形式问题

1. 需要展示及介绍测试平台。
2. 对于自己假设的参数，如V_{TH}，需要提前说明。
3. 没有给出推算过程或逻辑，直接给出结果的一律无效。
4. 尽量使用工程单位um, nm, fF等，而不是数学单位e-6
5. 请将作业整理到一个PDF，题号回答清晰，建议全电子版书写；手写作业请确保字迹清晰，字迹模糊无法辨认的直接判错。
6. 作业迟交最高按60%分值计算，请确保按时提交作业。

Homework 1

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.8V**，强反转区的gm推导：

$$\begin{cases} L_{min} = 0.35\ \mu m \\ KP_n \approx 300\ \mu A/V^2 \end{cases} \Rightarrow \quad KP_n \approx 600uA/V^2$$

$$I_D = \frac{1}{2} KP_n \frac{W}{L} (V_{GS} - VTH)^2$$

$$I_D = 200uA, \Big|_{V_{TH}=0.46V} \qquad g_m = 1.2mA/V, \Big|_{V_{TH}=0.46V}$$

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.8V**，强反转区的r_0推导：

$$r_0 \approx \frac{1}{\lambda I_{DS}} = \frac{V_E \cdot L}{I_{DS}}$$

V_{En} = 4 V/μmL

$$r_0 \approx \frac{4 \cdot 0.18}{200u} = 3.6K\Omega$$

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.8V**，强反转区的gm和r_0检验：

	估算	仿真
Id	200u	100u
gm	1.2m	0.42m
r0	3.6K	100K

```
region = Saturati
id = 100.3509u
ibs = -1.6822e-20
ibd = -43.4021n
vgs = 800.0000m
vds = 1.8000
vbs = 0.0000
vth = 456.4051m
vdsat = 232.2942m
vod = 343.5949m
gm = 423.2997u
gds = 11.2628u
gmb = 98.3501u
cdtot = 988.0917a
cgtot = 1.9084f
cstot = 2.4746f
cbtot = 2.1628f
cgs = 1.3013f
cgd = 341.0737a
```

×估算与仿真有较大差距

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- 估算参数矫正

```
*  GENERAL  PARAMETERS
*
+CALCACM  = 1
+LMIN     = 1.5E-7                    LMAX     = 1.0E-5
+WMAX     = 1.0E-4                    TNOM     = 25.0
+TOX      = '3.87E-09+DTOX_N18'       TOXM     = 3.87E-09
+NCH      = 3.8694000E+17             LLN      = 1.1205959
+WLN      = 1.0599999                 WWN      = 0.8768474
+LL       = 2.6352781E-16             LW       = -2.2625584E-16
+WINT     = -1.4450482E-09            WL       = -2.3664573E-16
+WWL      = -4.0000000E-21            MOBMOD   = 1
+XL       = '1.8E-8+DXL_N18'          XW       = '0.00+DXW_N18'
```

✓栅极厚度预估正确

```
*  MOBILITY  PARAMETERS
*
+VSAT     = 8.2500000E+04             PVSAT    = -8.3000000E-10
+LUA      = 7.7349790E-19             PUA      = -1.0000000E-24
+UC       = 1.2000000E-10             PUC      = 1.5000000E-24
+PRWB     =  0.2400000                PRWG     = 0.4000000
+U0       = '(3.4000000E-02)*(1+0.05*Sigma)'           LU0
+A0       = 0.8300000                 KETA     = -3.0000000E-03
+A1       = 0.00                      A2       = 0.9900000
+B0       = 6.0000000E-08             B1       = 0.00
*
```

$\mu_p \approx 250\ cm^2/Vs$

$\mu_n \approx 600\ cm^2/Vs$

×载流子流速高估近一倍

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- 参数矫正

	调整后估算	仿真
Id	113u	100u
gm	0.68m	0.42m
r0	6.4K	89K

```
* ROUT PARAMETERS
*
+PCLM      = 1.2000000         PPCLM     = 2.9999999E-15
+PDIBLC2   = 3.8000000E-03     PPDIBLC2  = 2.7000001E-16
+DROUT     = 0.5600000         PSCBE1    = 3.4500000E+08
+PVAG      = 0.00              DELTA     = 1.0000000E-02
+ALPHA1    = 0.1764000         LALPHA1   = 7.6250000E-09
*
```

V_{En} = 4 V/μmL

- V_{En}在此工艺中调整为40V/um

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.5V**，弱反转区的gm推导：

$$I_{D,wi} = I_{D0}\frac{W}{L}e^{\frac{V_{GS}}{nkT/q}}$$

$$g_{m,wi} = \frac{I_{D,wi}}{nkT/q}$$

×n作为一个跟反转程度有关的量，随V_{GS}变化，无法预估

×I_{D0}未知

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.5V**，弱反转区的gm推导：（利用已有强反型区结果）

$$I_{DS}=K'\frac{W}{L}V_{GSTt}^2\cdot ln^2(1+e^v)\text{，}\quad v=\frac{V_{GST}}{V_{GSTt}}\qquad V_{GSTt}=2n\frac{kT}{q}\approx 70mV$$

