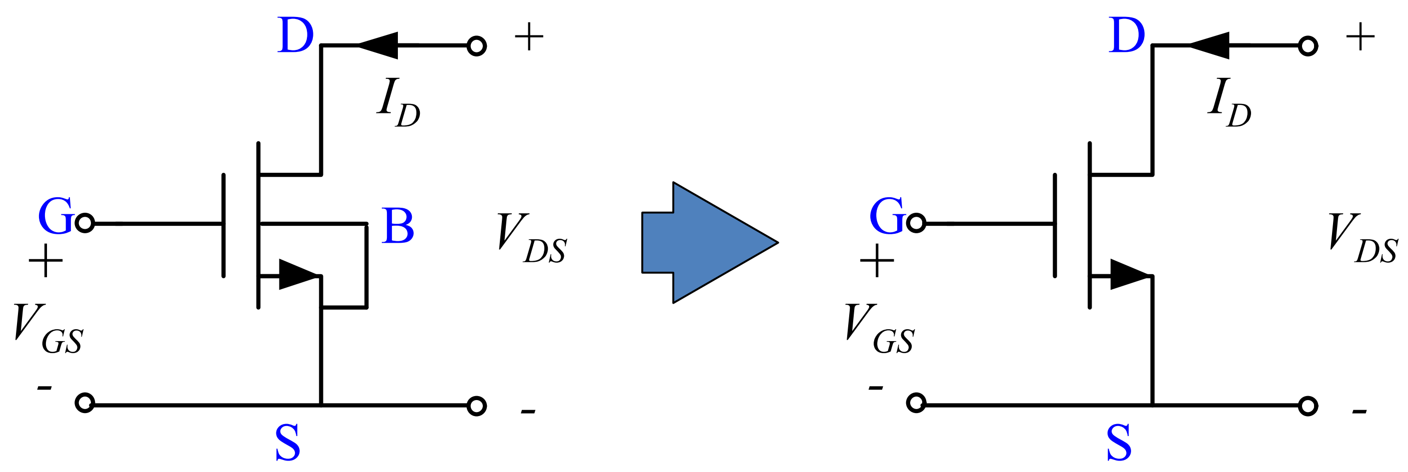
第八章 CMOS模拟集成电路

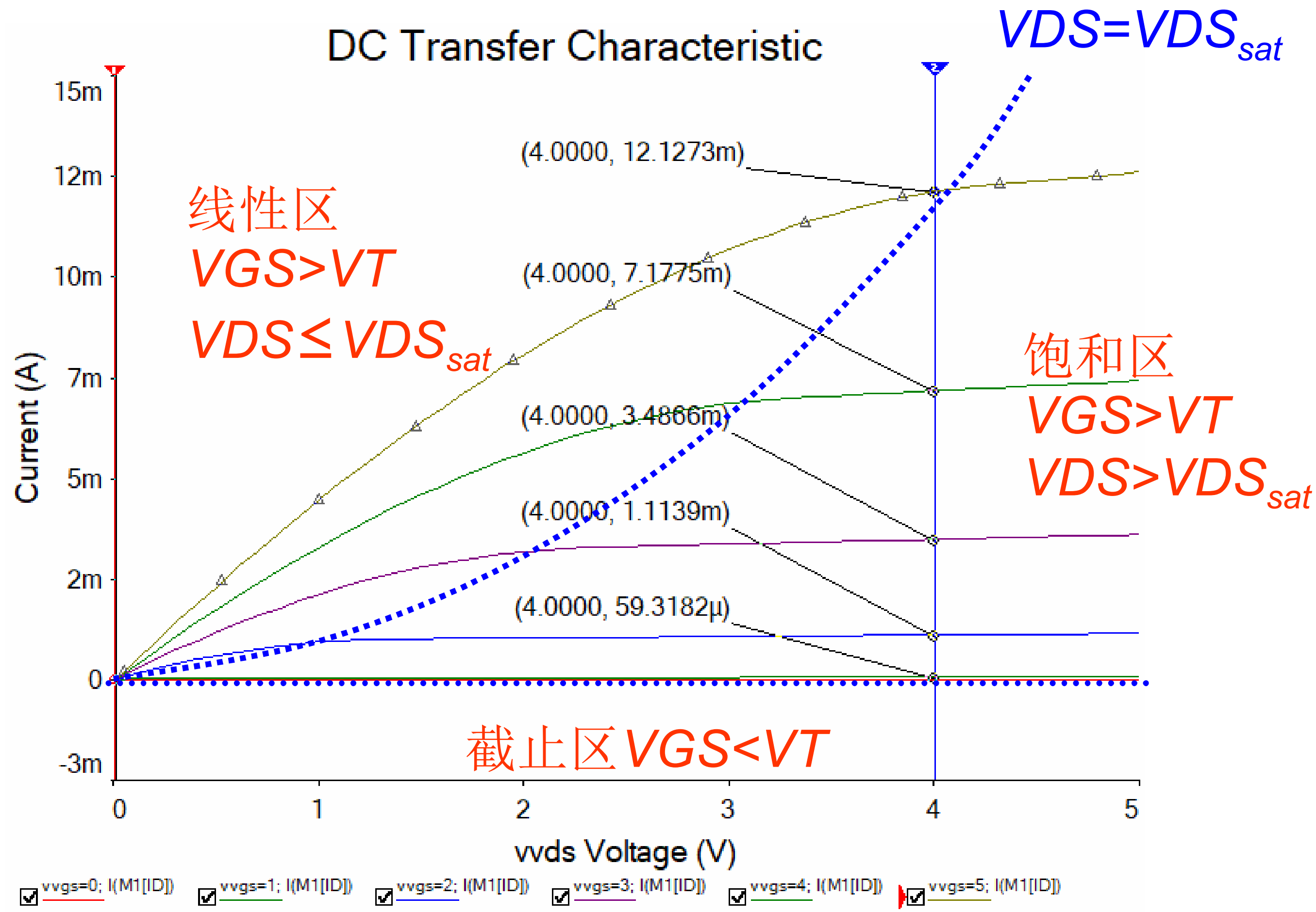
8.4 MOS晶体管交流小信号特性

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
  - VBS=0，避免考虑背栅效应



MOS管工作区



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

