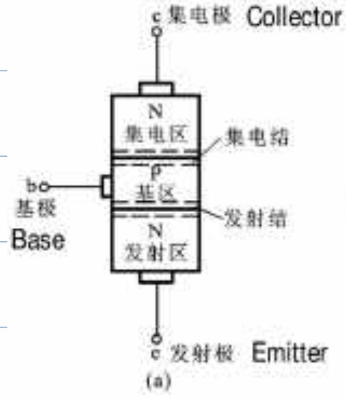
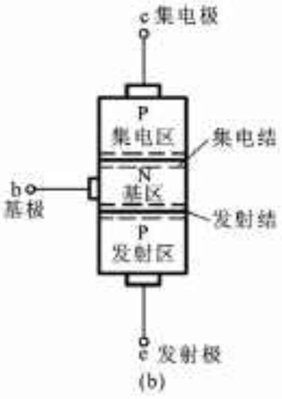
§5 双极结型三极管及其放大电路

① 双极结型三极管的结构及工作原理

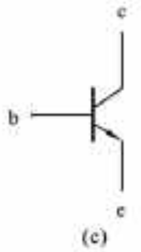
Bipolar Junction Transistor　BJT



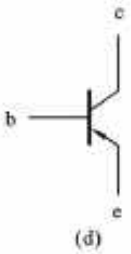
NPN型管结构示意图



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→N

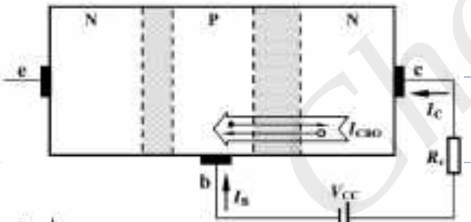
结构特点

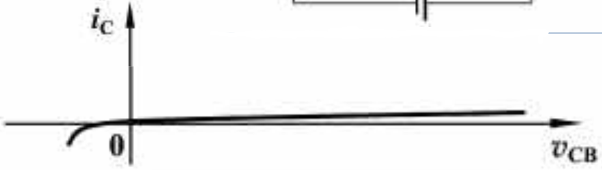
① 发射区的掺杂浓度最高

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



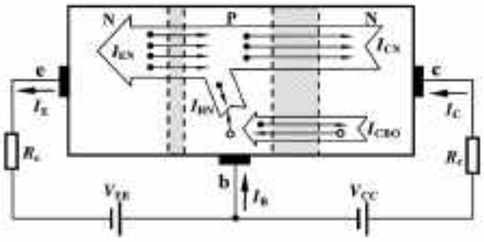


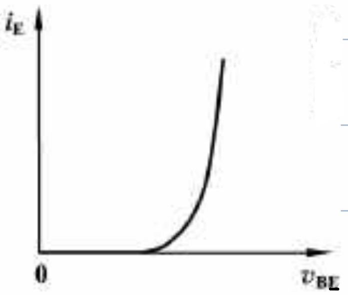
V_{CC} 使集电结反向偏置

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

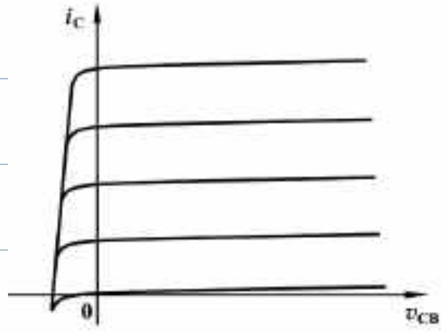
促进多子扩散，产生发射结电流 I_{EN}

（多子是掺杂引起的，不受温度影响）

基区复合电流 I_{BN}

$I_E = I_{EN}$　$I_B = I_{BN}$　$I_C = I_{CN} + I_{CBO}$

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



发射极电流 I_E 可以控制集电集电流 I_C

控制关系：

$$v_{BE} \rightarrow i_E \rightarrow i_C$$

电流放大系数

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

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

反映载流子在基区的复合比例，α/β 越大，复合比例越低.

BJT 控制关系 ⇒ 电流控制器件

$$I_C = \alpha I_E \qquad I_C = \beta I_B \qquad I_E = (1+\beta) I_B$$

工作条件 发射结正偏，集电结反偏

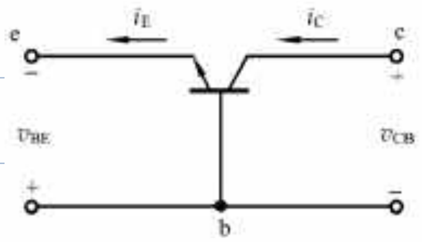
输入：发射极电流 I_E / 基极电流 I_B

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

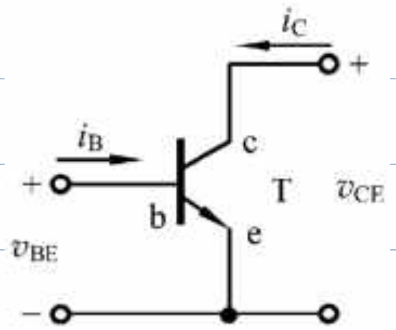


输入特性 $i_E = f(v_{BE})|_{v_{CB} = const}$

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

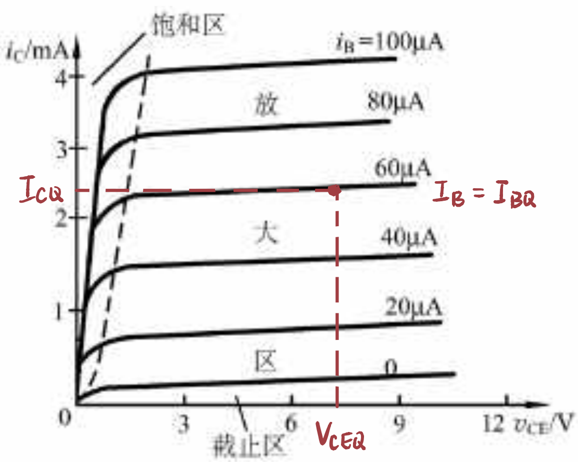
输出特性 $i_C = f(v_{CB})|_{v_{BE} = const}$

(2) 共发射极



输入特性 $i_B = f(v_{BE})\big|_{v_{CE} = const}$

输出特性 $i_C = f(v_{CE})\big|_{v_{BE} = const}$



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

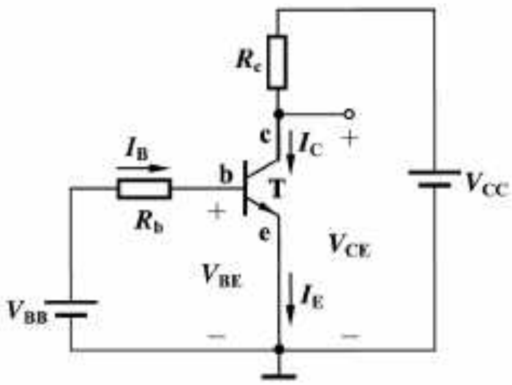
放大区 $i_C = \beta i_B$ i_C 与 v_{CE} 无关（理想）

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：发射结有合适的正偏，集电结有合适的反偏.



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

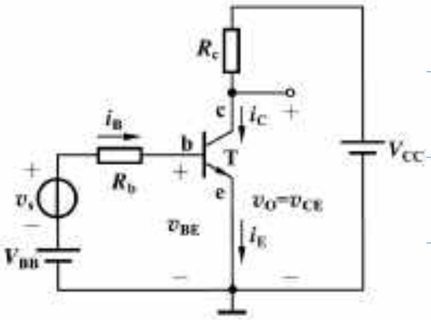
求静态工作点.

