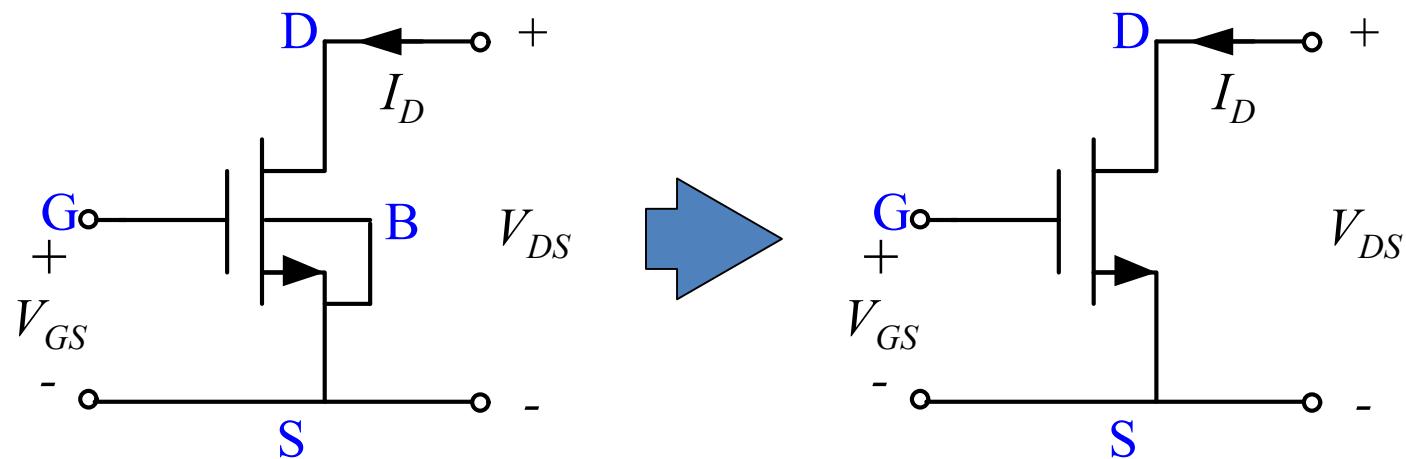


第八章 CMOS模拟集成电路

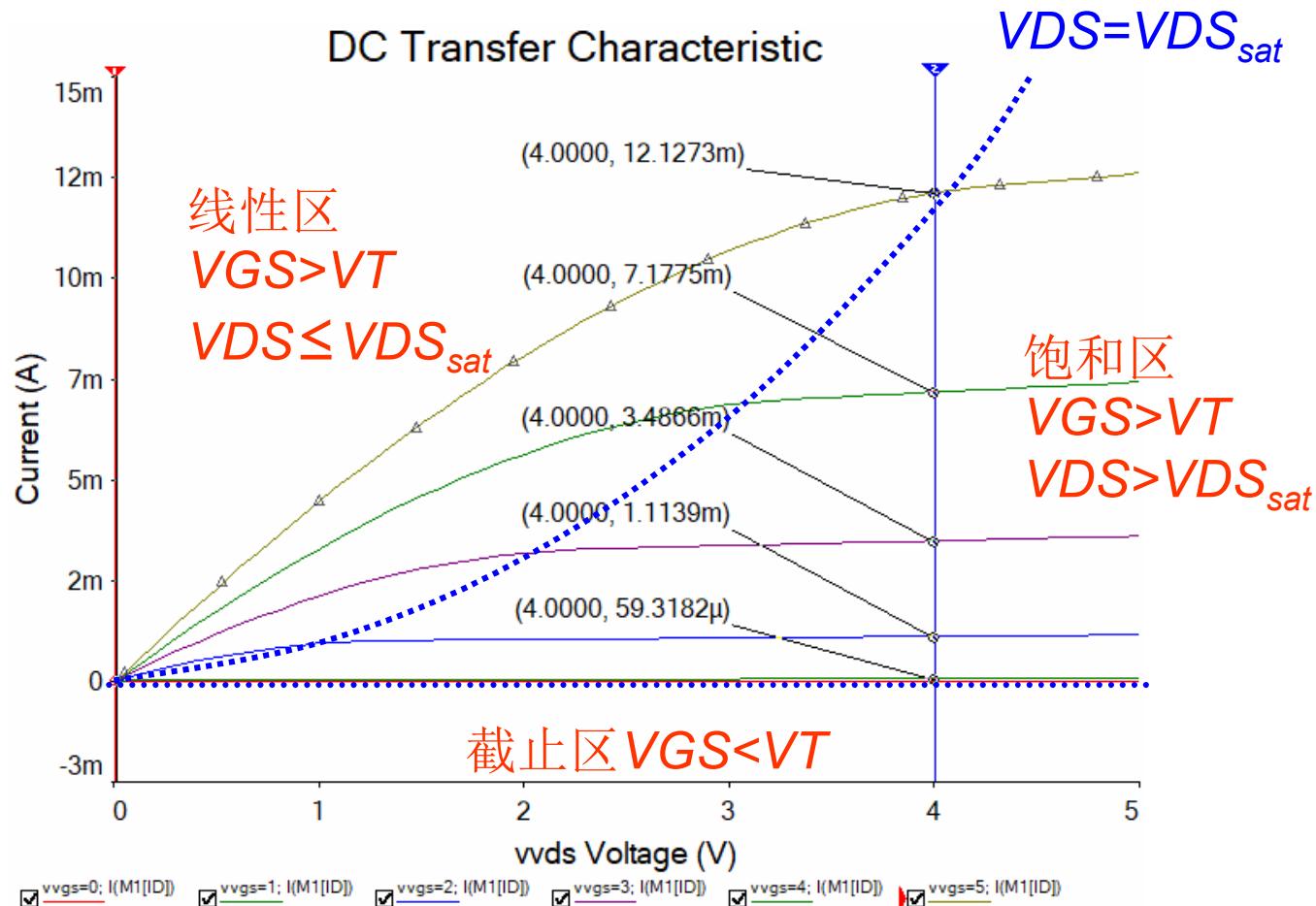
8.4 MOS晶体管交流小信号特性

MOS晶体管交流小信号特性

- ◆ 共源极接法的NMOS管，S与B连接在一起
 - $V_{BS}=0$, 避免考虑背栅效应



MOS管工作区



$$\text{饱和电压 } VDS_{sat} = VGS - VT$$

长沟道近似下NMOS管直流特性方程

- ◆ 栅极电流 $I_G = 0$

- ◆ 漏极电流
 - 截止区 $I_D = 0$
