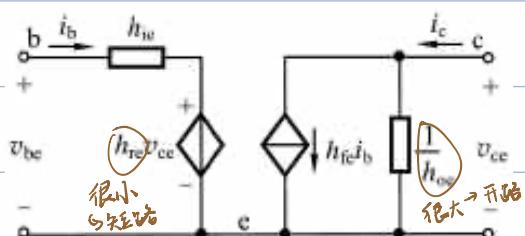
$$\text{输出特性 } i_C = f(V_{CE}) \mid V_{BE} = \text{const}$$

$$V_{BE} = f_1(i_B, V_{CE}) \quad i_C = f_2(i_B, V_{CE})$$

$$dV_{BE} = \frac{\partial V_{BE}}{\partial i_B} di_B + \frac{\partial V_{BE}}{\partial V_{CE}} dV_{CE}$$

$$di_C = \frac{\partial i_C}{\partial i_B} di_B + \frac{\partial i_C}{\partial V_{CE}} dV_{CE}$$

$$V_{BE} = h_{ie} i_B + h_{re} V_{CE} \quad i_C = h_{fe} i_B + h_{oe} V_{CE}$$



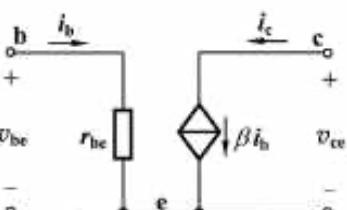
$$h_{ie} = \frac{\partial V_{BE}}{\partial i_B} = r_{be}$$

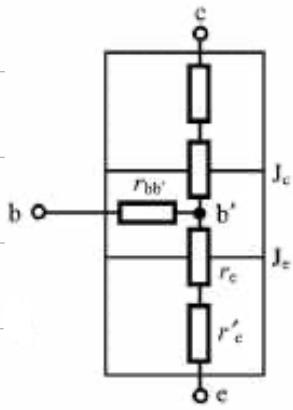
$$h_{re} = \frac{\partial V_{BE}}{\partial V_{CE}} = 10^{-3} \sim 10^{-4}$$

$$h_{fe} = \frac{\partial i_C}{\partial i_B} = \beta$$

$$h_{oe} = \frac{\partial i_C}{\partial V_{CE}} = \frac{1}{r_{ce}}$$

简化





$$r_{be} = \frac{v_{be}}{i_b} = \frac{i_b r_w + i_e (r_e + r'_e)}{i_b} = \frac{i_b r_{bb'} + (1+\beta) i_b (r_e + r'_e)}{i_b}$$

$$= r_{bb'} + (1+\beta)(r_e + r'_e) \approx r_{bb'} + (1+\beta)r_e$$

常温下发射极电阻  $r_e = \frac{kT (mV)}{I_{EQ} (mA)} = \frac{26 mV}{I_{EQ} (mA)} \approx \frac{26 mV}{I_{CA} (mA)}$

低频小功率管  $r_{bb'} \approx 200 \Omega$

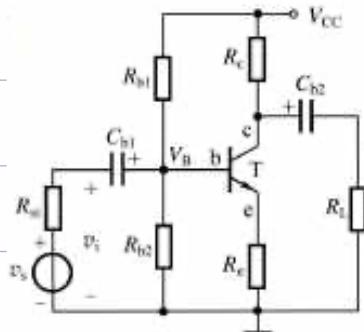
$$r_{be} \approx 200 \Omega + (1+\beta) \frac{26 mV}{I_{CA} (mA)} \quad r_{ce} = \frac{V_A}{I_{CA}}$$

注意

- ① BJT 必须工作在放大区，并且是小信号情况，模型才是可用的。
- ② 只用于交流信号或变化量的分析，不能用来分析静态工作点。
- ③  $r_{be}$  和  $r_{ce}$  与静态工作点的位置有关， $r_{be}$  更敏感。
- ④ 复杂电源  $\beta i_b$  的电流方向与控制电流  $i_b$  方向关联。

## (二) 用小信号模型分析放大电路

EXP 已知  $V_{CC} = 16 V$ ,  $R_{b1} = 56 k\Omega$ ,  $R_{b2} = 20 k\Omega$ ,  $R_c = 3.3 k\Omega$ ,



$$R_L = 6.2 k\Omega, R_{s1} = 500 \Omega,$$

BJT 的  $\beta = 80$ ,  $r_{ce} = 100 k\Omega$ ,  $V_{BEQ} = 0.7 V$ ,

$$\text{求 } A_V, R_i, A_{VS} = \frac{V_o}{V_s}, R_o.$$

(1) 静态。设  $I_{BQ} \ll I_i$

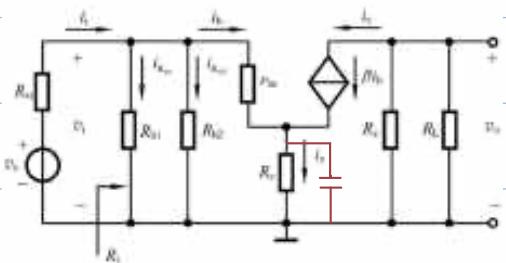
$$V_{BQ} = -\frac{R_{b2}}{R_{b1} + R_{b2}} V_{CC}$$

$$I_{CA} \approx I_{EQ} = \frac{V_{EQ}}{R_e} = \frac{V_{BQ} - V_{BEQ}}{R_e}$$

$$V_{CEQ} = V_{CC} - I_c R_c - I_e R_e \approx V_{CC} - I_c (R_c + R_e)$$

$$I_{BQ} = \frac{I_{CA}}{\beta} \quad \text{求出 } I_{EQ} \approx 1.76 mA$$

(2) 动态



$$H \text{ 参数 } r_{be} = 200 \Omega + (1+\beta) \frac{26 mV}{I_{EQ} (mA)} \approx 1.4 k\Omega$$

$$V_o = -i_c (R_c \parallel R_L) = -\beta i_b (R_c \parallel R_L)$$

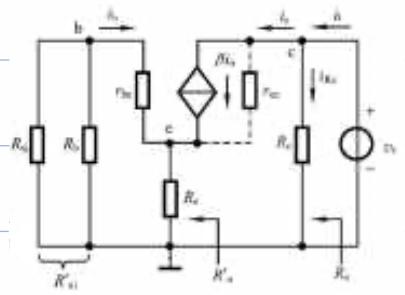
$$V_i = i_b r_{be} + i_e R_e = i_b r_{be} + (1+\beta) i_b R_e$$

$$A_V = \frac{V_o}{V_i} = -\frac{\beta (R_c \parallel R_L)}{r_{be} + (1+\beta) R_e} \approx -1.05$$

$$i_i = i_b + i_{Rb} = \frac{V_i}{r_{be} + (1+\beta) R_e} + \frac{V_i}{R_{b1}} + \frac{V_i}{R_{b2}}$$

$$R_i = \frac{V_i}{I_i} = \frac{1}{r_{be} + (1+\beta)R_e} = R_{b1} \parallel R_{b2} \parallel [r_{be} + (1+\beta)R_e] \approx 13.52 \text{ k}\Omega$$

$$A_{Vs} = \frac{V_o}{V_s} = \frac{V_o}{V_i} \cdot \frac{V_i}{V_s} = A_v \cdot \frac{R_i}{R_{si} + R_i} \approx -1.01$$



$$\text{基极回路 KVL: } i_b(r_{be} + R_{si}') + (i_b + i_c)R_e = 0$$

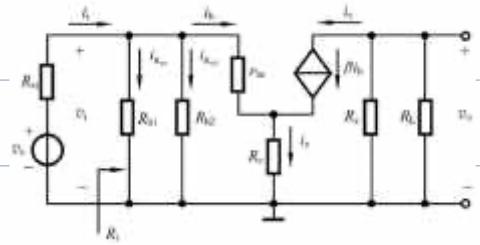
$$\text{其中 } R_{si}' = R_{si} \parallel R_b \quad R_b = R_{b1} \parallel R_{b2}$$

$$\text{集电极回路 KVL: } V_t - (i_c - \beta i_b)r_{ce} - (i_b + i_c)R_e = 0$$

$$R'_o = \frac{V_t}{i_c} \quad R_o = R'_o \parallel R_L$$

## 5 BJT 的三种基本放大电路和复合管

### (1) 共射极



$$\text{输入回路 } V_i = i_b r_{be} + (1+\beta) i_b R_e$$

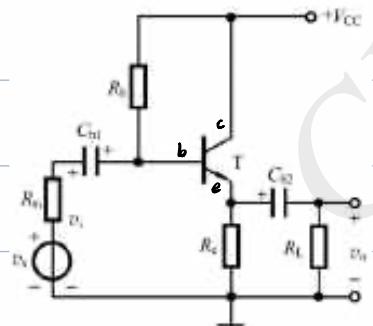
$$\text{输出回路 } V_o = -\beta i_b (R_o \parallel R_L)$$

$$A_v = \frac{V_o}{V_i} = -\frac{\beta (R_o \parallel R_L)}{r_{be} + (1+\beta) R_e}$$

$$\text{输入电阻 } R_i = R_{b1} \parallel R_{b2} \parallel [r_{be} + (1+\beta) R_e]$$

$$\text{输出电阻 } R_o = R_o' \parallel R_c \approx R_c$$

### (2) 共集电极



#### (1) 静态分析

$$\text{输入回路 } V_{cc} - V_{BEQ} - I_{BQ} R_b - (1+\beta) I_{BQ} R_e = 0$$

$$\Rightarrow I_{BQ} = \frac{V_{cc} - V_{BEQ}}{R_b + (1+\beta) R_e}$$

$$I_{CQ} = \beta I_{BQ} \approx I_{EQ}$$

$$\text{输出回路 } V_{CEQ} = V_{cc} - I_{EQ} R_e$$

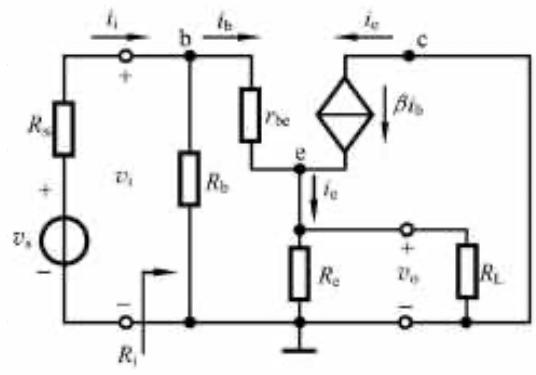
#### (2) 动态分析

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

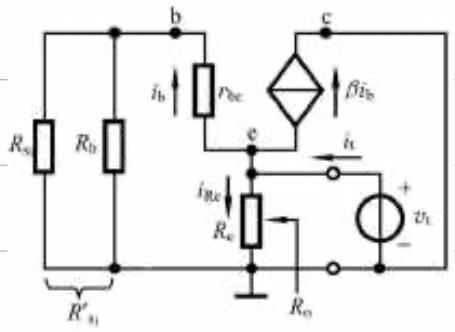
$$V_i = i_b r_{be} + (1+\beta) i_b (R_e \parallel R_b)$$

$$V_o = (1+\beta) i_b (R_e \parallel R_L)$$

$$A_v = \frac{(1+\beta) (R_e \parallel R_L)}{r_{be} + (1+\beta) (R_e \parallel R_L)}$$



若  $(1+\beta)(R_e \parallel R_L) \gg r_{be}$ ,  $A_v \approx 1$ ,  $V_o \approx V_i$  电压跟随器 / 射极跟随器



$$i_i = \frac{v_i}{R_b} + i_b = \frac{v_i}{R_b} + \frac{v_t}{r_{be} + (1+\beta)(R_e//R_L)}$$

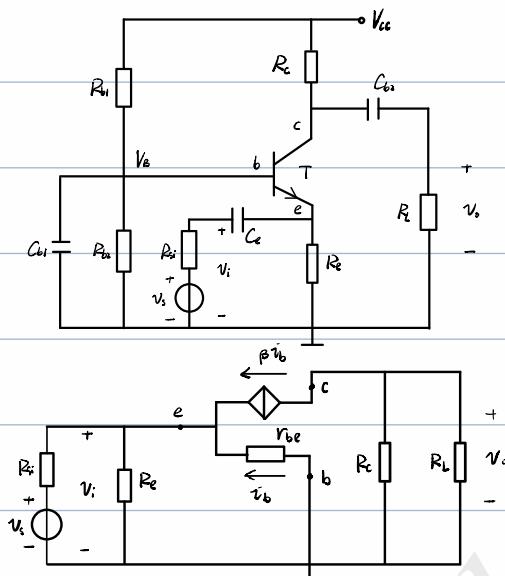
$$R_i = \frac{v_i}{i_i} = \frac{1}{\frac{1}{R_b} + \frac{1}{r_{be} + (1+\beta)(R_e//R_L)}} = R_b // [r_{be} + (1+\beta)(R_e//R_L)]$$

$$i_t = i_b + \beta i_b + i_{Re} = \frac{(1+\beta)v_t}{R_{si} + r_{be}} + \frac{v_t}{R_e}$$

$$R_o = \frac{v_t}{i_t} = R_e // \left( \frac{R_{si} + r_{be}}{1+\beta} \right)$$

- 特点**
- ① 电压增益小于1但接近1， $v_o$ 与 $v_i$ 同相
  - ② 输入电阻大，对电压信号源衰减小
  - ③ 输出电阻小，带电压负载能力强

### (3) 共基极



$$v_o = -i_c(R_c // R_L) = -\beta i_b(R_c // R_L)$$

$$v_i = -i_b r_{be}$$

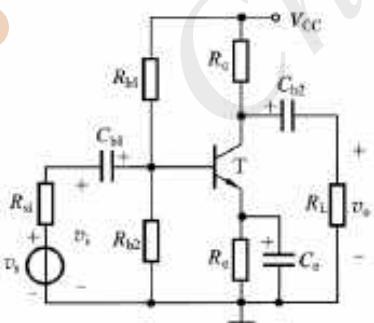
$$A_v = \frac{v_o}{v_i} = \frac{\beta(R_c // R_L)}{r_{be}}$$

$$i_i = \frac{v_i}{R_e} - (1+\beta)i_b = \frac{v_i}{R_e} + \frac{(1+\beta)v_i}{r_{be}}$$

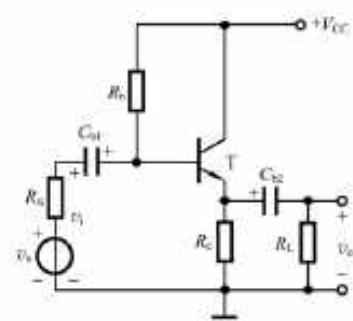
$$R_i = \frac{v_i}{i_i} = R_e // \left( \frac{r_{be}}{1+\beta} \right)$$

$$R_o = R_c$$

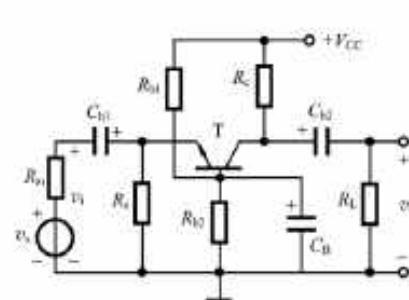
总结



共射极电路



共集电极电路



共基极电路

电压增益:  $\frac{\beta \cdot (R_c // R_L)}{r_{be}}$

$$\frac{(1+\beta) \cdot (R_c // R_L)}{r_{be} + (1+\beta)(R_c // R_L)} \approx 1$$

$$\frac{\beta \cdot (R_c // R_L)}{r_{be}}$$

输入电阻:  $R_b // r_{be}$

$$R_b // [r_{be} + (1+\beta)(R_c // R_L)] \text{ max}$$

$$R_e // \frac{r_{be}}{1+\beta} \text{ min}$$

输出电阻:  $R_c$

$$R_c // \frac{(R_s // R_b) + r_{be}}{1+\beta} \text{ min}$$

$$R_c$$

相位关系: 反相

同相

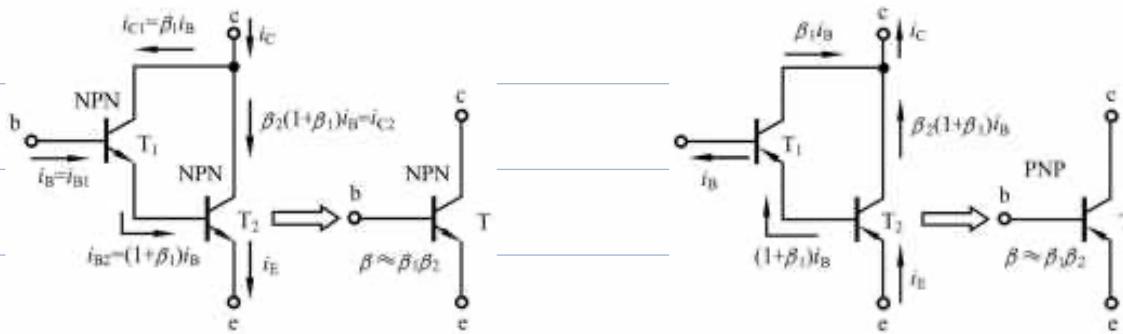
同相

用途: 多级放大电路的中间级      输入级、中间级、输出级      高频或宽频带电路

# 复合管

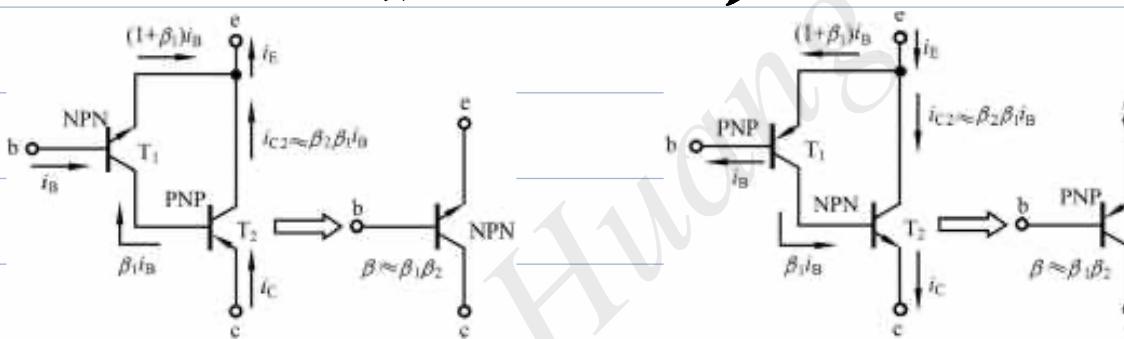
基本原则：BJT 各电极电流方向不能冲突

同类型：T<sub>1</sub>发射极 → T<sub>2</sub>基极



$$\text{等效基极-发射极电阻 } r_{be} = r_{be1} + (1 + \beta_1) r_{be2}$$

不同类型：T<sub>1</sub>集电极 → T<sub>2</sub>基极

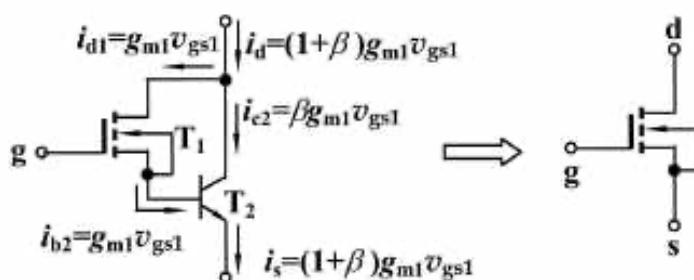


$$\text{等效基极-发射极电阻 } r_{be} \approx r_{be1}$$

复合管优点 ① 用简单的方法得到高  $\beta$  值三极管

② 分析电路时，可以简单地把它当作一个三极管

## BiMOS 复合管



$$\beta_m = (1 + \beta) g_m$$

6

MOSFET 和 BJT 比较及其基本放大电路共性归类

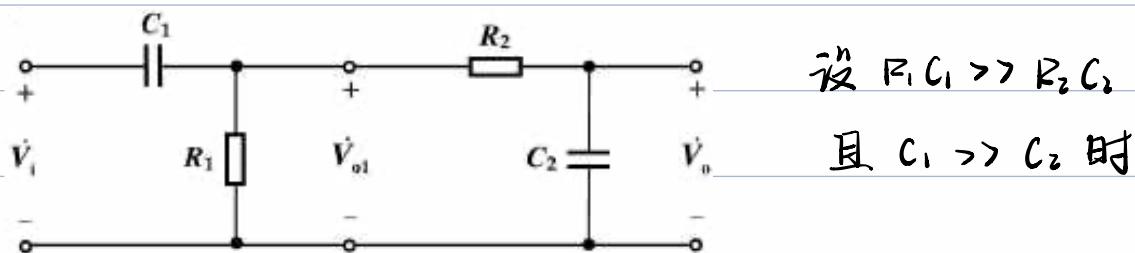
	增强型 NMOS 管	NPN 型 BJT
电路符号		
工作在放大区的两个条件	(1) 生成沟道 $v_{GS} \geq V_{TN}$ ( $=0.3 \sim 0.5V$ , 现代工艺可达到的数值) (2) 沟道出现预夹断 $v_{DS} \geq v_{GS} - V_{TN}$	(1) 发射结正偏 $v_{BE} \geq V_{th}$ ( $\approx 0.5V$ ) (2) 集电结反偏 或放宽为 $v_{BC} < 0.4V$ 且 $v_{CE} \geq 0.3V$
放大区的电流-电压关系	$i_D = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L} (v_{GS} - V_{TN})^2 (1 + \lambda v_{DS})$ $= K_n (v_{GS} - V_{TN})^2 (1 + \lambda v_{DS})$ $i_S = 0$	$i_E \approx I_{EQ} e^{v_{BE}/V_T}$ $i_C = \alpha i_E$ $i_B = i_C / \beta$
简化的低频小信号模型 (共源、共射)		
互导(或跨导) $g_m$	$g_m = 2K_n (V_{GSQ} - V_{TN}) = 2\sqrt{K_n I_{DQ}}$	$g_m = \beta / r_{be} \approx I_{EQ} / V_T$
共源、共射连接时三极管的输入电阻	$r_{in} = \infty$	$r_{in} = r_{be} + (1 + \beta) \frac{26mV}{I_{EQ} mA} \approx \frac{\beta}{g_m}$
三极管的输出电阻	$r_{out} = [\lambda K_n (v_{GS} - V_{TN})]^2 = \frac{1}{\mu_{EQ}} = \frac{V_A}{I_{EQ}}$ <span style="color:red;">通常</span>	$r_{out} \approx \frac{V_A}{I_{EQ}}$

	反相电压放大器	电压跟随器	电流跟随器
通用组态电路示意图			
组态命名依据的主要特征	不仅有 $v_0$ 与 $v_1$ 反相, 而且一般有 $ A_v  \gg 1$	$v_0 \approx v_1$ , $A_v \approx 1$ , 即 $v_0$ 与 $v_1$ 大小接近相等, 相位相同	$i_0 \approx i_1$ 对于 BJT 有 $i_c \approx i_e$ 对于 FET 有 $i_d \approx i_s$
电路名称	共源极电路 共射极电路	共漏电极电路 共集极电路	共栅极电路 共基极电路
用途	电压增益高, 输入电阻和输入电容均较大, 适用于多级放大电路的中间级	输入电阻高、输出电阻低, 可作阻抗变换, 用于输入级、输出级或缓冲级	输入电阻小, 输入电容小, 适用于高频、宽带电路

# §6 放大电路的频率响应

## 1 单时间常数RC电路的频率响应

1个电阻 + 1个电容



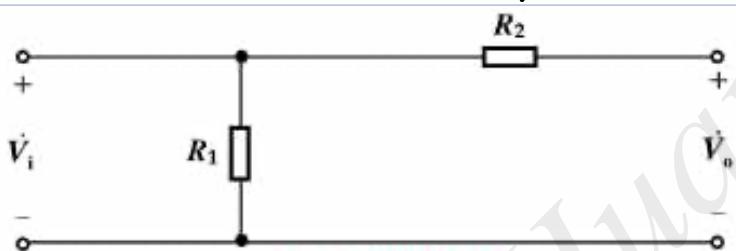
设  $R_1 C_1 \gg R_2 C_2$ .