已有 $I_D=113uA,\Big|_{V_{GST}=0.34V}$ ⇒ $ln^2(1+e^v)\approx 5^2=25$

⇓ $v=0.7,\Big|_{V_{GST}=0.04V}$

$I_D=5.5uA,\Big|_{V_{GST}=0.04V}$ ⇐ $ln^2(1+e^v)\approx 1.1^2=1.2$

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

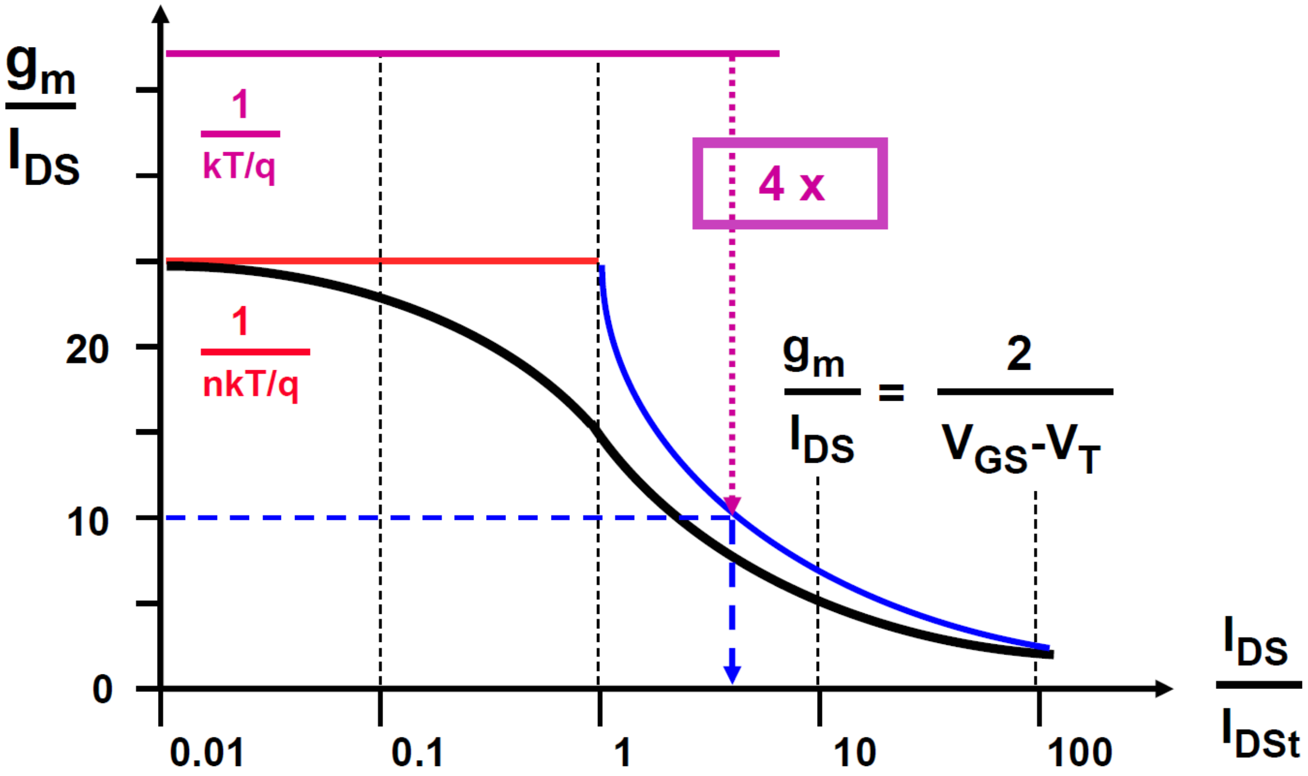
- **V_{GS}=0.5V**，弱反转区的gm推导：

$$I_D = 5.5uA,\Big|_{V_{GST}=0.04V}$$

$$ln^2(1+e^v) \approx 1.2$$

反型系数i: $i = \frac{I_{DS}}{I_{DSt}} = ln^2(1+e^v)$

$$g_m = 82.5u/V,\Big|_{V_{TH}=0.46V}$$



2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.5V**，弱反转区的r_0推导：

$$r_0 \approx \frac{1}{\lambda I_{DS}} = \frac{V_E \cdot L}{I_{DS}}$$

V_{en}=40V/um

$$r_0 \approx \frac{40 \cdot 0.18}{5.5u} = 1.3M\Omega$$

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=0.5V**，弱反转区的gm和r_0检验：

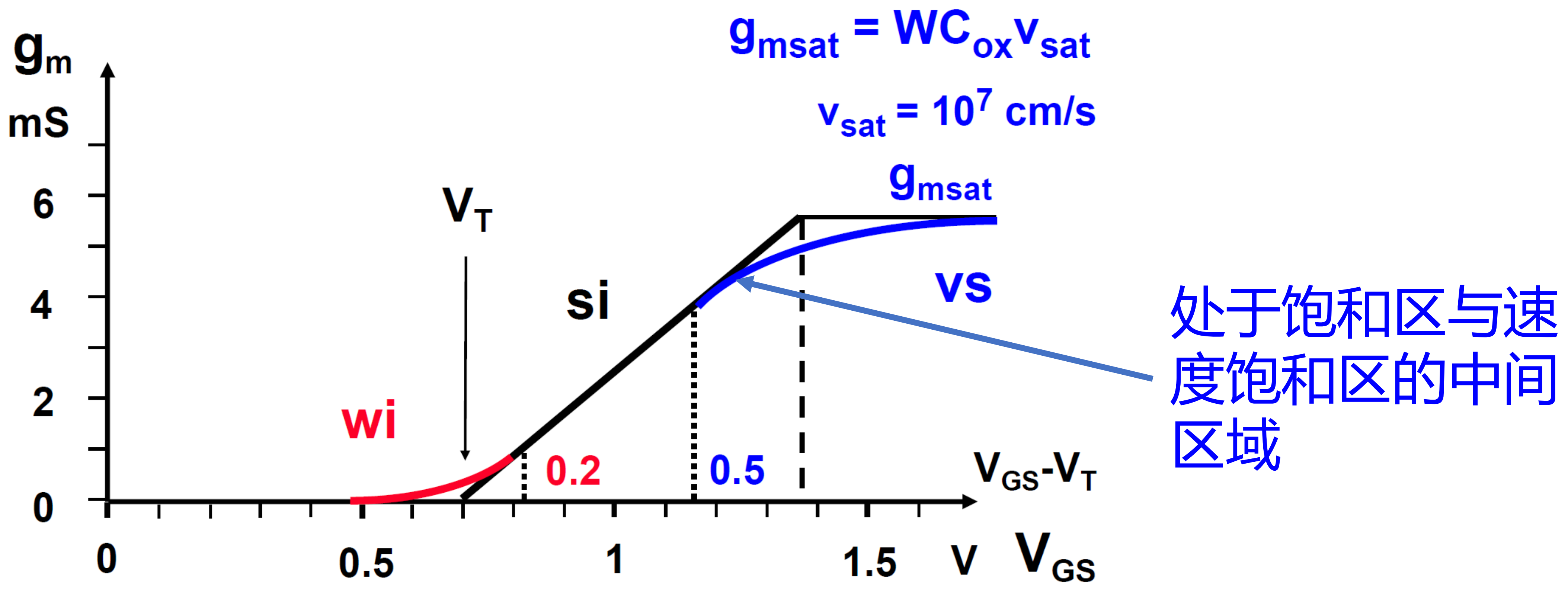
	估算	仿真
Id	5.5u	2u
gm	82.5u	28u
r0	1.3M	11M

✓估算基本正确

```
[ NM0 ]
region = Saturati
id = 2.0072u
ibs = -3.3839e-22
ibd = -902.0821p
vgs = 500.0000m
vds = 1.8000
vbs = 0.0000
vth = 404.6511m
vdsat = 116.1837m
vod = 95.3489m
gm = 28.8373u
gds = 85.4506n
gmb = 8.4268u
cdtot = 976.6265a
cgtot = 6.8587f
cstot = 7.1026f
cbtot = 4.5589f
cgs = 4.9752f
cgd = 343.2256a
```

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=1.1V**，速度饱和区的gm推导：



2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=1.1V**，速度饱和区的gm推导：

$$\frac{1}{g_m} = \frac{1}{g_{m,si}} + \frac{1}{g_{m,sat}}$$

$$g_{m,si} = 2KP_n\frac{W}{L}V_{GST} = 2.67m \qquad g_{m,sat} = WC_{OX}v_{sat} = 1m$$

$$g_m = 0.73m$$

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=1.1V**，速度饱和区的r0推导：

$$\frac{g_{m,si}}{I_D} = \frac{2}{V_{GST}} \qquad \frac{g_{m,sat}}{I_D} = \frac{1}{V_{GST}}$$

$$\Downarrow$$

$$I_D \approx \frac{1}{1.8} \cdot g_m \cdot V_{GST} = 260uA$$

$$r_0 \approx \frac{1}{\lambda I_{DS}} = \frac{V_E \cdot L}{I_{DS}}$$

$$r_0 \approx \frac{40 \cdot 0.18}{0.26m} = 28K\Omega$$

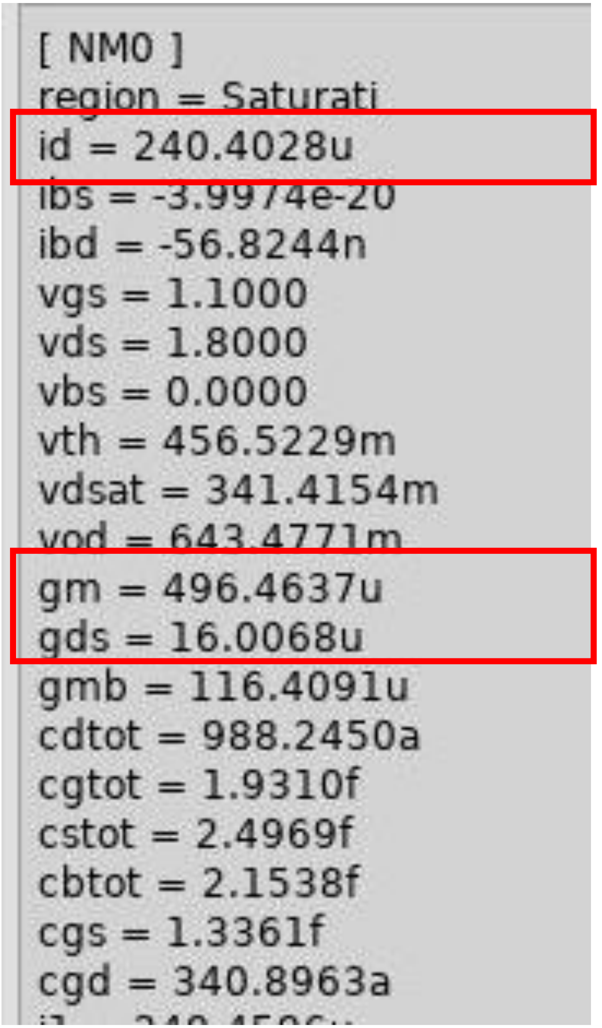
V_{en}=40V/um

2. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的g_m和r_0。

- **V_{GS}=1.1V**，速度饱和区的gm和r_0检验：

	估算	仿真
Id	260u	240u
gm	730u	500u
r0	28K	62.5K

✓**估算基本正确**



3. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的特征频率f_T，并通过AC仿真得到所求的特征频率。

$$f_T = \frac{g_m}{2\pi C_{GS}}$$

$$C_{GS} \approx \frac{2}{3} WLC_{ox}$$

≈ 2W fF/um for Lmin

$$L_{min}C_{ox} \approx L_{min}\frac{\varepsilon_{ox}}{t_{ox}} \approx 50\,\varepsilon_{ox} \approx 2\ \mathrm{fF}/\mu\mathrm{m}$$