 - 线性区

$$I_D = \mu_0 C_{ox} \frac{W}{L} \left[(V_{GS} - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \quad 0 < V_{DS} \leq V_{GS} - V_T$$

- 饱和区

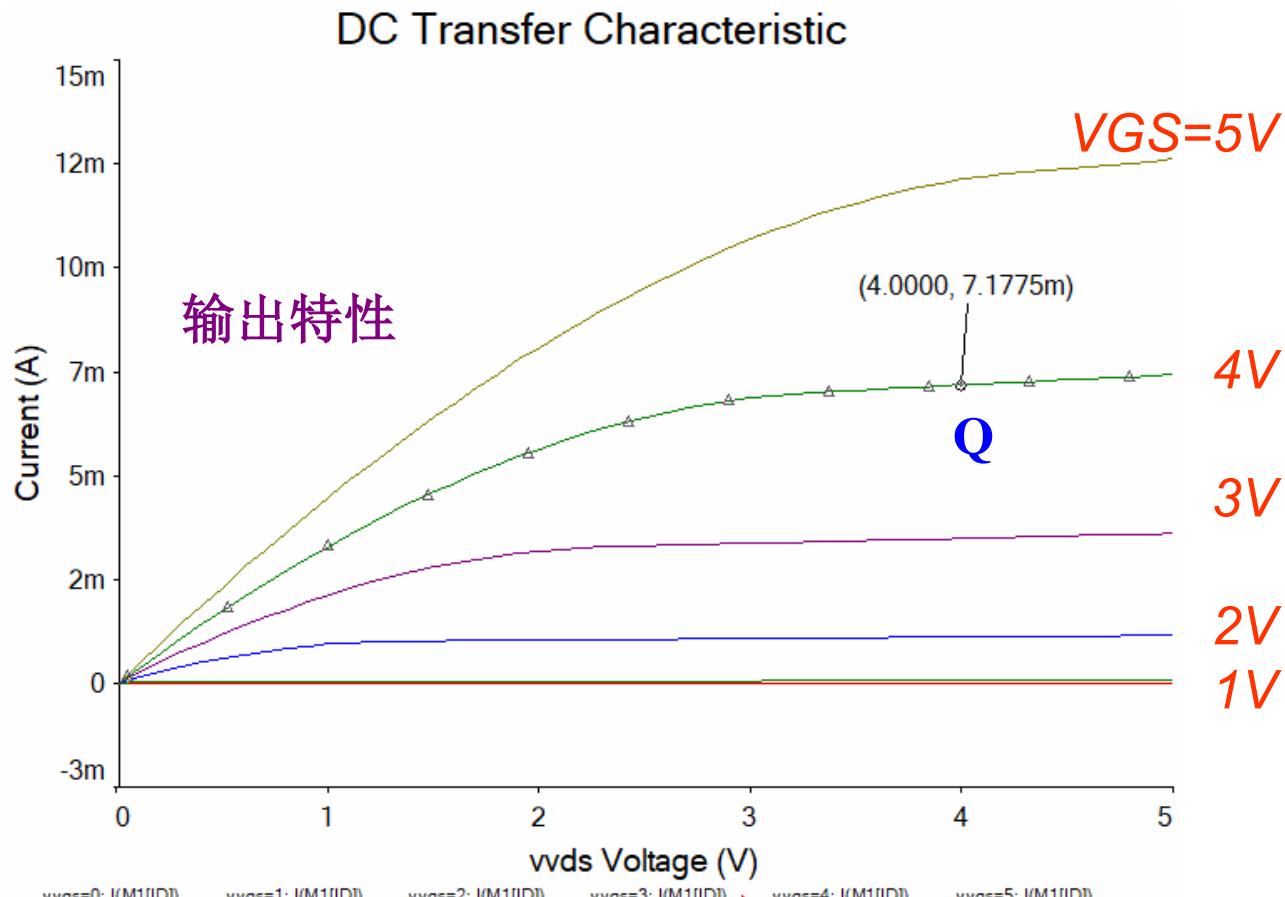
$$I_D = \frac{\mu_0 C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \quad 0 < V_{GS} - V_T \leq V_{DS}$$

