电子电路与系统基础I

理论课第九讲

分段折线法：**MOSFET**电流镜、反相器电路

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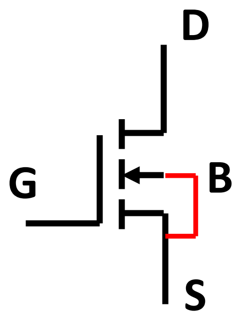
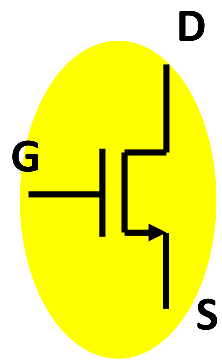
MOSFET电流镜、反相器电路　大纲

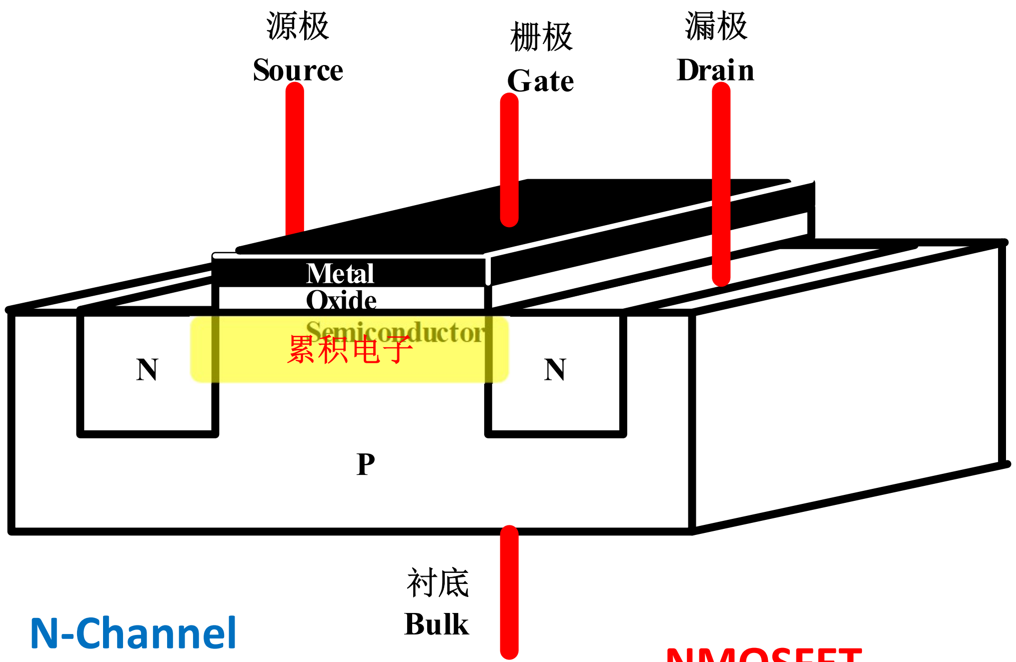
- **MOSFET**的分段折线电路模型
  - 晶体管物理结构
  - 端口伏安特性
    - 分段折线描述
- **MOSFET**电流源
  - 电流镜
- **MOSFET**反相器
  - **NMOS**反相器
  - **CMOS**反相器

NMOSFET结构





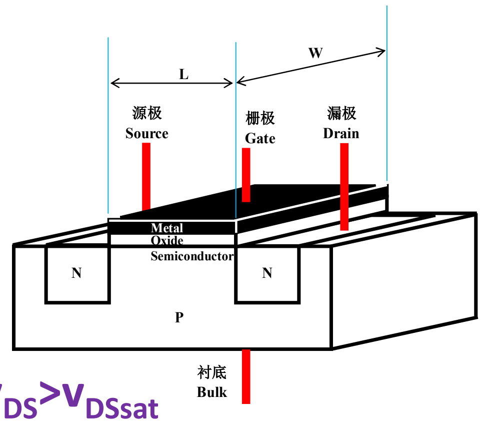
- **Metal-Oxide-Semiconductor Field-Effect Transistor**
  - 金属-氧化物-半导体结构的场效应晶体管
  - **Transistor: Transfer Resistor**
    - 晶体管，转移电阻器
    - 受控的非线性电阻
      - **MOS**电容
      - 沟道形状变化



N-Channel

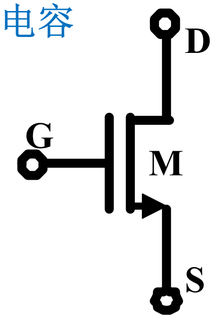
NMOSFET

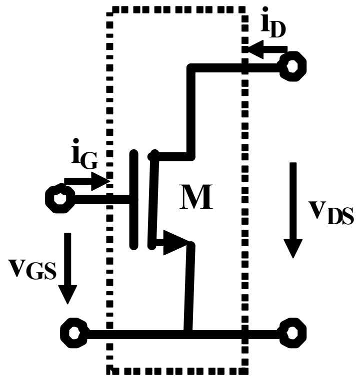
NMOSFET伏安特性方程



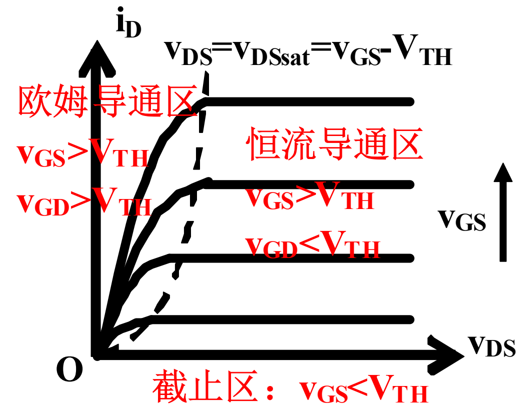
$$\beta_n = \frac{1}{2}\mu_n C_{ox}\frac{W}{L} \Leftrightarrow G = \sigma\frac{S}{l}$$

电子迁移率　单位面积电容　沟道宽长比





$v_{DS} < v_{DSsat}$ ~ $v_{GD} > V_{TH}$　　$v_{DS} > v_{DSsat}$ ~ $v_{GD} < V_{TH}$



$i_G = 0$　　栅衬为电容结构，低频开路

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

导电沟道未形成，截止区

直通沟道，欧姆区

夹断沟道，恒流区

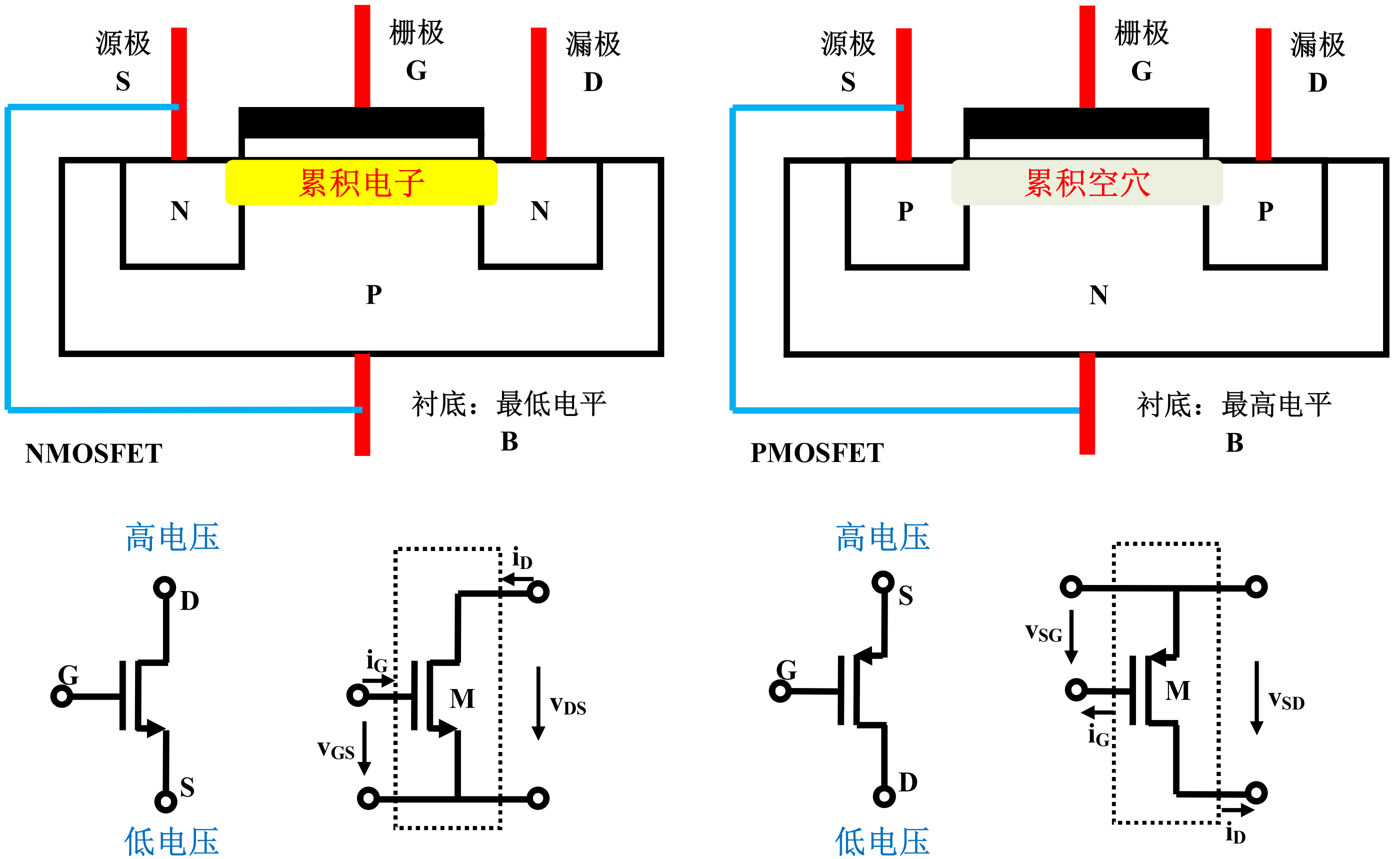
$v_{OD} = v_{GS} - V_{TH}$　过驱动电压

$v_{DS,sat} = v_{GS} - V_{TH}$　饱和电压

V_{TH} 阈值电压

$V_E = \frac{1}{\lambda}$　厄利电压

NMOS和PMOS



PMOS的元件约束方程和NMOS的形式一致：PMOS方程中，只要将NMOS方程中的v_{GS}换成v_{SG}，将v_{DS}换成v_{SD}，将β_n换成β_p，将μ_n换成μ_p，将$V_{TH,n}$换成$V_{TH,p}$，将λ_n换成λ_p，将$V_{E,n}$换成$V_{E,p}$后，方程形式没有任何其他变化。

分段线性化电路模型

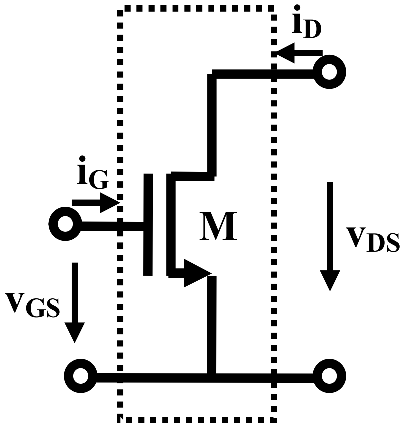
- 只要元件约束方程有明显的分区特性，原理性分析即可采用分段折线模型

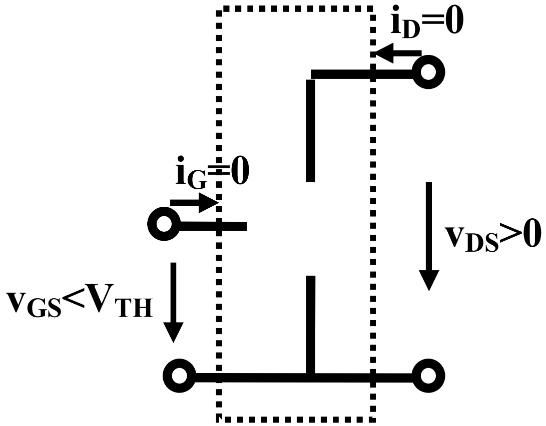
- **MOSFET**的三个分区有明确的物理含义，故而可三个区域分别线性化处理
  - 三个区均为线性电路模型
    - 截止区：电流为零，开路模型
    - 欧姆区：过原点抛物线方程，线性化为线性电阻
    - 恒流区：伏安特性曲线几乎平直，线性化为诺顿电流源

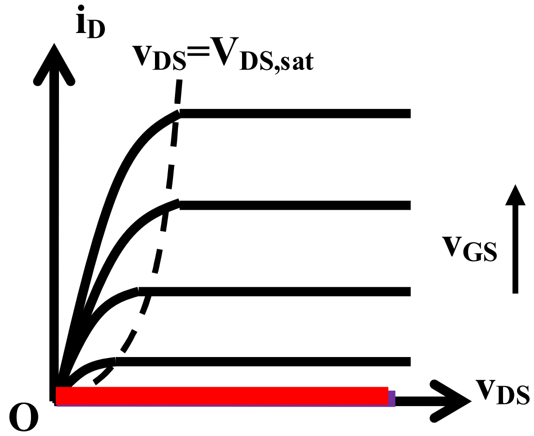
以**NMOSFET**为例

PMOSFET等效电路及**PMOS**电路练习留作作业

分段线性化：截止区电路模型



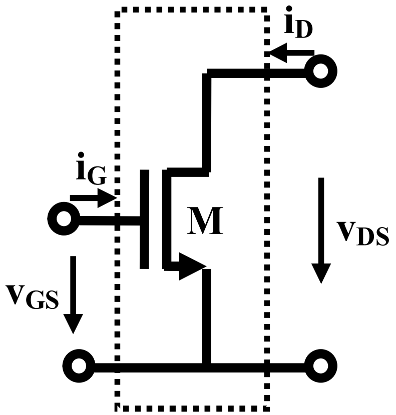


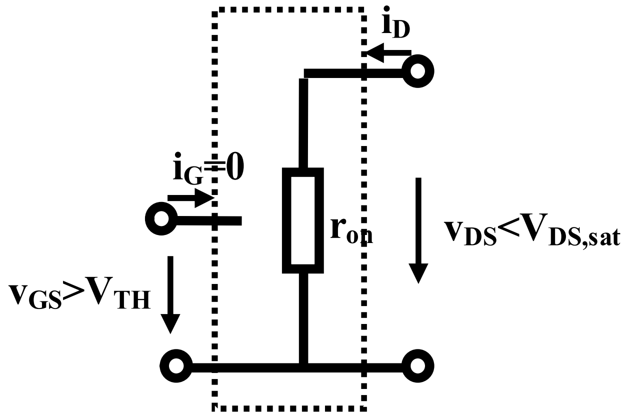


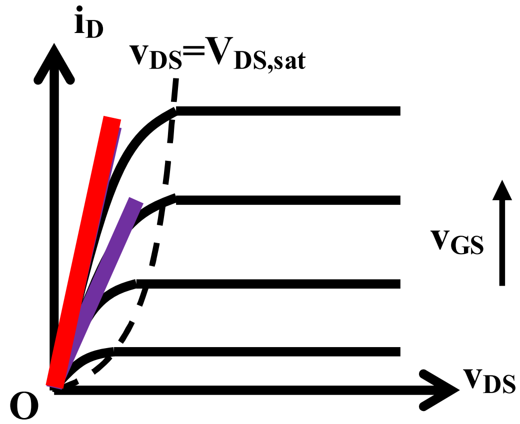
$$i_G = 0$$

$$v_{GS} < V_{TH} \qquad i_D = 0$$

分段线性化：欧姆区电路模型







$$r_{on}=\left(\frac{di_D}{dv_{DS}}\right)^{-1}_{v_{DS}=0}=\frac{1}{2\beta_n(v_{GS}-V_{TH})}$$

$$i_G=0$$

$$v_{GS}>V_{TH}$$

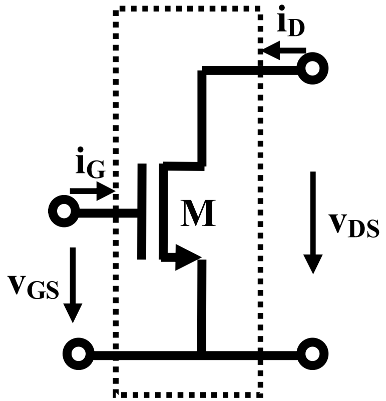
$$v_{DS}<V_{DS,sat}$$

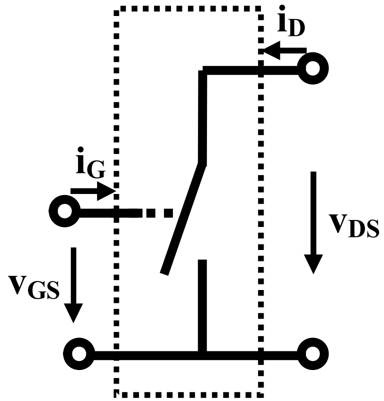
$$i_D=2\beta_n\left((v_{GS}-V_{TH})v_{DS}-0.5v_{DS}^2\right)$$

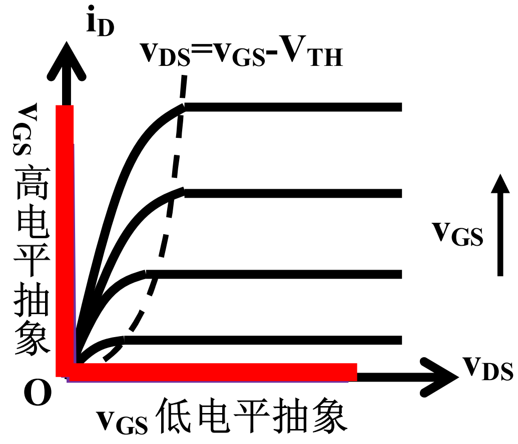
$$\approx 2\beta_n(v_{GS}-V_{TH})v_{DS}=v_{DS}/r_{on}$$

线性化为受控线性电阻

分段线性化：开关电路模型







$i_G = 0$

$$r_{on} = \frac{1}{2\beta_n(v_{GS} - V_{TH})}$$

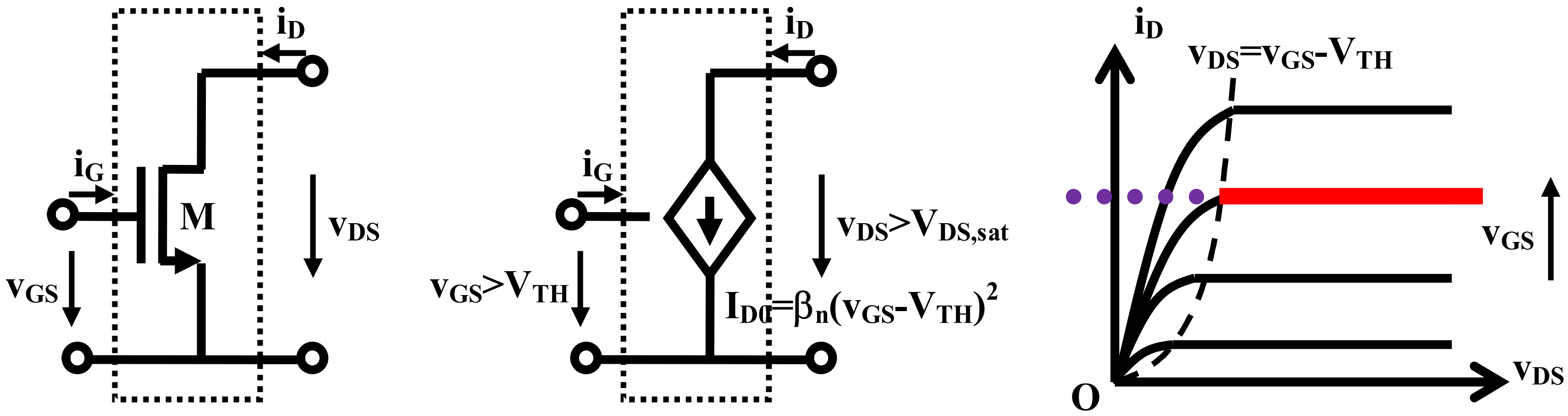
$i_D = 0$ $\qquad v_{GS} < V_{TH}$

很小的**v_G**，沟道未形成，抽象为开路

$v_{DS} = 0$ $\qquad v_{GS} > V_{TH}, v_{GD} > V_{TH}$

很大的**v_G**，形成厚沟道，导通电阻很小，抽象为短路

分段线性化：恒流区电路模型



$$i_G = 0$$

$$v_{GS} > V_{TH} \qquad i_D = I_{D0} = \beta_n \left(v_{GS} - V_{TH}\right)^2$$

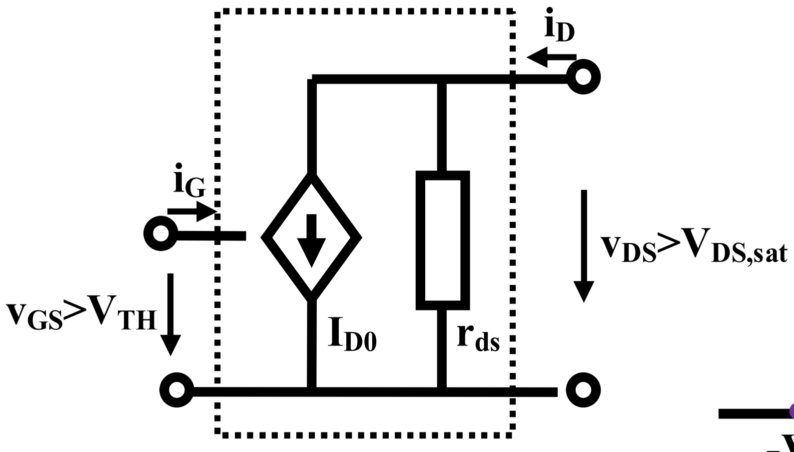
$$v_{DS} > V_{DS,sat}$$

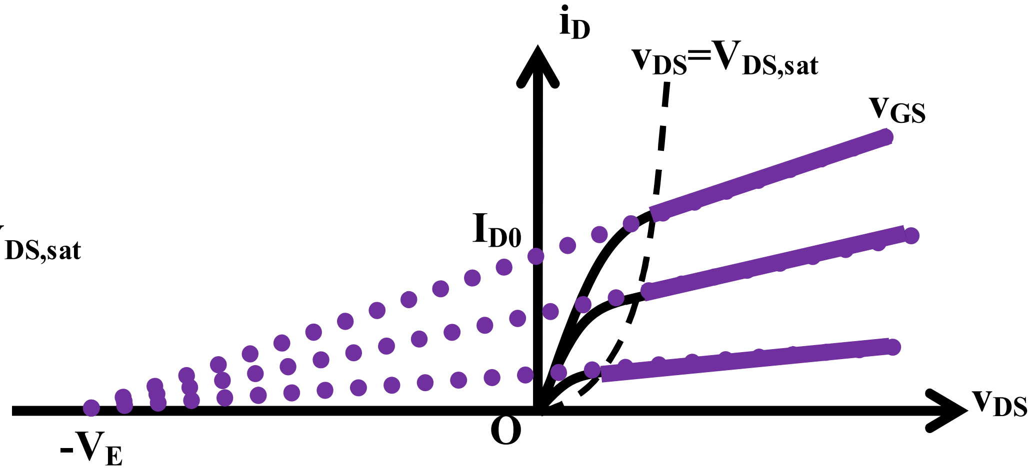
沟道夹断：非线性（平方律）受控的压控流源

厄利效应

分段折线化模型中，厄利效应大多被忽略不计

局部线性化分析中，厄利效应一般会加以考虑
形成有限的电压增益





$$i_D = \beta_n \left(v_{GS} - V_{TH}\right)^2 \left(1 + \frac{v_{DS}}{V_E}\right) = I_{D0}\left(1 + \frac{v_{DS}}{V_E}\right)$$