且  $C_1 \gg C_2$  时

(1) 中频响应  $\frac{1}{R_1 C_1} \ll \omega \ll \frac{1}{R_2 C_2}$

$\frac{1}{\omega C_1} \ll R_1$   $C_1$  可看作短路

$\frac{1}{\omega C_2} \gg R_2$   $C_2$  可看作开路

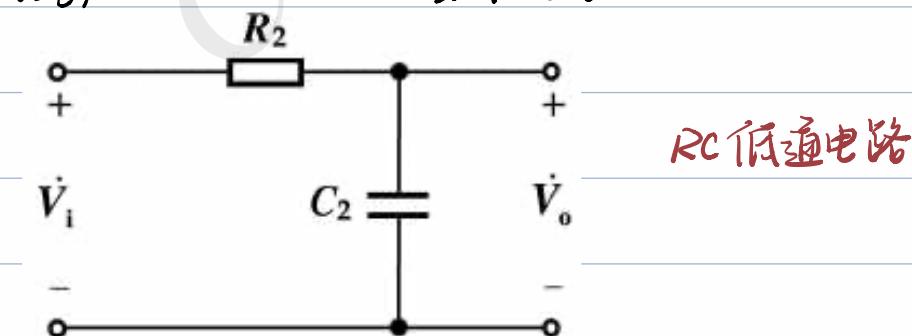


传递函数(电压增益)  $A_{VM} = \frac{\dot{V}_o}{\dot{V}_i} = 1$

$$|A_{VM}| = 1 \quad \varphi_m = \varphi_o - \varphi_i = 0$$

(2) 高频响应  $\omega$  接近或大于等于  $\frac{1}{R_2 C_2}$

$\frac{1}{\omega C_1} \ll R_1$   $C_1$  看作短路



RC低通电路

$$A_{VH} = \frac{\dot{V}_o}{\dot{V}_i} = \frac{\frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} = \frac{1}{1 + j\omega R_2 C_2}$$

令  $f_H = \frac{1}{2\pi R_2 C_2}$  称为上限截止频率.  $\omega = 2\pi f$

$$A_{VH} = \frac{1}{1 + j(\frac{f}{f_H})^2}$$

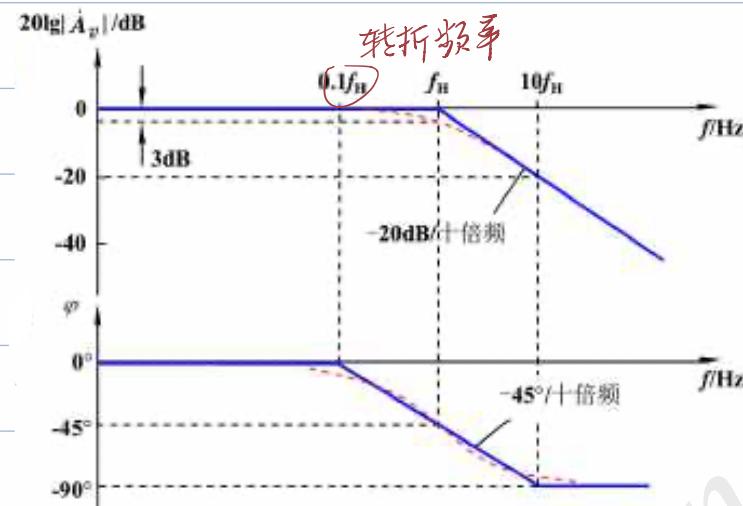
电压增益的幅值  $|A_{VH}| = \sqrt{1 + (\frac{f}{f_H})^2}$  幅频响应

电压增益的相角  $\varphi_H = \varphi_o - \varphi_i = \arctan(\frac{f}{f_H})$  相频响应

$$幅频响应 |\dot{A}_{vH}| = \sqrt{1 + \left(\frac{f}{f_H}\right)^2}$$

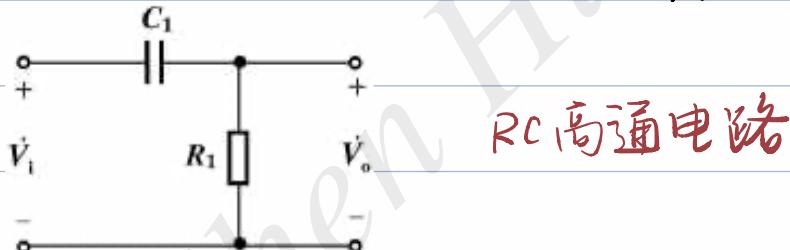
- 当  $f \ll f_H$  时,  $|\dot{A}_{vH}| \approx 1$ ,  $20 \lg |\dot{A}_{vH}| = 0$  (dB)  
 当  $f \gg f_H$  时,  $|\dot{A}_{vH}| \approx \frac{f_H}{f}$ ,  $20 \lg |\dot{A}_{vH}| \approx 20 \lg f_H - 20 \lg f$  (dB)

### 波特图:



(3) 低频响应  $\omega$  接近或小于等于  $\frac{1}{R_1 C_1}$

$$\frac{1}{\omega C_2} \gg R_2 \quad C_2 \text{ 看作开路}$$



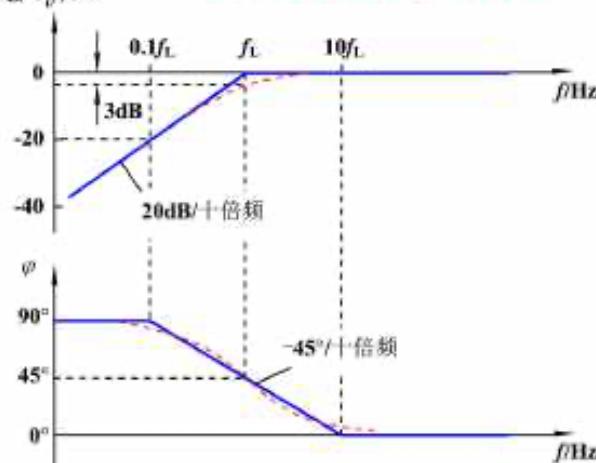
$$\dot{A}_{vL} = \frac{\dot{V}_o}{\dot{V}_i} = \frac{R_1}{R_1 + j\omega C_1} = \frac{1}{1 + j\omega R_1 C_1}$$

令  $f_L = \frac{1}{2\pi R_1 C_1}$  称为下限截止频率,  $\omega = 2\pi f$

$$\dot{A}_{vL} = \frac{1}{1 + j\left(\frac{f}{f_L}\right)}$$

$$|\dot{A}_{vL}| = \sqrt{1 + \left(\frac{f}{f_L}\right)^2} \quad \varphi_L = \varphi_o - \varphi_i = \arctan\left(\frac{jL}{j}\right)$$

RC高通电路(低频区等效电路)

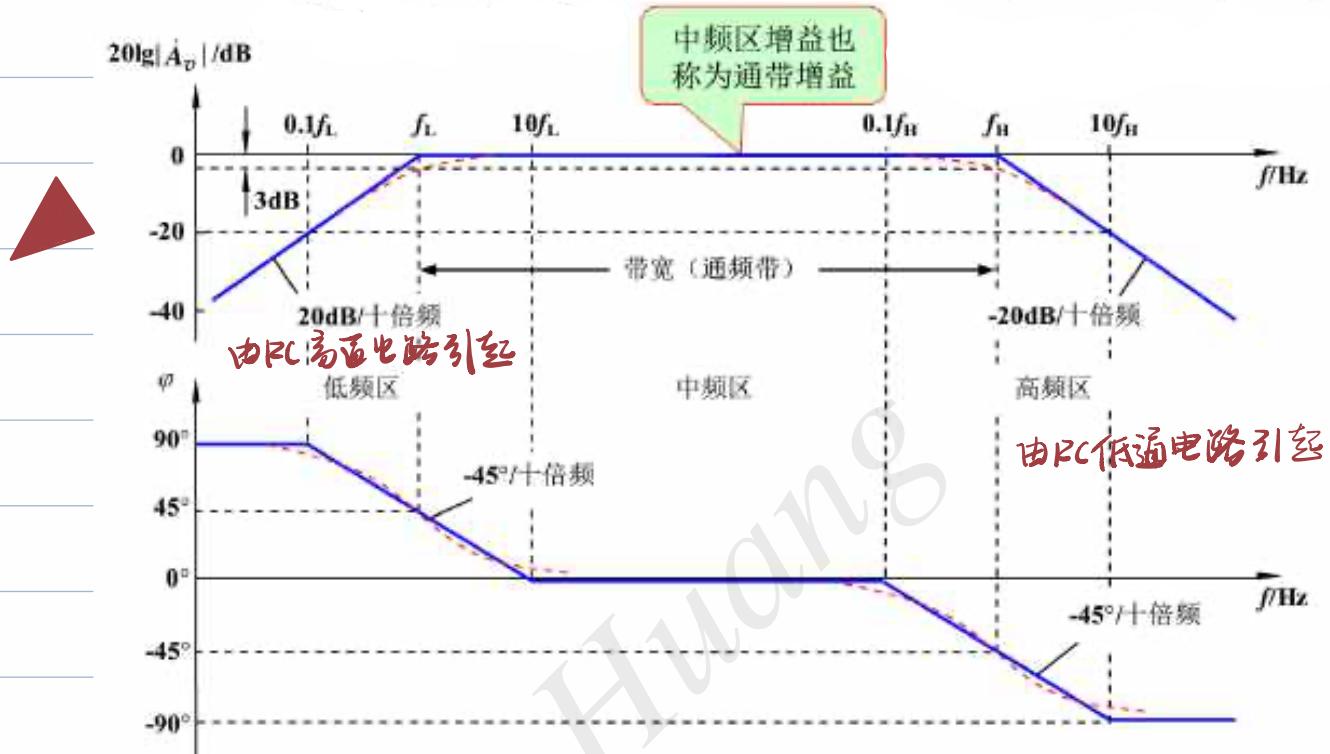


#### (4) 全频响应

上限频率:  $f_H$

下限频率:  $f_L$

带宽/通频带  $BW = f_H - f_L$  当  $f_H \gg f_L$  时,  $BW \approx f_H$



#### 结论

①  $f_H, f_L$  取决于时间常数  $\tau = RC$

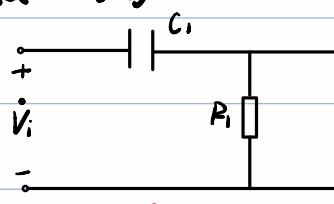
② 当输入信号的频率  $f = f_H$  或大时, 电路增益比通带增益下降 3dB, 或下降为通带增益的 0.707 倍, 且在通带相移的基础上产生  $-45^\circ$  或  $45^\circ$  的相移.

③ 每个转折频率产生的衰减速率是每十倍频衰减 20dB

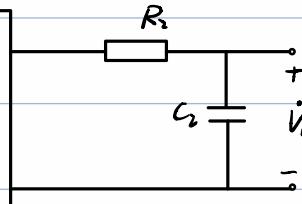
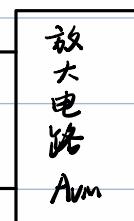
2 放大电路频率响应概述及三极管 高阶小信号模型

放大电路中存在: PN结电容、耦合电容、旁路电容 ...

等效电路:



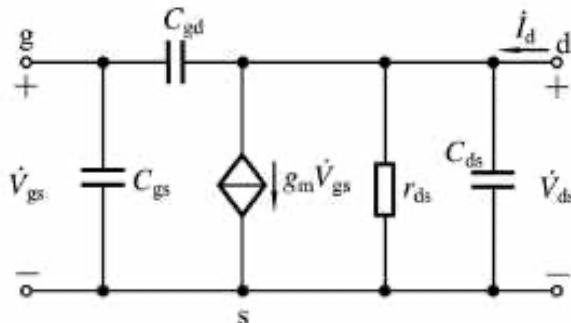
RC 高通



RC 低通

$$R, C_1 \gg R_2, C_2$$

## MOSFET 高频小信号模型



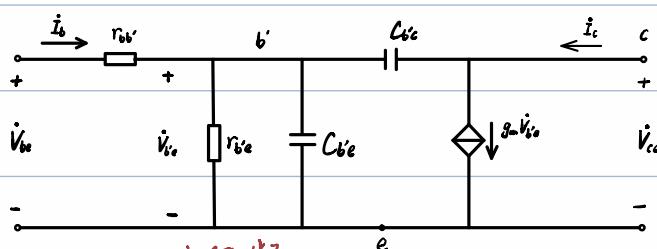
$$C_{gs} \approx 0.1 - 0.5 \text{ pF}$$

$$C_{gd} \approx 0.01 - 0.04 \text{ pF}$$

$C_{ds}$  更小

$$R_{ds} \approx 10^4 - 10^6 \Omega$$

## BJT 高频小信号模型

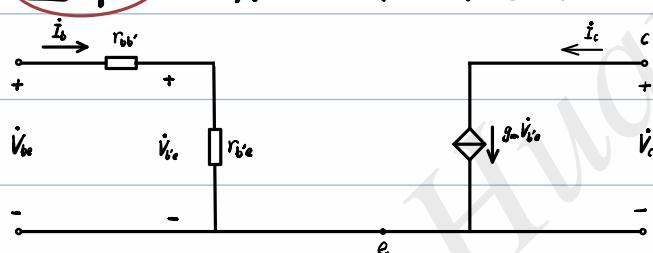


$$r_{bb'} \approx 200 \Omega$$

$$r_{be} = (1 + \beta) \frac{V_T}{I_{EQ}}$$

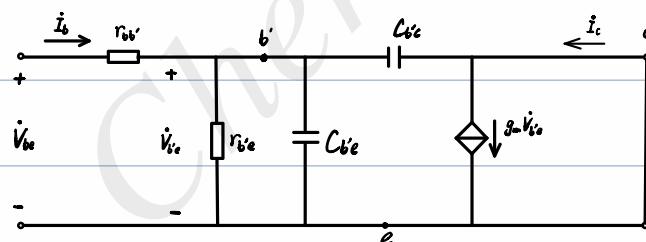
$$C_{be'e} \text{ 几皮法拉到几百皮法拉}$$

$$C_{bb'c} \approx 2 - 10 \text{ pF}$$



$$g_m = \frac{\beta_0}{r_{be}} \approx \frac{I_{EQ}}{V_T} \text{ 与频率无关}$$

## $\beta$ 的频率响应



$$\left\{ \begin{array}{l} \dot{I}_c = g_m \dot{V}_{be} - j\omega C_{be'e} \dot{V}_{be} \\ \dot{I}_b = \frac{\dot{V}_{be}}{r_{be}} + j\omega C_{bb'c} \dot{V}_{be} + j\omega C_{be'e} \dot{V}_{be} \end{array} \right.$$

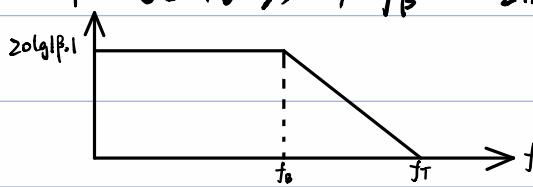
$$\beta = \frac{\dot{I}_c}{\dot{I}_b} = \frac{g_m - j\omega C_{be'e}}{\frac{1}{r_{be}} + j\omega (C_{bb'c} + C_{be'e})} \quad \propto \beta_0 = g_m r_{be}$$

当  $g_m \gg \omega C_{be'e}$  时

$$\beta = \frac{\beta_0}{1 + j\omega (C_{be'e} + C_{bb'c}) r_{be}}$$

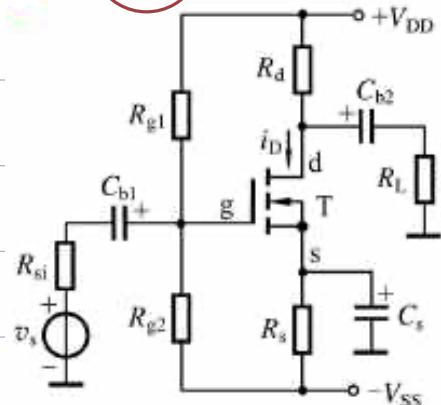
$$|\beta| = \sqrt{1 + (f/f_p)^2}$$

$$\beta \text{ 的上限频率 } f_\beta = \frac{1}{2\pi (C_{be'e} + C_{bb'c}) r_{be}} \quad \text{特征频率 } f_T$$



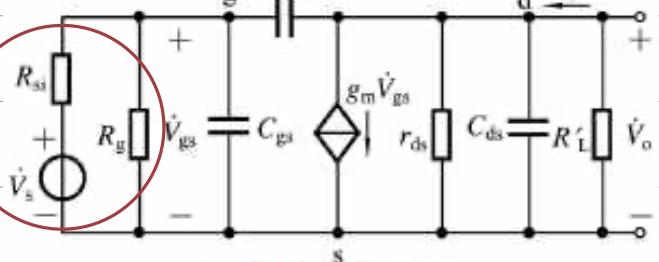
### 3 三极管放大电路的高频响应和带宽增益积

高频时耦合电容、旁路电容看作短路，直流电压源接地

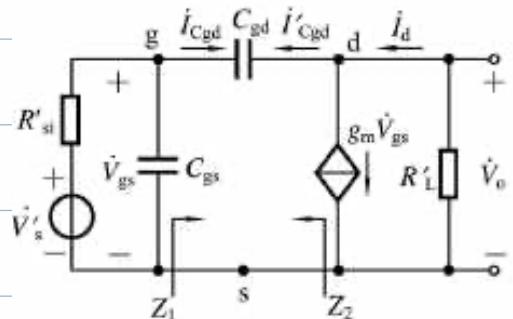


$$R_{\text{g}} = R_{g1} \parallel R_{g2}$$

$$R_L' = R_d \parallel R_L$$



$$\text{设 } r_{ds} \gg R_L' , \quad V_s' = \frac{R_{si}'}{R_{si}} V_s \quad R_{si} = R_{si} \parallel R_g$$



$$\text{设 } A_v' = \frac{V_o}{V_{gs}} , \text{ 则 } A_v'$$

$$I_{C_{gd}} = \frac{V_{gs} - V_o}{j\omega C_{gd}} = (1 - A_v') V_{gs} \cdot j\omega C_{gd}$$

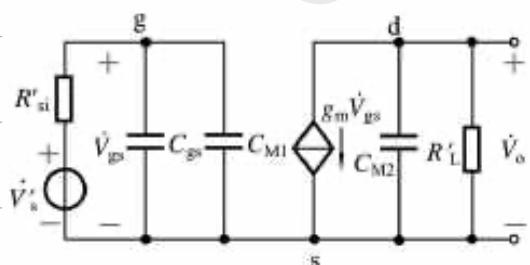
$$\text{阻抗 } Z_1 = \frac{V_{gs}}{I_{C_{gd}}} = (1 - A_v') \cdot j\omega C_{gd}$$

显然 Z<sub>1</sub> 是一个电容的阻抗,  $C_{m1} = (1 - A_v') C_{gd}$

同理 Z<sub>2</sub> 也是一个电容的阻抗  $C_{m2} = (1 - \frac{1}{A_v'}) C_{gd}$

$$I_{d} \approx g_m V_{gs} , \text{ 则 } A_v' = \frac{V_o}{V_{gs}} = \frac{-I_d R_L'}{V_{gs}} = -g_m R_L'$$

$$\left\{ \begin{array}{l} C_{m1} = C_{gd} (1 + g_m R_L') \\ C_{m2} = C_{gd} (1 + \frac{1}{g_m R_L'}) \end{array} \right.$$



输入回路  $f \uparrow \Rightarrow |V_{gs}| \downarrow$

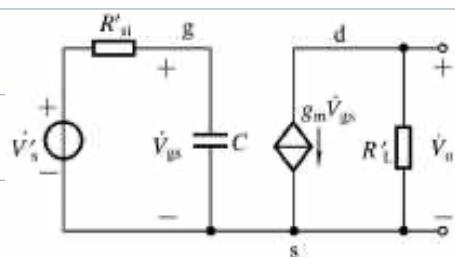
$R_{si}' (C_{gs} + C_{m1})$  为低通电路

输出回路  $f \uparrow \Rightarrow |V_o| \downarrow$

$R_L' C_{m2}$  为低通电路

通常  $g_m R_L' \gg 1$ , 则  $C_{m1} = C_{gd} (1 + g_m R_L') \gg C_{gd}$

$$(开路) C_{m2} = C_{gd} (1 + \frac{1}{g_m R_L'}) \approx C_{gd}$$

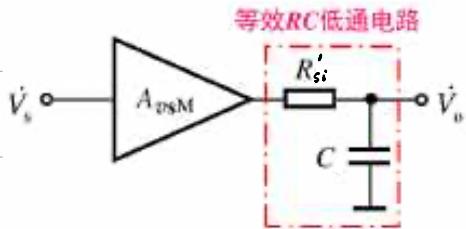


通常有  $V_{gs} = V_s'$

$$A_{vsm} = \frac{V_o}{V_s} = \frac{V_o}{V_{gs}} \cdot \frac{V_{gs}}{V_s} = \frac{V_o}{V_{gs}} \cdot \frac{V_s'}{V_s}$$

$$= -g_m R_L' \cdot \frac{R_{si}'}{R_{si}} = -g_m R_L' \cdot \frac{R_g}{R_{si} + R_g}$$

