

第二章 单级放大器及频率响应

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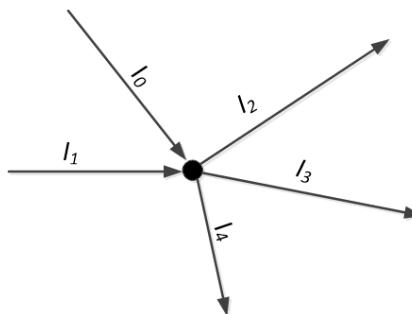
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背景知识 — 电路分析方法

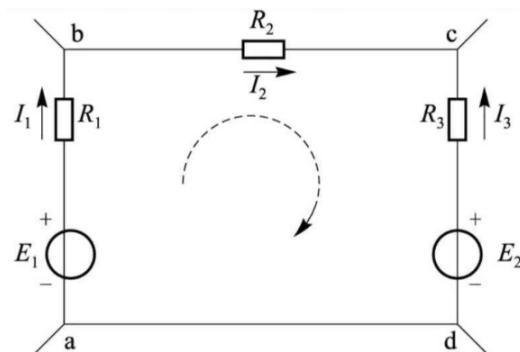
- 电路分析基础
 - 基尔霍夫电流定律

$$\sum_{j=0}^n I_j = 0$$



- 基尔霍夫电压定律

$$\sum_{k=0}^m V_k = 0$$



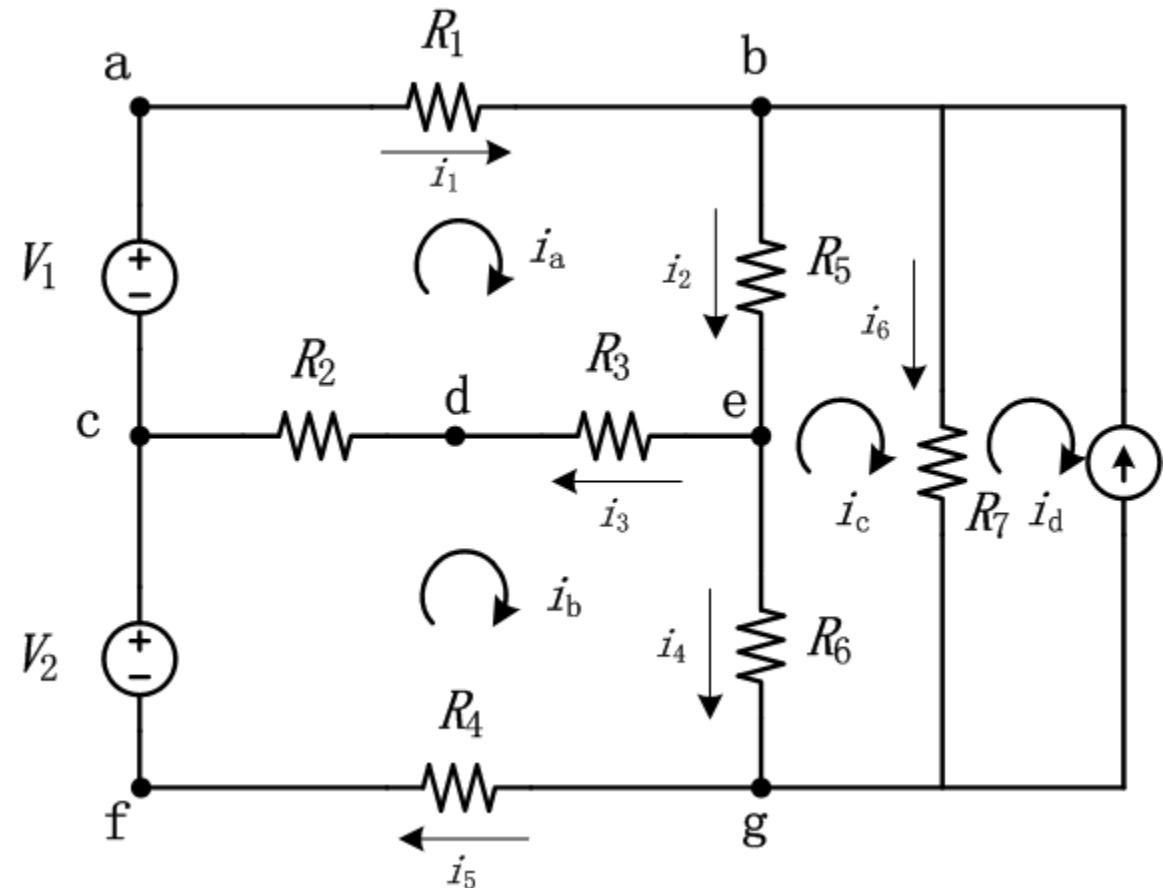
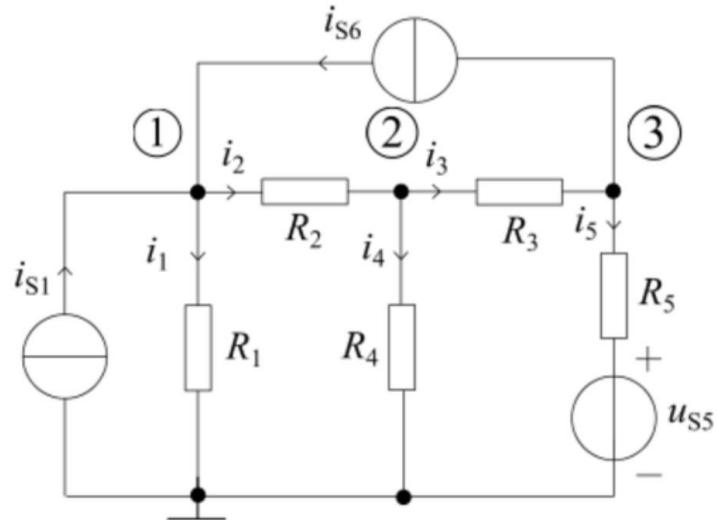
背景知识

- 电路分析基本方法

- 节点电压法

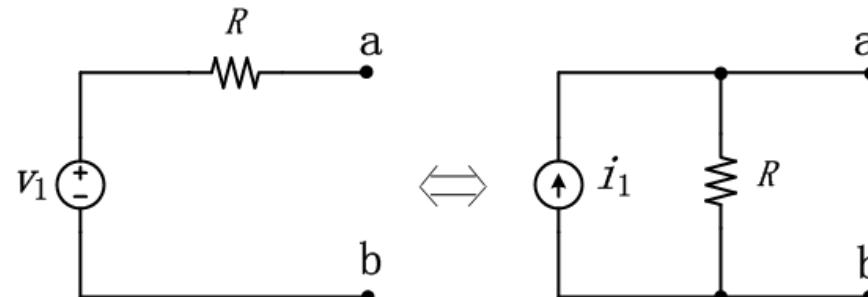
$$G_{n1}U_{n1} + G_{n2}U_{n2} + \dots + G_{nn}U_{nn} = I_{snn}$$

- 网孔电流法



背景知识

- 戴维南等效
 - 戴维南电阻 = 开路电压 / 短路电流
 - 含独立电源的线性电阻单口网络等效成电压源 + 内阻
- 诺顿等效
 - 戴维南等效 \leftrightarrow 诺顿等效
 - 独立电流源 + 诺顿等效电阻 (= 戴维南等效电阻)



背景知识

- 拉氏变换

- 将线性常系数微分方程转化为容易处理的线性多项式方程
- 将电流和电压变量的初始值自动引入多项式方程中。

元件	拉式变换
R	R
C	I/sC
L	sL

背景知识

- 转移函数

$$H(s) = \frac{Y(s)}{X(s)}$$

- 零极点

$$H(s) = \frac{K(s+z_1)(s+z_2)\cdots(s+z_n)}{(s+p_1)(s+p_2)\cdots(s+p_m)}$$

零点: $-z_1, -z_2, \dots, -z_n$

极点: $-p_1, -p_2, \dots, -p_m$

背景知识

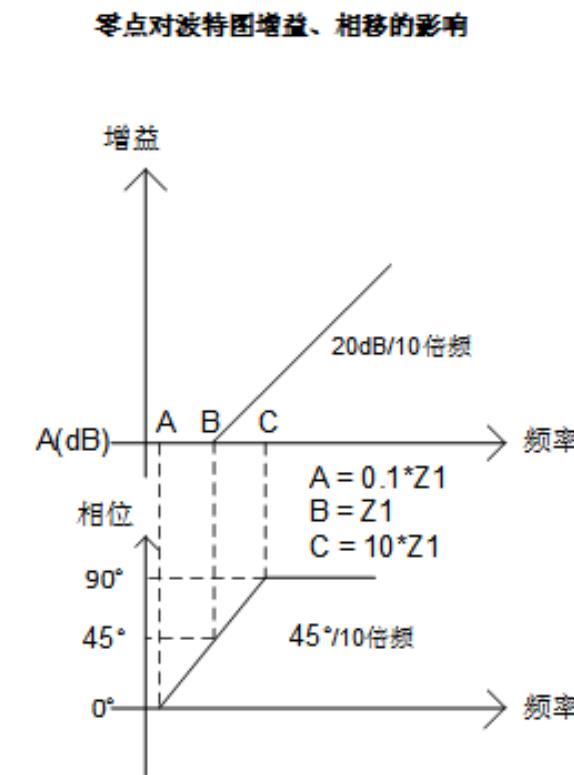
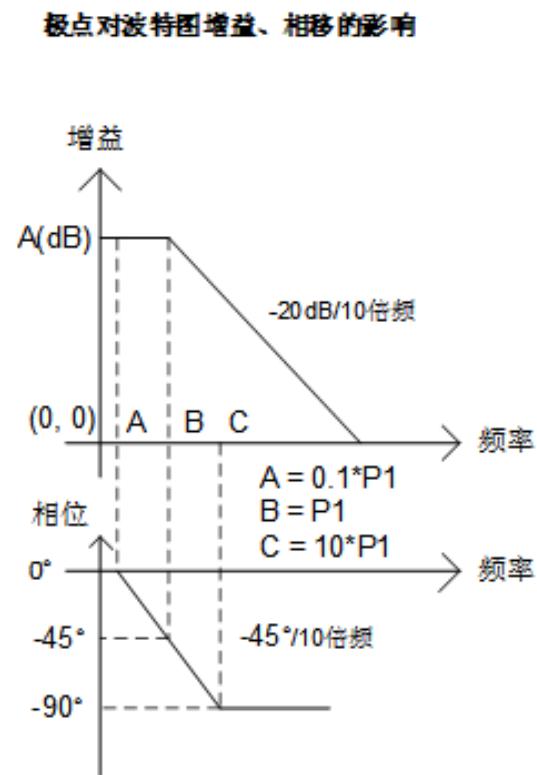
- 稳定性分析

极点： $\left\{ \begin{array}{ll} \text{左半}s\text{平面} \rightarrow h(t) \text{衰减} & \text{稳定系统 (极点在左半}s\text{平面)} \\ \text{右半}s\text{平面} \rightarrow h(t) \text{增长} & \text{非稳定系统 (极点在右半}s\text{平面)} \\ \text{虚轴上} \left\{ \begin{array}{ll} \text{一阶极点} \rightarrow h(t) \text{等幅振荡或阶跃} & \text{临界稳定} \\ \text{二阶极点} \rightarrow h(t) \text{呈增长形式} & \text{不稳定系统} \end{array} \right. \end{array} \right.$

$H(s)$ 的零点只影响 $h(t)$ 的幅度和相位，而不影响形状。

背景知识

- 零极点对幅度和相位的影响



背景知识

- 例：低通滤波器

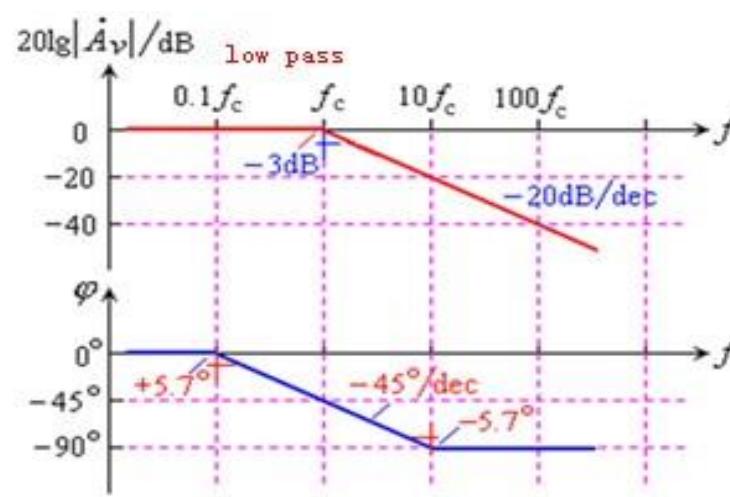
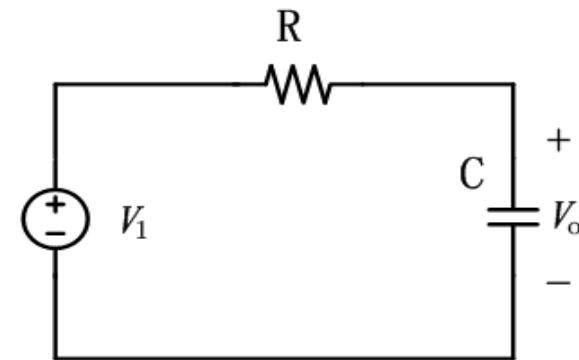
$$H(s) = \frac{\frac{1}{RC}}{s + \frac{1}{RC}}$$

$$|H(j\omega)| = \frac{\frac{1}{RC}}{\sqrt{\omega^2 + (\frac{1}{RC})^2}}$$

$$\theta(j\omega) = -\arctan\left(\frac{\omega}{\frac{1}{RC}}\right)$$

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

ω_c 是截止频率



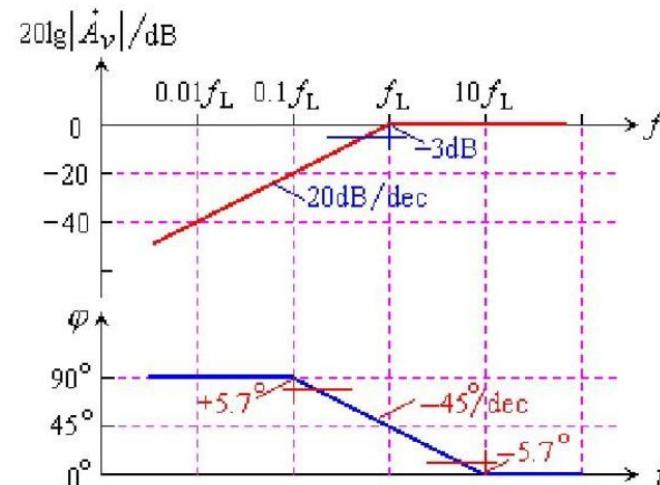
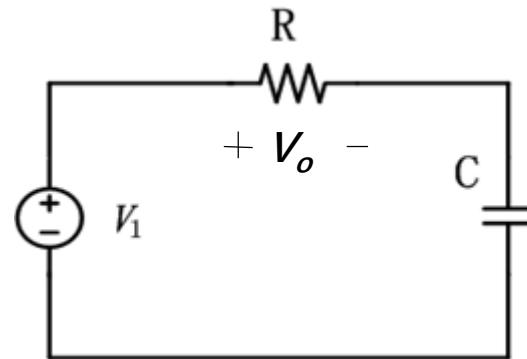
背景知识

- 例：高通滤波器

$$H(s) = \frac{s}{s + \frac{1}{RC}}$$

$$|H(j\omega)| = \frac{\omega}{\sqrt{\omega^2 + (\frac{1}{RC})^2}}$$

$$\theta(j\omega) = 90^\circ - \arctan(\frac{\omega}{\frac{1}{RC}})$$

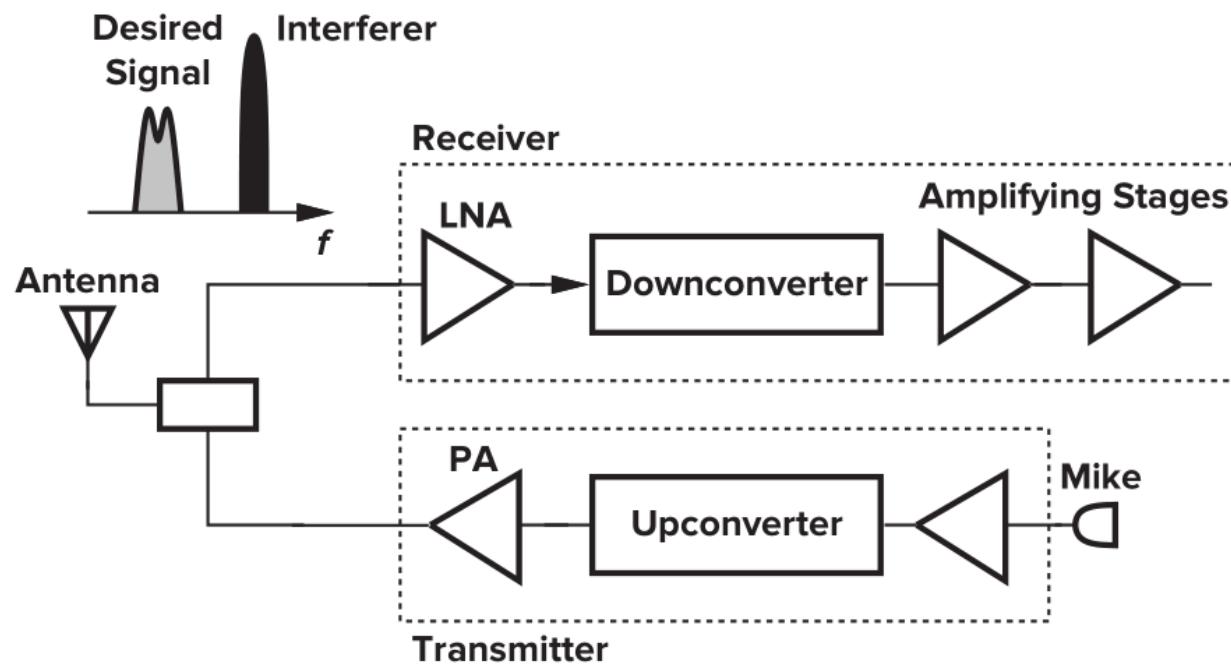


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低频单级放大器

- 前言



通用RF TRANSCIEVER架构

低频单级放大器

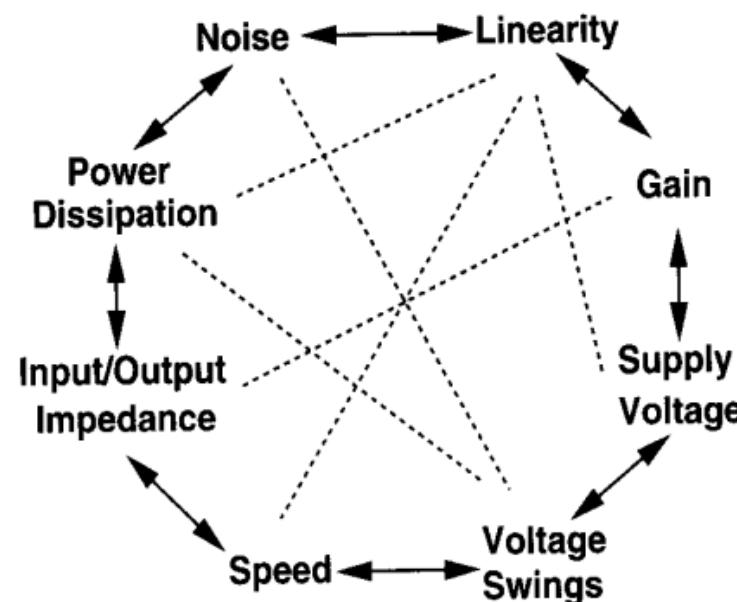
- 输入输出特性

$$y(t) \approx a_0 + a_1 x(t) + a_2 x^2(t) + \cdots + a_n x^n(t) \quad x_1 \leq x \leq x_2$$