$$f_T = \frac{g_m}{4\pi \cdot 1u \cdot fF/um}$$

3. 估算V_{GS}=0.5V，0.8V和1.1V且V_{DS}=1.8V时，W/L=1um/0.18um的NMOS的特征频率f_T，并通过AC仿真得到所求的特征频率。

$$f_T = \frac{g_m}{4\pi \cdot 1u \cdot fF/um}$$

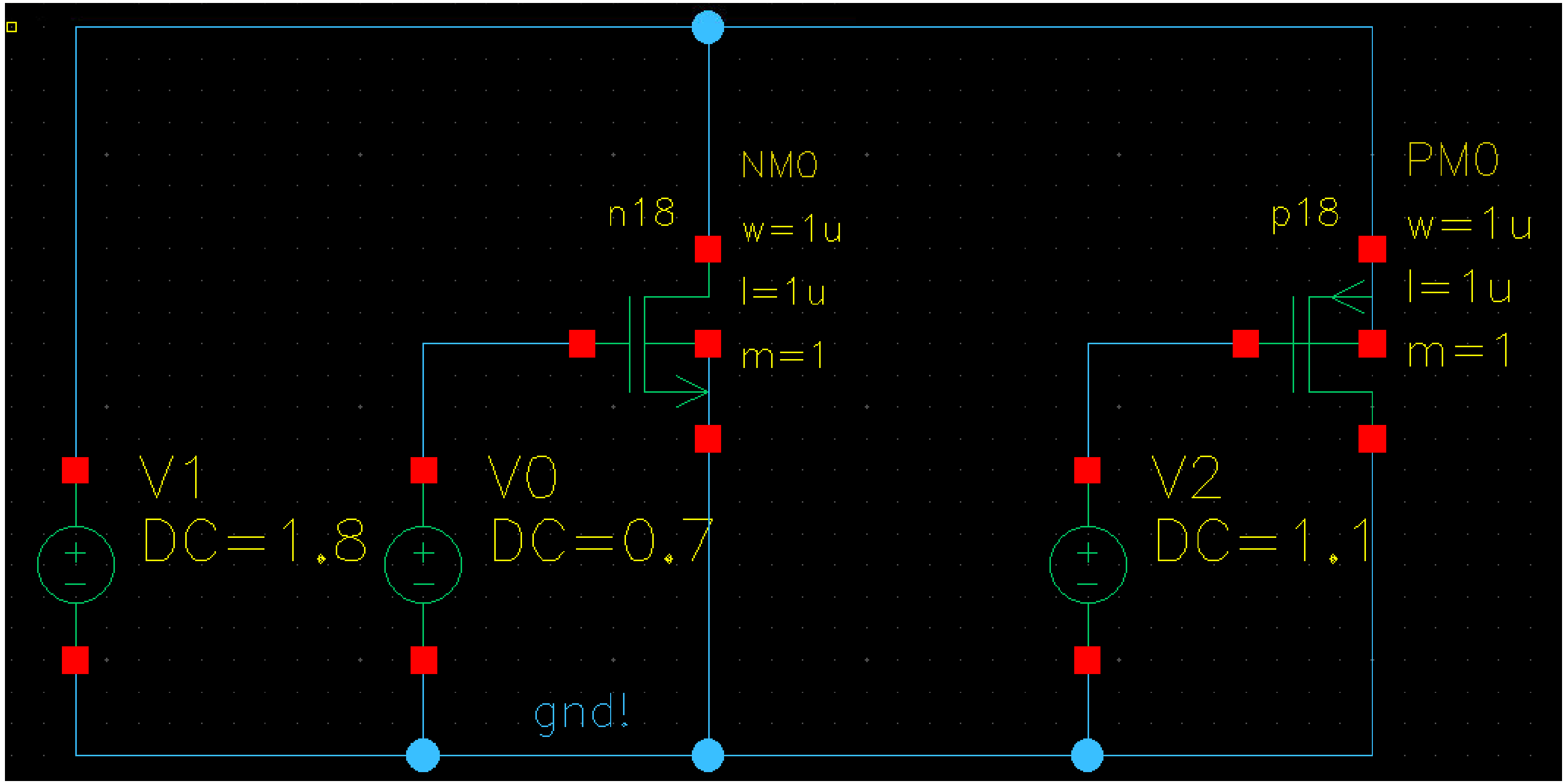
V_{GS}	仿真gm	算术fT	仿真fT
0.5V	28u	1.1G	12G
0.8V	420u	16.7G	36G
1.1V	500u	19.9G	41G

- **真实的Cgs=1.3fF，比我们预估的2fF略小**
- **弱反型区中的Cgs不能用C_{OX}类推**

Homework 2

- 利用仿真结果，找到我们所使用工艺的$u_{0p,n}$, C_{ox}, V_{THn}, V_{THp}

```
region = Saturati
id = 12.9769u
ibs = -2.1864e-21
ibd = -2.8580n
vgs = 700.0000m
vds = 1.8000
vbs = 0.0000
vth = 404.6616m
vdsat = 261.9176m
vod = 295.3384m
gm = 78.3552u
gds = 298.4982n
gmb = 22.6287u
cdtot = 976.9014a
cgtot = 7.3556f
cstot = 7.8072f
cbtot = 4.5240f
cgs = 5.6599f
```




```
region = Saturati
id = -2.4713u
ibs = 1.7020e-22
ibd = 11.4903p
vgs = -700.0000m
vds = -1.8000
vbs = 0.0000
vth = -422.6200m
vdsat = -250.9069m
vod = -277.3800m
gm = 16.0855u
gds = 61.2616n
gmb = 5.1132u
cdtot = 1.1470f
cgtot = 7.1159f
cstot = 8.3443f
cbtot = 4.1553f
cgs = 6.0843f
```

$$C_{OXn} = 8.55m \Leftarrow C_{GS} \approx \frac{2}{3} W L C_{OX} \Rightarrow C_{OXp} = 9.12m$$

$$u_{0n} = \frac{26u}{8.55m \cdot 0.09} = 33m \Leftarrow I_D = \frac{1}{2} u_0 C_{GS} \frac{W}{L} (V_{GS} - VTH)^2 \Rightarrow u_{0p} = \frac{4.94u}{9.12m \cdot 0.073} = 7.4\,m$$

- 利用仿真结果，找到我们所使用工艺的$u_{0p,n}$, C_{ox}, V_{THn}, V_{THp}

NMOS

```
* GENERAL PARAMETERS
*
+CALCACM  = 1
+LMIN     = 1.5E-7
+WMAX     = 1.0E-4
+TOX      = '3.87E-09+DTOX_N18'
+NCH      = 3.8694000E+17
```

$KP_n \approx 280uA/V^2$

```
* MOBILITY PARAMETERS
*
+VSAT     = 8.2500000E+04          PVSAT    = -8.
+LUA      = 7.7349790E-19          PUA      = -1.
+UC       = 1.2000000E-10          PUC      = 1.5
+PRWB     = -0.2400000             PRWG     = 0.4
+U0       = '(3.4000000E-02)*(1+0.05*Sigma)'
+A0       = 0.8300000              KETA     = -3.
```

PMOS

```
* GENERAL PARAMETERS
*
+CALCACM  = 1
+LMIN     = 1.5E-7
+WMAX     = 1.0E-4
+TOX      = '3.74E-09+DTOX_P18'
+NCH      = 5.5000000E+17
```

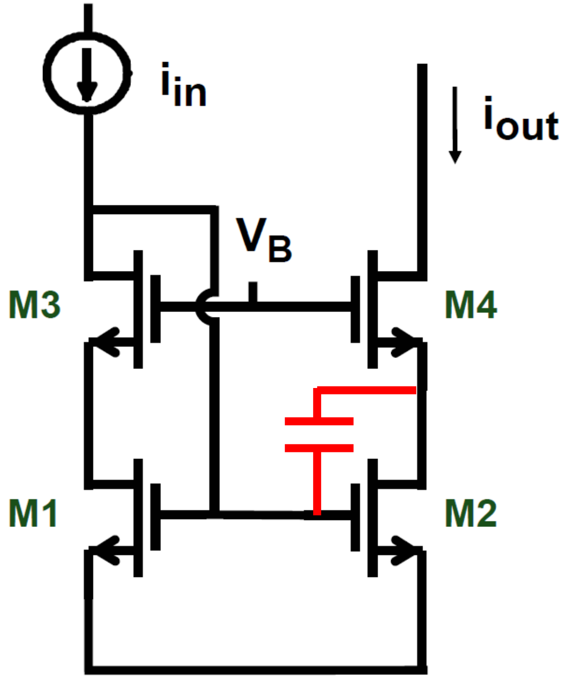
$KP_p \approx 70uA/V^2$

```
* MOBILITY PARAMETERS
*
+VSAT     = 1.0000000E+05          UA       = 2
+PUA      = -2.0000000E-24         UB       = 1
+WUC      = 3.1668000E-17          PUC      = -
+PRWB     = -0.4000000             PRWG     = 0
+U0       = '(8.6610000E-03)*(1+0.05*Sigma)'
+A0       = 1.0000000              KETA     = 2
```

$$C_{OXn} = 8.55m \qquad C_{GS} \approx \frac{2}{3}WLC_{OX} \qquad C_{OXp} = 9.12m$$

$$u_{0n} = \frac{26u}{8.55m \cdot 0.09} = 33m \qquad I_D = \frac{1}{2}u_0 C_{GS}\frac{W}{L}(V_{GS} - VTH)^2 \qquad u_{0p} = \frac{4.94u}{9.12m \cdot 0.073} = 7.4\,m$$

