电子电路与系统基础II

理论课第十一讲 晶体管电路的回顾与拓展

单晶体管放大器回顾
差分对放大器分析
寄生电容效应

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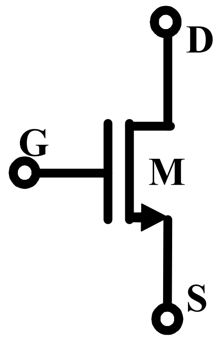
大纲

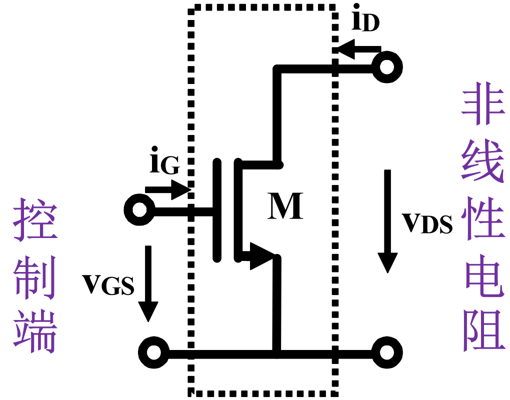
- 晶体管电阻电路回顾
  - 上学期内容回顾
- 差分对放大器分析
  - 如果上学期讲则属必考重点，本学期讲则属背景知识
- 晶体管寄生电容效应
  - 导致晶体管放大器的有源性降低

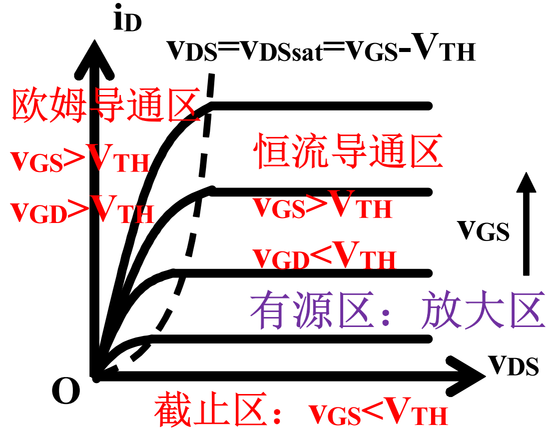
一、晶体管电阻电路回顾

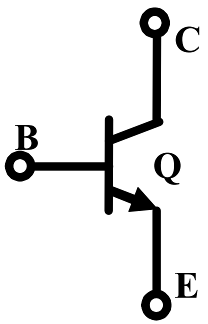
- **1.1** 晶体管分区特性及其电路模型
- **1.2** 反相器电路
- **1.3** 电流镜电路
- **1.4** 三种组态放大器

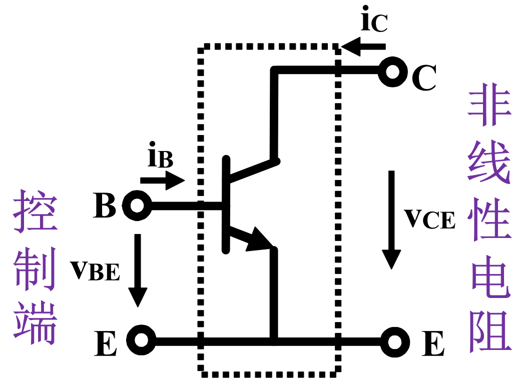
1.1 晶体管伏安特性具有分区特性

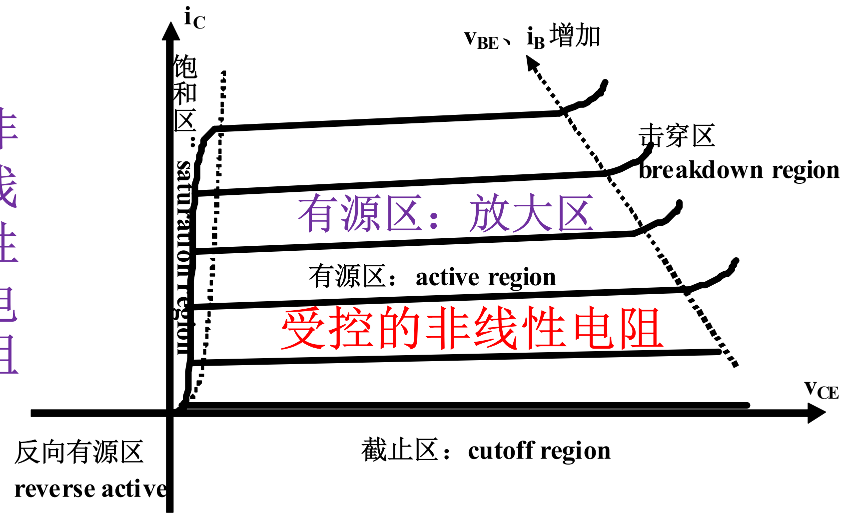




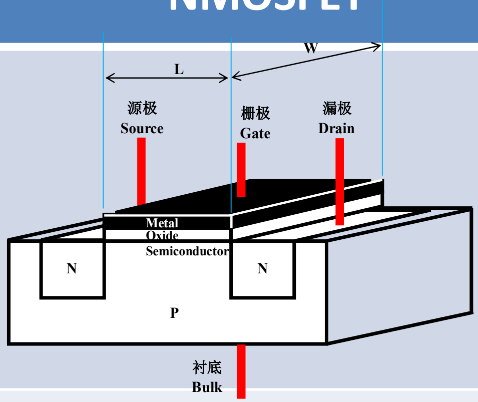
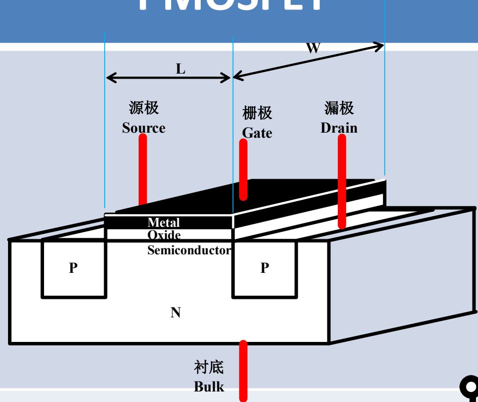
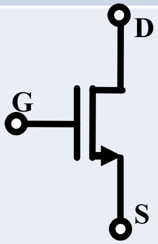
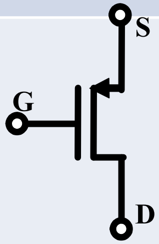
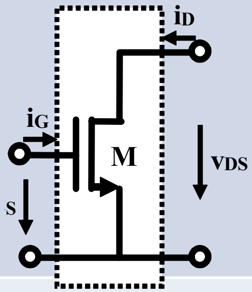
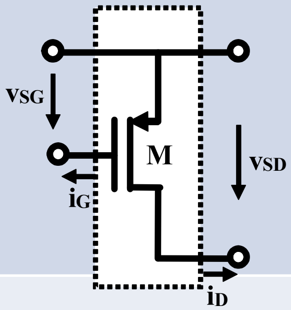




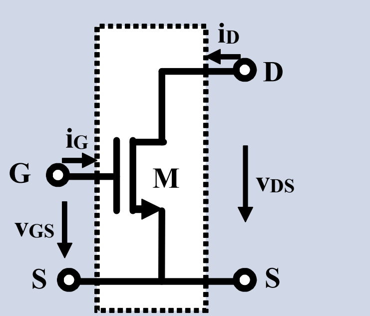
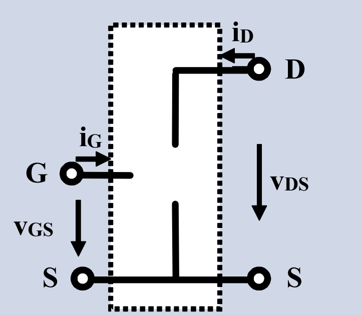
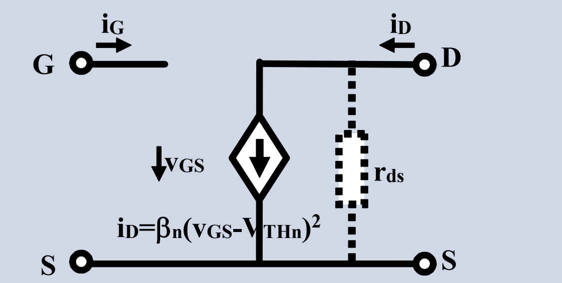
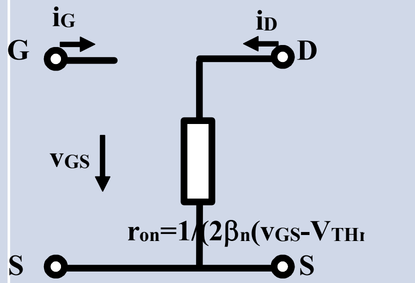
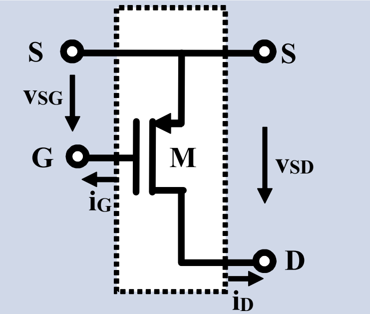
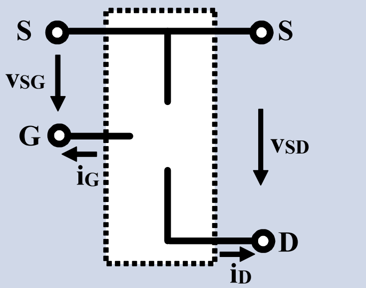
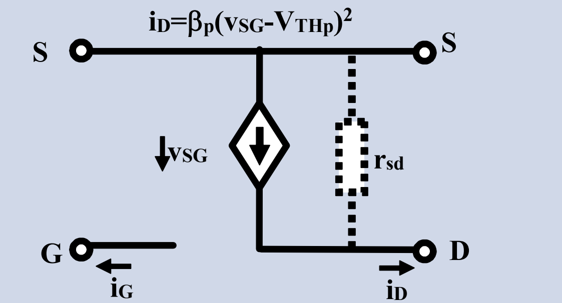
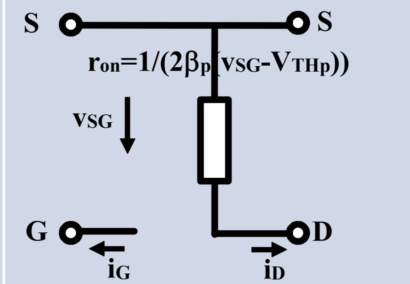




MOS描述

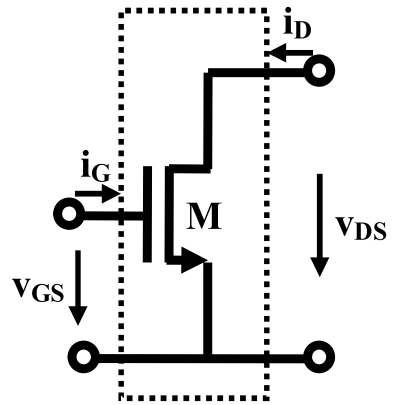
	NMOSFET	PMOSFET
结构		
电路符号		
二端口定义		
元件约束方程	$i_G = 0$ $\quad \beta_n = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}$ $i_D = \begin{cases} 0 & v_{GS} < V_{TH} \\ 2\beta_n\left((v_{GS} - V_{TH})v_{DS} - 0.5v_{DS}^2\right) & v_{GS} > V_{TH}, v_{GD} > V_{TH} \\ \beta_n(v_{GS} - V_{TH})^2(1 + \lambda v_{DS}) & v_{GS} > V_{TH}, v_{GD} < V_{TH} \end{cases}$	

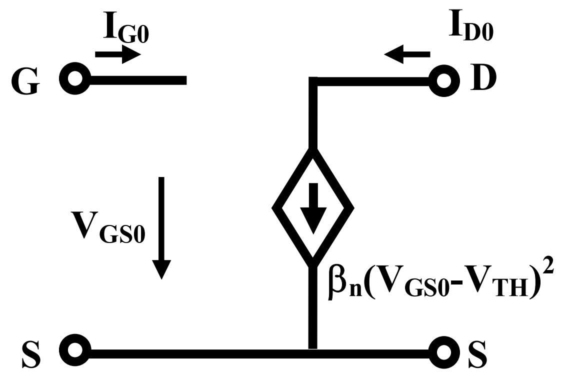
MOS分区描述

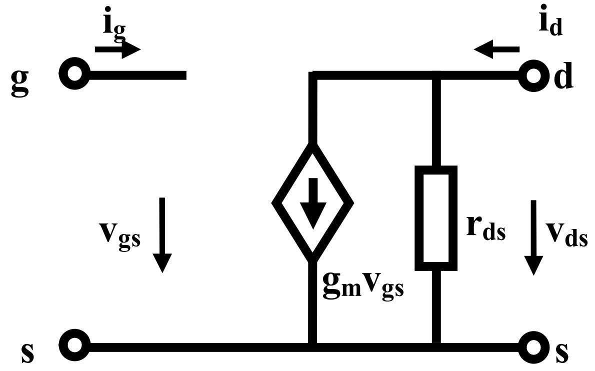
	二端口定义	截止区	有源区（恒流区，饱和区）	欧姆区
NMOS 电路符号				
端口描述	$\begin{bmatrix} v_{GS}, i_G \\ v_{DS}, i_D \end{bmatrix}$	未形成导电沟道 $v_{GS} < V_{THn}, i_G = 0$ $v_{DS} > 0, i_D = 0$	沟道夹断 $v_{GS} > V_{THn}$ $v_{DS} > v_{GS} - V_{THn}$	沟道畅通 $v_{GS} > V_{THn}$ $v_{DS} < v_{GS} - V_{THn}$
PMOS 电路符号				
端口描述	$\begin{bmatrix} v_{SG}, i_G \\ v_{SD}, i_D \end{bmatrix}$	未形成导电沟道 $v_{SG} < V_{THp}, i_G = 0$ $v_{SD} > 0, i_D = 0$	沟道夹断 $v_{SG} > V_{THp}$ $v_{SD} > v_{SG} - V_{THp}$	沟道畅通 $v_{SG} > V_{THp}$ $v_{SD} < v_{SG} - V_{THp}$

恒流区交直流分析电路模型

$$\mathbf{y}_{MOSFET}=\begin{bmatrix}0 & 0\\ g_m & g_{ds}\end{bmatrix}$$

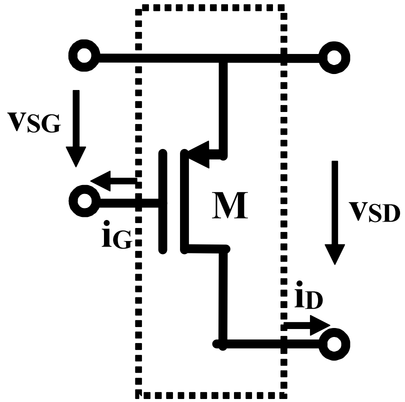


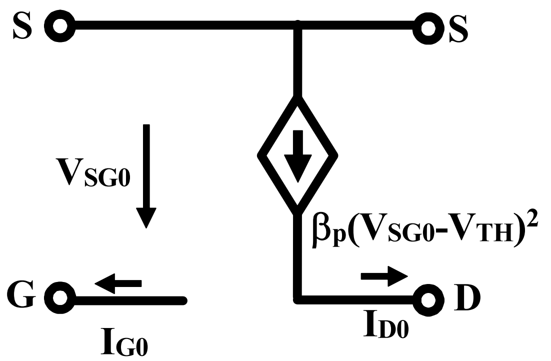


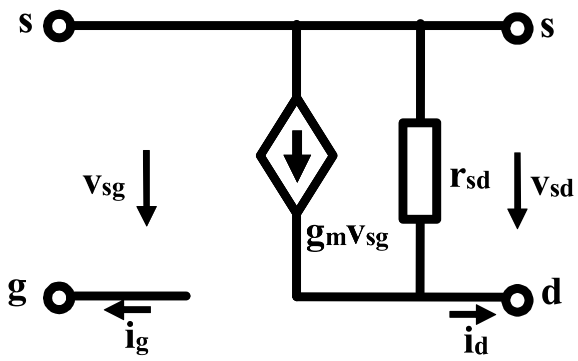


$$g_m \approx \frac{2I_{D0}}{V_{od}},\ r_{ds} \approx \frac{V_A}{I_{D0}}$$

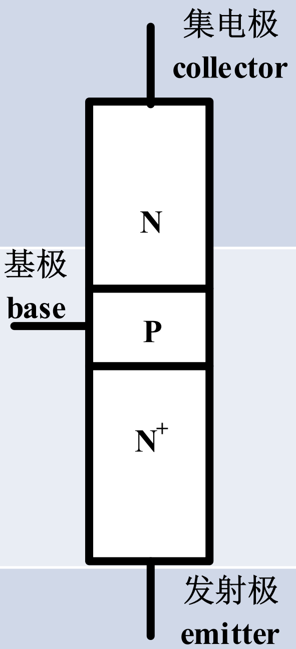
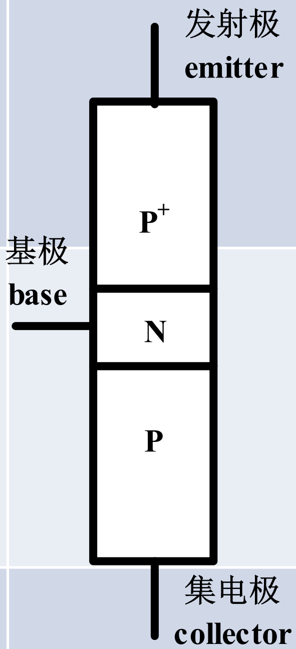
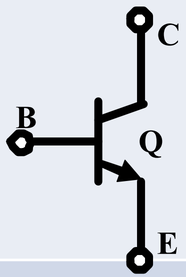
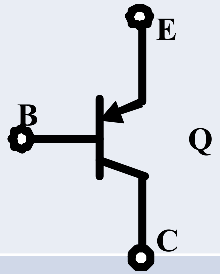
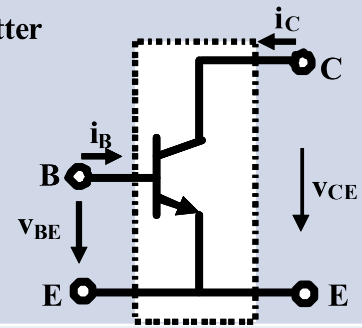
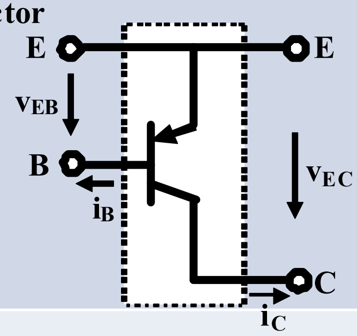
（a）二端口网络表述 （b）直流分析电路模型 （c）交流分析y参量等效电路



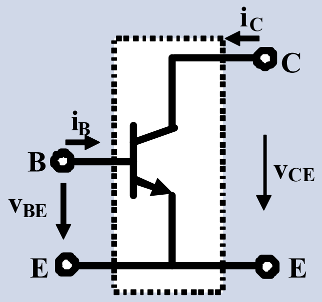
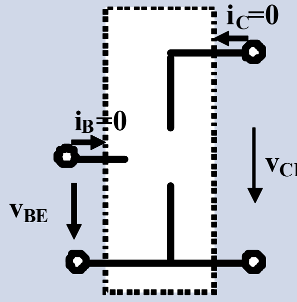
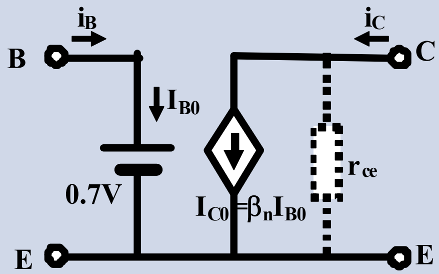
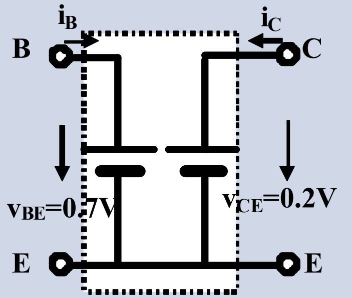
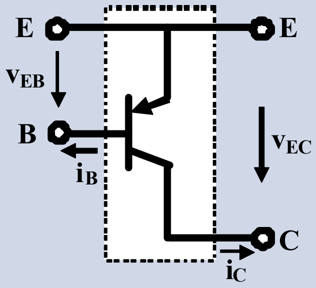
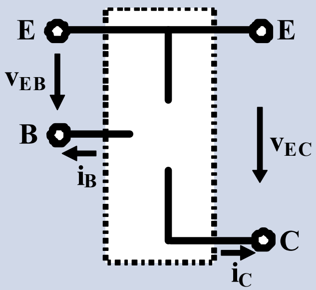
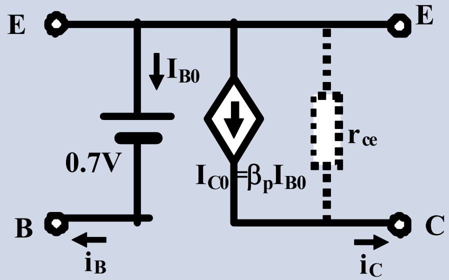
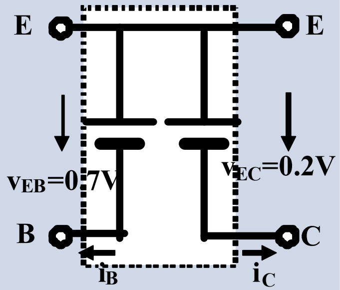