- 线形输出系统

$$y(t) \approx a_0 + a_1 x(t)$$

- 模拟电路设计的八边形法则

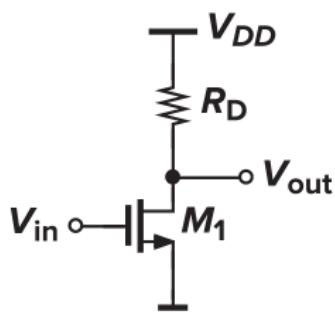


低频单级放大器

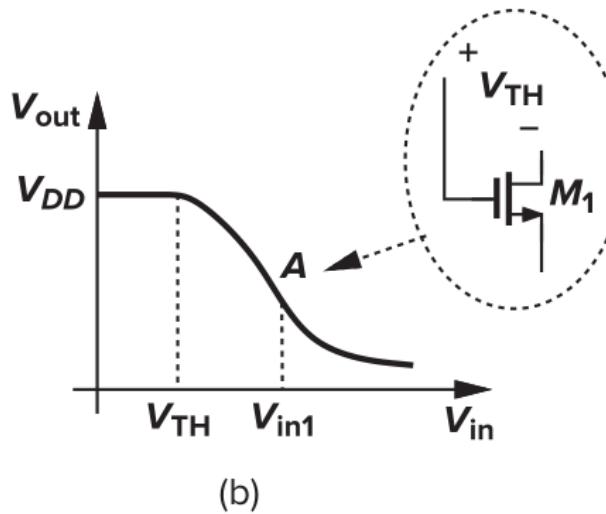
- 共源级放大器
 - 电阻负载
 - 二极管负载
 - 电流源负载
 - 动态负载
 - 源级负反馈

共源级放大器

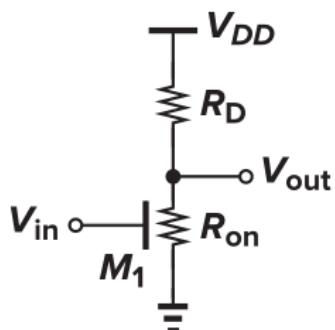
- 电阻负载



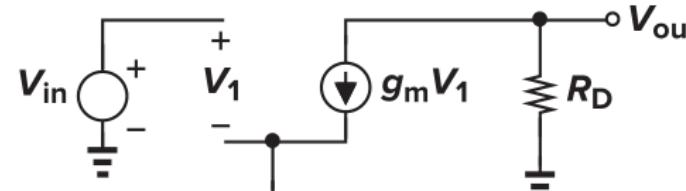
(a)



(b)



(c)



(d)

- (a) 共源级放大器结构
- (b) 输入输出特性
- (c) 工作在线形区的模型
- (d) 饱和区小信号模型

共源级放大器 — 电阻负载

- 放大倍数表达式 (线性区)

$$A_v = \frac{\partial V_{out}}{\partial V_{in}} = \frac{-\mu_n C_{ox} (W/L) R_D V_{out}}{1 + \mu_n C_{ox} (W/L) R_D (V_{in} - V_{TH} - V_{out})}$$

- 深线形区输出电压表达式

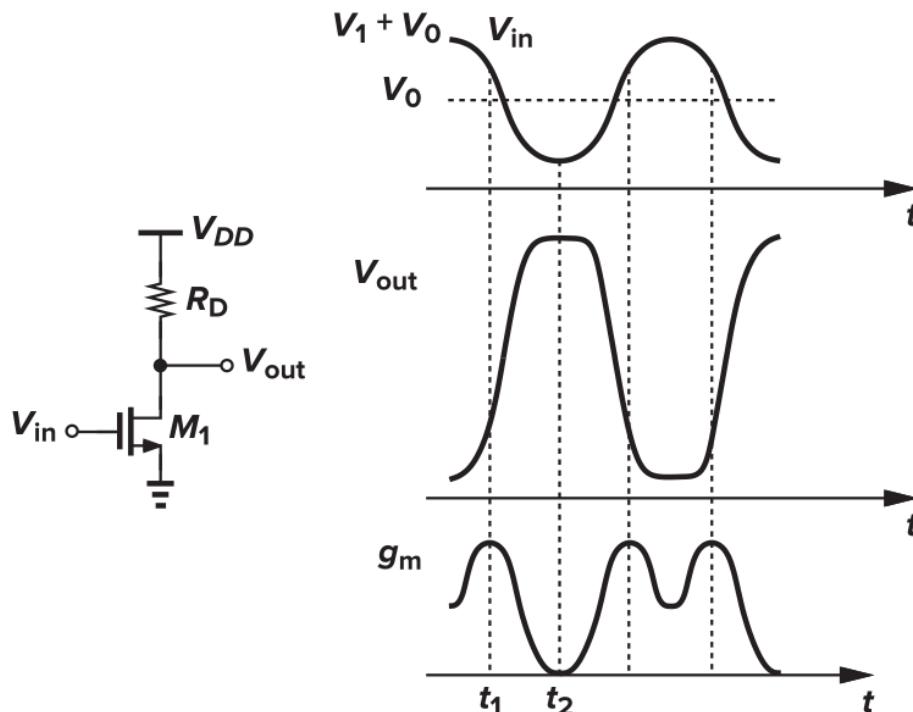
$$V_{out} = V_{DD} \frac{R_{on}}{R_{on} + R_D} = \frac{V_{DD}}{1 + \mu_n C_{ox} \frac{W}{L} R_D (V_{in} - V_{TH})}$$

- 饱和区放大倍数

$$A_v = -R_D \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH}) = -g_m R_D$$

例1

- 如果 $V_{in} = V_1 \cos \omega t + V_0$, V_1 足够大可以使晶体管 M_1 关闭或进入线性区，画出 g_m 与时间的草图。



g_m 随着大信号的变化而变化!

放大倍数推导 (续)

$$V_{out} = V_{DD} - R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2 (1 + \lambda V_{out})$$

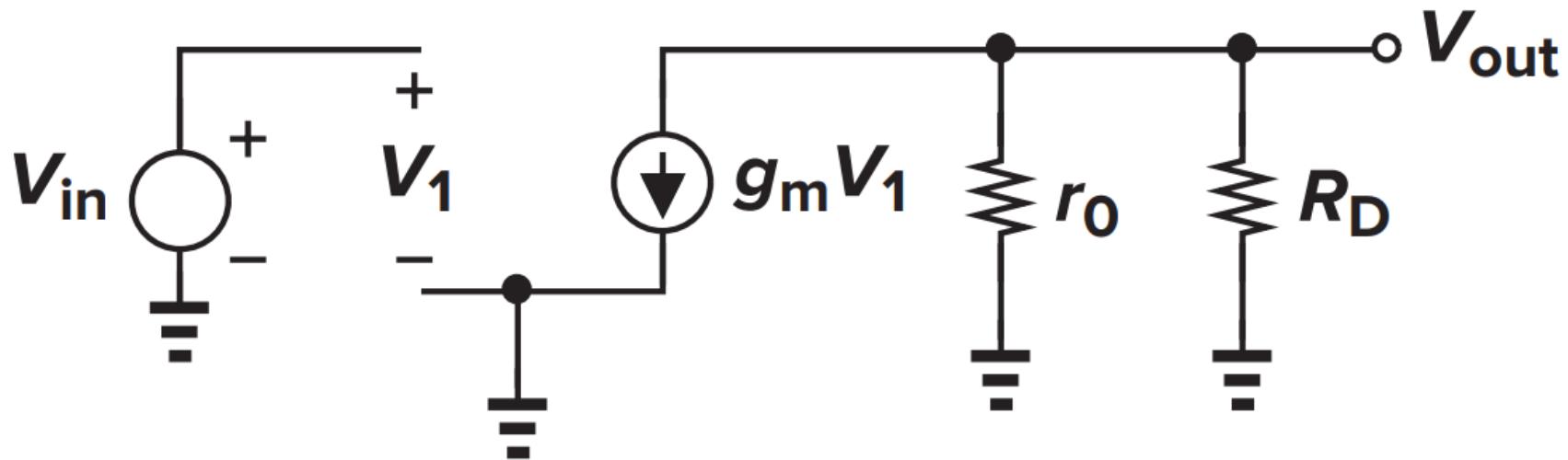
求导: $\frac{\partial V_{out}}{\partial V_{in}} = -R_D \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})(1 + \lambda V_{out})$

$$-R_D \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH})^2 \lambda \frac{\partial V_{out}}{\partial V_{in}}$$

已知: $(1/2) \mu_n C_{ox} (W/L) (V_{in} - V_{TH})^2 \lambda = 1/r_O$

因此 $A_v = -R_D g_m - \frac{R_D}{r_O} A_v \iff A_v = -g_m \frac{r_O R_D}{r_O + R_D}$

小信号电路

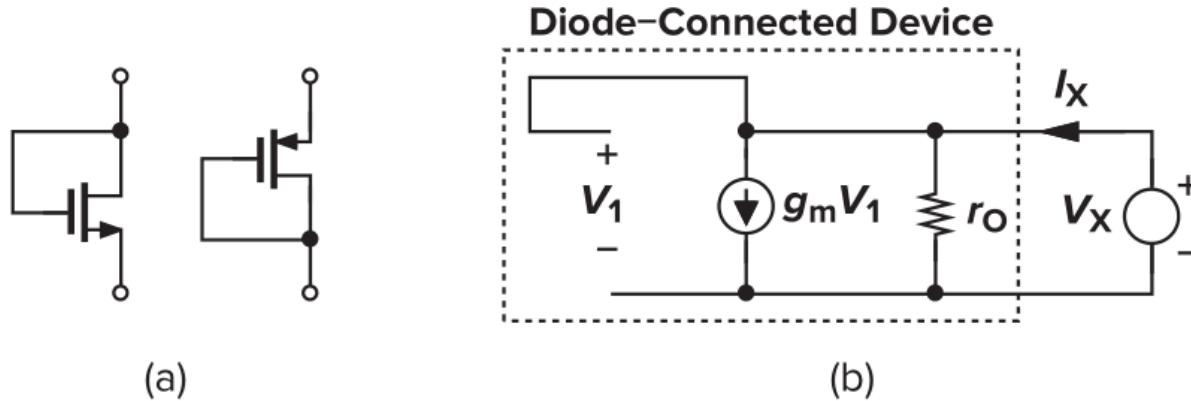


$$A_v = -g_m \frac{r_o R_D}{r_o + R_D}$$

低频单级放大器

- 共源级放大器
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 - 二极管负载
 - 电流源负载
 - 动态负载
 - 源级负反馈

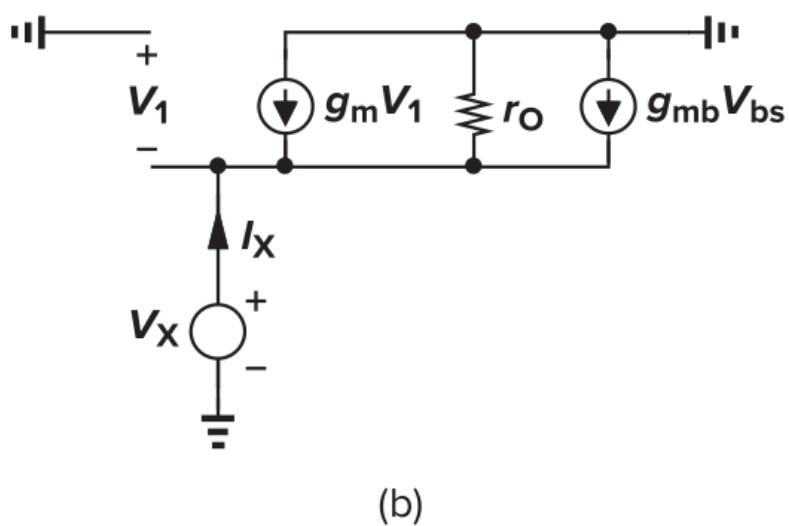
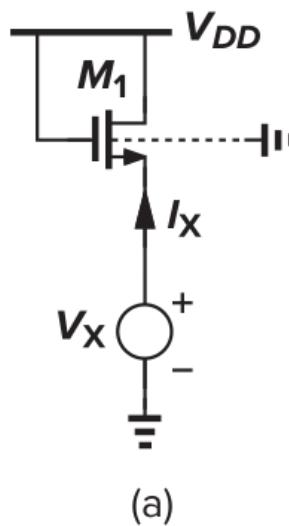
原理



$$V_1 = V_X$$

$$I_X = \frac{V_X}{r_o} + g_m V_X \quad \longrightarrow \quad \frac{V_X}{I_X} \approx \frac{1}{g_m}$$

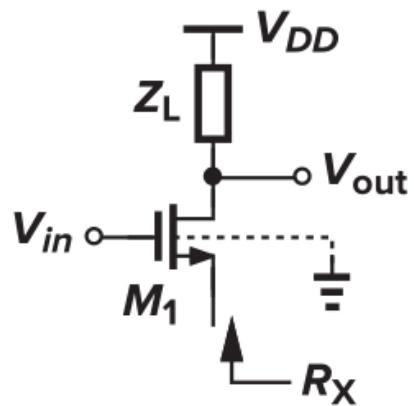
源端负载



$$\begin{aligned}\frac{V_X}{I_X} &= \frac{1}{g_m + g_{mb} + r_O^{-1}} \\ &= \frac{1}{g_m + g_{mb}} \| r_O \\ &\approx \frac{1}{g_m + g_{mb}}\end{aligned}$$

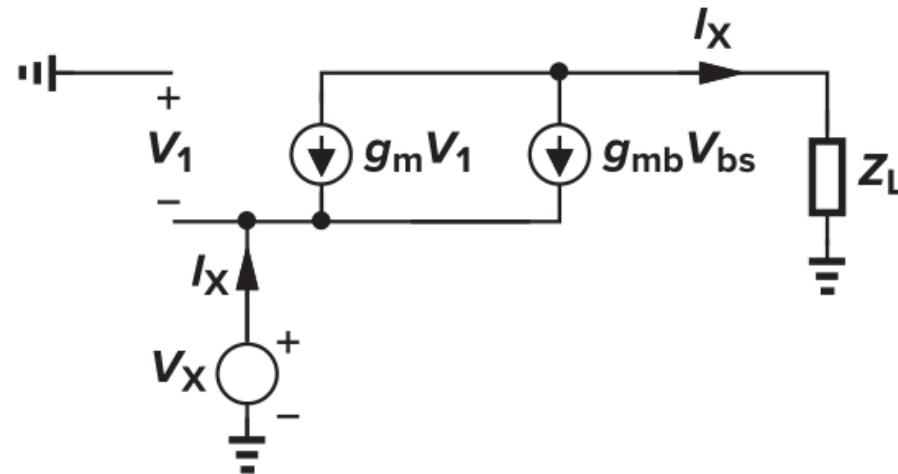
例2

- $\lambda=0$



(a)

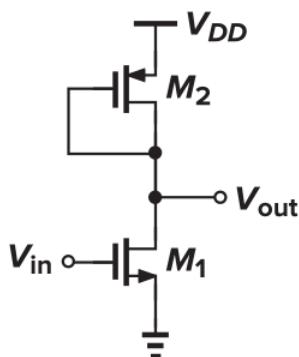
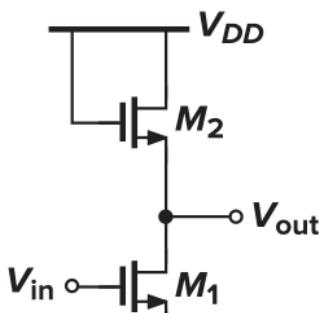
$$(g_m + g_{mb})V_X = I_X$$



(b)

$$\frac{V_X}{I_X} = \frac{1}{g_m + g_{mb}}$$

二极管负载放大器



$$A_v = -g_{m1} \frac{1}{g_{m2} + g_{mb2}}$$
$$= -\frac{g_{m1}}{g_{m2}} \frac{1}{1 + \eta}$$

$$A_v = -\frac{\sqrt{2\mu_n C_{ox} (W/L)_1 I_{D1}}}{\sqrt{2\mu_n C_{ox} (W/L)_2 I_{D2}}} \frac{1}{1 + \eta}$$

