模拟与数字电路

Analog and Digital Circuits

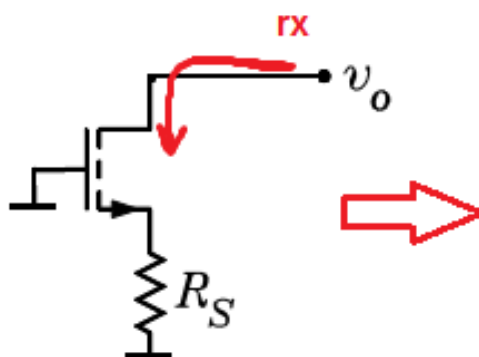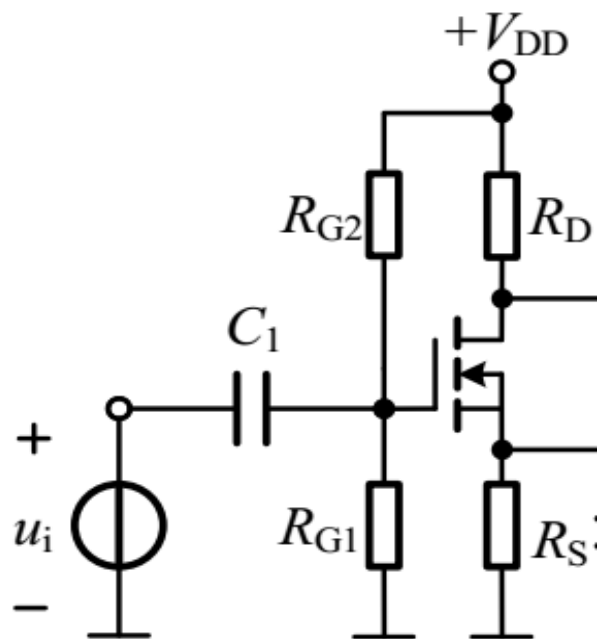第 四 讲： **Single Transistor Amplifier (II)**

Lecture 4: **单晶体管放大器电路 （II)**

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Instructor： Chixiao Chen

课程主页 扫一扫

具有源级电阻的共源放大电路

- 小信号模型分析
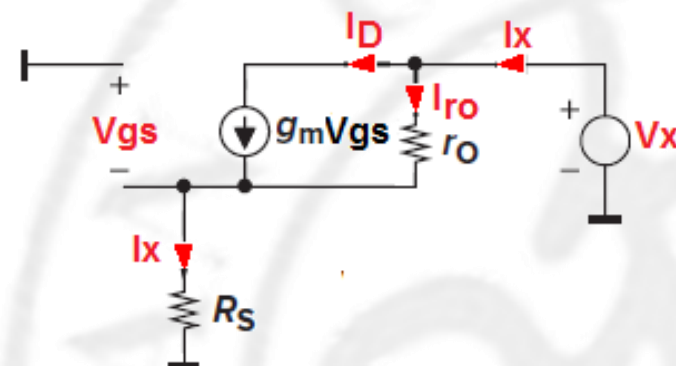Common Source Amplifier with source degeneration

增益：

$$V_1 = V_{in} - I_D R_S = V_{in} - g_m V_1 R_S$$

$$\Rightarrow V_1 = \frac{V_{in}}{1 + g_m R_S} \Rightarrow$$

$$\Rightarrow V_{out} = -g_m V_1 R_D$$

$$A_v \approx \frac{-g_m R_D}{1 + g_m R_S}$$

输出电阻：

$$V_X = I_{ro} * ro + I_X * R_S$$

$$I_{ro} = I_X - gm * V_{GS}$$
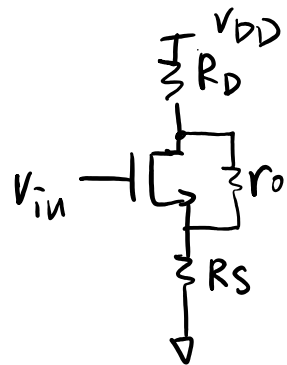
$$V_X = (I_X - (gm(-I_X)R_S)) ro + I_X R_S$$

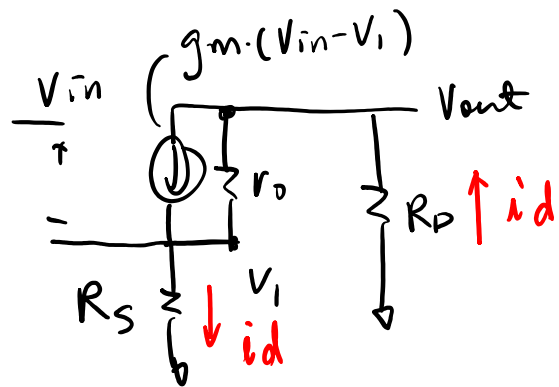And solve for I_X

$$I_X = \frac{V_X}{R_S + ro + gm * R_S * ro}$$

And finally we have

$$r_x = R_S + ro + gm * R_S * ro = ro(1 + gmR_S + \frac{R_S}{ro})$$

$$r_x = ro * (1 + gmR_S) + R_S$$

$$i_D = -\frac{V_{out}}{Rd} \quad \text{①}$$

$$i_D = g_m \cdot (V_{in} - V_1) + \frac{V_{out} - V_1}{r_o} \quad \text{②}$$

$$i_D = \frac{V_1}{R_S} \quad \text{③}$$

由 ①·③: $\dfrac{-V_{out}}{Rd} = \dfrac{V_1}{R_S}$ $\quad V_{out} = -\dfrac{Rd}{R_S} V_1 \quad \text{④}$