$$I_{D0} = \beta_n \left(v_{GS} - V_{TH}\right)^2$$

$$= I_{D0} + \frac{I_{D0}}{V_E} v_{DS} = I_{D0} + g_{ds} v_{DS} = I_{D0} + \frac{v_{DS}}{r_{ds}}$$

$$r_{ds} = \frac{V_E}{I_{D0}}$$

二、MOSFET电流源

MOSFET工作在恒流区，即可等效为恒流源

- MOSFET的二极管连接方式
- MOSFET电流镜
- 分压偏置电流源
  - 负反馈

确保晶体管偏置在恒流区

为了简化分析，下述分析均不考虑厄利效应

$N-MOSFET$ V_{GS},V_{GD},V_{DS}

$P-MOSFET$ V_{SG},V_{DG},V_{SD}

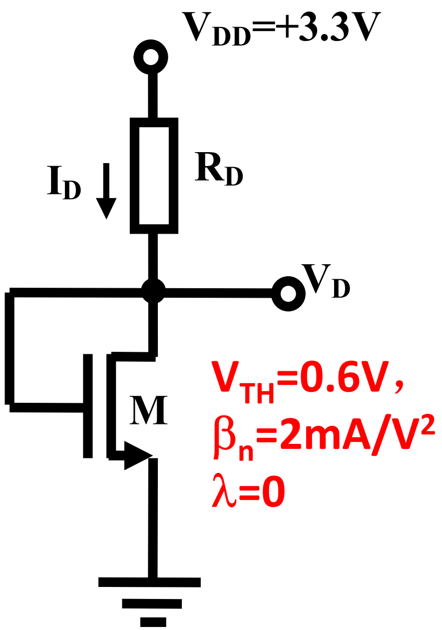
$$V_{od}=V_{GS}-V_{TH}$$

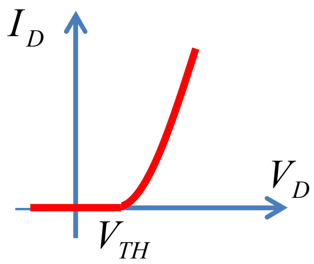
$$V_{DS,sat}=V_{GS}-V_{TH}$$

晶体管分析，首先分析在哪个区工作	截止区	导通区	
	$V_{od}<0$ $V_{GS}<V_{TH}$	$V_{od}>0$ $V_{GS}>V_{TH}$	
熟记		欧姆导通	恒流导通
工作区条件		$V_{GD}>V_{TH}$ $V_{DS}<V_{DS,sat}$	$V_{GD}<V_{TH}$ $V_{DS}>V_{DS,sat}$

例1 MOSFET的二极管连接方式

$$I_D=\begin{cases}0 & V_D\le V_{TH}\\ \beta_n\left(V_D-V_{TH}\right)^2 & V_D>V_{TH}\end{cases}$$





$$V_{GD}=0V<0.6V=V_{TH}$$

$$I_D=\beta_n\left(V_{GS}-V_{TH}\right)^2$$

二极管：反偏($V_{GS}<V_{TH}$)截止电流为0，正偏($V_{GS}>V_{TH}$)导通时，端口电压端口电流具有平方律关系

给出R_D取值，使得I_D=1mA

$$I_D=\beta_n V_{od}^2=2V_{od}^2=1mA$$

$$V_{od}=0.71V$$

$$V_D=V_G=V_{GS}=V_{od}+V_{TH}$$
$$=0.71+0.6=1.31V$$

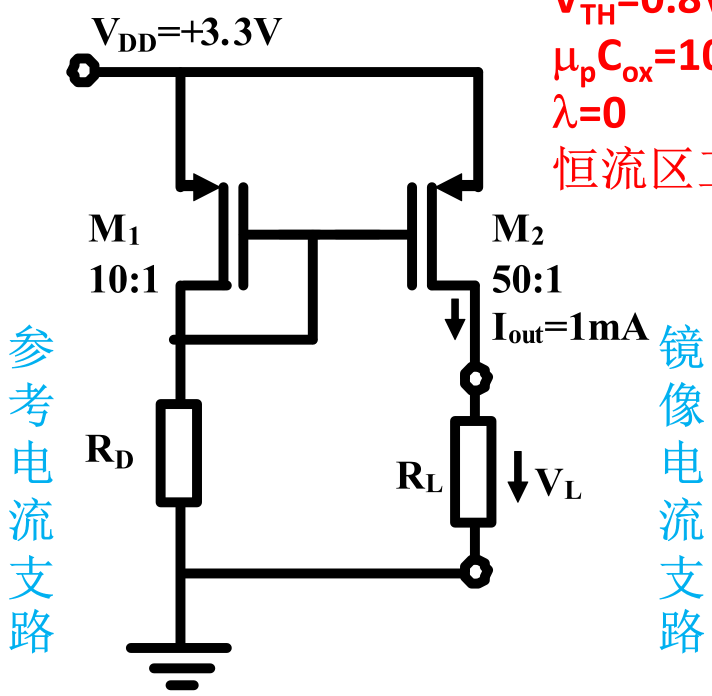
$$R_D=\frac{V_{DD}-V_D}{I_D}=\frac{3.3-1.31}{1m}=1.99k\Omega$$

例2 电流镜current mirror

两个工艺参量一模一样的晶体管

给出R_D取值，使得电流源输出电流I_{out}=1mA

V_{TH}=0.8V，
$\mu_p C_{ox}$=100μA/V²
λ=0
恒流区工作



参考电流支路是控制支路（输入）
镜像电流支路是受控支路（输出）

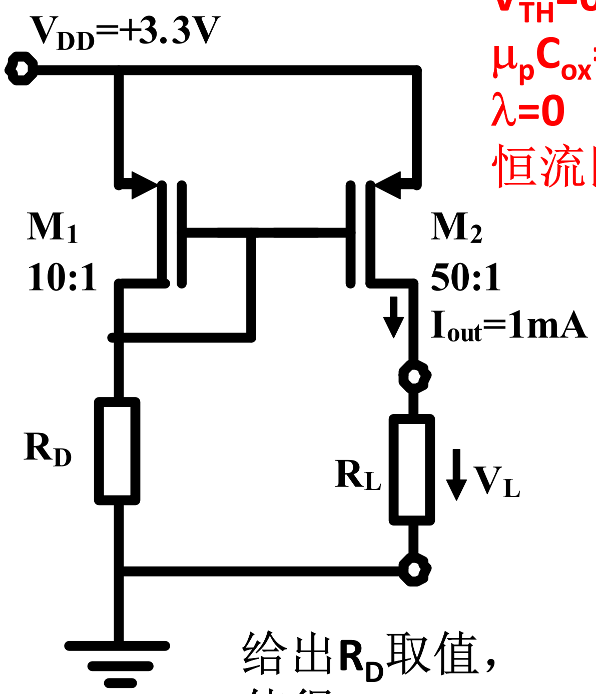
$$I_{D1}=\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_1 (V_{SG1}-V_{TH})^2$$

$$I_{D2}=\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_2 (V_{SG2}-V_{TH})^2$$

$$V_{SG1}=V_{SG2}$$

$$\frac{I_{D2}}{I_{D1}}=\frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}=\frac{50}{10}=5$$

电流镜特点：镜像电流大小由晶体管尺寸决定



$V_{TH}=0.8V$，
$\mu_p C_{ox}=100\mu A/V^2$
$\lambda=0$
恒流区工作

给出R_D取值，
使得$I_{out}=1mA$

$$\frac{I_{D2}}{I_{D1}}=\frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}=\frac{50}{10}=5$$

$$I_{D2}=I_{out}=1mA$$

$$I_{D1}=\frac{I_{D2}}{5}=200\mu A$$

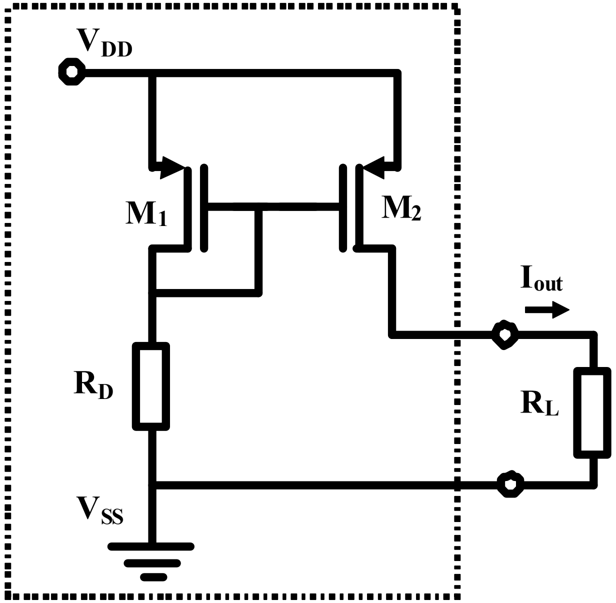
$$V_{od1}=V_{SG1}-V_{TH}=\sqrt{\frac{I_{D1}}{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_1}}=\sqrt{\frac{200}{\frac{1}{2}\times 100\times 10}}=0.63V$$

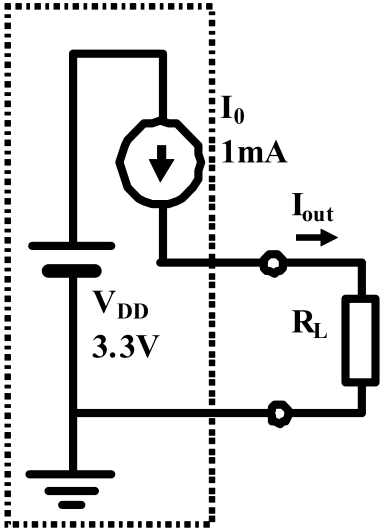
$$V_{SG1}=V_{od1}+V_{TH}=0.63+0.8=1.43V$$

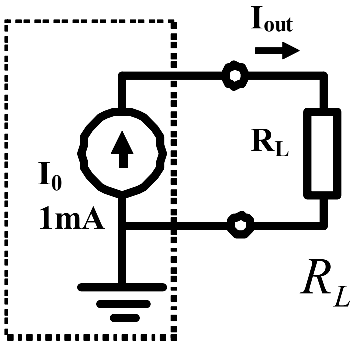
$$V_{G2}=V_{D1}=V_{G1}=V_{DD}-V_{SG1}=3.3-1.43=1.87V$$

$$R_D=\frac{V_{D1}}{I_{D1}}=\frac{1.87V}{0.2mA}=9.3k\Omega$$

恒流源等效的限定性条件







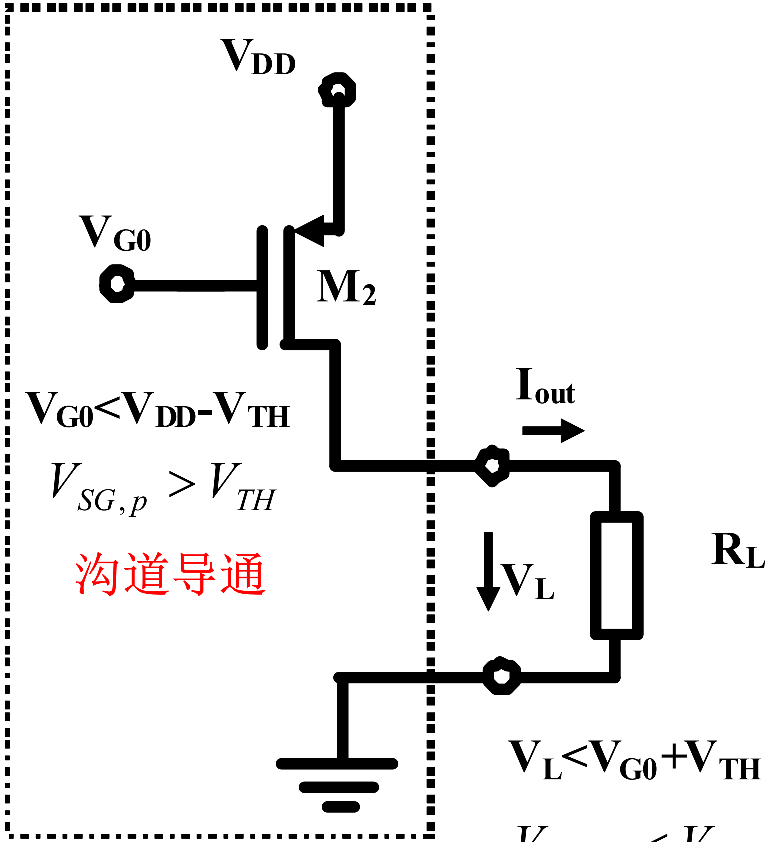
$R_L \le 2.67k\Omega$

$$V_{SD2} \ge V_{SD2,sat} = V_{SG2} - V_{TH} = 0.63V$$

$$V_{D2} = V_{DD} - V_{SD2} \le 3.3 - 0.63 = 2.67V$$

$$R_L \le \frac{V_{D2,\max}}{I_{out}} = 2.67k\Omega$$

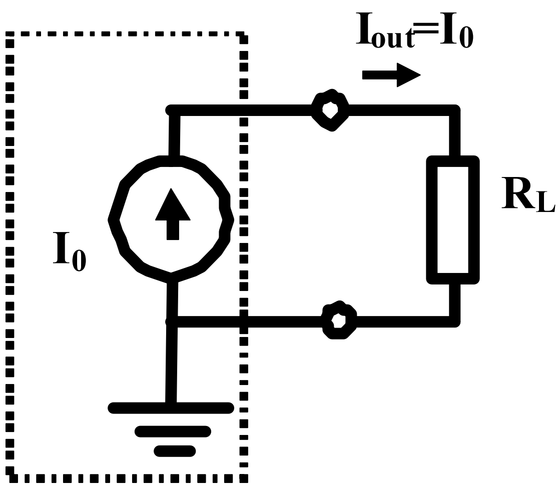
只需合适偏置，晶体管即可等效为恒流源



$V_L<V_{G0}+V_{TH}$

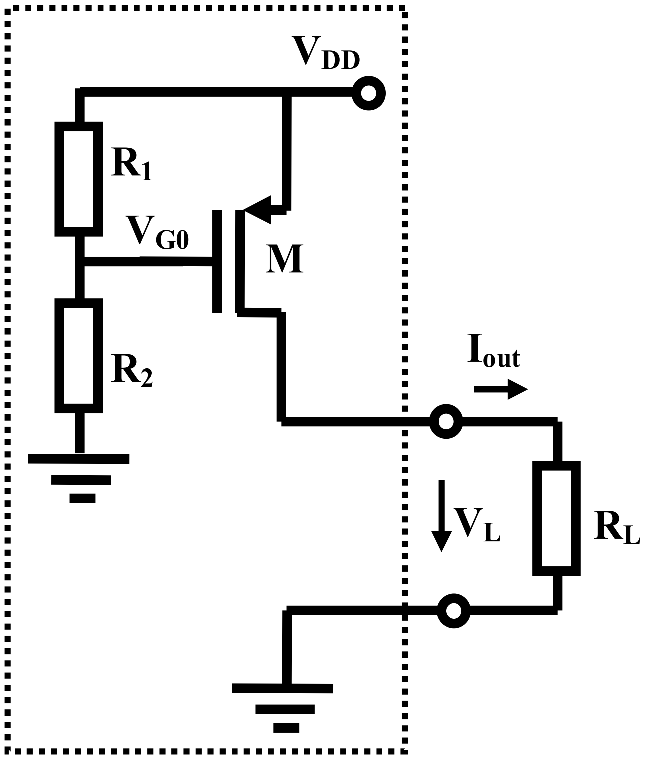
$V_{DG,p} < V_{TH}$ 沟道夹断

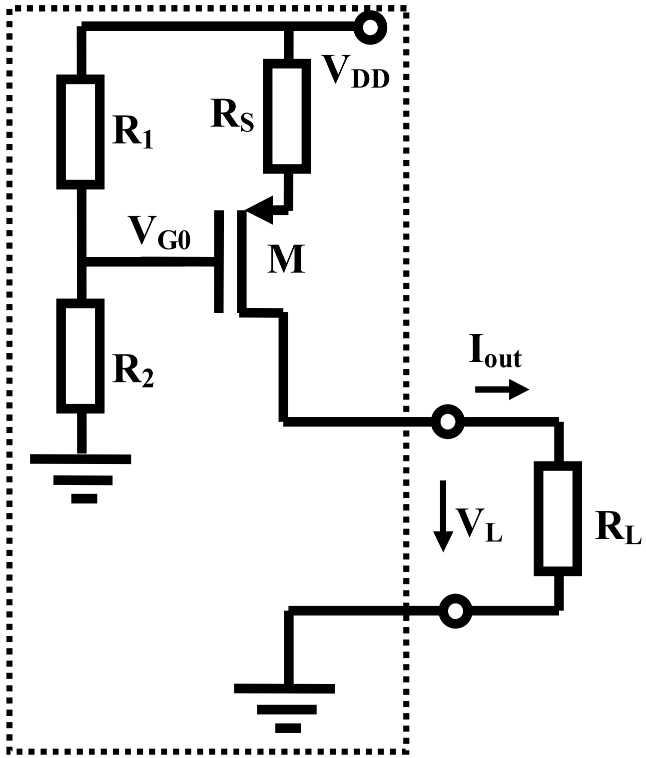
$I_0=\beta_p(V_{DD}-V_{G0}-V_{TH})^2$



电流镜电路：采用**MOSFET**的二极管连接方式提供V_{G0}直流偏压，有什么好处？

分压偏置电路



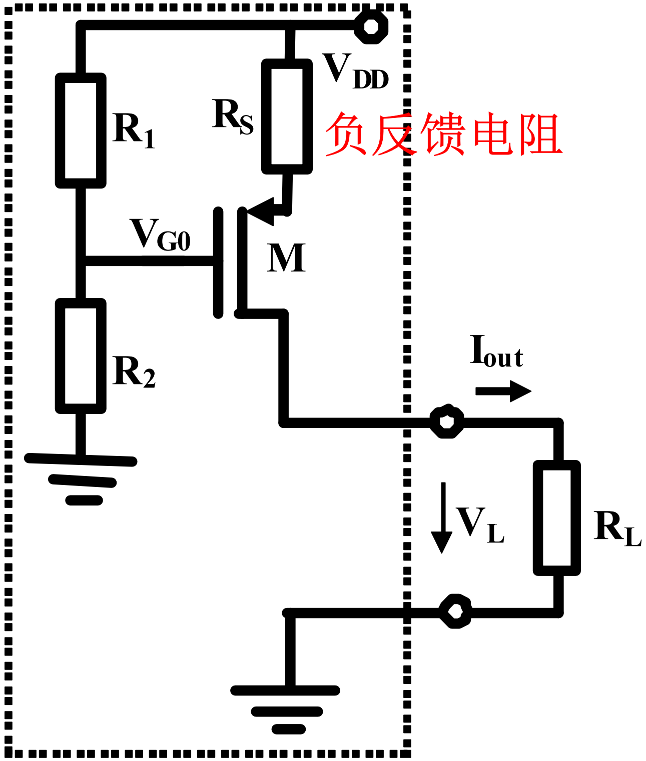


通过电阻分压网络，实现直流偏置

带负反馈电阻的分压偏置电路

负反馈

- 环路一周后，扰动影响降低，则为负反馈；扰动影响增强，则为正反馈

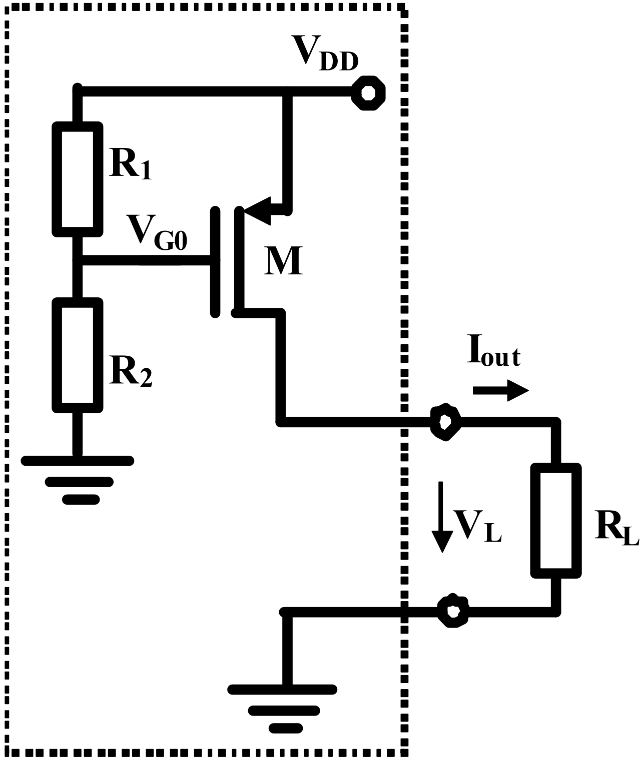


假设有一个外来扰动使得晶体管**M**的漏极电流增加了，那么R_S电阻上的分压必然上升，导致**PMOS**晶体管源栅电压下降，由于漏极电流和源栅电压的平方律关系，漏极电流下降。