- 通过公式描述V_B的取值范围（提示：晶体管M1-M4均需要工作在饱和区）



$$\begin{cases} V_{DS1} > V_{GS1} - V_{TH1} \\ V_{DS3} > V_{GS3} - V_{TH3} \end{cases}$$

$$V_{GS3} + V_{GS1} - V_{TH1} < V_B < V_{GS1} + V_{TH3}$$

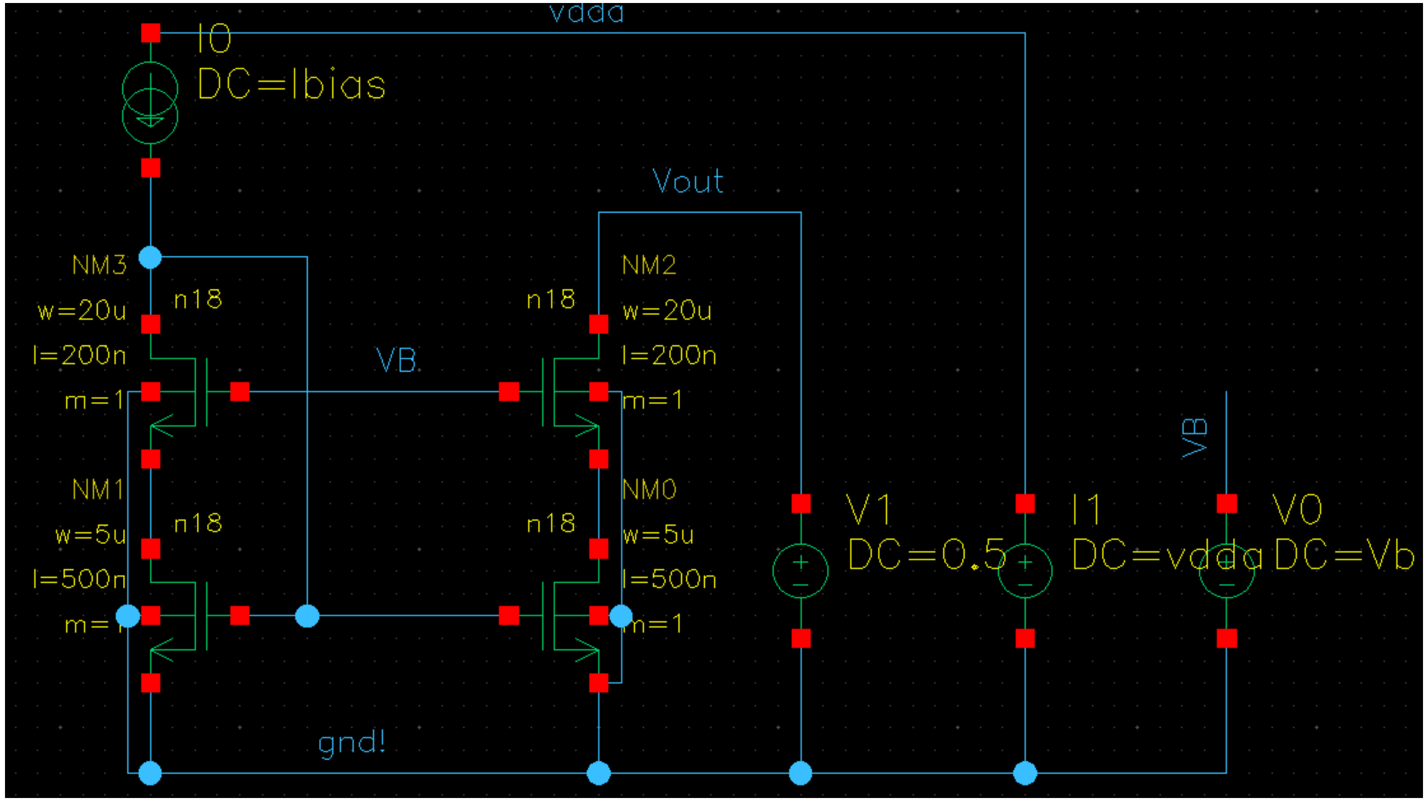
$$V_{GS3} - V_{TH1} < V_B - V_{GS1} < V_{TH3}$$