BJT 描述

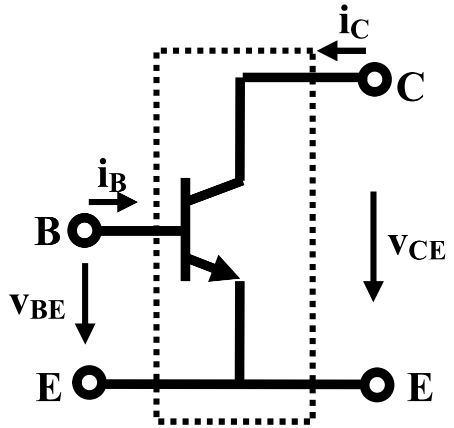
	NPN	PNP
结构		
电路符号		
二端口定义		
有源区元件约束	$\begin{cases} i_B = A_J J_{BS0,n}\left(e^{\frac{v_{BE}}{v_T}} - 1\right) \\ i_C = \beta_n A_J J_{BS0,n}\left(e^{\frac{v_{BE}}{v_T}} - 1\right)\left(1 + \frac{v_{CE}}{V_{A,n}}\right) \end{cases}$	$\begin{cases} i_B = A_J J_{BS0,p}\left(e^{\frac{v_{EB}}{v_T}} - 1\right) \\ i_C = \beta_p A_J J_{BS0,p}\left(e^{\frac{v_{EB}}{v_T}} - 1\right)\left(1 + \frac{v_{EC}}{V_{A,p}}\right) \end{cases}$

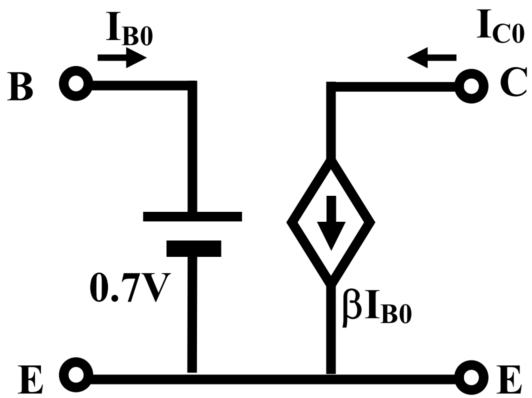
BJT分区描述

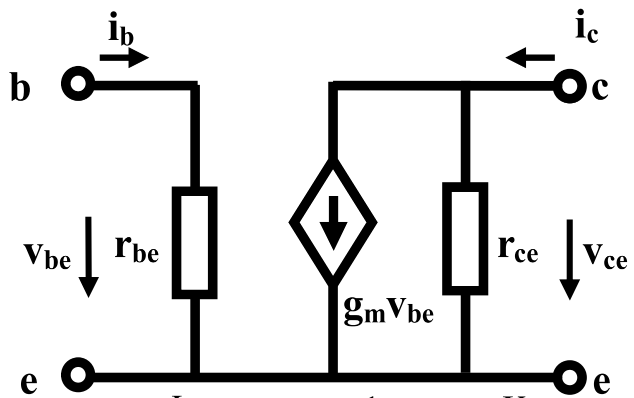
	二端口定义	截止区	有源区（恒流区）	饱和区
NPN 电路符号				
端口描述	$\begin{bmatrix} v_{BE}, i_B \\ v_{CE}, i_C \end{bmatrix}$	**BE**结反偏，**BC**结反偏 $v_{BE} < 0.7V, i_B = 0$ $v_{CE} > 0, i_C = 0$	**BE**结正偏，**BC**结反偏 $v_{BE} = 0.7V, i_B > 0$ $v_{CE} > v_{CE,sat}, i_C = \beta_n i_B$	**BE**结正偏，**BC**结正偏 $v_{BE} = 0.7V, i_B > 0$ $v_{CE} = v_{CE,sat}, i_C < \beta_n i_B$
PNP 电路符号				
端口描述	$\begin{bmatrix} v_{EB}, i_B \\ v_{EC}, i_C \end{bmatrix}$	**EB**结反偏，**CB**结反偏 $v_{EB} < 0.7V, i_B = 0$ $v_{EC} > 0, i_C = 0$	**EB**结正偏，**CB**结反偏 $v_{EB} = 0.7V, i_B > 0$ $v_{EC} > v_{EC,sat}, i_C = \beta_p i_B$	**EB**结正偏，**CB**结正偏 $v_{EB} = 0.7V, i_B > 0$ $v_{EC} = v_{EC,sat}, i_C < \beta_p i_B$

恒流区交直流分析电路模型

$$\mathbf{y}_{BJT}=\begin{bmatrix} g_{be} & 0 \\ g_m & g_{ce} \end{bmatrix}$$

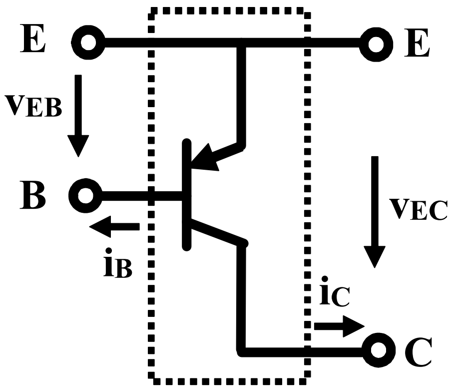


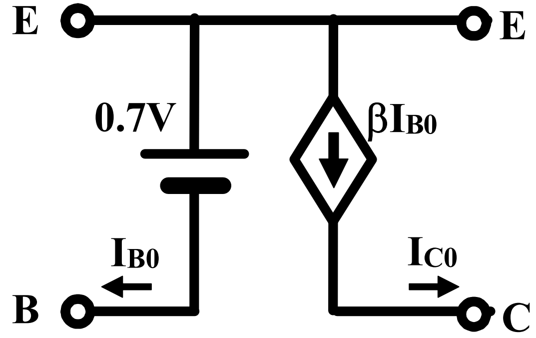


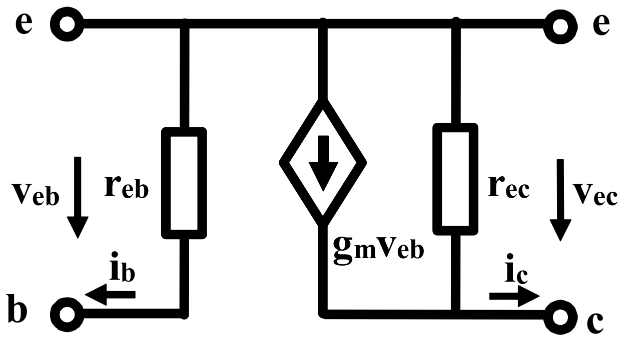


$$g_m \approx \frac{I_{C0}}{v_T}, r_{be} \approx \beta \frac{1}{g_m}, r_{ce} \approx \frac{V_A}{I_{C0}}$$

（a）二端口网络表述 （b）直流分析电路模型 （c）交流分析y参量等效电路

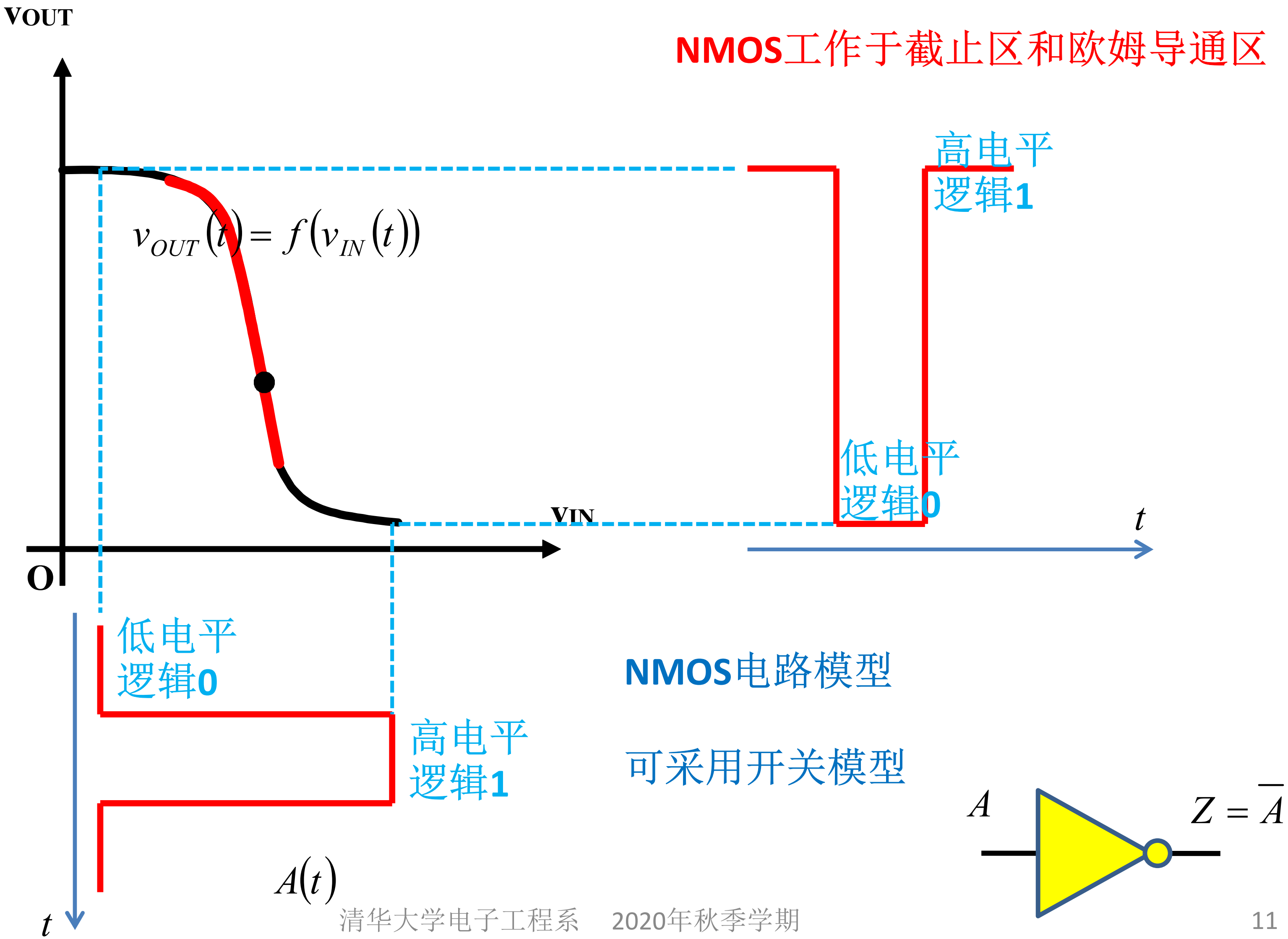






1.2 反相器电路
反相特性及其数字非门应用

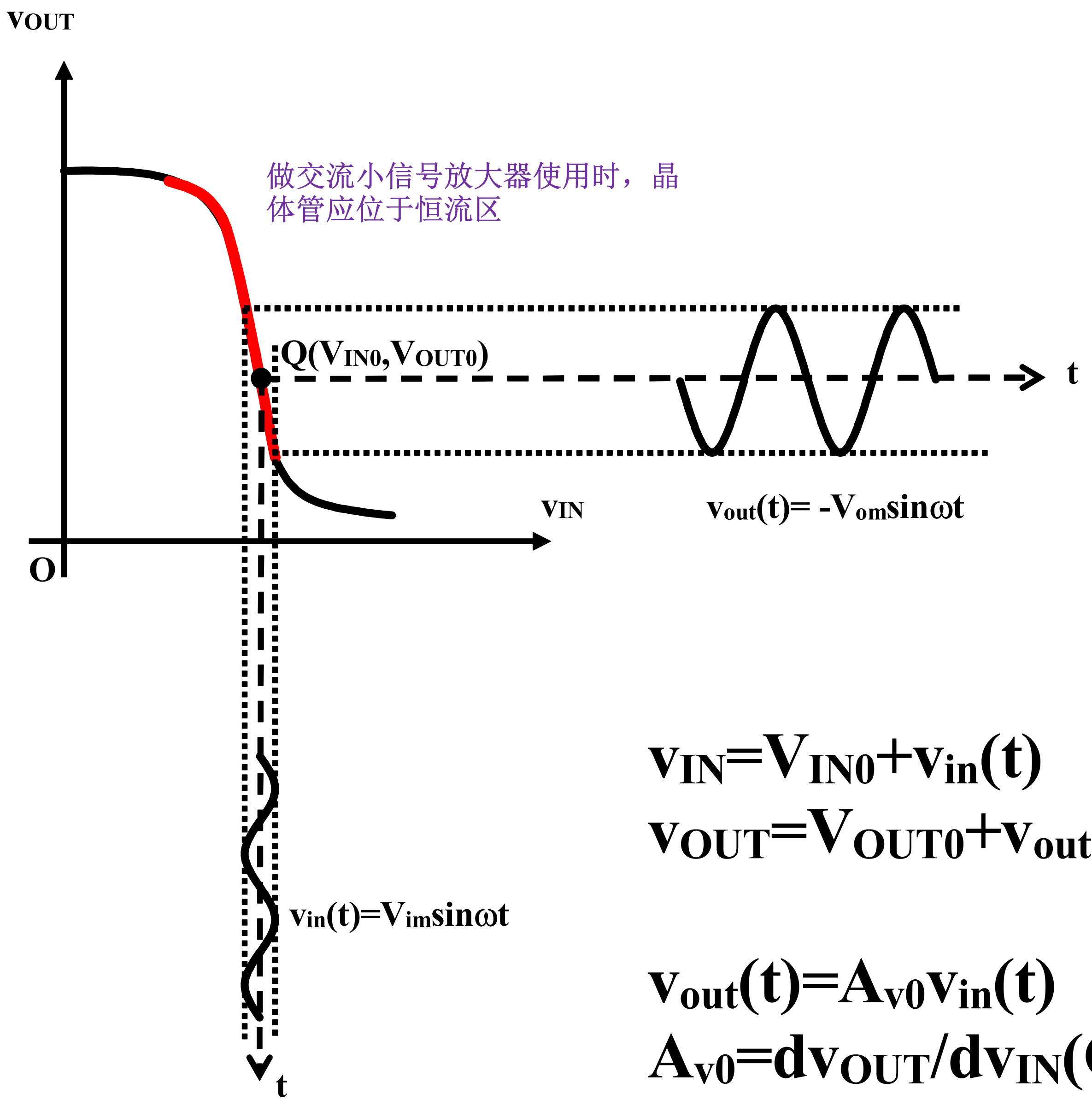
NMOS工作于截止区和欧姆导通区



NMOS电路模型

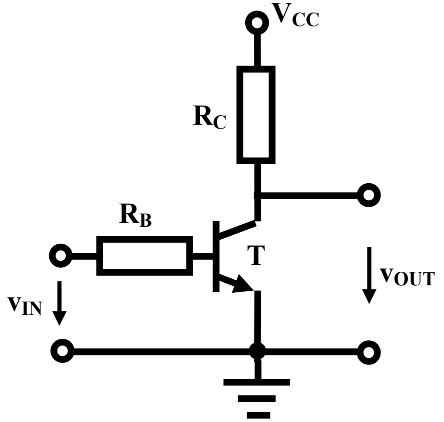
可采用开关模型

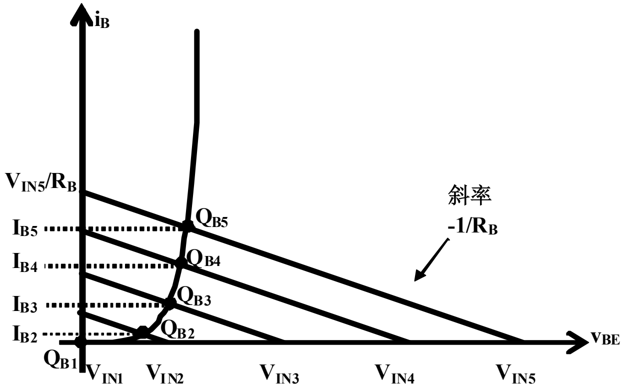
反相特性及其反相放大应用

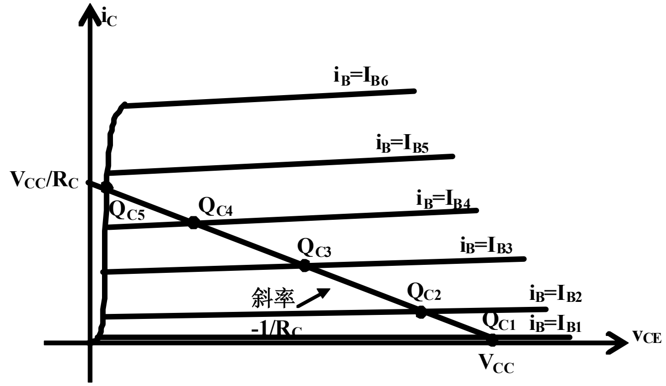


$$v_{IN}=V_{IN0}+v_{in}(t)$$
$$v_{OUT}=V_{OUT0}+v_{out}(t)$$

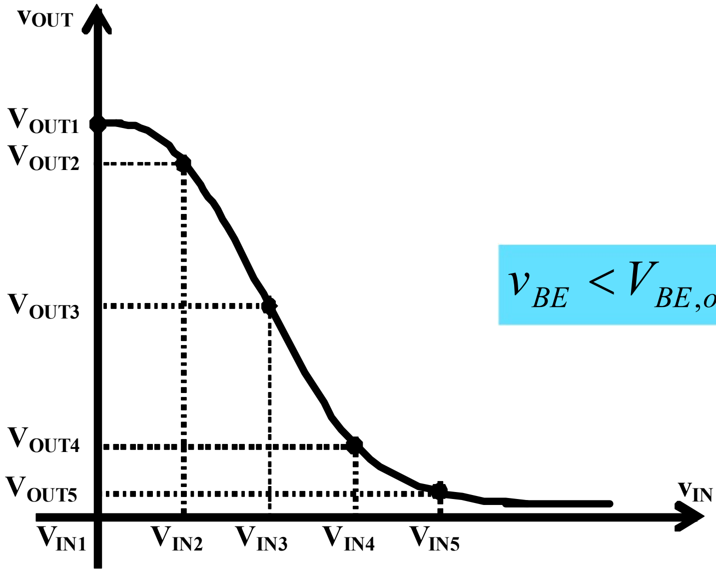
$$v_{out}(t)=A_{v0}v_{in}(t)$$
$$A_{v0}=dv_{OUT}/dv_{IN}(Q)<0$$