这就是负反馈：负反馈环路的存在，使得外加扰动的影响力降低，电路变得更加稳定。

串串负反馈：通过反馈电压稳定输出电流…电流源更加稳定可靠（更加接近理想恒流源，更加稳定）

电阻取值确保晶体管工作在恒流区



$$V_{G0} = \frac{R_2}{R_1 + R_2} V_{DD} < V_{DD} - V_{TH}$$

$V_{SGp} > V_{THp}$使得沟道形成，进入导通区

$$\frac{R_1}{R_2} > \frac{V_{TH}}{V_{DD} - V_{TH}}$$

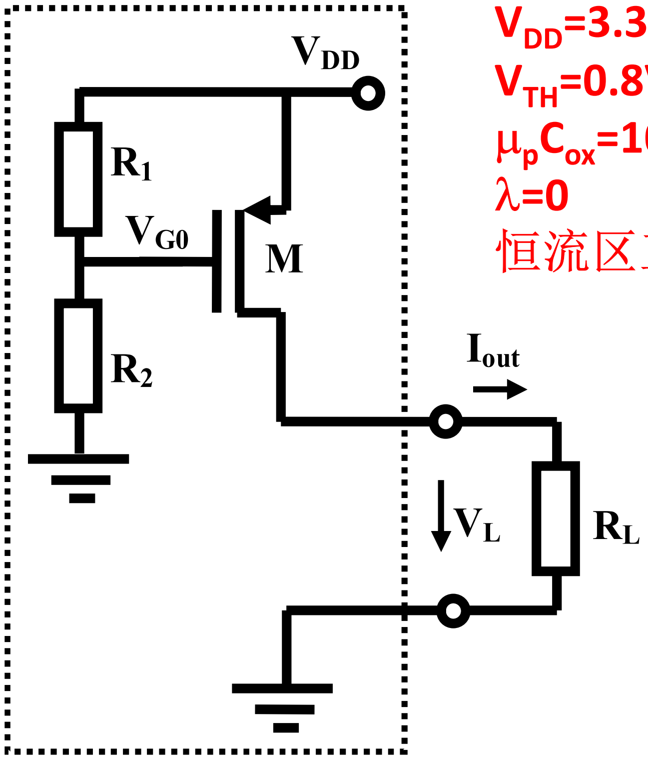
$$V_{DG} = V_D - V_{G0} = V_L - V_{G0} < V_{TH}$$

$V_{DGp} < V_{THp}$使得沟道夹断，进入恒流导通区

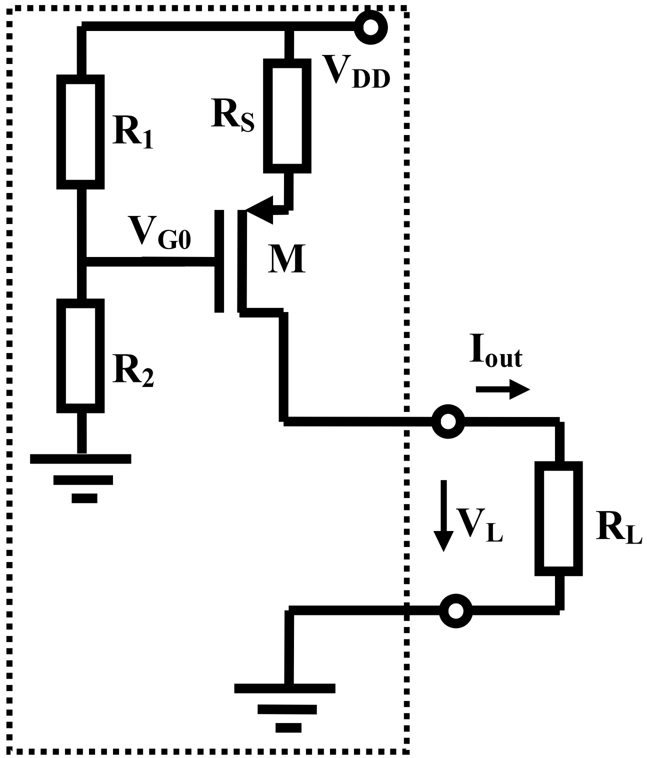
$$V_L < \frac{R_2}{R_1 + R_2} V_{DD} + V_{TH}$$

电流镜电路比这个电路有什么优势？
为什么要加负反馈电阻？根本原因是稳定性问题

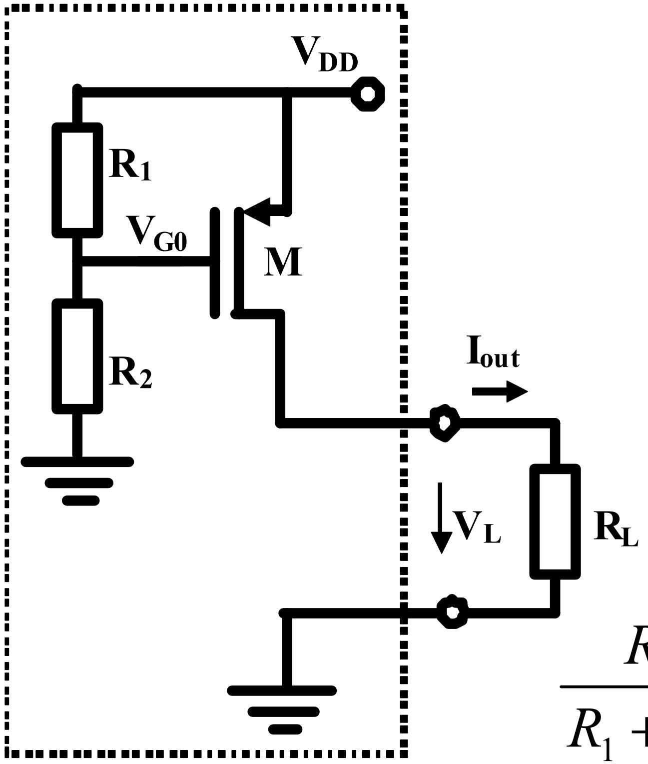
例3 分压偏置电路设计



V_{DD}=3.3V
V_{TH}=0.8V，
$\mu_p C_{ox}$=100μA/V^2
λ=0
恒流区工作



设计分压偏置电路，使得恒流输出I_{out}=1mA
已知W/L=50



$$I_D = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(V_{SG2} - V_{TH}\right)^2$$

$$V_{SG2} = \sqrt{\frac{2I_D}{\mu_p C_{ox}\frac{W}{L}}} + V_{TH} = \sqrt{\frac{2\times 1mA}{100\ \mu A/V^2 \times 50}} + 0.8$$

$$= \sqrt{\frac{2\times 1000}{100\times 50}} + 0.8 = \sqrt{0.4} + 0.8 = 0.63 + 0.8 = 1.43V$$

$$\frac{R_1}{R_1+R_2} = \frac{V_{SG}}{V_{DD}} \qquad \frac{R_1}{R_2} = \frac{V_{SG}}{V_{DD}-V_{SG}} = \frac{1.43}{3.3-1.43} = \frac{1.43}{1.87}$$

$$\frac{V_{DD}}{R_1+R_2} \le \frac{1}{10} I_{out} = 100\mu A \qquad R_1 + R_2 \ge \frac{3.3V}{100\mu A} = 33k\Omega$$

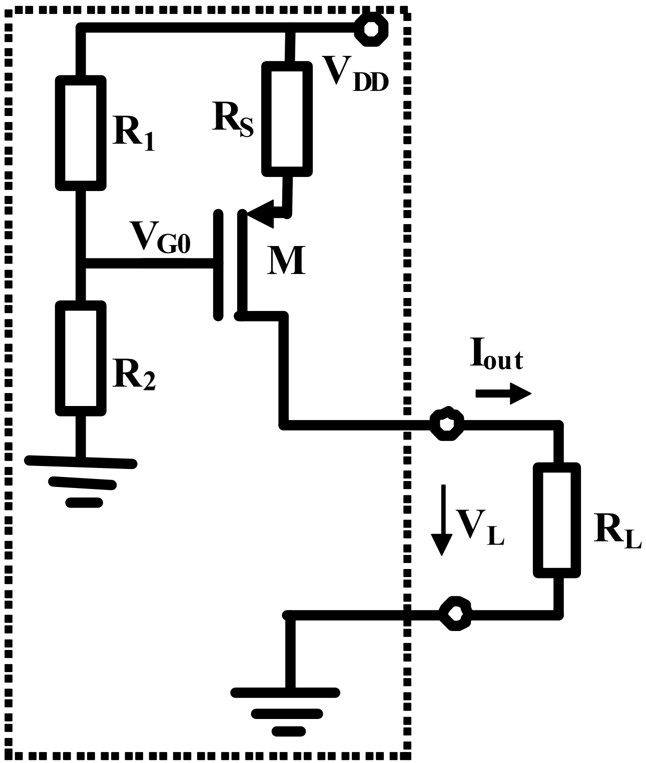
取 $R_1 = 14.3k\Omega$

$R_2 = 18.7k\Omega$

同时要求 $V_L \le 2.67V$

$R_L \le 2.67k\Omega$

确保晶体管工作在恒流区



负反馈电阻R_S不宜取值过大，
否则输出端口电压空间过小

取 $R_S = 500\Omega$ 输出电压空间压缩**0.5V**

$$V_L \le 2.17V$$
$$R_L \le 2.17k\Omega$$

代价：恒流源等效适用范围降低

$$V_{G0} = V_{DD} - I_S R_S - V_{SG} = 3.3 - 0.5 - 1.43 = 1.37V$$

$$\frac{R_2}{R_1 + R_2} V_{DD} = V_{G0} = 1.37V$$

$$\frac{R_2}{R_1} = \frac{1.37}{3.3 - 1.37} = \frac{1.37}{1.93}$$

添加负反馈电阻的优势如何体现？

消除不确定性！电路变得稳定可靠！

取 $R_1 = 19.3k\Omega$

$R_2 = 13.7k\Omega$

工艺参量不确定性的体现

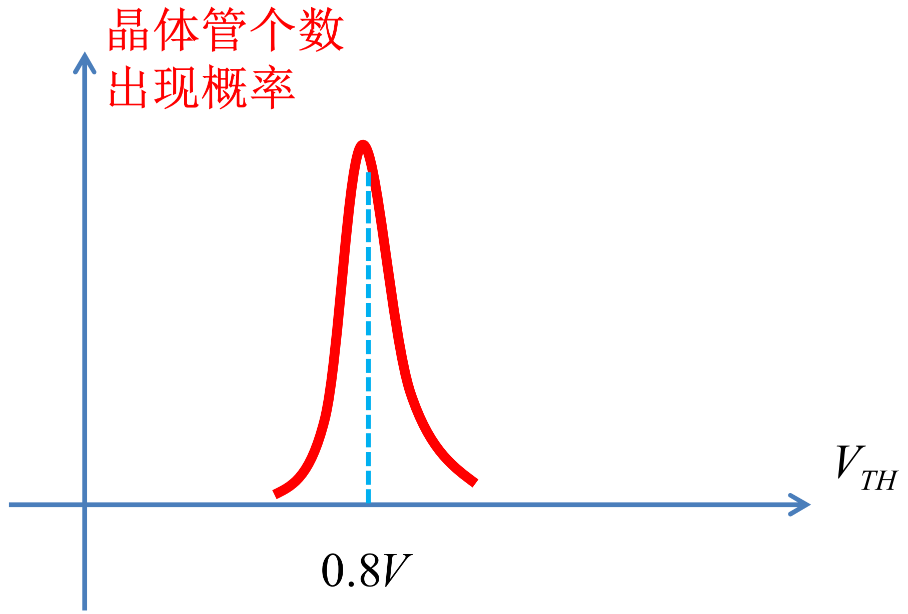
- 由于工艺参量的不确定性和环境温度的变化，实际制作的晶体管，其工艺参量将偏离设计值，提供的各种工艺参量大多是平均值（或有效值）

$$I_D = \frac{1}{2}\underline{\underline{\mu_p C_{ox}}}\,\underline{\underline{\frac{W}{L}}}\left(V_{SG2} - \underline{\underline{V_{TH}}}\right)^2$$

$\mu_p C_{ox}$=100μA/V²

W/L=50

V_{TH}=0.8V



例4 负反馈降低电路不确定性

- 由于工艺参数不确定及环境温度的变化，使得**PMOSFET**的阈值电压**V_{TH}**偏离设计值**0.8V+5%**，请分析确认，有负反馈电阻的分压偏置电路较无反馈电阻的设计确定性更高：实际输出电流偏离设计值小

特定问题方法：将新的**V_{TH}=0.8V+5%=0.84V**代入设计电路，考察两个电流源电路输出电流偏离**1mA**大小

$$I_D = \frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(V_{SG2} - V_{TH}\right)^2$$

无负反馈电阻

原理性分析的通用方法：对非线性方程线性化，只考察线性误差项

$$I_D = f(V_{TH}) = f(V_{TH0} + \Delta V_{TH}) = f(V_{TH0}) + f'(V_{TH0})\Delta V_{TH} + \ldots$$

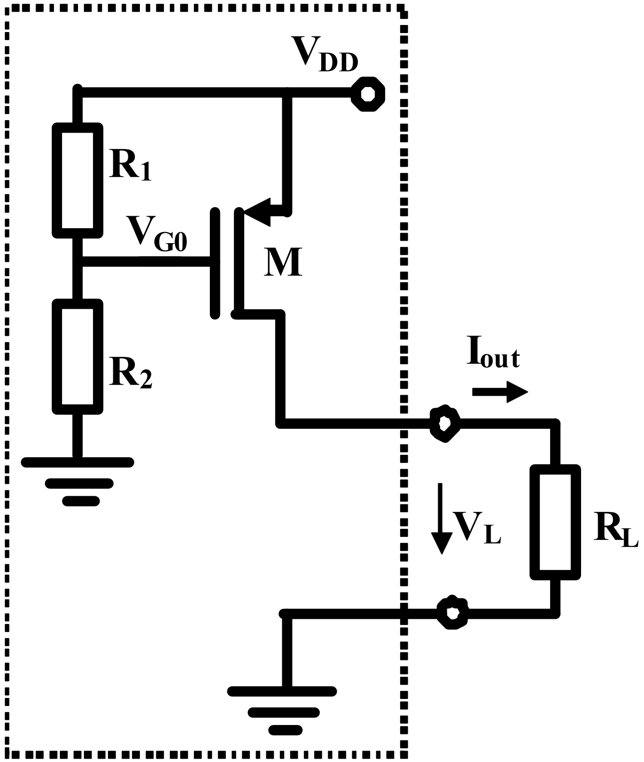
$$\approx f(V_{TH0}) + f'(V_{TH0})\Delta V_{TH} = I_{D0} + \Delta I_D$$

良好的工艺确保偏差不会太大

$$\Delta I_D = I_D - I_{D0} \approx f'(V_{TH0})\Delta V_{TH}$$

灵敏度越小，
电路越稳定

$$\frac{\Delta I_D}{I_{D0}} \approx \left(\frac{f'(V_{TH0})}{f(V_{TH0})}V_{TH0}\right)\frac{\Delta V_{TH}}{V_{TH0}} = S_{V_{TH}}^{I_D} \cdot \frac{\Delta V_{TH}}{V_{TH0}}$$



$$I_{out} = I_D = \beta_p V_{od}^2 = \beta_p \left(V_{DD} - V_{G0} - V_{TH}\right)^2$$

$$= \frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(\frac{R_1}{R_1+R_2}V_{DD} - V_{TH}\right)^2$$

都有可能存在偏差，导致输出电流偏离设计值

$$\frac{\partial I_{out}}{\partial V_{TH}} = \frac{\partial I_{out}}{\partial V_{od}} \cdot \frac{\partial V_{od}}{\partial V_{TH}}$$

$$= 2\beta_p V_{od} \times (-1) = -2\beta_p V_{od} = -\frac{\partial I_D}{\partial V_{SG}} = -g_m$$

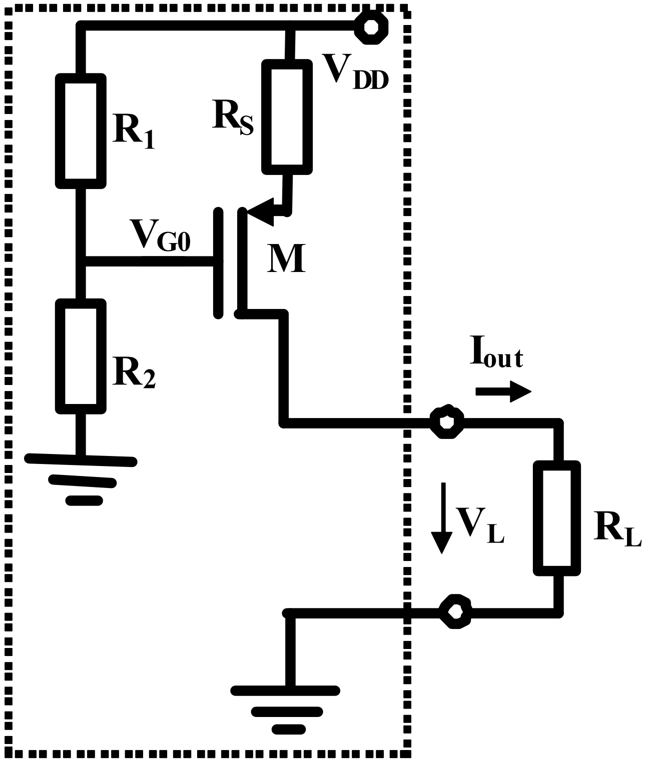
阈值电压的偏差，可以等价为源栅电压的反向偏差，都会导致输出电流偏离设计值

$$g_m = \frac{\partial I_D}{\partial V_{SG}} = 2\beta_p V_{od} = 2\times\left(\frac{1}{2}\times 100\,\mu A/V^2 \times 50\right)\times 0.63V = 3.17mS$$

微分跨导增益

$$\frac{\Delta I_{out}}{I_{out}} \approx \frac{\frac{\partial I_{out}}{\partial V_{TH}}\Delta V_{TH}}{I_{out}} = -\frac{g_m V_{TH}}{I_{out}}\frac{\Delta V_{TH}}{V_{TH}} = \frac{-3.17\times 0.8}{1}\times 5\% = -2.54\times 5\% = -12.7\%$$

灵敏度**-2.54**



$$I_{out}=I_D=\beta_p V_{od}^2=\beta_p\left(V_{DD}-I_D R_S-V_{G0}-V_{TH}\right)^2$$

$$=\frac{1}{2}\mu_p C_{ox}\frac{W}{L}\left(\frac{R_1}{R_1+R_2}V_{DD}-I_{out}R_S-V_{TH}\right)^2$$

串串负反馈：检测输出电流变化，转换为负反馈电压，从输入电压中扣除后，作用于原放大器：输出电流中的不确定性因而降低

$$\frac{\partial I_{out}}{\partial V_{TH}}=\frac{\partial I_{out}}{\partial V_{od}}\cdot\frac{\partial V_{od}}{\partial V_{TH}}$$

$$=2\beta_p V_{od}\times\left(-\frac{\partial I_{out}}{\partial V_{TH}}R_S-1\right)=-g_m\left(\frac{\partial I_{out}}{\partial V_{TH}}R_S+1\right)$$

$$\frac{\partial I_{out}}{\partial V_{TH}}=-\frac{g_m}{1+g_m R_S}=-\frac{3.17mS}{1+3.17mS\times 0.5k\Omega}=-1.23mS$$

负反馈的存在，使得阈值电压变化导致的电流变化降低了

$$\frac{\Delta I_{out}}{I_{out}}=\frac{\frac{\partial I_{out}}{\partial V_{TH}}\Delta V_{TH}}{I_{out}}=-\frac{g_m}{1+g_m R_S}\frac{V_{TH}}{I_{out}}\frac{\Delta V_{TH}}{V_{TH}}=-0.98\times 5\%=-4.9\%$$

灵敏度**-0.98**
灵敏度降低了

灵敏度降低了

$$\frac{\Delta I_{out}}{I_{out}} \approx \frac{\frac{\partial I_{out}}{\partial V_{TH}}\Delta V_{TH}}{I_{out}} = -g_m \frac{V_{TH}}{I_{out}}\frac{\Delta V_{TH}}{V_{TH}}$$

无负反馈电阻

$$S_{V_{TH}}^{I_{out}} = -g_m \frac{V_{TH}}{I_{out}}$$

$$\frac{\Delta I_{out}}{I_{out}} \approx \frac{\frac{\partial I_{out}}{\partial V_{TH}}\Delta V_{TH}}{I_{out}} = -\frac{g_m}{1+g_m R_S}\frac{V_{TH}}{I_{out}}\frac{\Delta V_{TH}}{V_{TH}}$$

有负反馈电阻

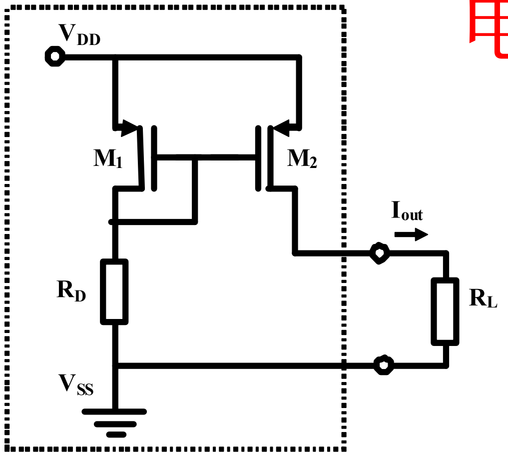
$$S_{V_{TH}}^{I_{out}} = -\frac{g_m}{1+g_m R_S}\frac{V_{TH}}{I_{out}}$$