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

BJT电流关系 $I_{CQ} = \beta I_{BQ}$

输出回路 $V_{CEQ} = V_{CC} - I_{CQ} R_c$

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



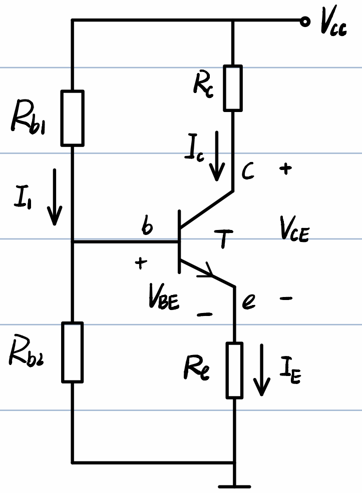
输入信号后 $v_{BE} = V_{BB} + v_s - i_b R_b$

$i_B = I_{BQ} + i_b$

$i_C = \beta i_B$

$v_o = v_{CE} = V_{CC} - i_C R_b$

EXP 基极分压射极偏置电路



当满足 $I_1 >> I_B$ 时

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

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

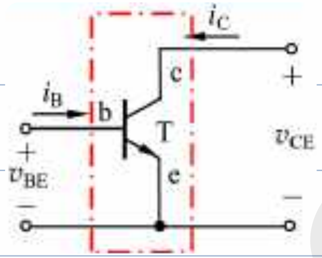
$$V_{CQE} = V_{CC} - I_C R_c - I_E R_e \approx V_{CC} - I_{CQ}(R_c + R_e)$$

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

检验是否满足 $I_1 >> I_B$

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



输入特性 $i_B = f(v_{BE})\big|_{v_{CE}=const}$

输出特性 $i_C = f(v_{CE})\big|_{v_{BE}=const}$

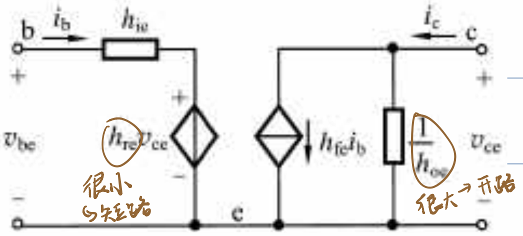
$v_{BE} = f_1(i_B, v_{CE})$　　$i_C = f_2(i_B, v_{CE})$

取全微分

$$dv_{BE} = \frac{\partial v_{BE}}{\partial i_B} di_B + \frac{\partial v_{BE}}{\partial v_{CE}} dv_{CE}$$

$$di_C = \frac{\partial i_C}{\partial i_B} di_B + \frac{\partial i_C}{\partial v_{CE}} dv_{CE}$$

$v_{be} = h_{ie} i_b + h_{re} v_{ce}$　　$i_c = h_{fe} i_b + h_{oe} v_{ce}$



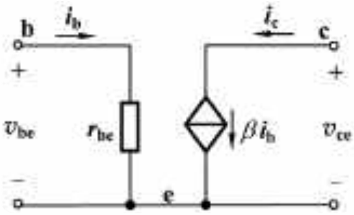
$$h_{ie} = \frac{\partial v_{BE}}{\partial i_B} = r_{be}$$

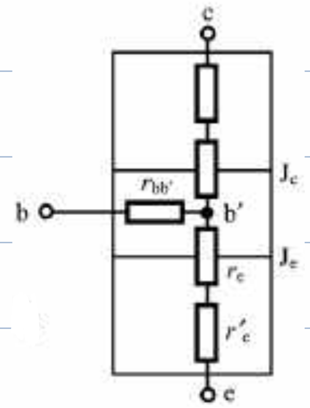
$$h_{re} = \frac{\partial v_{BE}}{\partial v_{CE}} = 10^{-3} \sim 10^{-4}$$

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

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

简化





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

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

常温下发射结电阻 $r_e = \frac{V_T(mV)}{I_{EQ}(mA)} = \frac{26\,mV}{I_{EQ}(mA)} \approx \frac{26\,mV}{I_{CQ}(mA)}$

低频小功率管 $r_{bb'} \approx 200\Omega$

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

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

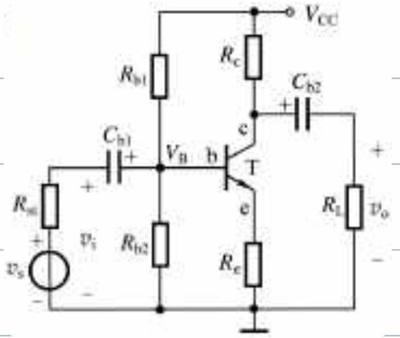
④ 受控源 βi_b 的电流方向与控制电流 i_b 方向关联

(二) 用小信号模型分析放大电路

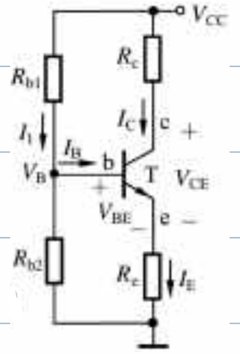
Exp 已知 $V_{CC} = 16V$, $R_{b1} = 56k\Omega$, $R_{b2} = 20k\Omega$, $R_c = 3.3k\Omega$, $R_L = 6.2k\Omega$, $R_{s1} = 500\Omega$,

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

求 A_v, R_i, $A_{vs} = \frac{v_o}{v_s}$, R_o



(1) 静态，设 $I_{BQ} << I_1$



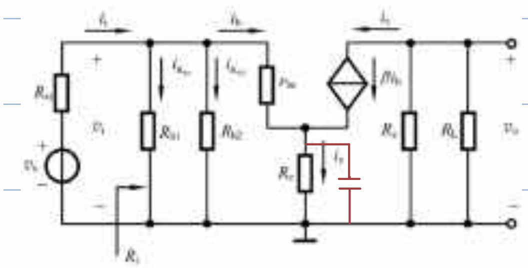
$$V_{BQ} = \frac{R_{b2}}{R_{b1} + R_{b2}} V_{CC}$$

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

$$V_{CEQ} = V_{CC} - I_C R_C - I_E R_e \approx V_{CC} - I_C(R_c + R_e)$$

$I_{BQ} = \frac{I_{CQ}}{\beta}$ 求出 $I_{EQ} \approx 1.76\,mA$

(2) 动态



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

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

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

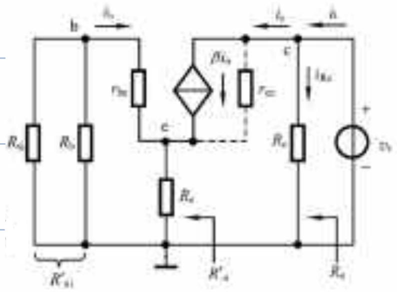
$$A_v = \frac{v_o}{v_i} = -\frac{\beta(R_c \parallel R_L)}{r_{be} + (1+\beta)R_e} \approx -1.05$$

影响放大（并联电容）

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

$$R_i = \frac{v_i}{i_i} = \frac{1}{\frac{1}{r_{be}+(1+\beta)R_e} + \frac{1}{R_{b1}} + \frac{1}{R_{b2}}} = R_{b1} /\!/ R_{b2} /\!/ [r_{be}+(1+\beta)R_e] \approx 13.52\,k\Omega$$

$$A_{vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i}\cdot\frac{v_i}{v_s} = A_v \cdot \frac{R_i}{R_{si}+R_i} \approx -1.01$$



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

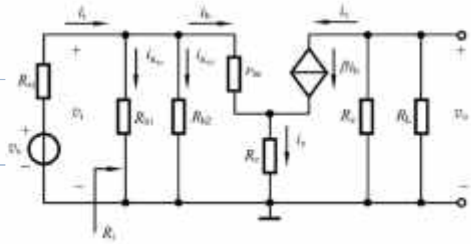
其中 $R'_{si} = R_{si} /\!/ R_b \qquad R_b = R_{b1} /\!/ R_{b2}$

