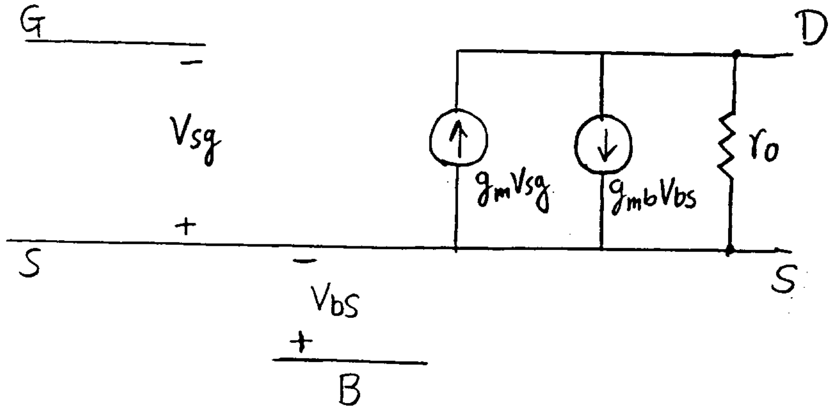
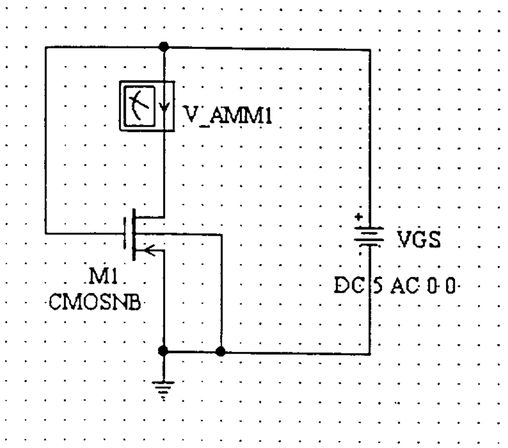
Chapter 9.

Problem 9.1

The small signal model of P-Channel MOSFET is shown below:



Problem 9.2



```
*** Top Level Netlist ***
M1        9 1 0 0 CMOSNB  L=5u W=5u
V_AMM1         1 9 0V
VGS     1 0      DC 5 AC 0 0

***** Spice models and macro models *****

.MODEL CMOSNB NMOS LEVEL=4
+VFB=-9.73820E-01, LVFB=3.67458E-01,WVFB=-4.72340E-02
... ...
+pbsw=0.8   mj=0.66036   mjsw=0.178543   wdf=0   dell=0


***** End of spice models and macro models *****

.DC VGS 0 5 0.1
.end
```