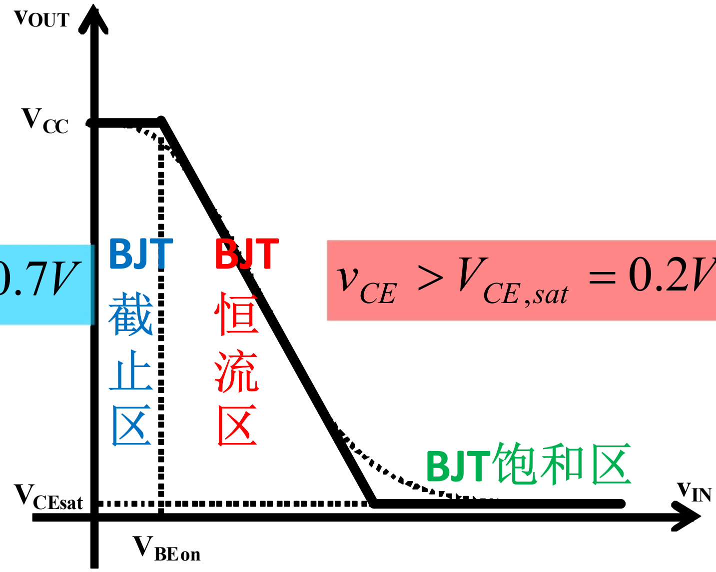




NPN-BJT反相器



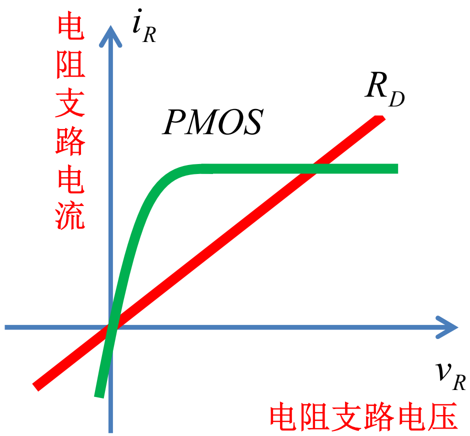
$v_{BE} < V_{BE,on} = 0.7V$

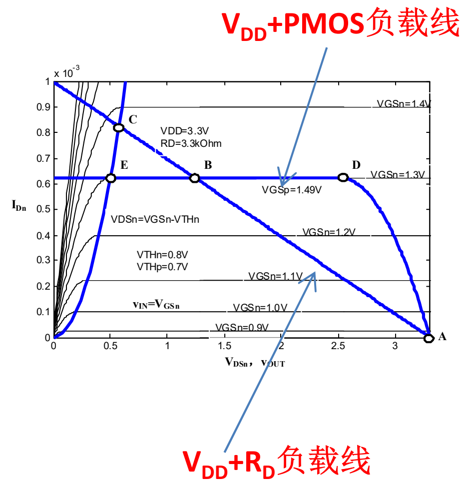


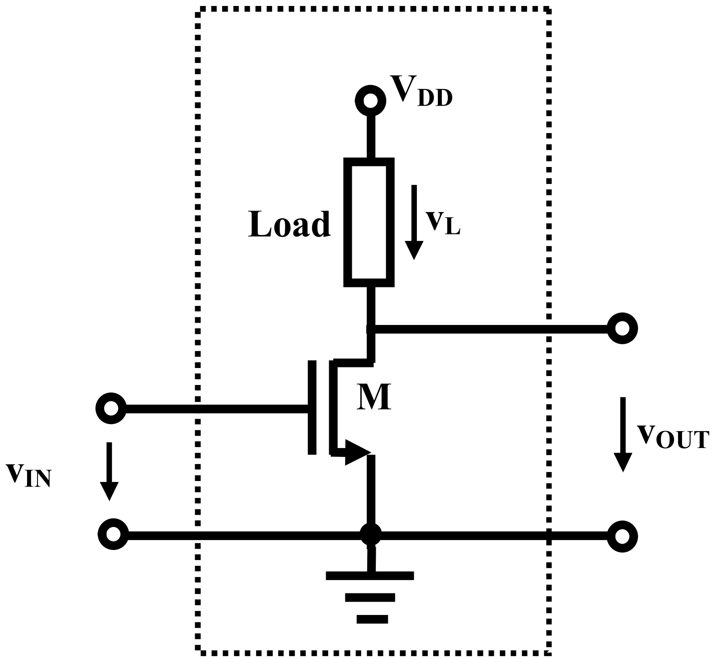
$v_{CE} > V_{CE,sat} = 0.2V$

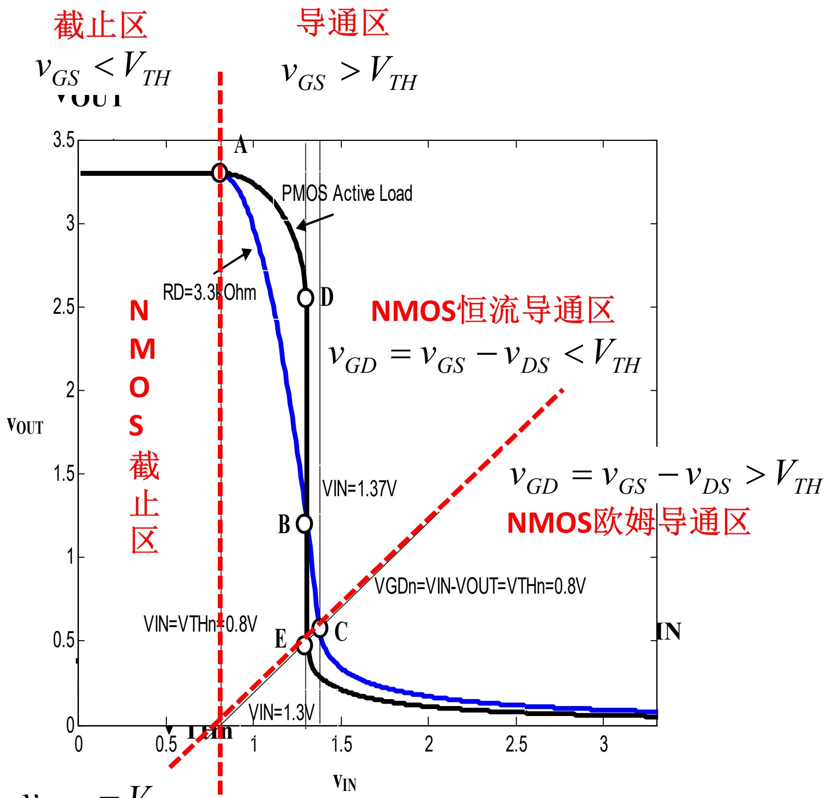
$v_{CE} = V_{CE,sat} = 0.2V$

NMOS反相器







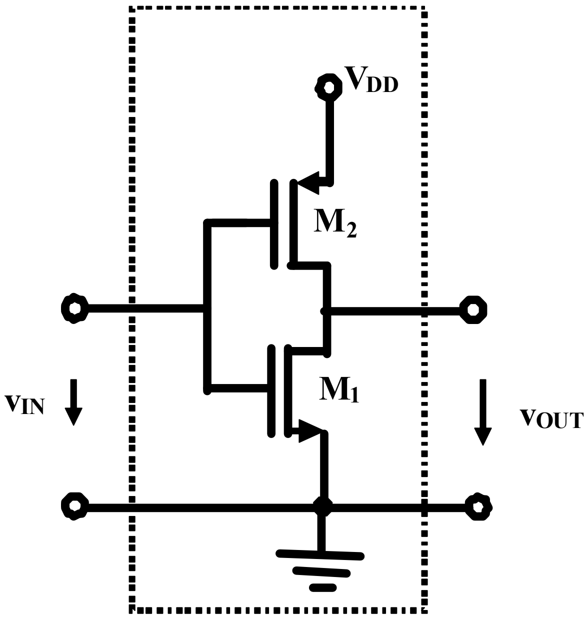


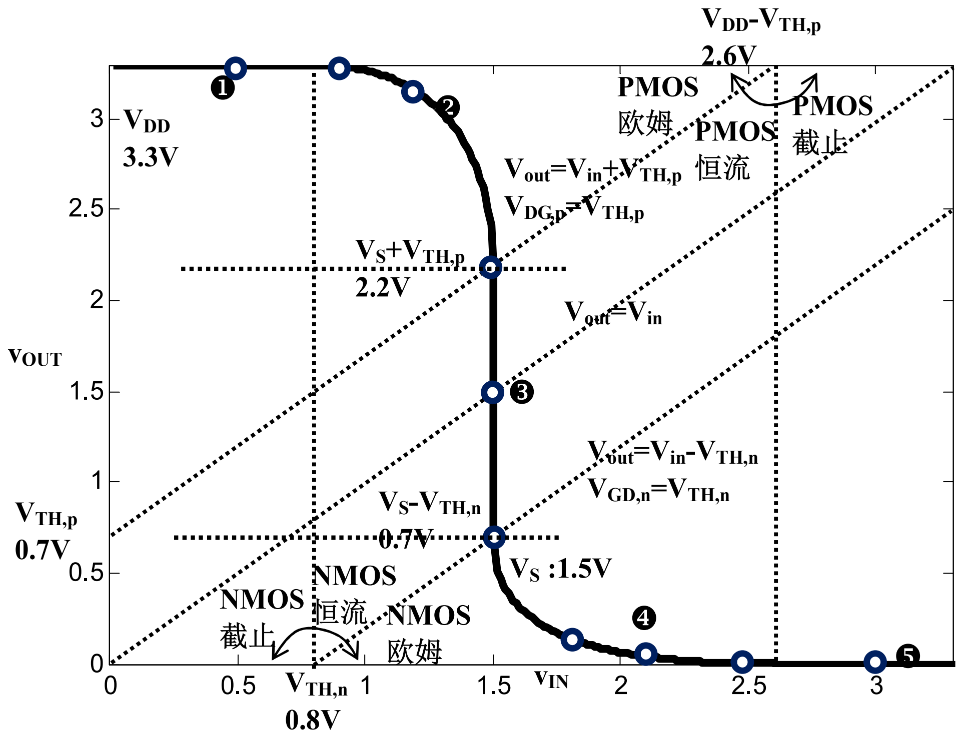
$v_{GD} = v_{IN} - v_{OUT} = V_{TH}$

$v_{IN} = V_{TH}$

晶体管位于恒流区，反相特性有剧烈的变化：斜率最大区位于晶体管恒流区，做交流小信号放大器使用时，晶体管应位于恒流区

CMOS反相器

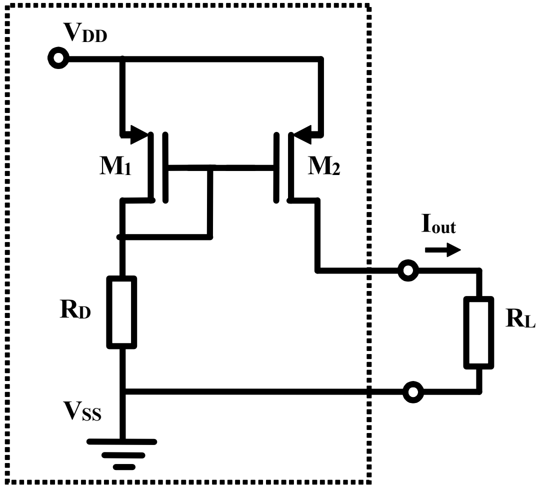


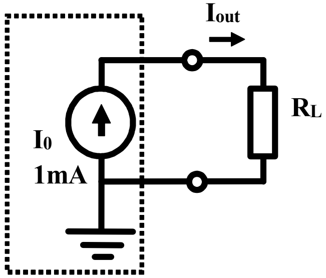


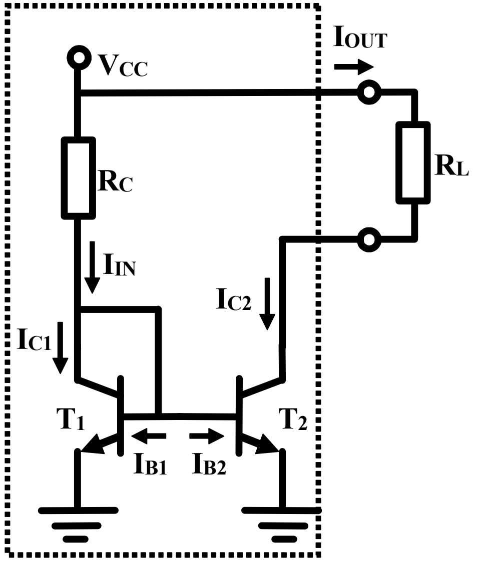
CMOS反相器主要用于数字非门：低功耗

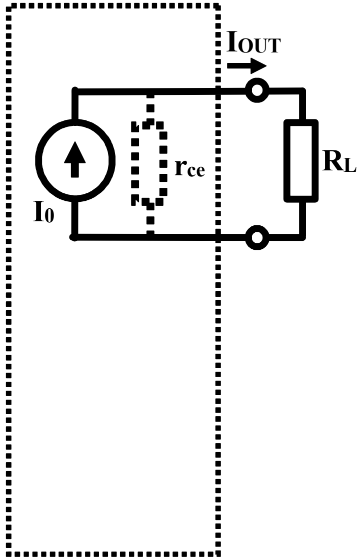
在逻辑0，1状态，两个晶体管中有一个是截止的，故而无静态功耗

1.3 电流镜电路









$$\frac{I_{D2}}{I_{D1}} = \frac{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_2 (V_{SG2} - V_{TH})^2 \left(1 + \frac{V_{SD2}}{V_E}\right)}{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_1 (V_{SG1} - V_{TH})^2 \left(1 + \frac{V_{SD1}}{V_E}\right)}$$

$$= \frac{\left(\frac{W}{L}\right)_2 \left(1 + \frac{V_{SD2}}{V_E}\right)}{\left(\frac{W}{L}\right)_1 \left(1 + \frac{V_{SD1}}{V_E}\right)} \approx \frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

$$\frac{I_{OUT}}{I_{IN}} = \frac{I_{C2}}{I_{C1} + I_{B1} + I_{B2}} \approx \frac{I_{C2}}{I_{C1}}$$

$$= \frac{\beta A_{J2} J_{BS0} \cdot \left(e^{\frac{V_{BE2}}{v_T}} - 1\right)\left(1 + \frac{V_{CE2}}{V_A}\right)}{\beta A_{J1} J_{BS0} \cdot \left(e^{\frac{V_{BE1}}{v_T}} - 1\right)\left(1 + \frac{V_{CE1}}{V_A}\right)} \approx \frac{A_{J2}}{A_{J1}}$$

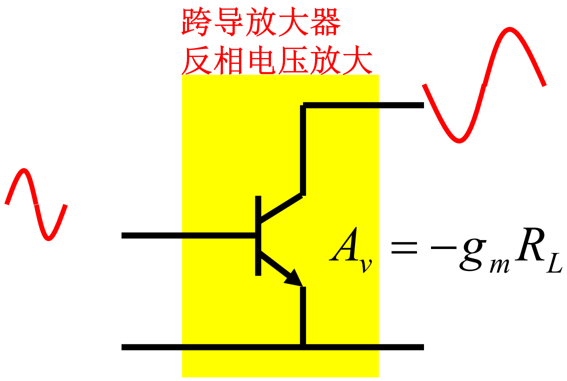
电流镜原理

- 电流镜电路利用的是同工艺同基片位置同时完成制作的晶体管的一致性，两晶体管的工艺参量可以对消，从而电流电量之比完全由晶体管尺寸之比决定，也就实现了相对精准的电流控制

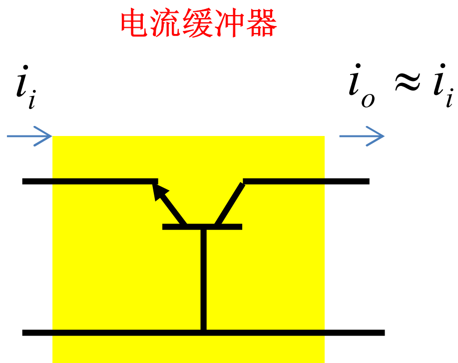
- 电流镜电路是集成电路的特征电路之一

1.4 三种组态

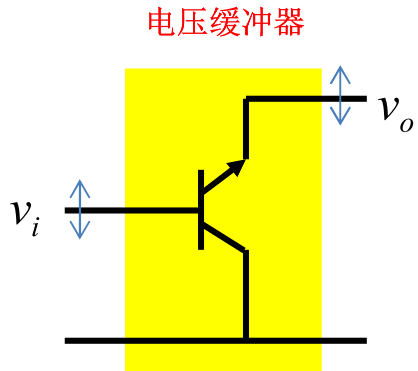
晶体管位于恒流导通区



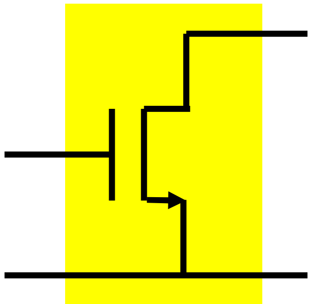
Common Emitter
CE： 共射组态



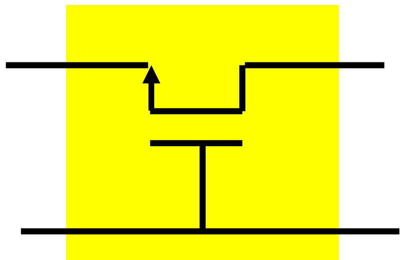
Common Base
CB： 共基组态



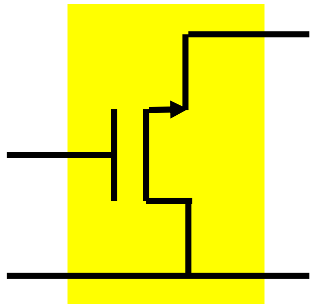
Common Collector
CC： 共集组态



Common Source
CS： 共源组态



Common Gate
CG： 共栅组态

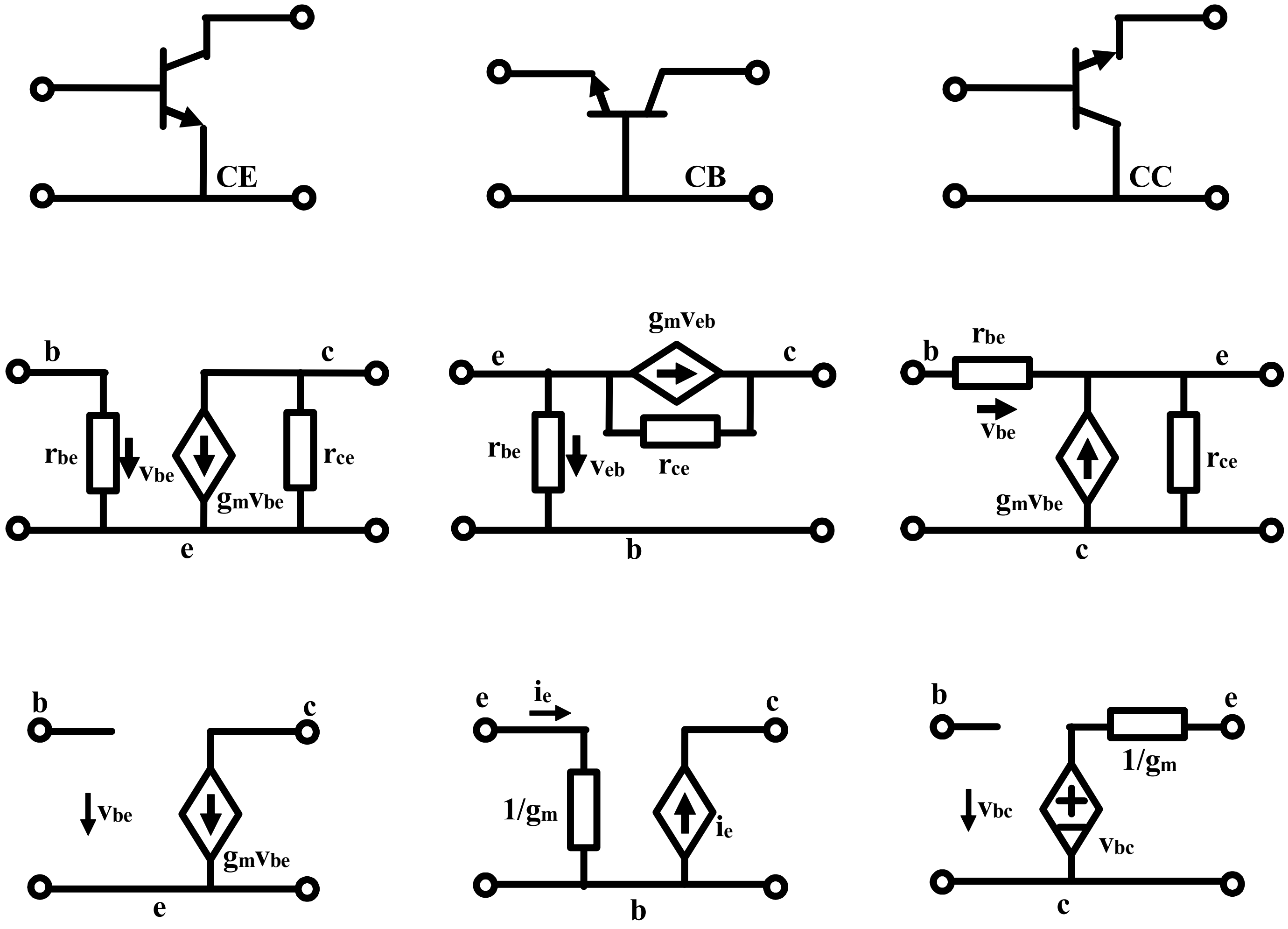


Common Drain
CD： 共漏组态

三种组态放大器基本参量

	CE	CB	CC
输入阻抗	r_{be}	$r_{be} \parallel \dfrac{R_L + r_{ce}}{1 + g_m r_{ce}}$	$r_{be} + r_{ce} \parallel R_L + g_m r_{be}\left(r_{ce} \parallel R_L\right)$
输出阻抗	r_{ce}	$r_{be} \parallel R_S + r_{ce} + g_m\left(r_{be} \parallel R_S\right) r_{ce}$	$r_{ce} \parallel \dfrac{r_{be} + R_S}{1 + g_m r_{be}}$
最大功率增益	$\dfrac{1}{4} g_m r_{ce} \cdot \beta$	$\sim\prec g_m r_{ce}$	$\sim\prec \beta = g_m r_{be}$
理想模型	反相跨导 **G_{m0} =-g_m**	电流缓冲 **A_{i0}=1**	电压缓冲 **A_{v0}=1**
输入输出阻抗	r_{be} r_{ce}	$r_{in} \approx 1/g_m$	$r_{out} \approx 1/g_m$
单向化条件		$R_L \ll r_{ce}$ 充分非必要	$R_S \ll r_{be}$