# 共源极放大电路的等效RC低通电路：



$$A_{vsm} = -g_m R_i' \frac{R_g}{R_{si} + R_g}$$

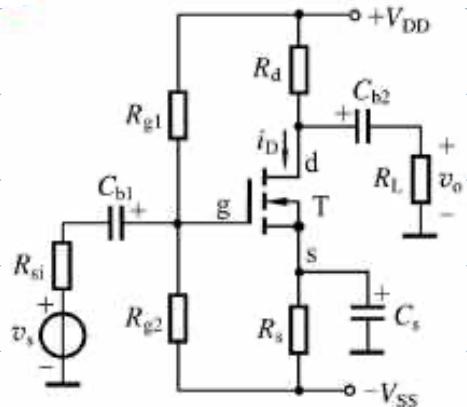
$$f_H = \frac{1}{2\pi R_{si} C}$$

哪些参数会影响上限频率？

$$R_{si}' = R_{si} \parallel R_{g1} \parallel R_{g2} \quad \uparrow \text{明显提高}$$

$$C = C_{gs} + C_{mi} = C_{gs} + \underline{C_{gd}} (1 + g_m R_i') \quad \downarrow \text{变小的}$$

$$g_m = 2\sqrt{k_n I_{DQ}}$$



## 增益带宽积

$$|A_{vsm} \cdot BW| \approx |A_{vsm} \cdot f_H| = g_m R_i' \cdot \frac{R_g}{R_{si} + R_g} \cdot \frac{1}{2\pi R_{si} C}$$

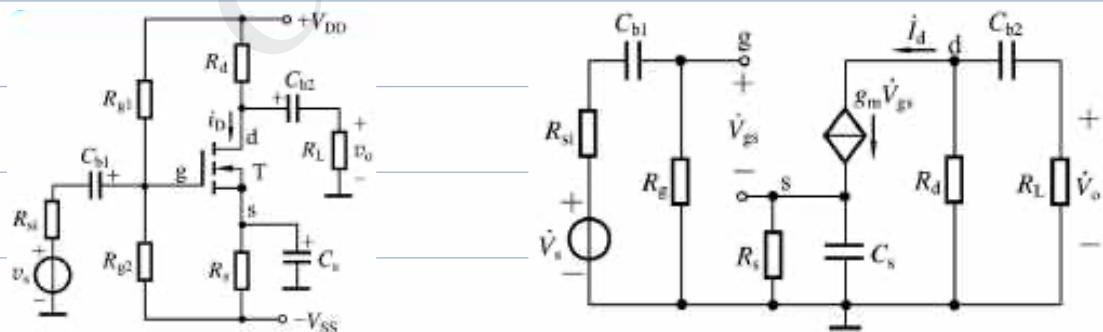
$$= g_m R_i' \cdot \frac{R_g}{R_{si} + R_g} \cdot \frac{1}{2\pi (R_{si} \parallel R_g) [C_{gs} + (1 + g_m R_i') C_{gd}]}$$

通常有  $R_g \gg R_{si}$ ,  $g_m R_i' \gg 1$ ,  $(1 + g_m R_i') C_{gd} \gg C_{gs}$

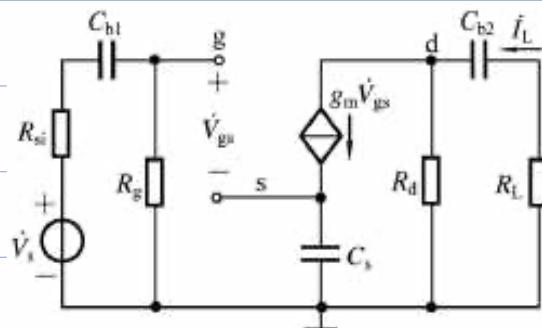
$$|A_{vsm} \cdot BW| \approx \frac{1}{2\pi R_{si} C_{gd}} \quad \text{近似为常数}$$

## 4 阻容耦合放大电路的低频响应及全频率响应

低频时 MOSFET 极间电容开路，保留耦合电容和旁路电容。



设  $C_s$  足够大,  $\frac{1}{w C_s} \ll R_s$



$$\dot{V}_d = \frac{R_g}{R_{si} + R_g + \frac{1}{j\omega C_{bi}}} \cdot \dot{V}_s$$

$$\dot{V}_g = \dot{V}_{gs} + g_m \dot{V}_{gs} \frac{1}{j\omega C_s}$$

$$\Rightarrow \dot{V}_{gs} = \frac{1}{1 + \frac{g_m}{j\omega C_s} R_{si} + R_g + \frac{1}{j\omega C_{bi}}} \cdot \dot{V}_s$$

$$\dot{I}_L = g_m \dot{V}_{GS} \frac{R_d}{R_d + R_L + j\omega C_{b2}}$$

$$\dot{V}_o = -\dot{I}_L R_L = -g_m \dot{V}_{GS} \frac{R_d}{R_d + R_L + j\omega C_{b2}} \cdot R_L$$

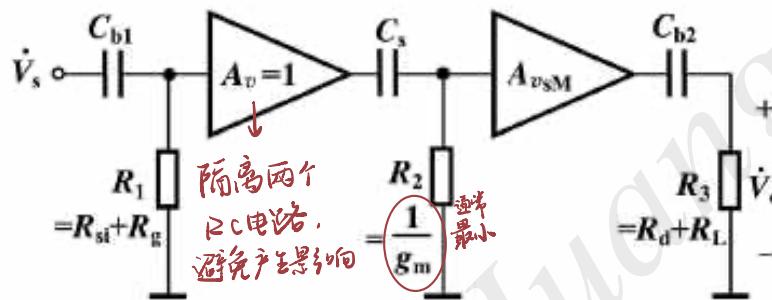
源电压增益

$$\begin{aligned} \dot{A}_{vSL} &= \frac{\dot{V}_o}{\dot{V}_s} = \frac{\dot{V}_o}{\dot{V}_{GS}} \cdot \frac{\dot{V}_{GS}}{\dot{V}_s} = -g_m \frac{R_d}{R_d + R_L + j\omega C_{b2}} \cdot \frac{1}{1 + \frac{g_m}{j\omega C_S}} \cdot \frac{R_g}{R_{Si} + R_g + j\omega C_{b1}} \\ &= A_{vSM} \cdot \frac{1}{1 - j(\frac{f_u}{f})} \cdot \frac{1}{1 - j(\frac{f_u}{f})} \cdot \frac{1}{1 - j(\frac{f_u}{f})} \end{aligned}$$

其中  $A_{vSM} = -g_m R_L' \frac{R_g}{R_{Si} + R_g}$

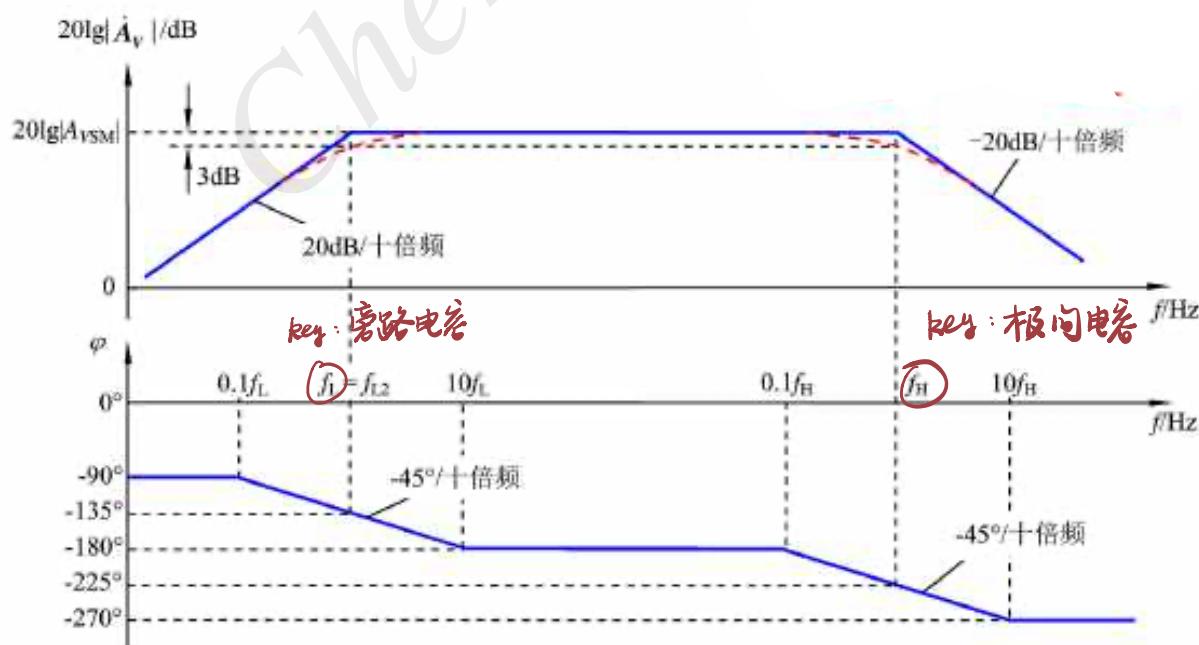
下限频率  $f_u = \frac{1}{2\pi(R_{Si} + R_g)C_{b1}}$        $f_{L2} = \frac{1}{2\pi(\frac{1}{g_m})C_S}$        $f_3 = \frac{1}{2\pi(R_d + R_L)C_{b2}}$

等效模型：



若  $f_{L2} > 4f_u$ ,  $f_u > 4f_{L3}$ , 则  $f_L \approx f_u$

### 全频率响应



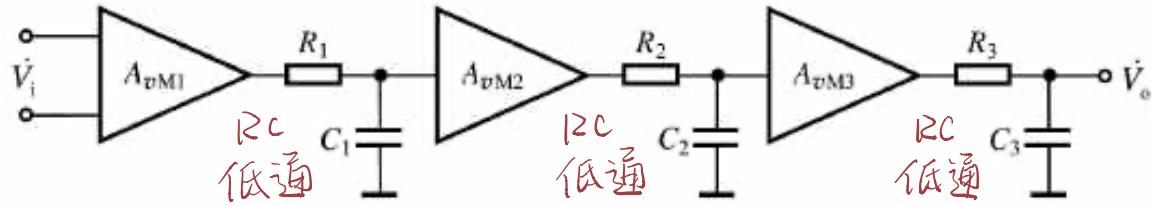
共源极放大电路的低频响应波特图（忽略了  $f_{L2}$  和  $f_{L3}$  的影响）

增大带宽  $\rightarrow$  增大  $f_H$   $\rightarrow$  选极间电容小的三极管

## 5 多级放大电路的频率响应

### (1) 直接耦合多级放大电路

每级都可以等效成一个与频率无关的放大电路和一个RC低通电路的串联



$$\dot{A}_{vh} = \dot{A}_{vh1} \dot{A}_{vh2} \dot{A}_{vh3}$$

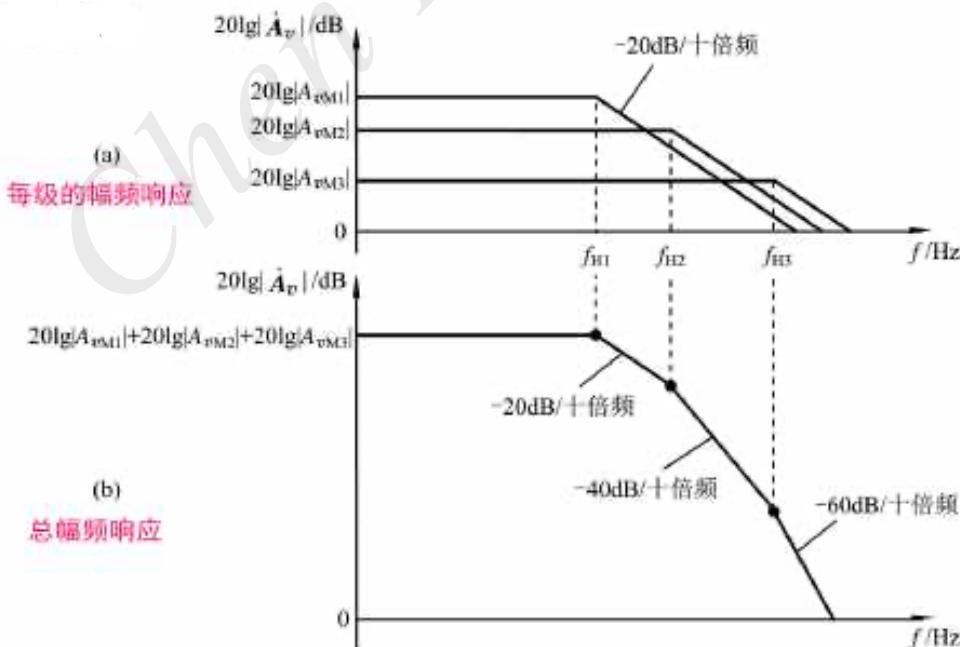
$$= \frac{A_{vh1}}{1 + j(\frac{f}{f_{H1}})} \cdot \frac{A_{vh2}}{1 + j(\frac{f}{f_{H2}})} \cdot \frac{A_{vh3}}{1 + j(\frac{f}{f_{H3}})}$$

$$\text{转折频率 } f_{H1} = \frac{1}{2\pi R_1 C_1} \quad f_{H2} = \frac{1}{2\pi R_2 C_2} \quad f_{H3} = \frac{1}{2\pi R_3 C_3}$$

$$\text{幅频响应 } |\dot{A}_{vh}| = |\dot{A}_{vh1}| \cdot |\dot{A}_{vh2}| \cdot |\dot{A}_{vh3}|$$

$$= \frac{|A_{vh1}|}{\sqrt{1 + (f/f_{H1})^2}} \cdot \frac{|A_{vh2}|}{\sqrt{1 + (f/f_{H2})^2}} \cdot \frac{|A_{vh3}|}{\sqrt{1 + (f/f_{H3})^2}}$$

$$20 \lg |\dot{A}_{vh}| = 20 \lg |\dot{A}_{vh1}| + 20 \lg |\dot{A}_{vh2}| + 20 \lg |\dot{A}_{vh3}|$$



相频响应 (设通带内无反相)

$$\varphi_H = -\arctan\left(\frac{f}{f_{H1}}\right) - \arctan\left(\frac{f}{f_{H2}}\right) - \arctan\left(\frac{f}{f_{H3}}\right)$$

## (2) 阻容耦合多级放大电路的频率响应

设  $A_{VMI_2} = A_{VMI_1}$ ,  $f_{L2} = f_{L1}$ ,  $f_{H2} = f_{H1}$

则总增益  $(0.707 A_{VMI_1})^2 = 0.5 A_{VMI_1}^2 < 0.707 A_{VMI_1}^2$

$\Rightarrow f_L > f_{L1}$ ,  $f_H < f_{H1}$

多级放大电路的通频带一定比构成它的任何一级都窄

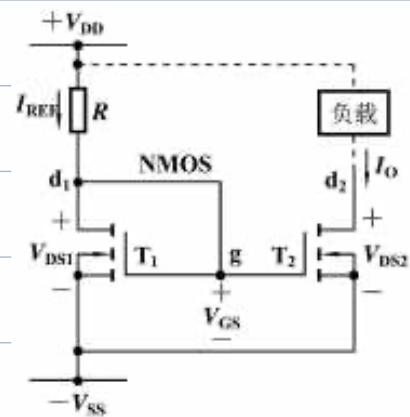
跨接在输入输出端口之间的电容会产生密勒效应



# §7 模拟集成电路

## 1 直流电流源

### (1) MOSFET 镜像电流源



$$V_{DS1} = V_{GS} \text{ 只要满足 } V_{GS} > V_{TN}$$

$$\text{必有 } V_{DS1} = V_{GS} > V_{GS} - V_{TN}$$

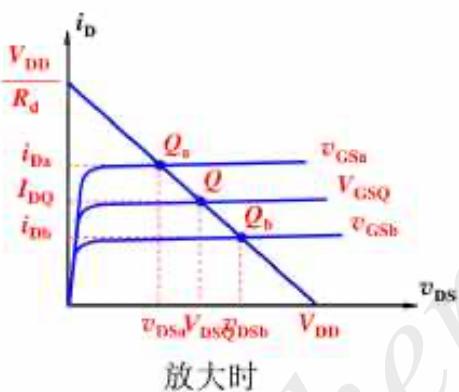
T<sub>1</sub> 必工作在饱和区

$$\text{又 } V_{GS2} = V_{GS1} = V_{GS}, \text{ 只要 } V_{DS2} > V_{GS} - V_{TN}.$$

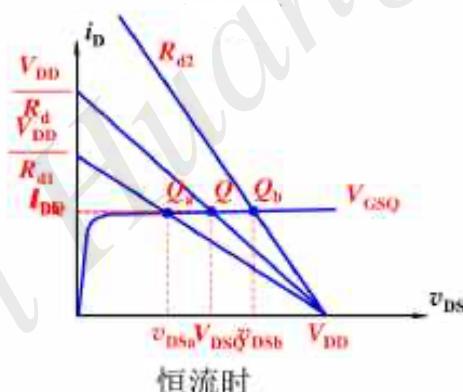
T<sub>2</sub> 必工作在饱和区

$$I_o = I_{D2} = I_{D1} = I_{REF} = \frac{V_{DD} + V_{SS} - V_{GS}}{R}$$

$$I_o = I_{REF} = I_{D1} = k_n (V_{GS} - V_{TN})^2 \quad \text{与负载无关, 表现恒流}$$



放大时



恒流时

MOSFET做电流源需满足 ①  $V_{GS}$  保持不变

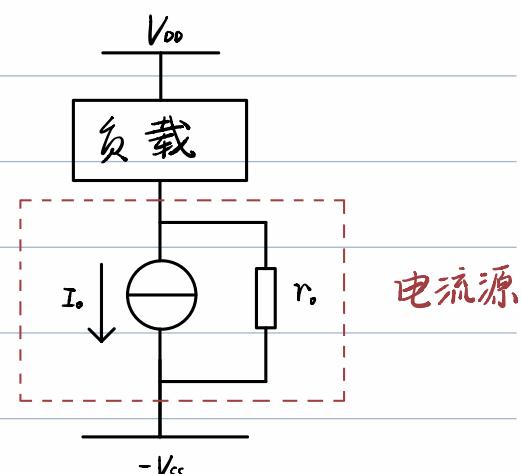
② MOS管工作在饱和区

考虑沟道长度调制效应  $r_o = \frac{1}{\lambda I_D}$

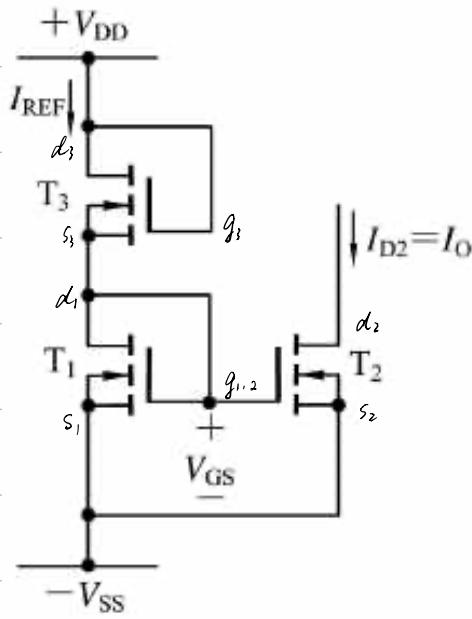
$$I_{REF} = I_{D1} = \frac{k'_n}{2} \left( \frac{W}{L} \right)_1 (V_{GS} - V_{TN})^2$$

$$I_o = I_{D2} = \frac{k'_n}{2} \left( \frac{W}{L} \right)_2 (V_{GS} - V_{TN})^2$$

$$\frac{I_o}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1} = m \quad \text{电流传输比}$$



等效电流电阻很大



设  $T_1$  和  $T_3$  参数完全相同，且  $I_{D1} = I_{D3}$

$$I_{D3} = I_{D1}$$

$$V_{as3} = V_{as1} = V_{as}$$

$$\text{又 } V_{DD} + V_{SS} = V_{DS3} + V_{DS1} = V_{as3} + V_{as1} = 2V_{as}$$

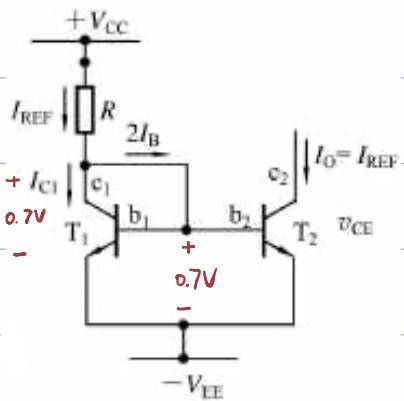
只要满足  $V_{DD} + V_{SS} > 2V_{TN}$

就一定有  $V_{as} > V_{TN}$  和  $V_{DS} > V_{as} - V_{TN}$

$$V_{as} = \frac{1}{2}(V_{DD} + V_{SS})$$

$$I_o = I_{D2} = \frac{k_n}{2} \left( \frac{W}{L} \right)_2 (V_{as} - V_{TN})^2$$

## (2) BJT 电流源



$$V_{BE1} = V_{BE2}$$

若  $\beta \gg 1$ , 则

$$I_o = I_{C2} \approx I_{C1} = I_{REF} = \frac{V_{cc} + V_{ee} - V_{be}}{R} \approx \frac{V_{cc} + V_{ee}}{R}$$

## (3) 电流源作有源负载

### 2 零点漂移及差分式放大电路的一般概念和指标

#### 1) 直接耦合放大电路中的零点漂移

**零点漂移**: 当放大电路的输入端短路时，输出端仍有缓慢变化的电流产生。

产生原因: (1) 温度变化引起，也称温漂

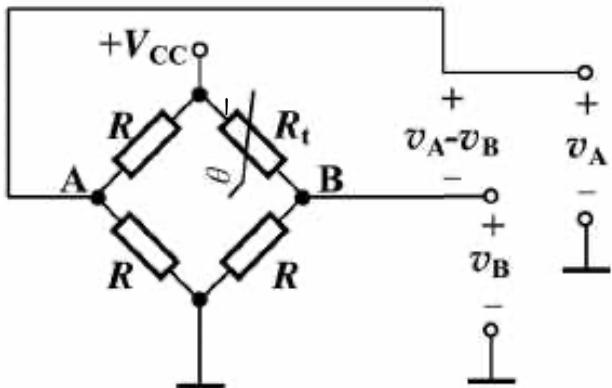
(2) 电源电压波动

温漂指标  $\frac{\Delta V_o}{A_v} / ^\circ C$

只有在直接耦合放大电路中才需解决零点漂移问题。

差分式放大电路 (解决放大信号和抑制零漂的矛盾)