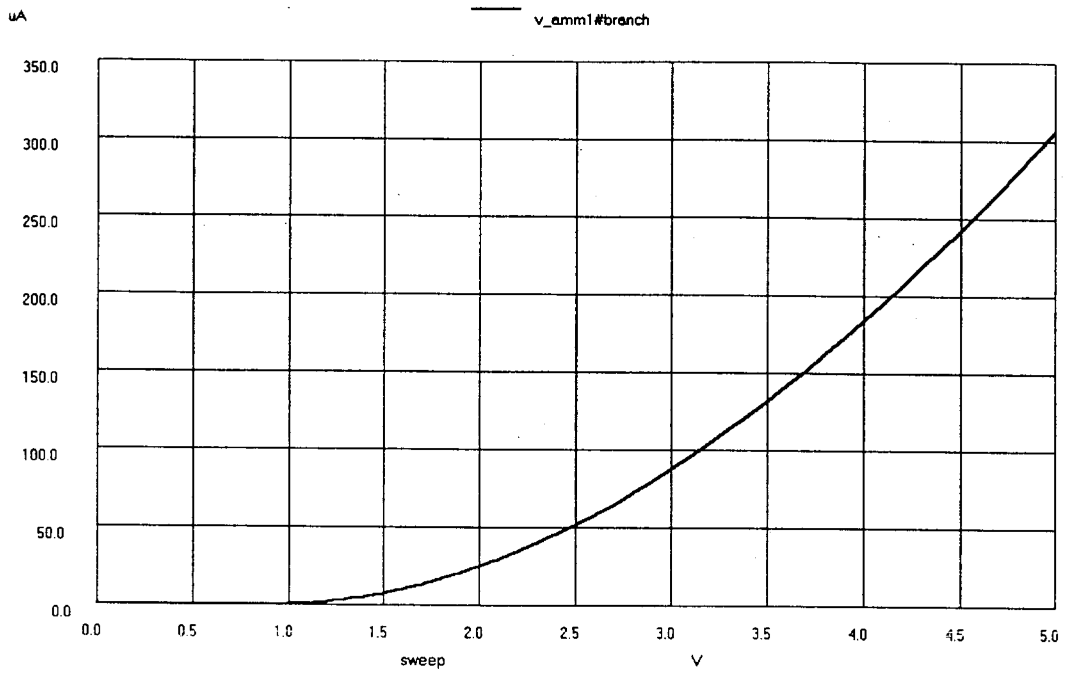


Fig 9.2(a) Drain current vs Vgs

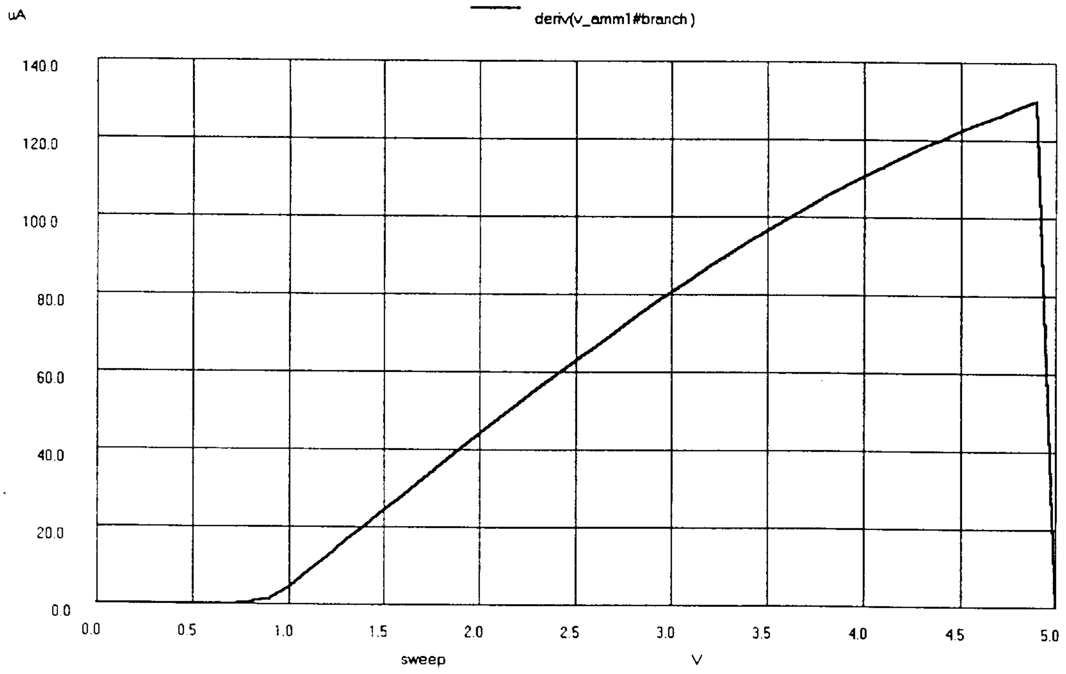
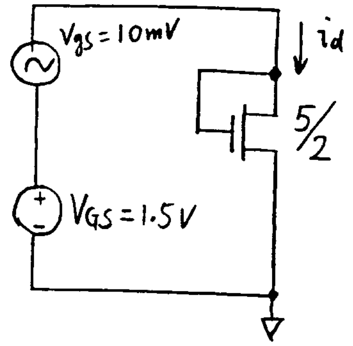


Fig 9.2(b) Derivative of curve in Fig 9.2(a)

The line tangent at Vgs = 2V is about 44 uA/V. The reciprocal of this slop corresponds to the resistance of the MOSFET in diode connection.