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

  - 饱和区

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

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

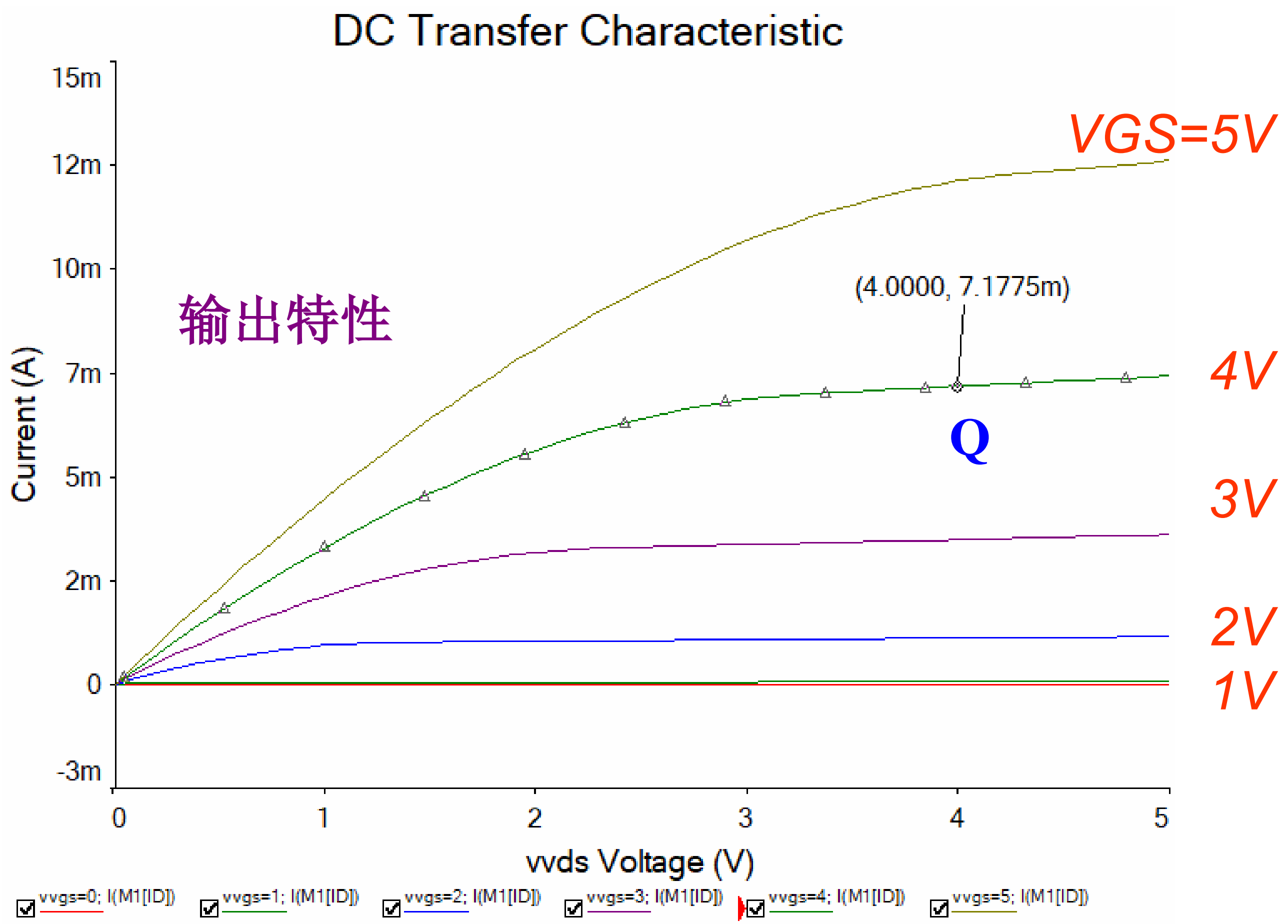
直流工作点