- ◆ 阈值电压 $V_T = V_{T0} + \gamma \left(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|} \right)$

直流工作点

- ◆ 模拟电路中，一般要求MOS管工作于饱和区
- ◆ MOS管的工作区由直流工作点决定
- ◆ 给MOS管施加特定的电压/电流
- ◆ → 确定它的直流工作点
- ◆ → 让MOS管工作于我们所期望的区域

确定直流工作点



Q: VGS=4V, VDS=4V, ID=7.2mA

确定直流工作点

- ◆ MOS管工作于饱和区时，ID与VDS几乎无关
 - 不用限制VDS的取值

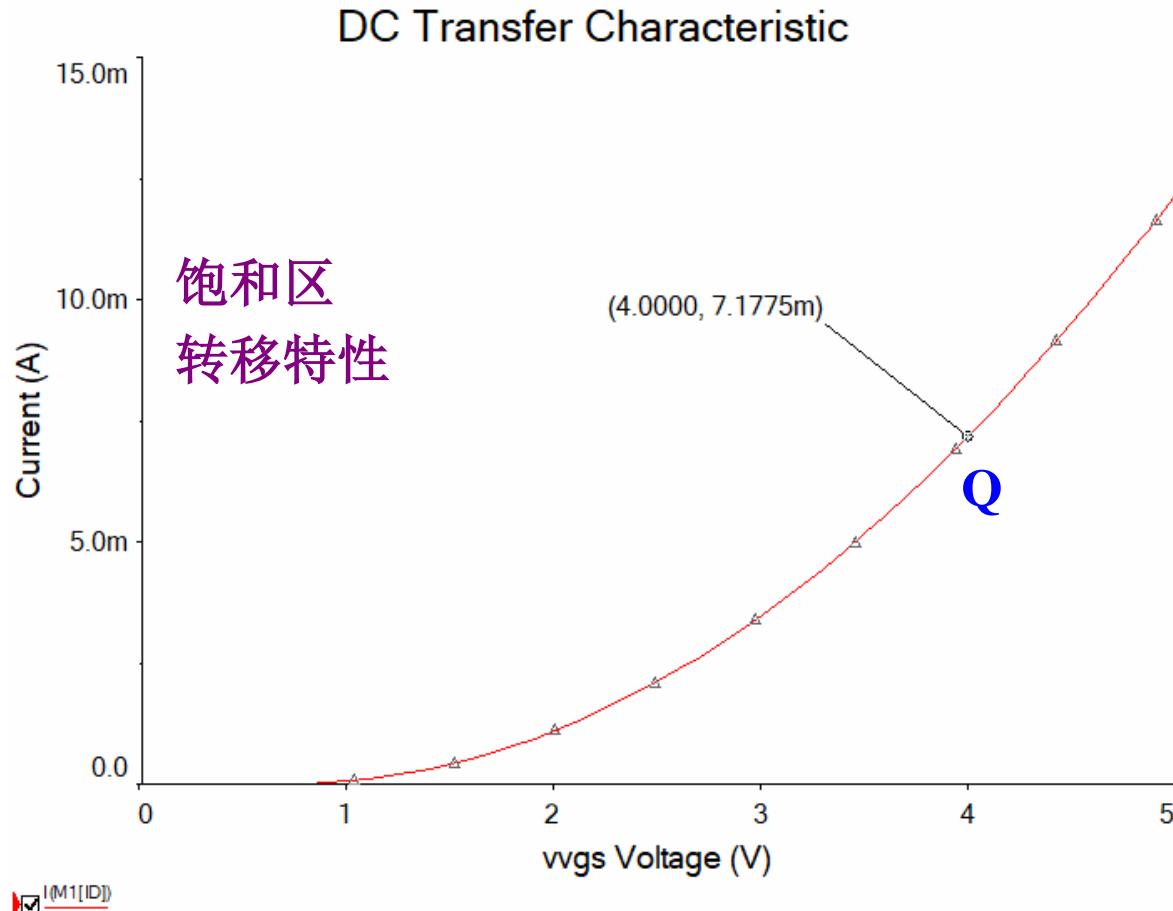
规定 $V_{GS}=4V$,
对应 $ID=7.2mA$

电压偏置

规定 $ID=7.2mA$,
对应 $V_{GS}=4V$

电流偏置

确定直流工作点



交流小信号

- ◆ 交流信号的电压和电流，叠加在直流工作点上

$$v_{GS} = V_{GSQ} + v_{gs}$$

$$i_D = I_{DQ} + i_d$$

- ◆ V_{GSQ}, I_{DQ} ：直流工作点对应的直流电压、电流
- ◆ v_{gs}, i_d ：交流分量
- ◆ 交流小信号：交流分量比直流分量小得多
 - 不影响晶体管的偏置状态