由 ②·④·③: $\dfrac{V_1}{R_S} = g_m \cdot (V_{in} - V_1) + \dfrac{-Rd/R_S - 1 \cdot V_1}{\cdot r_o}$ $\rightarrow g_m \cdot V_{in} = \dfrac{1}{R_S} + g_m + \dfrac{Rd/R_S + 1}{r_o} V_1$

$A_v \urcorner$

$$\frac{V_{out}}{V_{in}} = \frac{-Rd/R_S \; V_1}{\frac{1}{R_S} + g_m + \frac{Rd/R_S + 1}{r_o}} \cdot g_m$$

$$= -\frac{g_m \, Rd}{1 + g_m \cdot R_S + \frac{1}{r_o}(Rd + R_S)}$$

if $\dfrac{1}{r_o} \to 0$ $\quad A_v \doteq -\dfrac{g_m \, Rd}{1 + g_m \cdot R_S}$

if $g_m \cdot R_S \gg 1$ $\quad A_v \doteq -\dfrac{Rd}{Rd}$

共栅放大电路

1. 静态分析

根据直流通路有

$$I_{DQ} = I$$

由 $I_{DQ} = K_n(V_{GSQ} - V_{TN})^2$

可得 V_{GSQ}

又 $V_S = -V_{GSQ}$ $V_D = V_{DD} - I_{DQ}R_d$

所以 $V_{DSQ} = V_D - V_S$

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

需验证是否工作在饱和区
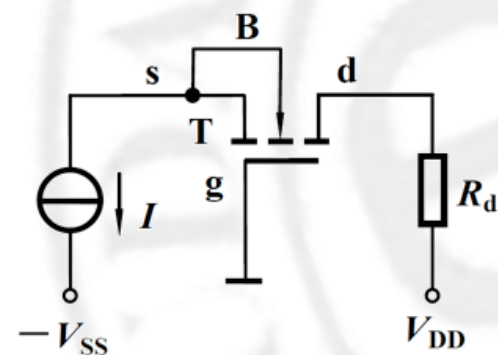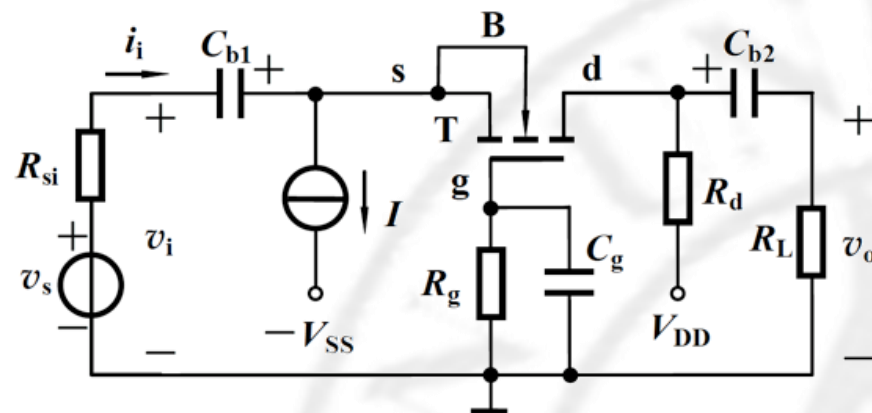
共栅放大电路

2. 动态分析

设 $\lambda=0$

电压增益

$$v_i = -v_{gs}$$

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

$$A_v = \frac{v_o}{v_i} = g_m(R_d \parallel R_L)$$

源电压增益

$$v_s = v_i + i_i R_{si} = -v_{gs} - g_m v_{gs} R_{si}$$

$$A_{vs} = \frac{v_o}{v_s} = \frac{g_m(R_d \parallel R_L)}{1 + g_m R_{si}}$$

输出与输入同相

输入电阻

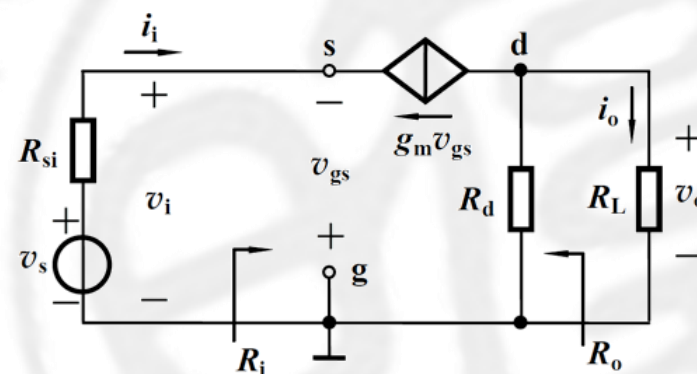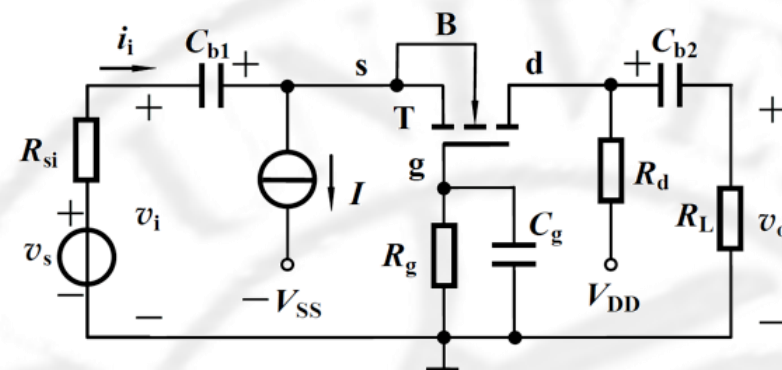$$R_i = \frac{v_i}{i_i} = \frac{-v_{gs}}{-g_m v_{gs}} = \frac{1}{g_m}$$