跨导器模型及其简化



R_s<<r_{be}， R_L<<r_{ce}

R_L<<r_{ce}

R_s<<r_{be}

三种组态

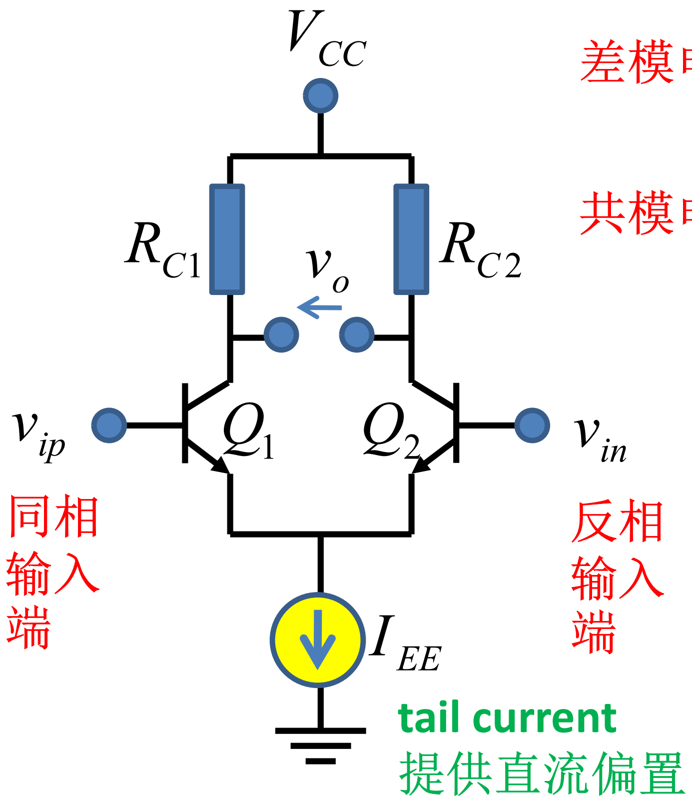
- 晶体管放大器可能是晶体管三种组态之一，也可能是三种组态的组合，或者是三种组态的级联等形态，因此晶体管的三种组态分析是晶体管放大器分析的核心

二、差分对 **Differential Pairs**

- 差分对是集成电路的特征电路之一
  - 数模混合电路必须采用
  - 运放电路的基本单元

- **2.1** 差分对结构
- **2.2 MOSFET**差分对共模特性
- **2.3 MOSFET**差分对差模特性
- **2.4** 小信号电路模型
- **2.5** 双端输出转单端输出
  - 差分电流的合成

2.1 差分对结构

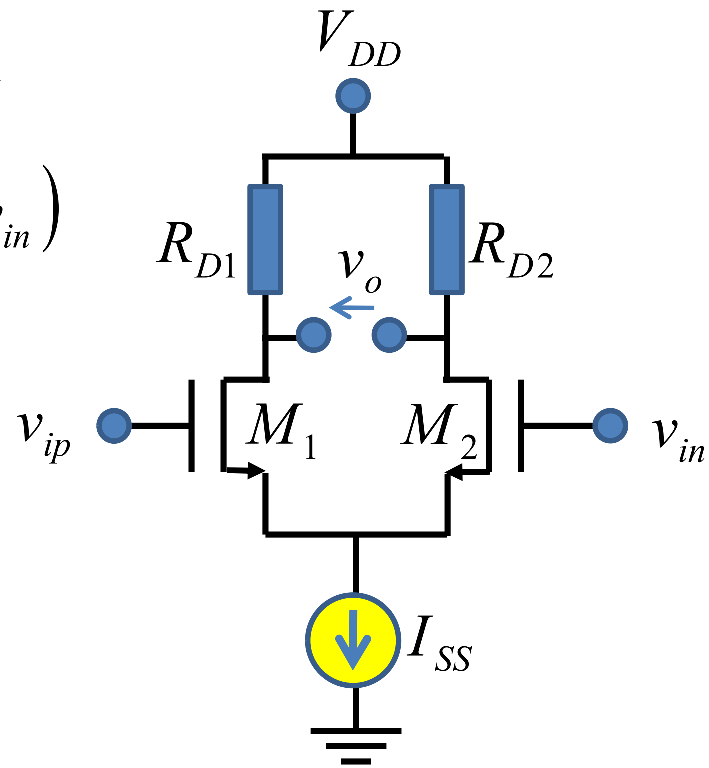


差模电压 $v_{id} = v_{ip} - v_{in}$

共模电压 $v_{ic} = \frac{1}{2}\left(v_{ip} + v_{in}\right)$

$$v_{ip} = v_{ic} + 0.5 v_{id}$$

$$v_{in} = v_{ic} - 0.5 v_{id}$$



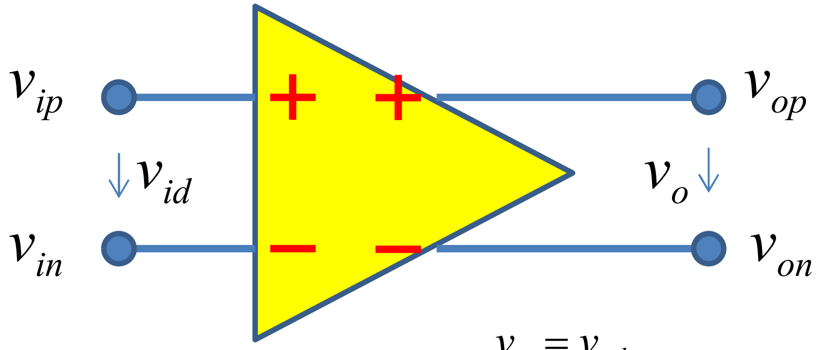
设计中，结构是完全对称的，输出差模电压中，只有对差模输入电压$\mathbf{v_{id}}$的放大，而没有对共模电压$\mathbf{v_{ic}}$的放大，故称差分对

$$v_o = A_{dd} v_{id} + A_{dc} v_{ic} = A_{dd} v_{id} = A_0 v_{id}$$

$$CMRR = 20\log_{10}\left|\frac{A_{dd}}{A_{dc}}\right| \to \infty$$

共模抑制比

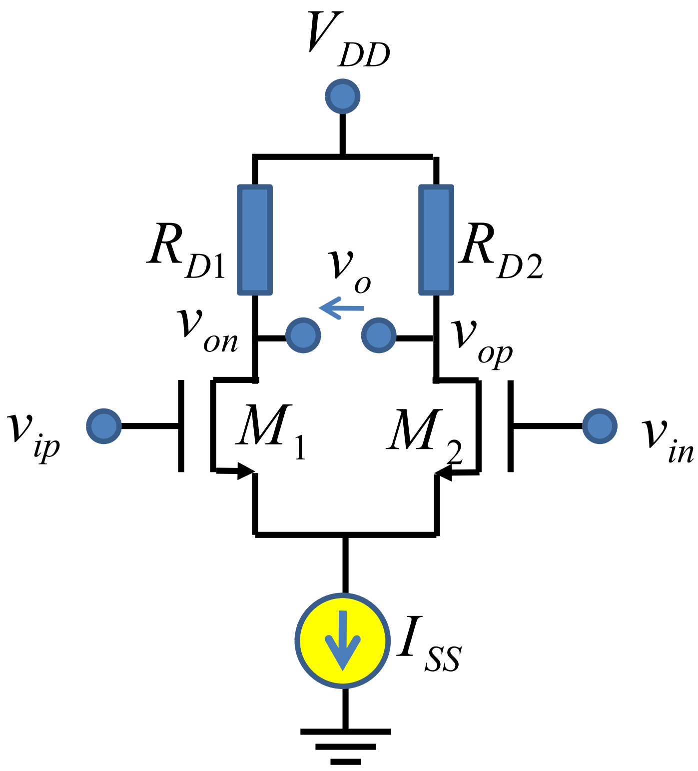
差分端口
共模与差模

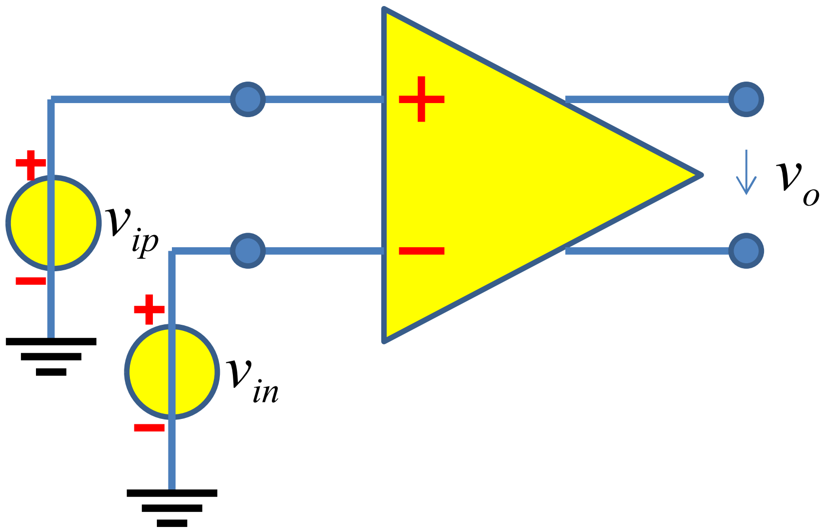


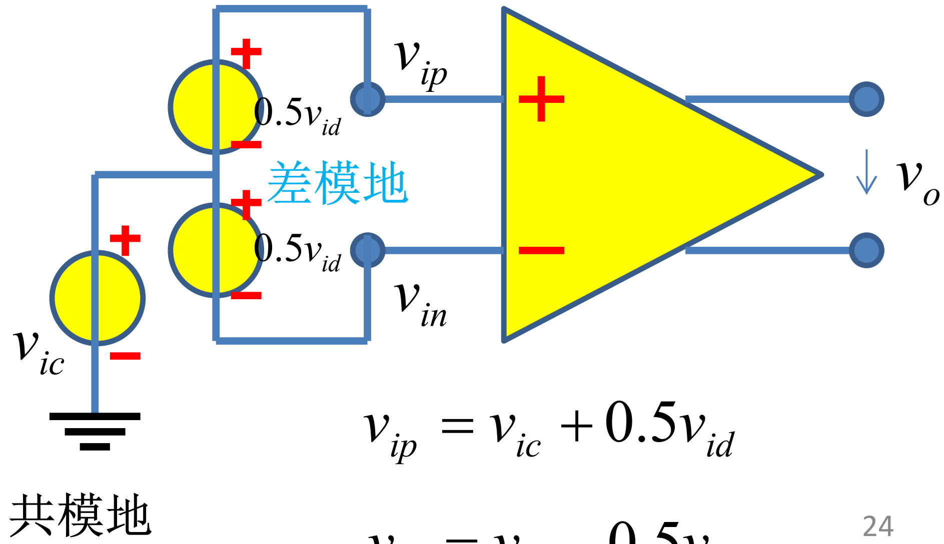
全差分结构

$$v_o = v_{od}$$

$$v_{oc} = V_{DD} - 0.5 I_{SS} R_D$$





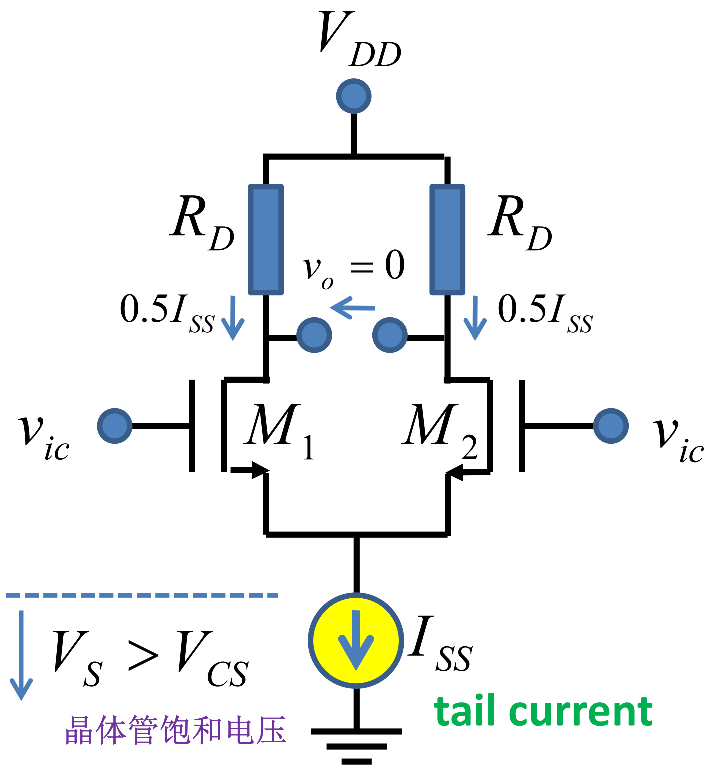


$$v_{ip} = v_{ic} + 0.5v_{id}$$

$$v_{in} = v_{ic} - 0.5v_{id}$$

2.2 MOSFET差分对：共模输入范围

确保所有晶体管均工作在恒流区的共模信号范围



$$v_{ip} = v_{in} = v_{ic} \qquad R_{D1} = R_{D2} = R_D$$

$$0.5I_{SS} = \beta_n V_{od0}^2 \qquad \beta_n = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}$$

直流分析不考虑厄利效应

$$V_{od0} = \sqrt{\frac{I_{SS}}{2\beta_n}} \qquad V_{od} = V_{GS} - V_{TH}$$

$$v_{D1} = v_{D2} = V_{DD} - 0.5I_{SS}R_D$$

$$v_o = v_{D2} - v_{D1} = 0$$

对称差分对不放大共模信号

为了实现有效的差模放大，应确保晶体管始终工作在有源区

$$v_{GD} < V_{TH} \qquad v_{ic} = v_G < v_D + V_{TH} = V_{DD} - 0.5I_{SS}R_D + V_{TH} = V_{I,CM,\max}$$

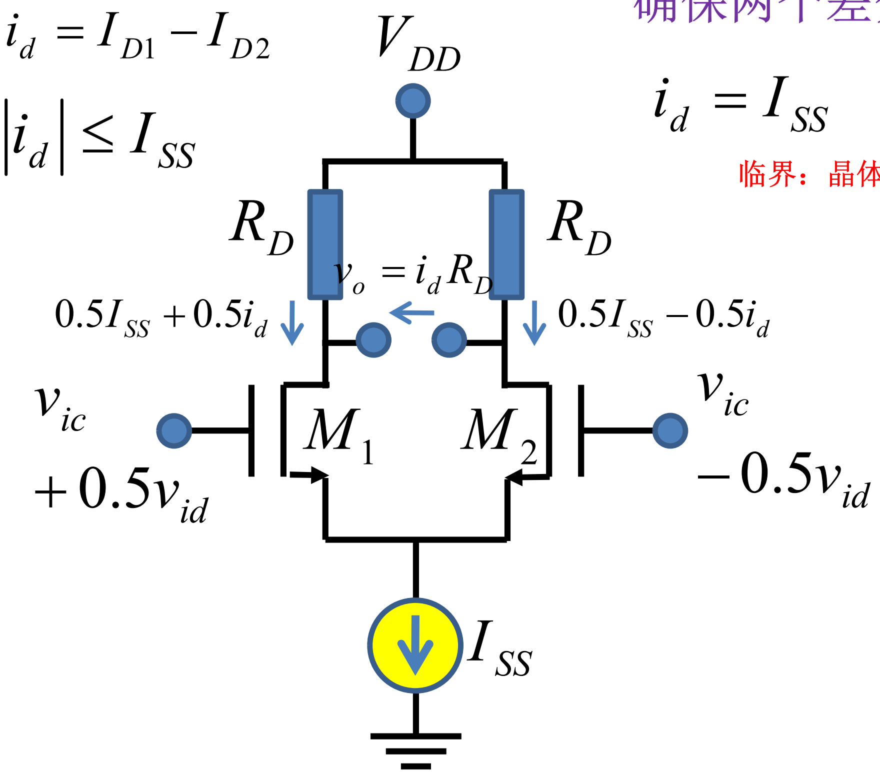
$$v_{ic} = v_G = v_S + V_{GS} > V_{CS} + V_{TH} + V_{od0} = V_{I,CM,\min}$$

2.3 MOSFET差分对：差模输入范围

确保两个差分对管同时工作在恒流区的差模信号范围

$i_d = I_{D1} - I_{D2}$

$|i_d| \le I_{SS}$



$i_d = I_{SS}$ $\quad I_{D1} = I_{SS} = \beta_n V_{od1}^2$ $\quad I_{D2} = 0 = \beta_n V_{od2}^2$

临界：晶体管仍然位于有源区

$V_{od1} = \sqrt{\dfrac{I_{SS}}{\beta_n}}$ $\quad V_{od2} = 0$

$V_{GS2} = V_{TH}$

$$v_{id,\max} = v_{G1} - v_{G2} = v_{GS1} - v_{GS2}$$

$$= V_{od1} - V_{od2} = \sqrt{\frac{I_{SS}}{\beta_n}} = \sqrt{2} V_{od0}$$

$v_{id} > +v_{id,\max}$

M$_1$恒流 $I_{D1} = I_{SS}$, $V_{GS1} = \sqrt{2}V_{od0} + V_{TH}$

M$_2$截止 $I_{D2} = 0$, $V_{GS2} < V_{TH}$

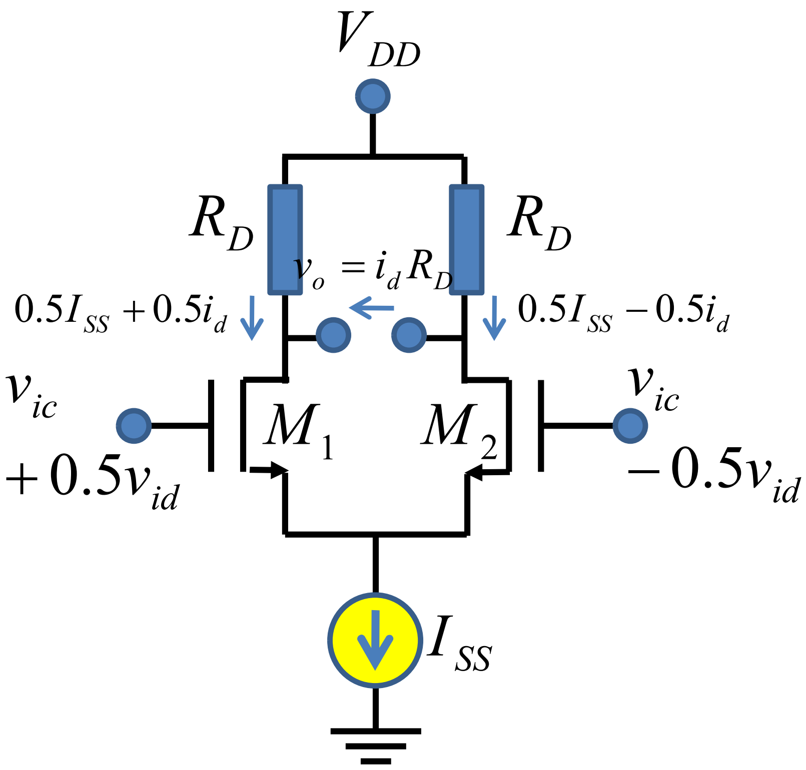
$v_{id} < -v_{id,\max}$

M$_1$截止 $I_{D1} = 0$, $V_{GS1} < V_{TH}$

M$_2$恒流 $I_{D2} = I_{SS}$, $V_{GS2} = \sqrt{2}V_{od0} + V_{TH}$

在共模、差模信号范围内，差分对管工作在恒流区

大信号电流电压转移关系



$$V_{GS1}-V_{GS2}=v_{id}$$

$$|v_{id}| \le +v_{id,\max} = \sqrt{2}V_{od0}$$

$$i_d \le I_{SS}$$

$$0.5I_{SS}+0.5i_d = \beta_n\left(V_{GS1}-V_{TH}\right)^2$$

$$0.5I_{SS}-0.5i_d = \beta_n\left(V_{GS2}-V_{TH}\right)^2$$

晶体管工作在恒流区

$$V_{GS1}-V_{TH} = \sqrt{\frac{0.5I_{SS}+0.5i_d}{\beta_n}}$$

$$V_{GS2}-V_{TH} = \sqrt{\frac{0.5I_{SS}-0.5i_d}{\beta_n}}$$

大信号跨导转移特性

$$V_{GS1} = \sqrt{\frac{I_{SS} + i_d}{2\beta_n}} + V_{TH} \qquad V_{GS2} = \sqrt{\frac{I_{SS} - i_d}{2\beta_n}} + V_{TH}$$