## (2) 差分式放大电路的一般概念和指标

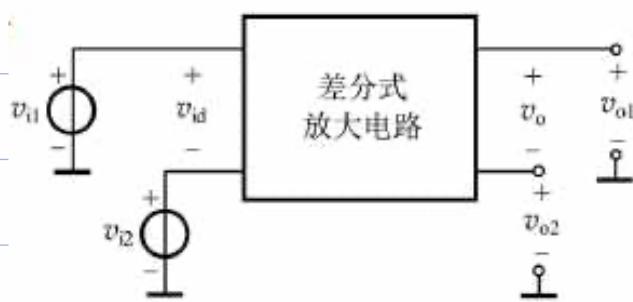


T = 0°C 时，电桥平衡， $v_A - v_B = 0$

T > 0°C 时， $v_A - v_B \neq 0$

差值电压  $v_A - v_B$  反映温度的高低

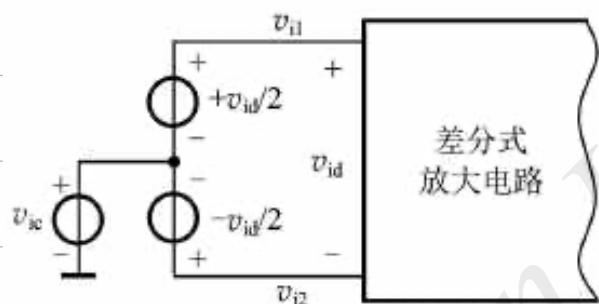
差模信号  $v_A - v_B$



差模输入电压  $v_{id} = v_{i1} - v_{i2}$

共模输入电压  $v_{ic} = \frac{1}{2}(v_{i1} + v_{i2})$

$$\begin{cases} v_{i1} = v_{ic} + \frac{1}{2}v_{id} \\ v_{i2} = v_{ic} - \frac{1}{2}v_{id} \end{cases}$$



两输入端中

共模信号：大小相等，相位相同

差模信号：大小相等，相位相反

输出信号  $v_o = v_{od} + v_{oc} = A_{vd}v_{id} + A_{vc}v_{ic}$

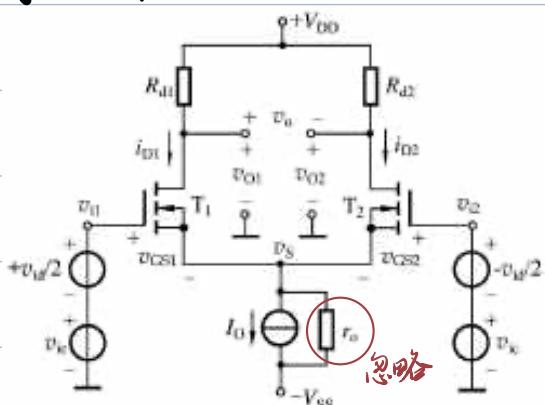
差模电压增益  $A_{vd} = \frac{v_{od}}{v_{id}}$

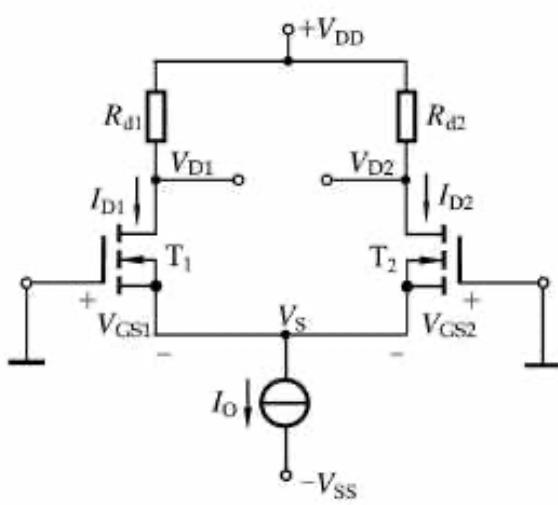
共模电压增益  $A_{vc} = \frac{v_{oc}}{v_{ic}}$

共模抑制比  $K_{CMR} = \left| \frac{A_{vd}}{A_{vc}} \right|$

$K_{CMR} = 20 \lg \left| \frac{A_{vd}}{A_{vc}} \right| \text{ dB}$

### 3 MOSFET 源极耦合差分放大电路





静态时  $V_{i1} = V_{i2} = 0$

设电路完全对称  $R_{d1} = R_{d2} = R_d$

则  $I_{D1Q} = I_{D2Q} = I_{DQ} = \frac{1}{2} I_0$

已知MOSFET参数

$$I_{DQ} = k_n (V_{GSQ} - V_{TN})^2 \Rightarrow V_{GSQ}$$

源极电压  $V_{SQ} = 0 - V_{GSQ} = -V_{GSQ}$

漏极电压  $V_{DQ} = V_{DD} - I_{DQ} R_d$

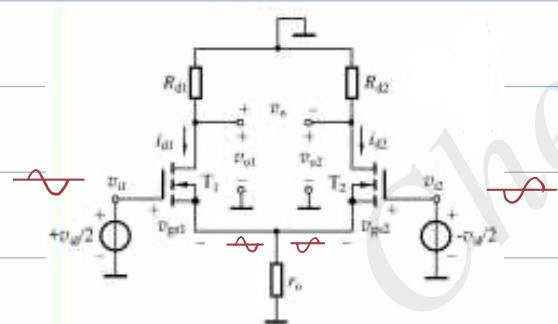
漏源压差  $V_{DSQ} = V_{DQ} - V_{SQ} = V_{DD} - I_{DQ} R_d + V_{GSQ}$

检验是否满足  $V_{DS} > V_{GS} - V_{TN}$

静态时  $V_o = V_{o1} - V_{o2} = V_{D1Q} - V_{D2Q} = 0$

**动态小信号分析** 仅有差模信号时

直流电压源短路，直流电压源开路并保留内阻



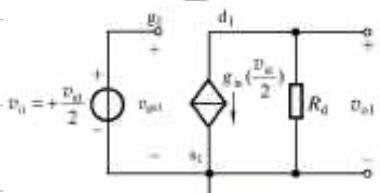
$$A_{v11} = \frac{V_{o1}}{V_{id}} = \frac{-g_m (\frac{V_{id}}{2}) R_d}{V_{id}} = -\frac{1}{2} g_m R_d$$

$$A_{v12} = A_{v11}$$

$$A_{vd} = \frac{V_o}{V_{id}} = \frac{V_{o1} - V_{o2}}{V_{id}} = \frac{2V_{o1}}{V_{id}} = -2g_m R_d$$

带负载时

$$A_{vd} = -g_m (R_d \parallel \frac{1}{2} R_L)$$

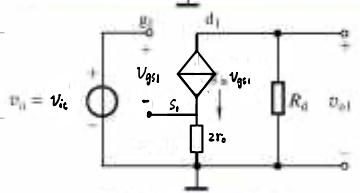
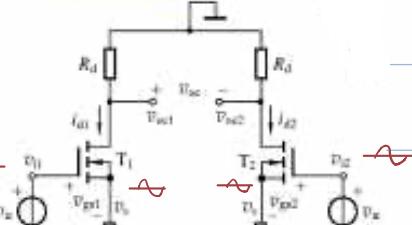


仅有共模信号时

$$A_{vc1} = \frac{V_{o1}}{V_{ic}} = \frac{-g_m V_{gs1} R_d}{V_{gs1} + g_m V_{gs1}(2r_o)} = -\frac{g_m R_d}{1 + g_m(2r_o)}$$

$$V_{ic1} = V_{ic2} = V_{ic} \Rightarrow V_{oc1} = V_{oc2}$$

$$A_{vc} = \frac{V_{oc1} - V_{oc2}}{V_{ic}} = \frac{0}{V_{ic}} = 0$$



$$\text{双端输出时 } A_{vc} = 0 \quad A_{vd} = -g_m(R_d / (R_d + \frac{1}{2}R_L))$$

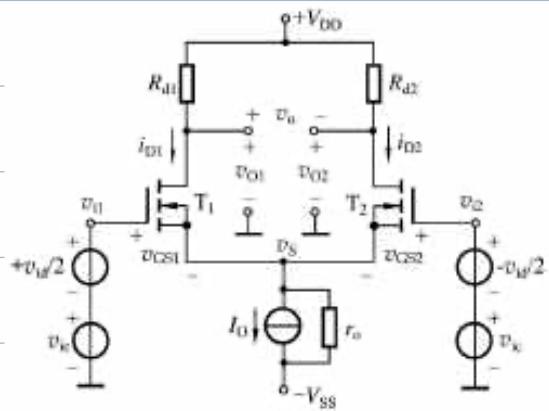
$$K_{CMR} = \left| \frac{A_{vd}}{A_{vc}} \right| \rightarrow \infty$$

$$\text{单端输出时 } A_{vc1} \approx -\frac{R_d}{2r_0} \quad A_{vd1} = -\frac{1}{2}g_m R_d$$

$$K_{CMR} = \left| \frac{A_{vd1}}{A_{vc1}} \right| = g_m r_0 \quad \text{恒流源内阻大}$$

提高共模抑制比

#### 4 MOSFET 差分式放大电路的传输特性



$$i_{D1} = K_n (V_{GS1} - V_{TN})^2$$

$$i_{D2} = K_n (V_{GS2} - V_{TN})^2$$

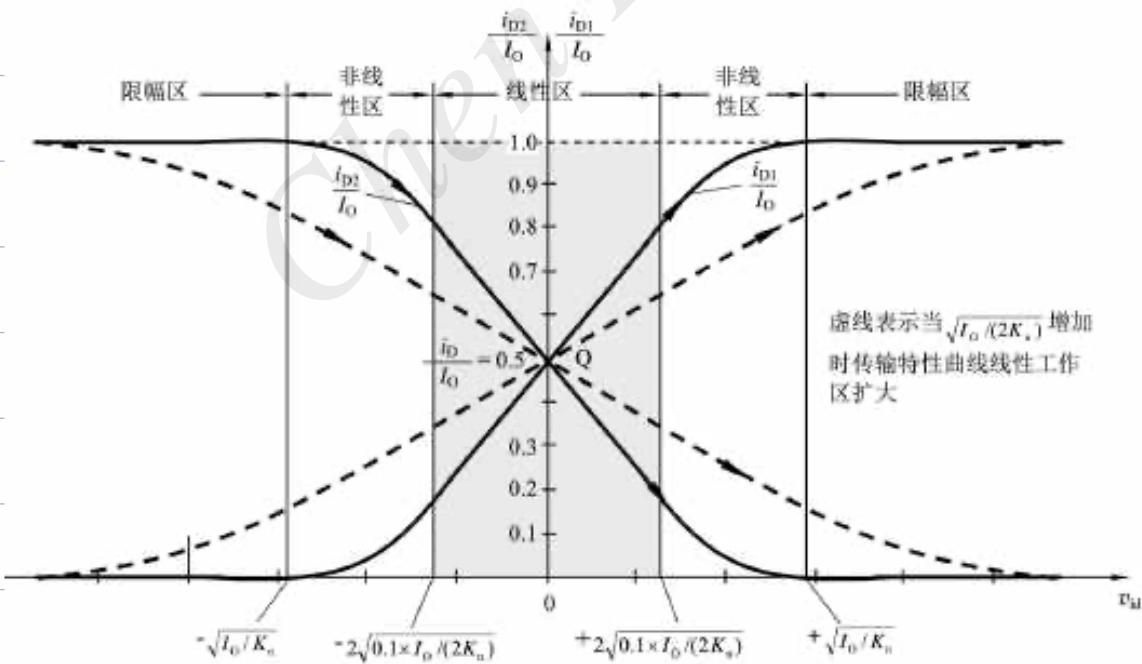
$$\begin{aligned} V_{id} &= (V_{GS1} + V_s) - (V_{GS2} + V_s) \\ &= V_{GS1} - V_{GS2} \end{aligned}$$

$$i_{D1} + i_{D2} = I_o$$

$$i_{D1} = \frac{I_o}{2} + \sqrt{2K_n I_o} \left( \frac{V_{id}}{2} \right) \sqrt{1 - \frac{(V_{id}/2)^2}{I_o/(2K_n)}}$$

$$i_{D2} = \frac{I_o}{2} - \sqrt{2K_n I_o} \left( \frac{V_{id}}{2} \right) \sqrt{1 - \frac{(V_{id}/2)^2}{I_o/(2K_n)}}$$

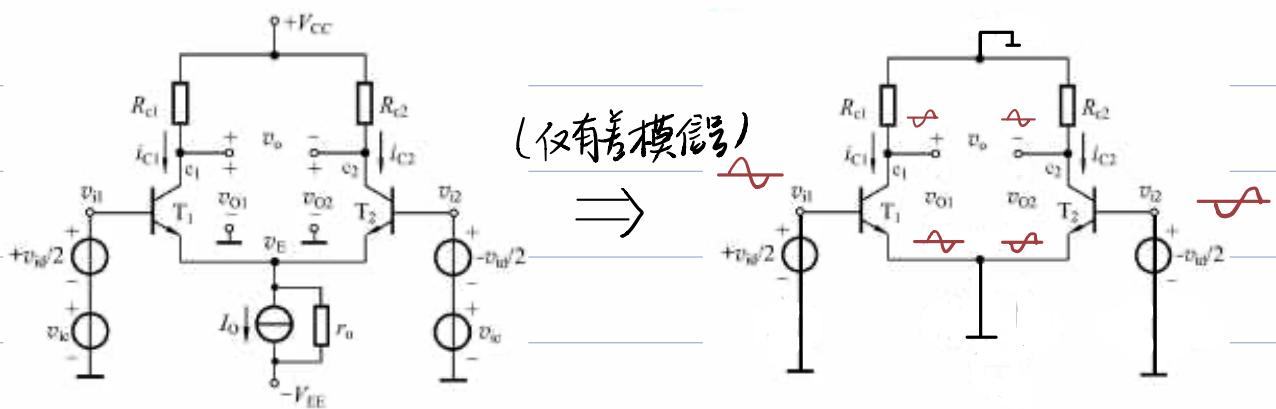
注意，在  $|V_{id}| \leq \sqrt{\frac{I_o}{K_n}}$  时，以上两式才成立



#### 5 BJT 差分式放大电路和带有源负载的差放

##### (1) BJT 差分式放大电路

动态小信号分析

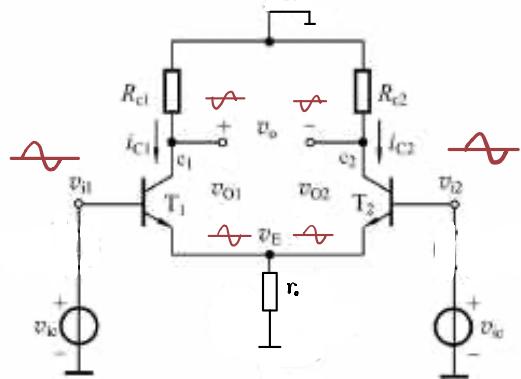


单端输出差模增益

$$A_{vd1} = \frac{V_{o1}}{V_{id}} = \frac{-\beta i_b R_c}{2 i_b r_{be}} = -\frac{1}{2} \frac{\beta R_c}{r_{be}}$$

双端输出差模增益

$$A_{vd} = \frac{V_o}{V_{id}} = -\frac{\beta R_c}{r_{be}}$$



(仅有差模信号)

$$A_{vc1} = \frac{V_{o1}}{V_{ic}} = \frac{-\beta R_c}{r_{be} + (1+\beta)(2r_o)} \approx -\frac{R_c}{2r_o}$$

$$A_{vc} = \frac{V_o}{V_{ic}} = \frac{0}{V_{ic}} = 0$$

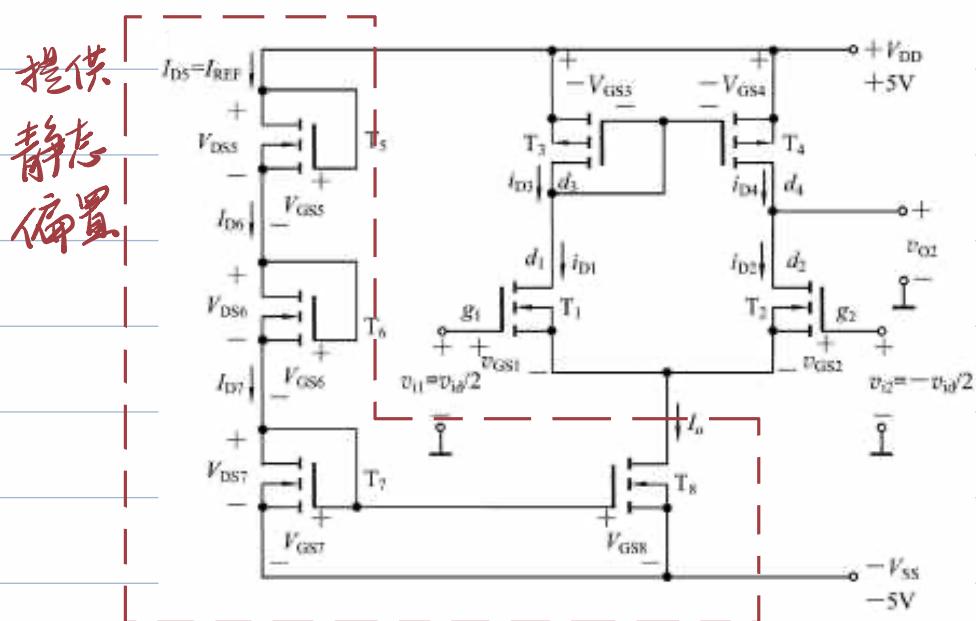
单端  $K_{CMR} = \left| \frac{A_{vd1}}{A_{vc1}} \right| = -\frac{\beta r_o}{r_{be}}$

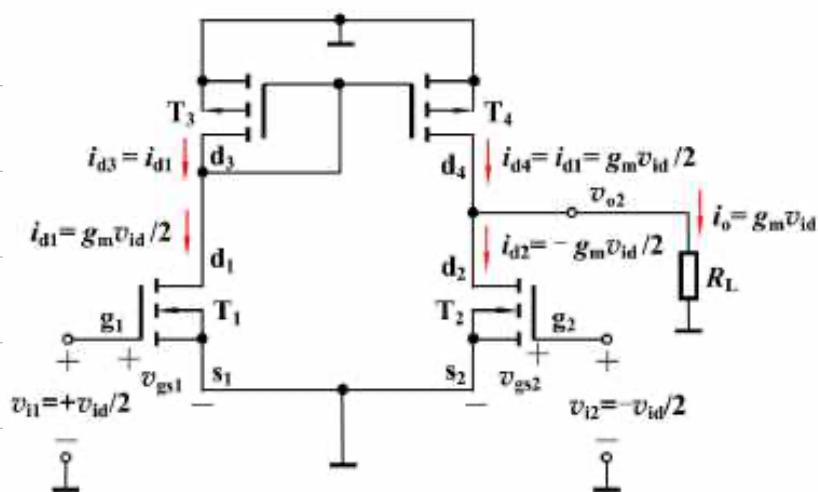
双端  $K_{CMR} = \left| \frac{A_{vd}}{A_{vc}} \right| \rightarrow \infty$

差模输入电阻  $R_{id} = 2r_{be}$

共模输入电阻  $R_{ic} = \frac{1}{2} [r_{be} + (1+\beta)(2r_o)]$

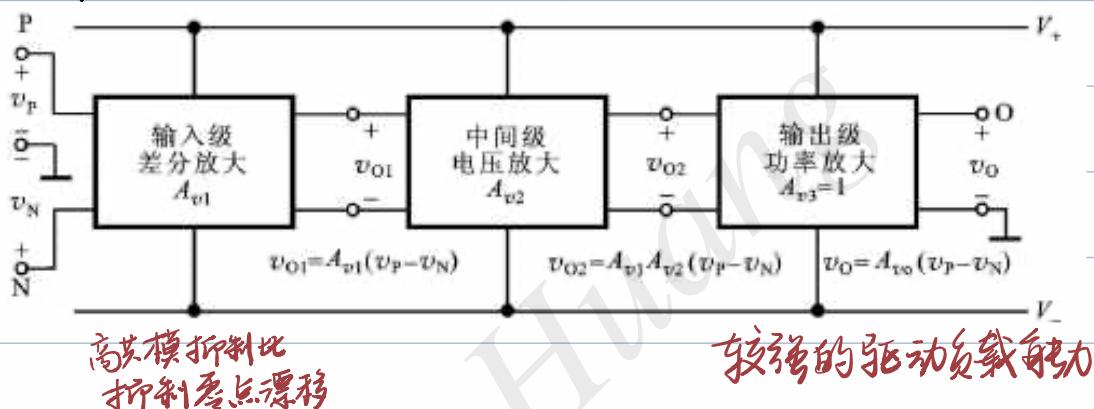
## (2) 带有源负载的差分式放大电路





## 6 集成运算放大器简介

### 集成运算放大器的内部典型结构



### 集成运放的一般结构及特点

- ① 差分式输入级有很高的共模抑制比和很大的输入电阻
- ② 中间级提供很高的增益
- ③ 输出级有很小的输出电阻和很强的带载能力
- ④ 采用直接耦合方式
- ⑤ 电流源提供静态偏置
- ⑥ 有过载保护电路

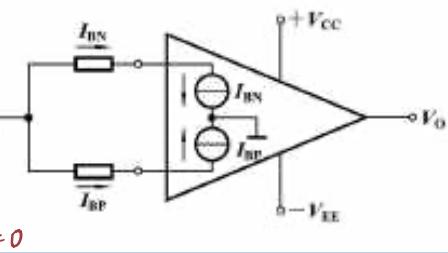
## 7 集成运放的主要参数及其在实际运用中的影响

### (1) 输入直流误差特性

- ① 输入失调电压  $V_{IO}$

- ② 输入偏置电流  $I_{IB} = \frac{1}{2}(I_{BN} + I_{BP})$

- ③ 输入失调电流  $I_{IO} = |I_{BN} - I_{BP}| \Big|_{V_I=0}$



### ③ 温度漂移

输入失调电压温漂  $\frac{\Delta V_{IO}}{\Delta T}$

输入失调电流温漂  $\frac{\Delta I_{IO}}{\Delta T}$

### (2) 差模特性

① 开环差模电压增益  $A_{vd}$

开环带宽  $BW(f_H)$

单位增益带宽  $BW_0(f_T)$

② 差模输入电阻  $r_{id}$

输出电阻  $r_o$

③ 最大差模输入电压  $V_{idmax}$

最大输出电压  $V_{omax}$

### (3) 共模特性

① 共模抑制比  $K_{CMR}$

共模输入电阻  $r_{ic}$

② 最大共模输入电压  $V_{icmax}$

### (4) 大信号动态特征

① 转换速率  $S_R = \left. \frac{dV_o(t)}{dt} \right|_{max}$

② 全功率带宽  $BWP = f_{max} = \frac{S_R}{2\pi V_{om}}$

### (5) 电源特性

① 电源电压抑制比  $K_{SVR} = \frac{\Delta V_{IO}}{\Delta(V_{CC} + V_{EE})}$

② 静态功耗  $P_v = V_{CC} I_{CO} + V_{EE} I_{EO}$

能否消除失调电压和失调电流的影响与是否是轨到轨的运算放大器没有必然的联系，失调电压和失调电流取决于运算放大器的结构是否对称等。

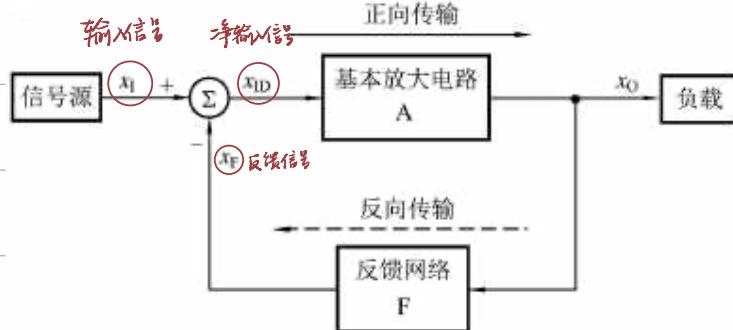
需要考虑输入信号的变化范围，来决定输出静态直流电压。例如，当输入是正负对称的信号时，单电源工