- 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

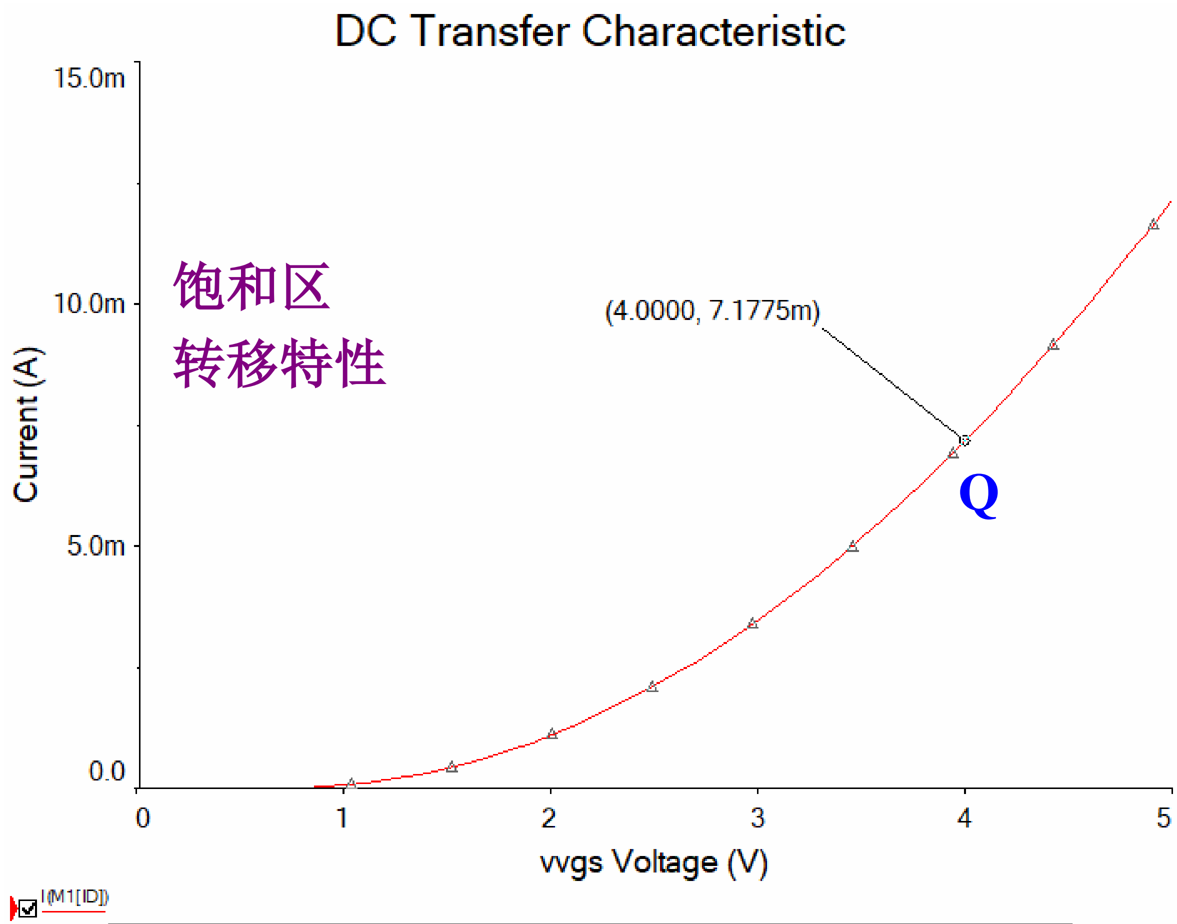
规定VGS=4V，
对应ID=7.2mA

电压偏置

规定ID=7.2mA，
对应VGS=4V

电流偏置

确定直流工作点



Q（饱和区）：VGS=4V，ID=7.2mA

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

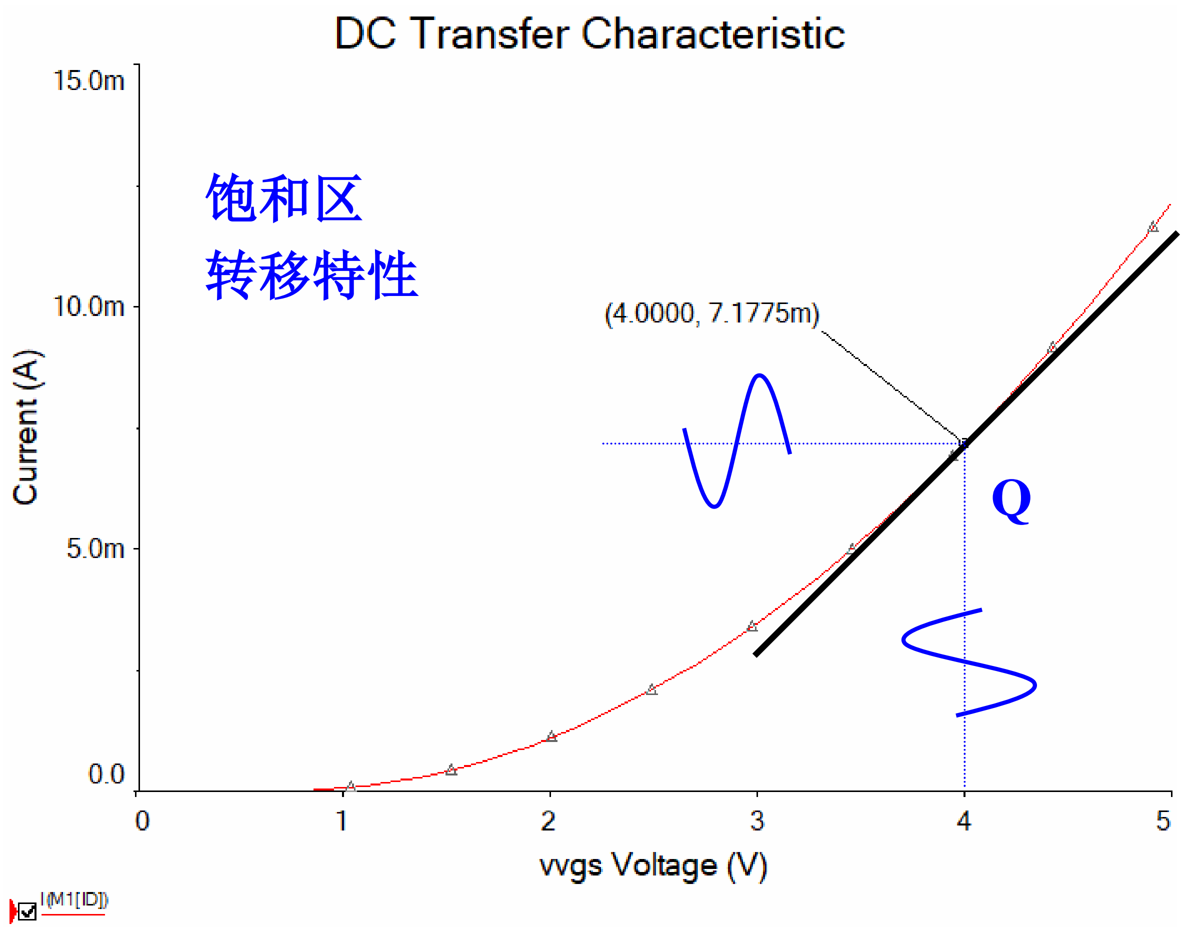
- 反映漏极交流电流受栅极交流电压的控制

$$i_d = g_m v_{gs}$$

- 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



DC Transfer Characteristic
15.0m
10.0m
5.0m
0.0
饱和区
转移特性
(4.0000, 7.1775m)
Q
Current (A)
0
1
2
3
4
5
vvgs Voltage (V)
I(M1[ID])