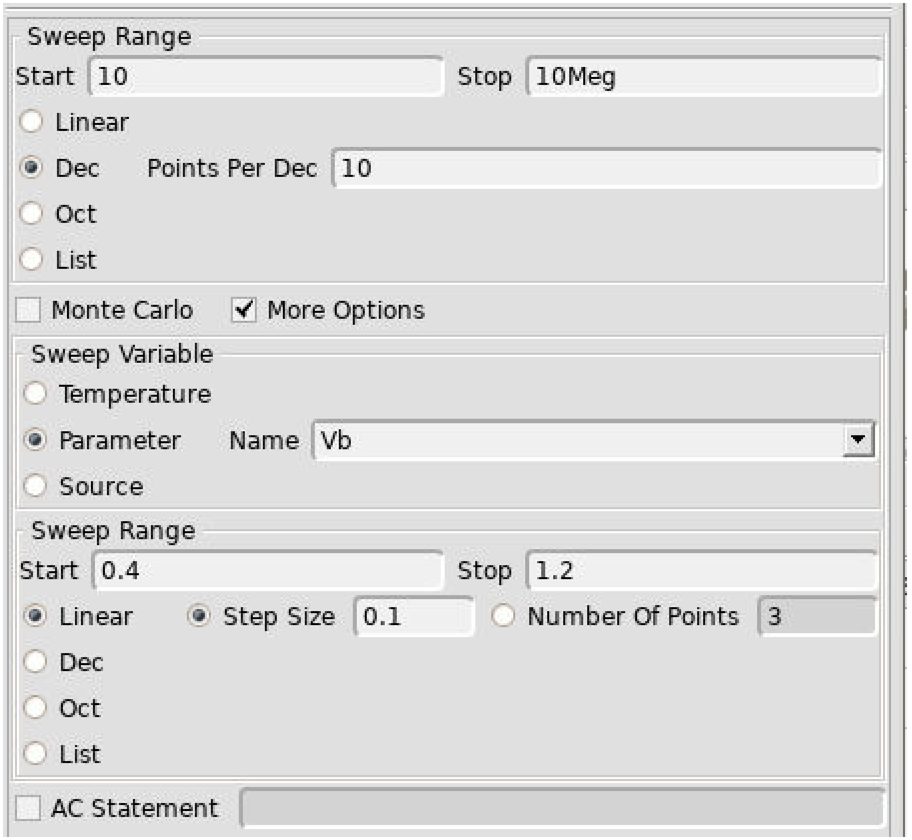
减小V_{GS3}以增加V_B的取值范围

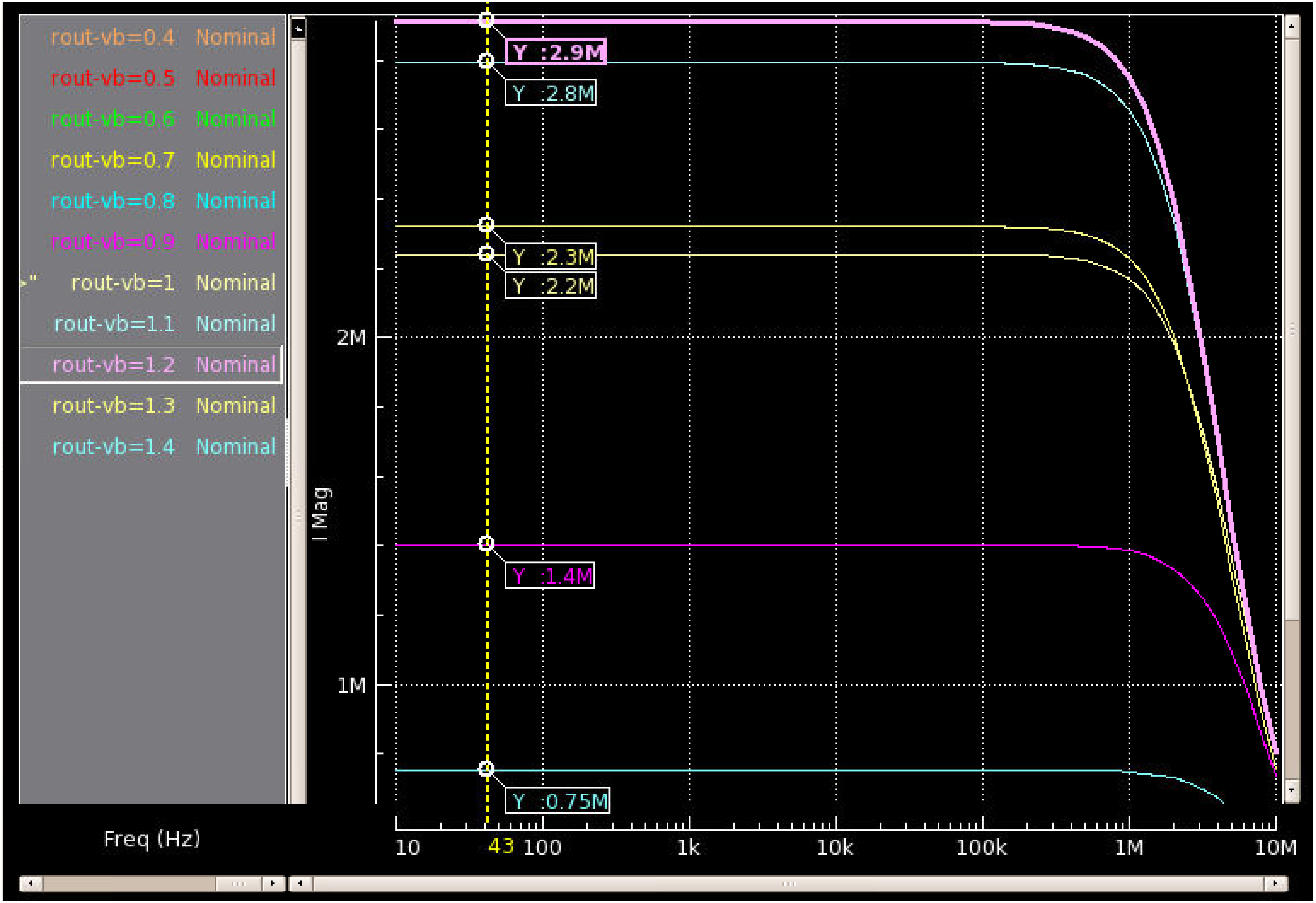
改变V_{GS1}以改变V_B的电势偏移

令 $V_{GS3} = 0.4V, V_{GS1} = 0.6V$ 得 $0.6 < V_B < 1$

- 通过公式描述V_B的取值范围（提示：晶体管M1-M4均需要工作在饱和区）

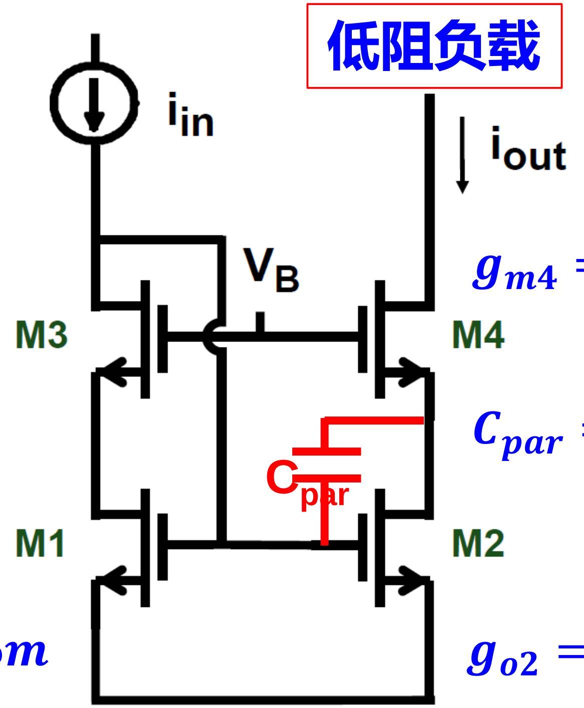






rout-vb=0.4 Nominal
rout-vb=0.5 Nominal
rout-vb=0.6 Nominal
rout-vb=0.7 Nominal
rout-vb=0.8 Nominal
rout-vb=0.9 Nominal
rout-vb=1 Nominal
rout-vb=1.1 Nominal
rout-vb=1.2 Nominal
rout-vb=1.3 Nominal
rout-vb=1.4 Nominal
Y :2.9M
Y :2.8M
Y :2.3M
Y :2.2M
Y :1.4M
Y :0.75M
2M
1M
I Mag
Freq (Hz)
10
43
100
1k
10k
100k
1M
10M