作的运放电路的输出静态电压要设置为二分之一的电源电压；而当输入在0到某一个正电压值范围内时，单电源同相放大电路的输出静态电压就要设置为0V。

## 1 反馈的基本概念及直流、交流反馈

无反馈：开环放大电路

有反馈：闭环放大电路

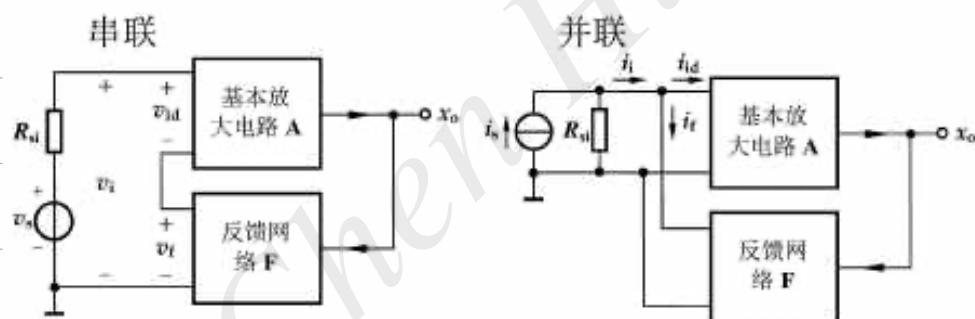


$$x_{ID} = x_I - x_F$$

理想情况下，电源线和地线不是反馈通路

## 2 串联/并联反馈 电压/电流反馈

### (1) 串联反馈 vs 并联反馈

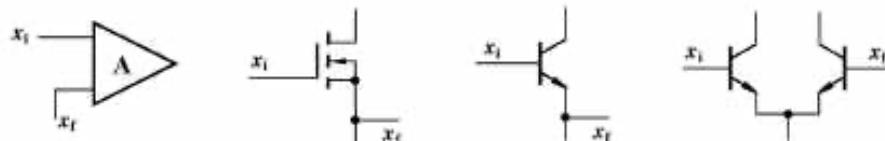


串联： $v_{id} = v_i - v_f$  (kVL)

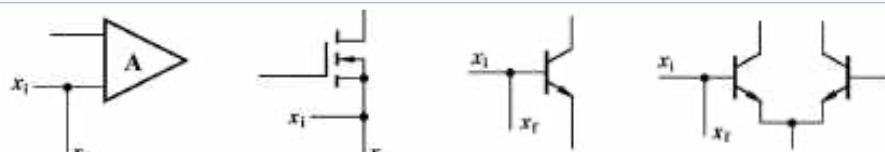
并联： $i_{id} = i_i - i_f$  (kCL)

### 判断方法

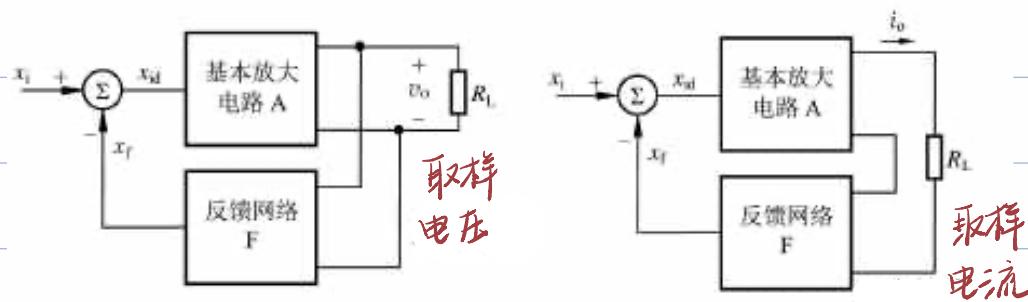
串联：输入量与反馈量接于不同的输入端



并联：输入量与反馈量接于相同的输入端



## (2) 电压反馈 vs 电流反馈



$$\text{电压: } x_f = F v_o$$

$$R_L \downarrow \rightarrow v_o \downarrow \rightarrow x_f \downarrow \xrightarrow{x_i \text{一定时}} x_{id} \uparrow - \\ v_o \uparrow \leftarrow$$

作用: 稳定输出电压

$$\text{电流: } x_f = F i_o$$

$$R_L \uparrow \rightarrow i_o \downarrow \rightarrow x_f \downarrow \xrightarrow{x_i \text{一定时}} x_{id} \uparrow - \\ i_o \uparrow \leftarrow$$

作用: 稳定输出电流

**判断方法: 负输出短路法**

若输出短路,  $v_o = 0$ , 若  $x_f$  也为 0, 则为电压反馈

若  $x_f \neq 0$ , 则为电流反馈

### 3 正反馈与负反馈

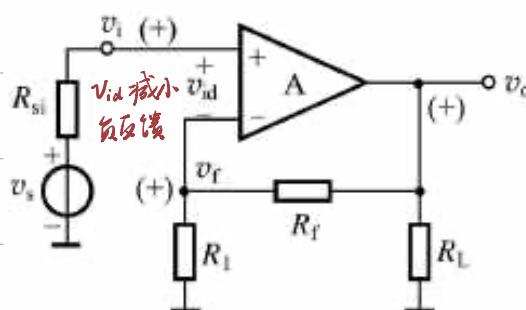
负反馈: 输入量不变时, 引入反馈后输出量变小

正反馈: 输入量不变时, 引入反馈后输出量变大

**判断方法: 瞬时极性法**

$\Delta$ 瞬时极性: 指某一时刻, 电路中有关节点电压的斜率

EXP:



负反馈

## 4 负反馈放大电路的四种组态

**电压串联**  $v_{id} = v_i - v_f$ , 稳定输出电压  $\Rightarrow$  电压控制的电压源

电压  $\rightarrow$  电压 (电压放大器)  $(VCVS)$

**电压并联**  $i_{id} = i_i - i_f$ , 稳定输出电压  $\Rightarrow$  电流控制的电压源

电流  $\rightarrow$  电压 (互阻放大器)  $(CCVS)$

**电流串联**  $v_{id} = v_i - v_f$ , 稳定输出电流  $\Rightarrow$  电压控制的电流源

电压  $\rightarrow$  电流 (互导放大器)  $(VCCS)$

**电流并联**  $i_{id} = i_i - i_f$ , 稳定输出电流  $\Rightarrow$  电流控制的电流源

电流  $\rightarrow$  电流 (电流放大器)  $(CCCS)$

## 总结

输入信号不变时  $\left\{ \begin{array}{l} \text{正反馈} \rightarrow \text{增大增益} \\ \text{负反馈} \rightarrow \text{减小增益} \end{array} \right.$

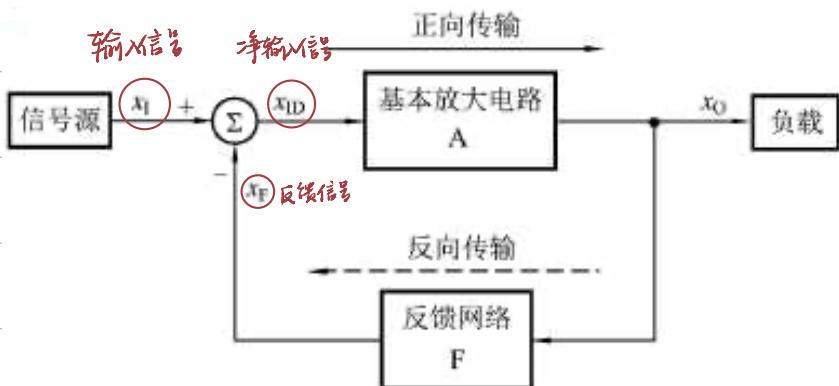
$\left\{ \begin{array}{l} \text{直流负反馈: 稳定静态工作点} \\ \text{交流/交直流反馈: 对信号放大产生影响} \end{array} \right.$

端口  $\left\{ \begin{array}{l} \text{串联: 以电压形式求和} \\ \text{并联: 以电流形式求和} \end{array} \right.$

$\left\{ \begin{array}{l} \text{电压负反馈: 稳定输出电压} \\ \text{电流负反馈: 稳定输出电流} \end{array} \right.$

$\left\{ \begin{array}{l} \text{电压负反馈: 稳定输出电压} \\ \text{电流负反馈: 稳定输出电流} \end{array} \right.$

## 5 负反馈放大电路增益的一般表达式



$$\text{开环增益 } A = \frac{x_o}{x_{id}}$$

$$\text{闭环增益 } A_f = \frac{x_o}{x_i}$$

$$\text{反馈系数 } F = \frac{x_f}{x_o}$$

$$A_f = \frac{x_o}{x_i} = \frac{x_o}{x_{id} + x_f} = \frac{x_o}{\frac{x_o}{A} + Fx_o} = \frac{A}{1+AF}$$

$$\frac{\dot{A}}{1+\dot{A}F}$$

反馈深度  $1 + AF$   $|1 + AF|$  可能小于 1

环路增益  $AF = \frac{x_o}{x_{id}} \cdot \frac{x_f}{x_o} = \frac{x_f}{x_{id}}$   $\dot{A}_f$

$$\dot{A}_f = \frac{\dot{A}}{1 + \dot{A}F}$$

(1) 当  $|1 + \dot{A}F| > 1$  时,  $|\dot{A}_f| < |\dot{A}|$ , 一般负反馈

(2) 当  $|1 + \dot{A}F| \gg 1$  时, 深度负反馈,  $\dot{A}_f \approx \frac{1}{F}$

(3) 当  $|1 + \dot{A}F| < 1$  时,  $|\dot{A}_f| > |\dot{A}|$ , 正反馈

(4) 当  $|1 + \dot{A}F| = 0$  时,  $|\dot{A}_f| \rightarrow \infty$ , 自激振荡

## 6 负反馈对放大电路性能的影响

牺牲增益, 改善其他性能指标

### (1) 提高增益的稳定性

$$\frac{\Delta A_f}{A_f} = \frac{1}{1 + A'F} \frac{\Delta A}{A}$$
 引入负反馈后, 增益的相对变化量减小

### (2) 减小非线性失真

只能减小反馈环内产生的失真

### (3) 负反馈对输入电阻和输出电阻的影响

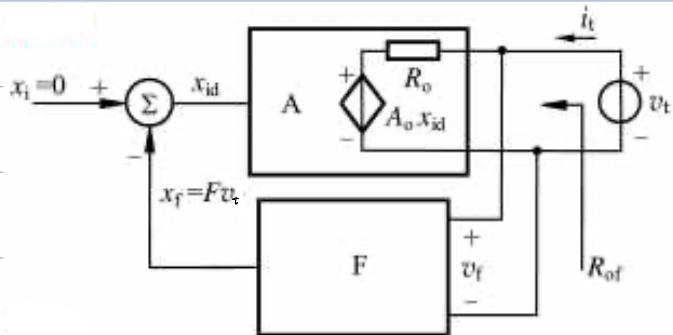
#### ▶ 串联负反馈

$$\text{闭环输入电阻 } R_{if} = \frac{v_i}{i_i} = \frac{v_{id} + v_f}{i_i} = \frac{v_{id} + AF v_{id}}{i_i} = (1 + AF) R_i$$

#### ▶ 并联负反馈

$$\text{闭环输入电阻 } R_{if} = \frac{v_i}{i_i} = \frac{v_i}{i_{id} + i_f} = \frac{v_i}{i_{id} + AF i_{id}} = \frac{R_i}{1 + AF}$$

#### ▶ 电压负反馈



$$\begin{cases} v_t = i_t R_o + A_o x_{id} \\ x_{id} = 0 - x_f = -F v_t \end{cases}$$

闭环输出电阻

$$R_{of} = \frac{v_t}{i_t} = \frac{R_o}{1 + A_o F}$$

#### ▶ 电流负反馈

$$\text{闭环输出电阻 } R_{of} = \frac{v_t}{i_t} = (1 + A_o F) R_o$$

# 总结

串联负反馈增大输入电阻

并联负反馈减小输入电阻

电压负反馈 减小输入电阻，稳定输出电压

电流负反馈增大输出电阻，稳定输出电流

注意：对环外电阻不起作用

特性	负反馈组态			
	电压串联	电流串联	电压并联	电流并联
$x_i, x_f, x_{id}$	$v_i, v_f, v_{id}$	$v_i, v_f, v_{id}$	$i_i, i_f, i_{id}$	$i_i, i_f, i_{id}$
输出信号 $x_o$	$v_o$	$i_o$	$v_o$	$i_o$
开环增益 $A = \frac{x_o}{x_{id}}$	$A_v = \frac{v_o}{v_{id}}$ 电压增益	$A_g = \frac{i_o}{v_{id}}$ 互导增益	$A_r = \frac{v_o}{i_{id}}$ 互阻增益	$A_i = \frac{i_o}{i_{id}}$ 电流增益
反馈系数 $F = \frac{x_f}{x_o}$	$F_v$ 电压反馈系数	$F_r$ 互阻反馈系数	$F_g$ 互导反馈系数	$F_i$ 电流反馈系数
闭环增益 $A_f = \frac{x_o}{x_i}$	$A_{vf} = \frac{v_o}{v_i} = \frac{A_v}{1 + A_v F_v}$	$A_{gf} = \frac{i_o}{v_i} = \frac{A_g}{1 + A_g F_r}$	$A_{rf} = \frac{v_o}{i_i} = \frac{A_r}{1 + A_r F_g}$	$A_{if} = \frac{i_o}{i_i} = \frac{A_i}{1 + A_i F_i}$
负反馈对 $A_f$ 影响	$A_{vf}$ 减小，其稳定性提高	$A_{gf}$ 减小，其稳定性提高	$A_{rf}$ 减小，其稳定性提高	$A_{if}$ 减小，其稳定性提高
闭环输入电阻 $R_{in}$	增加	增加	减小	减小
闭环输出电阻 $R_{out}$	减小	增加	减小	增加
其他	减小非线性失真、抑制干扰和噪声、扩展通频带(但增益 - 带宽积几乎不变)			

## (4) 扩展带宽

$$\text{开环增益高频率响应 } A_H = \frac{\dot{A}_M}{1 + j(\frac{f}{f_H})}$$

$$\text{闭环增益高频率响应 } A_{HF} = \frac{\dot{A}_H}{1 + A_H F} = \frac{\dot{A}_M F}{1 + j(\frac{f}{f_H})}$$

$$\text{闭环通带增益 } A_{MF} = \frac{\dot{A}_M}{1 + A_M F}$$

$$\text{闭环上限频率 } f_{HF} = (1 + A_M F) f_H \quad \uparrow$$

$$\text{闭环下限频率 } f_{LF} = \frac{f_L}{1 + A_M F} \quad \downarrow$$

$$\text{增益带宽积 } |A_{MF} f_{HF}| = |A_{MF} f_{LF}| = \text{const} \quad (\text{注意条件})$$

增加带宽

## 7 深度负反馈下的近似计算

深度负反馈的特点：

$$1 + AF \gg 1 \Rightarrow A_f = \frac{A}{1+AF} \approx \frac{1}{F}$$

$$\left\{ \begin{array}{l} A_f = \frac{x_o}{x_i} \\ F = \frac{x_f}{x_i} \end{array} \right. \Rightarrow x_i \approx x_f \Rightarrow x_{id} = x_i - x_f \approx 0$$

虚短 / 虚断

## 8 负反馈放大电路的稳定性

自激振荡  $|1 + \dot{AF}| = 0 \Rightarrow \dot{AF} = -1$

{ 幅值条件  $|\dot{AF}| = 1$

相位条件  $\Delta\varphi_a + \Delta\varphi_f = \pm(2n+1) \times 180^\circ \quad n=0,1,2,\dots$

负反馈放大电路稳定性要求

$$\left\{ \begin{array}{l} |\dot{AF}| < 1 \\ \Delta\varphi_a + \Delta\varphi_f = \pm 180^\circ \end{array} \right.$$

或

$$\left\{ \begin{array}{l} |\dot{AF}| = 1 \\ \Delta\varphi_a + \Delta\varphi_f < 180^\circ \end{array} \right.$$

增益裕度  $G_m$

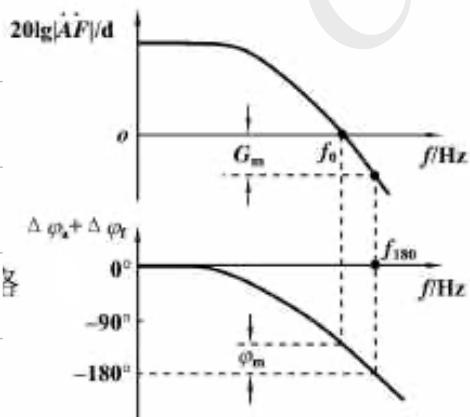
相位裕度  $\varphi_m$

$$\left\{ \begin{array}{l} 20\lg|\dot{AF}| + G_m = 0 \\ \Delta\varphi_a + \Delta\varphi_f = \pm 180^\circ \end{array} \right.$$

或

$$\left\{ \begin{array}{l} 20\lg|\dot{AF}| = 0 \\ |\Delta\varphi_a + \Delta\varphi_f| + \varphi_m = 180^\circ \end{array} \right.$$

工程设计上一般要求  $G_m \geq 10\text{dB}$  或  $\varphi_m \geq 45^\circ$



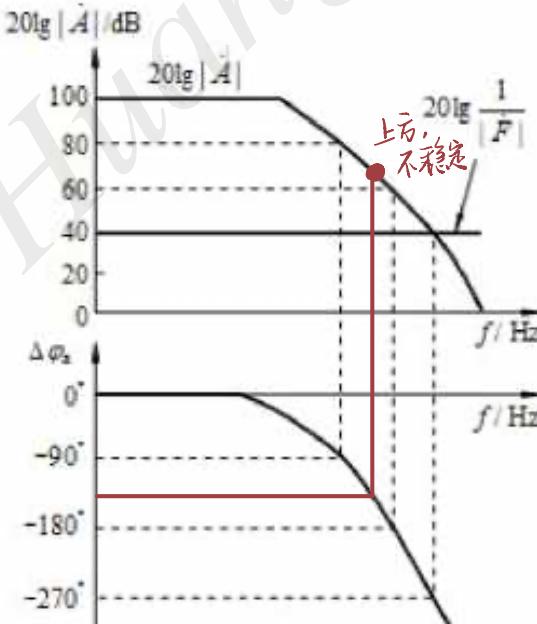
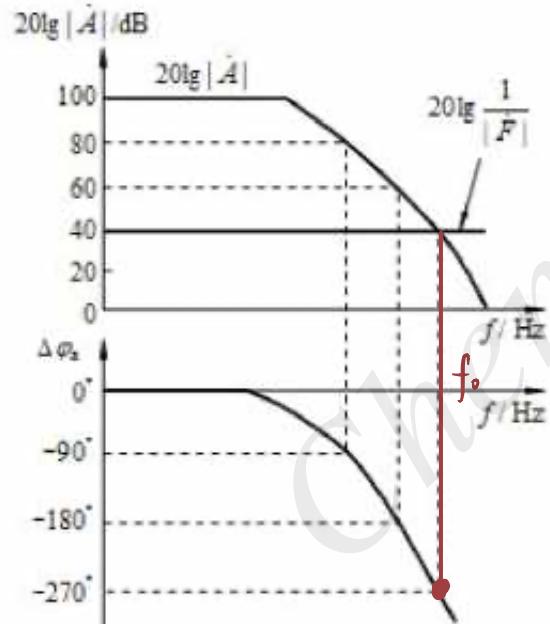
## 稳定性分析的具体步骤

(1) 作出  $A$  的幅频响应和相频响应的波特图

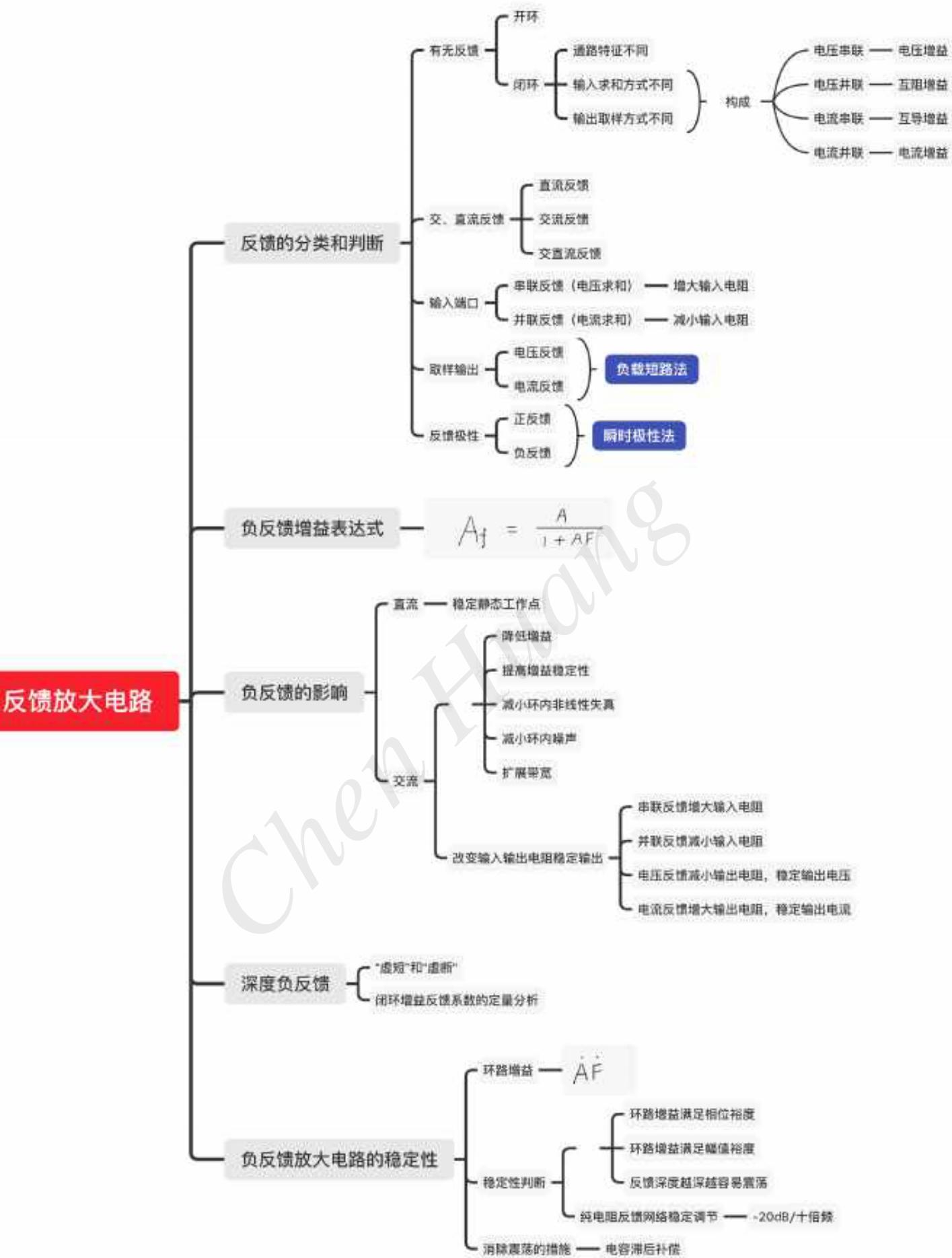
(2) 作出  $20\lg|F|$  的水平线

(3) ① 判断反馈系数的水平线与开环增益幅频响应曲线交点对应的附加相移是否满足相位裕度：  
 $\begin{cases} > 45^\circ \text{ 稳定} \\ \text{otherwise 不稳定} \end{cases}$