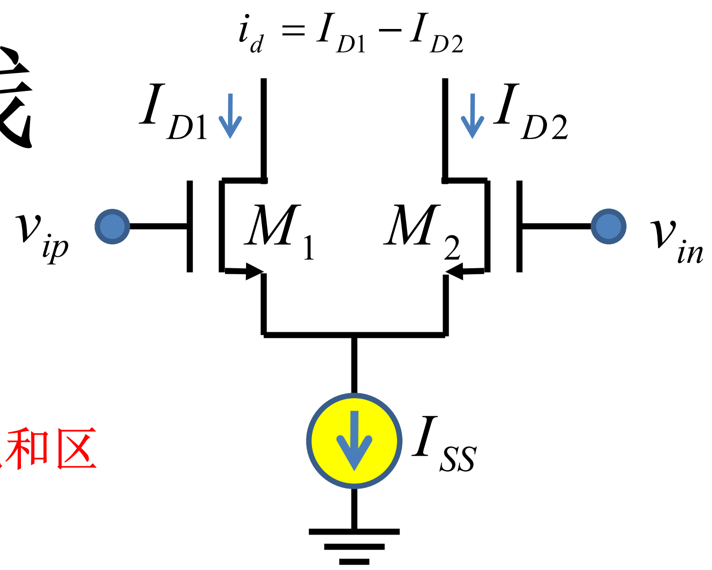
$$V_{GS1} - V_{GS2} = v_{id}$$

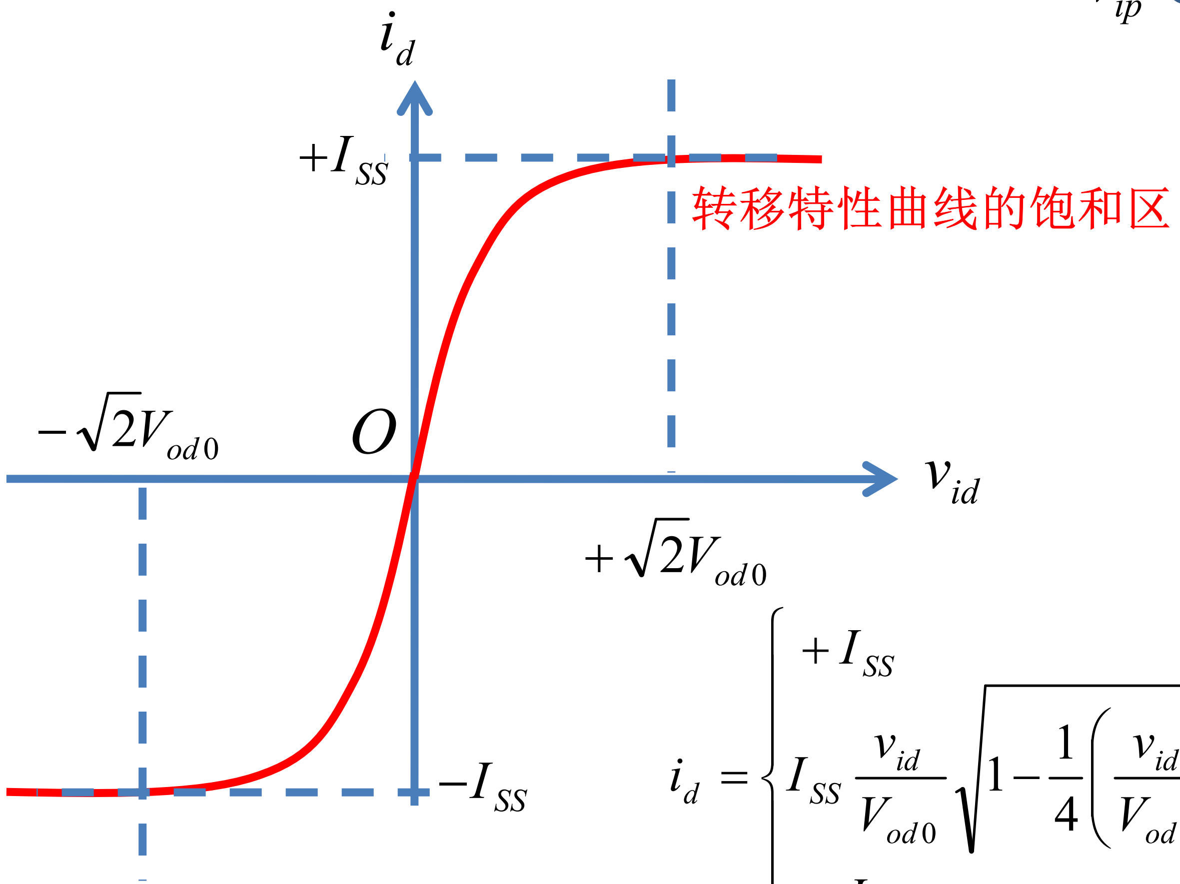
$$v_{id} = \sqrt{\frac{I_{SS} + i_d}{2\beta_n}} - \sqrt{\frac{I_{SS} - i_d}{2\beta_n}} = \sqrt{V_{od0}^2 + \frac{i_d}{2\beta_n}} - \sqrt{V_{od0}^2 - \frac{i_d}{2\beta_n}}$$

$$i_d = \beta_n v_{id} \sqrt{4V_{od0}^2 - v_{id}^2} = I_{SS} \frac{v_{id}}{V_{od0}} \sqrt{1 - \frac{1}{4}\left(\frac{v_{id}}{V_{od0}}\right)^2}$$

$$\left|v_{id}\right| \le +v_{id,\max} = \sqrt{2} V_{od0} = \sqrt{\frac{I_{SS}}{\beta_n}} \qquad V_{od0} = \sqrt{\frac{I_{SS}}{2\beta_n}}$$

非线性转移特性曲线



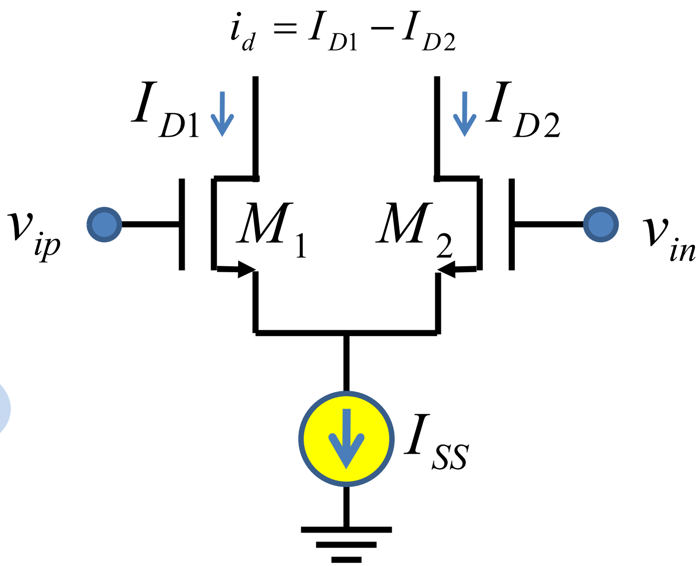


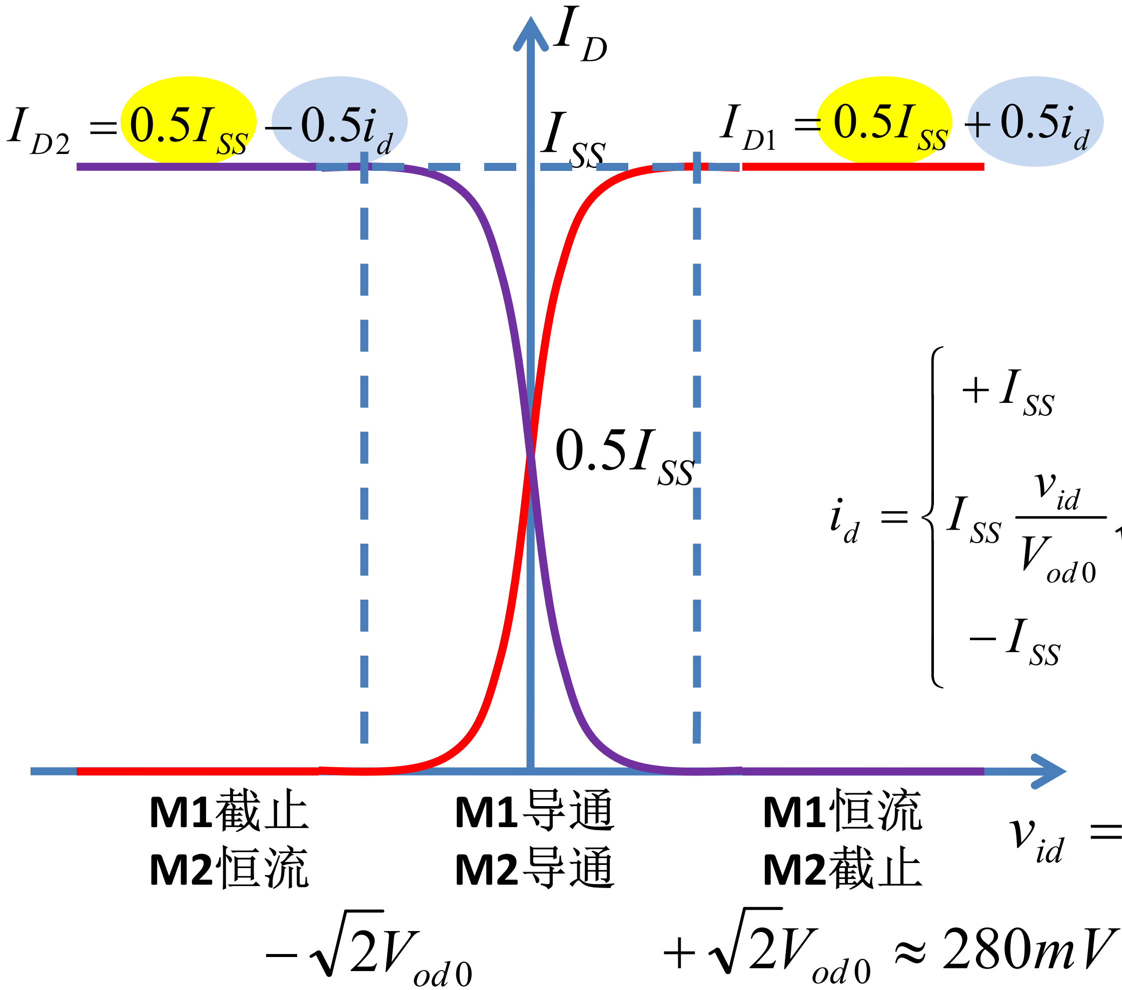
$V_E \to \infty$ 忽略厄利效应

$$i_d = \begin{cases} +I_{SS} & v_{id} \ge +\sqrt{2}V_{od0} \\ I_{SS}\dfrac{v_{id}}{V_{od0}}\sqrt{1-\dfrac{1}{4}\left(\dfrac{v_{id}}{V_{od0}}\right)^2} & |v_{id}| \le \sqrt{2}V_{od0} \\ -I_{SS} & v_{id} \le -\sqrt{2}V_{od0} \end{cases}$$

$$V_{od0} = \sqrt{\frac{I_{SS}}{2\beta_n}}$$

MOSFET差分对双管工作状态





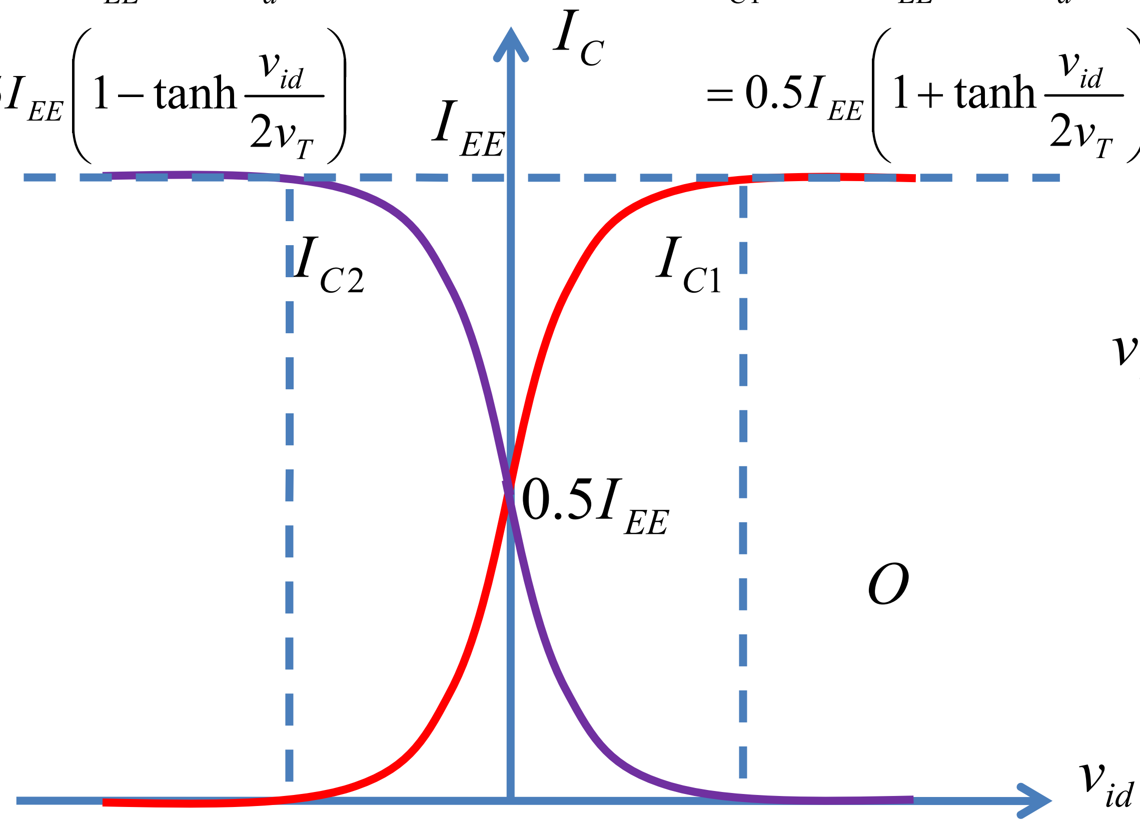
$$
i_d = \begin{cases} +I_{SS} & v_{id} \geq +\sqrt{2}V_{od0} \\ I_{SS}\dfrac{v_{id}}{V_{od0}}\sqrt{1-\dfrac{1}{4}\left(\dfrac{v_{id}}{V_{od0}}\right)^2} & |v_{id}| \leq \sqrt{2}V_{od0} \\ -I_{SS} & v_{id} \leq -\sqrt{2}V_{od0} \end{cases}
$$

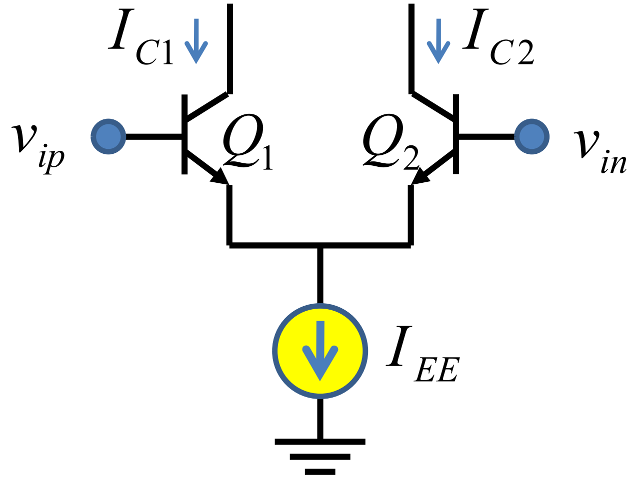
$$
V_{od0} = \sqrt{\frac{I_{SS}}{2\beta_n}}
$$

BJT差分对电流电压转移特性曲线

$$I_{C2}=0.5I_{EE}-0.5i_d=0.5I_{EE}\left(1-\tanh\frac{v_{id}}{2v_T}\right)$$

$$I_{C1}=0.5I_{EE}+0.5i_d=0.5I_{EE}\left(1+\tanh\frac{v_{id}}{2v_T}\right)$$





Q1截止 Q2恒流	Q1导通 Q2导通	Q1恒流 Q2截止

$-4.6v_T$

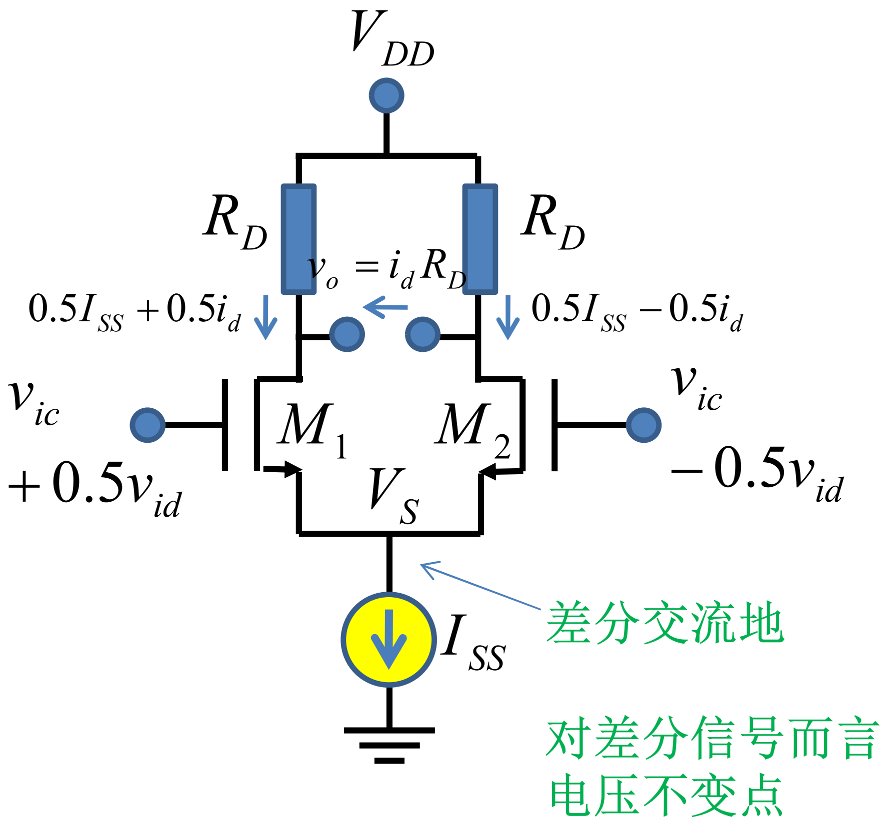
$+4.6v_T\approx 120mV$

$\tanh 2.3=0.98$

$$i_d=I_{C1}-I_{C2}=I_{EE}\tanh\frac{v_{id}}{2v_T}$$

作业2：推导该公式

2.4 差分对的源极电压不变？



$$V_{GS1}-V_{TH}=\sqrt{\frac{0.5I_{SS}+0.5i_d}{\beta_n}}$$

$$V_{GS2}-V_{TH}=\sqrt{\frac{0.5I_{SS}-0.5i_d}{\beta_n}}$$

$$v_{ic}-V_S-V_{TH}=\frac{1}{2}\left(\sqrt{\frac{I_{SS}+i_d}{2\beta_n}}+\sqrt{\frac{I_{SS}-i_d}{2\beta_n}}\right)$$

$$V_S=v_{ic}-V_{TH}-\frac{V_{od0}}{2}\left(\sqrt{1+\frac{i_d}{I_{SS}}}+\sqrt{1-\frac{i_d}{I_{SS}}}\right)$$