- 在Cascode电流镜中，假设有寄生电容C_{par}，利用公式估算并用仿真验证该电流镜的频率特性。（可以自由设置偏置、晶体管的尺寸以及寄生电容）



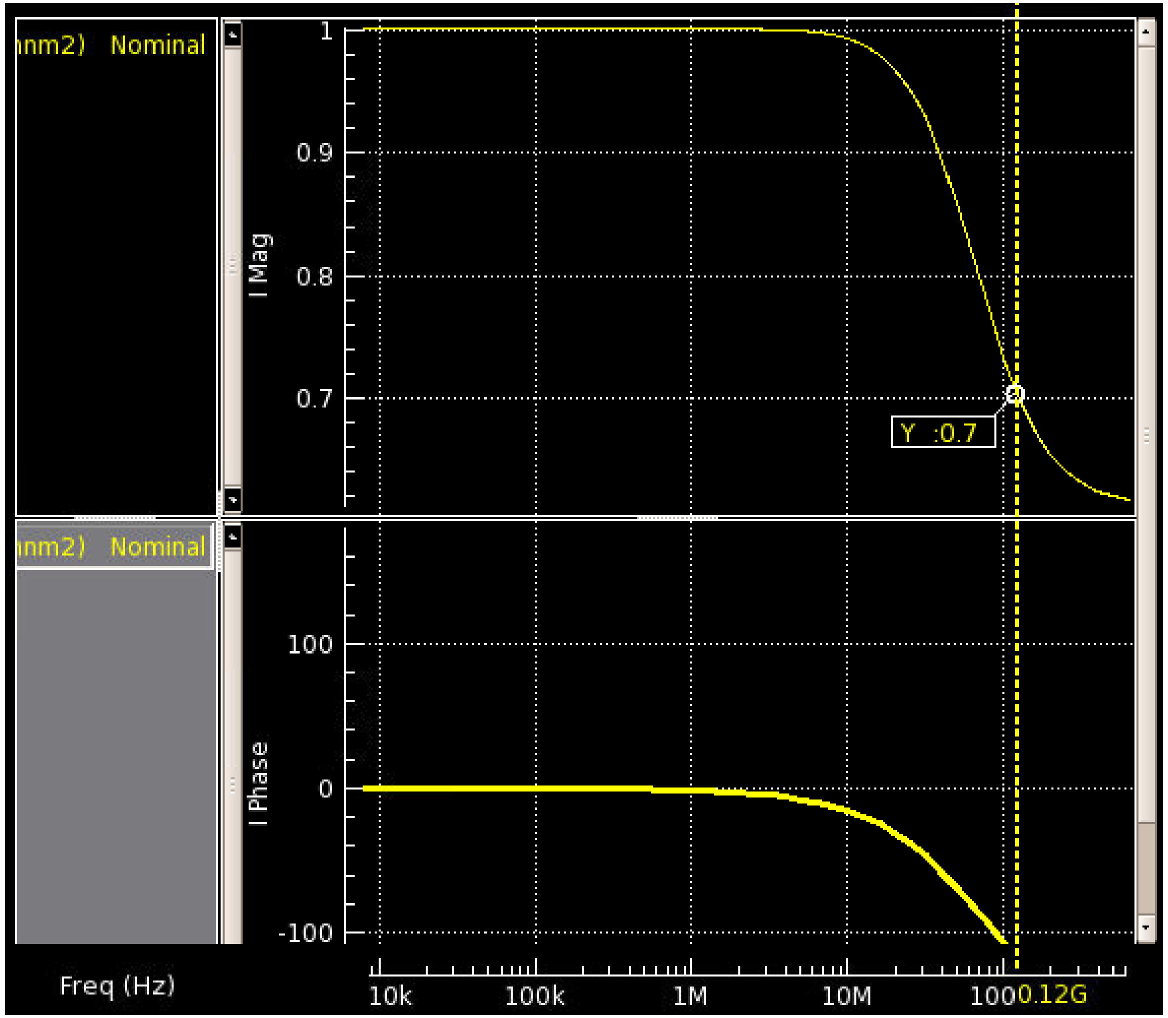
$g_{m4} = 1.73m$

$C_{par} = 1pF$

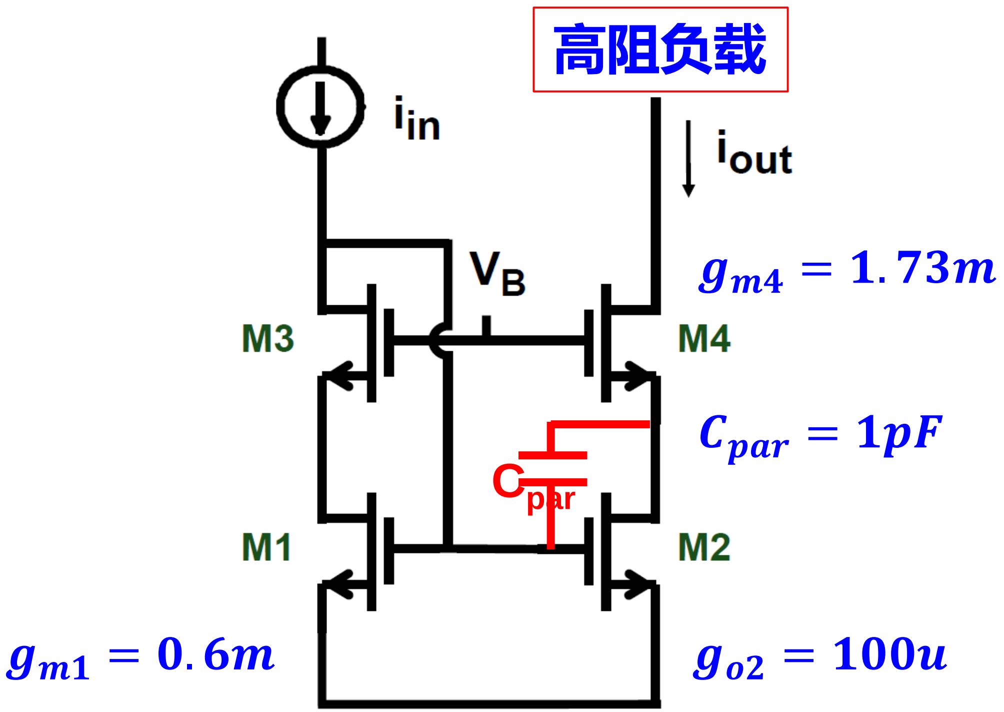
$g_{m1} = 0.6m$

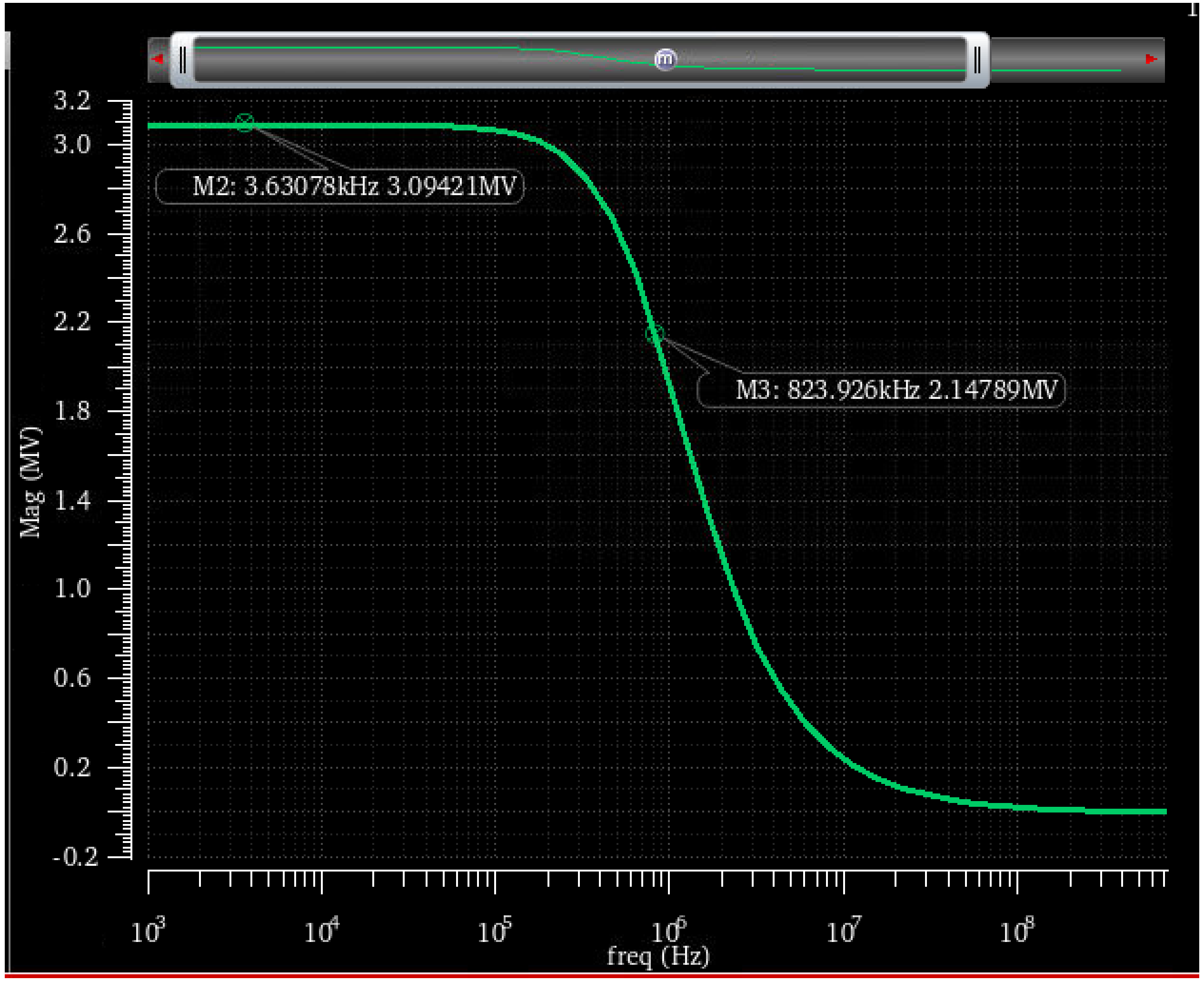
$g_{o2} = 100u$

$$f_c = \frac{g_{m4}}{2\pi \cdot (1+B) \cdot C_{par}} = 0.14GHz$$



- 在Cascode电流镜中，假设有寄生电容C_{par}，利用公式估算并用仿真验证该电流镜的频率特性。（可以自由设置偏置、晶体管的尺寸以及寄生电容）





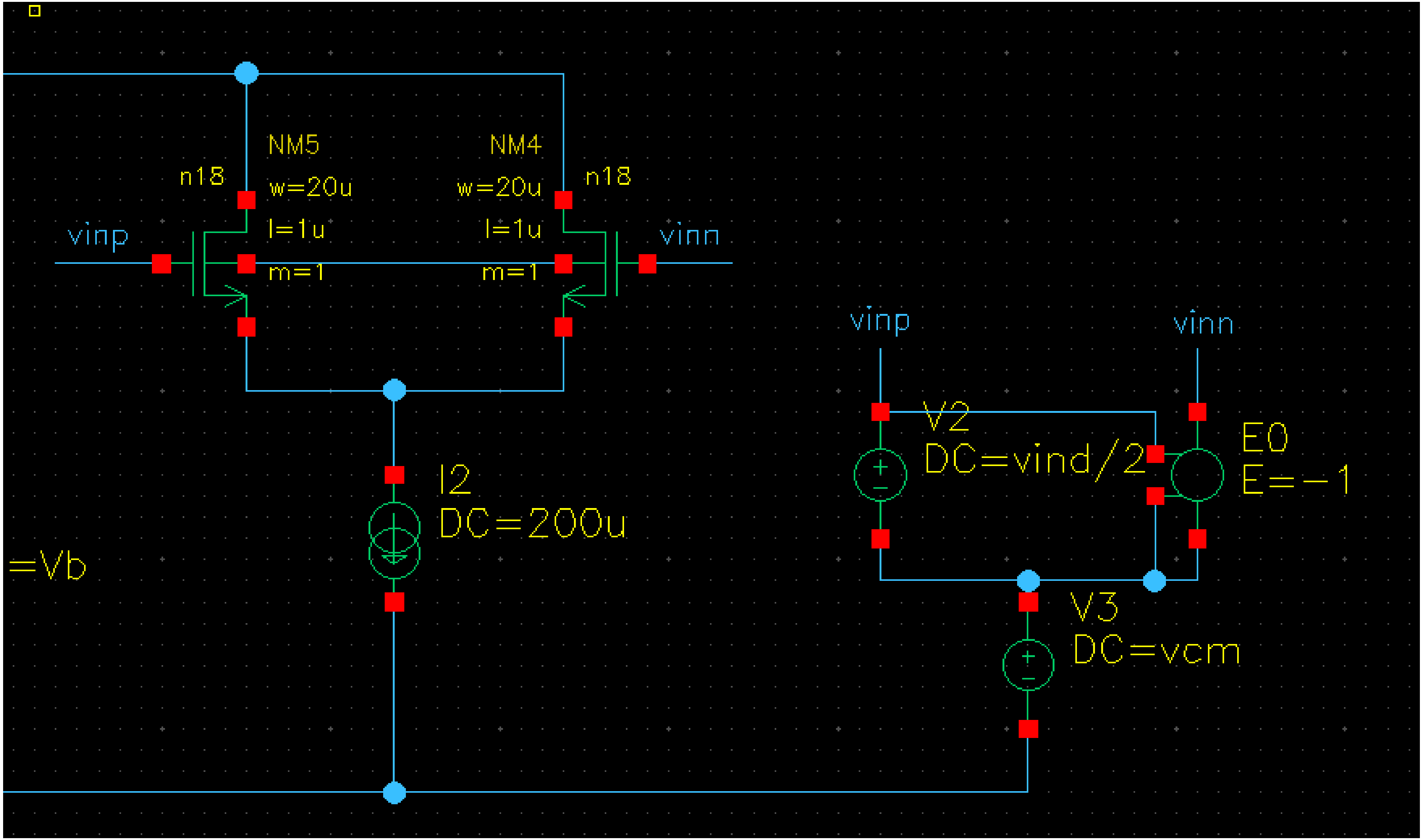
$$f_c = \frac{g_{o2}}{2\pi \cdot (1+B) \cdot C_{par}} = 796kHz$$