② 对应附加相移绝对值  $135^\circ$  作垂线，与  $A$  的幅频响应曲线相交，若交点在水平线下方，则环路增益  $< 1$ ，不稳定。



△ 在斜率为  $-20\text{dB/十倍频}$  的线段上时，负反馈放大电路是不稳定的



# §9 功率放大电路

## 1 放大电路的四类工作状态和乙类互补对称放大电路

目的：输出较大功率；带负载能力强

重点：提高效率、减小失真、保护管子

### (1) 功率放大电路四类工作状态的特点

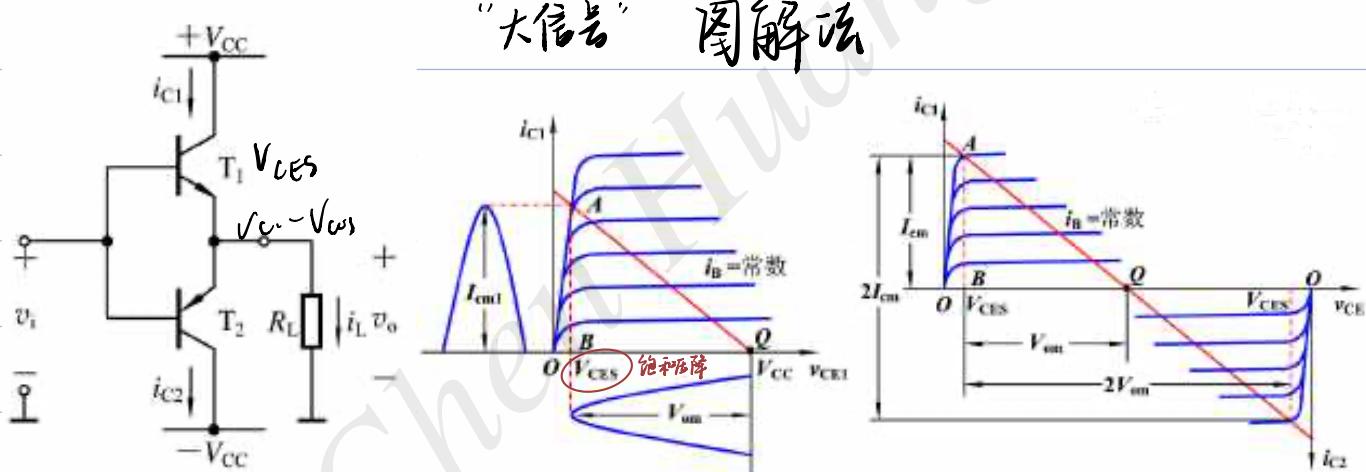
甲类：一个周期内均导通

乙类：导通角 =  $\pi$  效率↑

甲乙类：导通角 >  $\pi$

丙类：导通角 <  $\pi$  效率 max，但不能驱动所有负载

### (2) 乙类双电源互补对称功率放大电路



$$\textcircled{1} \text{ 输出功率 } P_o = V_o \cdot I_o = \frac{V_{om}}{\sqrt{2}} \cdot \frac{V_{om}}{\sqrt{2} R_L} = \frac{V_{om}^2}{2 R_L}$$

当  $V_{om} = V_{com}$  (最大不失真幅度) 时，得

$$P_{om} = \frac{V_{om}^2}{2 R_L} = \frac{(V_{cc} - V_{ces})^2}{2 R_L} \approx \frac{V_{cc}^2}{2 R_L}$$

### ② 三极管消耗的功率

$$\text{设 } V_o = V_{om} \sin \omega t$$

$$\begin{aligned} P_{T1} &= \frac{1}{2\pi} \int_0^\pi V_{CE1} i_{C1} d(\omega t) = \frac{1}{2\pi} \int_0^\pi (V_{cc} - V_o) \frac{V_o}{R_L} d(\omega t) \\ &= \frac{1}{2\pi} \int_0^\pi (V_{cc} - V_{om} \sin \omega t) \frac{V_{om} \sin \omega t}{R_L} d(\omega t) \\ &= \frac{1}{R_L} \left( \frac{V_{cc} V_{om}}{\pi} - \frac{V_{om}^2}{4} \right) \end{aligned}$$

$$P_T = P_{T1} + P_{T2} = \frac{2}{R_L} \left( \frac{V_{cc} V_{om}}{\pi} - \frac{V_{om}^2}{4} \right)$$

### ③ 直流电源供给的功率 $P_V$

$$P_V = P_0 + P_T = \frac{2V_{CC}V_{om}}{\pi R_L}$$

当  $V_{om} \approx V_{CC}$  时, 最大输出功率  $P_{Vm} = \frac{2}{\pi} \frac{V_{CC}^2}{R_L}$

### ④ 效率

$$\eta = \frac{P_0}{P_V} = \frac{\frac{V_{om}^2}{2R_L}}{\frac{2V_{CC}V_{om}}{\pi R_L}} = \frac{\pi}{4} \cdot \frac{V_{om}}{V_{CC}}$$

当  $V_{om} \approx V_{CC}$  时,  $\eta_{max} = \frac{\pi}{4} \approx 78.5\%$ .

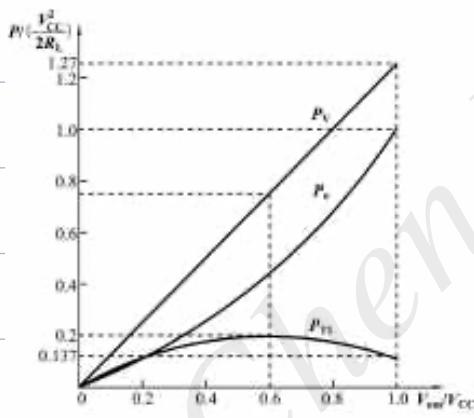
### ⑤ 最大管耗和最大输出功率的关系

$$\frac{dP_{T1}}{dV_{om}} = \frac{1}{R_L} \left( \frac{V_{CC}}{\pi} - \frac{V_{om}}{2} \right)$$

$$\text{令 } \frac{dP}{dV_{om}} = 0 \Rightarrow V_{om} = \frac{2}{\pi} V_{CC} \approx 0.6 V_{CC}$$

$$\text{最大输出功率 } P_{Vm} = \frac{V_{om}^2}{2R_L} \approx \frac{V_{CC}^2}{2R_L}$$

$$\text{最大管耗 } P_{T1m} = P_{T2m} = \frac{1}{R_L} \left[ \frac{V_{CC}}{\pi} \cdot \frac{2V_{CC}}{\pi} - \frac{1}{4} \left( \frac{2V_{CC}}{\pi} \right)^2 \right] = \frac{1}{\pi^2} \cdot \frac{V_{CC}^2}{R_L} = \frac{2}{\pi^2} \cdot \frac{V_{CC}^2}{2R_L}$$



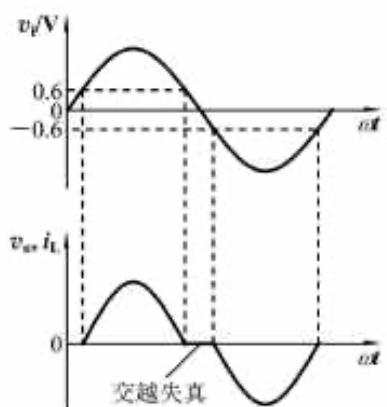
$$= \frac{2}{\pi^2} P_{Vm} \approx 0.2 P_{Vm} \quad \text{选管依据之一}$$

### 功率BJT的选择

$$\begin{cases} P_{CM} > 0.2 P_{Vm} \\ V_{(BR)CEO} > 2 V_{CC} \\ I_{CM} > \frac{V_{CC}}{R_L} \end{cases}$$

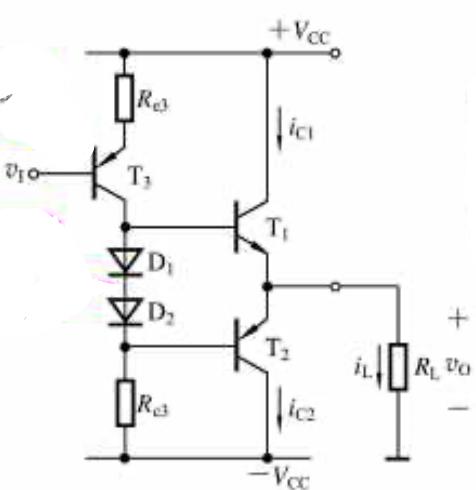
## 2 甲乙类互补对称功率放大电路

### 乙类互补电路存在的问题



### (1) 甲乙类双电源互补对称功率放大电路

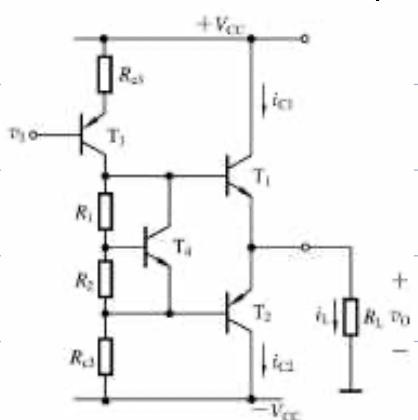
利用二极管进行偏置克服交越失真



二极管：恒压降模型

$D_1, D_2$  上的压降为 $V_D$ , 为提供一个适当的偏压, 使 $T_1, T_2$ 处于微导通状态

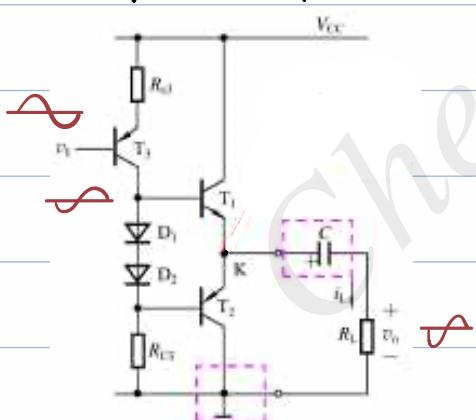
利用 $V_{BE}$ 扩大小信号进行偏置克服交越失真



$$V_{CE4} \approx \frac{R_1 + R_2}{R_2} V_{BE4}$$

$$V_{BE4} \approx 0.6 - 0.7 \text{ V (硅管)}$$

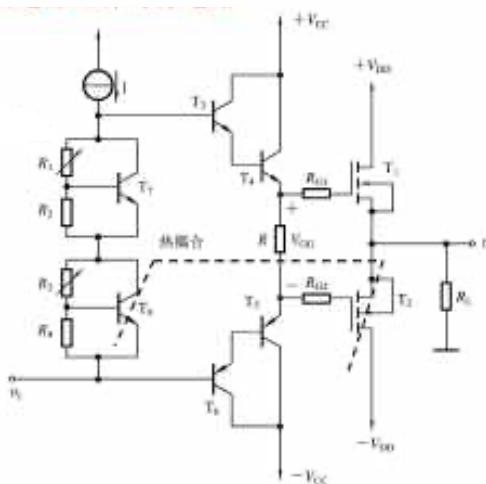
## (2) 甲乙类单电源互补对称电路(OTL电路)



$$\text{直流时 } V_k = V_c = \frac{1}{2} V_{cc}$$

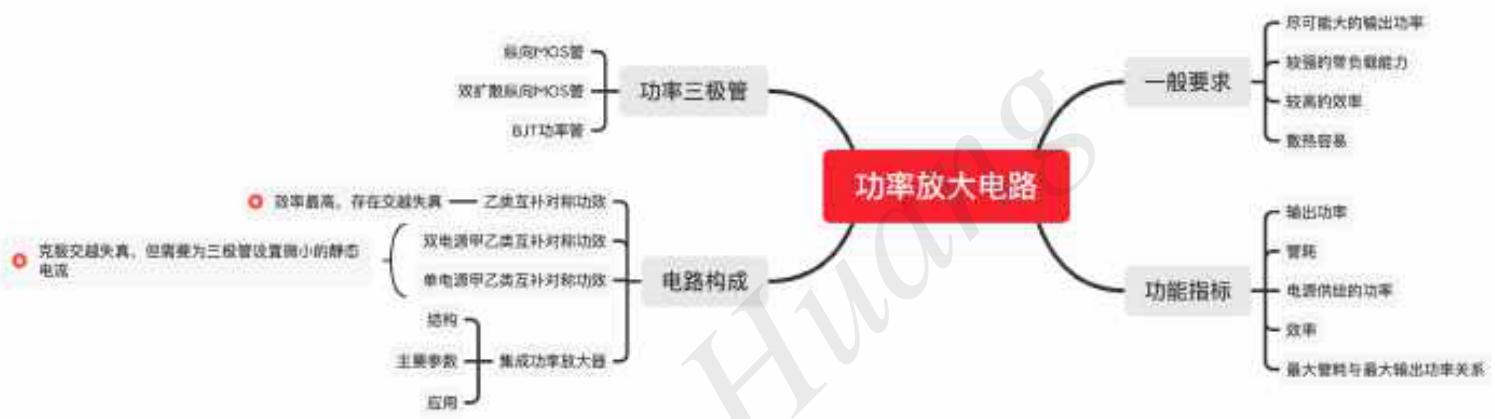
通过调整 $R_{f3}, R_{c3}$ 阻值或 $T_3$ 的静态工作点  
来调整两二极管间电压

## (3) MOS管甲乙类双电源互补对称电路



$$V_{an} = \left(1 + \frac{R_3}{R_4}\right) V_{BE8} + \left(1 + \frac{R_1}{R_2}\right) V_{BE7} - 4 V_{BE}$$

### 3 集成功率放大器和功率管简介



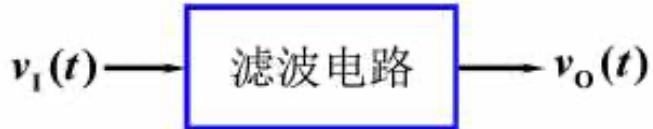
## §10 信号处理与信号产生电路

### 1 有源滤波器的基本知识及一阶有源滤波器

#### (1) 有源滤波器的基本知识

滤波器：“频率选择”，一般由R、C、L构成

RC有源滤波器：由R、C和运算放大器组成



$$\text{传递函数 } A(s) = \frac{V_o(s)}{V_i(s)} \quad s = j\omega$$

$$A(j\omega) = |A(j\omega)| e^{j\varphi(\omega)} = |A(j\omega)| \angle \varphi(\omega)$$

$|A(j\omega)|$ ：模，幅频响应

$\varphi(\omega)$ ：相位角，相频响应

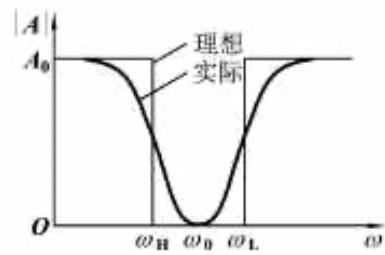
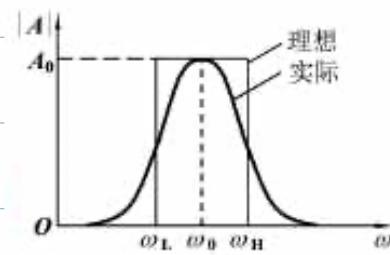
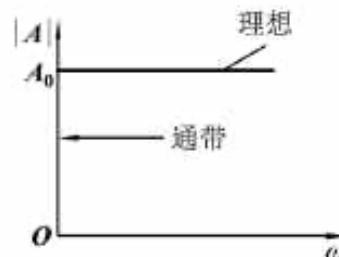
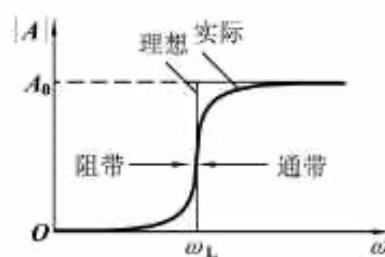
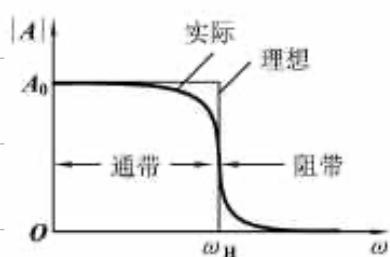
时延响应  $\tau = -\frac{d\varphi(\omega)}{d\omega}$  (s) 反映不同频率的信号通过滤波器产生的时延

频率失真 / 线性失真 { 幅度失真

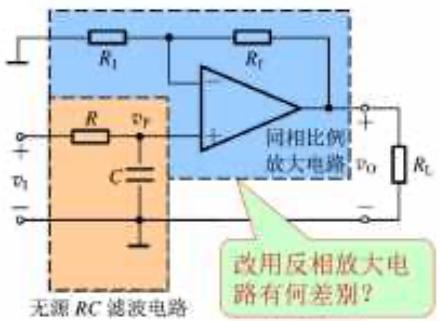
相位失真

通带：滤波器允许通过的频率范围

阻带：阻碍信号通过的频率范围



## (2) 一阶有源滤波器



$$A(s) = \frac{V_o(s)}{V_i(s)} = \frac{V_o(s)}{V_p(s)} \cdot \frac{V_p(s)}{V_i(s)}$$

$$= \left(1 + \frac{R_f}{R_1}\right) \cdot \frac{\frac{1}{sC}}{\frac{1}{sC} + R} = \frac{A_0}{1 + \frac{s}{\omega_c}} = \frac{A_0}{1 + j \frac{\omega}{\omega_c}}$$

$$A_0 = 1 + \frac{R_f}{R_1}$$

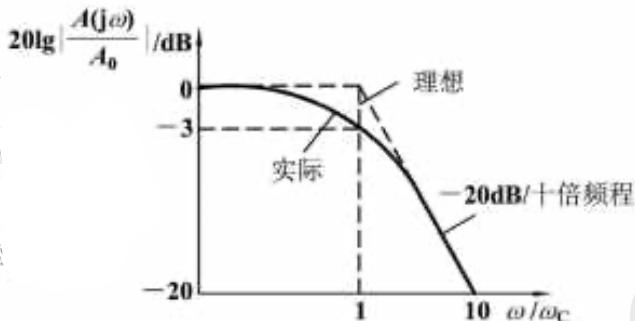
同相放大电路的电压增益

$$\omega_c = \frac{1}{RC}$$

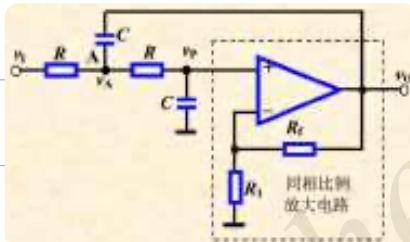
特征角频率

$$\text{幅频响应 } |A(j\omega)| = \frac{|V_o(j\omega)|}{|V_i(j\omega)|} = \frac{A_0}{\sqrt{1 + (\frac{\omega}{\omega_c})^2}}$$

$$3\text{分贝上限截止角频率 } \omega_H = \omega_c = \frac{1}{RC}$$



## 2 高阶有源滤波器



$$\left\{ \begin{array}{l} A_{VF} = \frac{V_o(s)}{V_p(s)} \\ V_p(s) = \frac{\frac{1}{sC}}{R + \frac{1}{sC}} V_A(s) \\ \frac{V_i(s) - V_A(s)}{R} - \frac{V_A(s) - V_o(s)}{\frac{1}{sC}} - \frac{V_A(s) - V_p(s)}{R} = 0 \end{array} \right.$$

$$A(s) = \frac{A_0 \frac{1}{R_1 R_2 C_1 C_2}}{s^2 + \left[ \frac{1}{R_1 C_1} + \frac{1}{R_2 C_1} + (1-A_0) \frac{1}{R_2 C_2} \right] s + \frac{1}{R_1 R_2 C_1 C_2}}$$

$$\text{令 } \omega_c^2 = \frac{1}{R_1 R_2 C_1 C_2}$$

$$\frac{\omega_c}{Q} = \frac{1}{R_1 C_1} + \frac{1}{R_2 C_1} + (1-A_0) \frac{1}{R_2 C_2} > 0$$

$$A(s) = \frac{A_0 \omega_c^2}{s^2 + \frac{\omega_c}{Q} s + \omega_c^2}$$

当  $R_1 = R_2 = R$ ,  $C_1 = C_2 = C$  时, 有

$$A_0 = A_{VF}$$

通带增益

$$\omega_c = \frac{1}{RC}$$

特征角频率

$$Q = \frac{1}{3-A_0}$$

等效品质因素, Q越大, 选择性越好, 通频带越窄

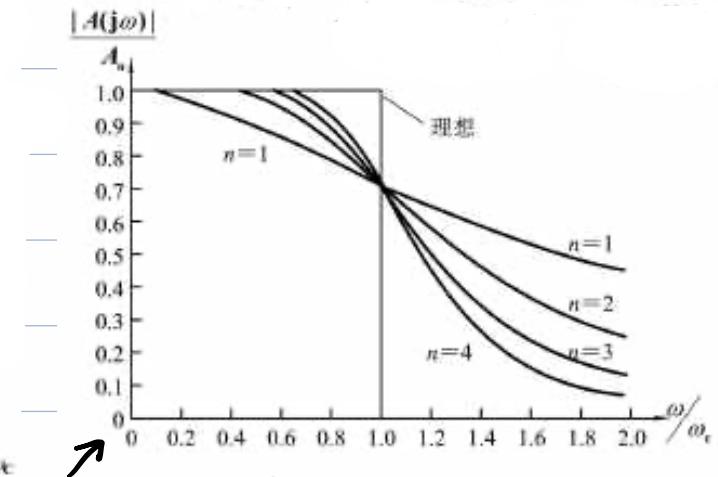
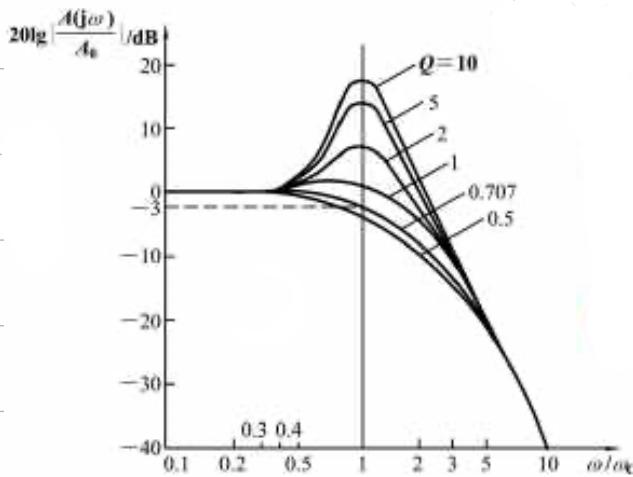
当  $3-A_0 > 0$  即  $A_0 < 3$  时, 滤波电路才能稳定工作