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

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

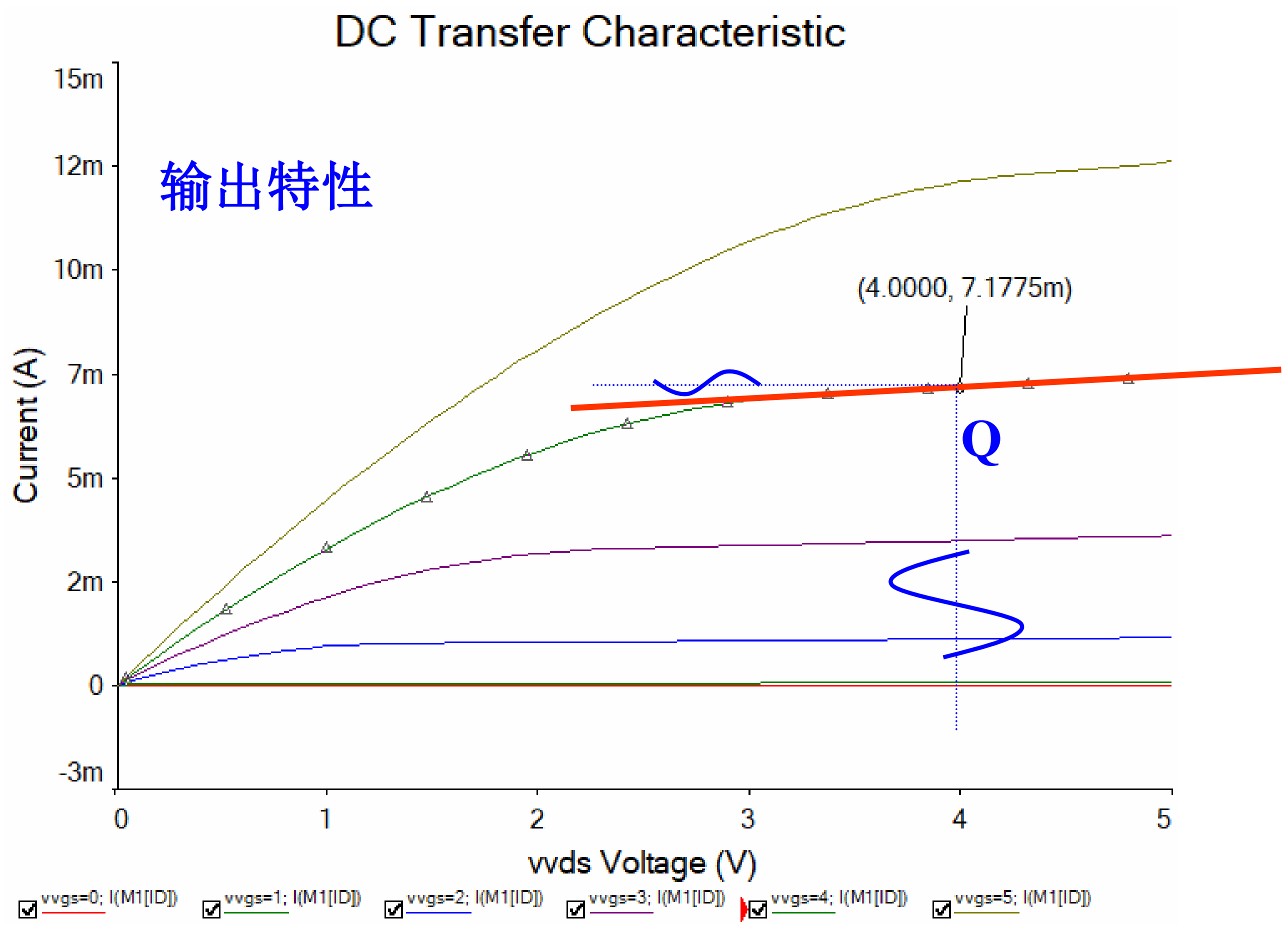
- 输出特性曲线在Q点处切线的斜率，或者在Q点处，电流关于电压VDS的偏导

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

- 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


DC Transfer Characteristic
输出特性
(4.0000, 7.1775m)
Q
15m
12m
10m
7m
5m
2m
0
-3m
Current (A)
0
1
2
3
4
5
vvds Voltage (V)
vvgs=0; I(M1[ID])
vvgs=1; I(M1[ID])
vvgs=2; I(M1[ID])
vvgs=3; I(M1[ID])
vvgs=4; I(M1[ID])
vvgs=5; I(M1[ID])

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

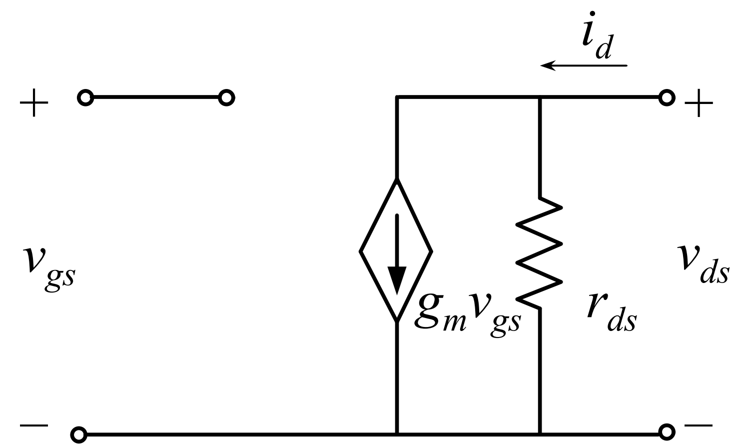
- 输入：开路　$i_g = 0$

- 输出：压控电流源与输出电阻并联

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

- 模型参数

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



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

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

- $$g_m = \left.\frac{\partial I_D}{\partial V_{GS}}\right|_Q = \mu_0 C_{ox}\frac{W}{L}\underline{(V_{GS}-V_T)}$$

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

$$= \underline{\sqrt{2\beta I_{DQ}}}$$

$$= \frac{2I_{DQ}}{V_{GS}-V_T}$$

与过驱动电压成正比

与电流开根号成正比

模型参数

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

$$= \lambda \frac{\mu_0 C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 \approx \underline{\lambda}\, \underline{I_{DQ}}$$