$$V_{od0}=\sqrt{\frac{I_{SS}}{2\beta_n}}$$

$$|v_{id}|\le\sqrt{2}V_{od0}$$

上述公式推导的前提条件

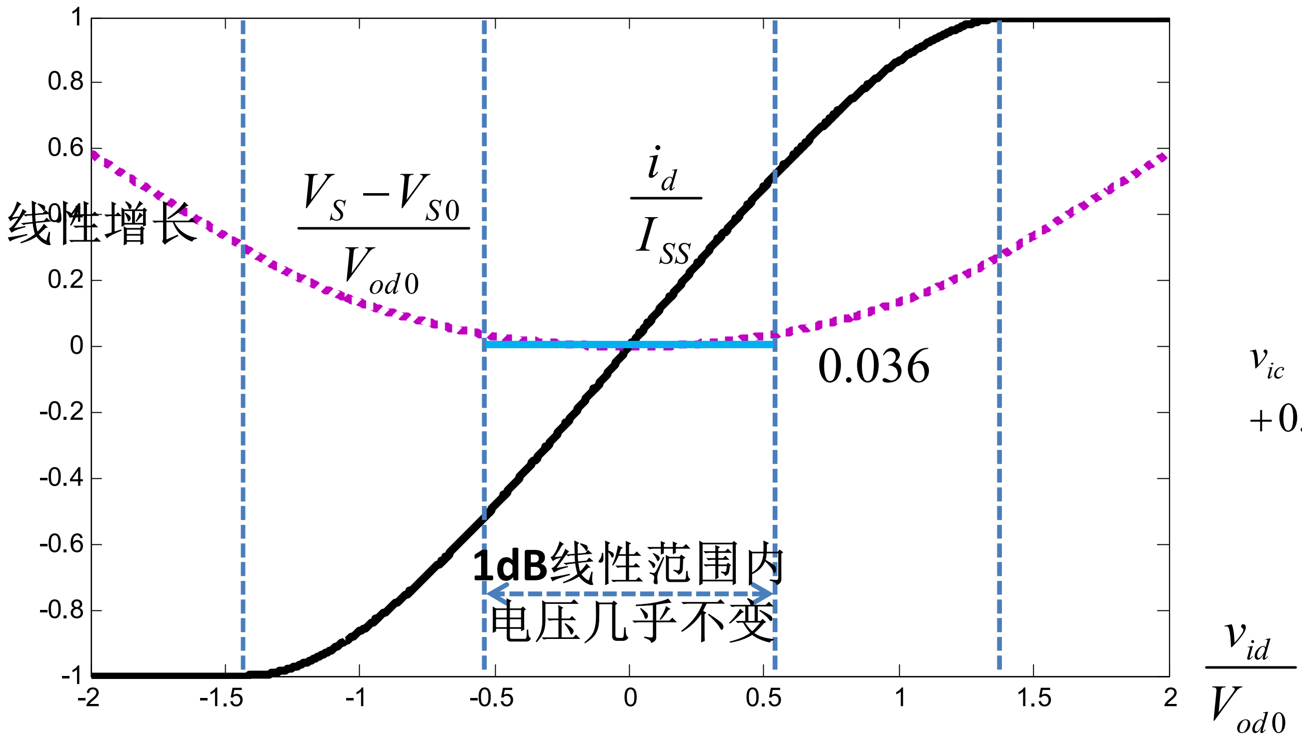
$$V_{S0}=v_{ic}-V_{TH}-V_{od0}$$

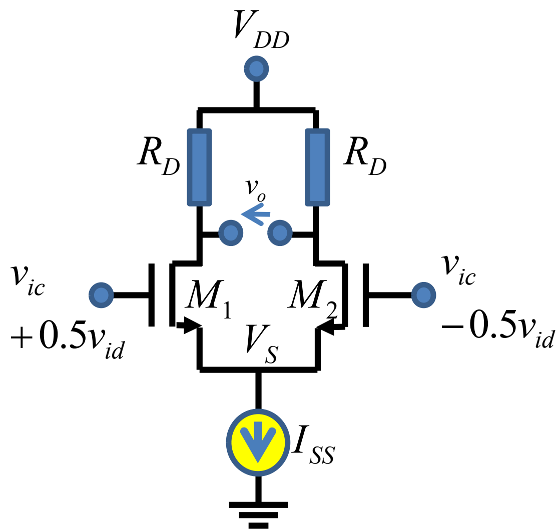
$$V_S = V_{S0} + \frac{V_{od0}}{2}\left(2 - \sqrt{1 + \frac{i_d}{I_{SS}}} - \sqrt{1 - \frac{i_d}{I_{SS}}}\right)$$

$$|v_{id}| \le \sqrt{2}V_{od0}$$

$$i_d = I_{SS}\frac{v_{id}}{V_{od0}}\sqrt{1 - \frac{1}{4}\left(\frac{v_{id}}{V_{od0}}\right)^2}$$

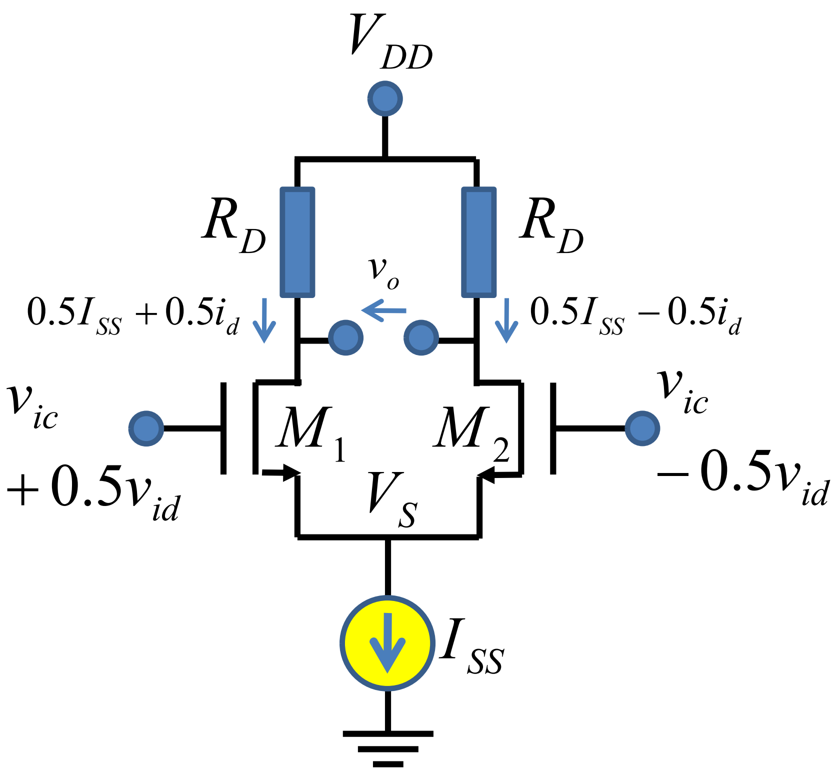
作业4：求1dB线性范围

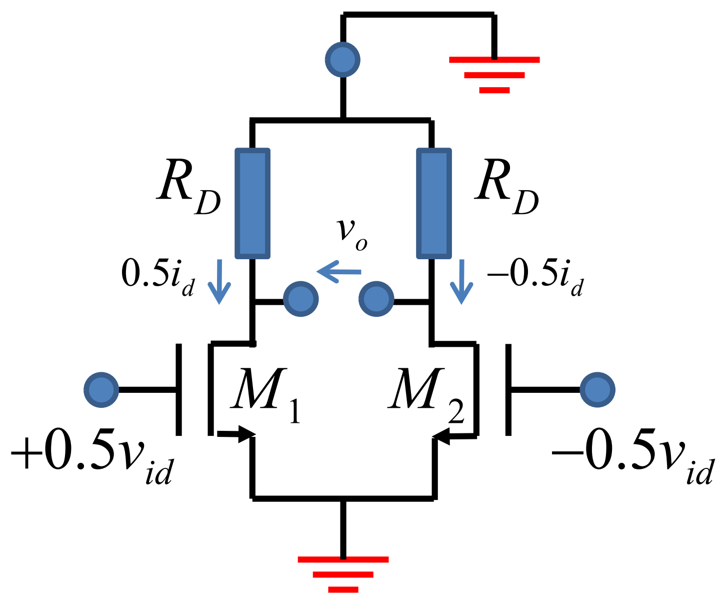




线性范围内，差分对源极视为差模交流地

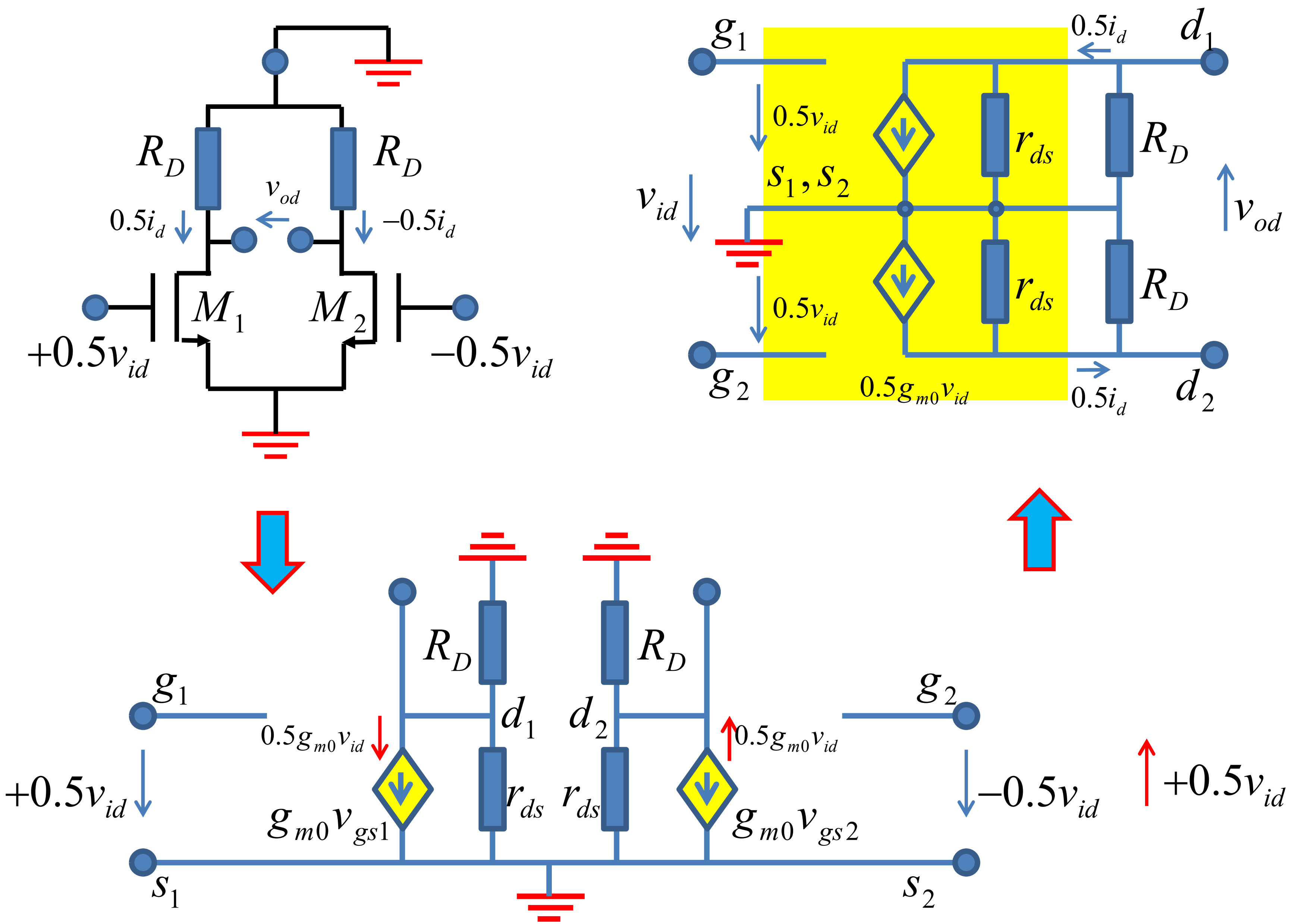
$$\left|v_{id}\right| \le 0.53V_{od0} \qquad V_S - V_{S0} \le 0.036V_{od0} \qquad V_S \approx V_{S0}$$





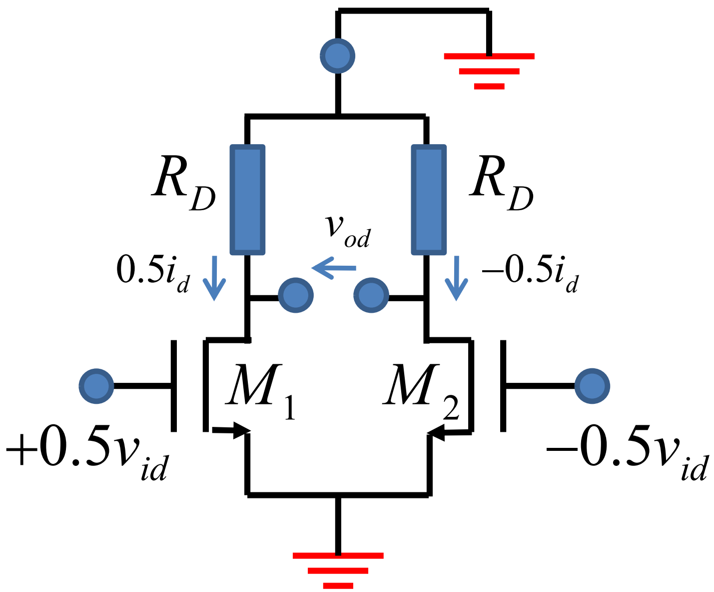
差模放大器：差模交流小信号分析

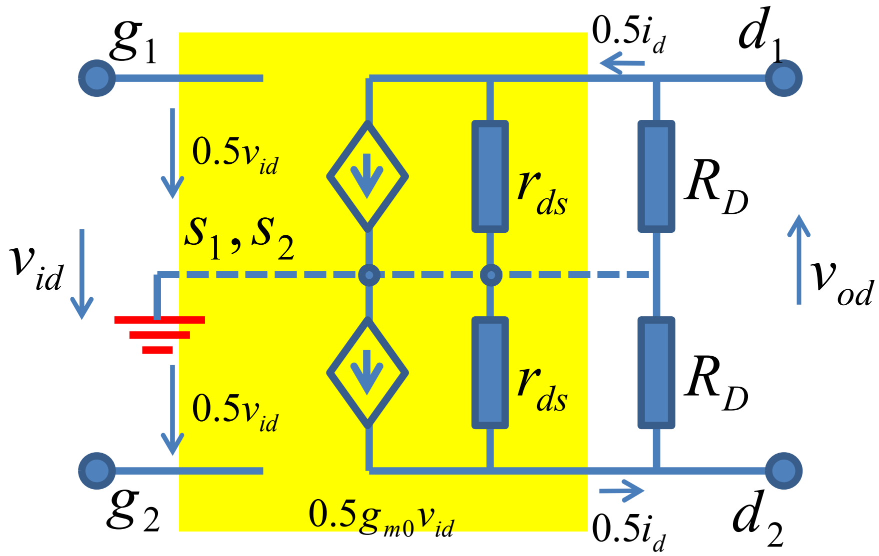
差模小信号分析



$$g_{m0} = \frac{2I_{D0}}{V_{od0}} = \frac{I_{SS}}{V_{od0}} \qquad r_{ds} = \frac{V_E}{0.5I_{SS}}$$

差模小信号电路分析



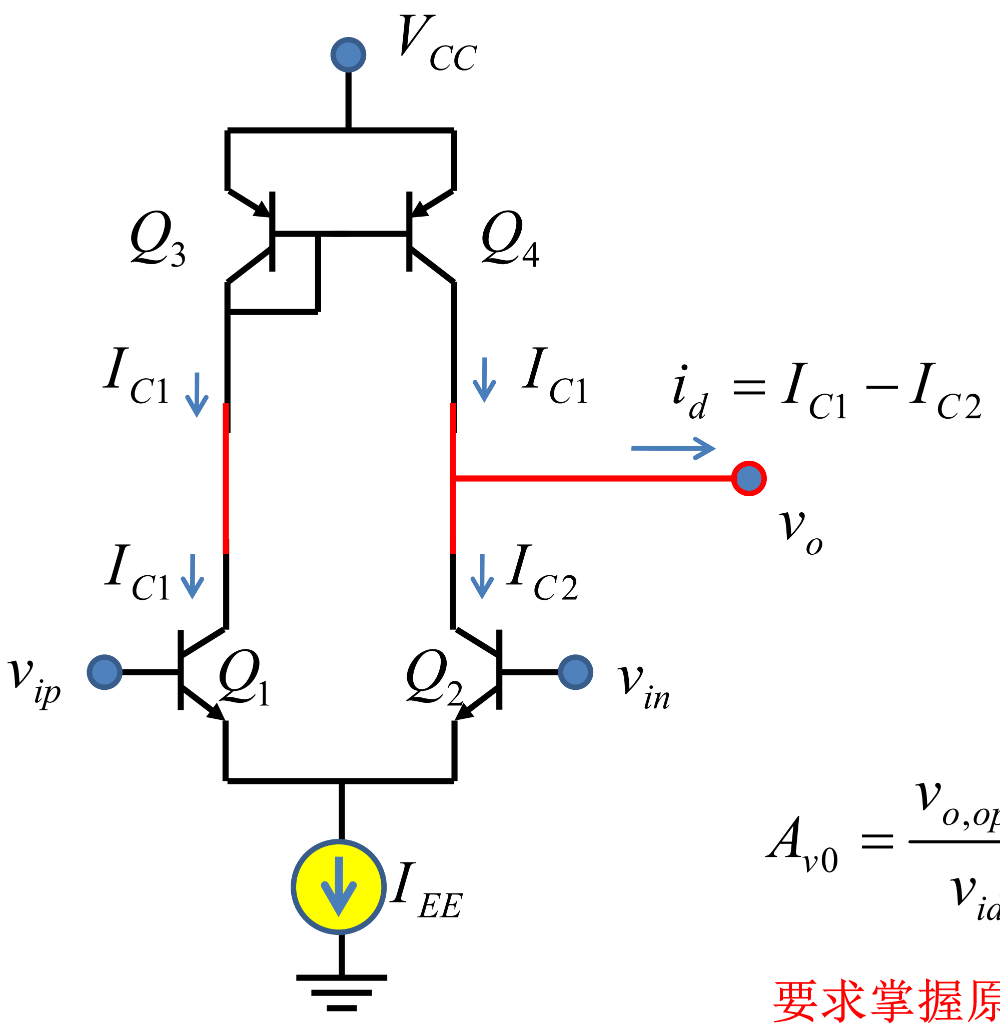


$$v_{od} = 0.5g_{m0}v_{id} \cdot \left(2r_{ds} \parallel 2R_D\right) = g_{m0}\left(r_{ds} \parallel R_D\right)v_{id}$$

$$A_{vd} = \frac{v_{od}}{v_{id}} = g_{m0}\left(r_{ds} \parallel R_D\right)$$

$$g_{m0} = \frac{2I_{D0}}{V_{od0}} = \frac{I_{SS}}{V_{od0}} \qquad r_{ds} = \frac{V_E}{0.5I_{SS}}$$