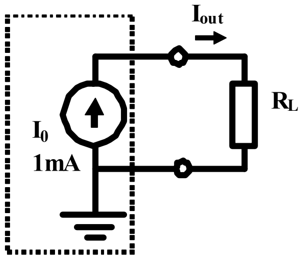
添加负反馈电阻后，灵敏度降低为原来的 $\frac{1}{1+g_m R_S}$ 倍

定义 $T = g_m R_S$ 为环路增益，环路增益越大，电路稳定性改善越明显

$T = 3.17mS \times 0.5k\Omega = 1.59$ 本例有改善，但改善程度不高

电流镜是模拟集成电路的特征电路





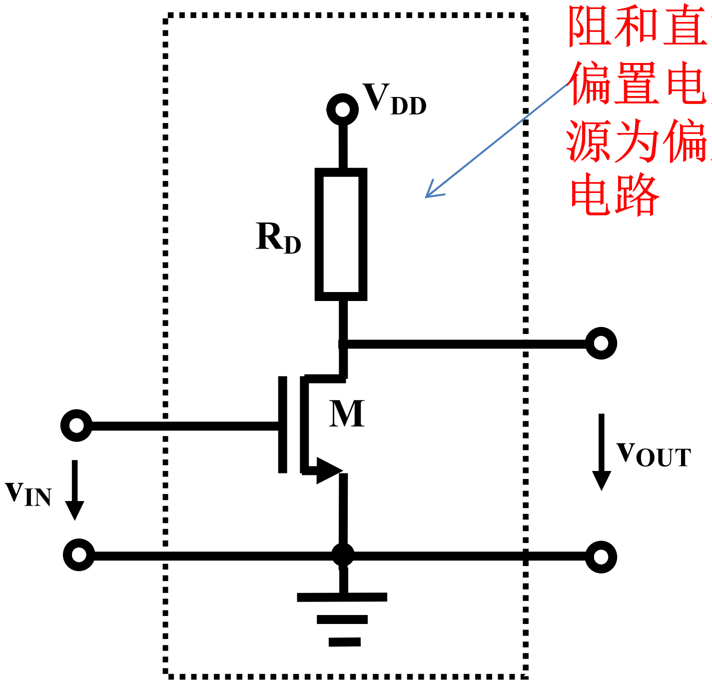
$$\frac{I_{D2}}{I_{D1}}=\frac{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_2 (V_{SG2}-V_{TH})^2}{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)_1 (V_{SG1}-V_{TH})^2}=\frac{\left(\frac{W}{L}\right)_2}{\left(\frac{W}{L}\right)_1}$$

- 晶体管工艺参量偏差有会导致严重的设计偏差，但是采用电流镜结构，由于集成电路内部制作时，两个晶体管紧邻一起，其工艺偏差是一致的，而电流镜的两个支路电流之比为宽长比之比，因而这种设计可以确保实际输出偏离设计值很小
  - 参考源支路的电流可以通过某种方式确保稳定
  - 集成电路内部多采用电流镜结构，有一个稳定参考源，其他支路电流通过电流镜电路，确保都是这个参考源电流的倍数，倍数由晶体管尺寸决定

三、MOSFET反相器

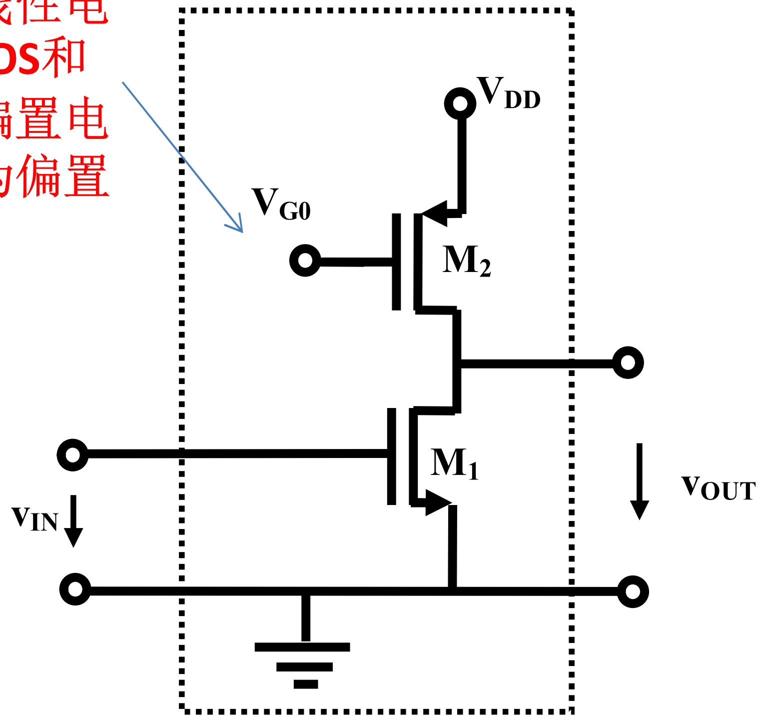
- **NMOS**反相器
  - 线性电阻为偏置负载
  - 非线性电阻为偏置负载
    - 以**PMOS**为非线性电阻例
- **CMOS**反相器
  - 留到习题课讨论
    - 本周作业为**PMOS**，配合**NMOS**形成**CMOS**，讲作业时顺带讨论**CMOS**反相器（如果有空）

NMOS反相器



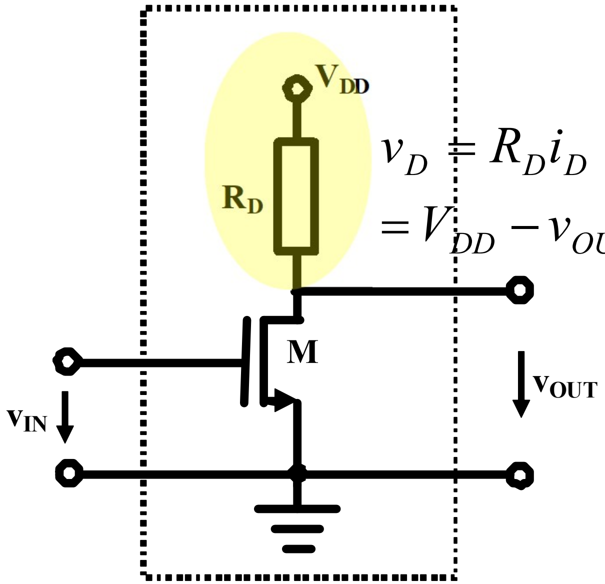
以线性电阻和直流偏置电压源为偏置电路

以非线性电阻**PMOS**和直流偏置电压源为偏置电路

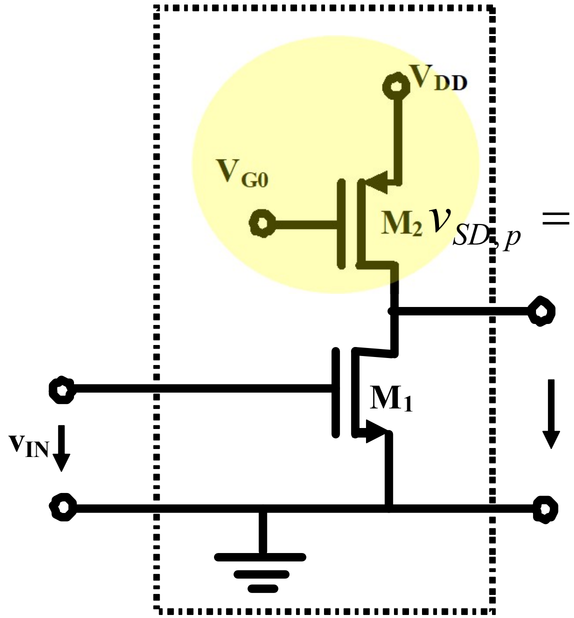


负载线方程

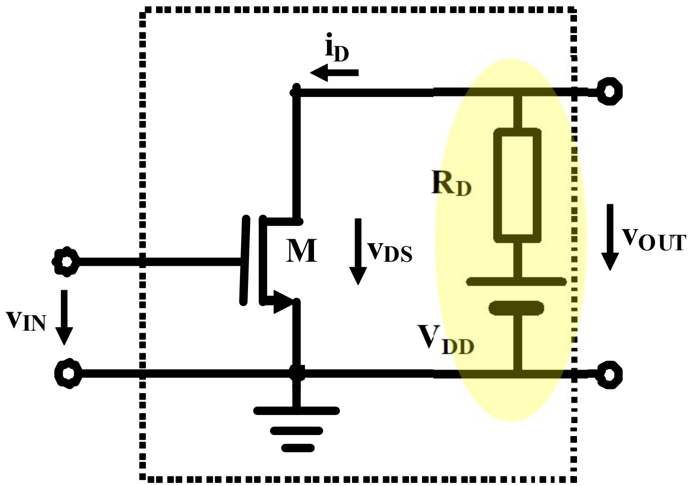
联立晶体管方程



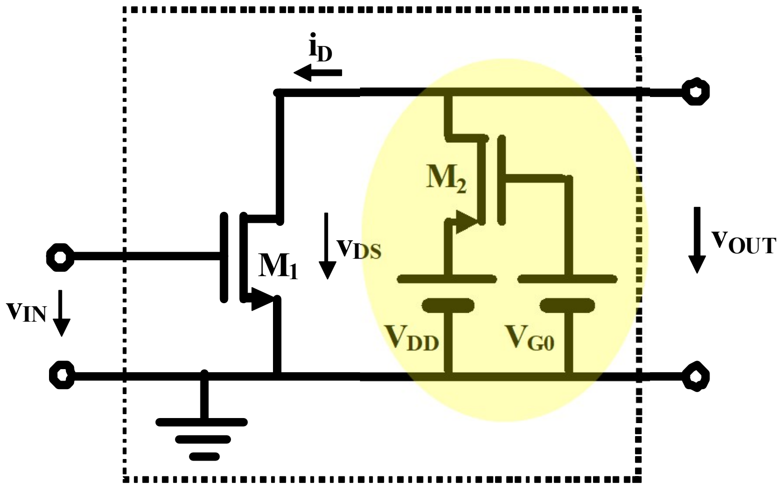
$$v_D = R_D i_D = V_{DD} - v_{OUT}$$



$$v_{SD,p} = V_{DD} - v_{OUT}$$

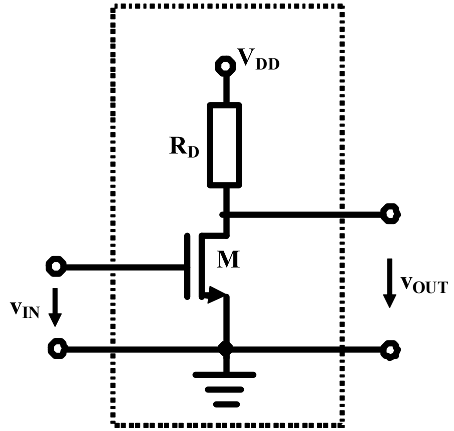


$$i_D = \frac{V_{DD} - v_{OUT}}{R_D}$$

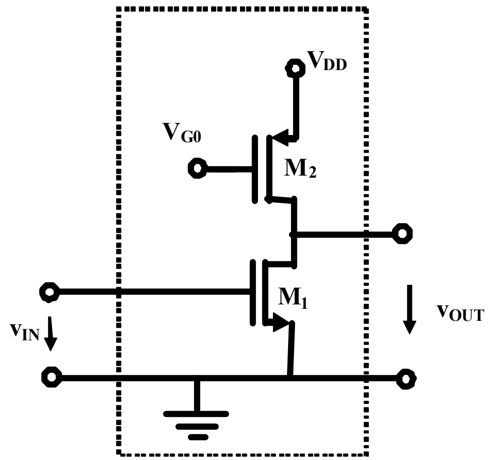


$$i_D = i_{D,p} = f_{PMOS}\left(v_{SG,p}, v_{SD,p}\right) = f_{PMOS}\left(V_{DD} - V_{G0}, V_{DD} - v_{OUT}\right)$$