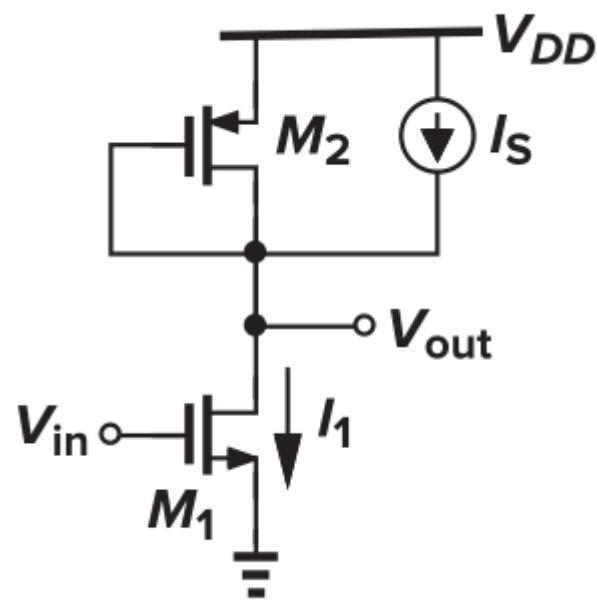
$$A_v = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \frac{1}{1 + \eta}$$

(NMOS负载)

$$A_v = -\sqrt{\frac{\mu_n (W/L)_1}{\mu_p (W/L)_2}}$$

(PMOS负载)

例3



$$I_S = 0.75 I_1$$

$$A_v = -\frac{g_m 1}{g_m 2}$$

$$= -\sqrt{\frac{4\mu_n(W/L)_1}{\mu_p(W/L)_2}}$$

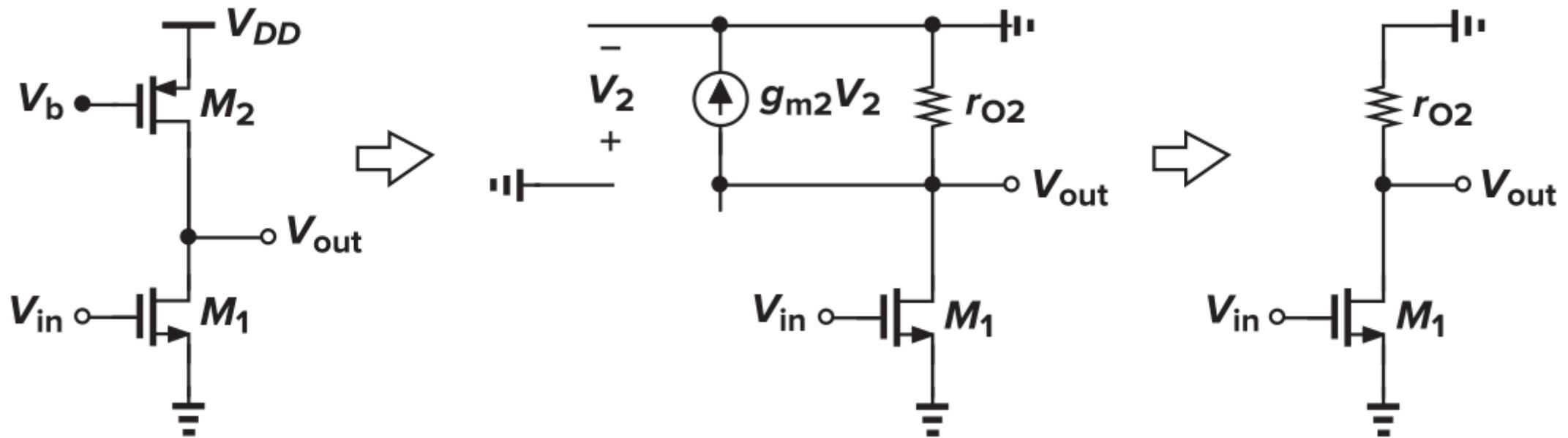
$$\mu_n \left(\frac{W}{L}\right)_1 (V_{GS1} - V_{TH1})^2 = 4\mu_p \left(\frac{W}{L}\right)_2 (V_{GS2} - V_{TH2})^2$$

$$\frac{|V_{GS2} - V_{TH2}|}{V_{GS1} - V_{TH1}} = \frac{A_v}{4}$$

低频单级放大器

- 共源级放大器
 - 电阻负载
 - 二极管负载
 - **电流源负载**
 - 动态负载
 - 源级负反馈

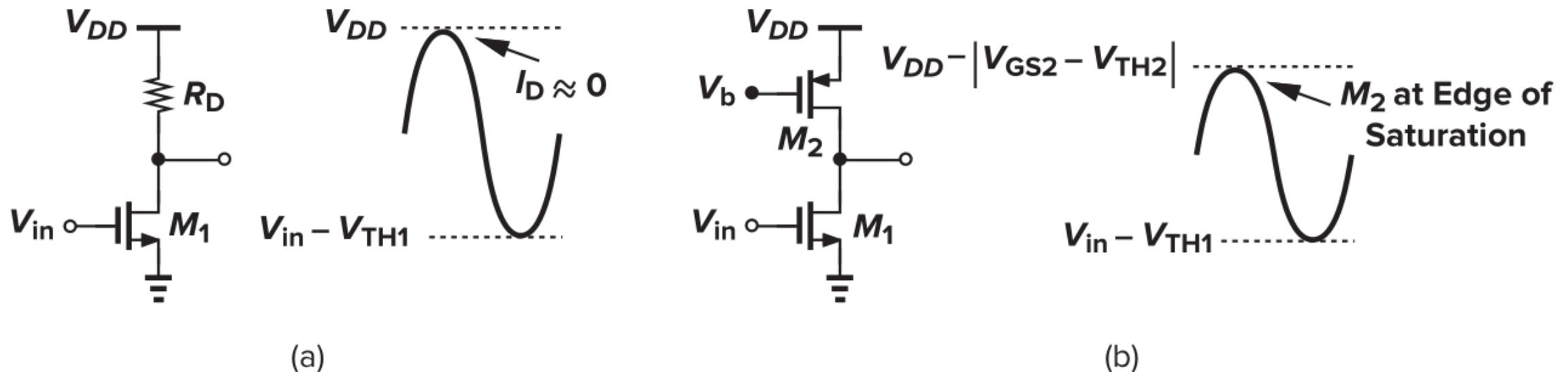
原理



$$A_v = -g_{m1}(r_{O1} \parallel r_{O2})$$

例4

- 比较电阻负载和电流源负载的输出摆幅

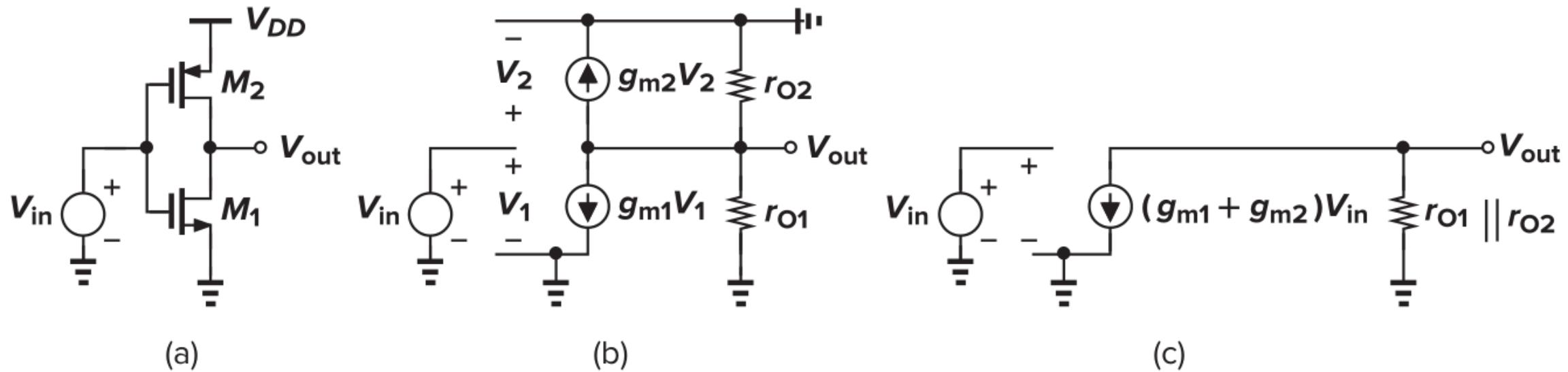


电流源负载的摆幅要小于电阻负载!

低频单级放大器

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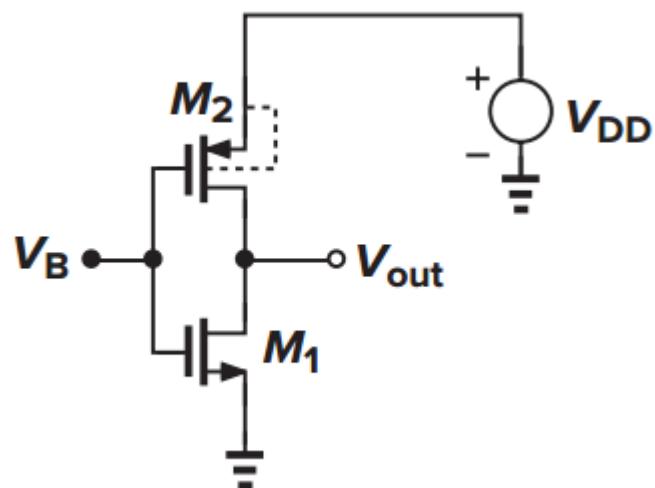
原理



$$A_v = -(g_{m1} + g_{m2})(r_{o1} || r_{o2}) = -g_m r_o \Big|_{g_{m1}=g_{m2}, r_{o1}=r_{o2}}$$

动态负载对VDD的敏感性

$$V_{GS1} + |V_{GS2}| = V_{DD}$$



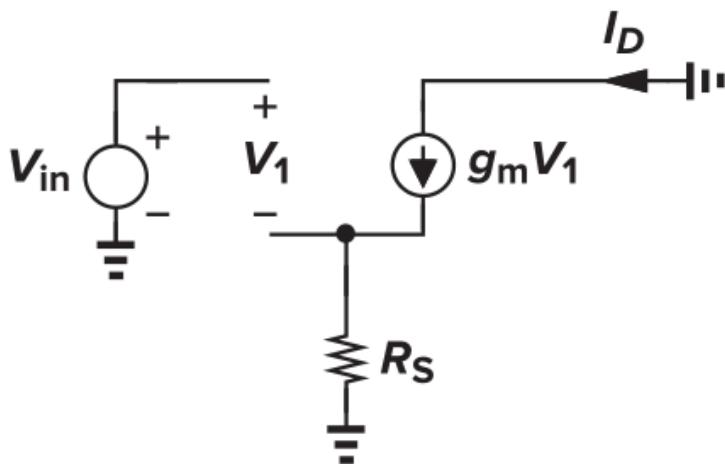
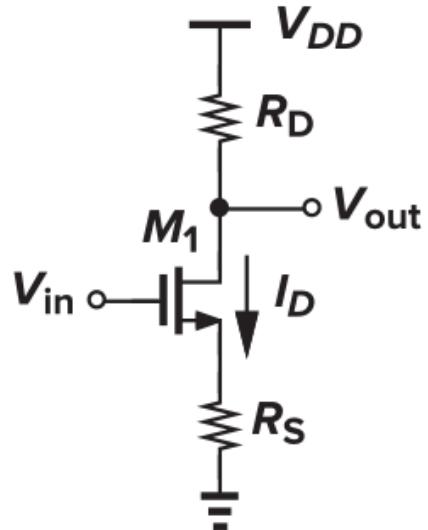
$$\begin{aligned}\frac{V_{out}}{V_{DD}} &= \frac{g_{m2}r_{O2} + 1}{r_{O2} + r_{O1}} r_{O1} \\ &= \left(g_{m2} + \frac{1}{r_{O2}} \right) (r_{O1} || r_{O2})\end{aligned}$$

很低的电源抑制能力!

低频单级放大器

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原理



$$G_m = \frac{\partial I_D}{\partial V_{in}} = \frac{\partial f}{\partial V_{GS}} \frac{\partial V_{GS}}{\partial V_{in}}$$

$$G_m = \left(1 - R_S \frac{\partial I_D}{\partial V_{in}}\right) \frac{\partial f}{\partial V_{GS}}$$

$$G_m = \frac{g_m}{1 + g_m R_S}$$

$$A_v = -G_m R_D$$

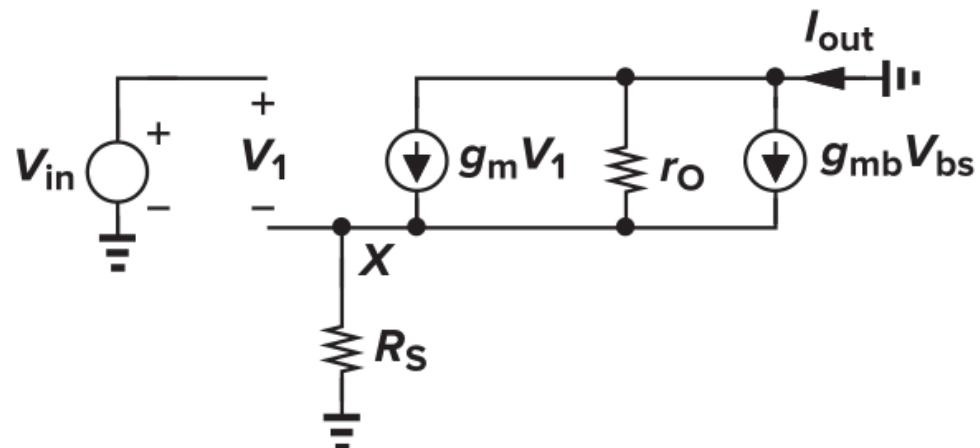
$$= \frac{-g_m R_D}{1 + g_m R_S}$$

完整的小信号模型

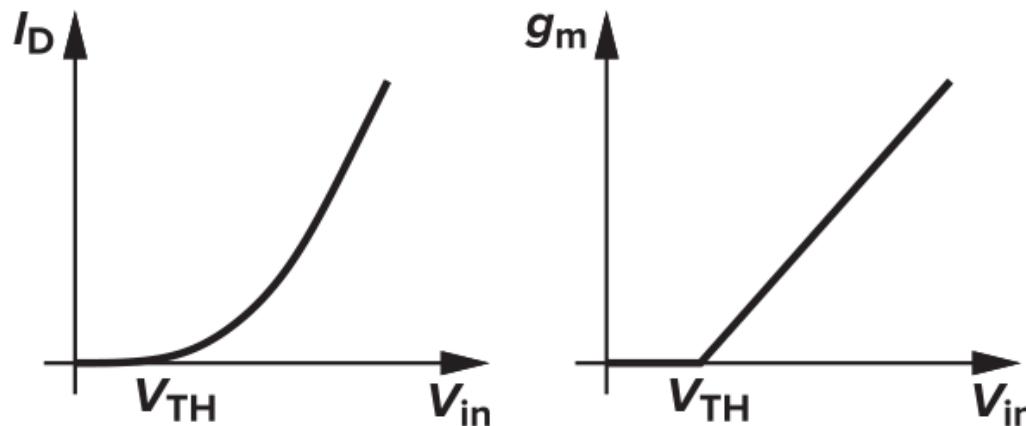
$$I_{out} = g_m V_1 - g_{mb} V_X - \frac{I_{out} R_S}{r_O}$$

$$= g_m (V_{in} - I_{out} R_S) + g_{mb} (-I_{out} R_S) - \frac{I_{out} R_S}{r_O}$$

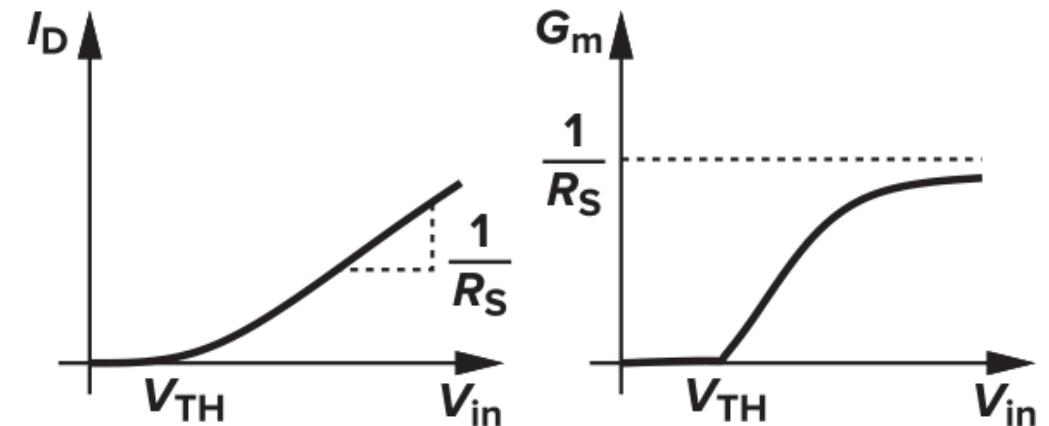
$$\begin{aligned} G_m &= \frac{I_{out}}{V_{in}} \\ &= \frac{g_m r_O}{R_S + [1 + (g_m + g_{mb}) R_S] r_O} \end{aligned}$$



有 R_S 和没有 R_S 的比较

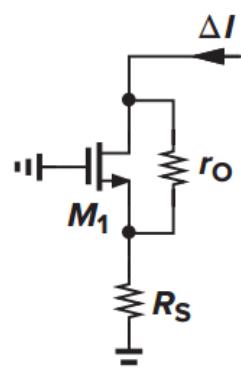
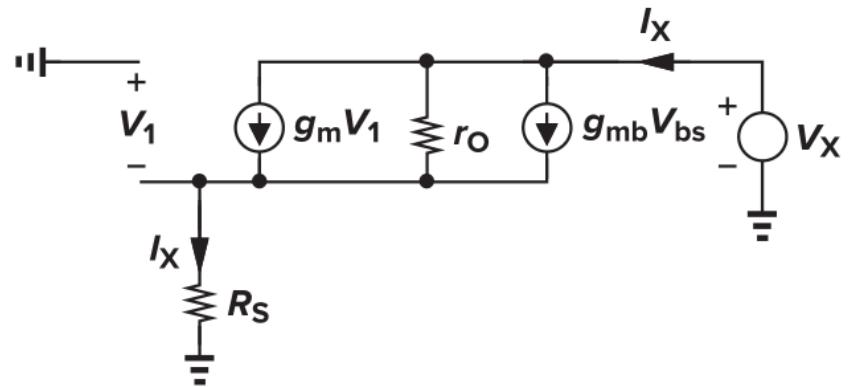