2.6 单端输出，差分电流合成



整体上看，这是一个差分输入单端输出的跨导器，跨导器输出阻抗为两个晶体管输出阻抗的并联

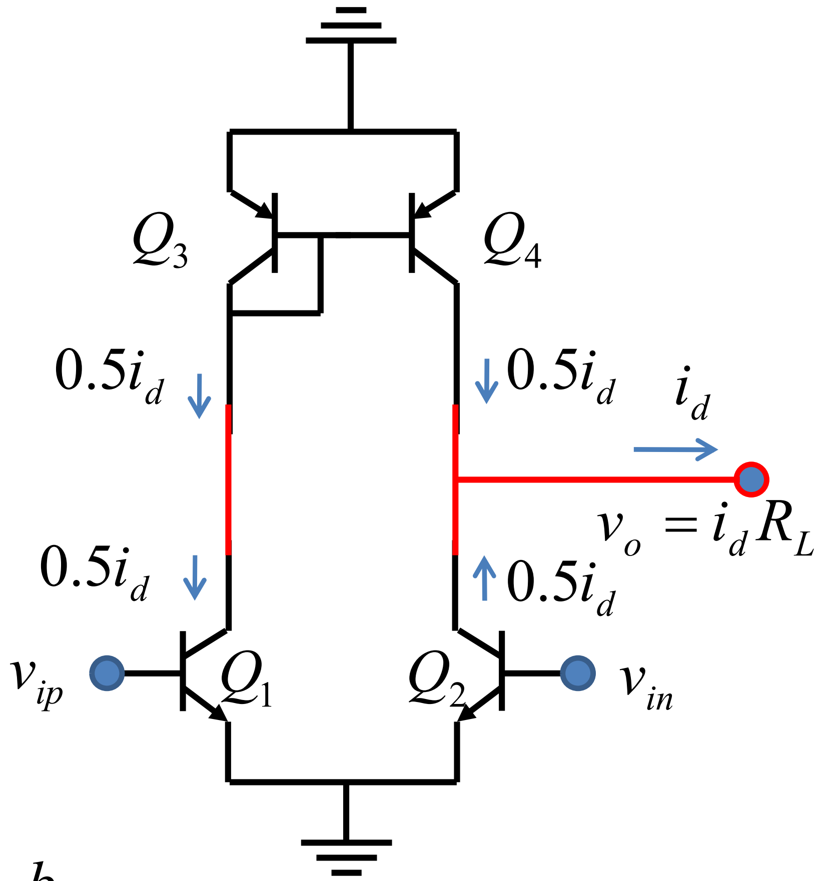
双端输入，单端输出

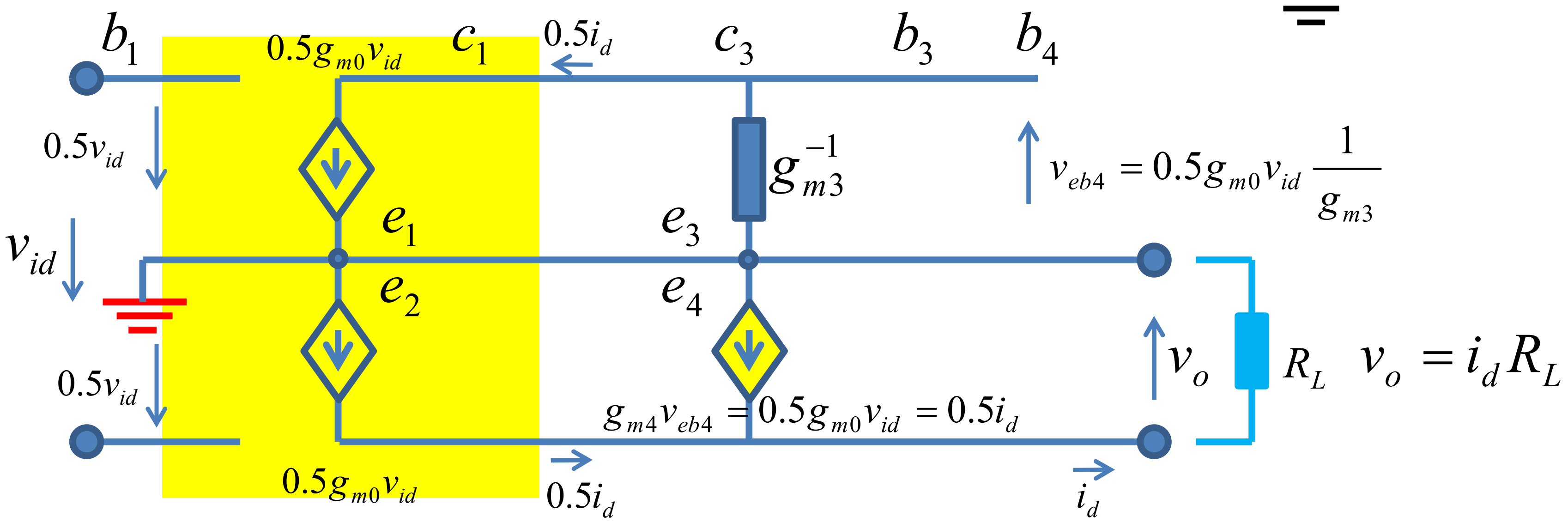
$$A_{v0} = \frac{v_{o,open}}{v_{id}} = \frac{i_d r_o}{v_{id}} = g_{m0}\left(r_{ce2} \,\|\, r_{ce4}\right)$$

要求掌握原理性描述分析

交流小信号
差分电流合成
原理分析

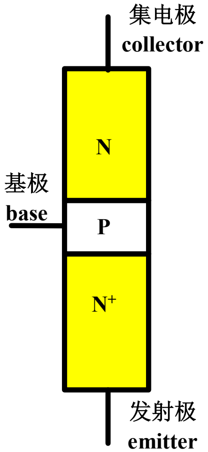
$V_A \to \infty$
$\beta \to \infty$

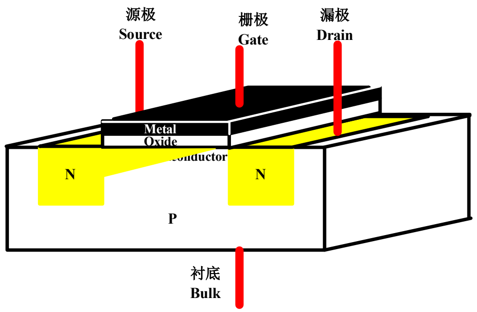




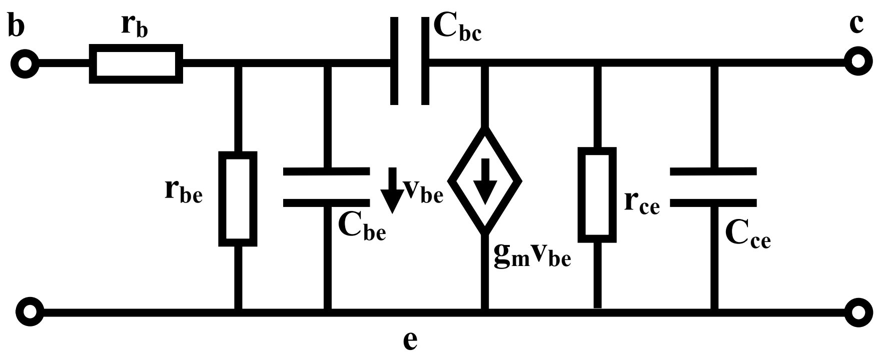
三、晶体管寄生电容效应

自学10.4节，了解基本概念，不必深入探索

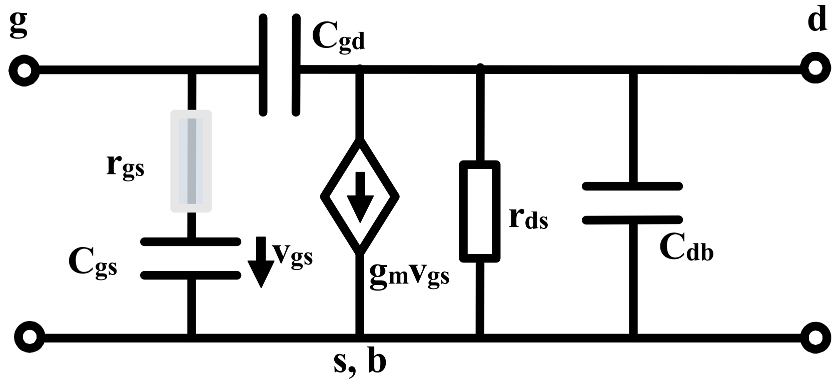




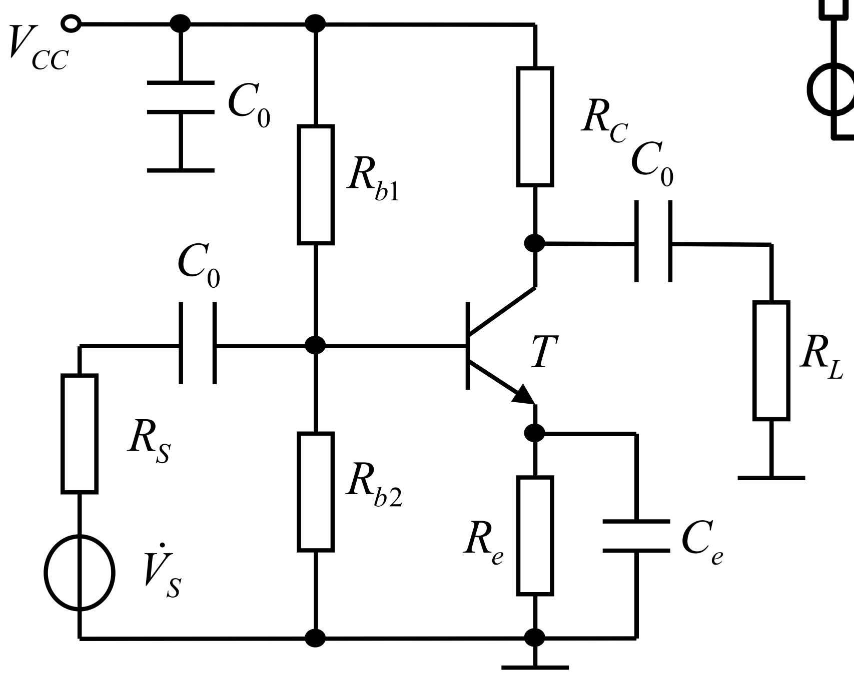
一旦进入射频/高速领域，晶体管寄生效应则不可回避，不考虑寄生电容效应，则无法理解晶体管的高频/高速特性：延时、带宽、…

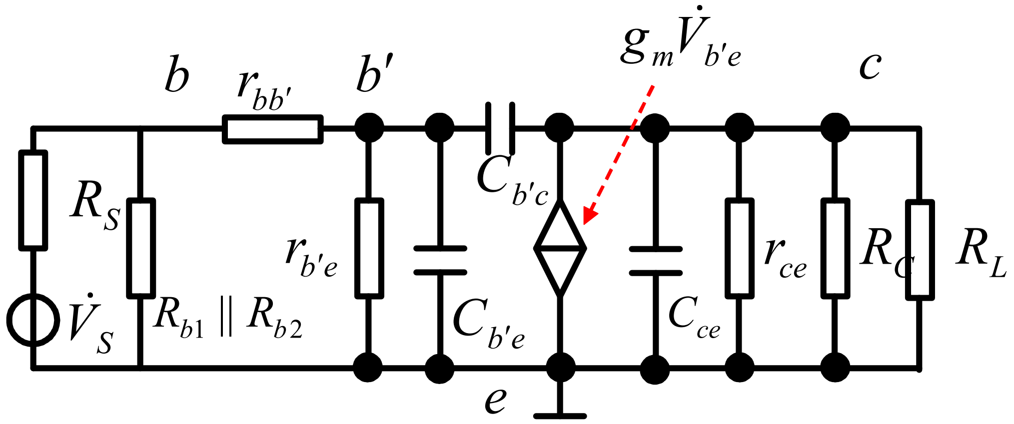


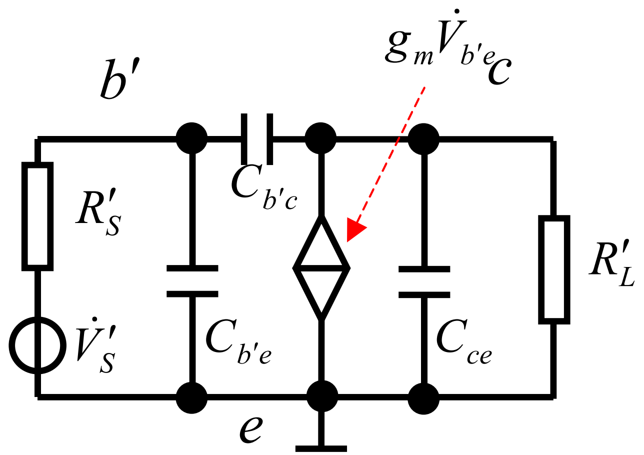
交流小信号高频模型



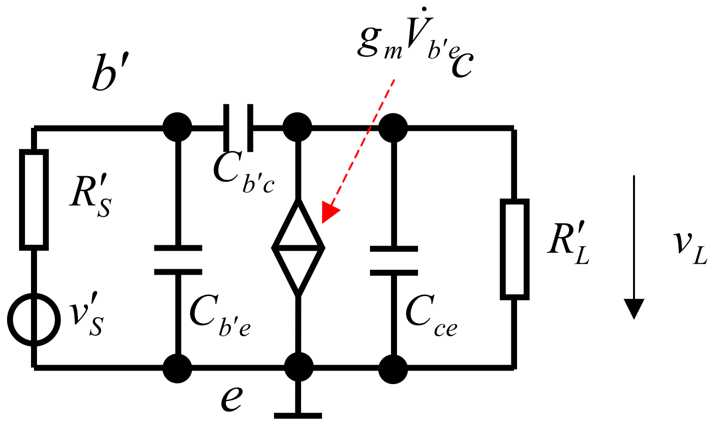
放大器效应一：高频增益下降







高频增益下降



$$A(s)=\frac{v_L}{v'_S}=-g_mR'_L\frac{1-\dfrac{s}{\omega_z}}{1+s\left(C_{b'e}R'_S+C_{b'c}\left(R'_S+R'_L+g_mR'_SR'_L\right)+C_{ce}R'_L\right)+s^2R'_SR'_L\left(C_{b'c}C_{b'e}+C_{b'e}C_{ce}+C_{ce}C_{b'c}\right)}$$

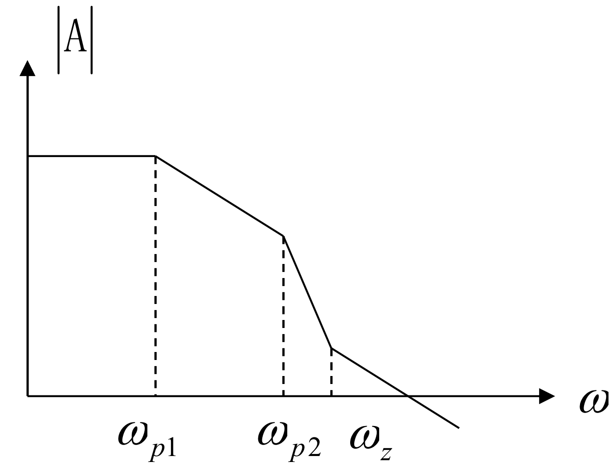
$$\omega_z=\frac{g_m}{C_{b'c}}$$

$$\left(1+\frac{s}{\omega_{p1}}\right)\left(1+\frac{s}{\omega_{p2}}\right)=1+s\left(\frac{1}{\omega_{p1}}+\frac{1}{\omega_{p2}}\right)+s^2\frac{1}{\omega_{p1}\omega_{p2}}$$

$$\omega_{p1}<<\omega_{p2}$$

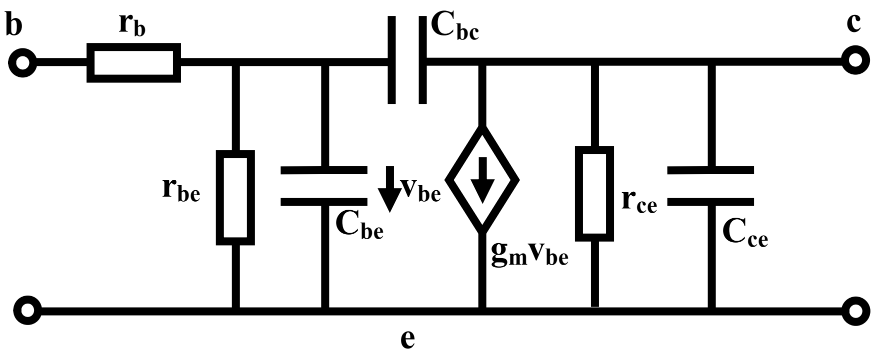
$$\frac{1}{\omega_{p1}}\approx\frac{1}{\omega_{p1}}+\frac{1}{\omega_{p2}}=C_{b'e}R'_S+C_{b'c}\left(R'_S+R'_L+g_mR'_SR'_L\right)+C_{ce}R'_L$$

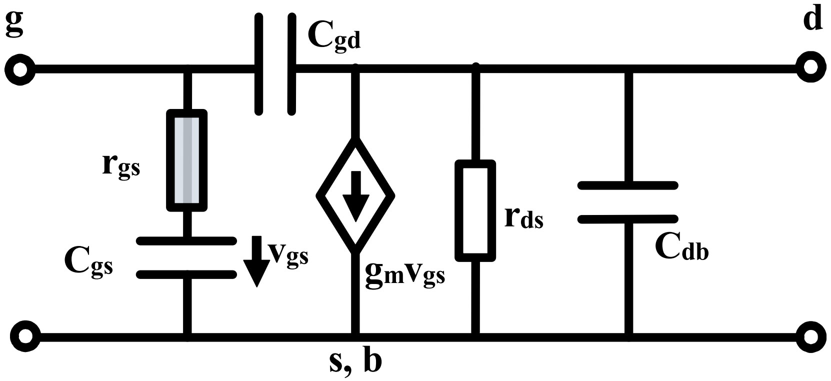
密勒效应



放大器效应二：极高频失却有源性失去功率放大能力

- 最高振荡频率f_{max}



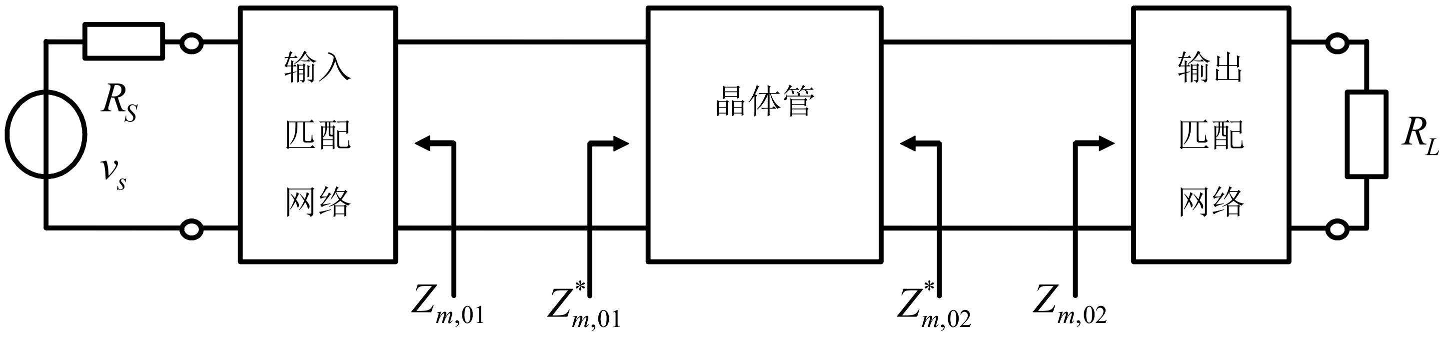


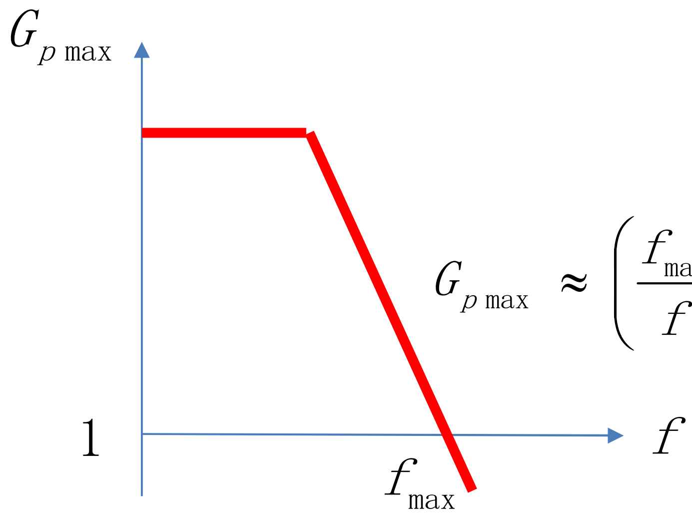
$$f_{max} = \frac{1}{4\pi}\sqrt{\frac{g_m^2 - 4g_{be}g_{ce}(1 + g_{be}r_b)}{\left(g_m C_{bc}(C_{be} + C_{bc}) + g_{be}C_{bc}^2 + g_{ce}(C_{be} + C_{bc})^2\right) r_b}}$$