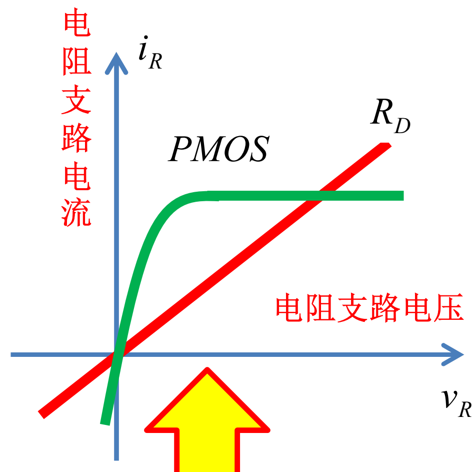
方程联立
曲线交点



$$i_{D,n} = \frac{V_{DD} - v_{OUT}}{R_D}$$

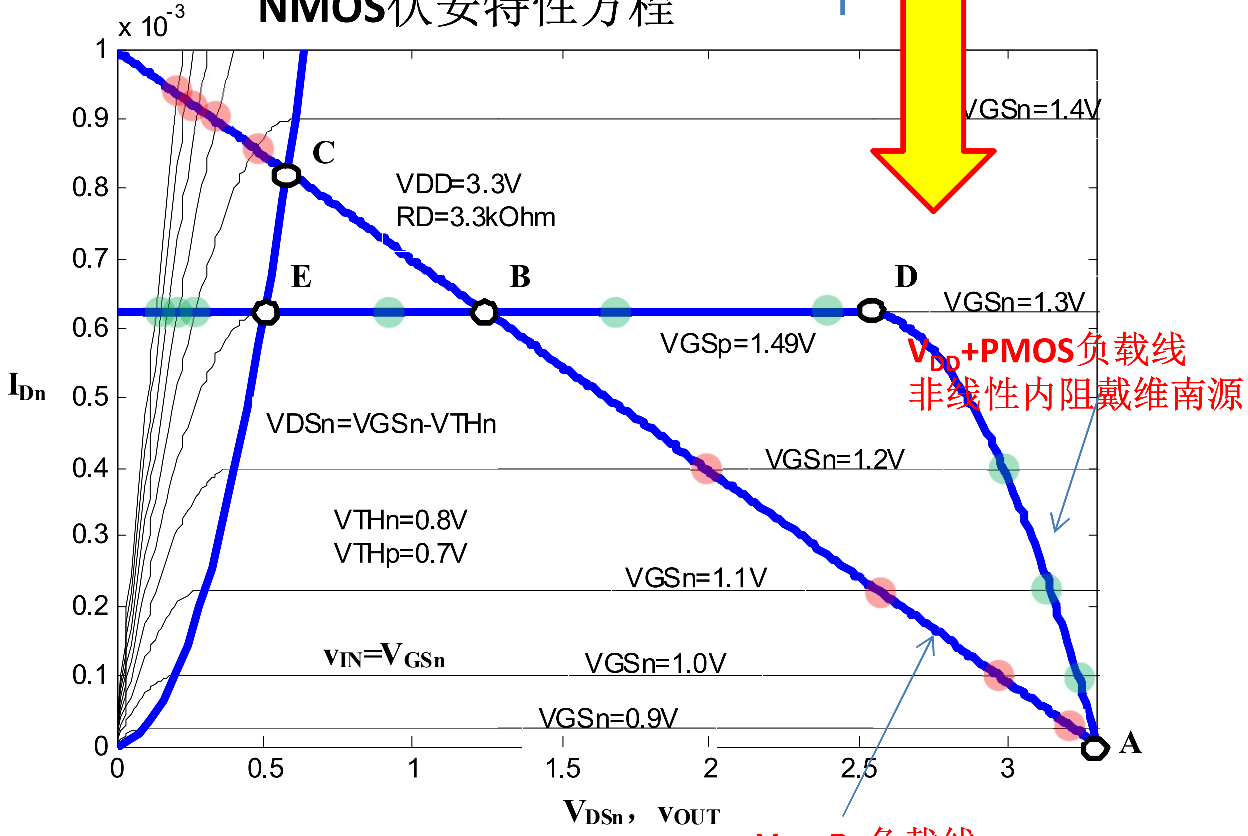


$$i_{D,n} = f_{PMOS}\left(V_{DD} - V_{G0}, V_{DD} - v_{OUT}\right)$$



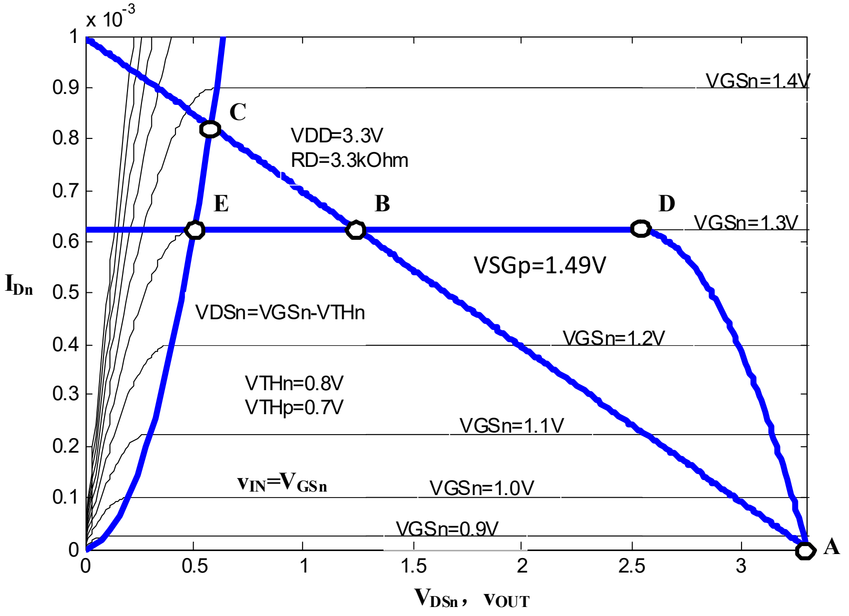
负载线方程 联立

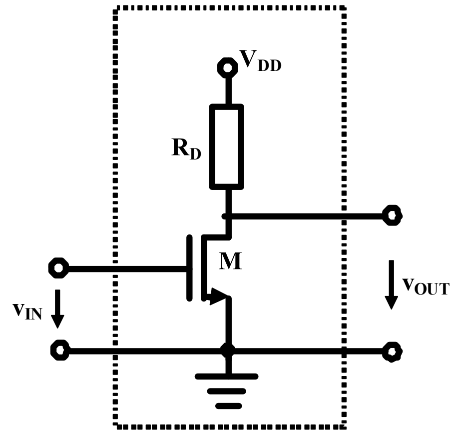
NMOS伏安特性方程



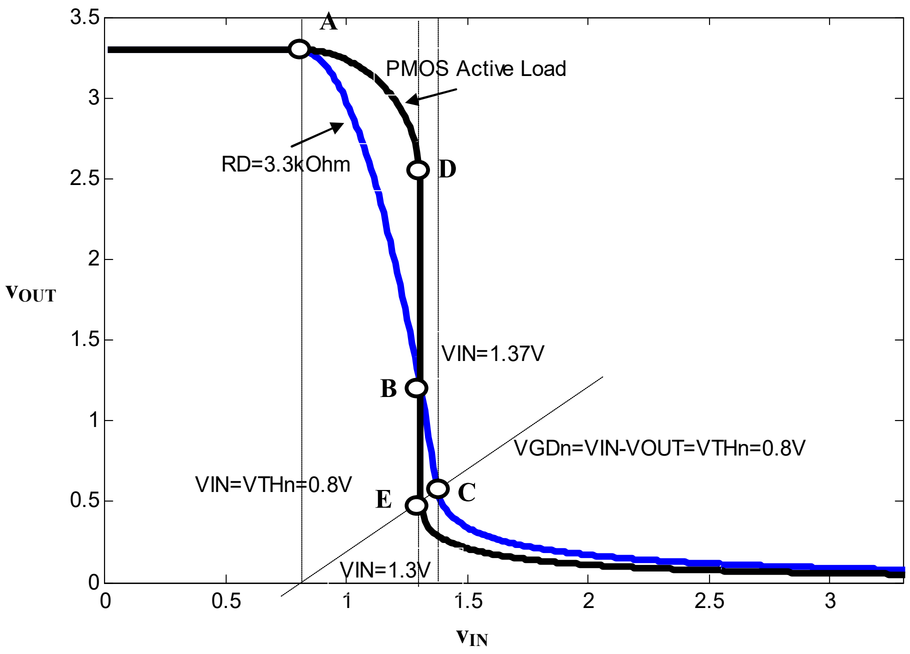
$V_{DD}+R_D$负载线
线性内阻戴维南源

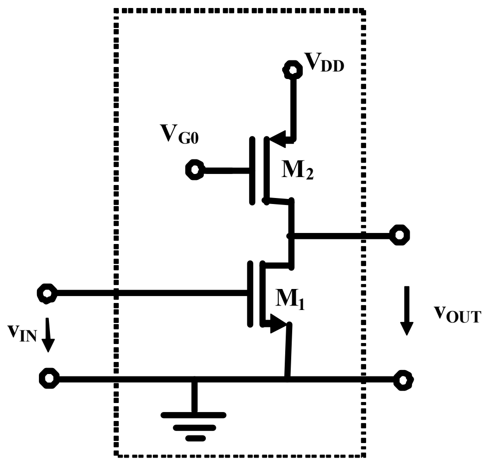
输入输出反相特性曲线



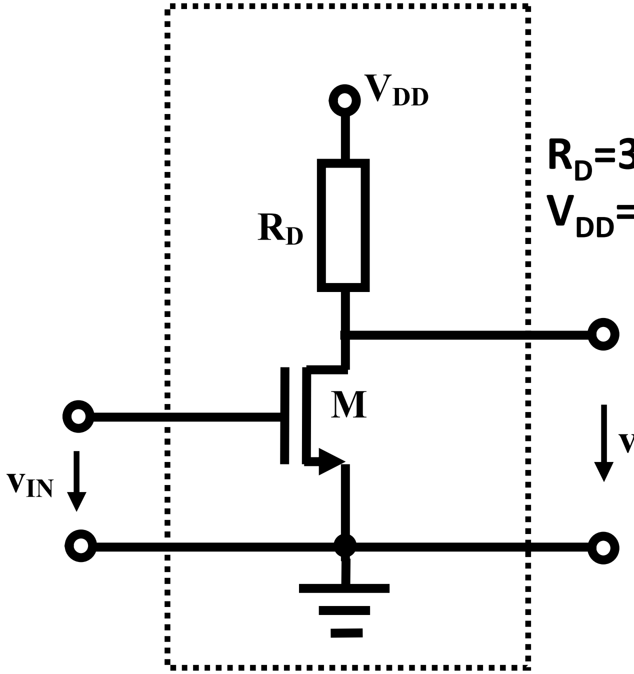


原理性图解分析





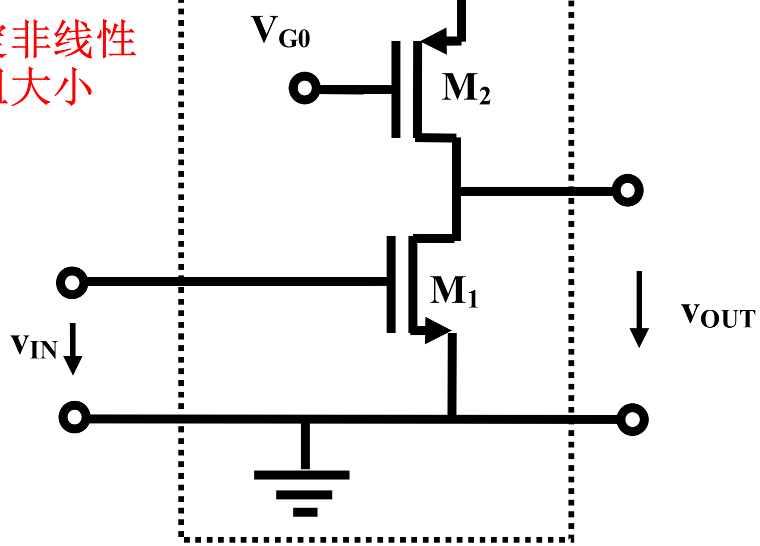
例5 用分段折线电路模型分析反相器



R_D=3.3kΩ，
V_{DD}=3.3V

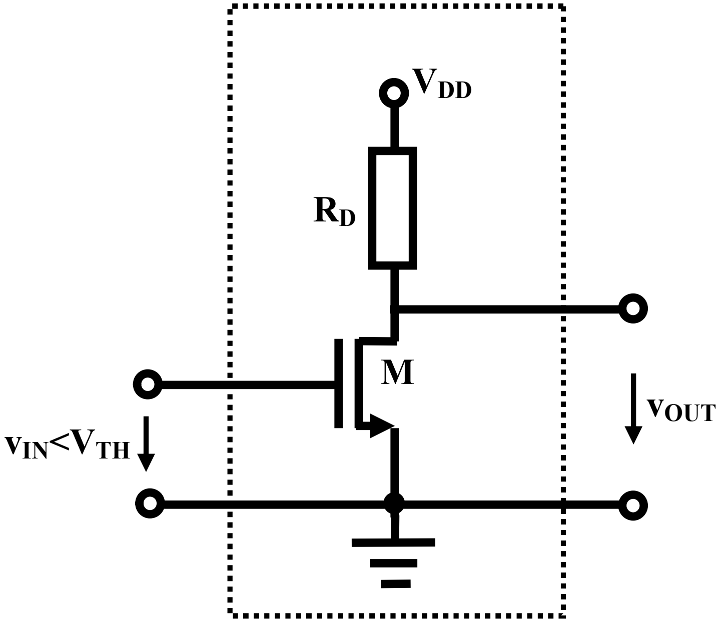
V_{DD}=3.3V
V_{G0}=1.81V

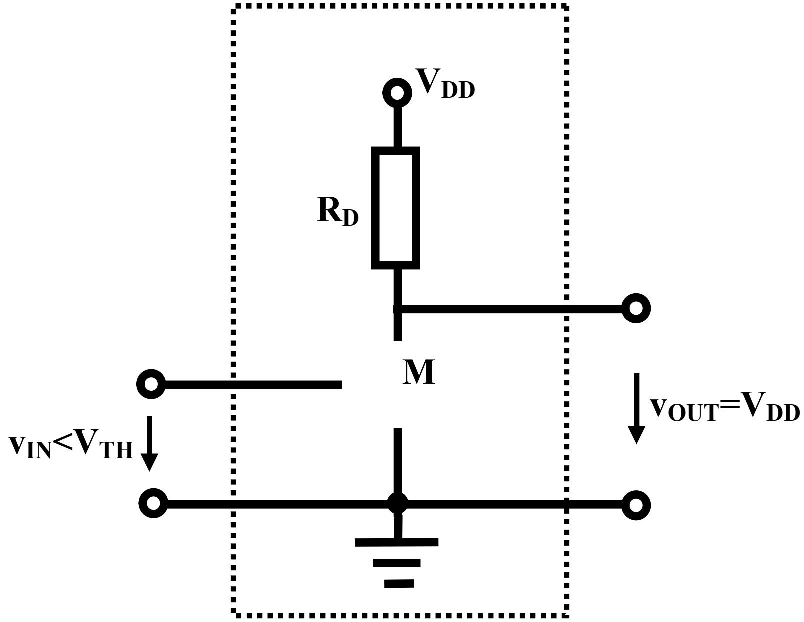
决定非线性
电阻大小



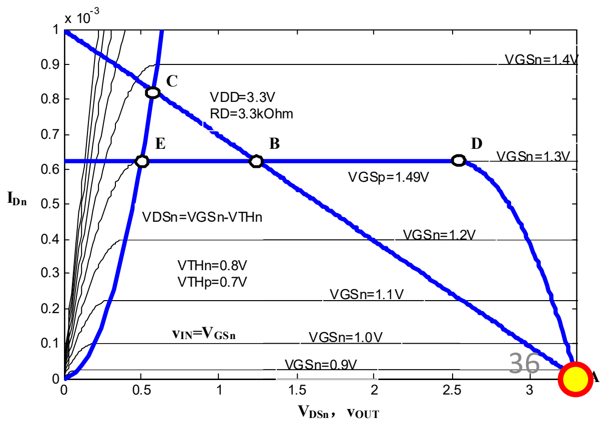
NMOSFET： β_n=2.5mA/V^2， V_{THn}=0.8V
PMOSFET： β_p=1mA/V^2， V_{THp}=0.7V

线性电阻负载：NMOS截止

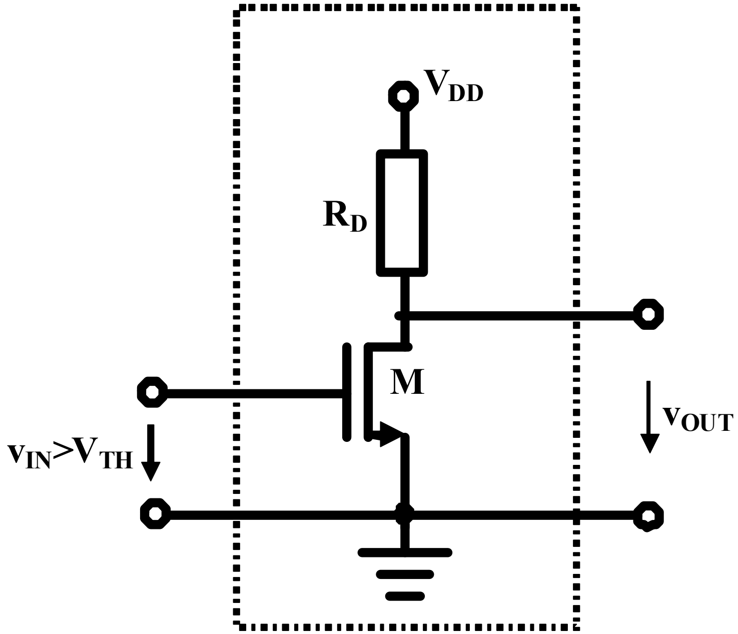


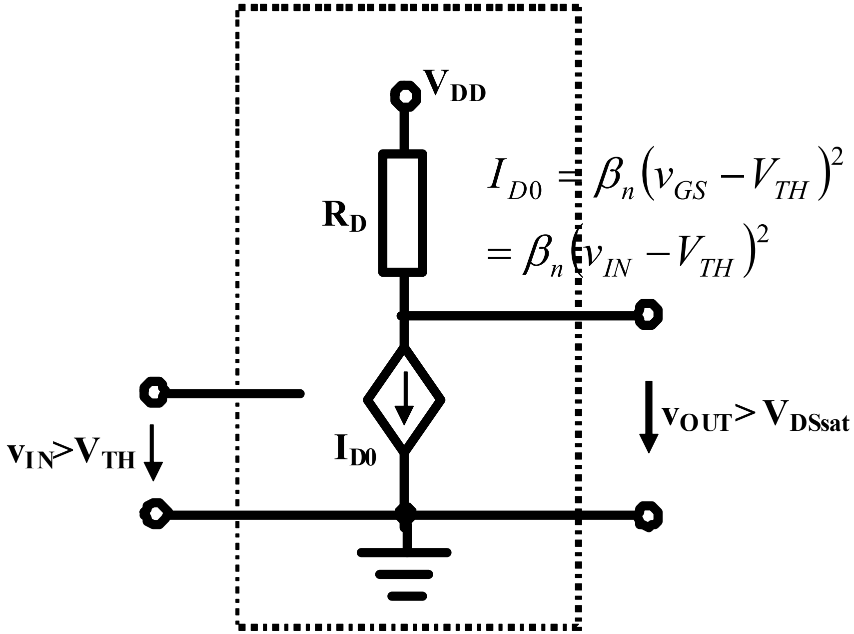


$$v_{IN} < V_{TH} \qquad v_{OUT} = V_{DD}$$



线性电阻负载：NMOS恒流导通



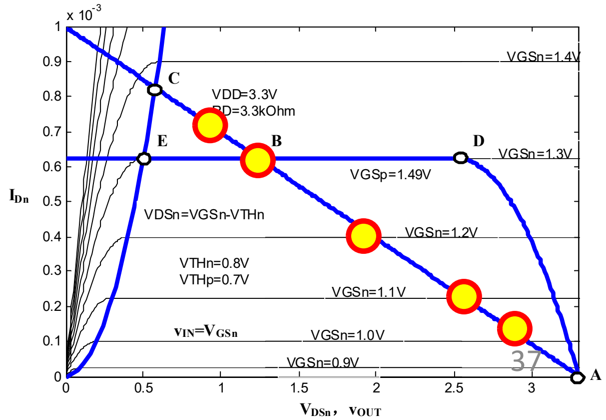


$$I_{D0} = \beta_n (v_{GS} - V_{TH})^2 = \beta_n (v_{IN} - V_{TH})^2$$

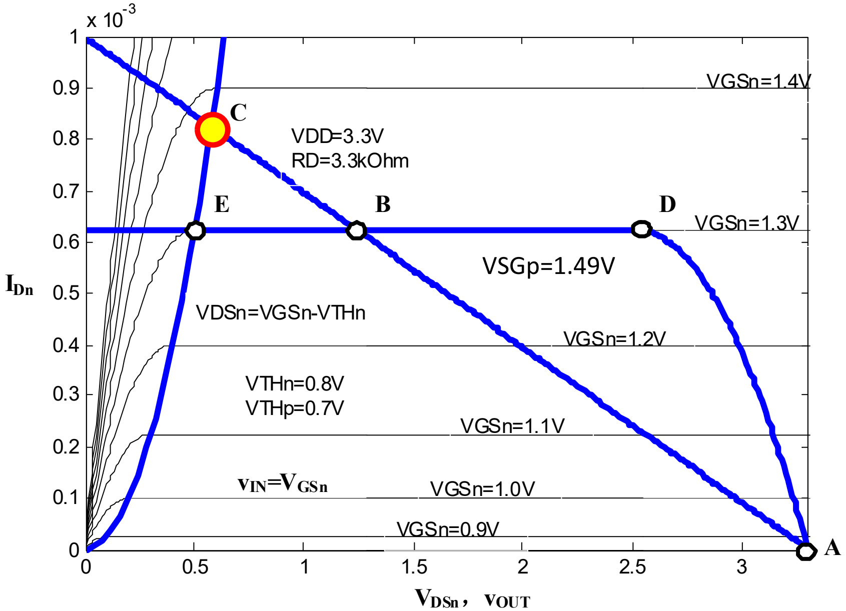
$$v_{IN} > V_{TH}$$

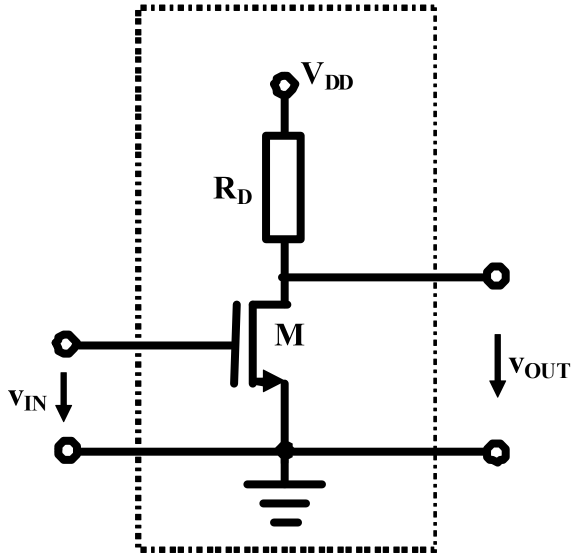
$$v_{OUT} > v_{IN} - V_{TH}$$

$$v_{OUT} = V_{DD} - I_{D0} R_D = V_{DD} - \beta_n (v_{IN} - V_{TH})^2 R_D$$



恒流导通区和欧姆导通区分界





$$v_{OUT}=V_{DD}-\beta_n\left(v_{IN}-V_{TH}\right)^2R_D=v_{IN}-V_{TH}$$

$$\beta_n\left(v_{IN}-V_{TH}\right)^2R_D+\left(v_{IN}-V_{TH}\right)-V_{DD}=0$$

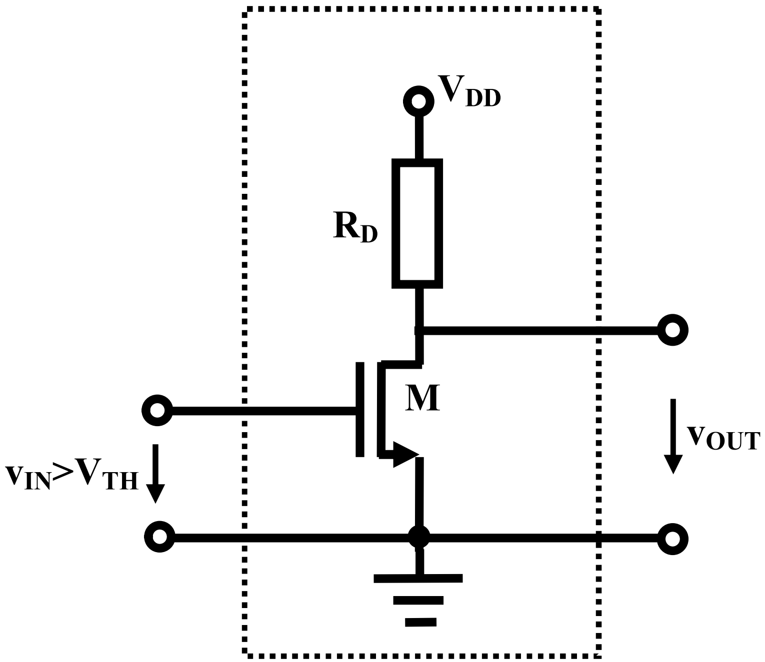
$$v_{IN,C}=V_{TH}+\frac{-1+\sqrt{1+4\beta_nR_DV_{DD}}}{2\beta_nR_D}=0.8+\frac{-1+\sqrt{1+4\times2.5\times3.3\times3.3}}{2\times2.5\times3.3}=1.37V$$

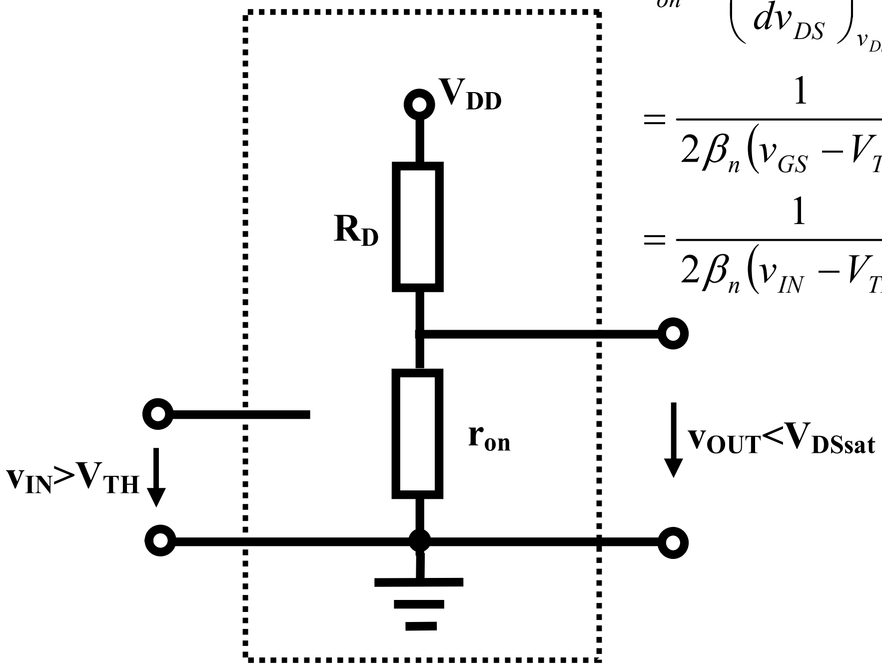
线性电阻负载：NMOS欧姆导通

$$r_{on}=\left(\frac{di_D}{dv_{DS}}\right)^{-1}_{v_{DS}=0}$$

$$=\frac{1}{2\beta_n\left(v_{GS}-V_{TH}\right)}$$

$$=\frac{1}{2\beta_n\left(v_{IN}-V_{TH}\right)}$$

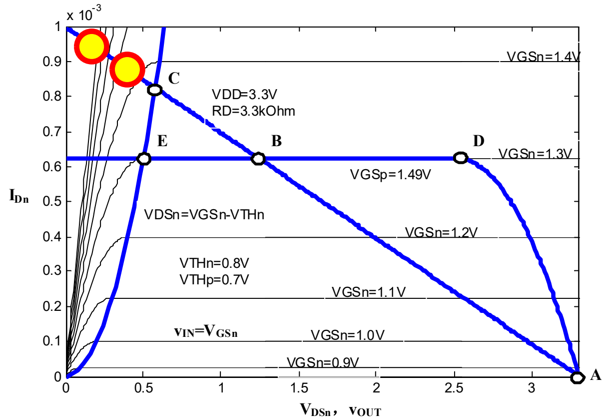




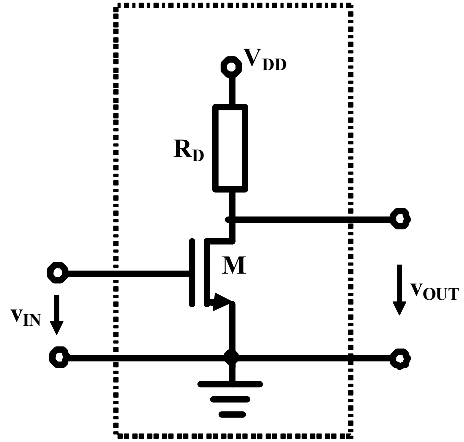
$$v_{IN}>1.37V$$

$$v_{OUT}=\frac{r_{on}}{r_{on}+R_D}V_{DD}$$

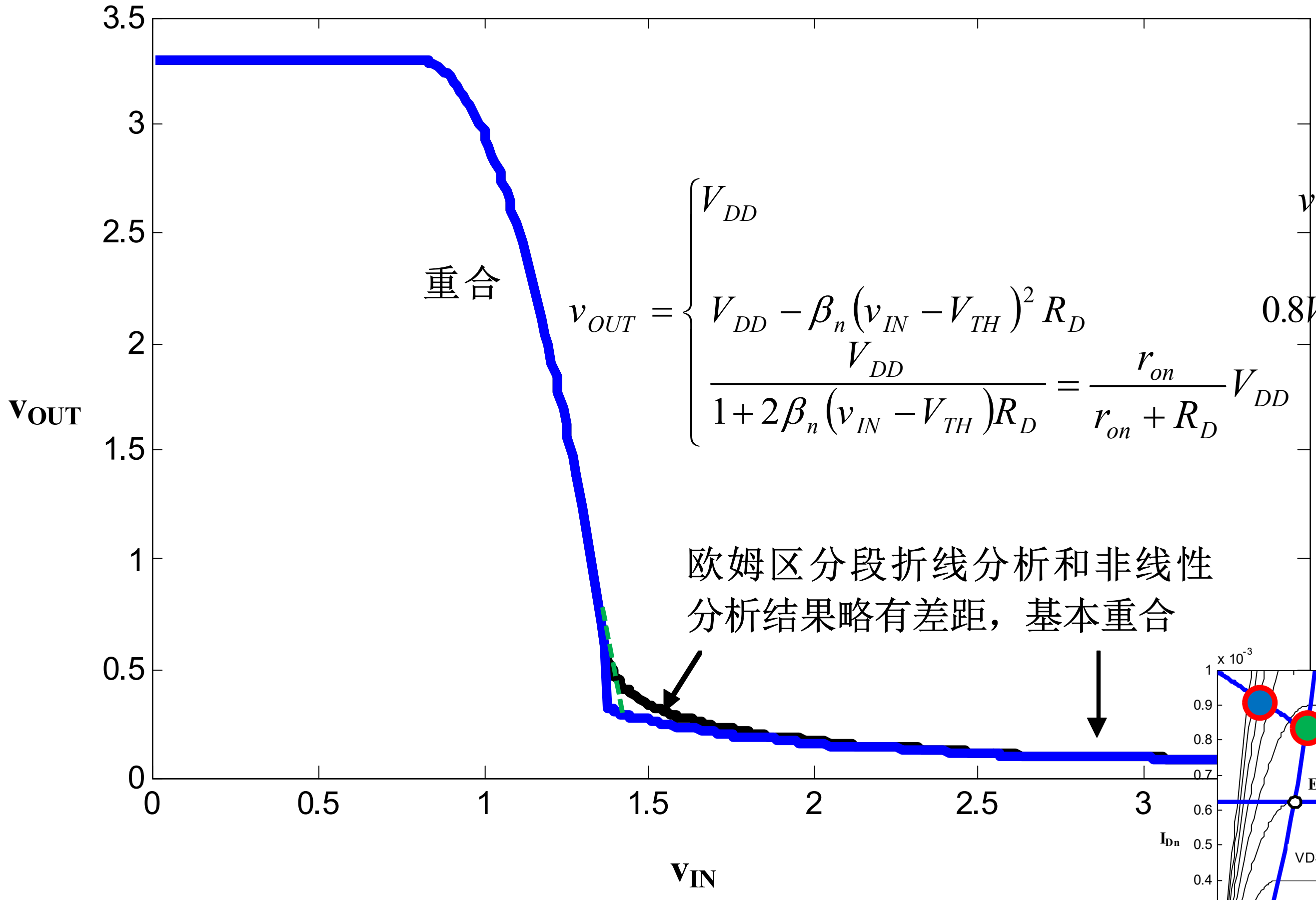
$$=\frac{1}{1+2\beta_n\left(v_{IN}-V_{TH}\right)R_D}V_{DD}$$