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

$$R'_o = \frac{v_t}{i_c} \qquad R_o = R'_o /\!/ R_c$$

5 BJT的三种基本放大电路和复合管

(1) 共射极



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

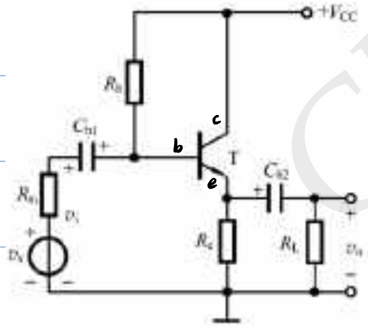
输出回路 $v_o = -\beta i_b (R_c /\!/ R_L)$

$$A_v = \frac{v_o}{v_i} = -\frac{\beta(R_c /\!/ R_L)}{r_{be} + (1+\beta)R_e}$$

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

输出电阻 $R_o = R'_o /\!/ R_c \approx R_c$

(2) 共集电极



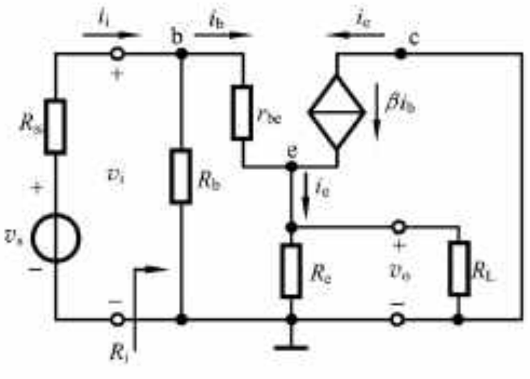
(1) 静态分析

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

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

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

输出回路 $V_{CEQ} = V_{CC} - I_{EQ}R_e$



(2) 动态分析

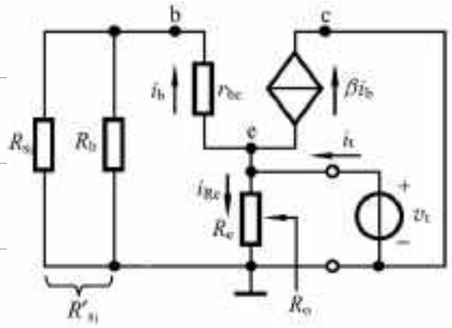
$$r_{be} = 200\Omega + (1+\beta)\frac{26mV}{I_{CQ}(mA)}$$

$$v_i = i_b r_{be} + (1+\beta) i_b (R_e /\!/ R_L)$$

$$v_o = (1+\beta) i_b (R_e /\!/ R_L)$$

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

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



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

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

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

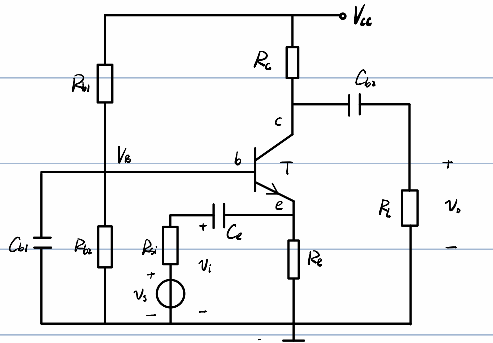
$$R_o = \frac{v_t}{i_t} = R_e // \left(\frac{R'_{si} + r_{be}}{1+\beta}\right)$$

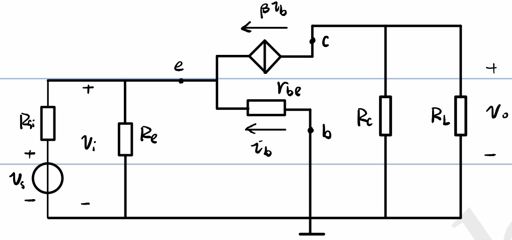
特点 ① 电压增益小于1但接近1，v_o 与 v_i 同相

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





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

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

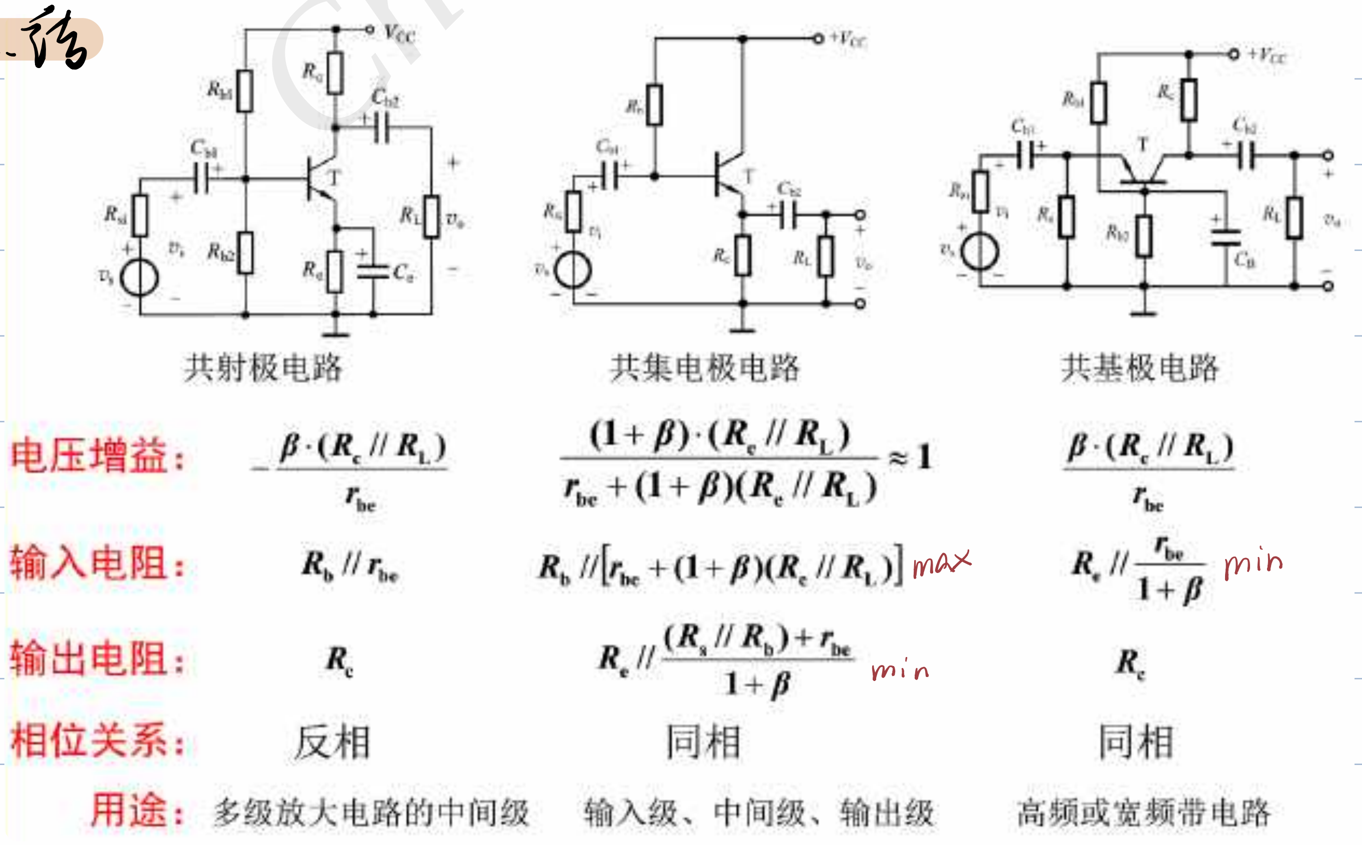
$$A_v = \frac{v_o}{v_i} = \frac{\beta(R_c // R_L)}{r_{be}}$$

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

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

$$R_o = R_c$$

总结

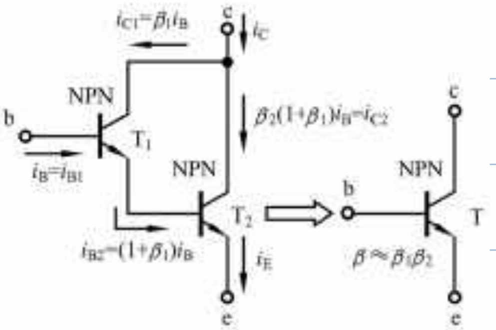


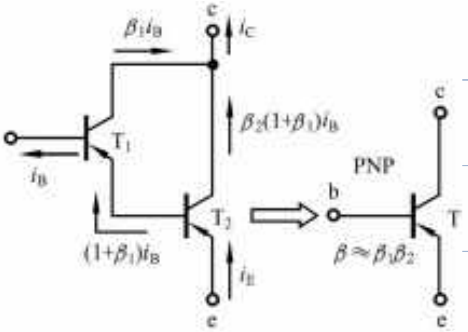
	共射极电路	共集电极电路	共基极电路
电压增益：	$-\frac{\beta \cdot (R_c // R_L)}{r_{be}}$	$\frac{(1+\beta)\cdot(R_e // R_L)}{r_{be} + (1+\beta)(R_e // R_L)} \approx 1$	$\frac{\beta \cdot (R_c // R_L)}{r_{be}}$
输入电阻：	$R_b // r_{be}$	$R_b // [r_{be} + (1+\beta)(R_e // R_L)]$ max	$R_e // \frac{r_{be}}{1+\beta}$ min
输出电阻：	R_c	$R_e // \frac{(R_s // R_b) + r_{be}}{1+\beta}$ 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