归一化中高频率响应

$$20 \lg \left| \frac{A(j\omega)}{A_0} \right| = 20 \lg \sqrt{\frac{1}{1 - \left(\frac{\omega}{\omega_c}\right)^2 + \left(\frac{\omega}{\omega_c Q}\right)^2}}$$

相频响应

$$\varphi(\omega) = -\arctan \frac{\frac{\omega}{\omega_c Q}}{1 - \left(\frac{\omega}{\omega_c}\right)^2}$$

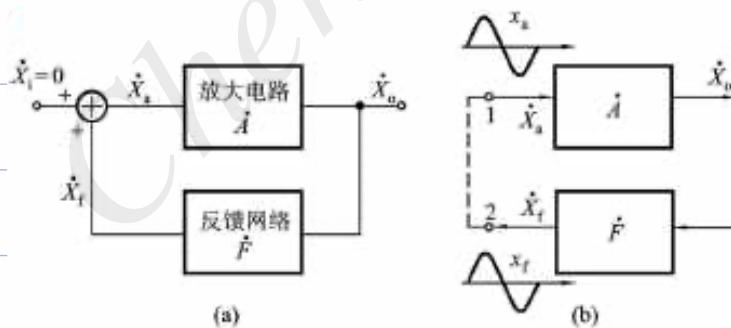


n阶巴特沃斯低通电路  $|A(j\omega)| = \sqrt{1 + \left(\frac{\omega}{\omega_c}\right)^{2n}}$

### 3 RC正弦波振荡电路

正弦波振荡电路 { RC正弦波振荡电路 ✓  
LC正弦波振荡电路

#### (1) 正弦波振荡电路基础



振荡条件  $\dot{A}(j\omega) \dot{F}(j\omega) = 1$

振幅平衡条件  $|\dot{A}(j\omega) \dot{F}(j\omega)| = A(\omega) F(\omega) = 1$

相位平衡条件  $\varphi_a(\omega) + \varphi_f(\omega) = 2n\pi$

选频 {  $A(\omega_0) F(\omega_0) = 1$

$\varphi_a(\omega_0) + \varphi_f(\omega_0) = 2n\pi$

起振条件 {  $A(\omega) F(\omega) > 1$

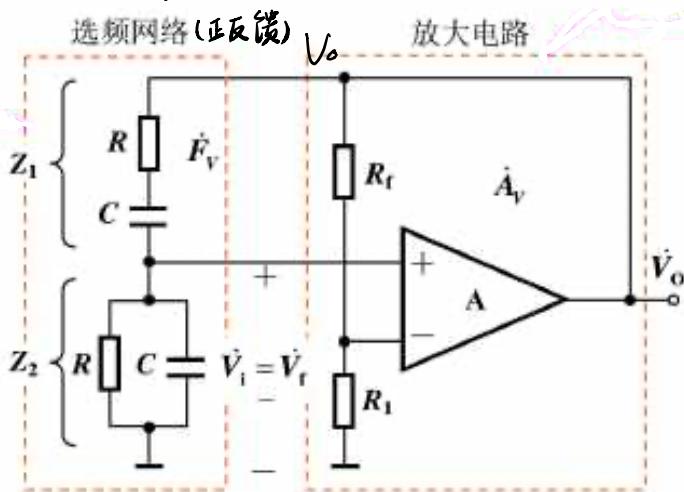
$\varphi_a(\omega) + \varphi_f(\omega) = 2n\pi$

稳幅  $A(\omega)F(\omega) = 1$

振荡电路的基本组成部分

放大，正反馈，选频，稳幅

## (2) RC 桥式正弦波振荡电路



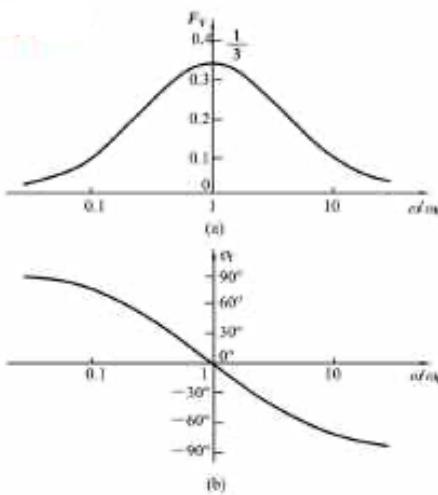
选频网络

$$\text{反馈系数 } F_v(s) = \frac{V_f(s)}{V_o(s)} = \frac{Z_2}{Z_1 + Z_2} = \frac{sCR}{1 + 3sCR + (SCR)^2}$$

$$= \frac{1}{3 + j\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)}$$

$$\text{中频响应 } F_v(\omega) = \frac{1}{\sqrt{3^2 + \left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2}}$$

$$\text{相频响应 } \varphi_f(\omega) = -\arctan \frac{\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}}{3}$$



当  $\omega = \omega_0 = \frac{1}{RC}$  时  
中频响应有最大值

$$F_{v\max} = \frac{1}{3}$$

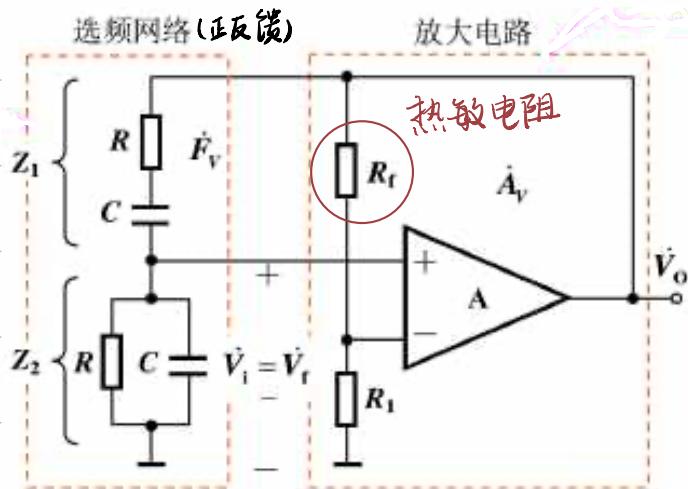
相频响应  $\varphi_f = 0$

放大电路  $\varphi_a = 0$  (同相)  $\Rightarrow \varphi_a + \varphi_f(\omega_0) = 0$

$$\text{若 } A_f = 1 + \frac{R_f}{R_1} = 3 \Rightarrow A_0 F_{v\max}(\omega_0) = 1$$

电路输出角频率为  $\omega_0 = \frac{1}{RC}$  的正弦波

## 起振和稳幅



起振时  $A_v = 1 + \frac{R_f}{R_i} > 3$

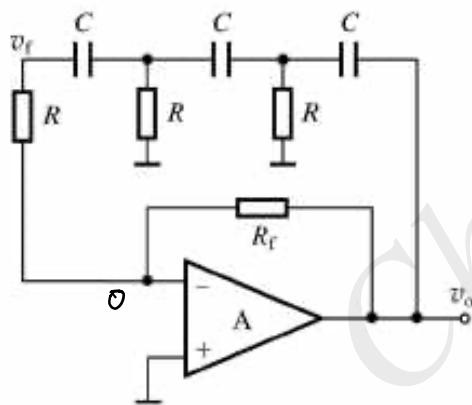
$A_v F_{vmax}(\omega_0) > 1$

## 热敏电阻的稳幅作用

$|V_o| \uparrow \Rightarrow |I_{R_f}| \uparrow \Rightarrow R_f \text{ 功耗} \uparrow \Rightarrow R_f \text{ 温度} \uparrow \Rightarrow R_f \text{ 阻值} \downarrow$

$$A_v > 3 \downarrow \Rightarrow A_v = 3$$

## (3) RC移相式正弦波振荡电路

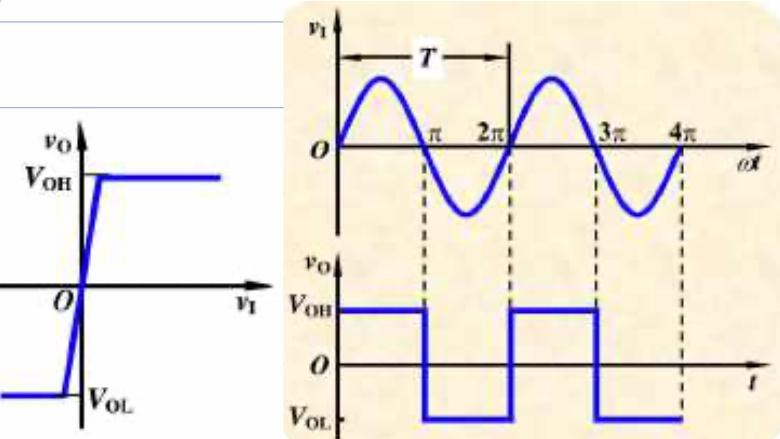
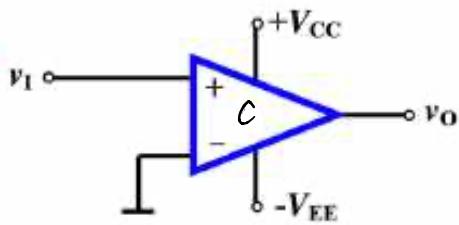


图示电路为移相式振荡器，选频网络由三级RC低通滤波电路构成，每一级RC电路的移相最大为90度，三级RC移相电路移相最大可达270度，而基本放大电路为反相放大电路，相移为180度，因而在某个频率下，RC移相网络的相移达到180度时，与反相放大电路的相移一起就构成360度的相移，可以满足相位平衡条件。

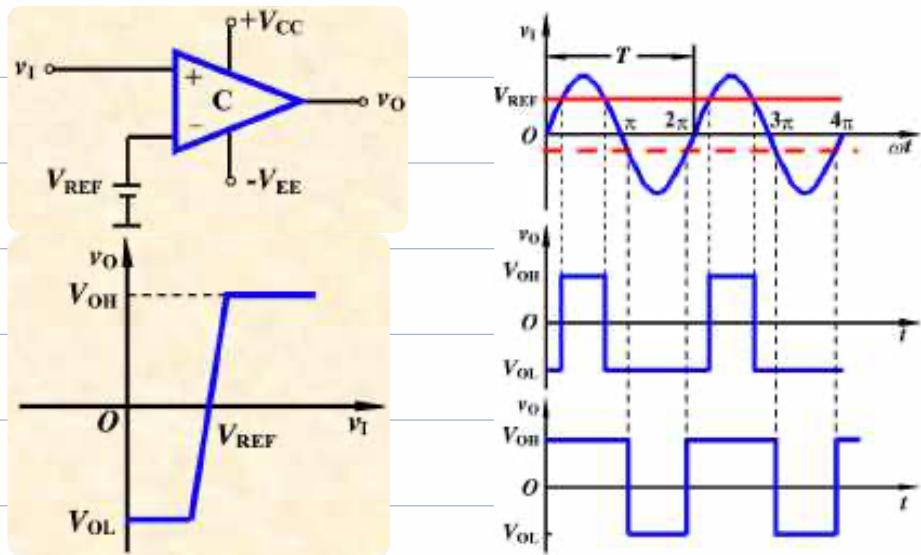
## 4 电压比较器

### (1) 单门限电压比较器

### 过零比较器



# 门限电压为 $V_{REF}$ 的比较器



注意 由于比较器工作在非线性状态，虚短不再成立  
由于输入电阻较大，虚断仍可利用

## (2) 反相迟滞比较器

引入正反馈

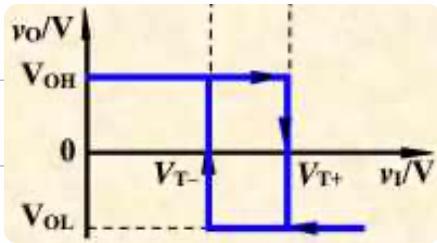


$$v_P = \frac{R_1 V_{REF}}{R_1 + R_2} + \frac{R_2 v_O}{R_1 + R_2}$$

$$V_{T+} = \frac{R_1 V_{REF}}{R_1 + R_2} + \frac{R_2 V_{OH}}{R_1 + R_2} \quad \text{上门限电压}$$

$$V_{T-} = \frac{R_1 V_{REF}}{R_1 + R_2} + \frac{R_2 V_{OL}}{R_1 + R_2} \quad \text{下门限电压}$$

$$\Delta V = V_{T+} - V_{T-} = \frac{R_2(V_{OH} - V_{OL})}{R_1 + R_2} \quad \text{回差电压}$$

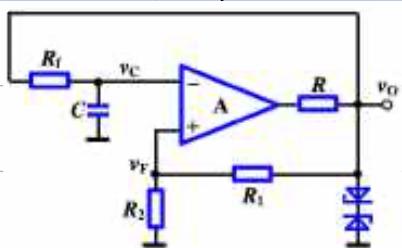


- 要点
- ① 输入介于两门限之间输出不变
  - ② 只有输入高于有效上门限或低于有效下门限时，输出才翻转，翻转方向取决于输入输出的相位关系
  - ③ 在反相迟滞比较器中，只要输入大于上门限，输出一定是低电平，只要输入小于下门限，输出一定是高电平。

同相迟滞比较器与此相反

## 5 方波和锯齿波产生电路

### (1) 方波产生电路 / 多谐振荡电路



$$V_{T+} = \frac{R_2 V_z}{R_1 + R_2}$$

$$V_{T-} = -\frac{R_2 V_z}{R_1 + R_2}$$

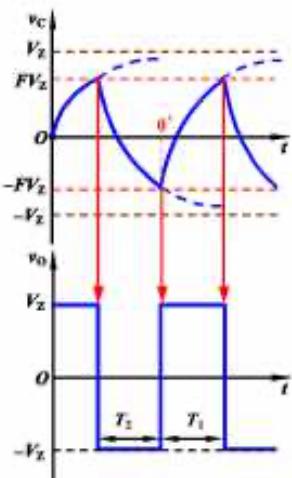
三要素法公式

$$V_c(t) = [V_c(0+) - V_c(\infty)] e^{-\frac{t}{\tau}} + V_c(\infty)$$

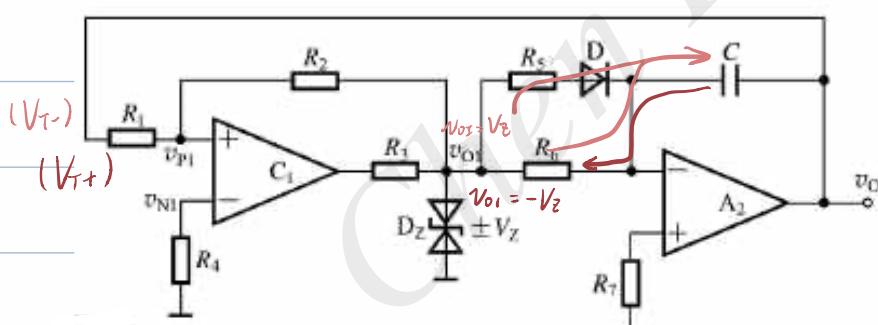
其中  $V_c(0+) = V_{T-}$        $V_c(\infty) = V_z$

$$\tau = R_f C \quad V_c(\frac{\tau}{2}) = V_{T+}$$

$$\text{得 } \tau = 2 R_f C \ln \left( 1 + \frac{2 R_2}{R_1} \right)$$



### (2) 锯齿波产生电路



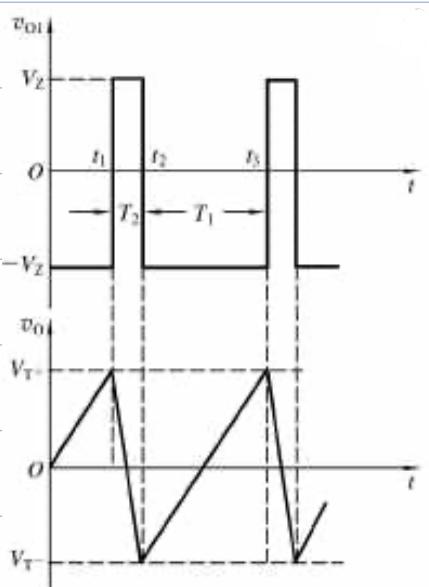
$$V_o = -\frac{R_1}{R_2} V_{o1}$$

$$V_{T+} = \frac{R_1}{R_2} V_z \quad (V_{o1} = -V_z)$$

$$V_{T-} = -\frac{R_1}{R_2} V_z \quad (V_{o1} = V_z)$$

同相迟滞比较器

积分电路

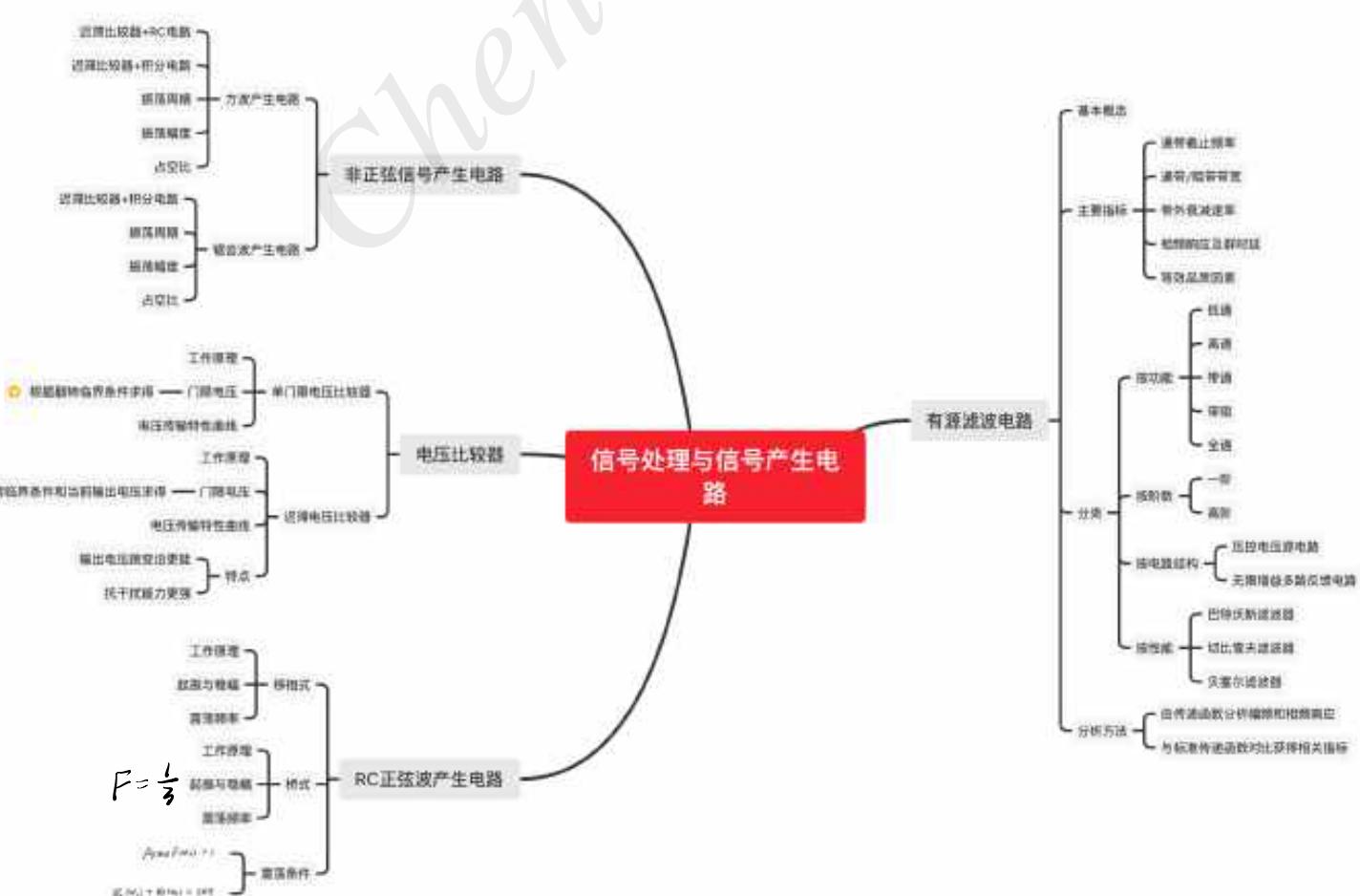


$$\tau = T_1 + T_2$$

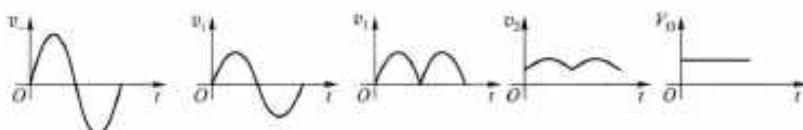
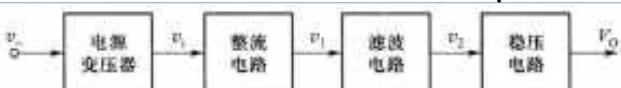
$$= \frac{2 R_1 R_6 C}{R_2} + \frac{2 R_1 (R_5 || R_6) C}{R_2}$$

$$= \frac{2 R_1 R_6 C (R_6 + 2 R_5)}{R_2 (R_5 + R_6)}$$

	<i>RC</i> 文氏电桥振荡电路	<i>RC</i> 移相式振荡电路(滞后)	<i>RC</i> 移相式振荡电路(超前)
电路原理示意图			
网络频率特性示意图			
振荡频率	$f_0 = \frac{1}{2\pi RC}$	$f_0 = \frac{\sqrt{6}}{2\pi RC}$	$f_0 = \frac{1}{2\pi\sqrt{6}RC}$
说明	当 $f = f_0$ 时, 正反馈最强, $F = 1/3$ , $\varphi_1 = 0^\circ$ , 只要配合 $A_v > 3$ 的同相放大器就能振荡	三级 <i>RC</i> 移相网络在 $f_0$ 下产生 $180^\circ$ 相移, 满足 $\varphi_1 + \varphi_2 = 2n\pi$ 条件, 只要 $A_v$ 适当就能振荡	三级 <i>RC</i> 移相网络在 $f_0$ 下产生 $180^\circ$ 相移, 满足 $\varphi_1 + \varphi_2 = 2n\pi$ 条件, 只要 $A_v$ 适当就能振荡