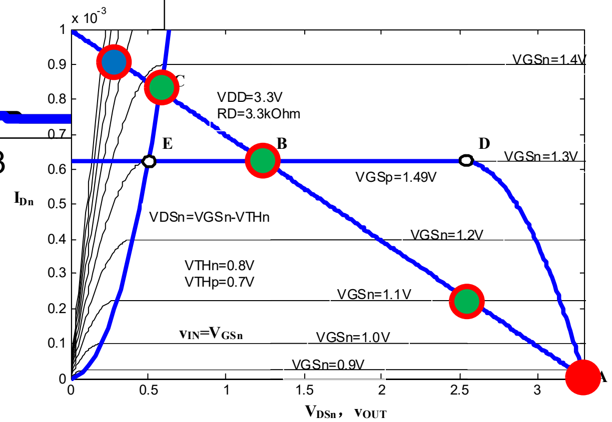


分段折线解



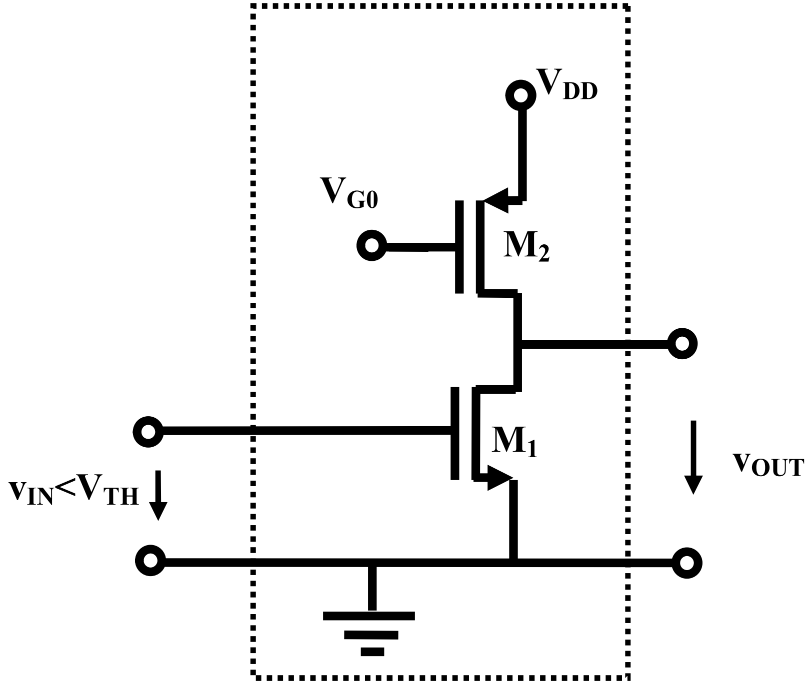
$$v_{OUT}=\begin{cases} V_{DD} & v_{IN}<V_{TH}=0.8V \quad \text{N截止} \\ V_{DD}-\beta_n\left(v_{IN}-V_{TH}\right)^2 R_D & 0.8V<v_{IN}<1.37V \quad \text{N恒流} \\ \dfrac{V_{DD}}{1+2\beta_n\left(v_{IN}-V_{TH}\right)R_D}=\dfrac{r_{on}}{r_{on}+R_D}V_{DD} & v_{IN}>1.37V \quad \text{N欧姆} \end{cases}$$

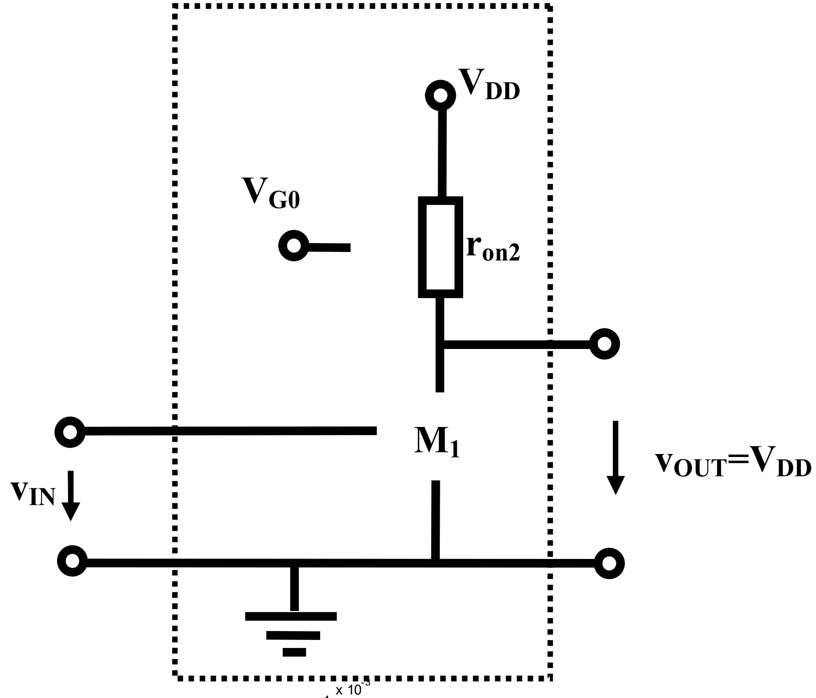




非线性电阻负载

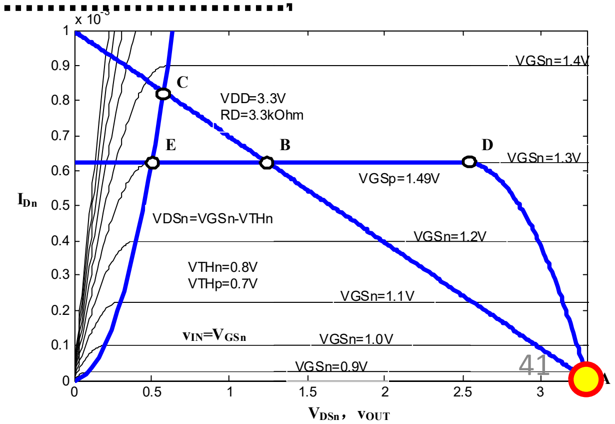
NMOS截止
PMOS欧姆导通





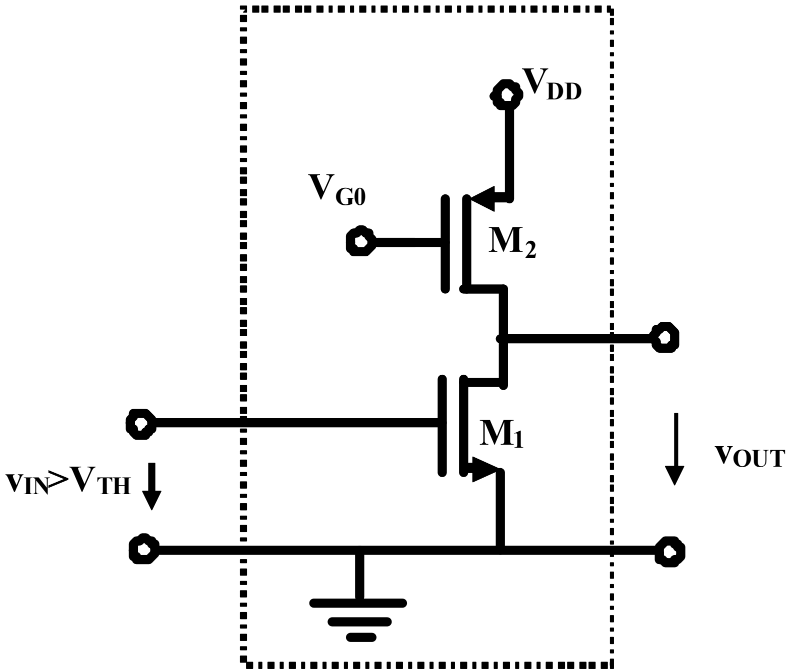
$$v_{OUT} = V_{DD}$$

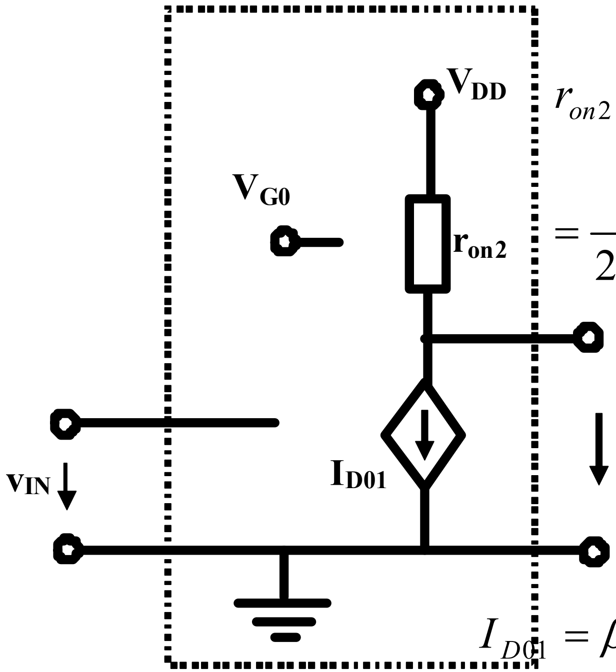
$$v_{IN} < V_{THn}$$



非线性电阻负载

NMOS恒流导通
PMOS欧姆导通





$$r_{on2} = \frac{1}{2\beta_p\left(v_{SG2} - V_{THp}\right)}$$

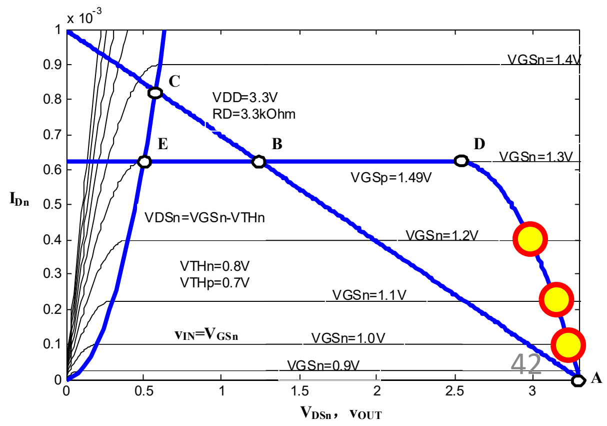
$$= \frac{1}{2\beta_p V_{odp}}$$

$$I_{D01} = \beta_n\left(v_{IN} - V_{THn}\right)^2$$

$$v_{IN} > V_{THn}$$

$$v_{OUT} = V_{DD} - I_{D01} r_{on2}$$

$$= V_{DD} - \frac{\beta_n}{2\beta_p} \frac{\left(v_{IN} - V_{THn}\right)^2}{V_{odp}}$$



非线性电阻负载

NMOS恒流导通
PMOS欧姆导通与恒流导通分界

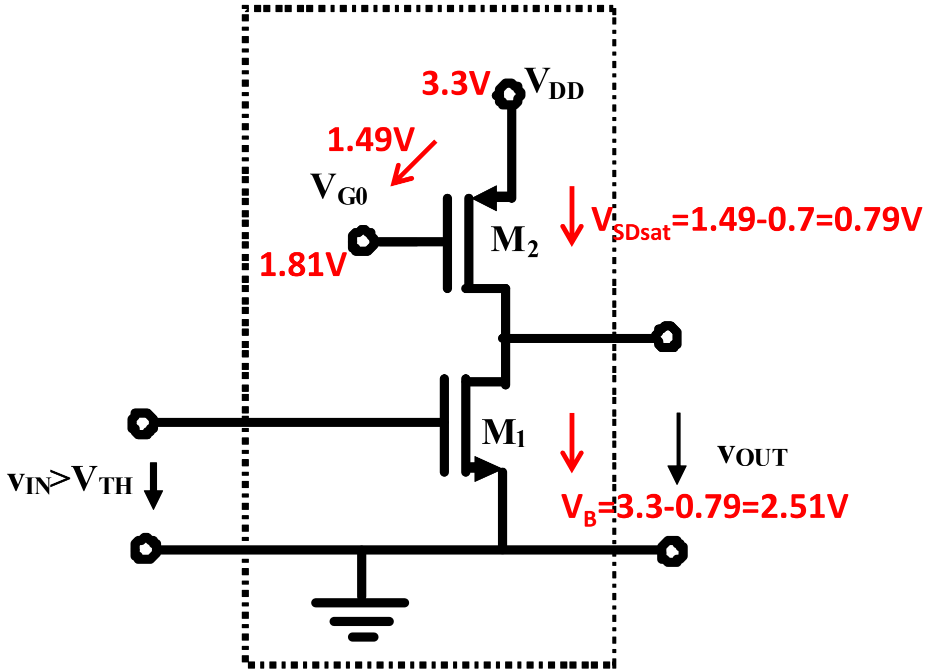
$$v_{SD,p,sat} = V_{SG,p} - V_{THp}$$
$$= V_{DD} - V_{G0} - V_{THp}$$
$$= 3.3 - 1.81 - 0.7 = 0.79V$$

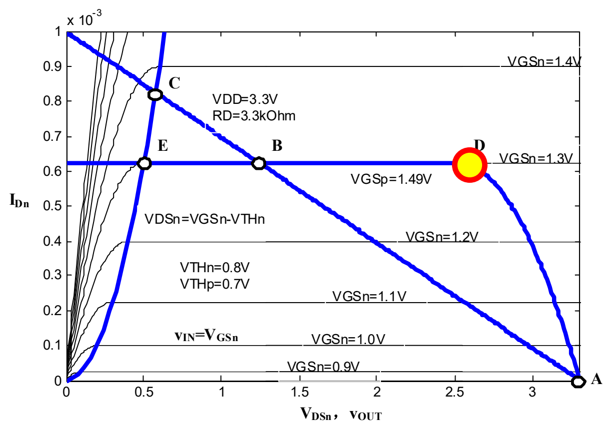
$$v_{OUT,D} = V_{DD} - v_{SG,p,sat}$$
$$= 3.3 - 0.79 = 2.51V$$

$$I_{Dn} = I_{Dp}$$ 均进入恒流导通

$$= \beta_n \left(v_{IN} - V_{THn}\right)^2 = \beta_p \left(V_{SG,p} - V_{THp}\right)^2$$

$$v_{IN} = V_{THn} + \sqrt{\frac{\beta_p}{\beta_n}} V_{odp} = 0.8 + \sqrt{\frac{1}{2.5}} \times 0.79 = 1.3V$$

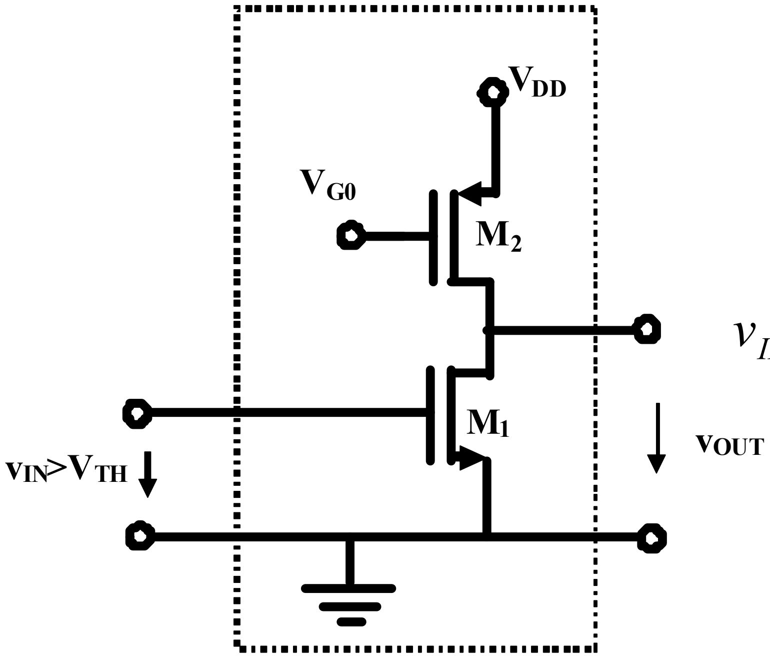




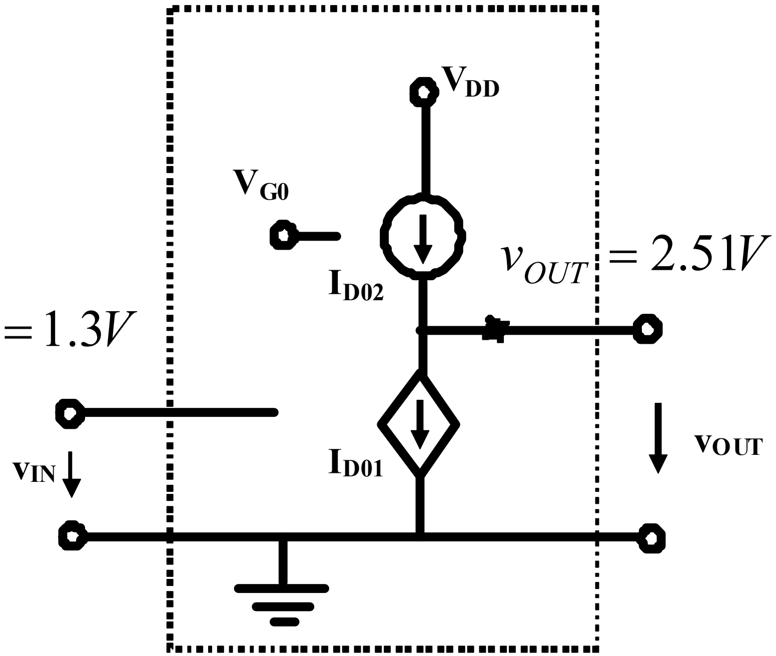
非线性电阻负载

NMOS恒流导通

PMOS恒流导通



$$v_{IN} = 1.3V$$



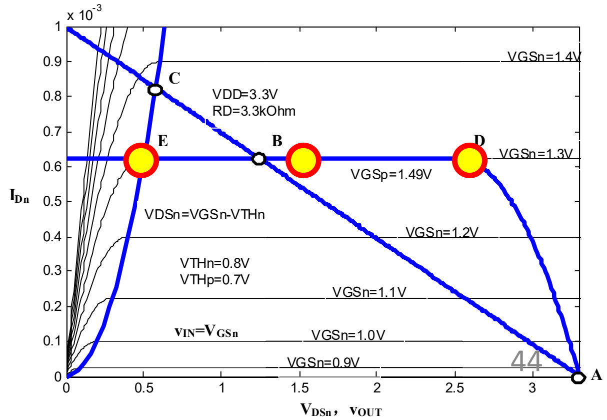
$$v_{OUT} = 2.51V \sim 0.50V$$

$v_{IN} = 1.3V$ 均进入恒流导通

$v_{GDn} = v_{IN} - v_{OUT} < V_{TH}$ **NMOS恒流导通条件**

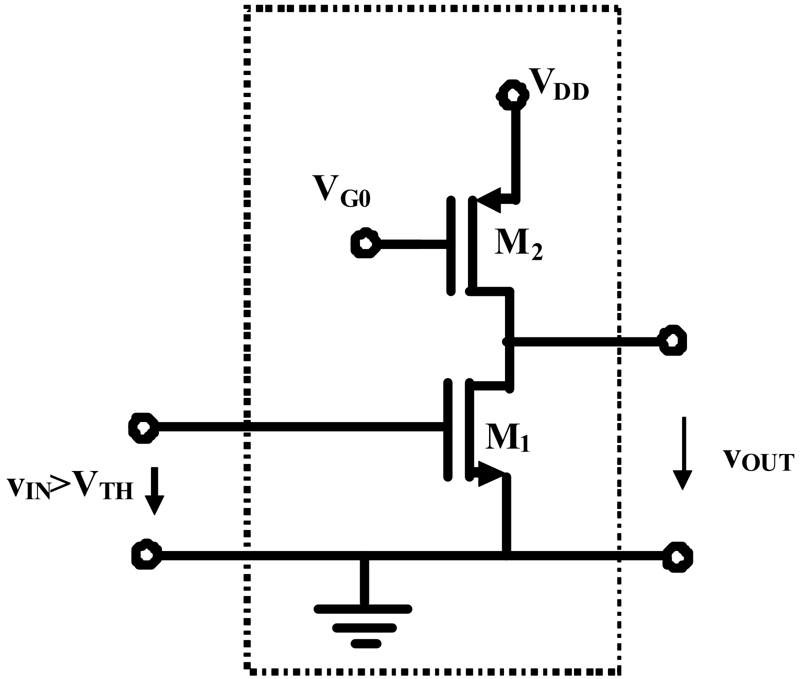
NMOS恒流导通和欧姆导通分界点

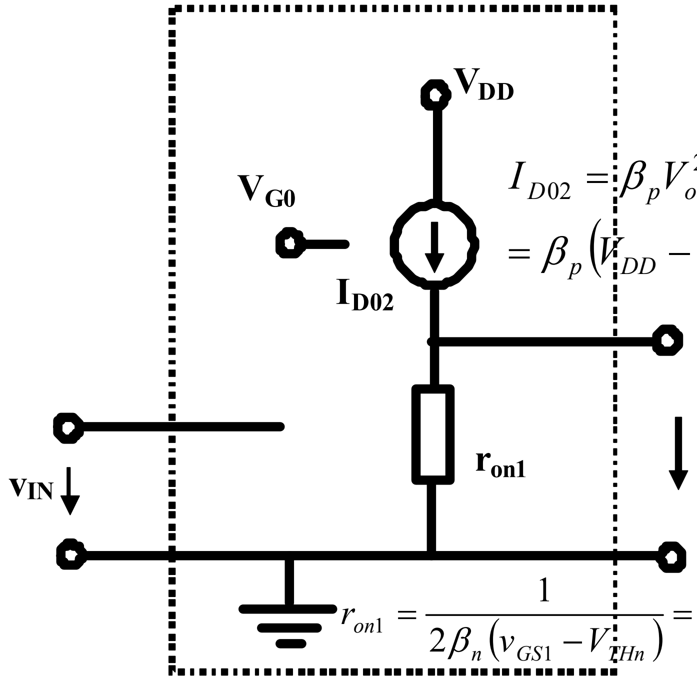
$$v_{OUT} > v_{IN} - V_{THn} = 1.3 - 0.8 = 0.5V$$