$$\approx \frac{1}{4\pi}\sqrt{\frac{g_m}{C_{bc}(C_{be} + C_{bc})r_b}}$$

$$f_{max} = \frac{g_m}{4\pi C_{gs}}\sqrt{\frac{r_{ds}}{r_{gs}}}$$

最高振荡频率与最大功率增益



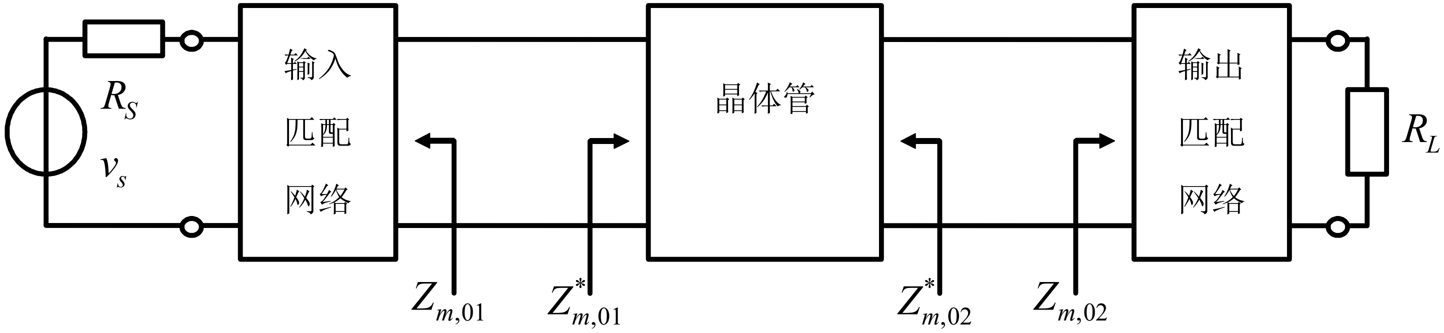


$$G_{p\max} \approx \left(\frac{f_{\max}}{f}\right)^2$$

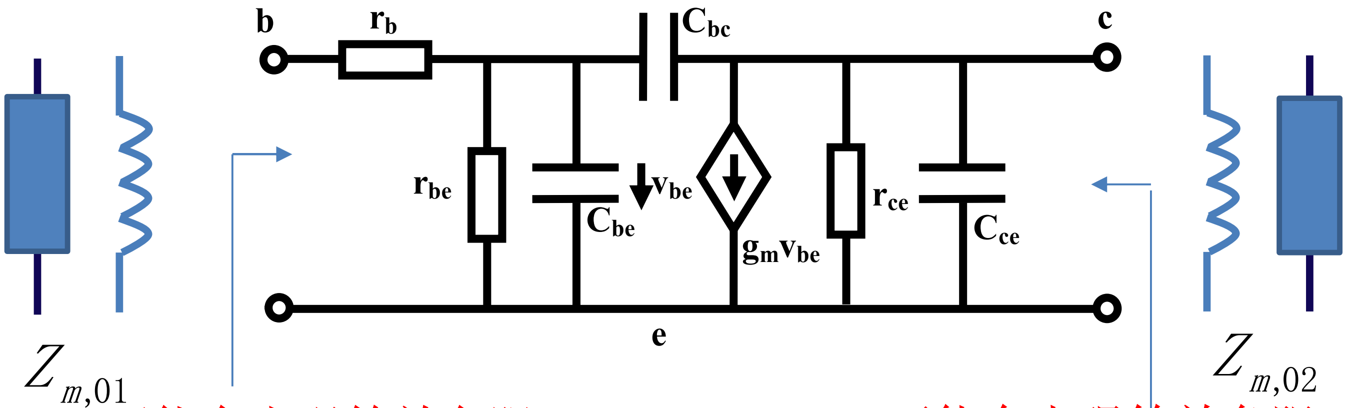
$$f < \frac{1}{4} f_{\max}$$

放大器和振荡器的工作频率范围

放大器效应三：高频稳定性变差
放大器变振荡器



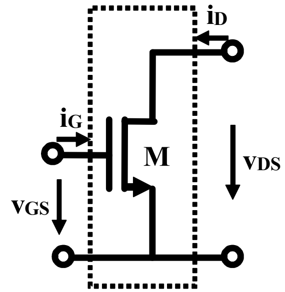
$$k=\frac{2ReY_{11}ReY_{22}-Re(Y_{12}Y_{21})}{|Y_{12}Y_{21}|}<1$$



可能会出现等效负阻　　可能会出现等效负阻

作业1 为何晶体管需要工作在恒流区

- 当晶体管做放大管使用时，需要将其偏置在恒流导通区，此区晶体管具有最大增益
  - 分析**CS**组态晶体管在不同工作区的跨导增益和电压增益
    - 交流小信号分析，分析其**y**参量矩阵及其模型



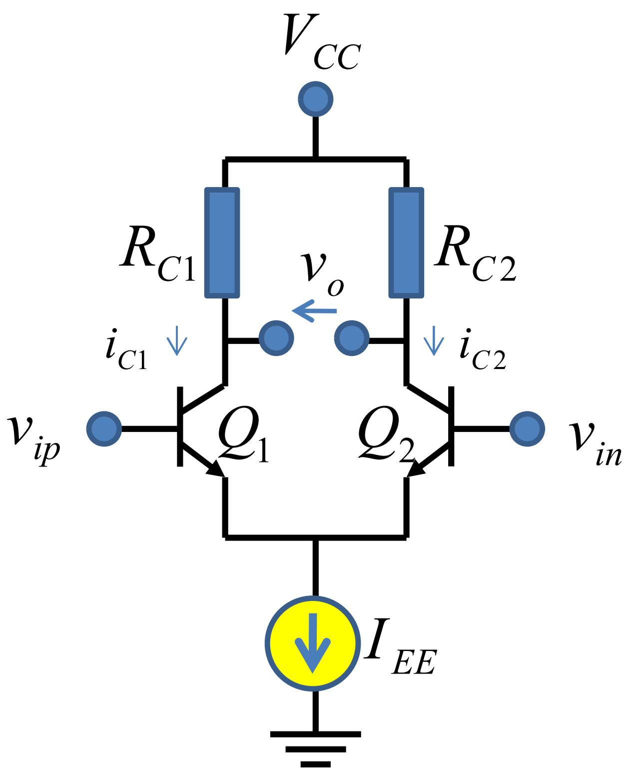
$$i_G = 0$$

$$i_D = \begin{cases} 0 & v_{GS} < V_{TH} \\ 2\beta_n\left(\left(v_{GS} - V_{TH}\right)v_{DS} - 0.5v_{DS}^2\right) & v_{GS} > V_{TH}, v_{GD} > V_{TH} \\ \beta_n\left(v_{GS} - V_{TH}\right)^2\left(1 + \lambda v_{DS}\right) & v_{GS} > V_{TH}, v_{GD} < V_{TH} \end{cases}$$

$$\beta_n = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}$$

45

作业2：BJT差分对跨导转移特性



证明**BJT**差分对跨导控制关系：

$$i_d = i_{C1} - i_{C2} = f(v_{id}) = I_{EE}\tanh\frac{v_{id}}{2v_T}$$

已知**BJT**跨导控制关系

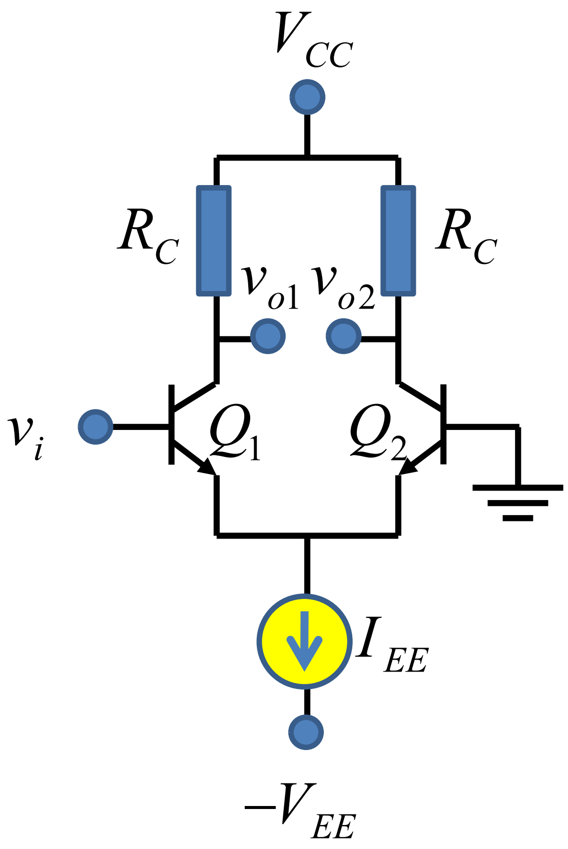
$$i_b \approx 0$$

$$i_c \approx I_{CS0} e^{\frac{v_{BE}}{v_T}}$$

忽略β、V_A的影响

$\beta \to \infty$, $V_A \to \infty$

作业3：差分放大器单端转双端



$I_{EE}=1mA$

- 电源电压为±**10V**，差分对管参数一致，**R_C=3kΩ**，画出如下三种输入情况下的两个输出电压**v_{o1},v_{o2}**的波形示意图

$$v_i=10\sin\left(2\pi\times10^3t\right)(mV)$$

$$v_i=0.5\sin\left(2\pi\times10^3t\right)(V)$$

$$v_i=50+100\sin\left(2\pi\times10^3t\right)(mV)$$

作业4：1dB线性范围

- 求差分对管的1dB线性范围

$$i_d = \begin{cases} +I_{SS} & v_{id} \geq +\sqrt{2}V_{od0} \\ I_{SS}\dfrac{v_{id}}{V_{od0}}\sqrt{1-\dfrac{1}{4}\left(\dfrac{v_{id}}{V_{od0}}\right)^2} & \left|v_{id}\right| \leq \sqrt{2}V_{od0} \\ -I_{SS} & v_{id} \leq -\sqrt{2}V_{od0} \end{cases} \underset{\approx}{1dB线性范围内} \; I_{SS}\frac{v_{id}}{V_{od0}} = \frac{I_{SS}}{V_{od0}}v_{id}$$

$$= g_{m0}v_{id}$$

$$i_d = I_{EE}tanh\frac{v_{id}}{2v_T} \underset{\approx}{1dB线性范围内} \; I_{EE}\frac{v_{id}}{2v_T} = \frac{I_{EE}}{2v_T}v_{id} = g_{m0}v_{id}$$

8.3.2节：相量域的有源和无源定义

- 线性时不变网络在相量域的有源性描述为：端口描述方程为线性代数方程的线性时不变网络，如果其端口总吸收实功恒不小于零，

$$P=\sum_{k=1}^{n}P_k=\frac{1}{2}\mathrm{Re}\sum_{k=1}^{n}\dot{V}_k\dot{I}_k^*=\frac{1}{2}\mathrm{Re}\,\dot{\mathbf{V}}^T\dot{\mathbf{I}}^*\geq 0 \qquad \left(\forall\dot{\mathbf{V}},\dot{\mathbf{I}},\mathbf{f}\left(\dot{\mathbf{V}},\dot{\mathbf{I}}\right)=0\right)$$

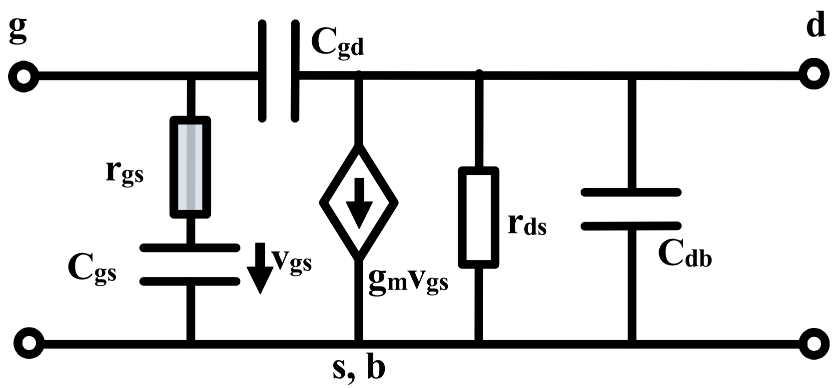
- 该网络就是无源网络。如果存在某种负载条件，使得端口总吸收实功小于**0**的情况可以出现，该网络则是有源的

$$P=\sum_{k=1}^{n}P_k=\frac{1}{2}\mathrm{Re}\sum_{k=1}^{n}\dot{V}_k\dot{I}_k^*=\frac{1}{2}\mathrm{Re}\,\dot{\mathbf{V}}^T\dot{\mathbf{I}}^*<0 \qquad \left(\exists\dot{\mathbf{V}},\dot{\mathbf{I}},\mathbf{f}\left(\dot{\mathbf{V}},\dot{\mathbf{I}}\right)=0\right)$$

-
- $\dot{\mathbf{V}}$ $\dot{\mathbf{I}}$是关联参考方向定义的端口电压和端口电流列向量
- $\mathbf{f}\left(\dot{\mathbf{V}},\dot{\mathbf{I}}\right)=0$ 则是该线性时不变网络在相量域的端口描述线性代数方程。

作业5：晶体管的有源性

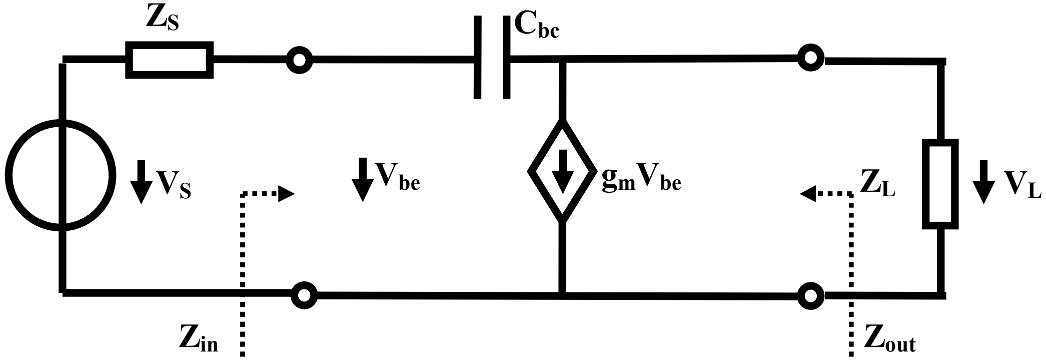
- 请分析如下网络的有源性条件
  - 列写其**y**参量矩阵
  - 由有源性定义证明有源性条件为$f<f_{max}$



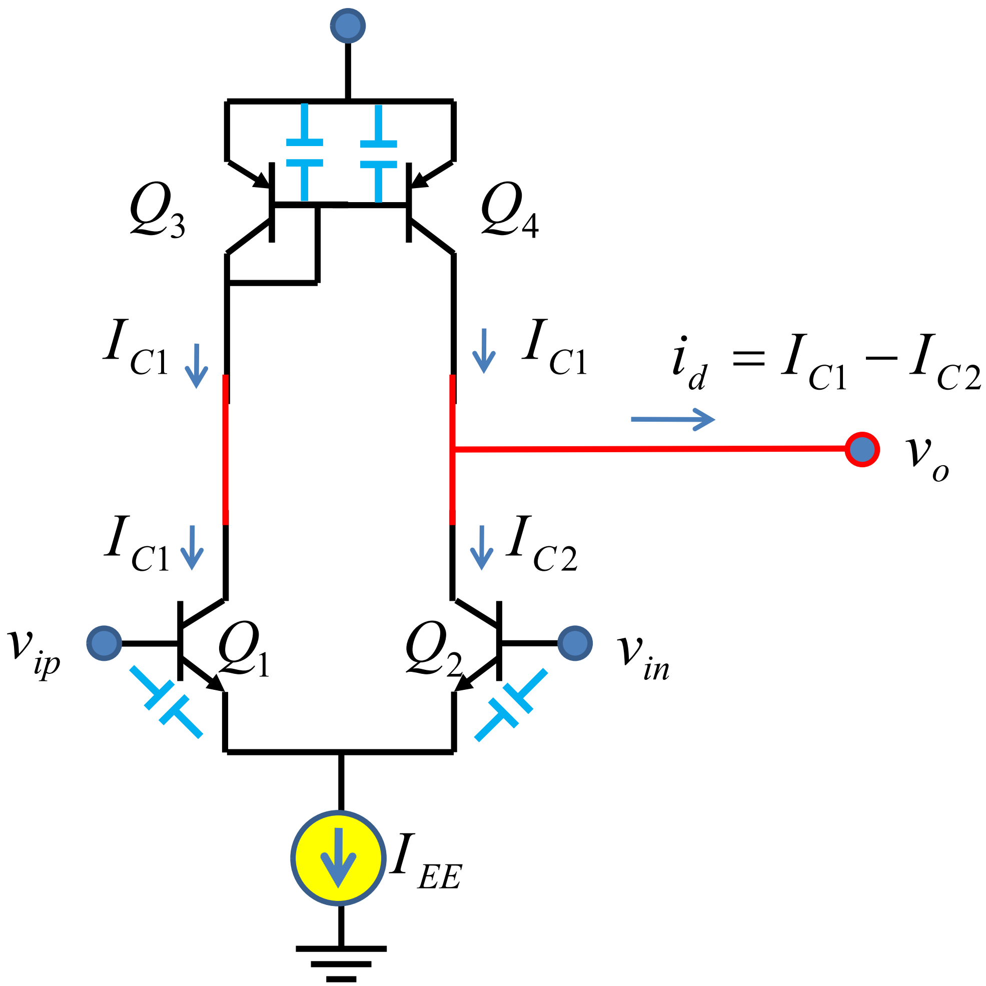
$$f_{\max}=\frac{g_m}{4\pi C_{gs}}\sqrt{\frac{r_{ds}}{r_{gs}}}$$

作业6：晶体管放大器不稳定的原因

- 练习**10.4.10**：图**E10.4.6**是用来考察**CE**组态晶体管C_{bc}对输入阻抗和输出阻抗影响的原理性电路，其中只剩下晶体管原本设计的压控流源和跨接在压控流源输出和输入之间的寄生电容C_{bc}，考察当$Z_L=R_L$，$j\omega L_2$两种负载情况下，输入阻抗Z_{in}的性质；考察当$Z_S=R_S$，$j\omega L_1$两种负载情况下，输出阻抗Z_{out}的性质。

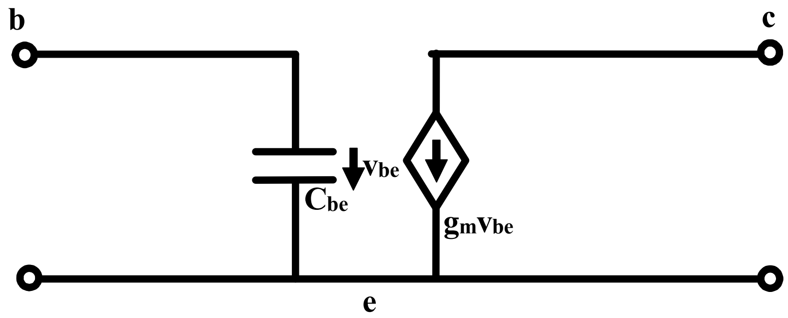


作业7：寄生电容对放大的影响



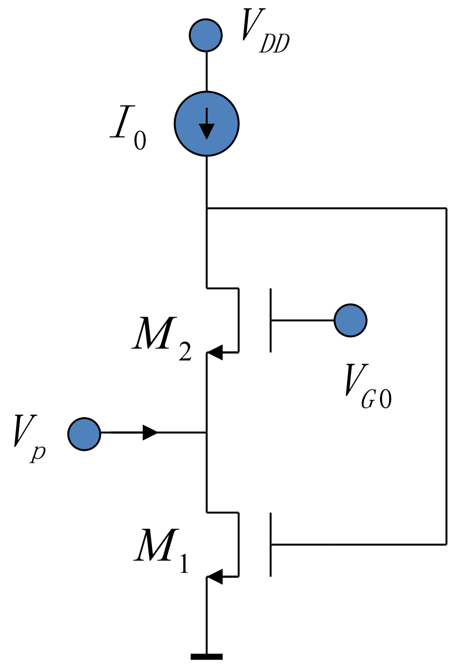
- 仅考虑寄生电容C_{be}影响，求传递函数表达式

$$H = \frac{i_d}{v_{id}}$$

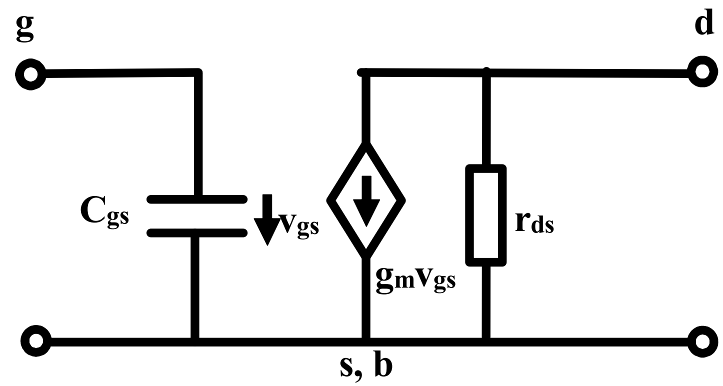


晶体管简化模型

作业8：寄生电容的回旋对偶变换导致阻容电路出现谐振现象



- 证明：考虑了晶体管的寄生电容效应后，从V_p端口看入，其等效电路为RLC并联谐振回路
  - 给出等价RLC



MOS简化模型

CAD仿真：N型负阻

加压求流，确认该端口具有**N**型负阻特性
加流求压？