输入电阻远小于其它两种组态

输出电阻

当 $r_{ds} \gg R_d$ 和 $r_{ds} \gg R_{si}$ 时

$$R_o \approx R_d$$
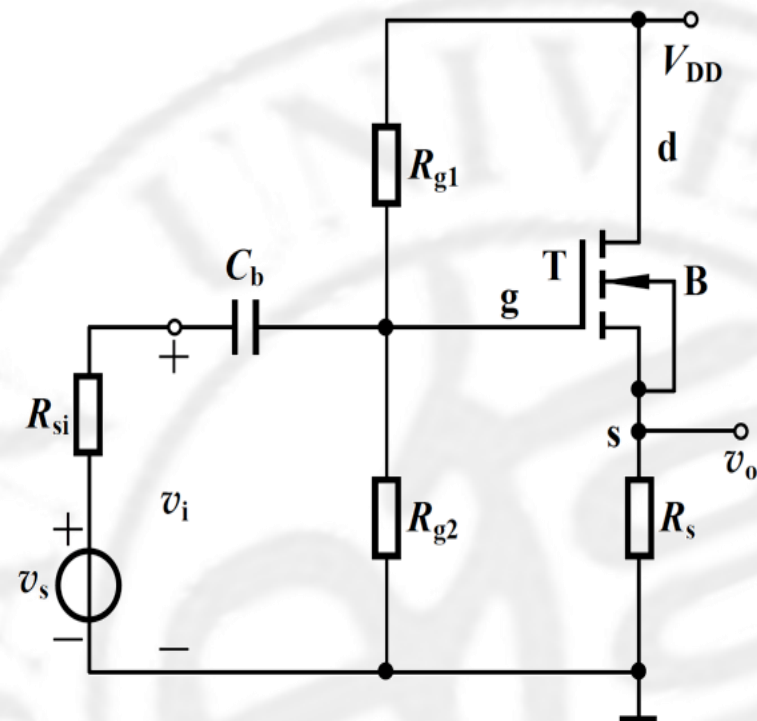
与共源电路同相

共漏放大电路

• 又称为源极跟随器

1. 静态分析

设MOS管工作于饱和区

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

需验证是否工作在饱和区

共漏放大电路

2. 动态分析

小信号等效电路

根据静态工作点可求得 g_m

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

电压增益

$$v_i = v_{gs} + v_o = v_{gs} + g_m v_{gs}(R_s \| r_{ds})$$

$$= v_{gs}[1 + g_m(R_s \| r_{ds})]$$

$$v_o = g_m v_{gs}(R_s \| r_{ds})$$

$$A_v = \frac{v_o}{v_i} = \frac{g_m v_{gs}(R_s \| r_{ds})}{v_{gs}[1 + g_m(R_s \| r_{ds})]}$$

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

输出与输入同相，且增益小于等于1

源电压增益

$$A_{vs} = \frac{v_o}{v_s} = \frac{v_o}{v_i} \cdot \frac{v_i}{v_s}$$

$$= \frac{g_m(R_d \| r_{ds})}{1 + g_m(R_d \| r_{ds})} \cdot \left(\frac{R_i}{R_i + R_{si}}\right)$$