非线性电阻负载

NMOS欧姆导通
PMOS恒流导通



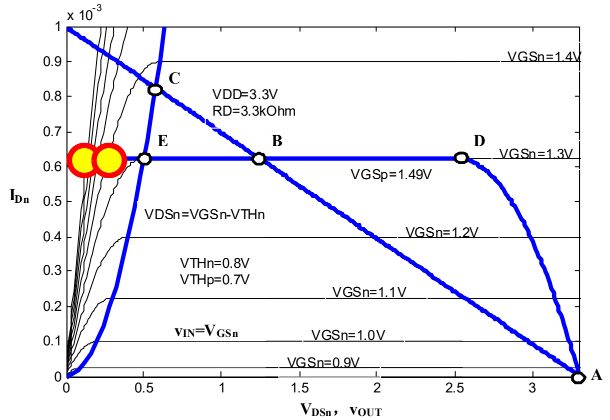


$$I_{D02}=\beta_p V_{odp}^2=\beta_p\left(V_{DD}-V_{G0}-V_{THp}\right)^2$$

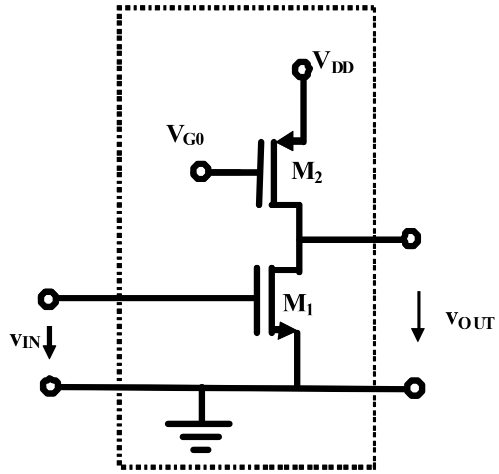
$$r_{on1}=\frac{1}{2\beta_n\left(v_{GS1}-V_{THn}\right)}=\frac{1}{2\beta_n\left(v_{IN}-V_{THn}\right)}$$

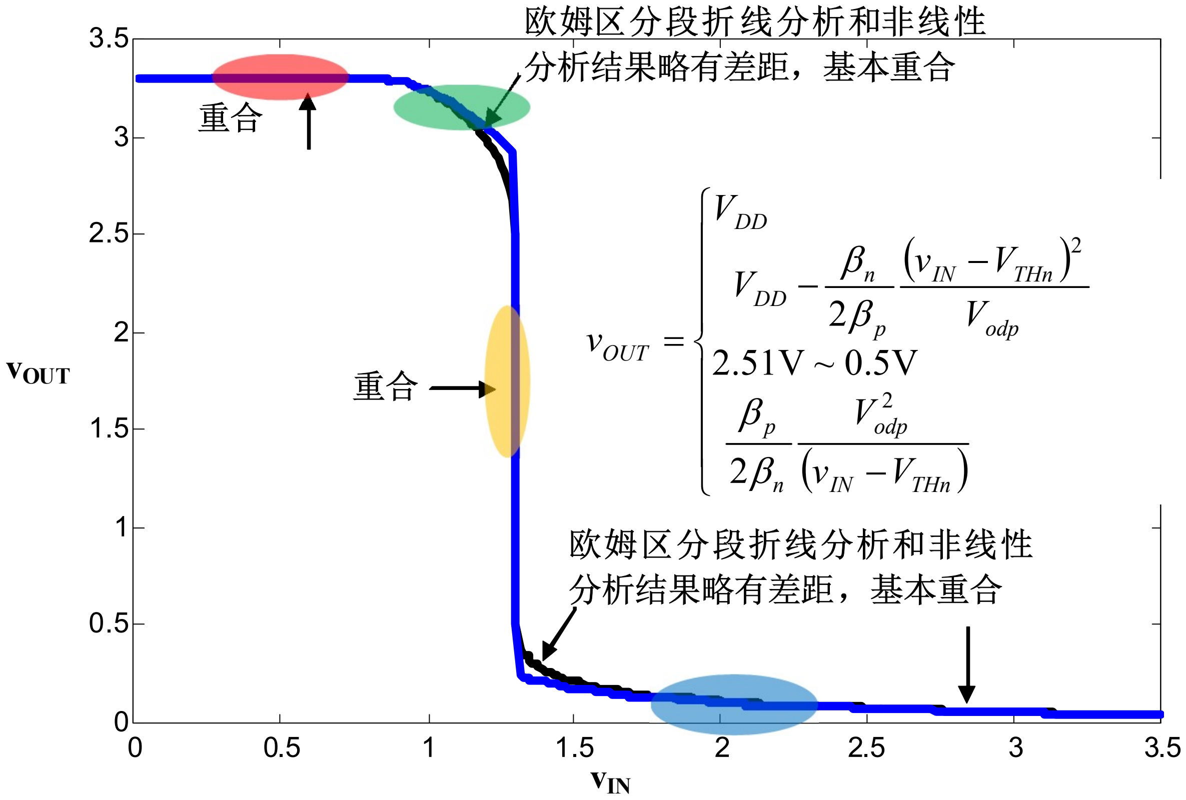
$v_{IN}>1.3V$ **NMOS进入欧姆导通区**

$$v_{OUT}=I_{D02}r_{on1}=\frac{\beta_p}{2\beta_n}\frac{V_{odp}^2}{\left(v_{IN}-V_{THn}\right)}$$



分段折线分析结果





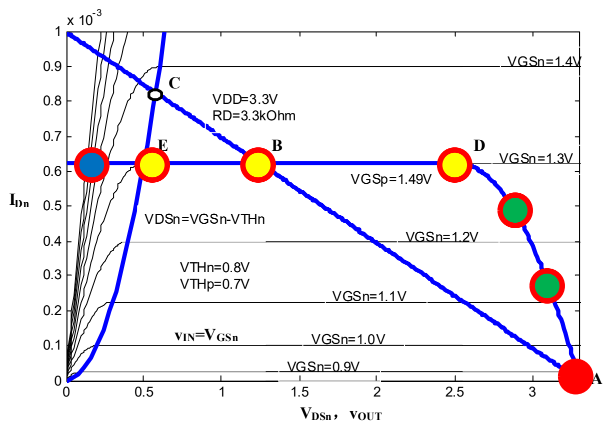
$$
v_{OUT}=\begin{cases} V_{DD} \\ V_{DD}-\dfrac{\beta_n}{2\beta_p}\dfrac{(v_{IN}-V_{THn})^2}{V_{odp}} \\ 2.51\text{V}\sim 0.5\text{V} \\ \dfrac{\beta_p}{2\beta_n}\dfrac{V_{odp}^2}{(v_{IN}-V_{THn})} \end{cases}
$$

$v_{IN} < V_{TH} = 0.8V$　N截止，P欧姆

$0.8V < v_{IN} < 1.3V$　N恒流，P欧姆

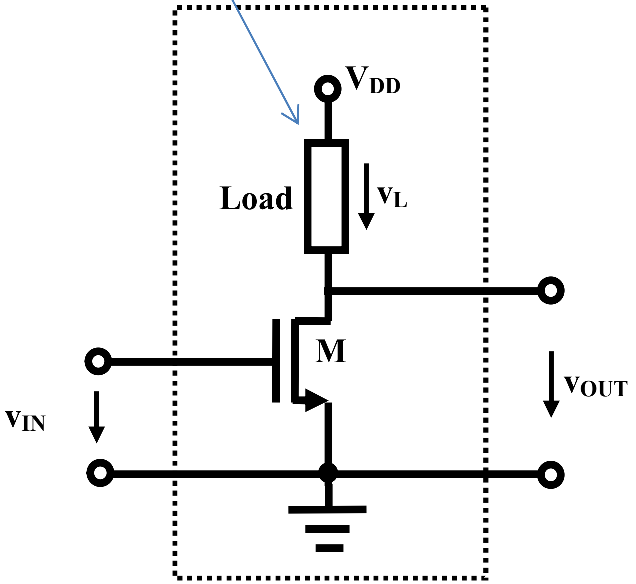
$v_{IN} = 1.3V$　N恒流，P恒流

$v_{IN} > 1.3V$　N欧姆，P恒流



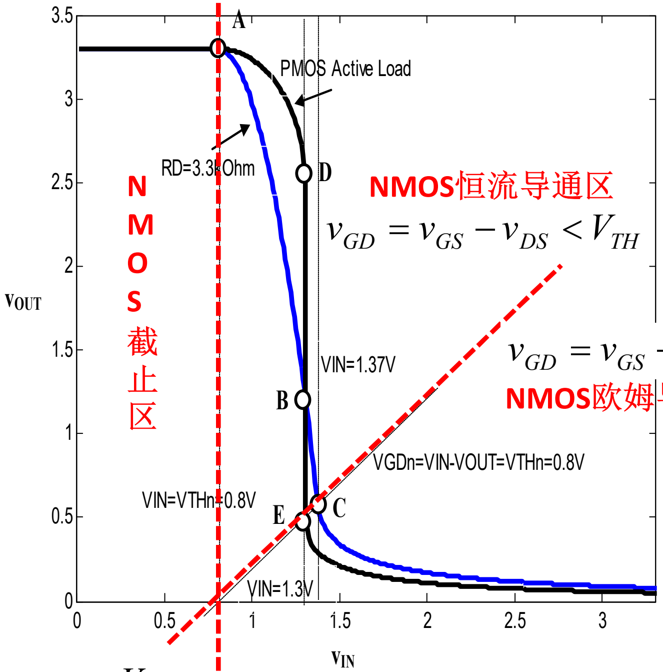
NMOS反相器小结

无论线性电阻或非线性电阻（如固定偏置的**PMOS**），只要是单调增电阻（随着支路电流的增加，支路电压是上升的）则可形成反相器功能



截止区 $v_{GS} < V_{TH}$

导通区 $v_{GS} > V_{TH}$

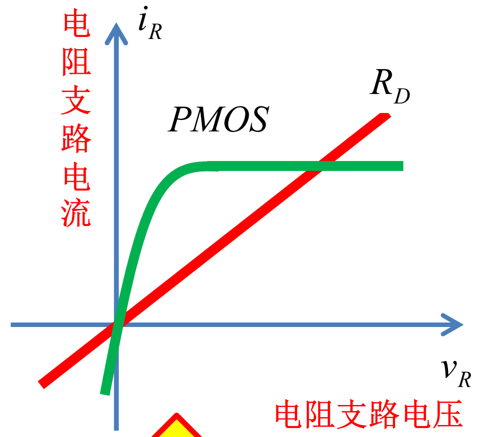


NMOS恒流导通区 $v_{GD} = v_{GS} - v_{DS} < V_{TH}$

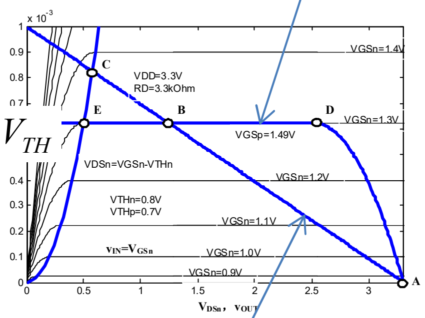
$v_{GD} = v_{GS} - v_{DS} > V_{TH}$ **NMOS欧姆导通区**

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

$v_{IN} = V_{TH}$



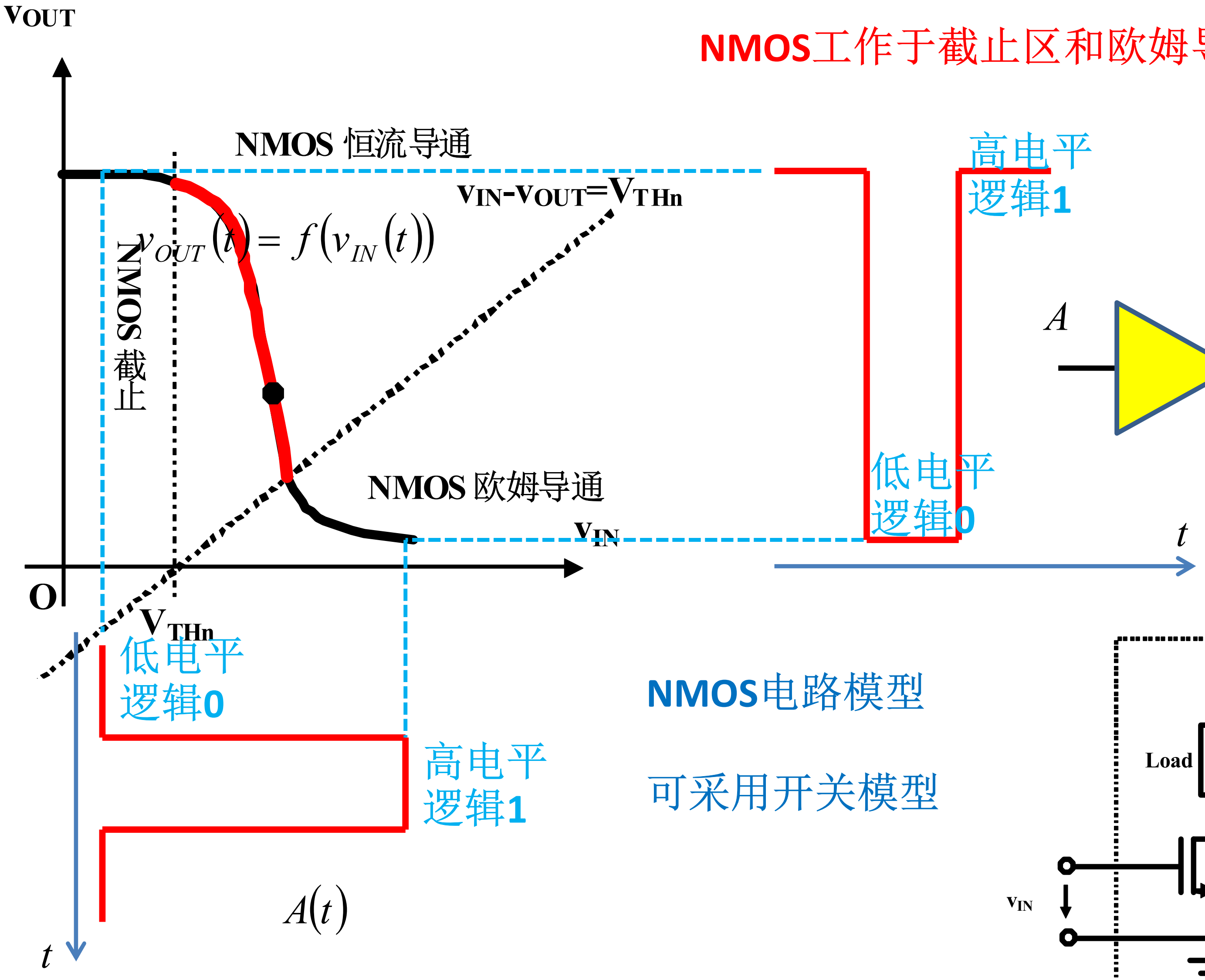
V_{DD}+PMOS负载线



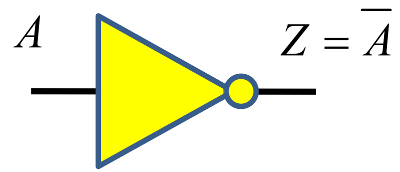
V_{DD}+R_D负载线

输入-输出转移特性曲线明显分三个区对应**NMOS**的截止区、恒流区和欧姆区

反相器应用1 数字非门

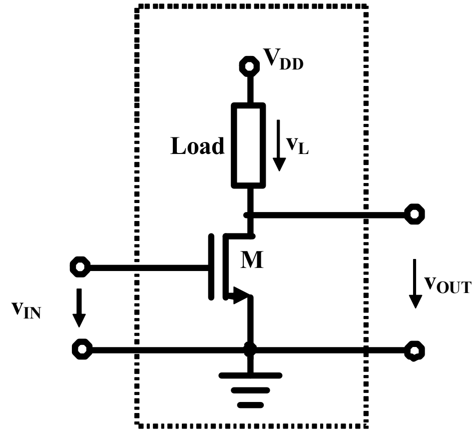


NMOS工作于截止区和欧姆导通区

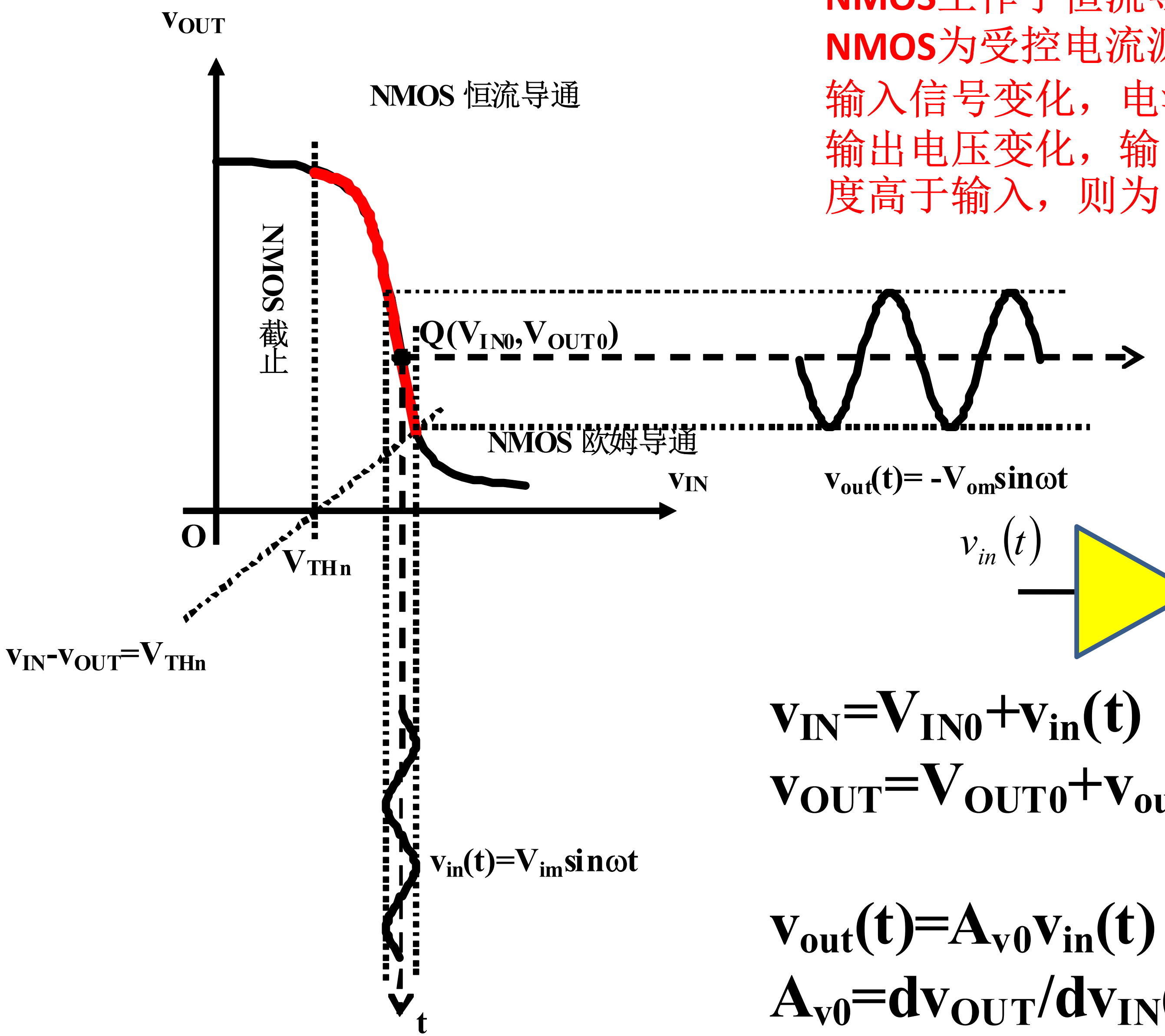


NMOS电路模型

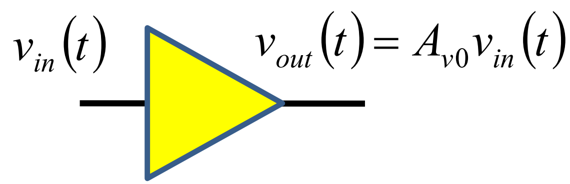
可采用开关模型



反相器应用2 反相电压放大



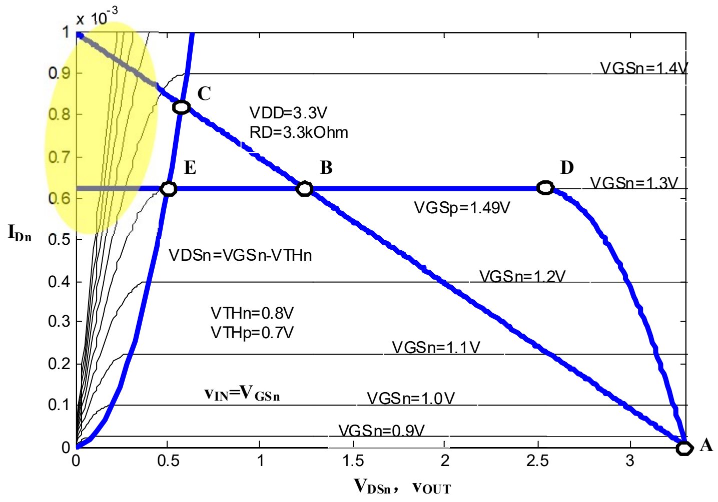
NMOS工作于恒流导通区
NMOS为受控电流源
输入信号变化，电流变化，输出电压变化，输出变化幅度高于输入，则为电压放大