Problem 9.3

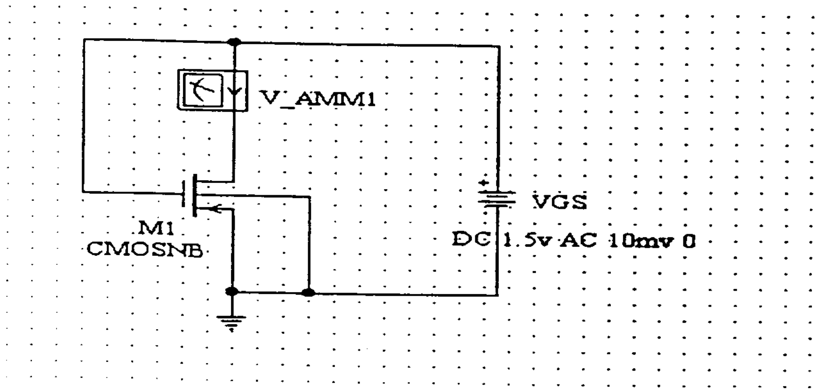


MOSFET operates in satulation region. $V_{THN} = 0.83V$

$$g_m = \beta(V_{GS} - V_{THN}) = K_{PN} \times \frac{W}{L}(V_{GS} - V_{THN})$$

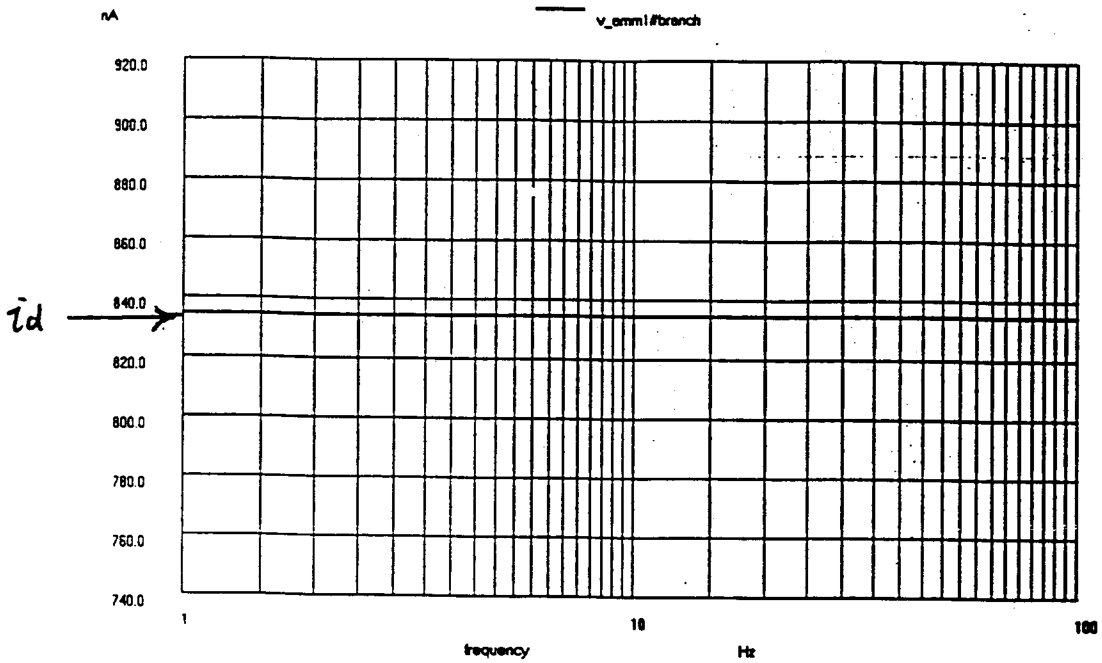
$$= 50\mu A/V^2 \times \frac{5\mu m}{2\mu m} \times (1.5v - 0.83v) = 83.75 \mu A/V$$

$$i_d = g_m v_{gs} = 83.75 \mu A/V \times 0.01V \approx \underline{0.838 \mu A}$$



```
*** (TurboSim V 1.87) Netlist for C:\TURBOSIM\EE445\P91.CKT

*** Top Level Netlist ***
M1        3 1 0 0 CMOSNB  L=2u W=5u
V_AMM1        1 3 0V
VGS       1 0      DC 1.5v AC 10mv 0

***** Spice models and macro models *****
.MODEL CMOSNB NMOS LEVEL=4
+VFB=-9.73820E-01, LVFB=3.67458E-01,WVFB=-4.72340E-02
... ...
+pbsw=0.8   mj=0.66036   mjsw=0.178543   wdf=0   dell=0

***** End of spice models and macro models *****
.ac LIN 100 1 100
.end
```

The AC SPICE simulation result is shown below:



Problem 9.4

1. Method one:

Generally, id = $\frac{\partial i_D}{\partial v_{DS}}$ vds.