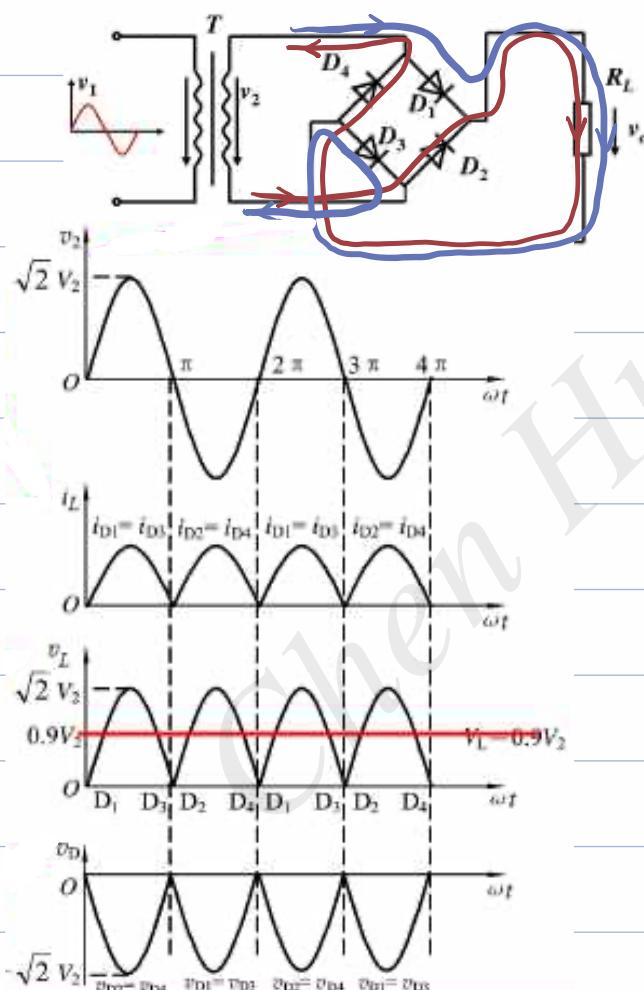
# § 11 直流稳压电源



## 1 小功率整流滤波电路

整流：交流电  $\rightarrow$  直流电

### (1) 单相桥式整流电路



变压器二次信号  $v_2$

负载电流  $i_L$

负载电压  $v_L$

二极管电压  $v_D$

$$\text{输出电压的平均值 } V_L = \frac{1}{\pi} \int_0^{\pi} \sqrt{2} V_2 \sin \omega t d(\omega t) = \frac{2\sqrt{2}}{\pi} V_2 \approx 0.9 V_2$$

$$\text{流过负载的平均电流 } I_L = \frac{0.9 V_2}{R_L}$$

$$\text{纹波系数 } K_r = \frac{V_{r2}}{V_L} = \frac{\sqrt{V_2^2 - V_L^2}}{V_L} = \sqrt{\left(\frac{V_L}{V_2}\right)^2 - 1} = 0.483$$

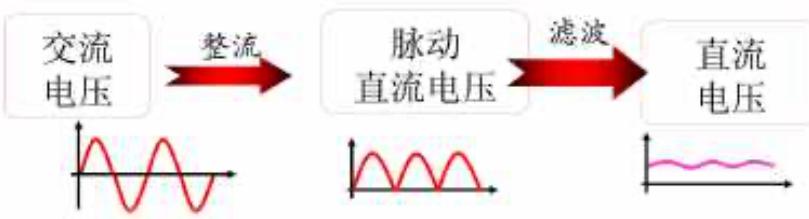
### 整流二极管的选择

轮流导通

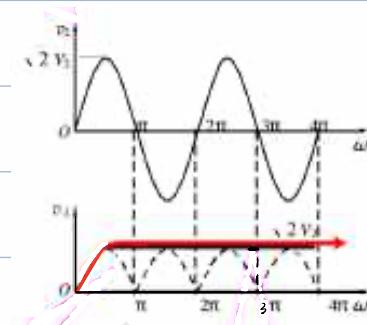
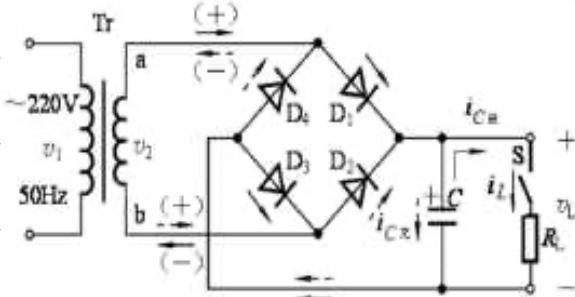
$$\text{整流管平均整流电流 } I_D = \frac{1}{2} I_L = \frac{0.45 V_2}{R_L}$$

$$\text{整流管的最大反向峰值电压 } V_{RM} = \sqrt{2} V_2$$

## (2) 滤波电路



### 电容滤波电路



设次级电压  $v_2$  从 0 开始上升

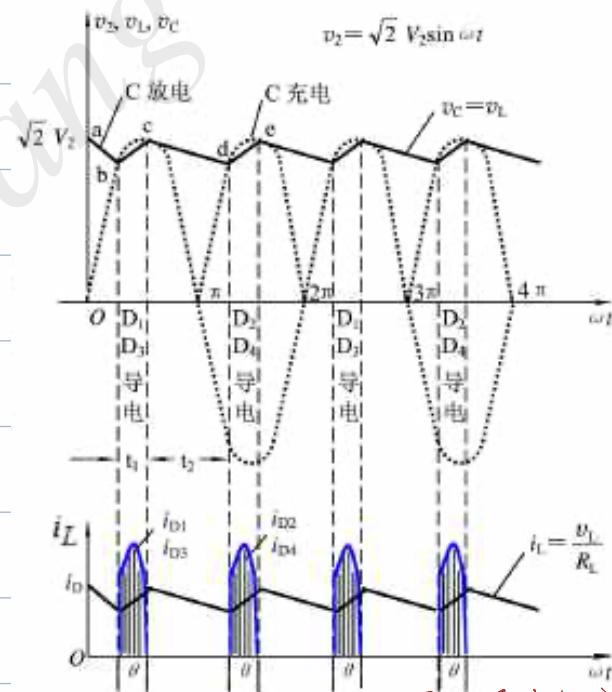
设负载接入前，

电容器已充电到  $\sqrt{2}V_2$

刚接入负载时， $v_L < v_0$

二极管截止，电容器放电

放电时间常数  $T_d = R_L C$



### 电容滤波电路特点

① 二极管导电角  $\theta < \pi$ ，二极管导电时间缩短，

二极管流过的瞬时电流很大

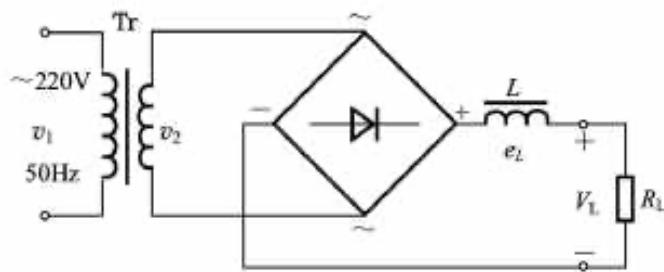
②  $T_d = R_L C$  越大，负载电压平均值  $V_L$  越高

负载电压平均值  $V_L$  越大，纹波显著减小，输出波形变得平滑。

当  $T_d \geq (3 \sim 5) \frac{T}{2}$  时， $V_L = (1.1 \sim 1.2) V_2$

③ 负载直流电压  $V_L$  随负载电流增加而减小

# 电感滤波电路



特点：①导电角大，无峰值电流，输出特性平滑  
②电感存在铁芯，体积大，易受磁场干扰。  
一般适用于小电压、大电流的场合

## 2 线性稳压电路

### (1) 稳压电路的主要技术指标

#### 特性指标

输出电压范围

最大输入 — 输出电压差

最小输入 — 输出电压差

负载输出电流范围

#### 质量指标

$$\text{电压调整率 } S_V = \frac{\Delta V_o / V_o}{\Delta V_i} \times 100\% \Big|_{\frac{\Delta I_o = 0}{\Delta T = 0}}$$

$$\text{稳压系数 } Y = \frac{\Delta V_o / V_o}{\Delta V_i / V_i} \Big|_{\frac{\Delta I_o = 0}{\Delta T = 0}}$$

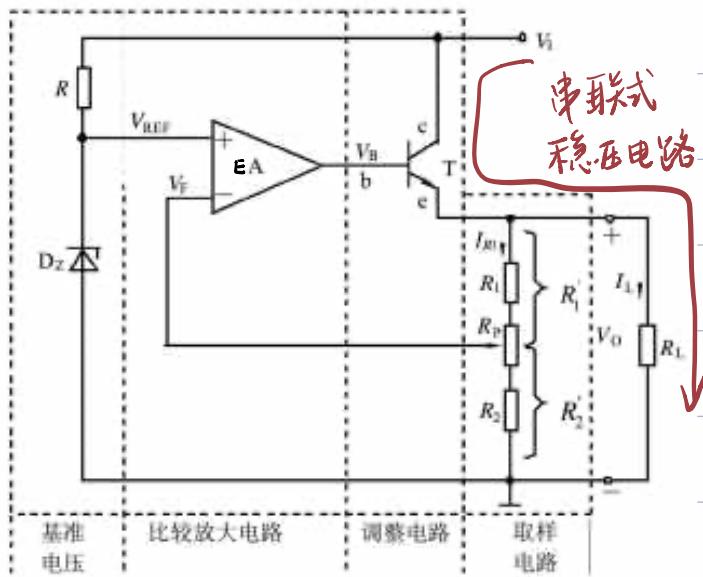
$$\text{输出电阻 } R_o = \frac{\Delta V_o}{\Delta I_o} \Big|_{\frac{\Delta V_i = 0}{\Delta T = 0}}$$

$$\text{纹波抑制比 } RR = 20 \lg \frac{\tilde{V}_{i_{\text{pp}}} / \tilde{V}_{o_{\text{pp}}}}{\tilde{V}_{o_{\text{pp}}}} \text{ dB}$$

### (2) 串联反馈式稳压电路的工作原理

$$V_I \downarrow \Rightarrow V_o \downarrow \Rightarrow V_F \downarrow \Rightarrow (V_{\text{REF}} - V_F) \uparrow \Rightarrow V_B \uparrow \Rightarrow V_C \downarrow$$

$$V_o \uparrow \leftarrow$$



$$V_I = V_{CE} + V_o$$

T  $\Rightarrow$  调整管

电压跟随器  
放大区

## 电压串联负反馈

满足深度负反馈，根据“虚短”和“虚断”，有

$$\left\{ \begin{array}{l} V_F = V_{REF} \\ \frac{V_F}{V_o} = \frac{R'_2}{R'_1 + R'_2} \end{array} \right. \Rightarrow V_o = \left( 1 + \frac{R'_1}{R'_2} \right) V_{REF}$$

$$V_{o\min} = \frac{R_1 + R_p + R_2}{R_2 + R_p} V_{REF}$$

$$V_{o\max} = \frac{R_1 + R_p + R_2}{R_2} V_{REF}$$

降压

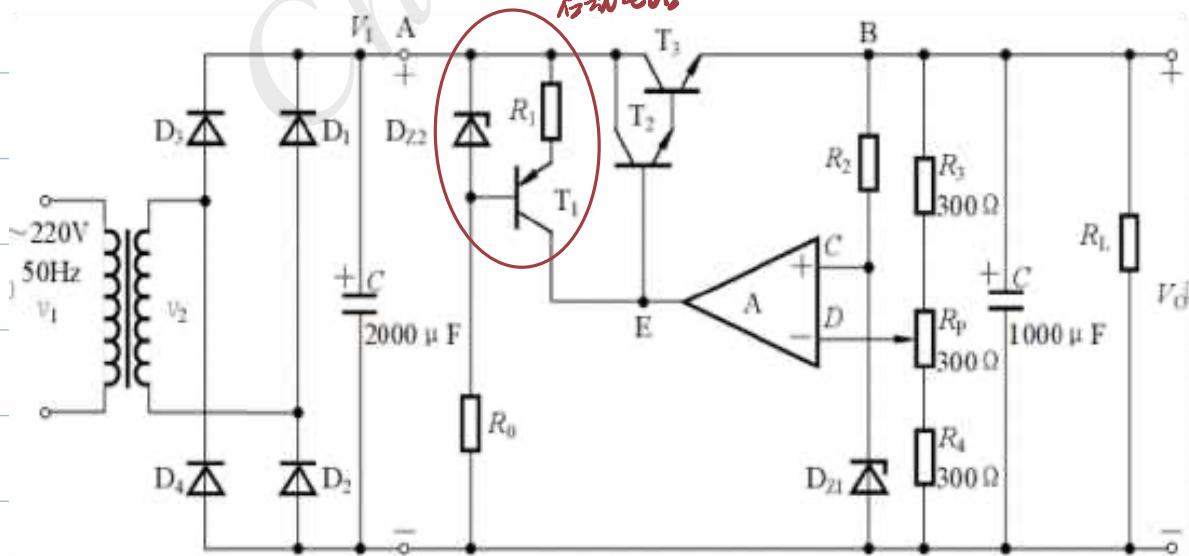
虚流

滤波

稳压

$$V_I = (1.1 \sim 1.2) V_2$$

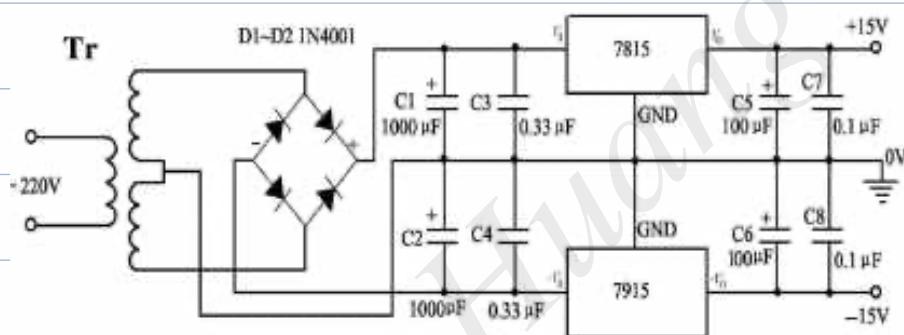
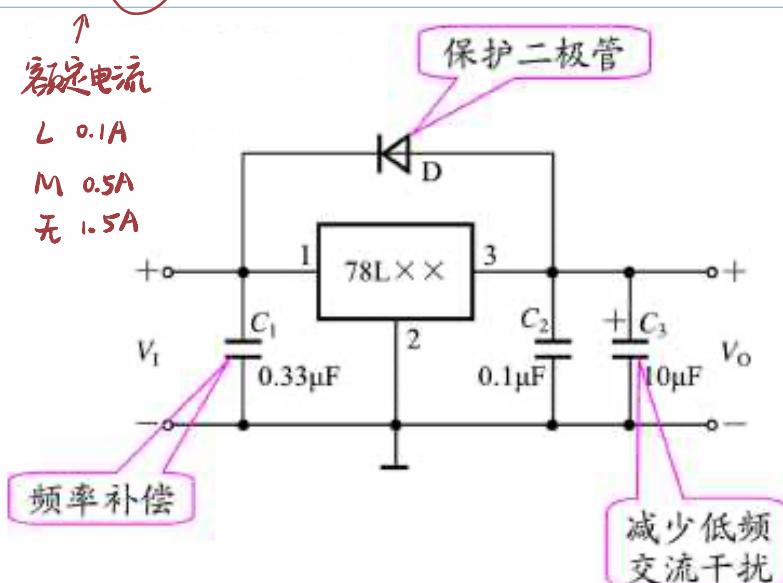
启动电路



### (3) 三端集成稳压器

78LXX 输出电压

78: 正电源 79: 负电源



### 3 开关稳压电路

#### 1) 特点和分类

① 效率高

调整管工作在开关状态，通过控制调整管的导通时间实现稳压

② 体积小、重量轻

③ 稳压范围宽

效率与输入电压的大小基本无关

④ 调整管的控制比较复杂

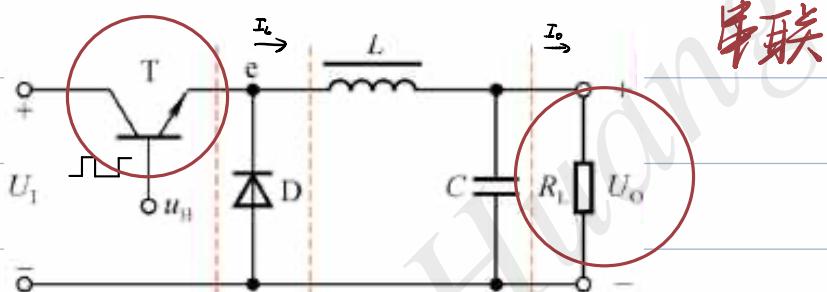
调整管工作在截止和饱和两种状态。

⑤ 输出电压纹波较大



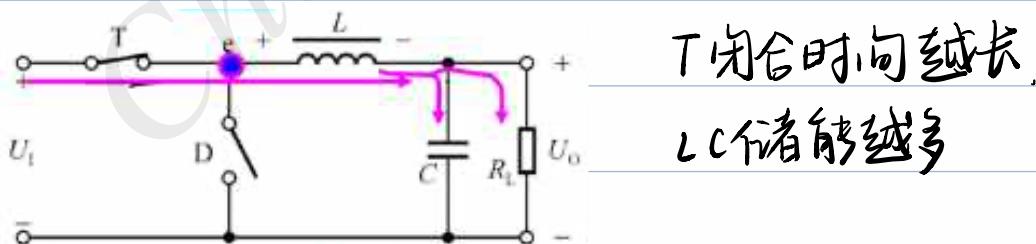
## (2) 开关式稳压电路的工作原理

**串联型**



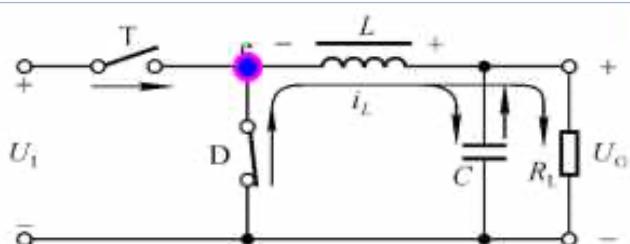
$V_B$  为高电平时, T饱和导通, D反偏截止

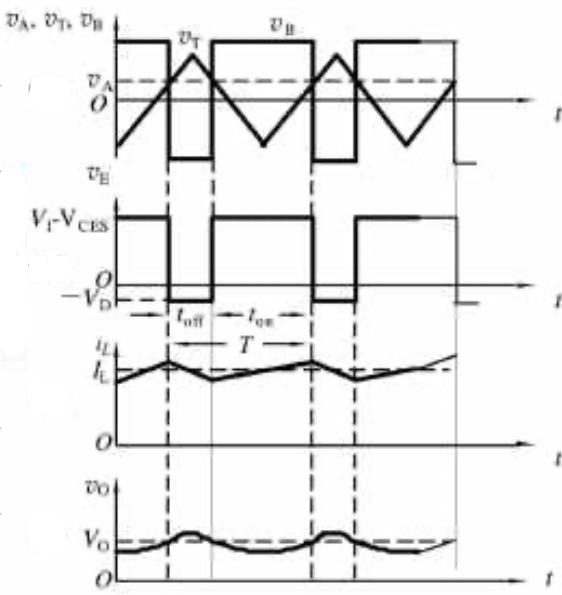
$$V_E = V_i - V_{CES} \quad L \text{储能}, C \text{充电}$$



$V_B$  为低电平时, T截止, D导通

$$V_E = -V_D$$





$t_{on}$  开关导通时间

$t_{off}$  开关截止时间

$$T = t_{on} + t_{off}$$

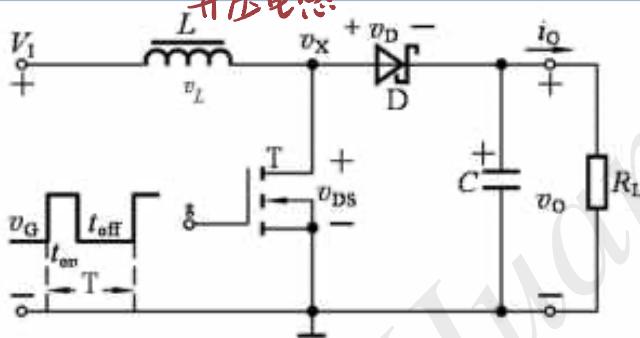
$$V_o = \frac{t_{on}}{T} (V_i - V_{ces}) - (-V_o) \frac{t_{off}}{T}$$

$$\approx V_i \frac{t_{on}}{T} = qV_i$$

2 脉冲中波形的占比

## 并联型

升压电感



T 导通时间越长  
L 储能越多

$v_A$  高电平时, T 导通, D 截止

$v_A$  低电平时, T 截止, D 导通



类型	单相桥式整流电路	桥式整流电容滤波电路
电路原理图		
工作原理	<p><math>v_2</math> 正半周, <math>D_1</math>、<math>D_3</math> 导通, <math>D_2</math>、<math>D_4</math> 截止  <math>v_2</math> 负半周, <math>D_2</math>、<math>D_4</math> 导通, <math>D_1</math>、<math>D_3</math> 截止</p>	<p><math>v_2</math> 正半周, <math>v_2 &gt; v_o</math> (<math>v_o</math>), <math>D_1</math>、<math>D_3</math> 导通, <math>D_2</math>、<math>D_4</math> 截止  <math>v_2</math> 负半周, <math> v_2  &gt; v_o</math> (<math>v_o</math>), <math>D_2</math>、<math>D_4</math> 导通, <math>D_1</math>、<math>D_3</math> 截止</p>
电路性能	<p>输出电压平均值 <math>V_o \approx 0.9V_2</math></p> <p>输出电流平均值 <math>I_o = \frac{0.9V_2}{R_L}</math></p> <p>二极管平均电流 <math>I_D = \frac{1}{2}I_o</math></p> <p>二极管最大反向电压 <math>V_{RM} = \sqrt{2}V_2</math></p>	<p><math>\tau_d = R_L C \geq (3 \sim 5) T/2</math></p> <p><math>V_o = (1.1 \sim 1.2)V_2</math>, 脉动系数 <math>S = 0.67</math></p> <p><math>I_o = (1.1 \sim 1.2)V_2/R_L</math></p> <p><math>Q &lt; \pi</math>, 尖峰电流大, <math>I_o = (2 \sim 3)I_o</math></p> <p><math>V_{RM} = \sqrt{2}V_2</math>, 选 <math>V_{RM} \geq 2V_2</math></p>
特点用途	<p>与单相半波整流比较, 输出电压高, 纹波小, 有集成整流桥产品, 用于小功率整流</p>	<p><math>RC</math> 大, <math>V_o</math> 高, <math>V_o</math> 随 <math>I_L</math> 增加而减小, 输出纹波小, 输出特性差, 用于 <math>V_o</math> 高, <math>I_o</math> 小, <math>R_L</math> 变化不大的场合</p>