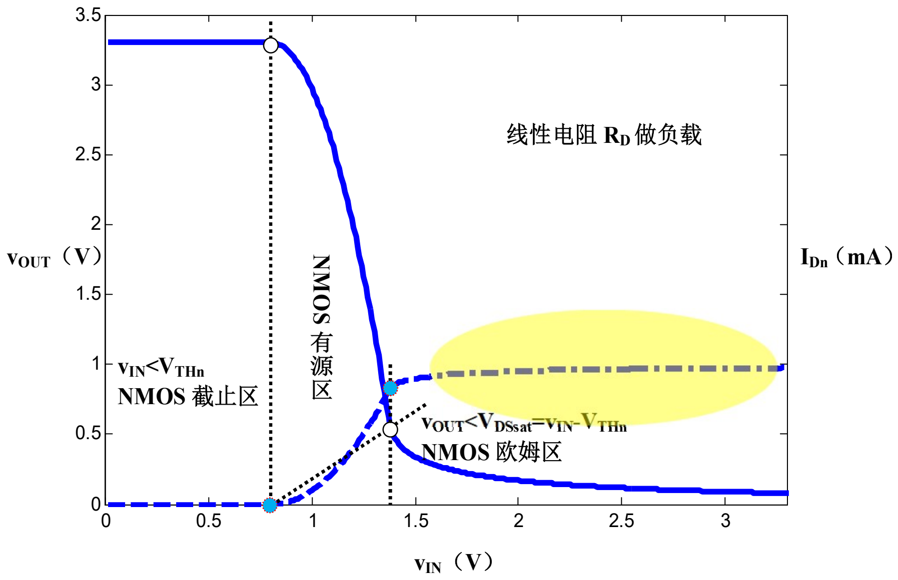


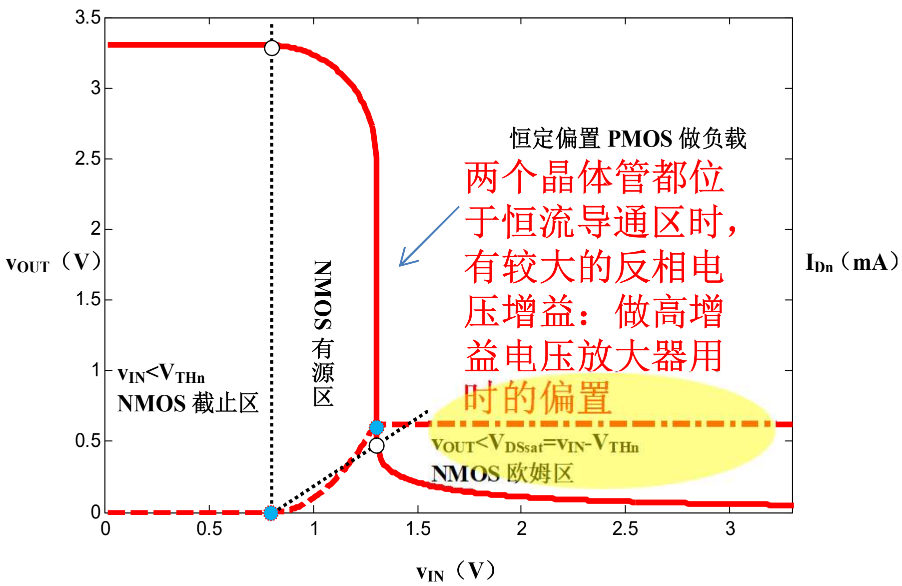
$$v_{IN} = V_{IN0} + v_{in}(t)$$
$$v_{OUT} = V_{OUT0} + v_{out}(t)$$

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

NMOS反相器特点与缺陷





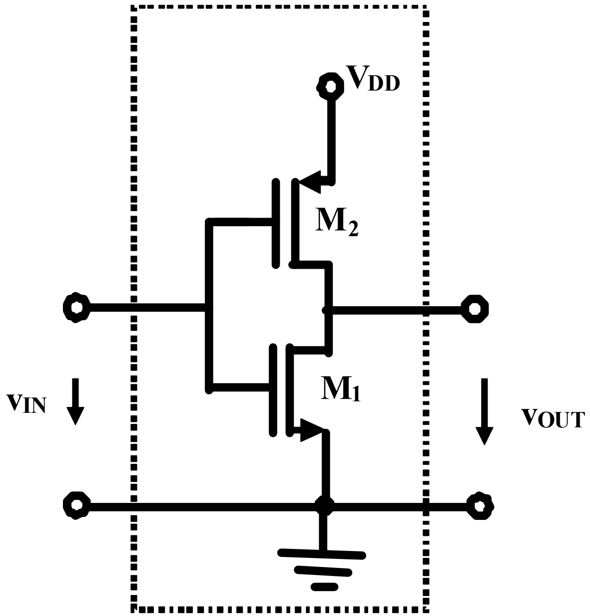


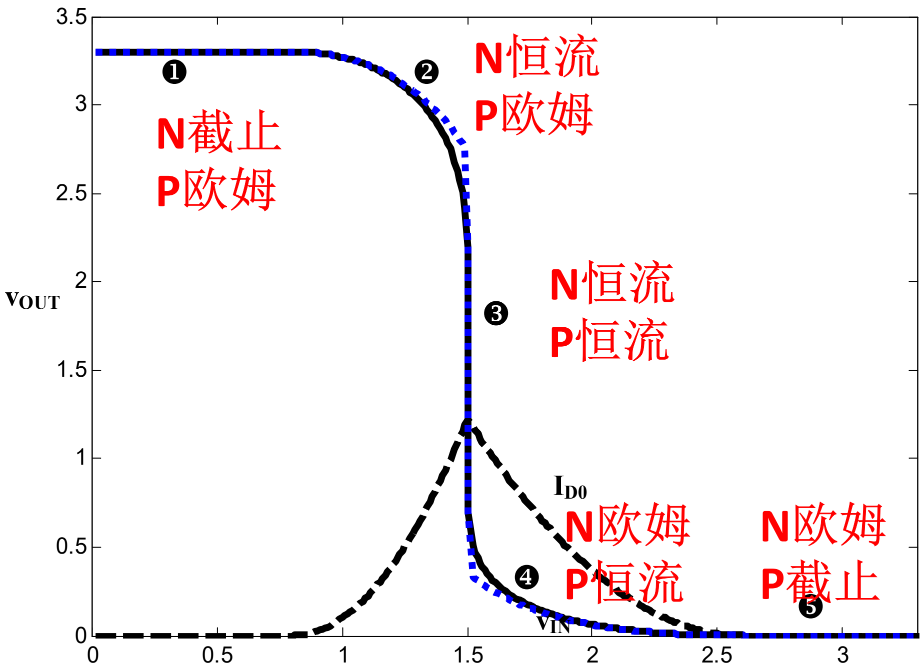
1、以PMOS为负载，有较大的电压增益（有源负载active load）

2、NMOS反相器做数字非门时，当其位于欧姆导通区时，电流趋于不变且较大，电路有较大的功耗；PMOS反相器同理

PMOS反相器分析留作作业

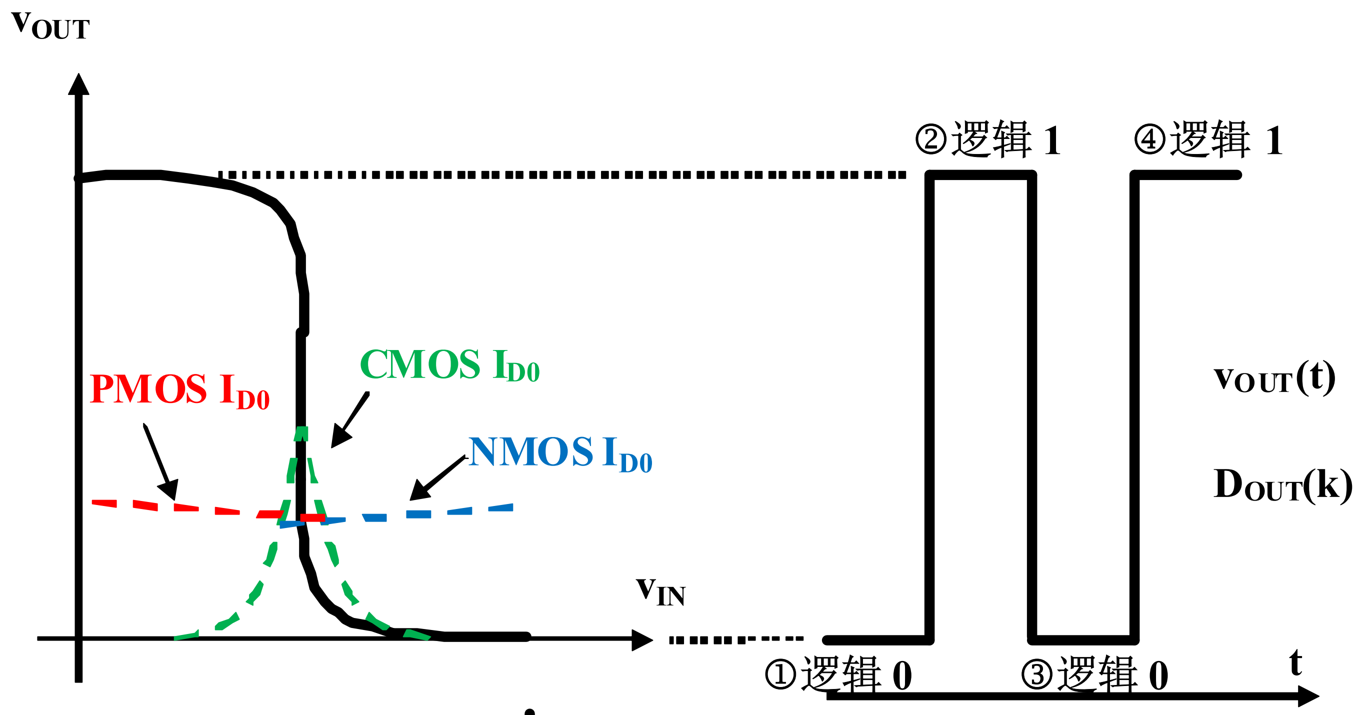
CMOS反相器做数字非门功耗低

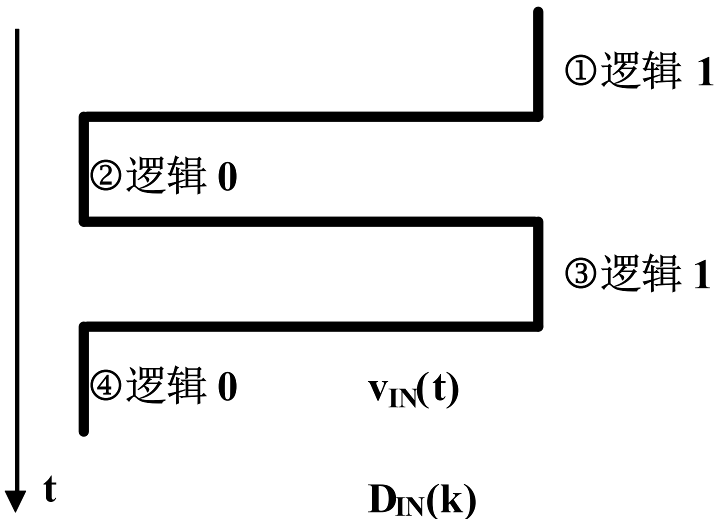




CMOS非门：工作在❶区和❺区，要么NMOS截止，要么PMOS截止，均无电流，均无静态功耗

习题课讨论：不要求掌握，只需理解即可





逻辑求非运算

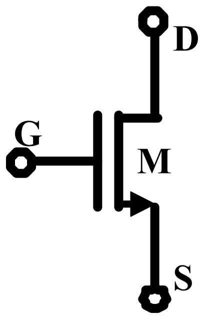
$D_{OUT}(k)=1$　　$D_{IN}(k)=0$

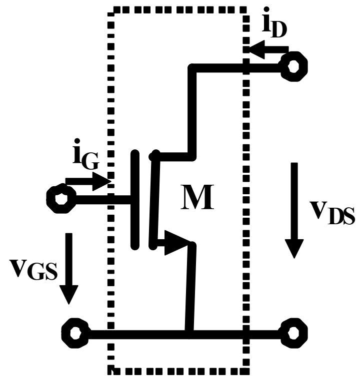
$D_{OUT}(k)=0$　　$D_{IN}(k)=1$

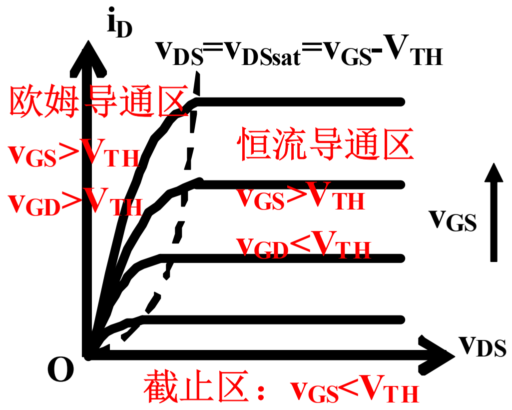
CMOS反相器主要应用于数字非门
模拟应用比较少，放在后面讲

作业1：NMOS晶体管

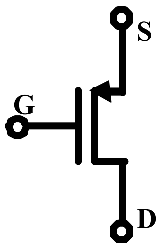
- （1）某NMOSFET的过驱动电压为0.5V，其饱和电压为多少？
- （2）该晶体管的β_n=2mA/V²，厄利电压为V_E=50V，则在V_{DS}=1V时，漏极电流为多少？
  - 必做：不考虑厄利效应；选作：考虑厄利效应
- （3）其等效电路模型中的源电流为多少？源内阻为多少？

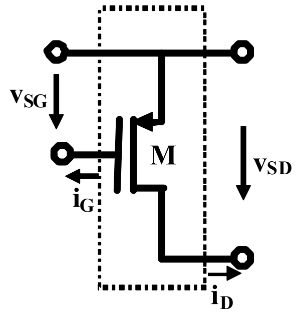




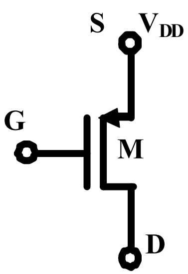


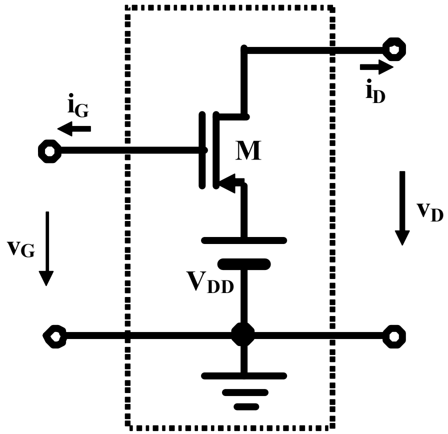
作业2：PMOS晶体管





- 画表格，一侧NMOS，一侧PMOS
- （1）画出NMOS、PMOS晶体管电路符号，二端口网络定义（端口电压、端口电流）
- （2）写出NMOS、PMOS晶体管的元件约束方程
- （3）画出伏安特性曲线示意图
- （4）对于图示的PMOS连接，给出二端口网络的元件约束方程，画出输出端口（有源负载）伏安特性曲线示意图

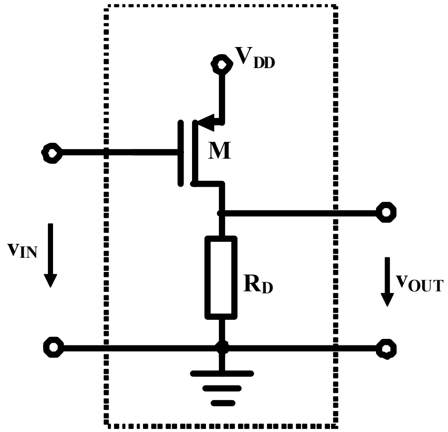


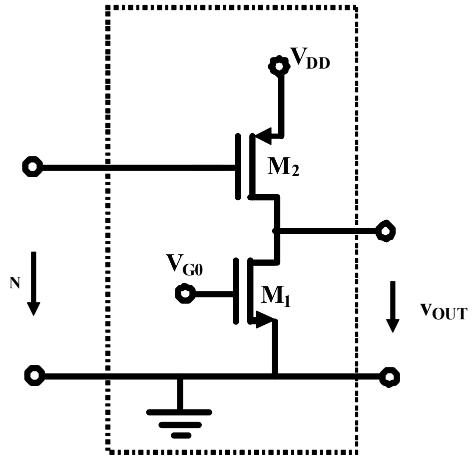


有源负载：可向外提供能量，具有非线性内阻的电压源，v_G固定则可作为NMOS的负载，v_G变化则可实现PMOS反相功能

作业3 PMOS反相器

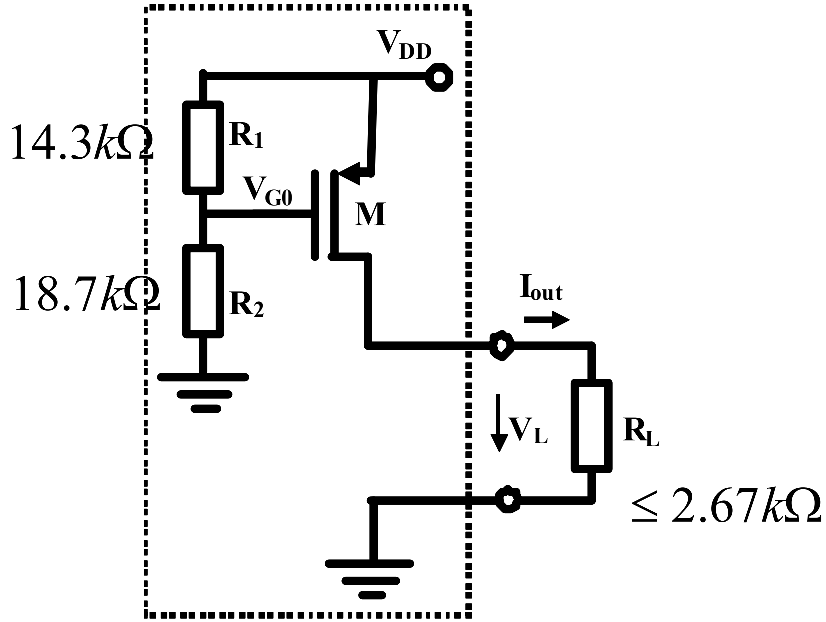
- 请用分段折线法分析如图所示**PMOS**反相器电路，画出其输入-输出电压转移特性曲线示意图
  - **NMOSFET**参量为 β_n**=2.5mA/V²**，V_{THn}**=0.8V**；**PMOSFET**参量为 β_p**=1mA/V²**，V_{THp}**=0.7V**；偏置电阻R_D**=3.3kΩ**，电源电压V_{DD}**=3.3V**
  - 假设通过某种偏置方式，使得图**b**所示**NMOSFET**的栅极电压被设置为 V_{G0}**=1.3V**，源栅电压为 V_{GSn}**=1.3V**，过驱动电压为 $V_{odn}=V_{GSn}-V_{THn}$**=0.5V**。



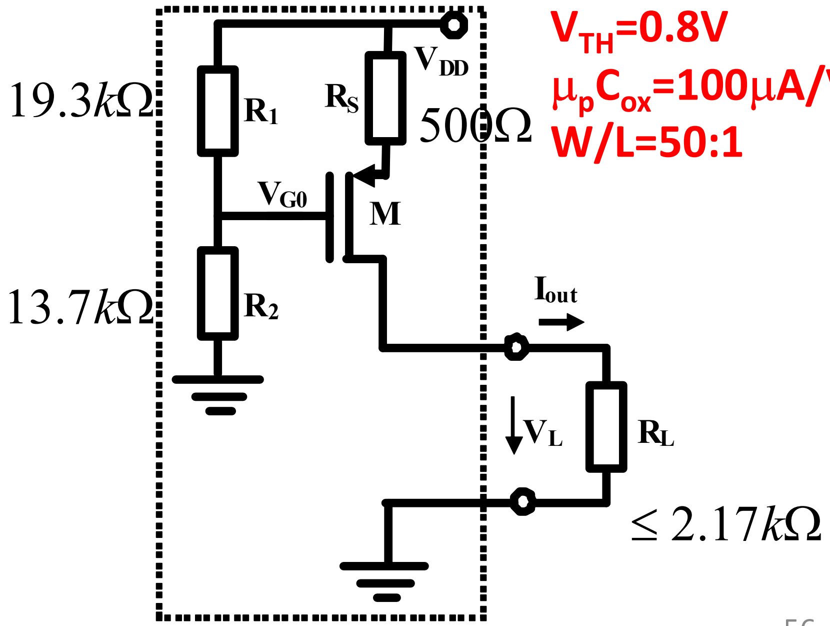


作业4 负反馈降低不确定性

- （1）验证例4设计：确认两个电流源输出电流都是**1mA**；确认其等效电路为恒流源
- （2）由于工艺参数不确定及环境温度的变化，使得**PMOSFET**的工艺参量$\mu_p C_{ox}$偏离设计值**100**μ**A/V²-5%**，请分析确认，图示两个电路结构的等效恒流源输出，有负反馈电阻的输出电流比没有负反馈电阻的输出电流更稳定，更接近设计值**1mA**



V_{DD}=3.3V
V_{TH}=0.8V
$\mu_p C_{ox}$=100μA/V²
W/L=50:1



CAD作业

- 在库中找一个**MOSFET**，通过端口加压求流，获得其伏安特性曲线，由伏安特性曲线提取其参量

- 设计一个**100uA**电流源
  - 采用图中结构
  - $\mathbf{V_{DD}=1.8V}$
  - 给出详尽的设计过程

- 仿真获得两种结构的输出电阻
  - 说明负反馈结构的输出电阻更大，更接近理想电流源