没有 R_S

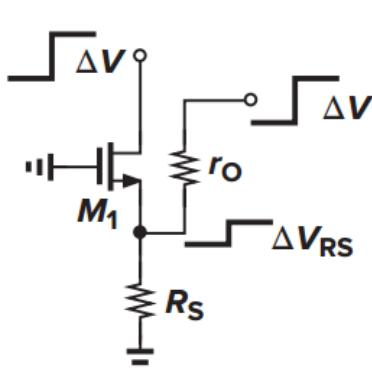


有 R_S

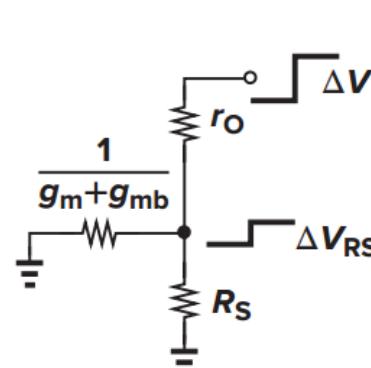
输出电阻



(a)



(b)



(c)

$$r_O[I_X + (g_m + g_{mb})R_SI_X] + I_XR_S = V_X$$

$$R_{out} = [1 + (g_m + g_{mb})R_S]r_O + R_S$$

$$= [1 + (g_m + g_{mb})r_O]R_S + r_O$$

$$R_{out} \approx (g_m + g_{mb})r_O R_S + r_O$$

$$= [1 + (g_m + g_{mb})R_S]r_O$$

一般情况的推导

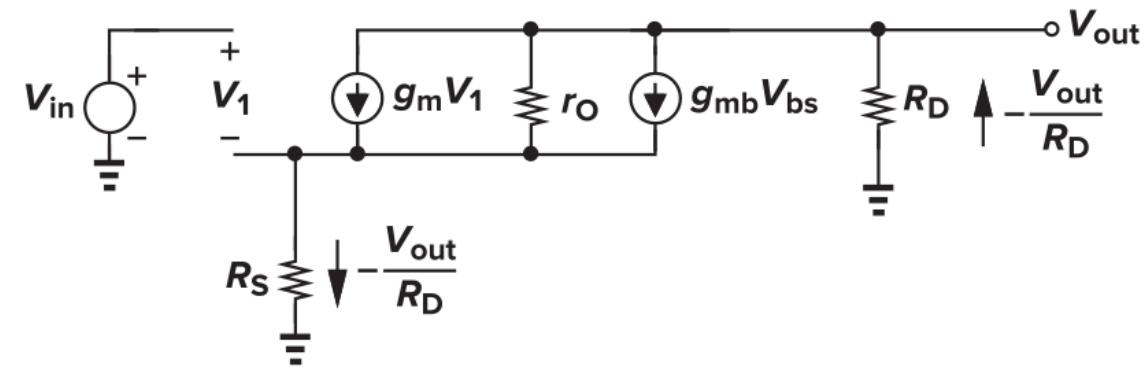
$$I_{ro} = -\frac{V_{out}}{R_D} - (g_m V_1 + g_{mb} V_{bs})$$

$$= -\frac{V_{out}}{R_D} - \left[g_m \left(V_{in} + V_{out} \frac{R_S}{R_D} \right) + g_{mb} V_{out} \frac{R_S}{R_D} \right]$$

$$V_{out} = I_{ro} r_O - \frac{V_{out}}{R_D} R_S$$

$$= -\frac{V_{out}}{R_D} r_O - \left[g_m \left(V_{in} + V_{out} \frac{R_S}{R_D} \right) + g_{mb} V_{out} \frac{R_S}{R_D} \right] r_O - V_{out} \frac{R_S}{R_D}$$

$$\frac{V_{out}}{V_{in}} = \frac{-g_m r_O R_D}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O} \approx -\frac{R_D}{R_S}$$



一般情况的推导 (续)

$$\begin{aligned} A_v &= \frac{-g_m r_O R_D [R_S + r_O + (g_m + g_{mb}) R_S r_O]}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O} \cdot \frac{1}{R_S + r_O + (g_m + g_{mb}) R_S r_O} \\ &= -\frac{g_m r_O}{R_S + r_O + (g_m + g_{mb}) R_S r_O} \cdot \frac{R_D [R_S + r_O + (g_m + g_{mb}) R_S r_O]}{R_D + R_S + r_O + (g_m + g_{mb}) R_S r_O} \end{aligned}$$



G_m

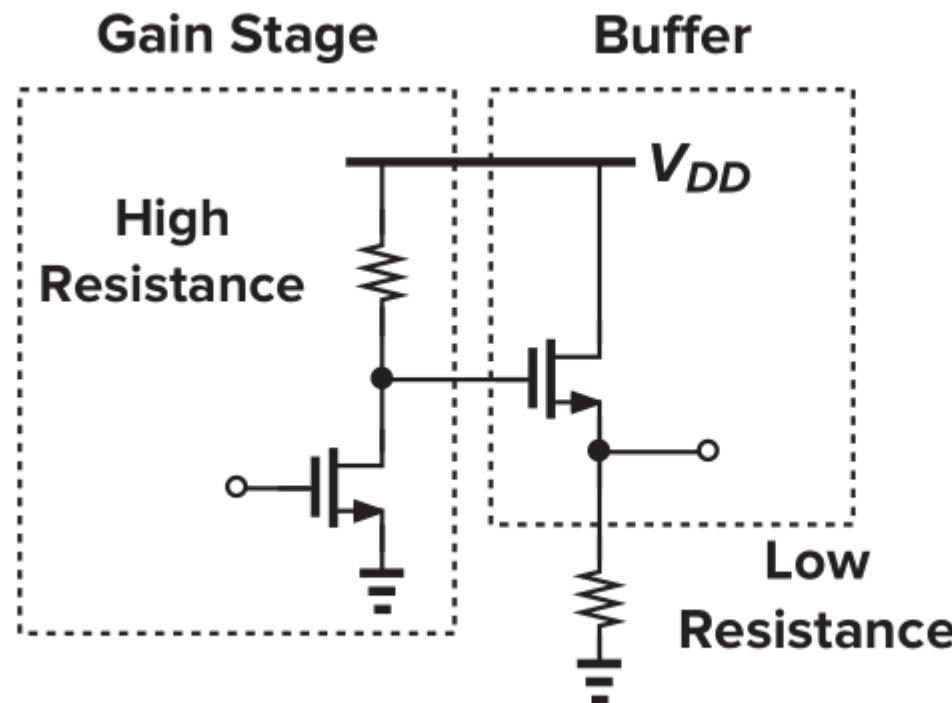
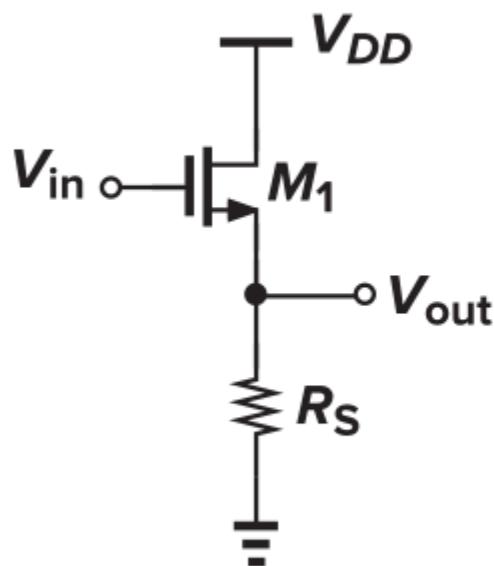


$R_D // R_{out}$

目录

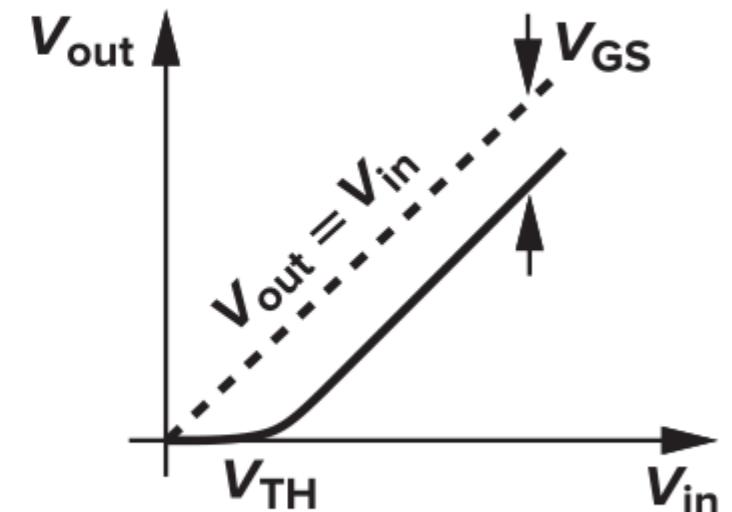
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- 单级放大器频率响应
 - 米勒效应
 - 简单电路频率分析方法

电压缓冲器（源极跟随器）



(a)

(b)



(c)

电压缓冲器 (续)

$$\frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out})^2 R_S = V_{out}$$

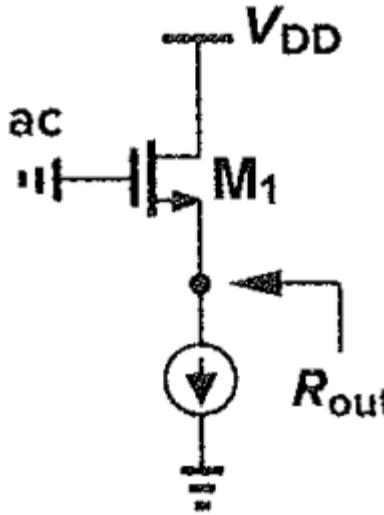
$$\frac{1}{2} \mu_n C_{ox} \frac{W}{L} 2(V_{in} - V_{TH} - V_{out}) \left(1 - \frac{\partial V_{TH}}{\partial V_{in}} - \frac{\partial V_{out}}{\partial V_{in}} \right) R_S = \frac{\partial V_{out}}{\partial V_{in}}$$

因为 $\partial V_{TH}/\partial V_{in} = (\partial V_{TH}/\partial V_{SB})(\partial V_{SB}/\partial V_{in}) = \eta \partial V_{out}/\partial V_{in}$

$$\frac{\partial V_{out}}{\partial V_{in}} = \frac{\mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out}) R_S}{1 + \mu_n C_{ox} \frac{W}{L} (V_{in} - V_{TH} - V_{out}) R_S (1 + \eta)}$$

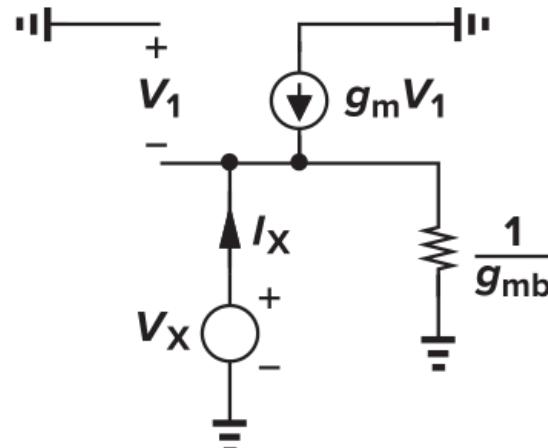
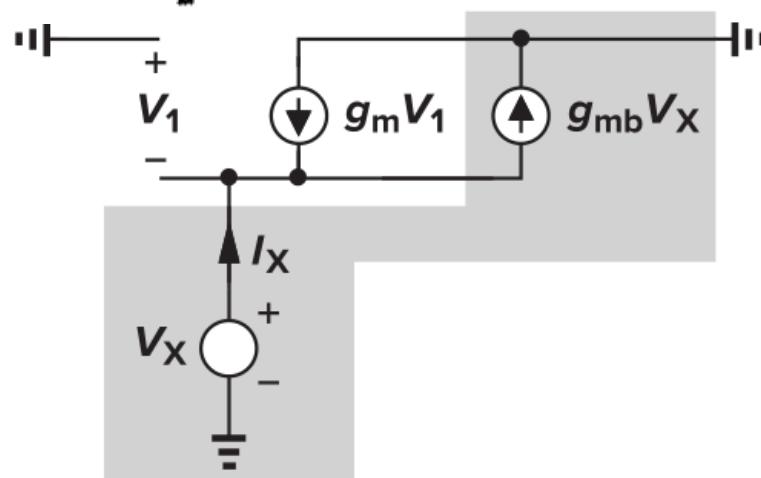
$$A_v = \frac{g_m R_S}{1 + (g_m + g_{mb}) R_S}$$

输出电阻

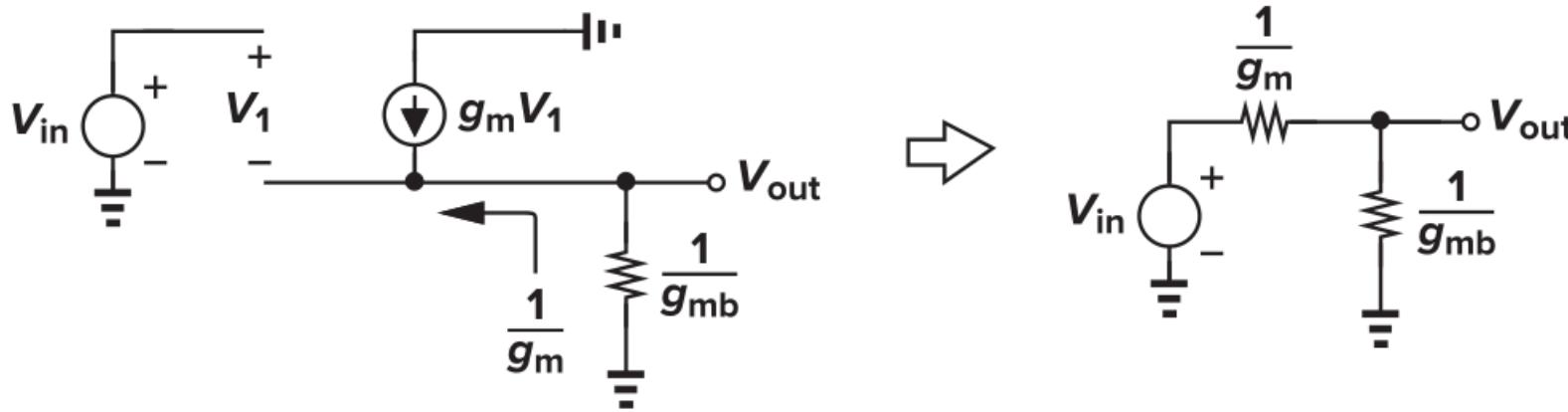


$$I_X - g_m V_X - g_{mb} V_X = 0$$

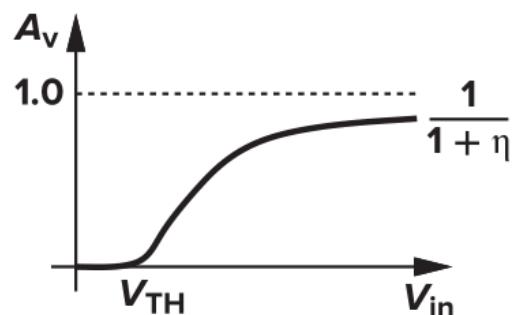
$$R_{out} = \frac{1}{g_m + g_{mb}}$$



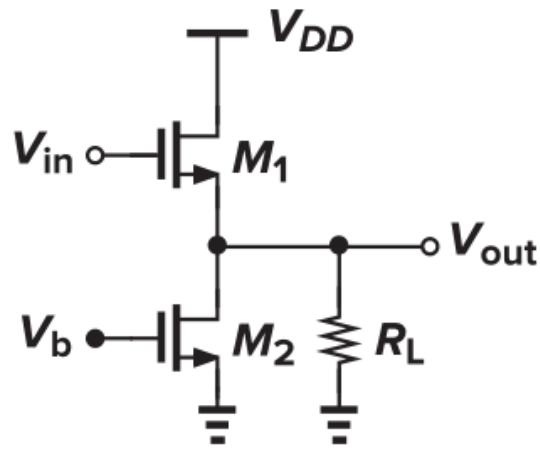
放大倍数



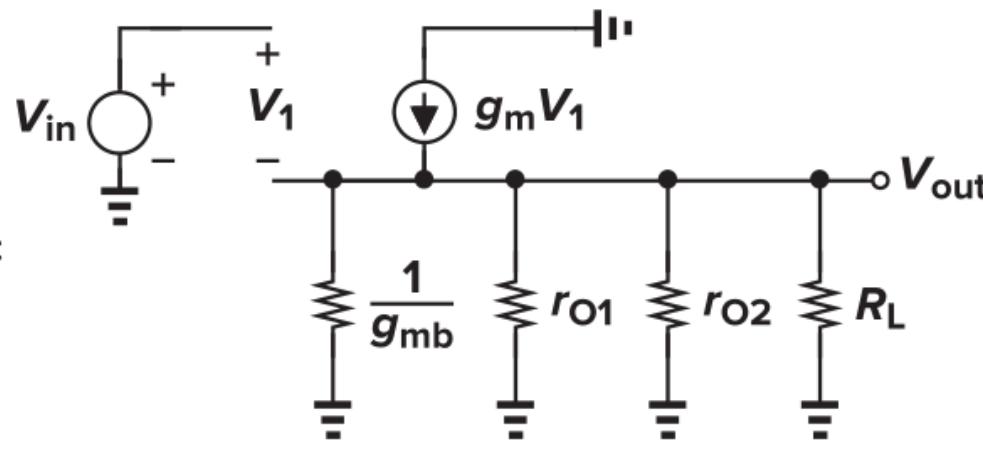
$$A_v = \frac{\frac{1}{g_{mb}}}{\frac{1}{g_m} + \frac{1}{g_{mb}}} = \frac{g_m}{g_m + g_{mb}}$$



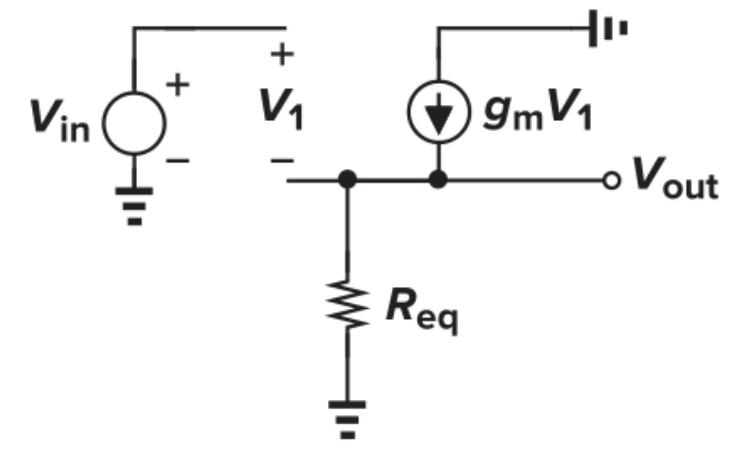
放大倍数 (续)