- 假设差分对偏置电流为200uA，W/L=20um/1um，根据理论分析和仿真验证。
  1. 计算$g_m > 99\% * g_{m,max}$的区间。
  2. 计算差分输出电流为198uA时的差分输入电压。
  3. 如果需要把问题2中求得的电压扩大一倍，差分对的W需要如何修改?

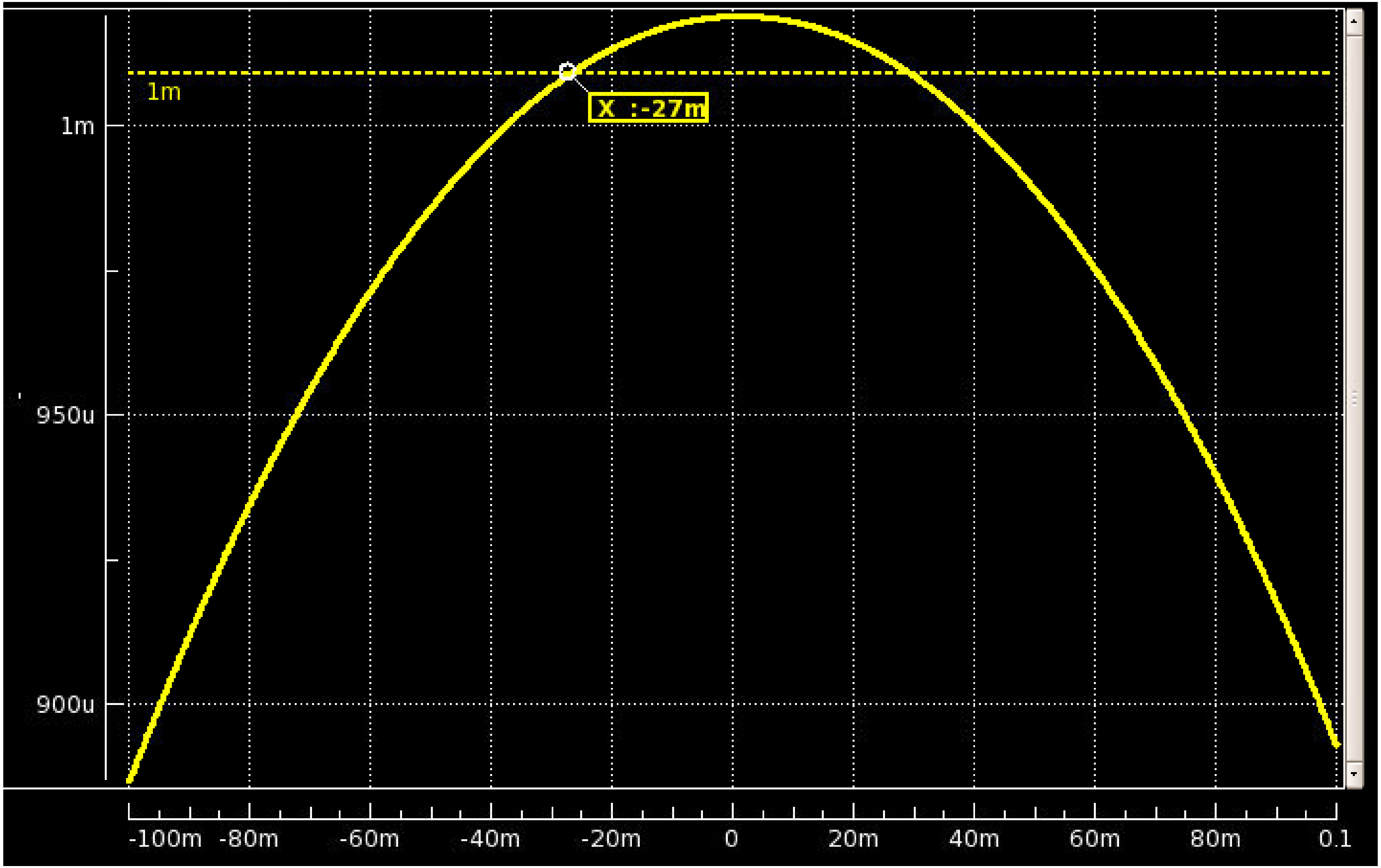
$$\frac{i_{Od}}{I_B} = \frac{v_{Id}}{(V_{GS}-V_T)} \sqrt{1 - \frac{1}{4}\left(\frac{v_{Id}}{V_{GS}-V_T}\right)^2}$$

$$\sqrt{1-\frac{1}{4}\left(\frac{V_{ID}}{V_{GST}}\right)^2} = 99\%$$

$$V_{ID} = 0.28 \cdot V_{GST} \Rightarrow V_{ID} = 53m$$



NM5
NM4
n18
w=20u
w=20u
n18
l=1u
l=1u
vinp
vinn
m=1
m=1
vinp
vinn
V2
DC=vind/2
E0
E=−1
I2
DC=200u
=Vb
V3
DC=vcm