跨导

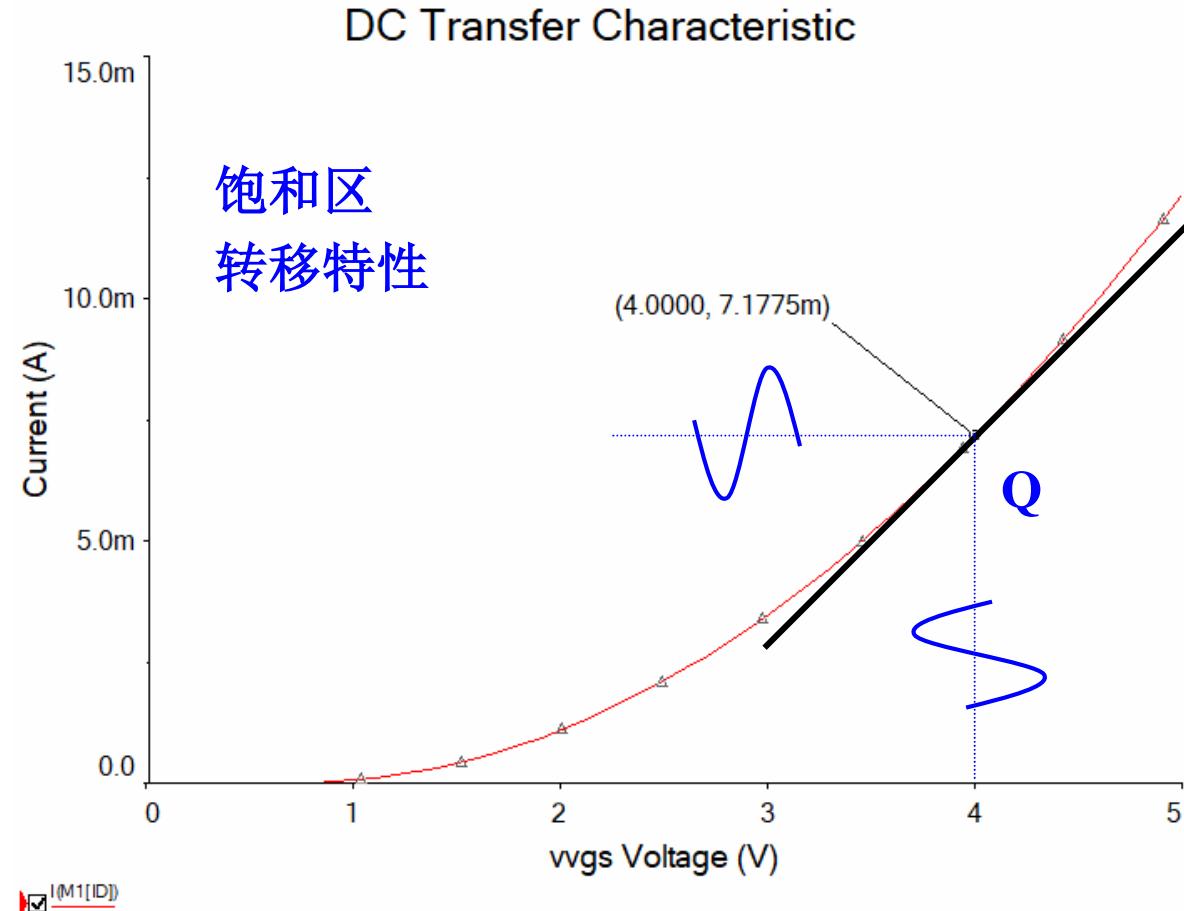
- 反映漏极交流电流受栅极交流电压的控制

$$i_d = g_m v_{gs}$$

- 转移特性曲线在Q点处切线的斜率，或者在Q点处，电流关于电压VGS的偏导

$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q$$

跨导



输出电导

- ◆ 反映漏极交流电流受漏极交流电压的影响
 - 也可以用输出电阻表示

$$i_d = g_{ds} v_{ds} \quad r_{ds} = \frac{1}{g_{ds}}$$

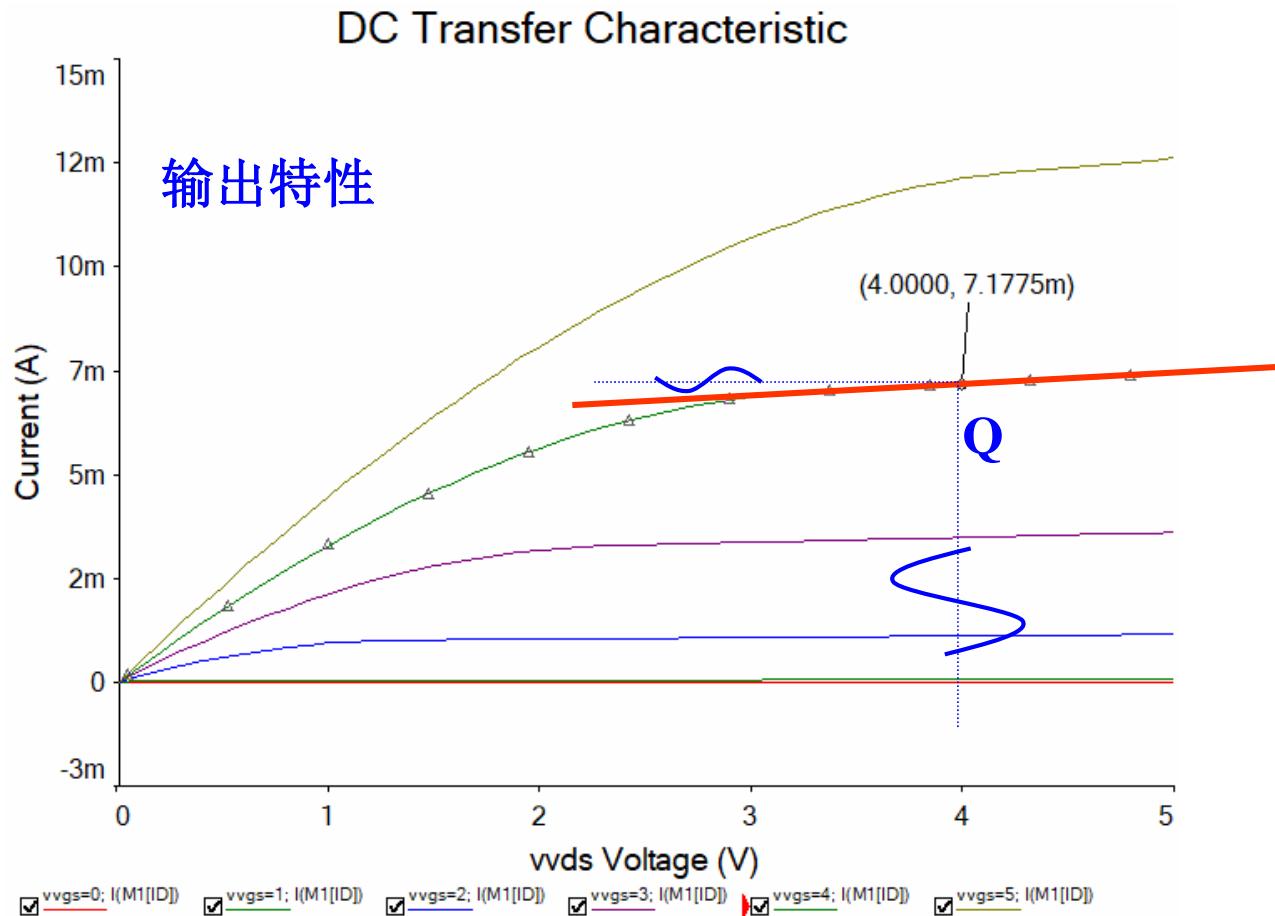
- ◆ 输出特性曲线在Q点处切线的斜率，或者在Q点处，电流关于电压VDS的偏导

$$g_{ds} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_Q$$

- ◆ 如果电流不随电压变化，切线斜率=0

$$g_{ds} = 0, \quad r_{ds} = \infty$$

输出电导



MOS管交流小信号模型

- ◆ 漏极电流

$$i_d = g_m v_{gs} + g_{ds} v_{ds}$$

$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q \quad g_{ds} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_Q$$

- ◆ 栅极电流

$$i_g = 0$$