(a)



(b)

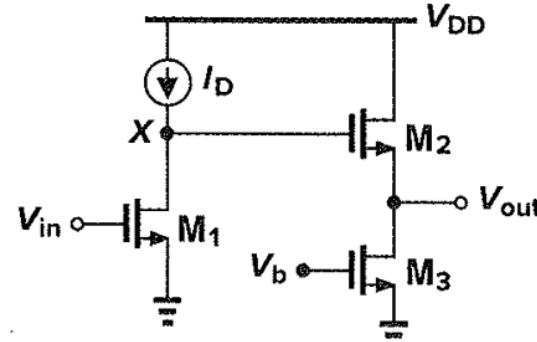


(c)

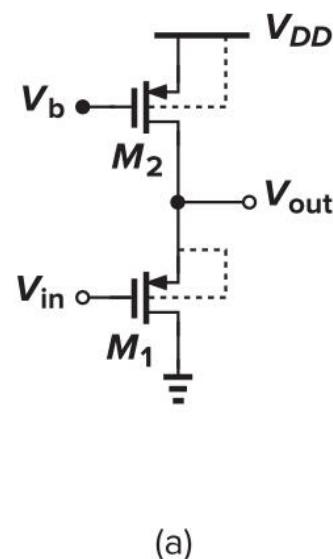
$$A_v = \frac{R_{eq}}{R_{eq} + \frac{1}{g_m}}$$

源极跟随器讨论

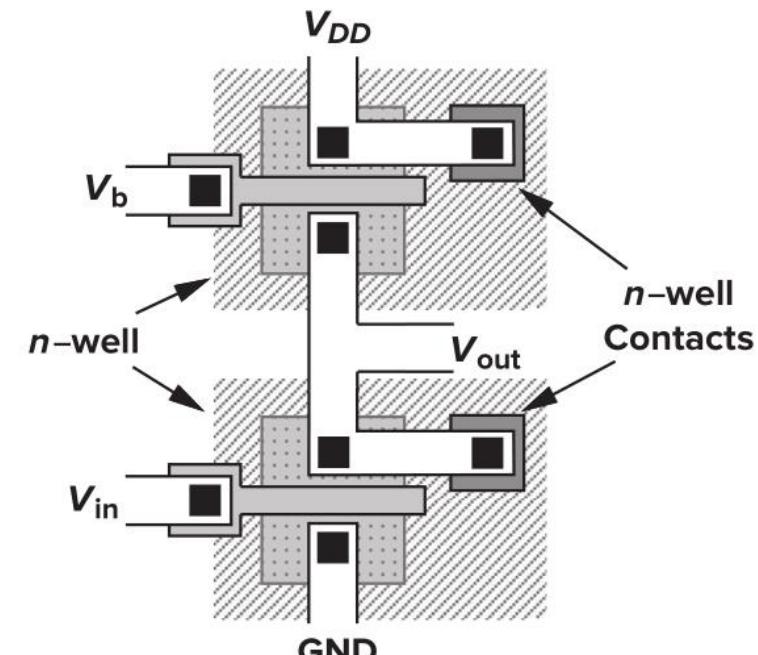
- + 高输入阻抗，中等输出阻抗
- 非线性
 - 阈值电压受源端电压调制
 - r_o 受 V_{DS} 变化的调制
- 电压动态余量小



$$V_X > V_{GS2} + (V_{GS3} - V_{TH3})$$



(a)



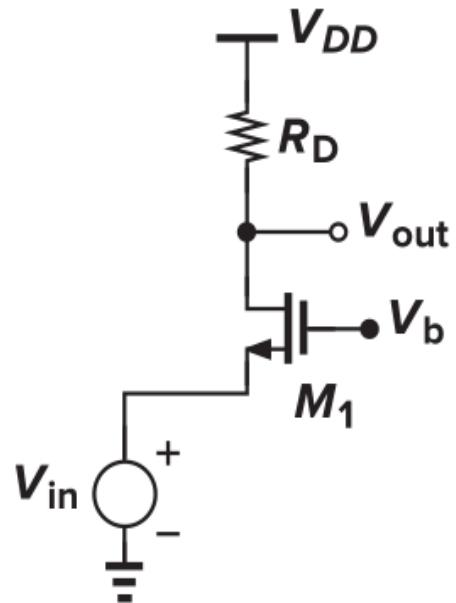
(b)

PMOS源极跟随器

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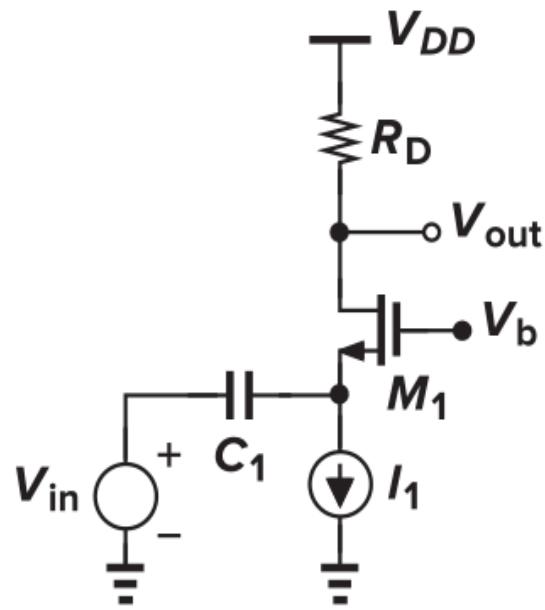
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 - 米勒效应
 - 简单电路频率分析方法

原理



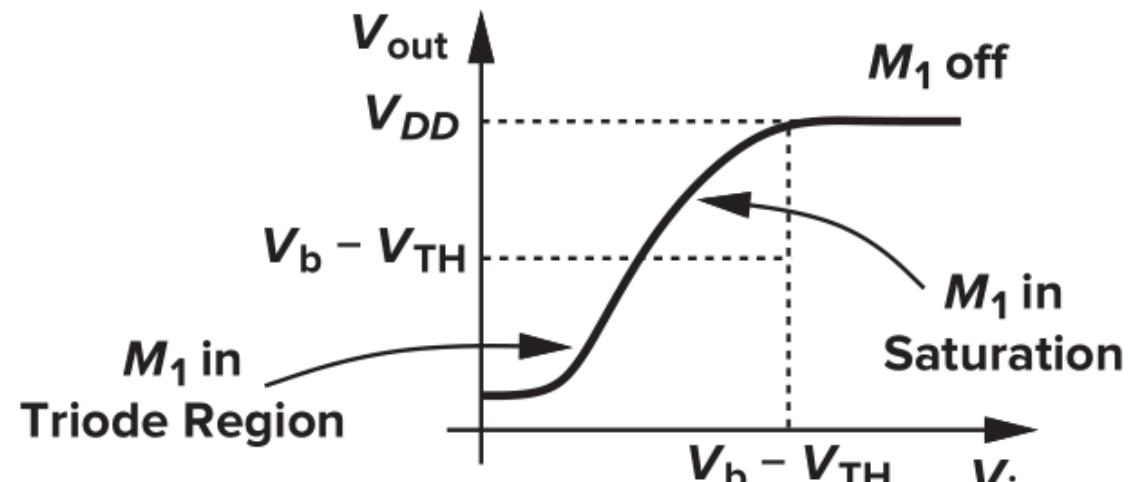
(a)

直接耦合



(b)

电容耦合



输入-输出特性

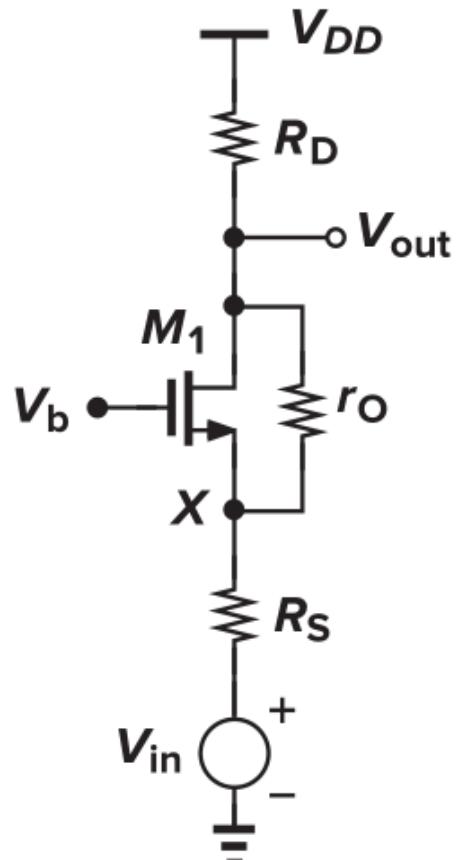
放大倍数

$$V_{out} = V_{DD} - \frac{1}{2}\mu_n C_{ox} \frac{W}{L} (V_b - V_{in} - V_{TH})^2 R_D$$

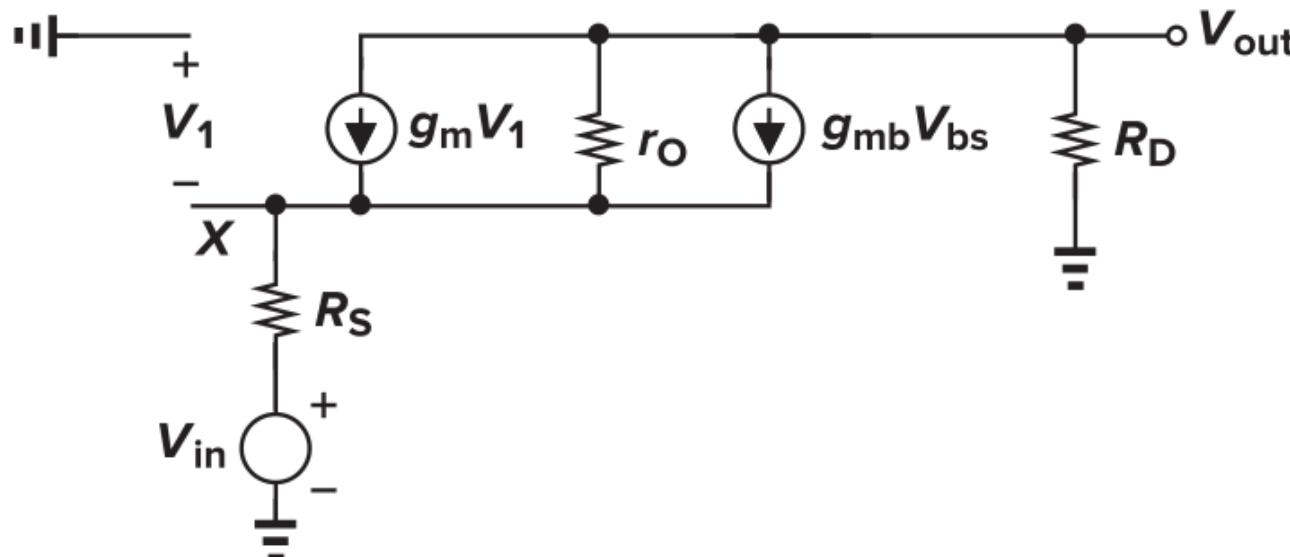
$$\frac{\partial V_{out}}{\partial V_{in}} = -\mu_n C_{ox} \frac{W}{L} (V_b - V_{in} - V_{TH}) \left(-1 - \frac{\partial V_{TH}}{\partial V_{in}} \right) R_D$$

$$\begin{aligned} \frac{\partial V_{out}}{\partial V_{in}} &= \mu_n C_{ox} \frac{W}{L} R_D (V_b - V_{in} - V_{TH})(1 + \eta) \\ &= g_m (1 + \eta) R_D \end{aligned}$$

带内阻的驱动



(a)



(b)

放大倍数

$$V_1 - \frac{V_{out}}{R_D} R_S + V_{in} = 0$$

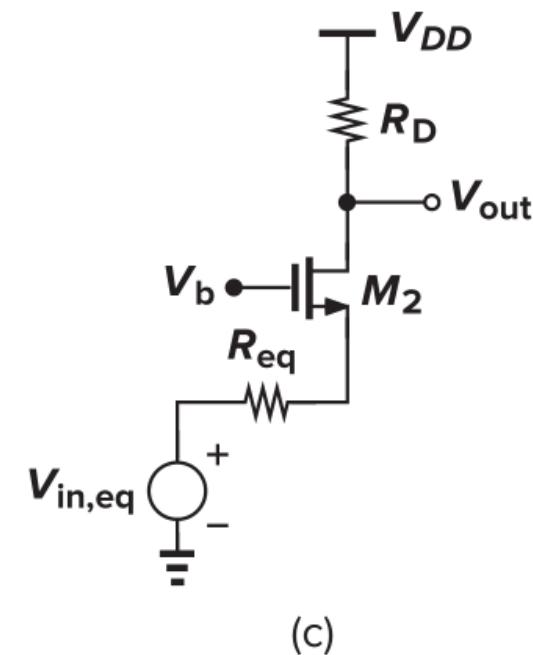
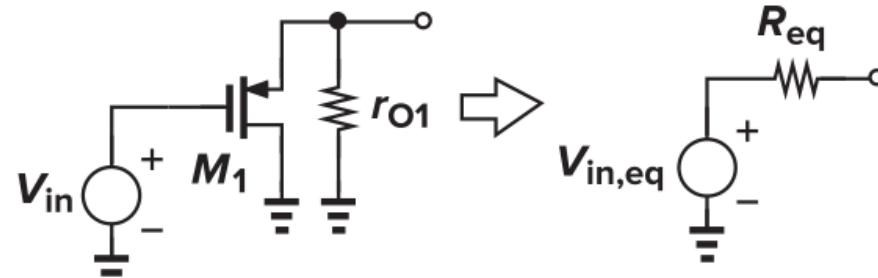
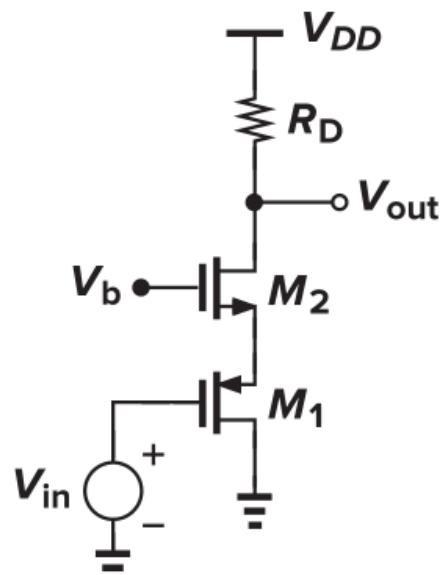
$$r_O \left(\frac{-V_{out}}{R_D} - g_m V_1 - g_{mb} V_1 \right) - \frac{V_{out}}{R_D} R_S + V_{in} = V_{out}$$

$$r_O \left[\frac{-V_{out}}{R_D} - (g_m + g_{mb}) \left(V_{out} \frac{R_S}{R_D} - V_{in} \right) \right] - \frac{V_{out} R_S}{R_D} + V_{in} = V_{out}$$

$$\frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

例5

- 计算增益



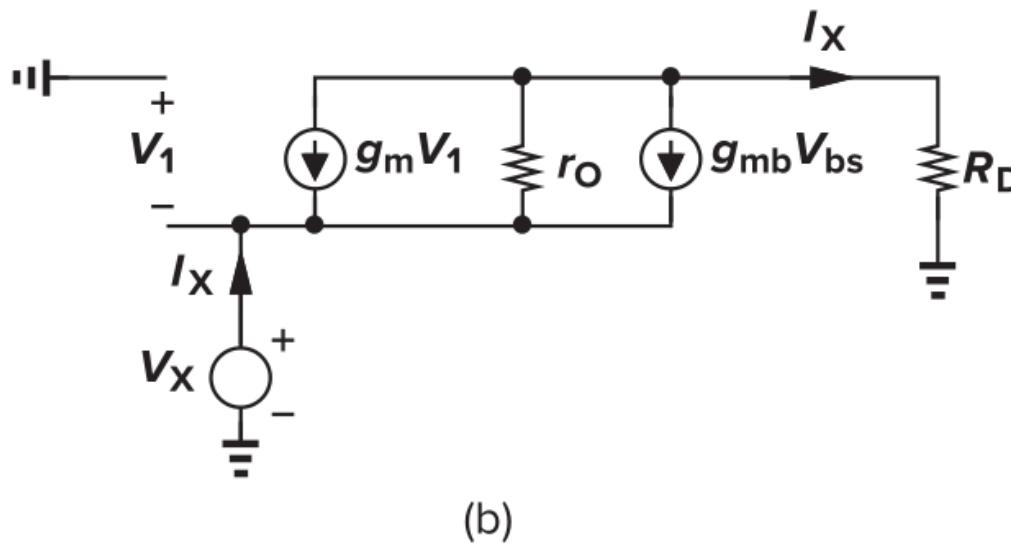
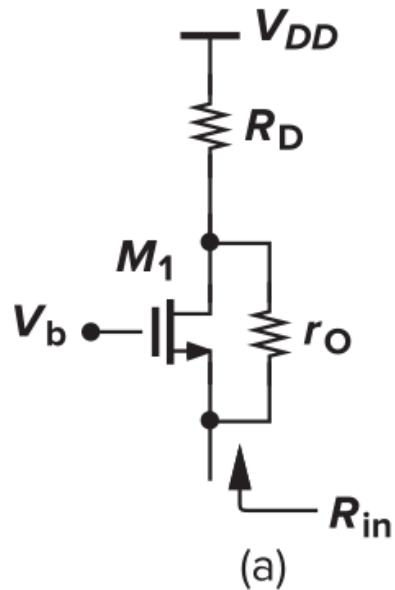
例5 (续)

$$V_{in,eq} = \frac{r_{O1} \left\| \frac{1}{g_{mb1}} \right\| V_{in}}{r_{O1} \left\| \frac{1}{g_{mb1}} + \frac{1}{g_{m1}} \right\|}$$

$$R_{eq} = r_{O1} \left\| \frac{1}{g_{mb1}} \right\| \left\| \frac{1}{g_{m1}} \right\|$$

$$\frac{V_{out}}{V_{in}} = \frac{(g_{m2} + g_{mb2})r_{O2} + 1}{r_{O2} + [1 + (g_{m2} + g_{mb2})r_{O2}] \left(r_{O1} \left\| \frac{1}{g_{mb1}} \right\| \left\| \frac{1}{g_{m1}} \right\| \right) + R_D} R_D \frac{r_{O1} \left\| \frac{1}{g_{mb1}} \right\|}{r_{O1} \left\| \frac{1}{g_{mb1}} + \frac{1}{g_{m1}} \right\|}$$