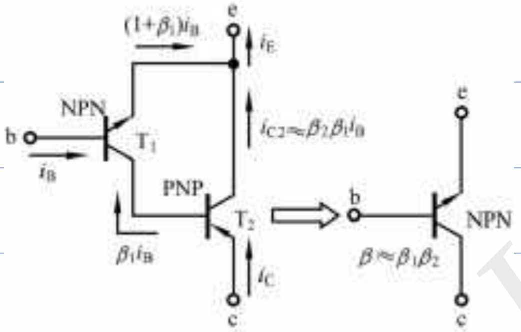
同类型：T_1发射极 → T_2基极

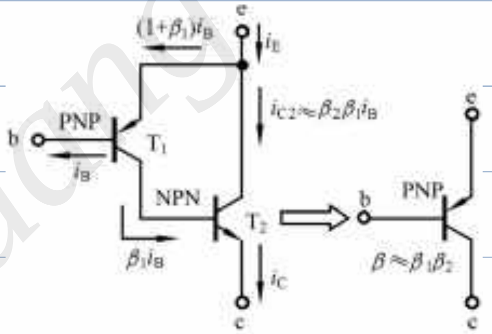




等效基极-发射极电阻 $r_{be} = r_{be1} + (1+\beta_1) r_{be2}$

不同类型：T_1集电极 → T_2基极



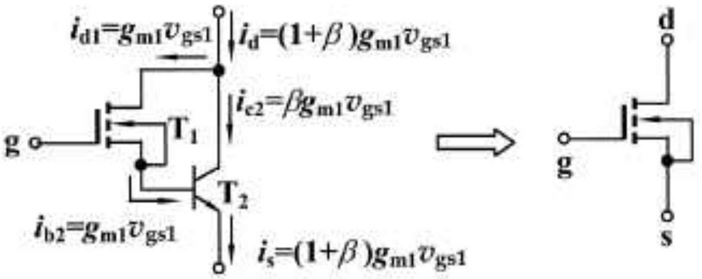


等效基极-发射极电阻 $r_{be} \approx r_{be1}$

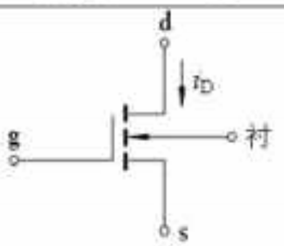
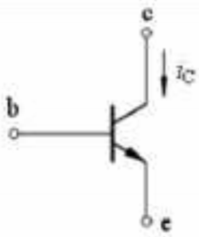
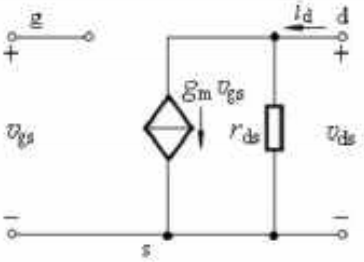
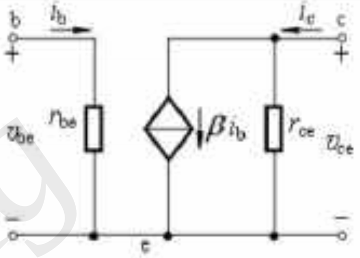
复合管优点. ① 用简单的方法得到高β值三极管

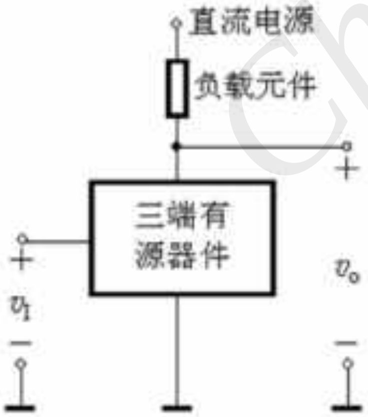
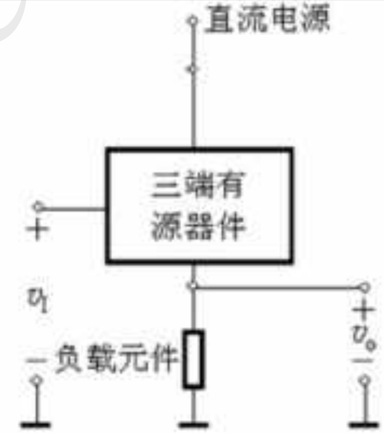
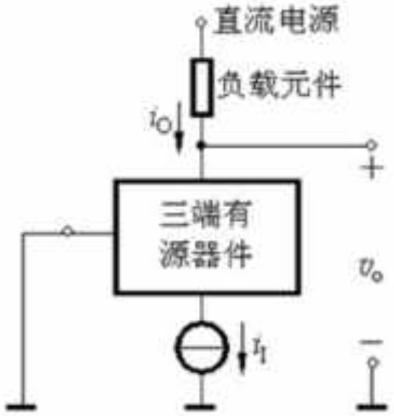
② 分析电路时，可以简单地把它当作一个三极管

BiMOS复合管



$$g_m = (1+\beta) g_{m1}$$

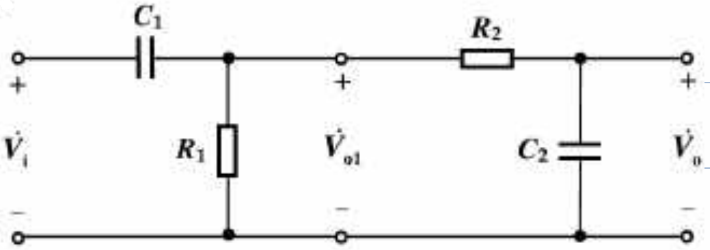
	增强型 NMOS 管	NPN 型 BJT
电路符号		
工作在放大区的两个条件	（1） 生成沟道 $v_{GS} \geq V_{TN}$（≈0.3 ~ 0.5V，现代工艺可达到的数值） （2） 沟道出现预夹断 $v_{DS} \geq v_{GS} - V_{TN}$	（1）发射结正偏 $v_{BE} \geq V_{th}$（≈0.5V） （2）集电结反偏 或放宽为 $v_{BC} < 0.4V$ 且 $v_{CE} \geq 0.3V$
放大区的电流-电压关系	$i_D = \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L}(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})$ $= K_n(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})$ $i_G = 0$	$i_E \approx I_{ES} e^{v_{BE}/V_T}$ $i_C = \alpha i_E$ $i_B = i_C / \beta$
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	$r_{gs} = \infty$	$r_{be} = r_{bb'} + (1+\beta)\frac{26mV}{I_{EQ}mA} \approx \frac{\beta}{g_m}$
三极管的输出电阻	$r_{ds} = \left[\lambda K_n(v_{GS} - V_{TN})^2\right]^{-1} = \frac{1}{\lambda I_{DQ}} = \frac{V_A}{I_{DQ}}$	通常 < $r_{ce} \approx \frac{V_A}{I_{CQ}}$

	反相电压放大电路	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_o 与 v_i 反相，而且一般有 $\|A_v\| \gg 1$	$v_o \approx v_i$， $A_v \approx 1$，即 v_o 与 v_i 大小接近相等，相位相同	$i_o \approx i_i$ 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