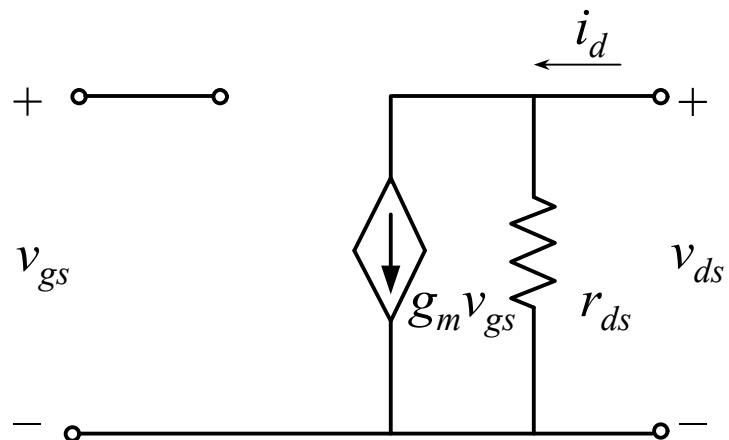
MOS管交流小信号模型

- ◆ 输入：开路 $i_g = 0$
- ◆ 输出：压控电流源与输出电阻并联

$$\dot{i}_d = g_m v_{gs} + g_{ds} v_{ds}$$

- ◆ 模型参数

$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q \quad g_{ds} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_Q$$



模型参数

- ◆ 长沟道近似下的简单直流MOS管模型，并假设器件工作于饱和区

$$I_D = \frac{\mu_0 C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS})$$

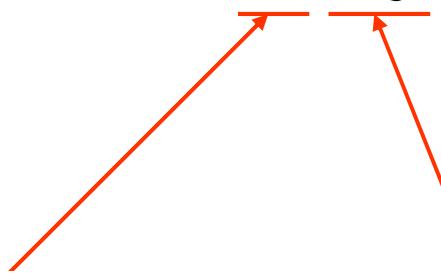
$$\begin{aligned} g_m &= \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q = \mu_0 C_{ox} \frac{W}{L} (V_{GS} - V_T) \\ &= \frac{\sqrt{2\beta I_{DQ}}}{2} \\ &= \frac{2I_{DQ}}{V_{GS} - V_T} \end{aligned}$$

$\beta = \mu_0 C_{ox} \frac{W}{L}$

与过驱动电压成正比

与电流开根号成正比

模型参数

- ◆
$$g_{ds} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_Q$$
$$= \lambda \frac{\mu_0 C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 \approx \lambda I_{DQ}$$


与沟道长度调制系数成正比 与电流成正比

背栅效应

- ◆ 如果VBS $\neq 0$, 还需要考虑背栅效应

$$i_d = g_m v_{gs} + g_{ds} v_{ds} + g_{mb} v_{bs}$$

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \Big|_Q \quad g_{mb} = \frac{\partial I_D}{\partial V_{BS}} \Big|_Q = \mu_0 C_{ox} \frac{W}{L} (V_{GS} - V_T) \left(-\frac{\partial V_T}{\partial V_{BS}} \right)$$

$$g_{ds} = \frac{\partial I_D}{\partial V_{DS}} \Big|_Q = g_m \left(\frac{\partial V_T}{\partial V_{SB}} \right)$$

$$g_{mb} = \frac{\partial I_D}{\partial V_{BS}} \Big|_Q = g_m \frac{\gamma}{2\sqrt{|2\Phi_F + V_{SB}|}}$$