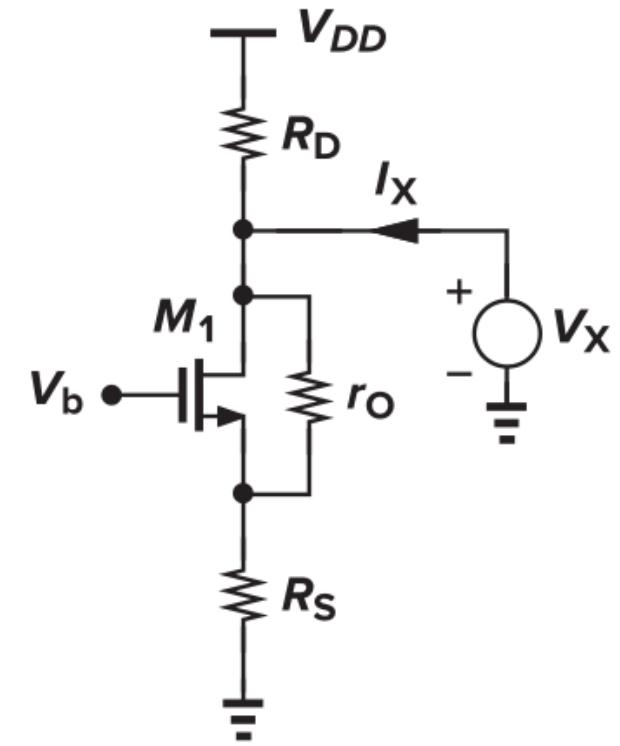
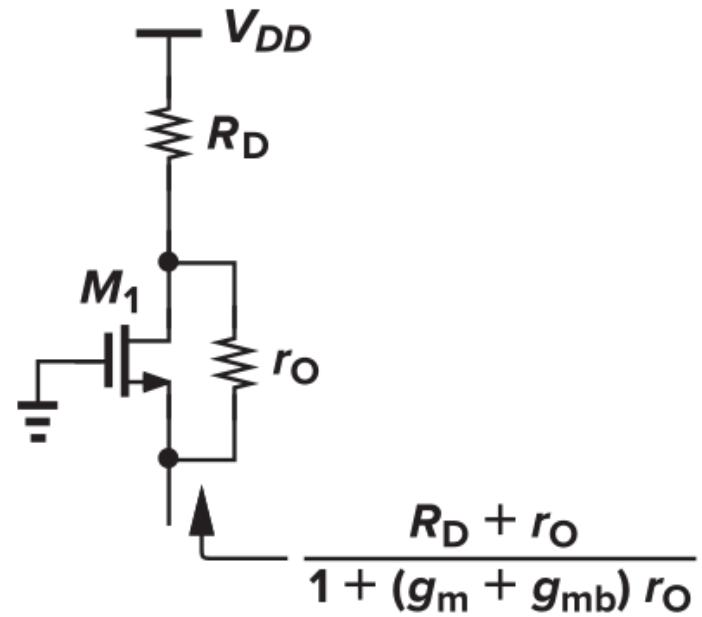
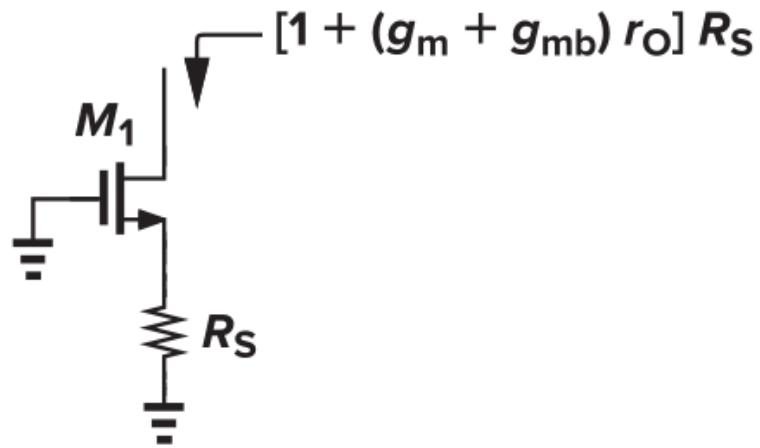
输入电阻



$$R_D I_X + r_O [I_X - (g_m + g_{mb}) V_X] = V_X \quad \rightarrow$$

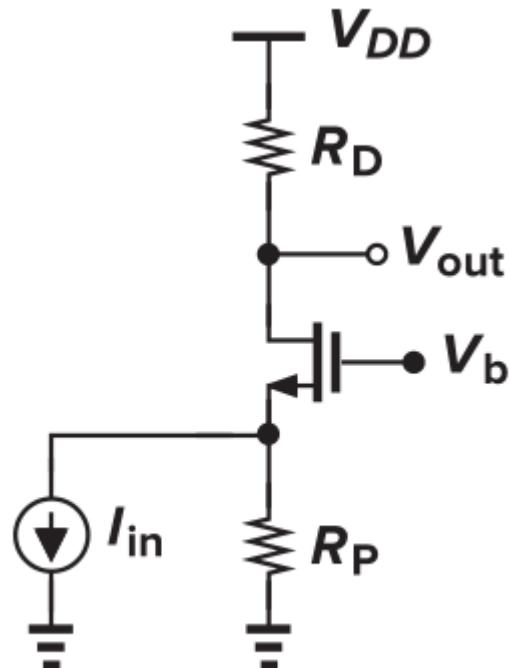
$$\begin{aligned} \frac{V_X}{I_X} &= \frac{R_D + r_O}{1 + (g_m + g_{mb})r_O} \\ &\approx \frac{R_D}{(g_m + g_{mb})r_O} + \frac{1}{g_m + g_{mb}} \end{aligned}$$

输出电阻



$$R_{out} = \{[1 + (g_m + g_{mb})r_O]R_S + r_O\} \parallel R_D$$

例6



$$\frac{V_{out}}{I_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_P + R_P + R_D} R_D R_P$$

↑

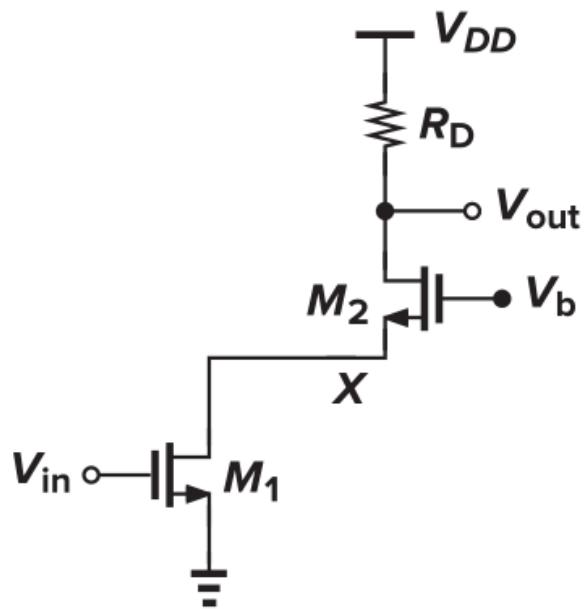
$$\frac{V_{out}}{V_{in}} = \frac{(g_m + g_{mb})r_O + 1}{r_O + (g_m + g_{mb})r_O R_S + R_S + R_D} R_D$$

$$R_{out} = \{[1 + (g_m + g_{mb})r_O]R_P + r_O\} \parallel R_D$$

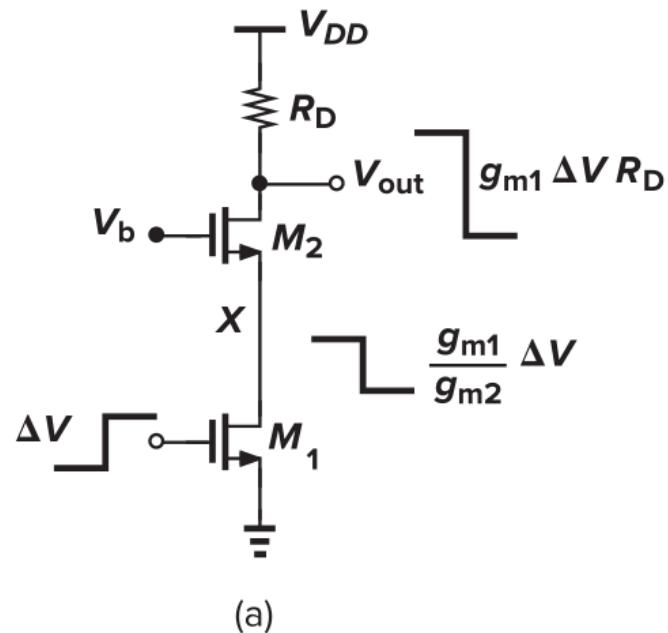
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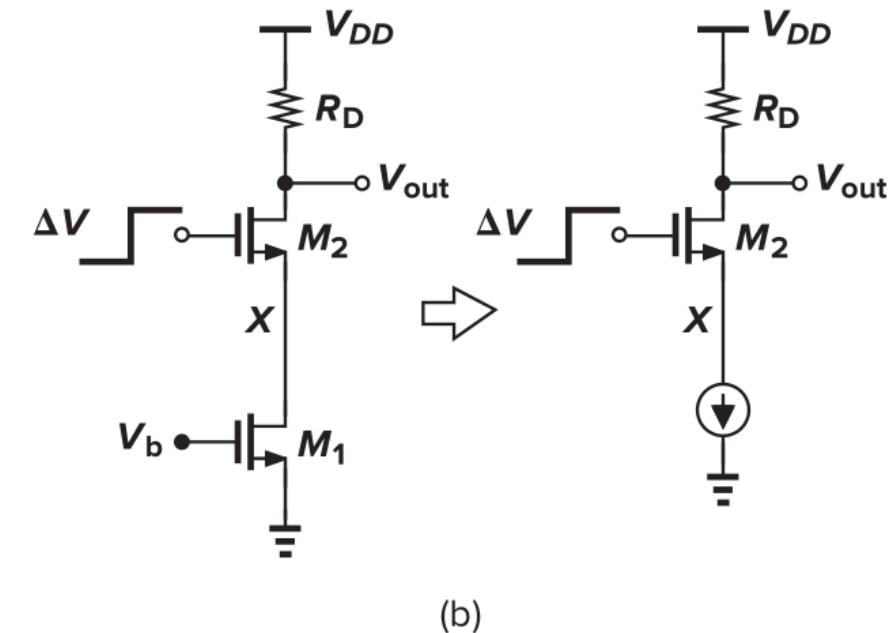
Cascode原理



原理图

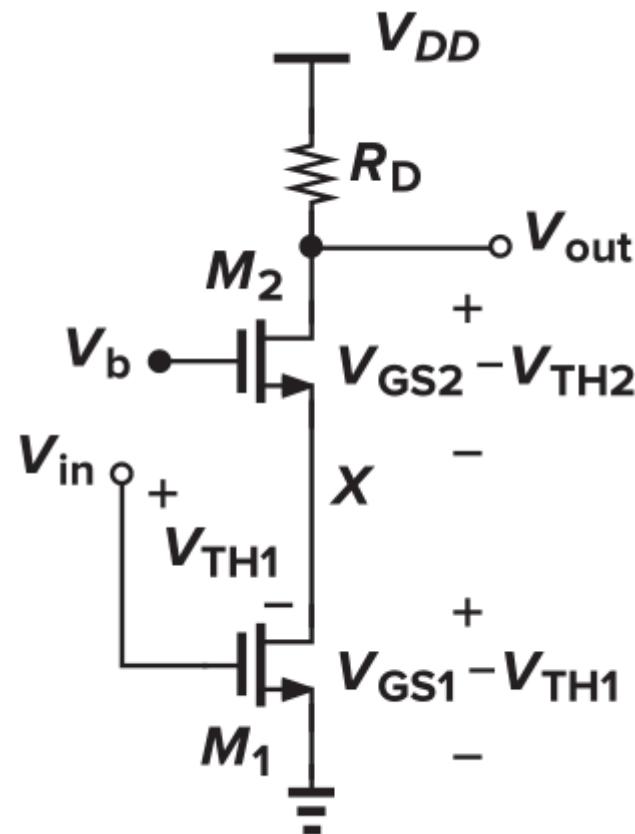


M₁作为输入端



M₂作为输入端

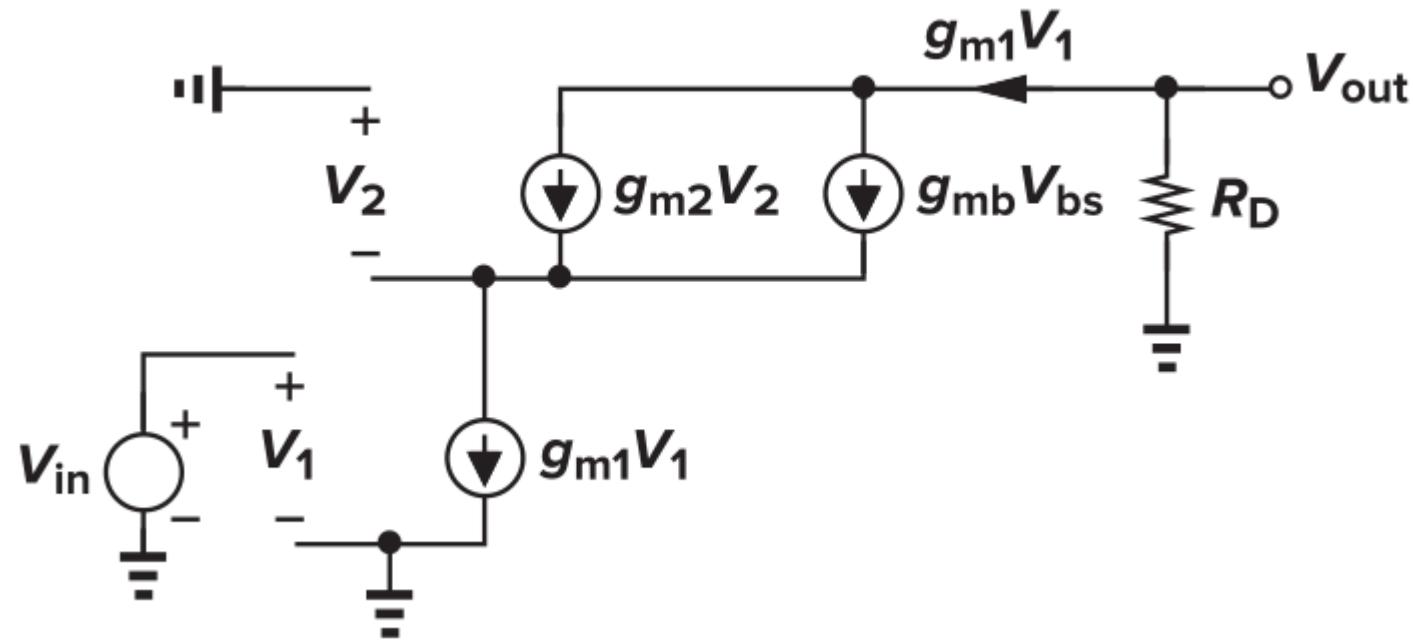
电压偏置条件



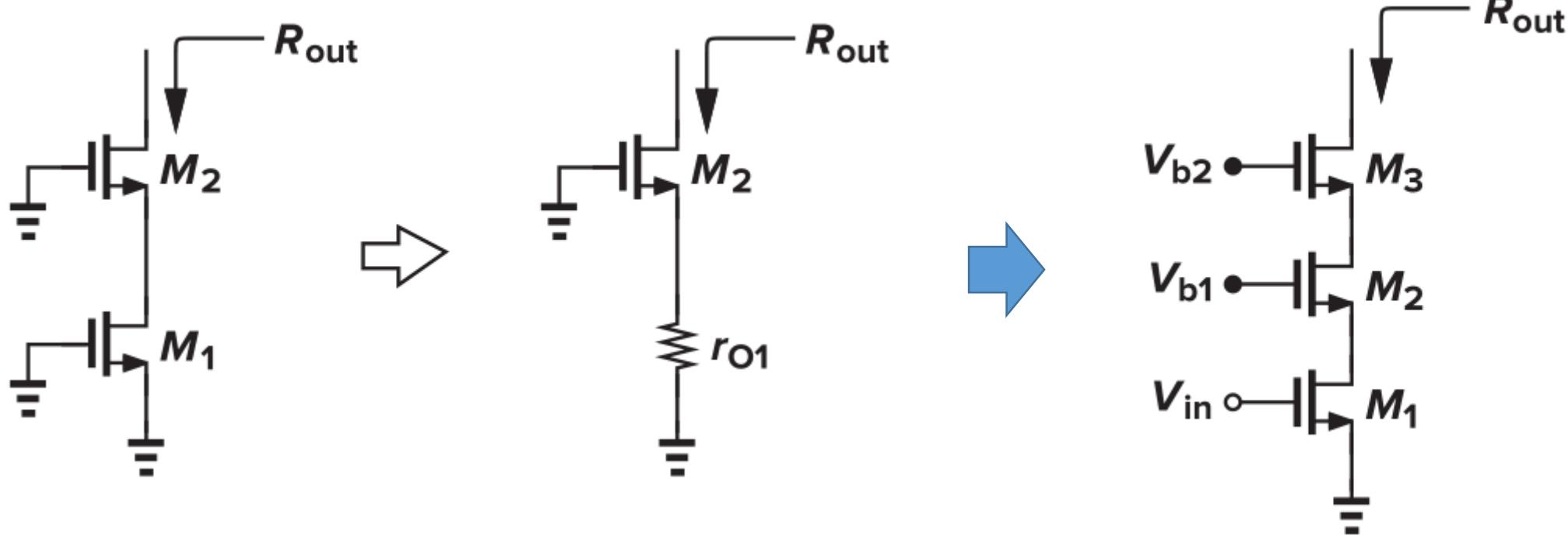
$$\begin{aligned}V_{out} &\geq V_{in} - V_{TH1} + V_{GS2} - V_{TH2} \\&= (V_{GS1} - V_{TH1}) + (V_{GS2} - V_{TH2})\end{aligned}$$