$\frac{\partial i_D}{\partial v_{DS}}$ = $(\beta n/2)*(VGS-Vthn)^2*\lambda$ = **(50/2)*(15/5)*(1.5-0.83)*0.06 = 2.02uA/V.**

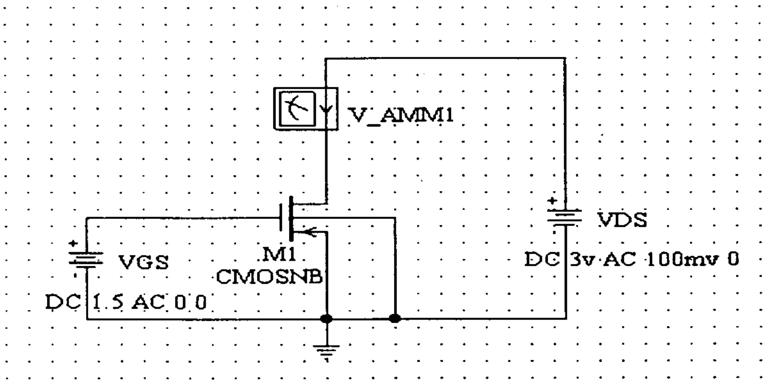
id = 2.02ua/V * 100mV = 202 nA.

2. Method Two-small signal model.

ID = $(\beta n/2)*(VGS-Vthn)^2$ and r0 = $1/(\lambda*ID)$. **Plug into the values ==> r0 = (1/2.02) V/uA.**

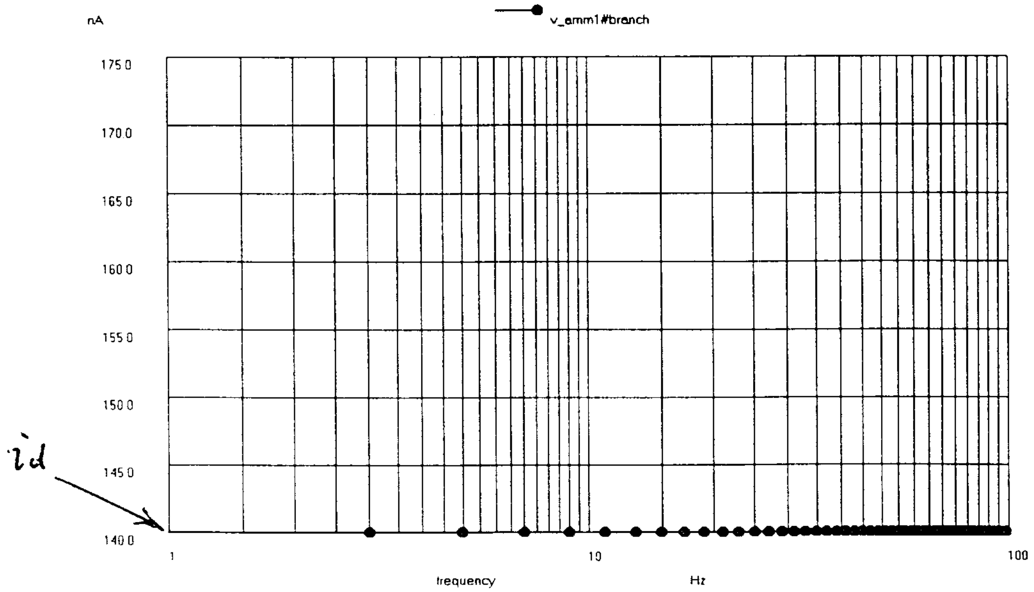
id = vds/r0 = 100mV/[(1/2.02) V/uA] = 202 nA.