输入电阻
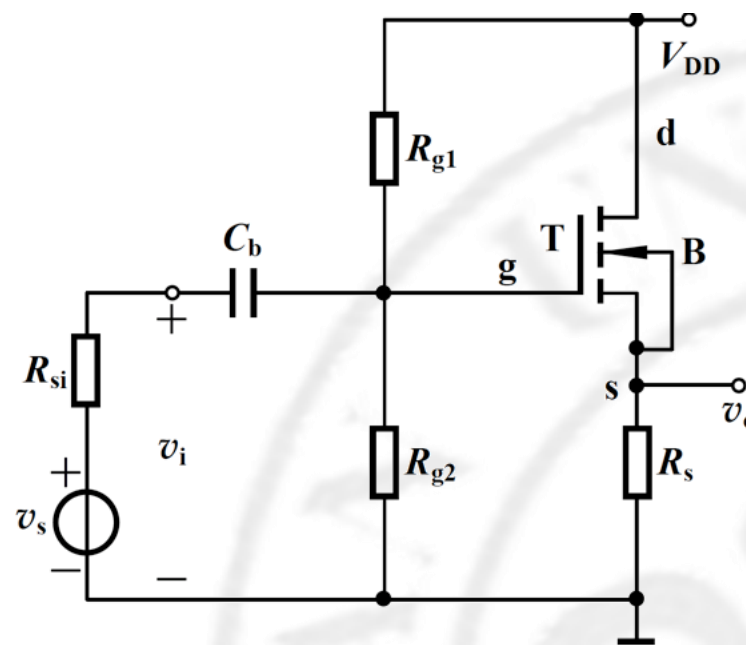
$$R_i = R_{g1} \| R_{g2}$$
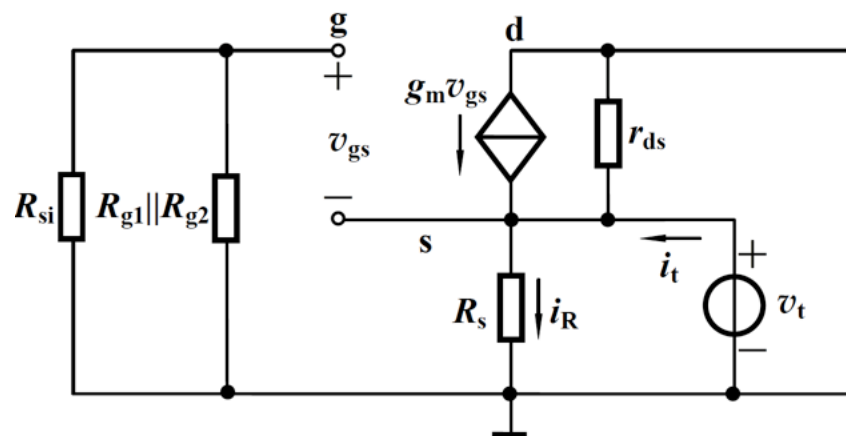
受静态偏置电路的影响，栅极绝缘的特性并未充分表现出来
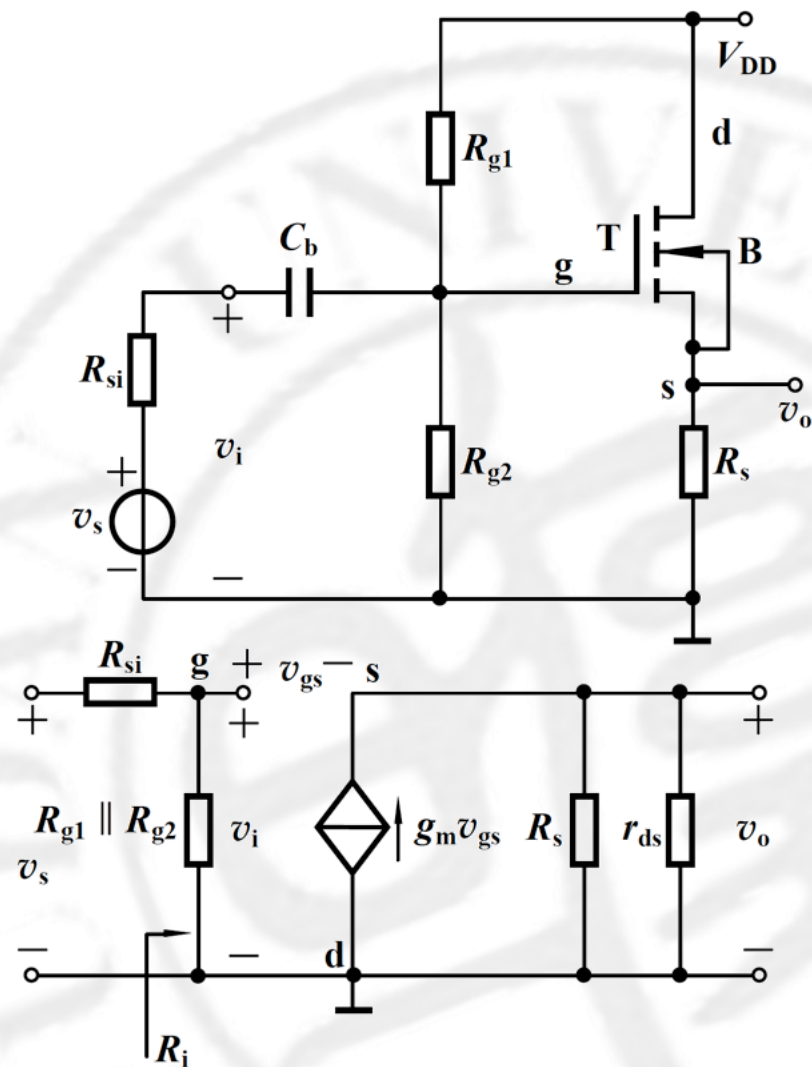
共漏放大电路