MOS管交流小信号模型

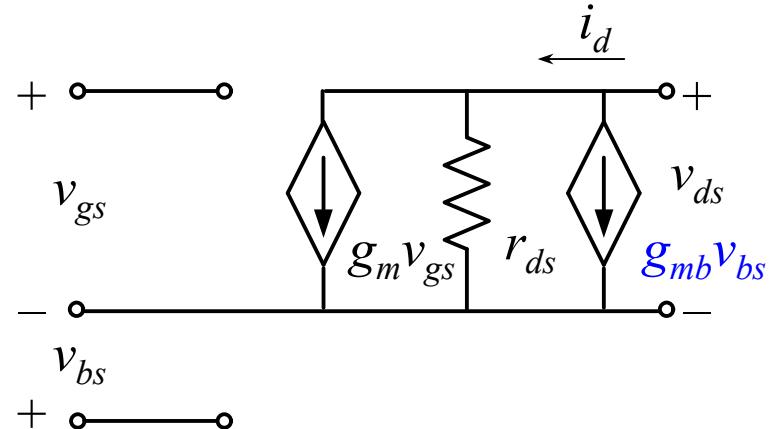
- ◆ 考虑背栅效应

$$i_d = g_m v_{gs} + g_{ds} v_{ds} + g_{mb} v_{bs}$$

$$g_m = \left. \frac{\partial I_D}{\partial V_{GS}} \right|_Q$$

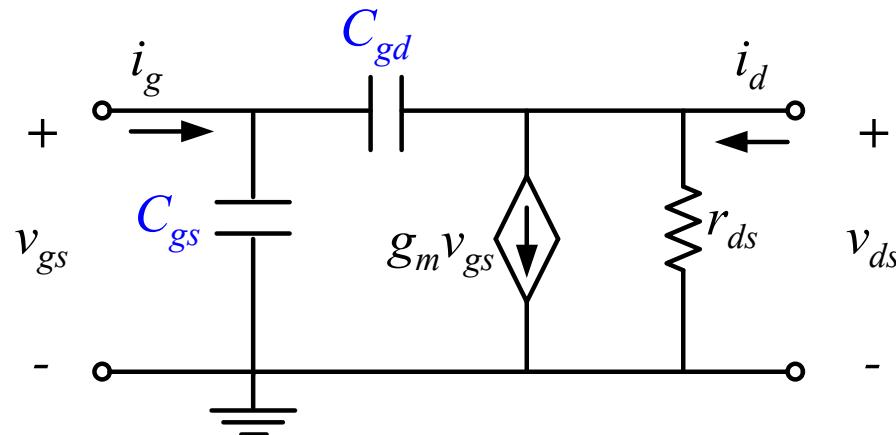
$$g_{ds} = \left. \frac{\partial I_D}{\partial V_{DS}} \right|_Q$$

$$g_{mb} = \left. \frac{\partial I_D}{\partial V_{BS}} \right|_Q$$



MOS管高频交流小信号模型

- ◆ 主要考虑栅源电容、栅漏电容
- ◆ 假设不存在背栅效应



0.8um CMOS工艺MOS管模型

- ◆ .MODEL: 关键词，表示模型定义
- ◆ +: 接上一行
- ◆ n08, p08: 模型名字
- ◆ NMOS, PMOS: 模型类型

```
.MODEL n08 NMOS VTO = 0.70 KP = 110U GAMMA = 0.4 LAMBDA = 0.04
+ PHI = 0.7 MJ = 0.5 MJSW = 0.38 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 770U CJSW = 380P LD = 0.016U TOX = 14N
.MODEL p08 PMOS VTO = -0.70 KP = 50U GAMMA = 0.57 LAMBDA = 0.05
+ PHI = 0.8 MJ = 0.5 MJSW = 0.35 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 560U CJSW = 350P LD = 0.014U TOX = 14N
```

0.8um CMOS工艺MOS管模型

- ◆ 电流公式相关参数：
- ◆ KP：饱和区跨导参数 $KP = \mu_0 C_{ox}$
- ◆ LAMBDA：沟道长度调制系数
- ◆ LD：用于计算有效沟道长度

$$L_{eff} = L - 2 \times LD$$

```
.MODEL n08 NMOS VTO = 0.70 KP = 110U GAMMA = 0.4 LAMBDA = 0.04
+ PHI = 0.7 MJ = 0.5 MJSW = 0.38 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 770U CJSW = 380P LD = 0.016U TOX = 14N
.MODEL p08 PMOS VTO = -0.70 KP = 50U GAMMA = 0.57 LAMBDA = 0.05
+ PHI = 0.8 MJ = 0.5 MJSW = 0.35 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 560U CJSW = 350P LD = 0.014U TOX = 14N
```