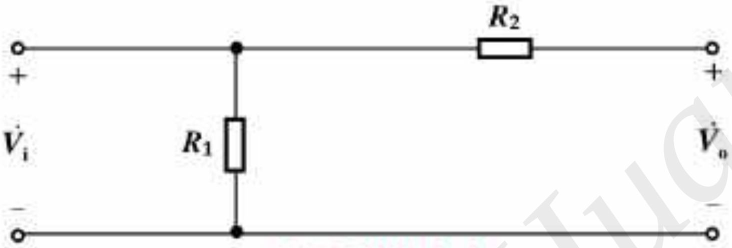
设 $R_1C_1 >> R_2C_2$

且 $C_1 >> C_2$ 时

(1) 中频响应 $\frac{1}{R_1C_1} << \omega << \frac{1}{R_2C_2}$

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

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



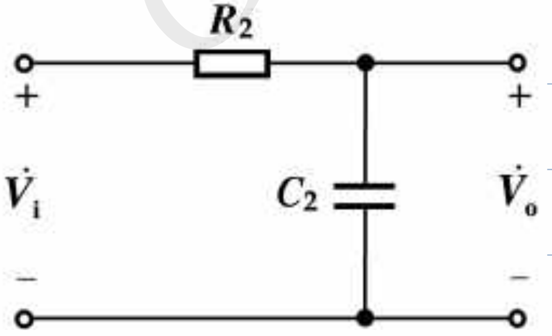
传递函数（电压增益）$\dot A_{VM} = \frac{\dot V_o}{\dot V_i} = 1$

M指中频区

$|\dot A_{VM}| = 1$ $\varphi_M = \varphi_o - \varphi_i = 0$

(2) 高频响应 ω接近或大于等于 $\frac{1}{R_2C_2}$

$\frac{1}{\omega C_1} << R_1$ C_1看作短路



RC低通电路

$$\dot A_{VH} = \frac{\dot V_o}{\dot V_i} = \frac{\frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} = \frac{1}{1 + j\omega R_2C_2}$$

令 $f_H = \frac{1}{2\pi R_2C_2}$ 称为上限截止频率，$\omega = 2\pi f$

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

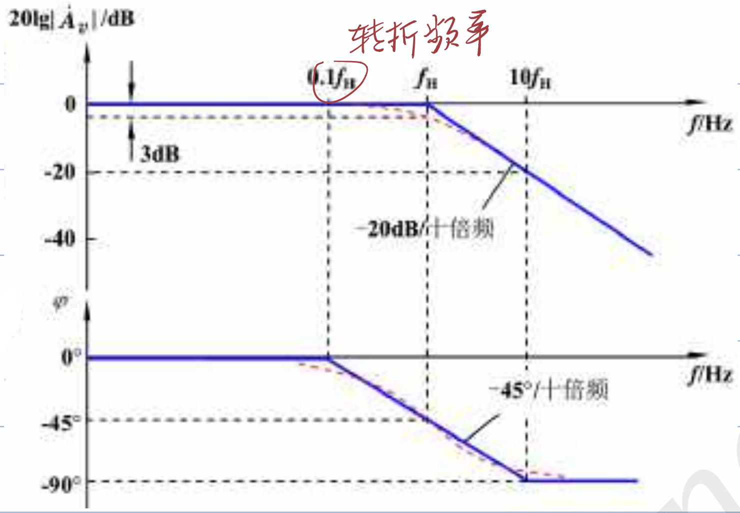
电压增益的幅值 $|\dot A_{VH}| = \frac{1}{\sqrt{1 + (\frac{f}{f_H})^2}}$ 幅频响应

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

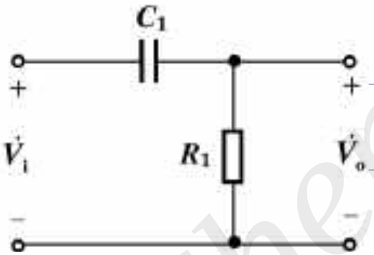
$\begin{cases} \text{当 } f \ll f_H \text{ 时，} |\dot{A}_{vH}| \approx 1,\ 20\lg|\dot{A}_{vH}| = 0\ (dB) \\ \text{当 } f \gg f_H \text{ 时，} |\dot{A}_{vH}| \approx \frac{f_H}{f},\ 20\lg|\dot{A}_{vH}| \approx 20\lg f_H - 20\lg f\ (dB) \end{cases}$

波特图：



(3) 低频响应　ω 接近或小于等于 $\frac{1}{R_1C_1}$

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



RC高通电路

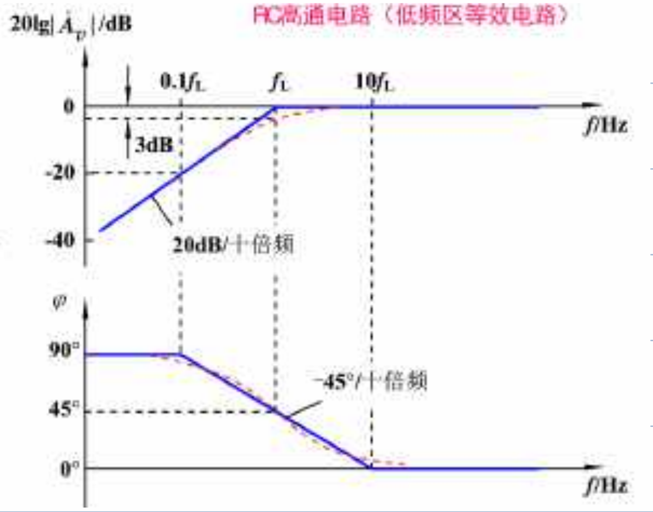
$\dot{A}_{vL} = \frac{\dot{V}_o}{\dot{V}_i} = \frac{R_1}{R_1 + \frac{1}{j\omega C_1}} = \frac{1}{1+\frac{1}{j\omega R_1C_1}}$