2. 动态分析

输出电阻

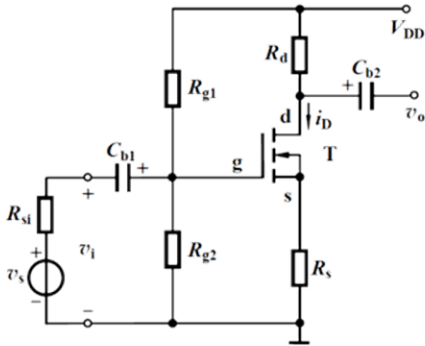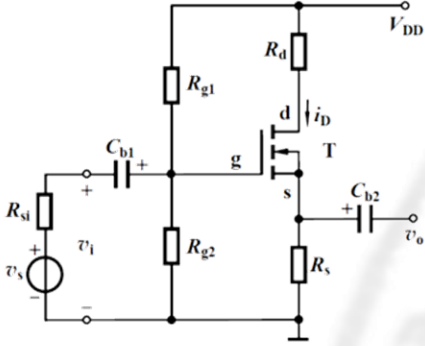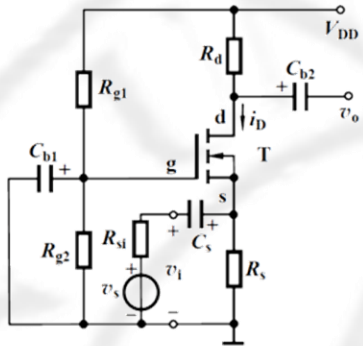$$\begin{cases} i_T = \dfrac{v_T}{R_s} + \dfrac{v_T}{r_{ds}} - g_m v_{gs} \\[4mm] v_{gs} = -v_T \end{cases}$$

$$R_o = \dfrac{v_T}{i_T} = \cfrac{1}{\dfrac{1}{R_s} + \dfrac{1}{r_{ds}} + g_m} = R_s \parallel r_{ds} \parallel \dfrac{1}{g_m}$$
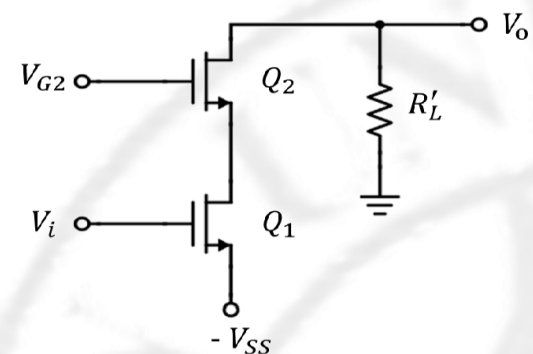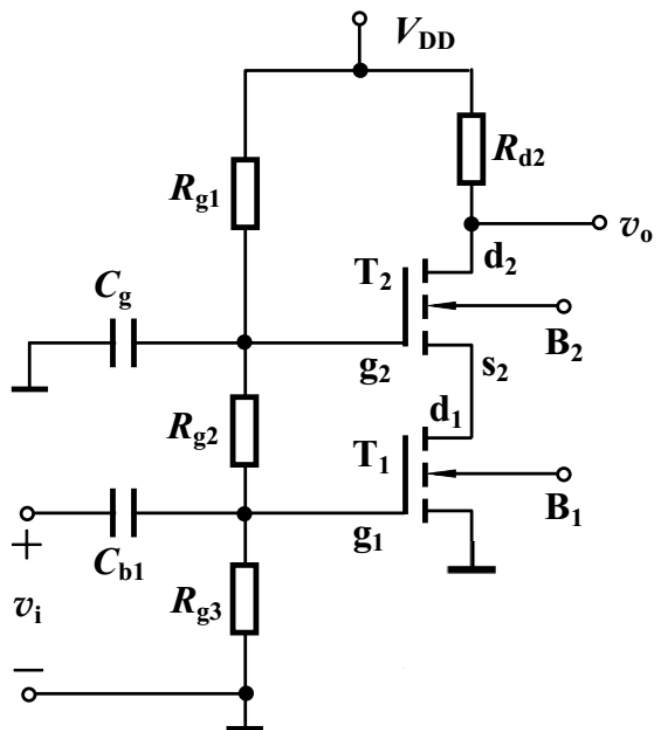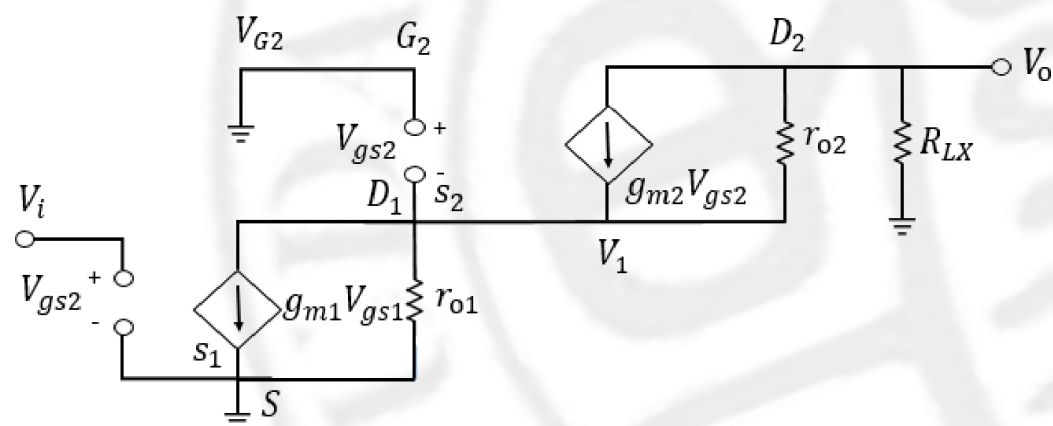
输出电阻较小