Problem 9.5



```
*** Top Level Netlist ***
M1       3 6 0 0 CMOSNB  L=5u W=15u
V_AMM1           1 3 0V
VDS      1 0     DC 3v AC 100mv 0
VGS      6 0     DC 1.5 AC 0 0

***** Spice models and macro models *****
.MODEL CMOSNB NMOS LEVEL=4
+VFB=-9.73820E-01, LVFB=3.67458E-01,WVFB=-4.72340E-02
... ...
+pbsw=0.8    mj=0.66036    mjsw=0.178543    wdf=0    dell=0


***** End of spice models and macro models *****
.ac LIN 100 1 100
.end
```

The AC SPICE simulation result is shown below:



Problem 9.6

$\because V_{DS} = 1.5V < V_{GS} - V_{THN} = 3V - 0.83V = 2.17V$

$\therefore$ MOSFET operates in triode region

$$R_{ch} = \frac{1}{\beta(V_{GS} - V_{THN}) - \beta V_{DS}} = \frac{1}{50\mu A/V^2 \times \frac{15\mu m}{5\mu m} \times (3V - 0.83V - 1.5V)}$$

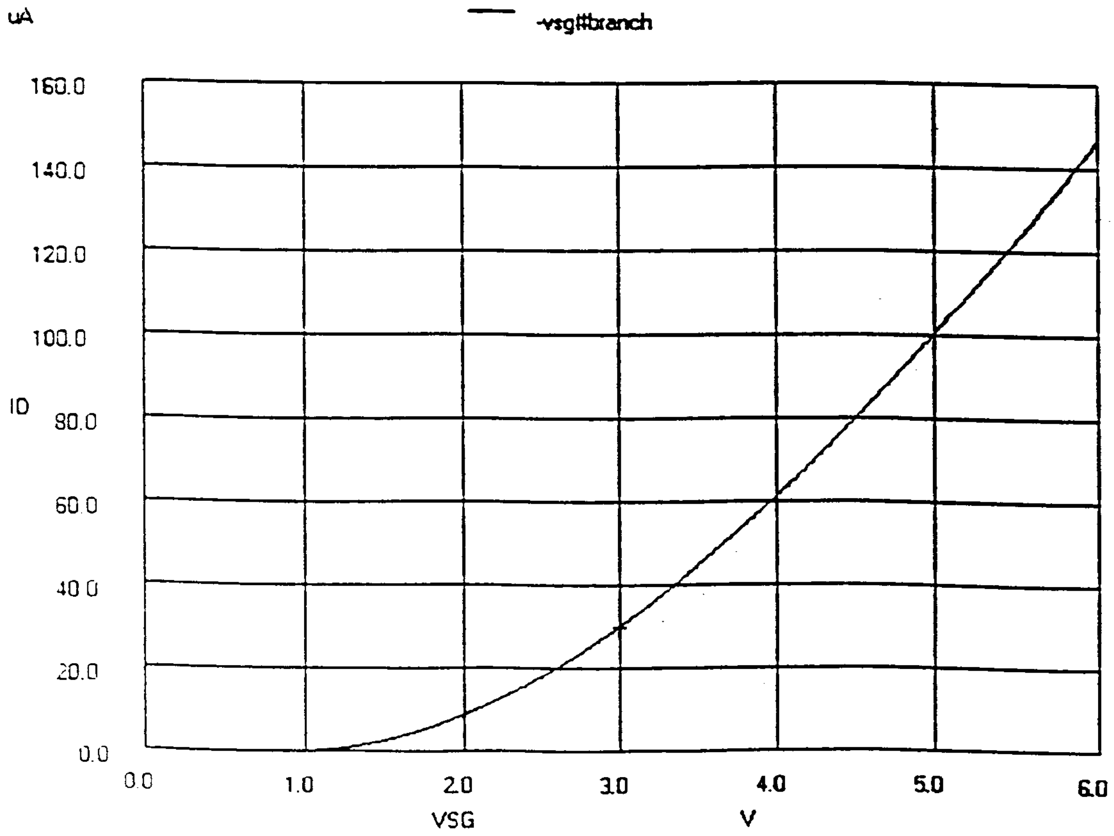
$$\approx 9.95K$$

$$i_d = \frac{V_{ds}}{R_{ch}} = \frac{100mV}{9.95K} \approx \underline{\underline{10.1\mu A}}$$

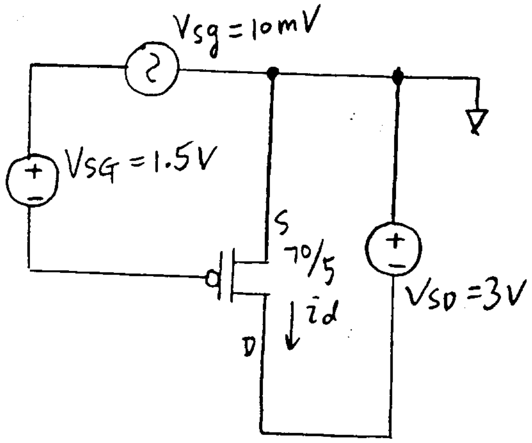
id = vds/r0 = 100mV/[(1/2.02) V/uA] = 202 nA.