令 $f_L = \frac{1}{2\pi R_1C_1}$ 称为下限截止频率，　$\omega = 2\pi f$

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

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

RC高通电路（低频区等效电路）

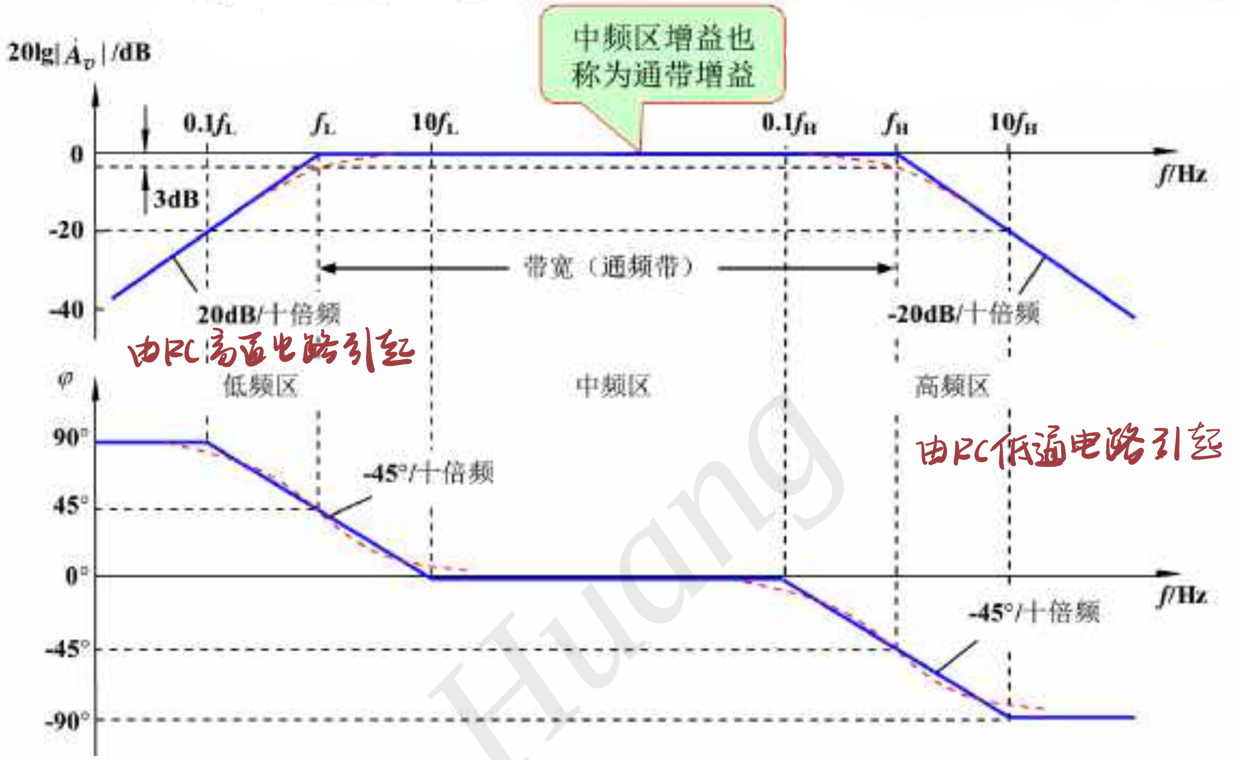


(4) 全频响应

上限频率：f_H

下限频率：f_L

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



结论

① f_H，f_L 取决于时间常数 $\tau = RC$

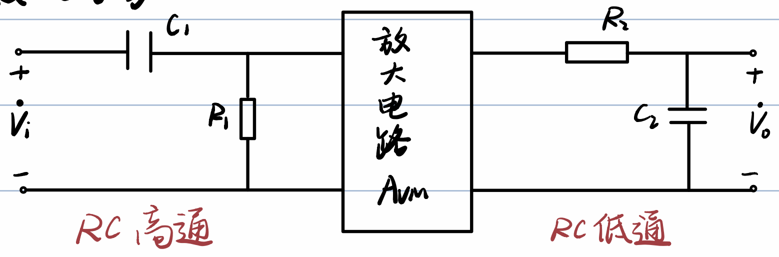
② 当输入信号的频率 $f = f_H$ 或 f_L 时，电路增益比通带增益下降 3dB，或下降为通带增益的 0.707倍，且在通带相移的基础上产生 -45° 或 45° 的相移.

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频小信号模型

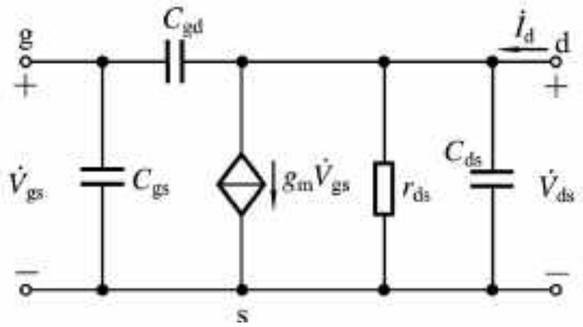
放大电路中存在：PN结电容、耦合电容、旁路电容 …

等效电路：



$R_1C_1 >> R_2C_2$

MOSFET高频小信号模型



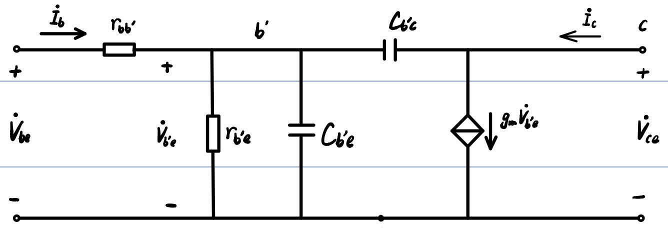
$C_{gs} \approx 0.1 - 0.5\ pF$

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

C_{ds} 更小

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

BJT 高频小信号模型



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

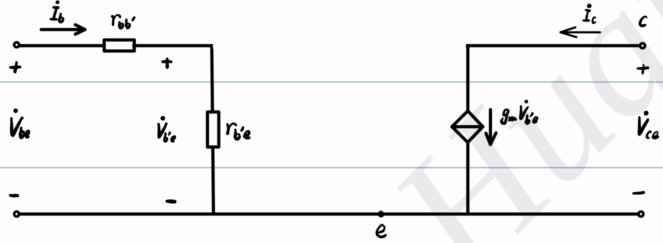
$r_{b'e} = (1+\beta)\frac{V_T}{I_{EQ}}$

$C_{b'e}$ 几十至几百pF

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

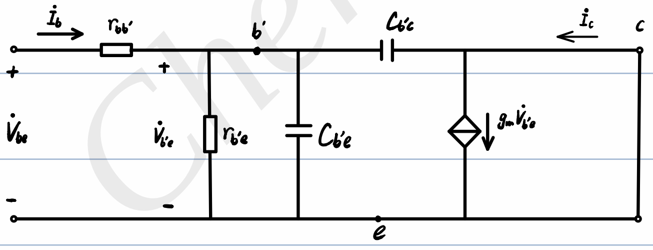
中低频

通带内 π模型与小信号模型等价



$g_m = \frac{\beta_0}{r_{b'e}} \approx \frac{I_{EQ}}{V_T}$ 与频率无关

β 的频率响应



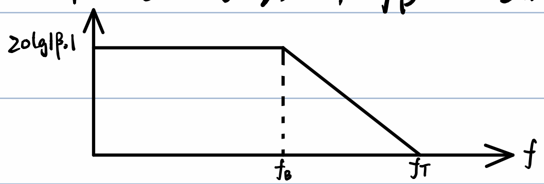
$$\begin{cases} \dot{I}_c = g_m\dot{V}_{b'e} - j\omega C_{b'c}\dot{V}_{b'c} \\ \dot{I}_b = \frac{\dot{V}_{b'e}}{r_{b'e}} + j\omega C_{b'c}\dot{V}_{b'c} + j\omega C_{b'e}\dot{V}_{b'e} \end{cases}$$

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

当 $g_m \gg \omega C_{b'c}$ 时

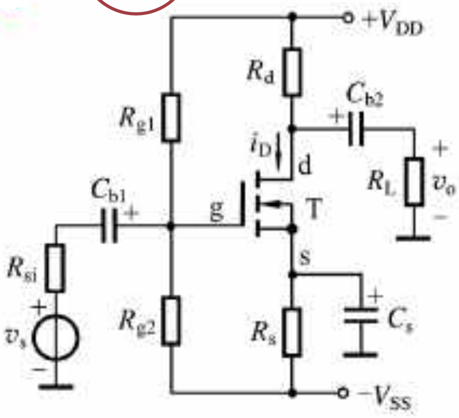
$$\dot{\beta} = \frac{\beta_0}{1+j\omega(C_{b'e}+C_{b'c})r_{b'e}} \qquad |\dot{\beta}| = \frac{\beta_0}{\sqrt{1+(f/f_\beta)^2}}$$

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

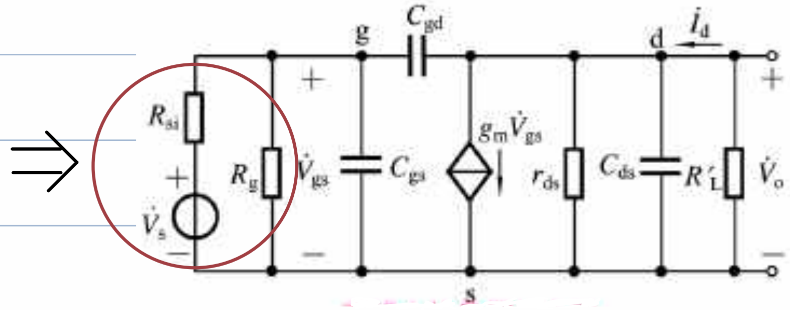


3 三极管放大电路的高频响应和带宽增益积

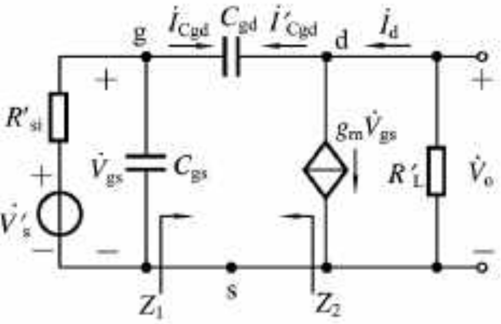
高频时耦合电容、旁路电容看作短路，直流电压源接地



$R_g = R_{g1} // R_{g2}$　　$R_L' = R_d // R_L$



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



设 $\dot{A}_v' = \frac{\dot{V}_o}{\dot{V}_{gs}}$，则

$\dot{I}_{C_{gd}} = \frac{\dot{V}_{gs} - \dot{V}_o}{\frac{1}{j\omega C_{gd}}} = (1-\dot{A}_v')\dot{V}_{gs} \cdot j\omega C_{gd}$