0.8um CMOS工艺MOS管模型

- ◆ 阈值电压公式相关参数：

$$V_T = V_{T0} + \gamma \left(\sqrt{|2\Phi_F + V_{SB}|} - \sqrt{|2\Phi_F|} \right)$$

VTO GAMMA PHI

- ◆ 工艺相关相关参数：

- ◆ TOX：SiO₂绝缘层的厚度

- ◆ 寄生电容相关参数

```
.MODEL n08 NMOS VTO = 0.70 KP = 110U GAMMA = 0.4 LAMBDA = 0.04  
+ PHI = 0.7 MJ = 0.5 MJSW = 0.38 CGBO = 700P CGSO = 220P CGDO = 220P  
+ CJ = 770U CJSW = 380P LD = 0.016U TOX = 14N  
.MODEL p08 PMOS VTO = -0.70 KP = 50U GAMMA = 0.57 LAMBDA = 0.05  
+ PHI = 0.8 MJ = 0.5 MJSW = 0.35 CGBO = 700P CGSO = 220P CGDO = 220P  
+ CJ = 560U CJSW = 350P LD = 0.014U TOX = 14N
```

MOS管OP仿真

.title n08_DC

M1 2 1 0 0 n08 W=10U L=1U
VDS 2 0 DC=4
VGS 1 0 DC=4

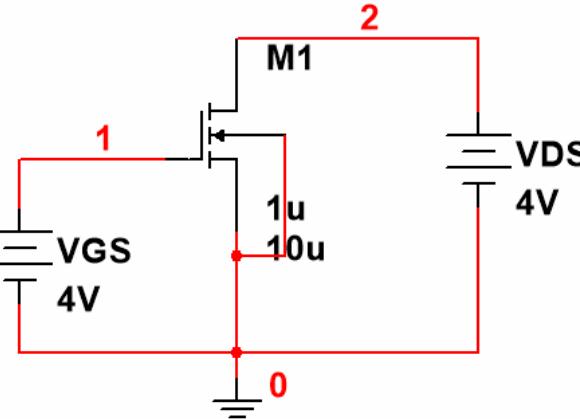
.OP

*直流工作点仿真

.option post probe

```
.MODEL n08 NMOS VTO = 0.70 KP = 110U GAMMA = 0.4 LAMBDA = 0.04
+ PHI = 0.7 MJ = 0.5 MJSW = 0.38 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 770U CJSW = 380P LD = 0.016U TOX = 14N
.MODEL p08 PMOS VTO = -0.70 KP = 50U GAMMA = 0.57 LAMBDA = 0.05
+ PHI = 0.8 MJ = 0.5 MJSW = 0.35 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 560U CJSW = 350P LD = 0.014U TOX = 14N
```

.end



元件标识首字母

M: MOS管

V: 电压源

I: 电流源

R: 电阻

C: 电容

L: 电感

X: 子电路

OP仿真结果

- ◆ 饱和区
- ◆ v_{th} : 阈值电压
- ◆ v_{dsat} : 饱和电压
- ◆ v_{od} : 过驱动电压, $v_{od}=v_{gs}-v_{th}$

```
subckt
element 0:m1
model 0:n08
region Saturati
id 7.1775m
ibs 0.
ibd -40.0000f
vgs 4.0000
vds 4.0000
vbs 0.
vth /00.0000m
vdsat 3.3000
vod 3.3000
beta 1.3182m
gam eff 400.0000m
gm 4.3500m
gds 247.5000u
gmb 1.0398m
cdtot 2.3273f
cgtot 21.1501f
cstot 18.1174f
cbtot 705.3490a
cgs 18.1174f
cgd 2.3273f
```

OP仿真结果

- ◆ 交流小信号模型参数

$$\beta = \mu_0 C_{ox} \frac{W}{L}$$

- ◆ 寄生电容

```
subckt
element 0:m1
model 0:n08
region Saturati
id 7.1775m
ibs 0.
ibd -40.0000f
vgs 4.0000
vds 4.0000
vbs 0.
vth 700.0000m
vdsat 3.3000
vod 3.3000
beta 1.3182m
gam_eff 400.0000m
gm 4.3500m
gds 247.5000u
gmb 1.0398m
cdtot 2.3273f
cg tot 21.1501f
cstot 18.1174f
cbtot 705.3490a
cgs 18.1174f
cq d 2.3273f
```

小结

- ◆ 前提：MOS管偏置在特定的直流工作点Q
- ◆ 交流小信号叠加在直流工作点Q上
 - 叠加后，电压、电流在直流工作点Q附近小幅变化
- ◆ 模型中的输入输出量，都是指交流分量
- ◆ 模型中的参数，都与直流工作点有关