Problem 9.7

The plot is shown below.



Problem 9.8



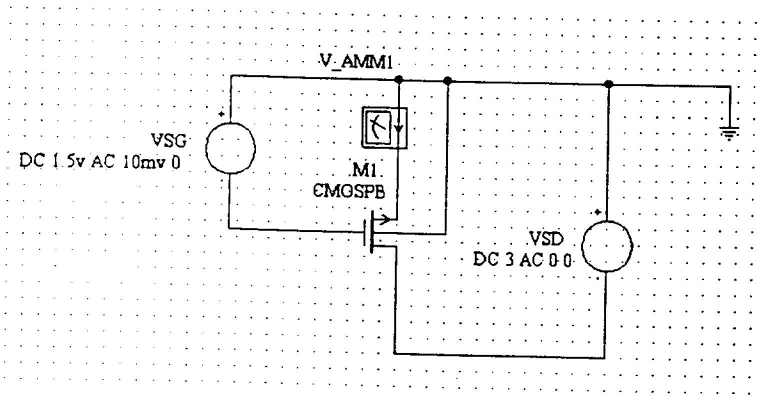
Since the source is common, its potential is irrelevant.

$$g_m = \beta(V_{SG} - V_{THP}) = KP_P \times \frac{W}{L} \times (V_{SG} - V_{THP}) = \frac{17\mu A}{V^2} \times \frac{70\mu m}{5\mu m} \times (1.5v - 0.91v$$

$$\approx 140.4\,\mu A/V$$

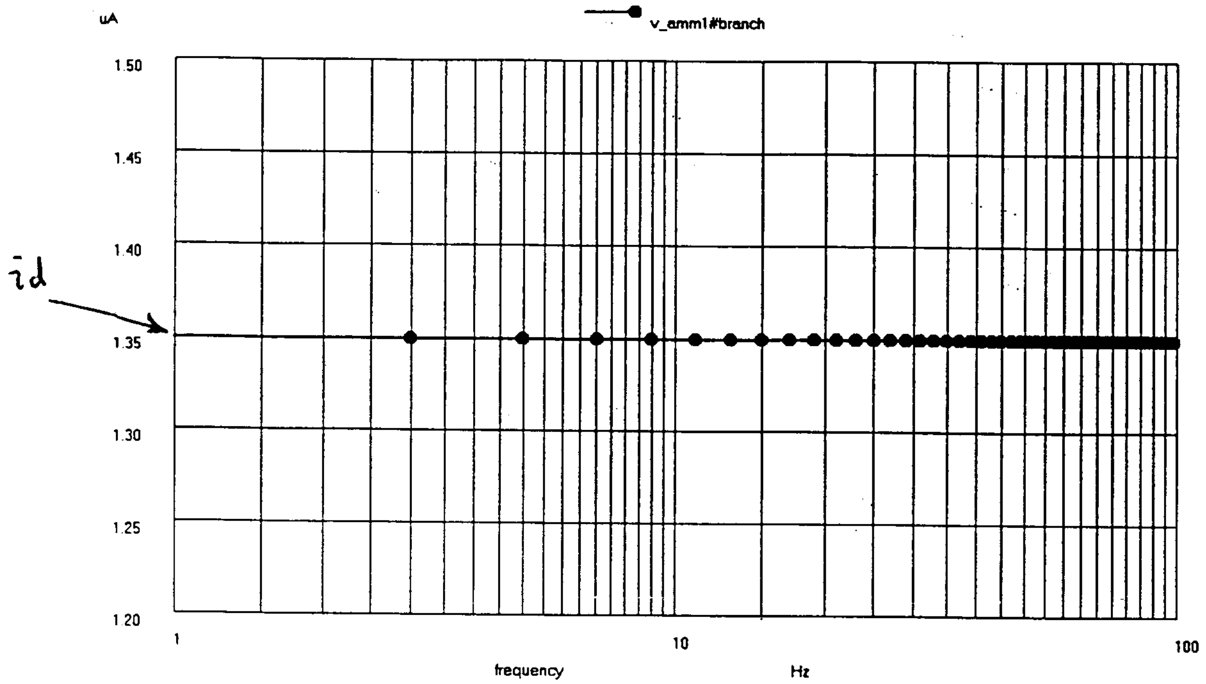
$$i_d = g_m v_{sg} = 140.4\mu A/V \times 0.01\,V \underline{\approx 1.4\,\mu A}$$