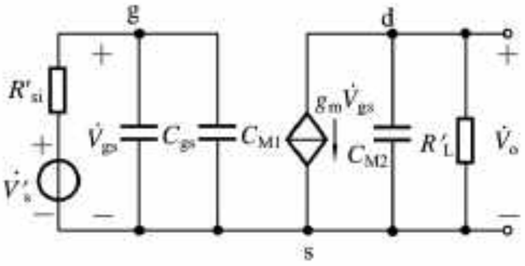
阻抗 $Z_1 = \frac{\dot{V}_{gs}}{\dot{I}_{C_{gd}}} = (1-\dot{A}_v') \cdot j\omega C_{gd}$

显然 Z_1 是一个电容的阻抗，$C_{M1} = (1-\dot{A}_v')C_{gd}$

同理 Z_2 也是一个电容的阻抗 $C_{M2} = (1-\frac{1}{\dot{A}_v'})C_{gd}$

$\dot{I}_d \approx g_m \dot{V}_{gs}$，则 $\dot{A}_v' = \frac{\dot{V}_o}{\dot{V}_{gs}} = \frac{-\dot{I}_d R_L'}{\dot{V}_{gs}} = -g_m R_L'$

$$\begin{cases} C_{M1} = C_{gd}(1+g_m R_L') \\ C_{M2} = C_{gd}(1+\frac{1}{g_m R_L'}) \end{cases}$$



输入回路 $f\uparrow \Rightarrow |\dot{V}_{gs}|\downarrow$

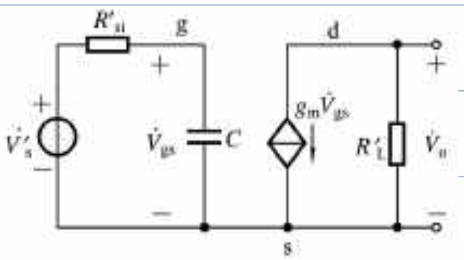
$R_{si}'(C_{gs}+C_{M1})$ 为低通电路

输出回路 $f\uparrow \Rightarrow |\dot{V}_o|\downarrow$

$R_L' C_{M2}$ 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) $\overset{\Downarrow}{C_{M2}} = C_{gd}(1+\frac{1}{g_m R_L'}) \approx C_{gd}$

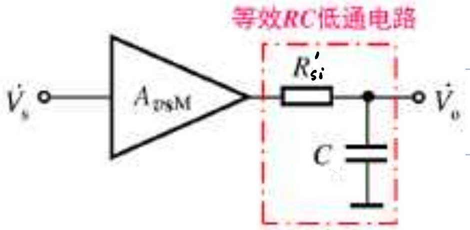


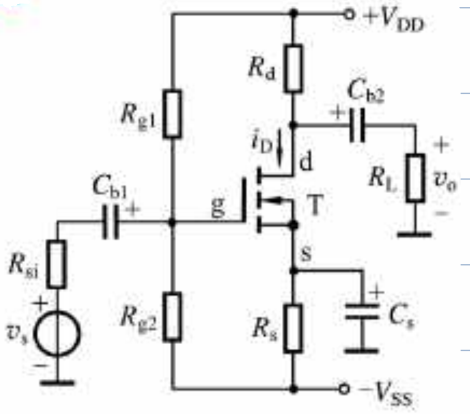
通带内有 $\dot{V}_{gs} = \dot{V}_s'$

$$A_{VSM} = \frac{\dot{V}_o}{\dot{V}_s} = \frac{\dot{V}_o}{\dot{V}_{gs}} \cdot \frac{\dot{V}_{gs}}{\dot{V}_s} = \frac{\dot{V}_o}{\dot{V}_{gs}} \cdot \frac{\dot{V}_s'}{\dot{V}_s}$$

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

共源极放大电路的等效RC低通电路：





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

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

哪些参数会影响上限频率？

$R_{si}' = R_{si} // R_{g1} // R_{g2}$ ↑ 明显提高

$C = C_{gs} + C_{M1} = C_{gs} + \underline{C_{gd}}(1+g_m R_L')$

选小的

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

增益带宽积

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

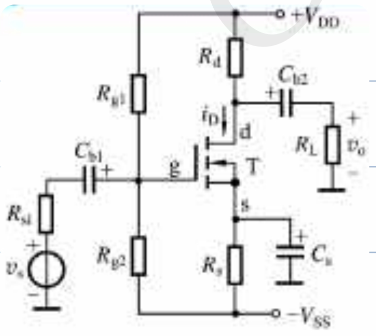
$$= g_m R_L' \cdot \frac{R_g}{R_{si}+R_g} \cdot \frac{1}{2\pi (R_{si} // R_g)[C_{gs} + (1+g_m R_L')C_{gd}]}$$

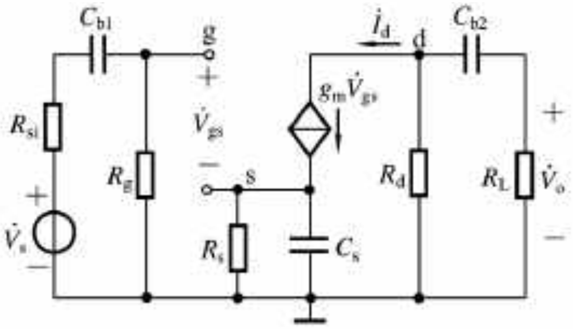
通常有 $R_g \gg R_{si}$，$g_m R_L' \gg 1$，$(1+g_m R_L')C_{gd} \gg C_{gs}$

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

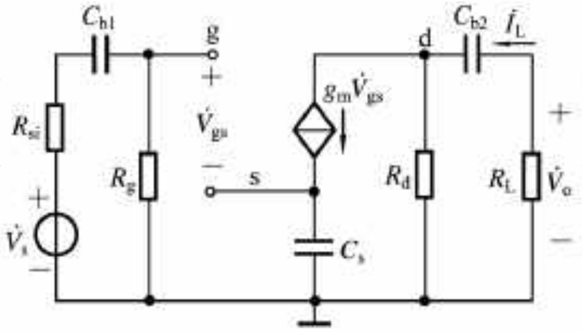
④ 阻容耦合放大电路的低频响应及全频率响应

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，$\frac{1}{\omega C_s} \ll R_s$



$$\dot V_g = \frac{R_g}{R_{si}+R_g+\frac{1}{j\omega C_{b1}}} \cdot \dot V_s$$

$$\dot V_g = \dot V_{gs} + g_m \dot V_{gs} \frac{1}{j\omega C_s}$$

$$\Rightarrow \dot V_{gs} = \frac{1}{1+\frac{g_m}{j\omega C_s}} \cdot \frac{R_g}{R_{si}+R_g+\frac{1}{j\omega C_{b1}}} \cdot \dot V_s$$

$$\dot{I}_L = g_m \dot{V}_{gs} \frac{R_d}{R_d + R_L + \frac{1}{j\omega C_{b2}}}$$

$$\dot{V}_o = -\dot{I}_L R_L = -g_m \dot{V}_{gs} \frac{R_d}{R_d + R_L + \frac{1}{j\omega C_{b2}}} \cdot R_L$$

源电压增益

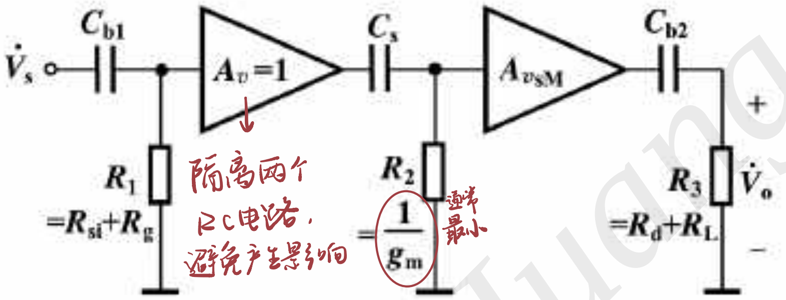
$$\dot{A}_{VsL} = \frac{\dot{V}_o}{\dot{V}_s} = \frac{\dot{V}_o}{\dot{V}_{gs}} \cdot \frac{\dot{V}_{gs}}{V_s} = -g_m \frac{R_d}{R_d + R_L + \frac{1}{j\omega C_{b2}}} \cdot \frac{1}{1 + \frac{g_m}{j\omega C_s}} \cdot \frac{R_g}{R_{si} + R_g + \frac{1}{j\omega C_{b1}}}$$

$$= A_{VsM} \cdot \frac{1}{1 - j(\frac{f_{L1}}{f})} \cdot \frac{1}{1 - j(\frac{f_{L2}}{f})} \cdot \frac{1}{1 - j(\frac{f_{L3}}{f})}$$