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≠0，还需要考虑背栅效应

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

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

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

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

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

$$= g_m \left(\frac{\partial V_T}{\partial V_{SB}}\right)$$

$$= g_m \frac{\gamma}{2\sqrt{|2\Phi_F + V_{SB}|}}$$

MOS管交流小信号模型

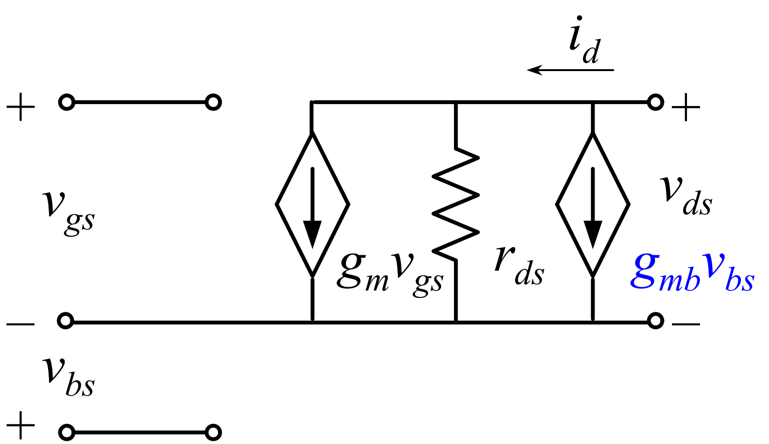
- 考虑背栅效应

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

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

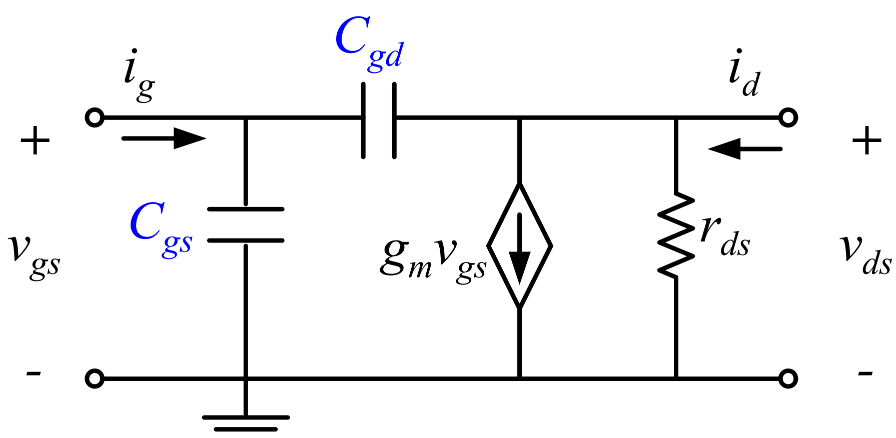
$$g_{ds} = \left.\frac{\partial I_D}{\partial V_{DS}}\right|_Q$$

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



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
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+ 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：**

$$\underbrace{V_T = V_{T0}}_{\text{VTO}} + \underbrace{\gamma}_{\text{GAMMA}}\left(\sqrt{\left|\underbrace{2\Phi_F}_{\text{PHI}} + V_{SB}\right|} - \sqrt{\left|2\Phi_F\right|}\right)$$

- **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
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+ PHI = 0.8 MJ = 0.5 MJSW = 0.35 CGBO = 700P CGSO = 220P CGDO = 220P
+ CJ = 560U CJSW = 350P LD = 0.014U TOX = 14N
```
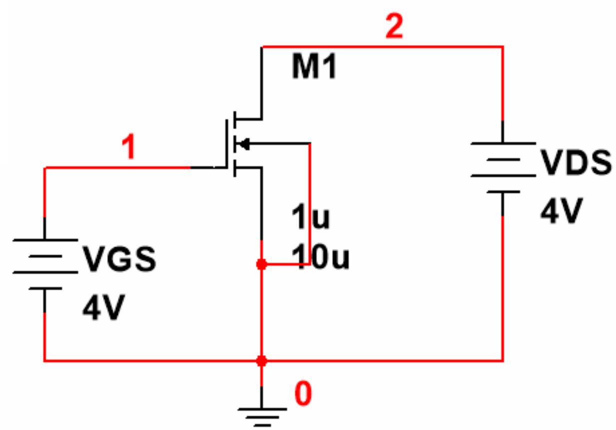

MOS管OP仿真



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

```
.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
```

OP仿真结果

- 饱和区

- vth：阈值电压
- vdsat：饱和电压
- vod：过驱动电压，vod=vgs-vth

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
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
cgtot	21.1501f
cstot	18.1174f
cbtot	705.3490a
cgs	18.1174f
cgd	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