练习题

- 请画出Cascode的小信号等效电路



输出电阻



$$R_{out} = [1 + (g_{m2} + g_{mb2})r_{o2}]r_{o1} + r_{o2}$$

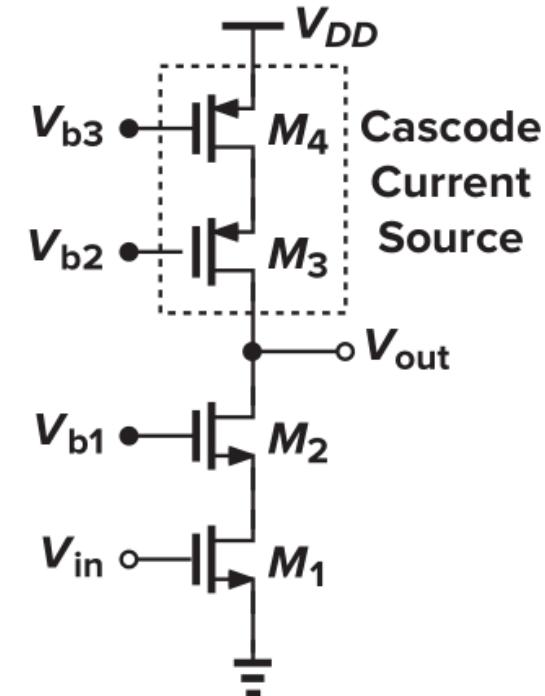
三级共源共栅

例7

- 套筒式结构
 - 电压摆幅小
 - 放大倍数高
 - 输出电阻高
 - 静态电流小

$$R_{out} = \{[1 + (g_{m2} + g_{mb2})r_{O2}]r_{O1} + r_{O2}\} \parallel \{[1 + (g_{m3} + g_{mb3})r_{O3}]r_{O4} + r_{O3}\}$$

$$|A_v| \approx g_{m1}[(g_{m2}r_{O2}r_{O1}) \parallel (g_{m3}r_{O3}r_{O4})]$$



$$V_{out,max} - V_{out,min} = V_{DD} - (V_{GS1} - V_{TH1}) - (V_{GS2} - V_{TH2}) - |V_{GS3} - V_{TH3}| - |V_{GS4} - V_{TH4}|$$

↳ $|V_{DS}| > |V_{GS} - V_{Th,p}| = |V_{ov}|$

例8

- 计算右图二者的区别

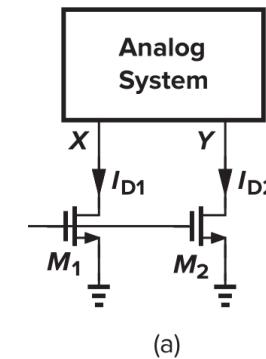
(a)

$$\begin{aligned} I_{D1} - I_{D2} &= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_b - V_{TH})^2 (\lambda V_{DS1} - \lambda V_{DS2}) \\ &= \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_b - V_{TH})^2 (\lambda \Delta V) \end{aligned}$$

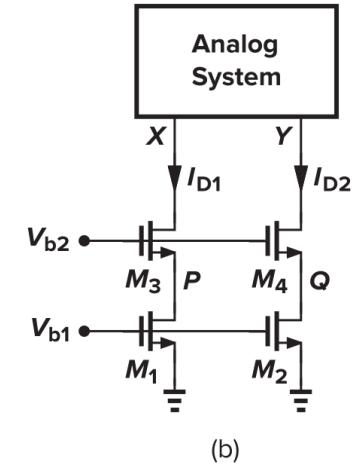
(b)

$$\begin{aligned} \Delta V_{PQ} &= \Delta V \frac{r_{O1}}{[1 + (g_{m3} + g_{mb3})r_{O3}]r_{O1} + r_{O3}} \\ &\approx \frac{\Delta V}{(g_{m3} + g_{mb3})r_{O3}} \end{aligned}$$

Cascode电流镜可以有效减少系统误差!



(a)

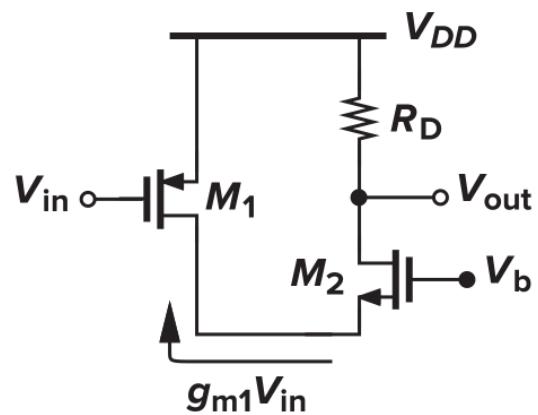


(b)

$$I_{D1} - I_{D2} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_b - V_{TH})^2 \frac{\lambda \Delta V}{(g_{m3} + g_{mb3})r_{O3}}$$

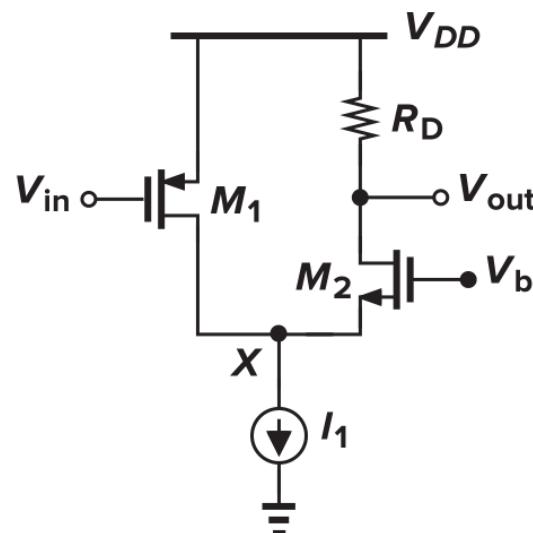
折叠式共源共栅结构

- 结构



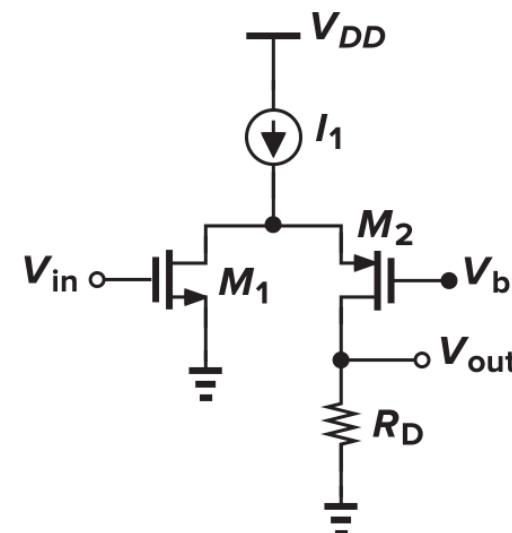
(a)

简单折叠式共源共栅



(b)

正确偏置的折叠式共源共栅



(c)

采用NMOS输入的折叠式共源共栅

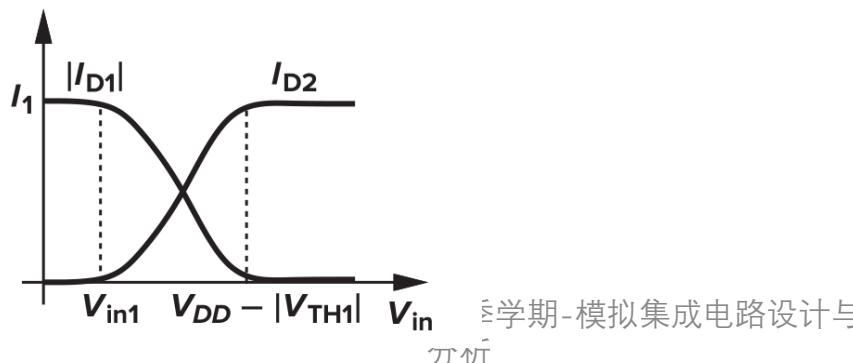
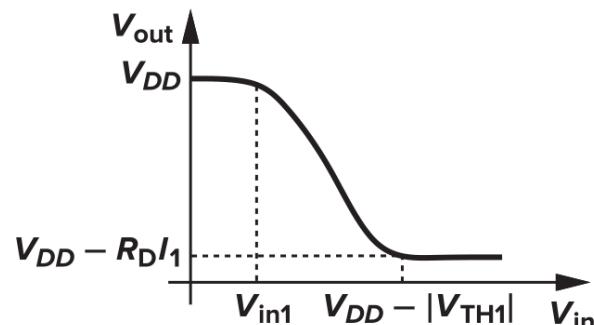
折叠式共源共栅结构

- 大信号特性

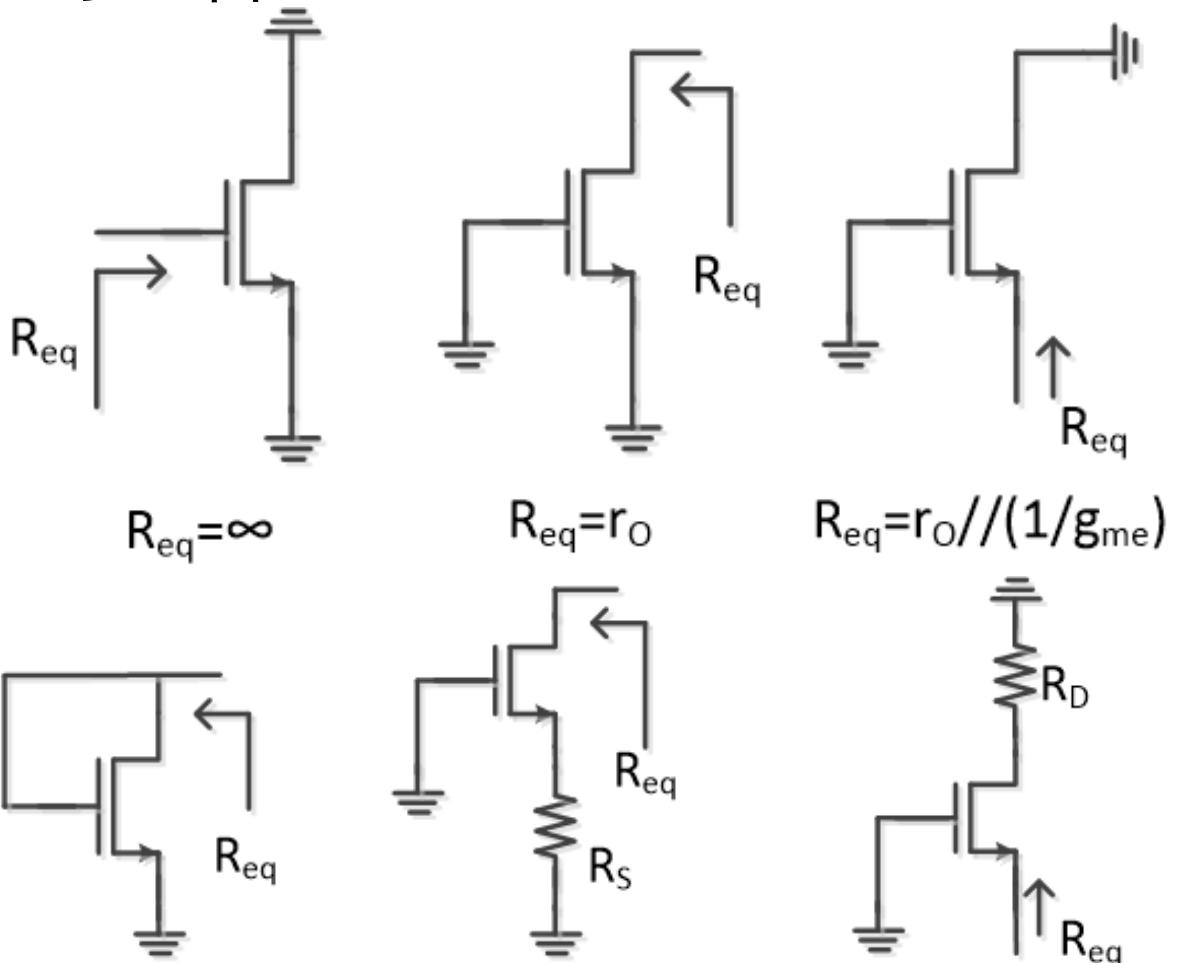
$$V_{in} > V_{DD} - |V_{TH1}| \quad V_{out} = V_{DD} - I_1 R_D \quad M_1 \text{关闭}$$

$$V_{in} < V_{DD} - |V_{TH1}| \quad I_{D2} = I_1 - \frac{1}{2} \mu_p C_{ox} \left(\frac{W}{L} \right)_1 (V_{DD} - V_{in} - |V_{TH1}|)^2 \quad M_1 \text{饱和}$$

当 $I_{D1} = I_1$ $V_{in1} = V_{DD} - \sqrt{\frac{2I_1}{\mu_p C_{ox}(W/L)_1}} - |V_{TH1}|$ M_1 线性



节点电阻小结



$$R_{eq} = r_o // (1/g_m) \quad R_{eq} = r_o + R_s + g_{me}r_oR_s \quad R_{eq} = (r_o + R_D)/(1 + g_{me}r_o)$$

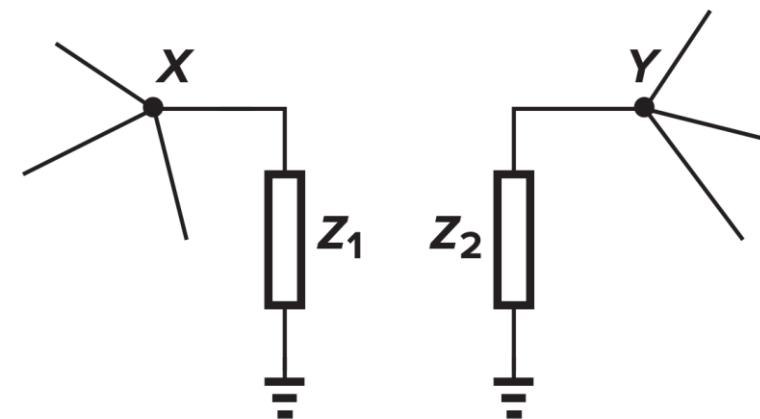
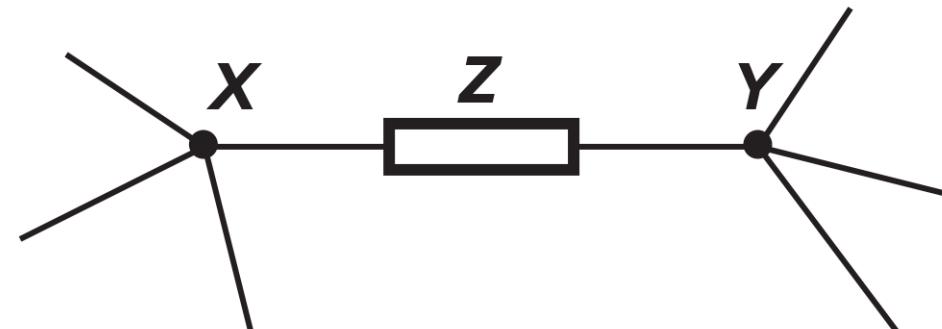
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单级放大器频率响应—密勒效应

- 密勒效应

- 寄生电容引起
- 输入端等效电容放大到 $(1+A)C_F$ 倍
- 频率特性下降
- 频率补偿&可控电容

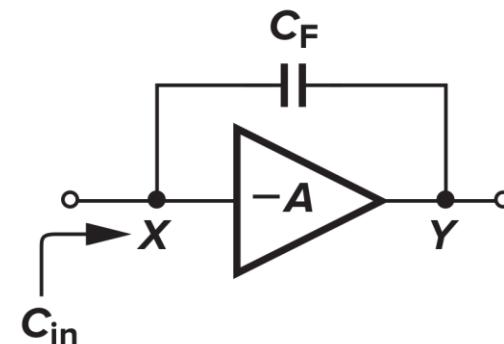


单级放大器频率响应—密勒定理

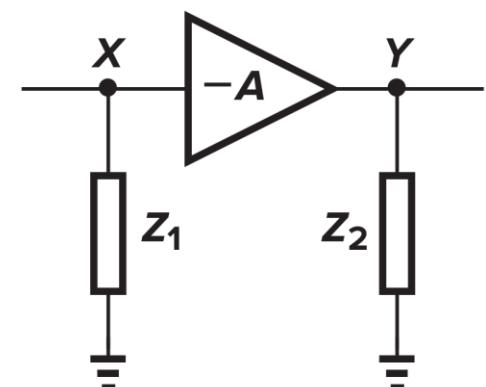
- 密勒定理
 - 成立条件: X与Y之间不止一个信号通道

$$Z_1 = \frac{Z}{1 - \frac{V_Y}{V_X}}$$

$$Z_2 = \frac{Z}{1 - \frac{V_X}{V_Y}}$$



(a)



(b)

单级放大器频率响应—密勒定理的局限性

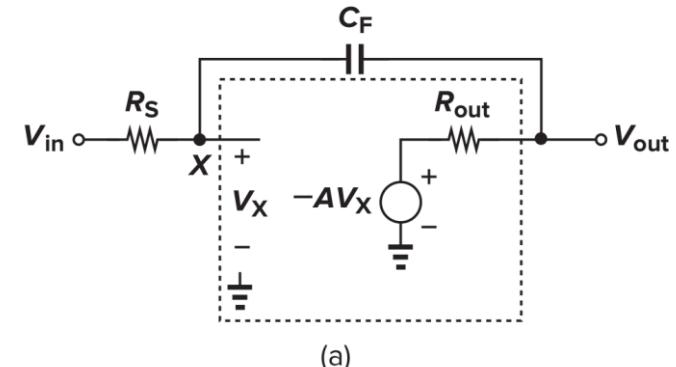
- 直接分析

$$\frac{V_{out}}{V_{in}}(s) = \frac{R_{out}C_F s - A}{[(A + 1)R_S + R_{out}]C_F s + 1}$$