其中 $A_{VsM} = -g_m R_L' \frac{R_g}{R_{si} + R_g}$

下限频率 $f_{L1} = \frac{1}{2\pi(R_{si} + R_g)C_{b1}}$　$f_{L2} = \frac{1}{2\pi(\frac{1}{g_m})C_s}$　$f_3 = \frac{1}{2\pi(R_d + R_L)C_{b2}}$

等效模型：

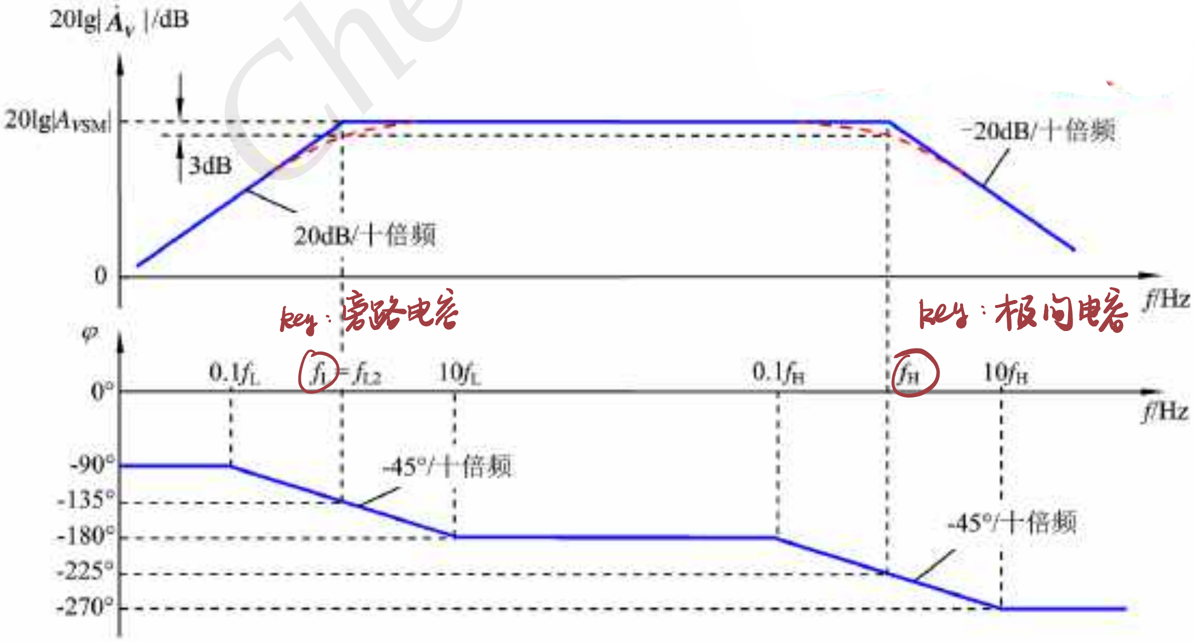


隔离两个RC电路，避免产生影响

通常最小

若 $f_{L2} > 4f_{L1}$，$f_{L2} > 4f_{L3}$，则 $f_L \approx f_{L2}$

全频率响应



key：旁路电容

key：极间电容

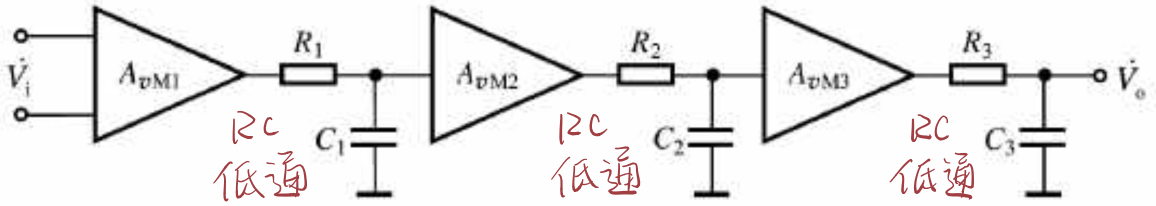
共源极放大电路的低频响应波特图（忽略了 f_{L1} 和 f_{L3} 的影响）

增大带宽 → 增大 f_H → 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



$$\dot{A}_{vH} = \dot{A}_{vH1}\dot{A}_{vH2}\dot{A}_{vH3}$$

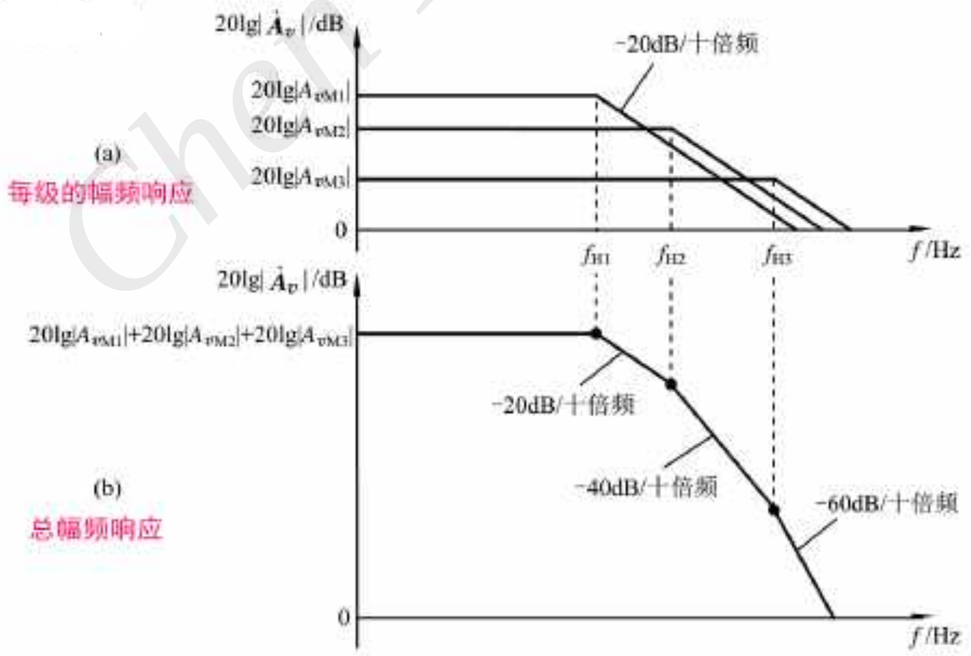
$$= \frac{A_{vM1}}{1+j(\frac{f}{f_{H1}})}\cdot\frac{A_{vM2}}{1+j(\frac{f}{f_{H2}})}\cdot\frac{A_{vM3}}{1+j(\frac{f}{f_{H3}})}$$

转折频率 $f_{H1} = \frac{1}{2\pi R_1C_1}$ $f_{H2} = \frac{1}{2\pi R_2C_2}$ $f_{H3} = \frac{1}{2\pi R_3C_3}$

幅频响应 $|\dot{A}_{vH}| = |\dot{A}_{vH1}|\cdot|\dot{A}_{vH2}|\cdot|\dot{A}_{vH3}|$

$$= \frac{|A_{vM1}|}{\sqrt{1+(f/f_{H1})^2}}\cdot\frac{|A_{vM2}|}{\sqrt{1+(f/f_{H2})^2}}\cdot\frac{|A_{vM3}|}{\sqrt{1+(f/f_{H3})^2}}$$

$$20\lg|\dot{A}_{vH}| = 20\lg|\dot{A}_{vH1}| + 20\lg|\dot{A}_{vH2}| + 20\lg|\dot{A}_{vH3}|$$



相频响应（设通带内无反相）

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

(2) 阻容耦合多级放大电路的频率响应

设 $A_{vm2} = A_{vm1}$, $f_{L2} = f_{L1}$, $f_{H2} = f_{H1}$

则总增益 $(0.707A_{vm1})^2 = 0.5A_{vm1}^2 < 0.707A_{vm1}^2$

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

多级放大电路的通频带一定比构成它的任何一级都窄

跨接在输入输出端之间的电容会产生密勒效应