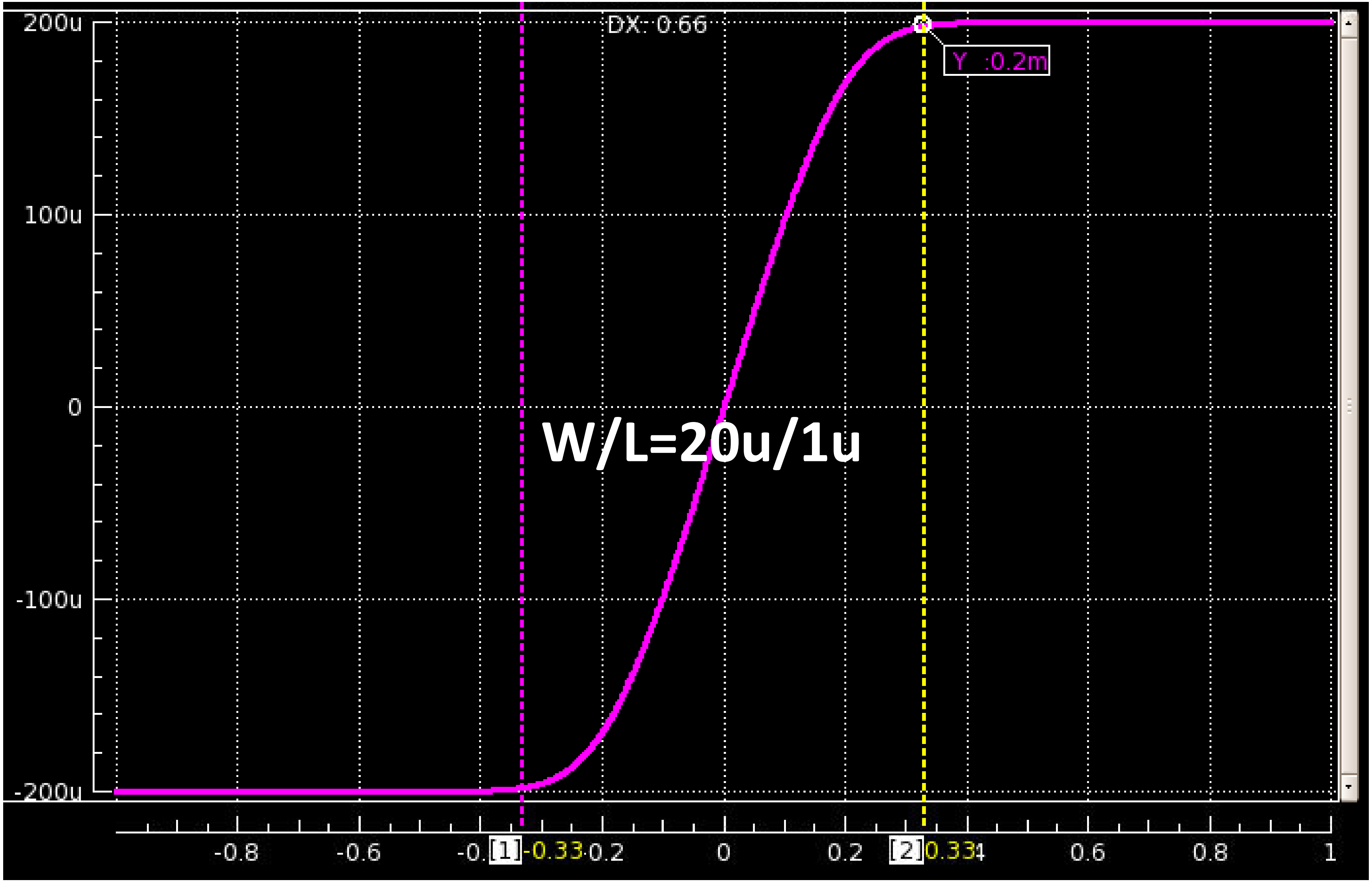
1m
X :-27m
1m
950u
900u
-100m
-80m
-60m
-40m
-20m
0
20m
40m
60m
80m
0.1

- 假设差分对偏置电流为200uA，W/L=20um/1um，根据理论分析和仿真验证。
  1. 计算g_m>99%*$g_{m,max}$的区间。
  2. 计算差分输出电流为198uA时的差分输入电压。
  3. 如果需要把问题2中求得的电压扩大一倍，差分对的W需要如何修改?

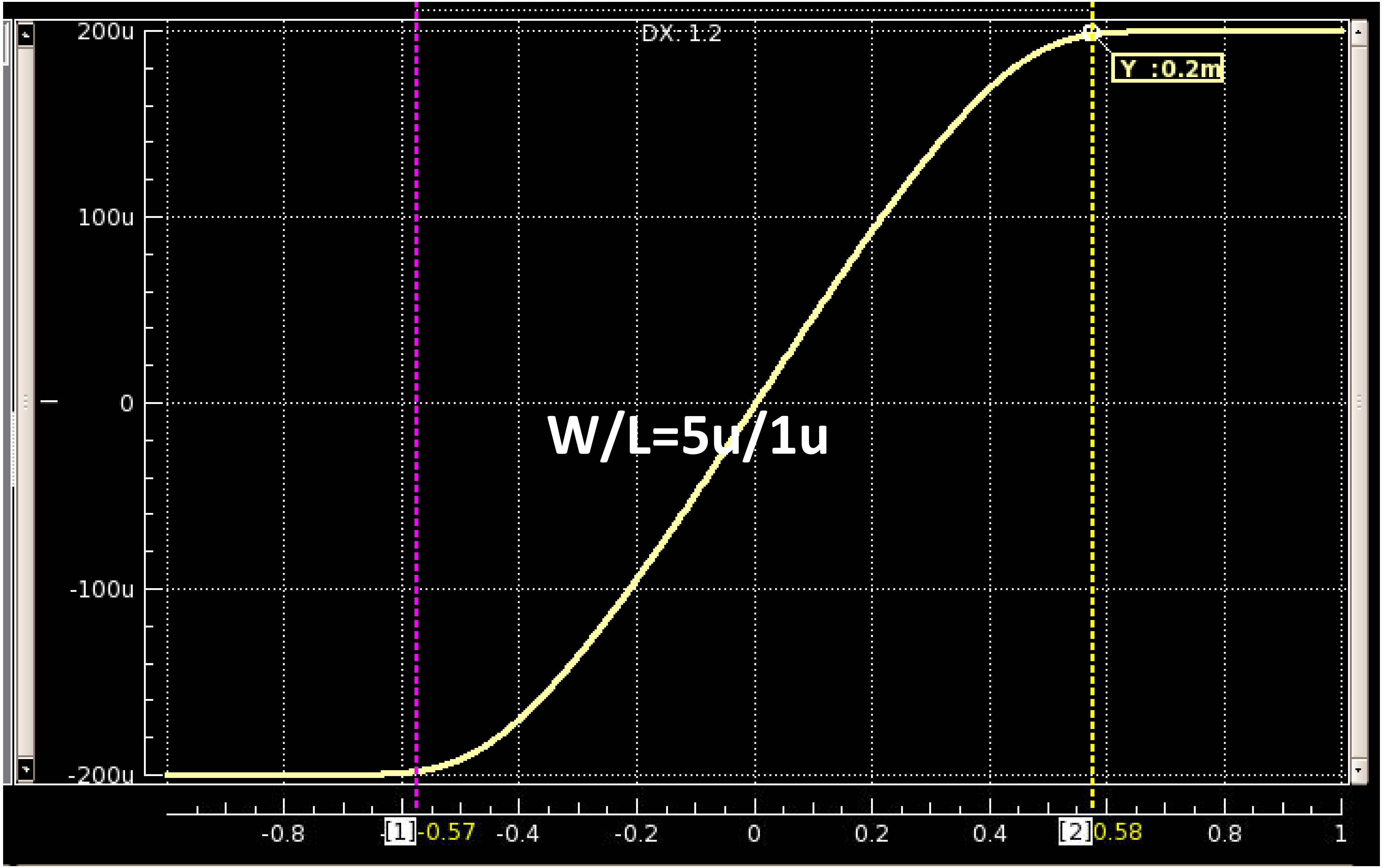
$$\frac{i_{Od}}{I_B} = \frac{v_{Id}}{(V_{GS}-V_T)}\sqrt{1-\frac{1}{4}\left(\frac{v_{Id}}{V_{GS}-V_T}\right)^2}$$

$$V_{ID} = \sqrt{2}\cdot V_{GST} \quad \Rightarrow \quad V_{ID} = 380m$$

V_{GST}扩大一倍 =》晶体管宽长减小到原来的1/4



DX: 0.66
Y :0.2m
W/L=20u/1u
200u
100u
0
-100u
-200u
-0.8
-0.6
[1]-0.33
0
0.2
[2]0.33
0.6
0.8
1



200u
100u
0
-100u
-200u
DX: 1.2
Y :0.2m
W/L=5u/1u
-0.8
[1] -0.57
-0.4
-0.2
0
0.2
0.4
[2] 0.58
0.8
1