三种组态总结比较

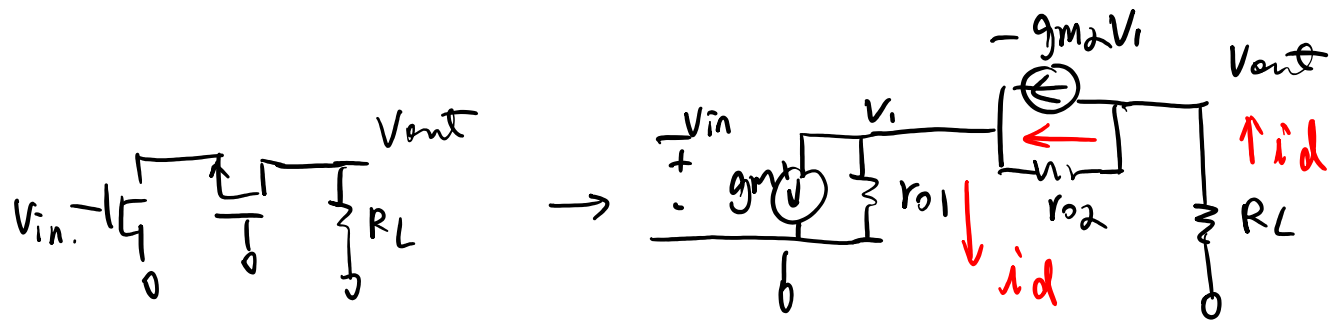|	共源	共漏	共栅
电压增益	$A_v = -g_m(r_{ds} \parallel R_d)$	$A_v = \dfrac{g_m(R_s \parallel r_{ds})}{1 + g_m(R_s \parallel r_{ds})} \approx 1$	$A_v = g_m(R_d \parallel R_L)$
输入电阻	很高	很高	$R_i \approx \dfrac{1}{g_m}$
输出电阻	$R_o \approx R_d$	$R_o = R_s \parallel r_{ds} \parallel \dfrac{1}{g_m}$	$R_o \approx R_d$

思考题：共源共栅放大电路

- Cascode Amplifier

$i_{d1} = -\dfrac{V_{out}}{R_L}$ ①

$i_d = g_{m2} \cdot (-V_1) - \dfrac{V_1 - V_{out}}{r_{o2}}$ ②

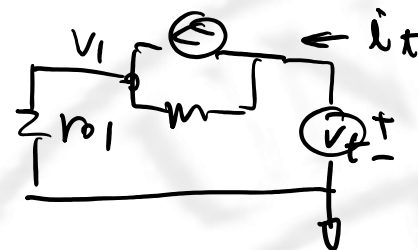$i_d = g_{m1} \cdot V_{in} + \dfrac{V_1}{r_{o2}}$ ③

$= \frac{1}{g_{m}} \| r_{o2}$

联立 ①+② $\quad V_{out} = V_1 \cdot (g_m + \frac{1}{r_{o2}}) \cdot R_L \| r_{o2}$ ④

联立 ①·③·④ $\quad V_{out} \left(\frac{1}{r_o} \cdot \dfrac{r_{o2} \| \frac{1}{g_{m2}}}{R_L \| r_{o2}} + \frac{1}{R_L} \right) = g_{m1} V_{in}$

$A_v = \dfrac{V_{out}}{V_{in}} = g_{m1} \left(R_L \| r_{o1} \cdot \dfrac{R_L \| r_{o2}}{r_{o2} \| \frac{1}{g_{m2}}} \right) \doteq \begin{cases} g_m R_L & r_{o1} 或 r_{o2} \gg R_L \\ g_{m1} g_{m2} r_{o1} r_{o2} R_L \gg r_{o1} 或 r_{o2} \end{cases}$
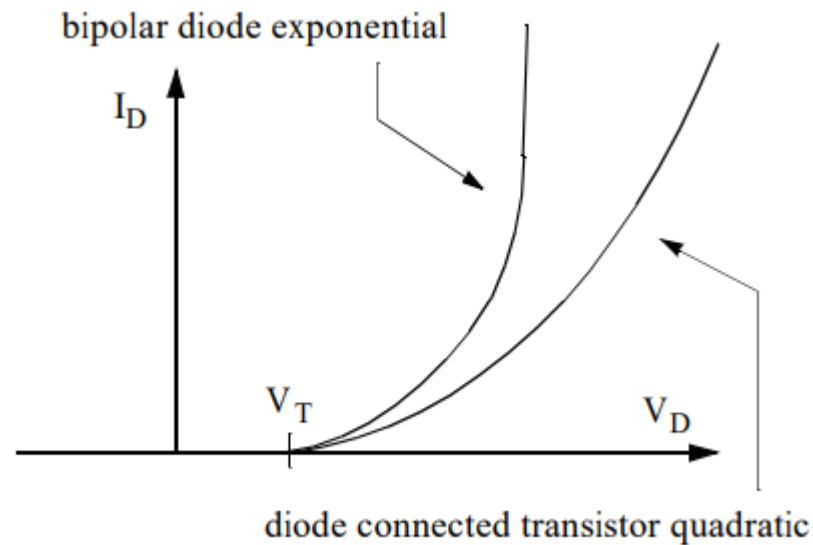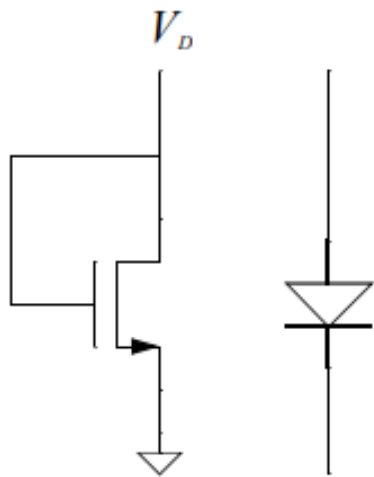
求输出电阻:

$R_{out} = \dfrac{V_t}{i_t} = \dfrac{V_1 + (g_m + \frac{1}{r_{o1}}) \cdot r_{o2} \cdot V_1}{V_1 / r_{o1}}$
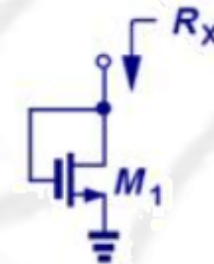
$= g_{m2} r_{o1} r_{o2} + r_{o1} + r_{o2}$

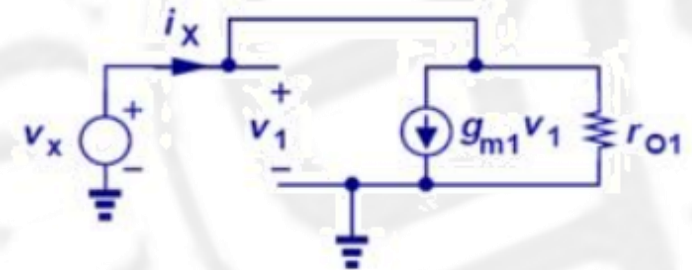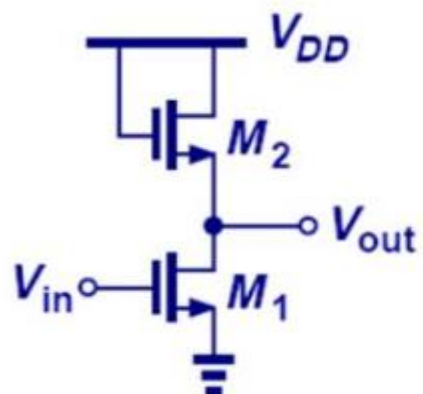$\doteq g_{m2} r_{o1} r_{o2}$

二极管偏置的晶体管

• Diode connected MOS

V_D

bipolar diode exponential

I_D

diode connected transistor quadratic

V_T

V_D

Diode-connected NMOSFET

R_X

M_1

$$R_X = \frac{1}{g_{m1}} \Big\| r_{o1}$$

Small-signal analysis circuit

i_X

v_X

v_1

$g_{m1}v_1$

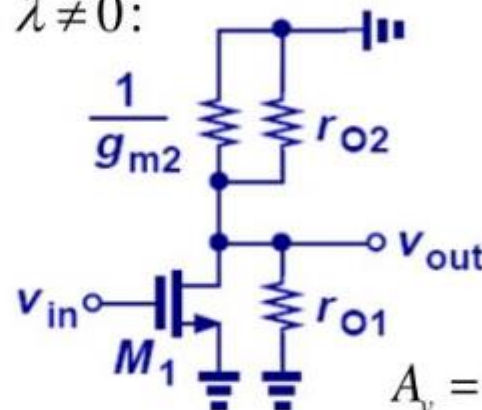r_{O1}

共源放大器 + 二极管偏置的放大电路

Amplifier circuit

If $\lambda = 0$:

$$A_v = -g_{m1} \cdot \frac{1}{g_{m2}} = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

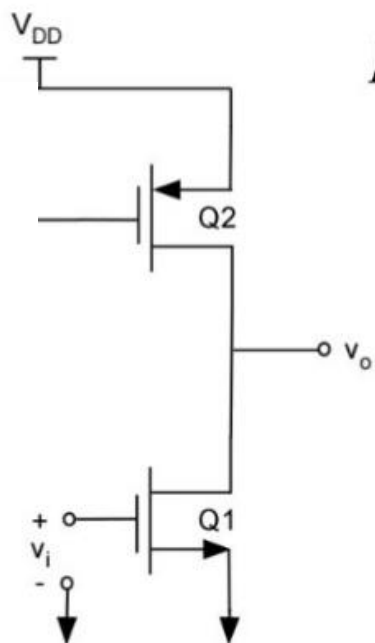**Small-signal analysis circuit including MOSFET output resistances**

$\lambda \neq 0$:

$$A_v = -g_{m1}\left(\frac{1}{g_{m2}} \parallel r_{O2} \parallel r_{O1}\right)$$

$$R_{out} = \frac{1}{g_{m2}} \parallel r_{O2} \parallel r_{O1}$$

$$I_{D,sat} = \frac{\mu_p \cdot C_{ox}}{2} \cdot \frac{W}{L} \cdot (V_{GS} - V_T)^2 \begin{cases} V_{GS} \leqslant V_T \\ V_{DS} \leqslant V_{GS} - V_T \end{cases}$$