Problem 9.9

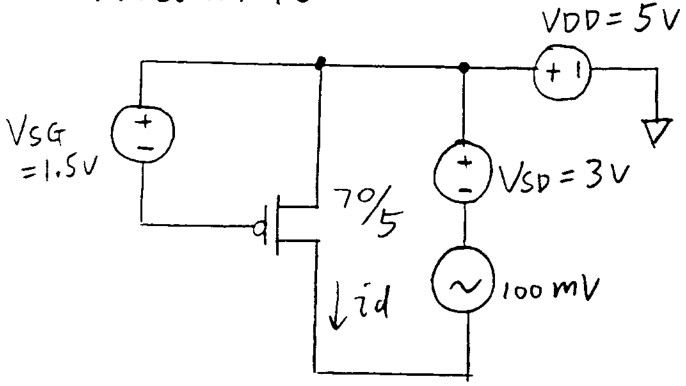


```
*** Top Level Netlist ***
M1        1 2 3 0 CMOSPB  L=5u W=70u
V_AMM1          0 3 0V
VSD       0 1     DC 3 AC 0 0
VSG       0 2     DC 1.5v AC 10mv 0

***** Spice models and macro models *****
.MODEL CMOSPB PMOS LEVEL=4
+ vfb=-2.65334E-01, lvfb=6.50066E-02, wvfb=1.48093E-01
... ...
+ pbsw=0.8,   mj=0.60438,   mjsw=0.244194,   wdf=0,   dell=0


***** End of spice models and macro models *****
.ac LIN 100 1 100
.end
```

The AC SPICE simulation result is shown below:



Problem9.10



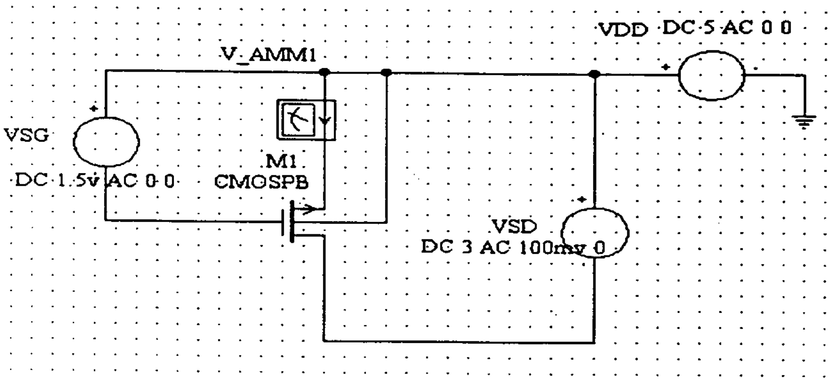
MOSFET operates in Saturation region.

$$I_D = \frac{17\mu A}{V^2} \times \frac{1}{2} \times \frac{70\mu m}{5\mu m} \times (1.5v - 0.91v)^2 \approx 41.4\mu A$$

$$r_o = \frac{1}{I_D \lambda} = \frac{1}{41.4\mu A \times 0.06 V^{-1}} = 0.402M = 402k\Omega$$