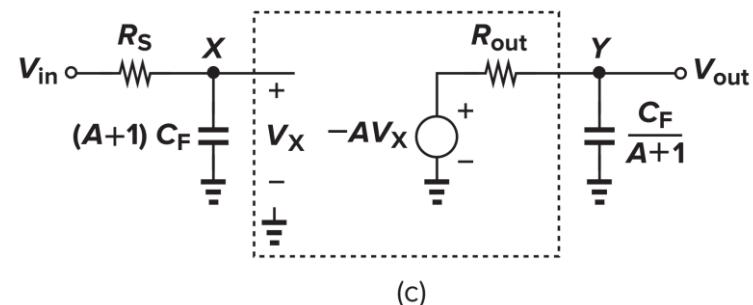
- 密勒近似

$$\frac{V_{out}}{V_{in}}(s) = \frac{-A}{[(1 + A)R_S C_F s + 1] \left(\frac{1}{1 + A^{-1}} C_F R_{out} s + 1 \right)}$$

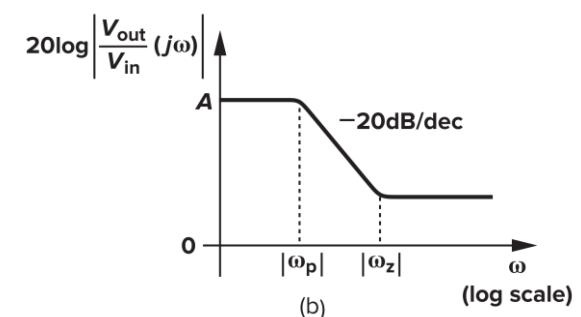
- 密勒定理的局限性
 - 消除零点
 - 增加了额外的极点
 - 输出阻抗不正确



(a)



(c)



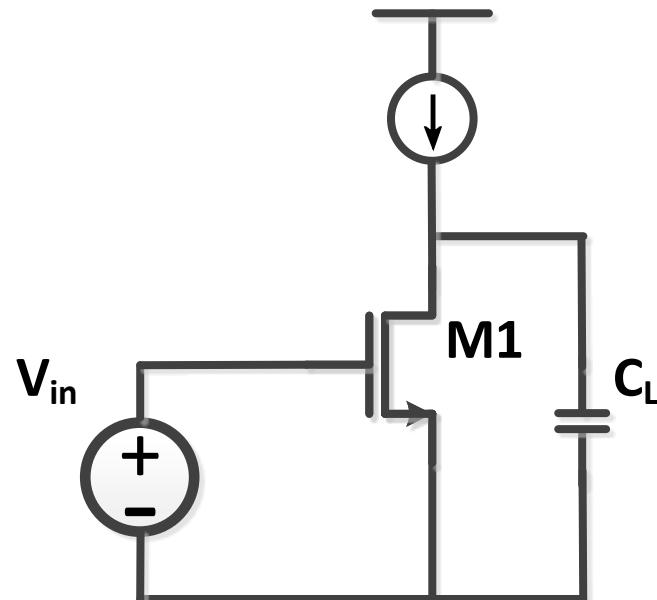
单级放大器频率响应- 简单电路

- 单级放大器

$$A_v = g_m r_o$$

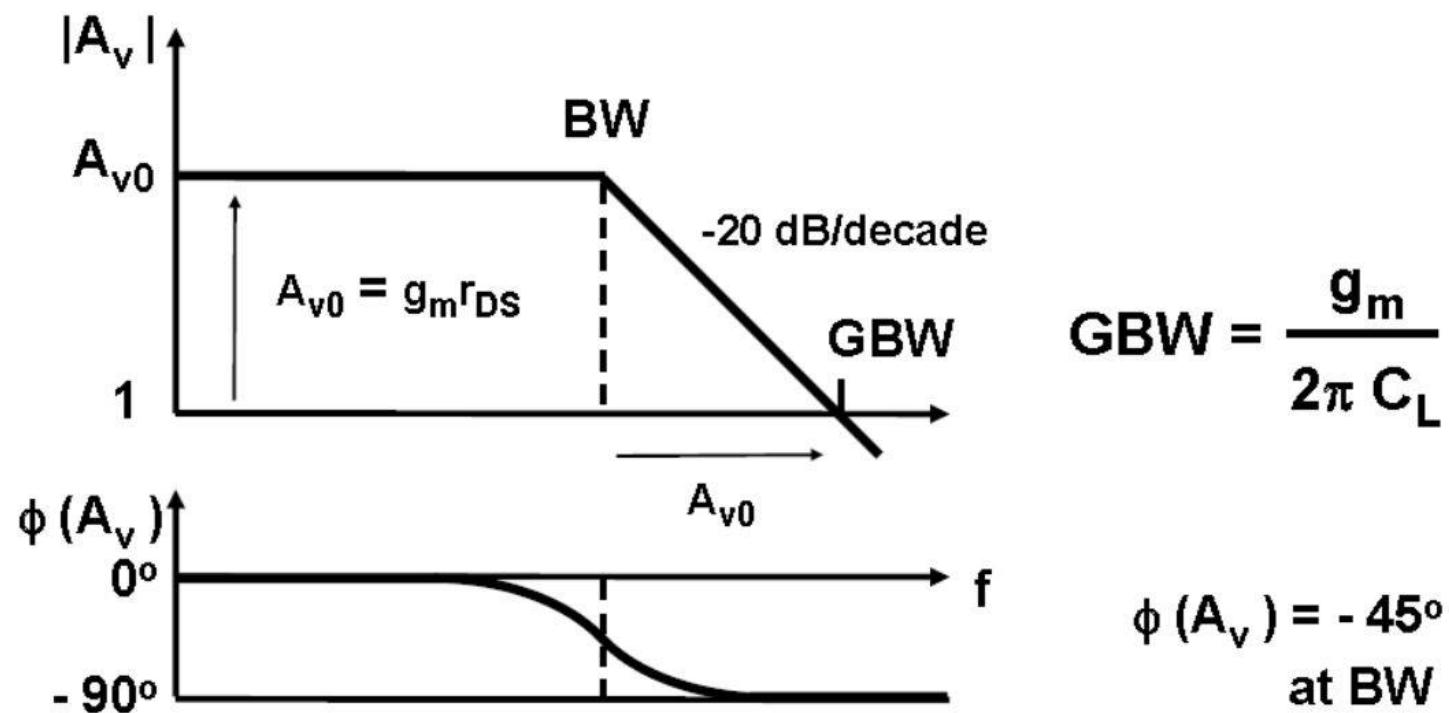
$$BW = \frac{1}{2\pi r_o C_L}$$

$$GBW = \frac{g_m}{2\pi C_L}$$



单级放大器频率响应- 简单电路

- 增益、带宽、增益带宽积的波特图



单级放大器频率响应- 简单电路

- 基本分析方法
 - 节点分析
 - 节点的电阻和电容构成极点
 - 没有考虑零点的存在
 - 有误差
- 传输函数
 - 精度比节点分析高
 - 计算量大

单级放大器频率响应- 简单电路

- 共源级
 - 节点分析法

$$A_v = g_m r_o$$

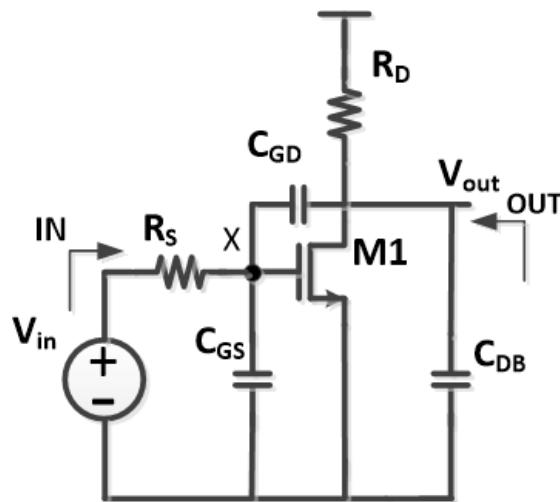
$$C_X = C_{GS} + (1 + A_v)C_{GD}$$

$$\omega_{in} = \frac{1}{R_S C_X}$$

$$C_{OUT} = C_{DB} + \left(1 + \frac{1}{A_v}\right) C_{GD} \approx C_{DB} + C_{GD}$$

$$\omega_{out} = \frac{1}{(r_o // r_{DS}) C_{OUT}}$$

$$H(S) = -\frac{A_v}{(1 + \frac{s}{\omega_{in}})(1 + \frac{s}{\omega_{OUT}})}$$



单级放大器频率响应- 简单电路

- 共源级

- 传输函数法

$$\frac{V_{OUT}}{V_{in}} = \frac{(C_{GD}s - g_m)R_D}{R_S R_D \xi s^2 + [R_S(1 + g_m R_D)C_{GD} + R_S C_{GS} + R_D(C_{GD} + C_{DB})]s + 1}$$

$$\xi = C_{GS}C_{GD} + C_{GS}C_{DB} + C_{GD}C_{DB}$$

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

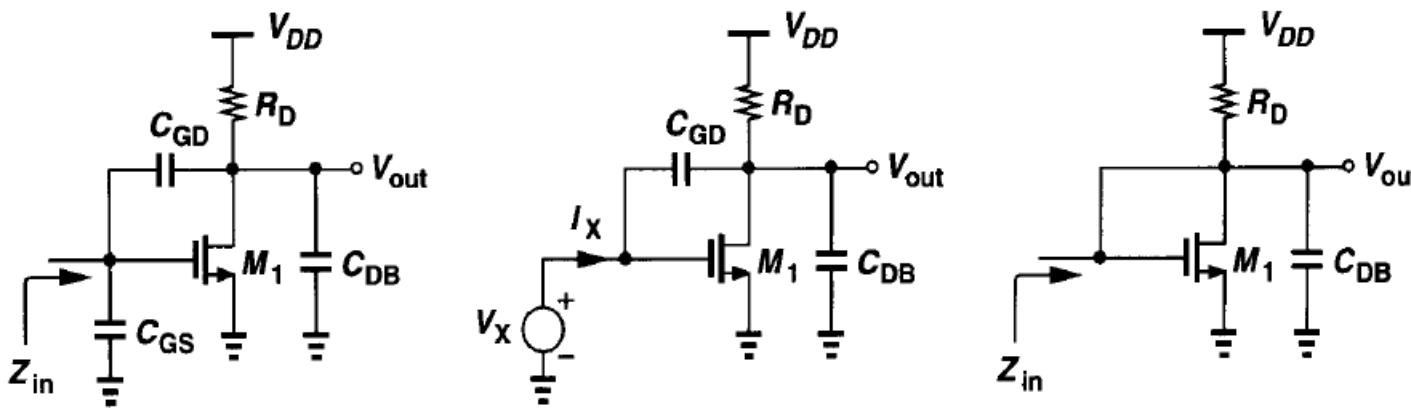
假定 $|\omega_{p2}| \gg |\omega_{p1}|$

$$\omega_{p1} = \frac{1}{R_S C_X + R_D(C_{GD} + C_{DB})}$$

$$\omega_{p2} = \frac{R_S(1 + g_m R_D)C_{GD} + R_S C_{GS} + R_D(C_{GD} + C_{DB})}{R_D R_S \xi}$$

单级放大器频率响应- 简单电路

- 共源级
 - 输入阻抗



(a) 一级近似

$$Z_{in} = \frac{1}{[C_{GS} + (1 + g_m R_D) C_{GD}] s}$$

(b) 推导结果

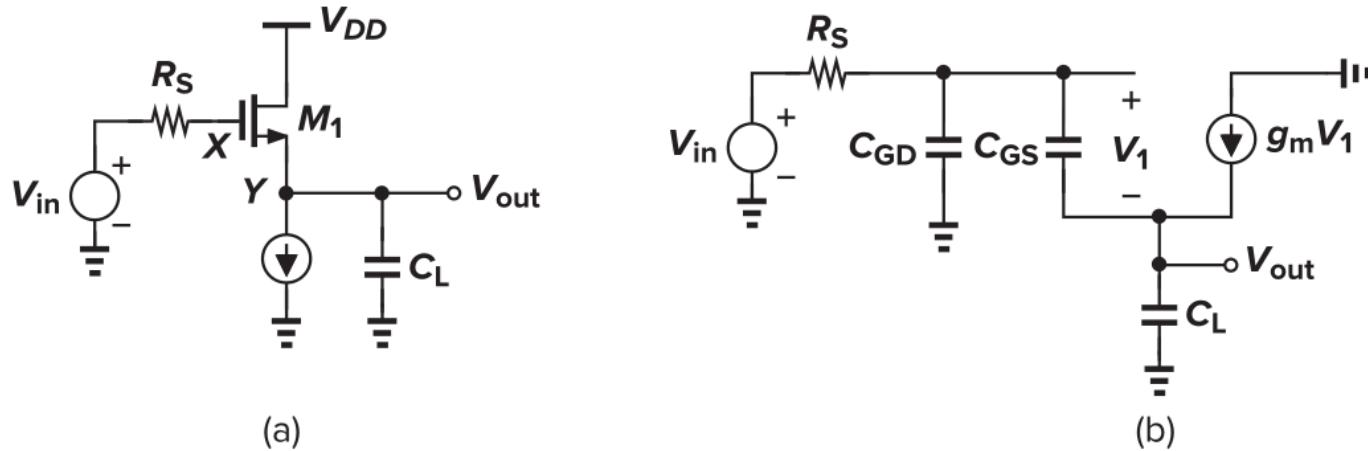
$$Z_{in} = \frac{1 + R_D(C_{GD} + C_{DB})s}{C_{GD}s(1 + g_mR_D + R_DC_{DB}s)} \parallel C_{GS}$$

(c) 近似结果

$$Z_{in} = \frac{1}{(1 + g_m R_D) C_{GDs}}$$

单级放大器频率响应—简单电路

- 源跟随器



$$H(S) = \frac{g_m + C_{GS}S}{R_S(C_{GS}C_L + C_{GS}C_{GD} + C_{GS}C_L)s^2 + (g_m R_S C_{GD} + C_L + C_{GS})s + g_m}$$

$$\omega_{p1} \approx \frac{g_m}{g_m R_S C_{GD} + C_L + C_{GS}} = \frac{1}{R_S C_{GD} + \frac{C_L + C_{GS}}{g_m}}$$

单级放大器频率响应- 简单电路

- 源跟随器

- 输入阻抗

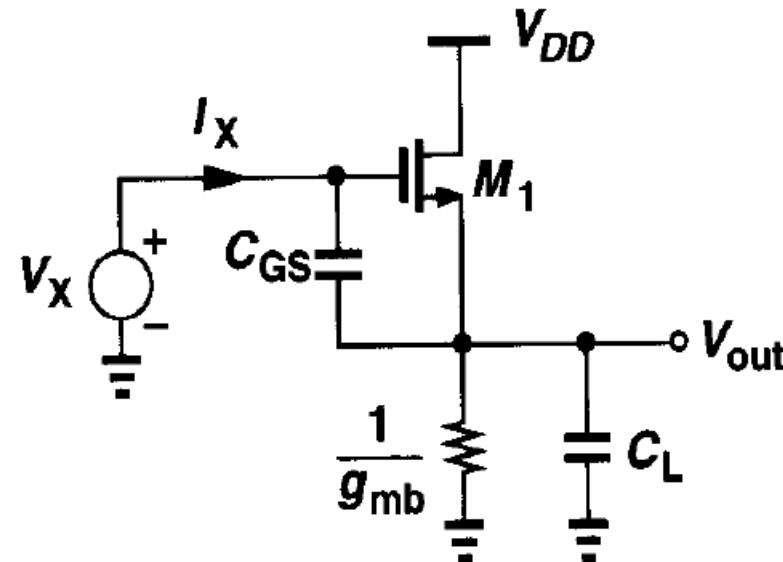
$$Z_{in} = \frac{1}{C_{GS}s} + (1 + \frac{g_m}{C_{GS}s}) \frac{1}{g_{mb} + C_L s}$$

- 低频

$$Z_{in} \approx \frac{1}{C_{GS}s} \left(1 + \frac{g_m}{g_{mb}} \right) + \frac{1}{g_{mb}}$$

- 高频

$$Z_{in} \approx \frac{1}{C_{GS}s} + \frac{1}{C_L s} + \frac{g_m}{C_{GS} C_L s^2}$$



单级放大器频率响应- 简单电路

- 源跟随器
 - 输出阻抗

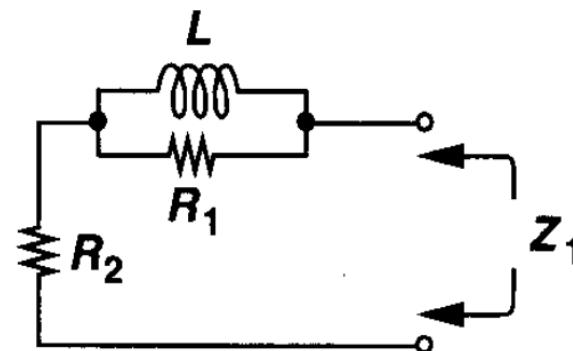
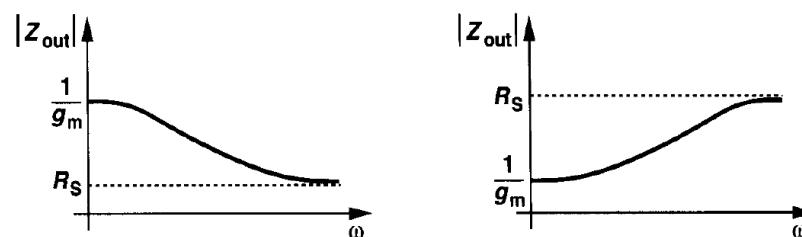
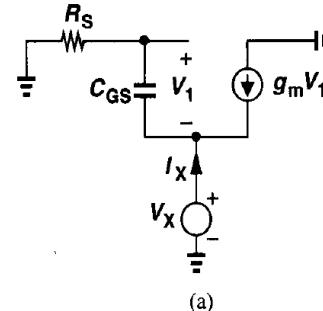
$$Z_{out} = \frac{R_S C_{GS} s + 1}{g_m + C_{GS} s}$$

- 低频

$$Z_{out} \approx 1/g_m$$

- 高频

$$Z_{out} \approx R_S$$



作业

- 3.17, 3.19
- 6.7