共源放大器 + 有源负载
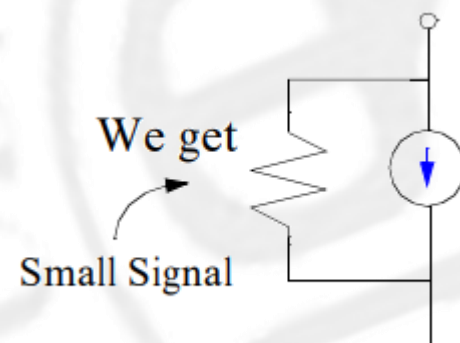

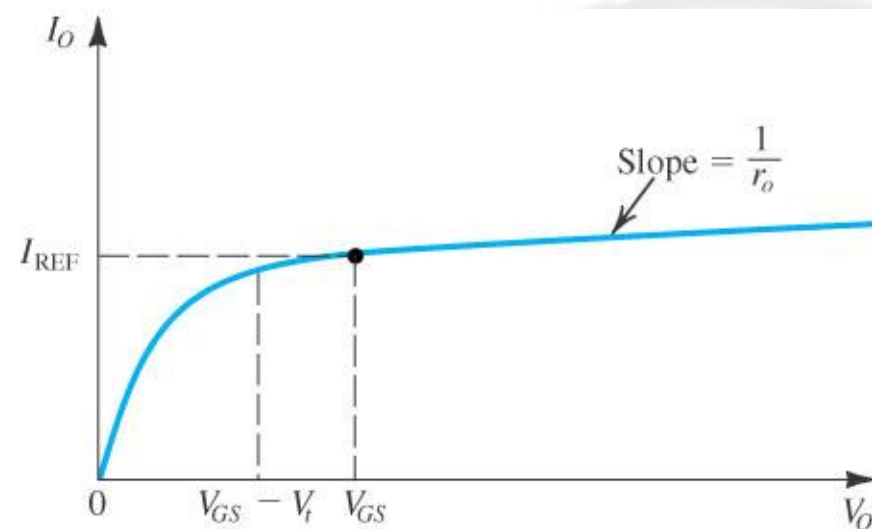$Let\ r_{ds1} = r_{o1}\ for\ Q_1$

$r_{ds2} = r_{o2}\ for\ Q_2$

$then,\ R_{out} = r_{o1} \parallel r_{o2}$
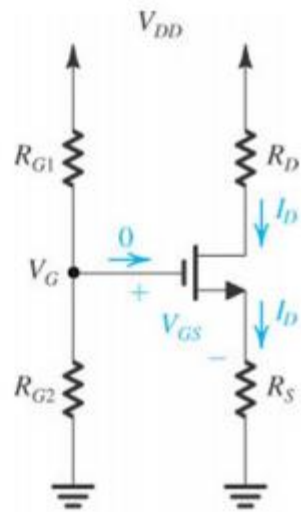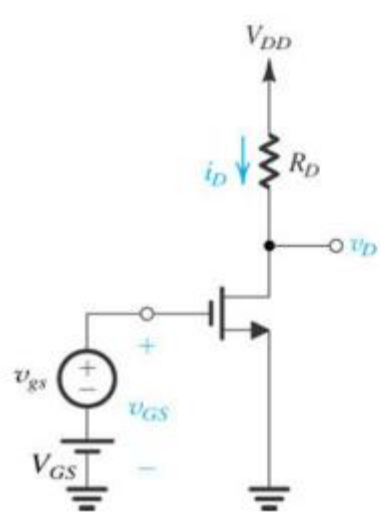
$A_{MB} = -g_{m1}R_{out}$

$Let\ g_{o1} = \dfrac{1}{r_{o1}} = g_{ds1}$

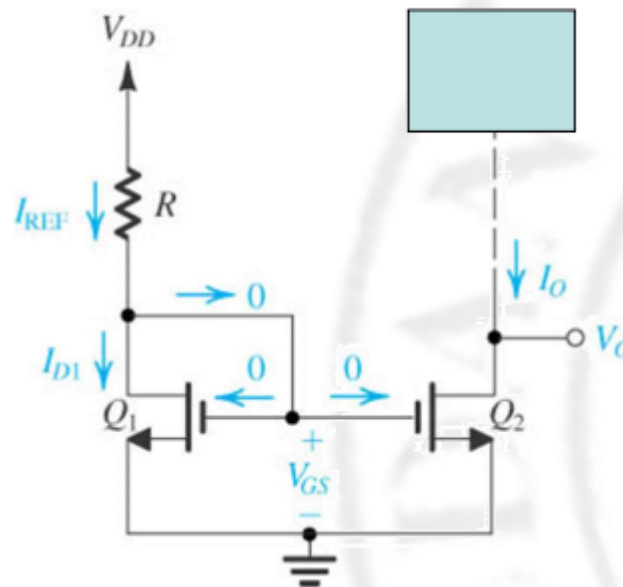$g_{o2} = \dfrac{1}{r_{o2}} = g_{ds2}$

We get

Small Signal

如何提供有源负载的偏置电压？

- 基于电阻分压的偏置电路

- 基于电流镜的偏置电路

$$I_{D1} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_1 (V_{GS} - V_t)^2$$

$$I_{D1} = I_{REF} = \frac{V_{DD} - V_{GS}}{R}$$

Assuming Q_1, Q_2 have same properties (k_n'),

$$I_O = I_{D2} = \frac{1}{2}k_n'\left(\frac{W}{L}\right)_2 (V_{GS} - V_{tn})^2$$

$$\frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}$$

Limitation on V_o? $V_O \geq V_{GS} - V_t$

电流镜 + 有源负载