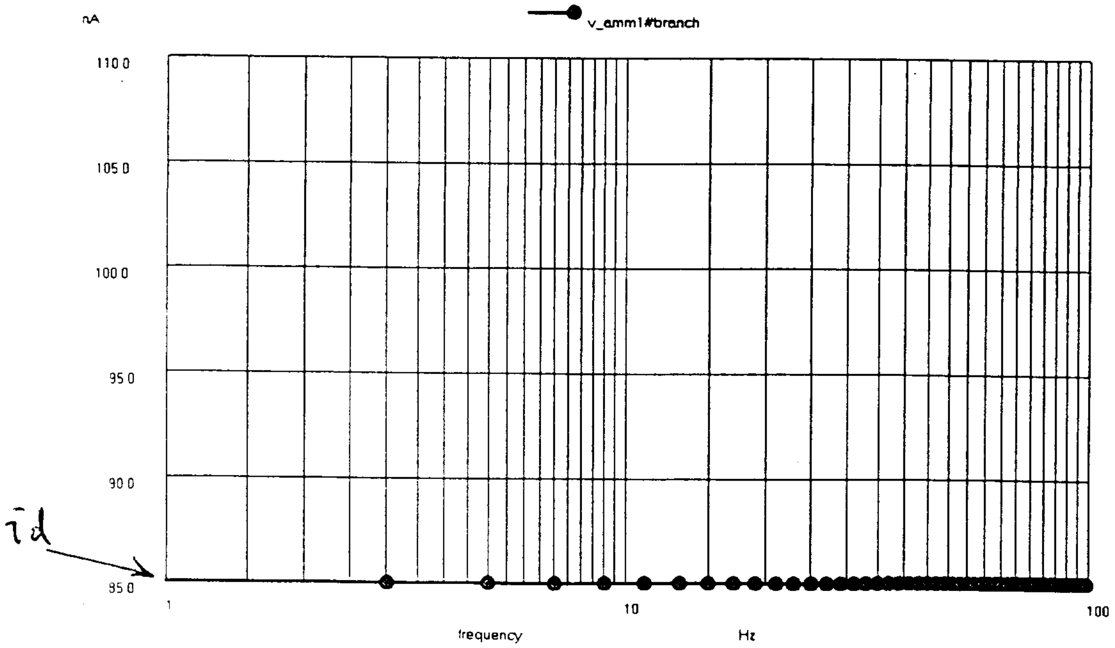
$$i_d = \frac{v_{sd}}{r_o} = \frac{100mV}{402k} \approx \underline{0.25\mu A}$$

Problem 9.10 (Cont.)



```
*** Top Level Netlist ***
M1       1 2 3 5 CMOSPB  L=5u W=70u
V_AMM1          5 3 0V
VDD      5 0    DC 5 AC 0 0
VSD      5 1    DC 3 AC 100mv 0
VSG      5 2    DC 1.5v AC 0 0

***** Spice models and macro models *****
.MODEL CMOSPB PMOS LEVEL=4
+ vfb=-2.65334E-01, lvfb=6.50066E-02, wvfb=1.48093E-01
... ...
+ pbsw=0.8,   mj=0.60438,   mjsw=0.244194,   wdf=0,   dell=0


***** End of spice models and macro models *****
.ac LIN 100 1 100
.end
```

The AC SPICE simulation result is shown below:

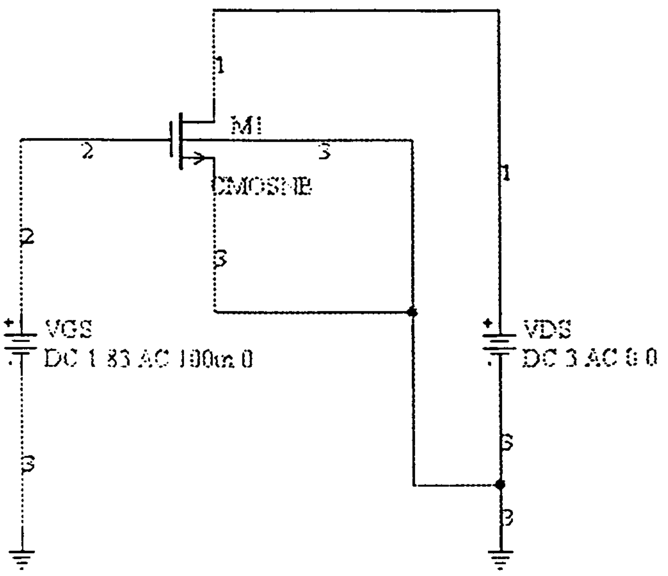


Problem 9.11

ANS: The size of the drain and source regions is 6umx14um. Assume VDB = VSB = 0.
Csb = Cdb = CJ*AD+CJSW*PD = 3.25x10 $^{-4}$ F/m^{2} x 6umx14um + 2.54x10 $^{-10}$ F/m x 2(14+6)um = 27.3 f + 10.16f = 37.46 fF.
Cgb = CGBO*L = 3.85x10 $^{-10}$ F/m * 10um = 3.85 fF.
In triode region: Cgs = Cgd = (1/2)Cox'WL = 0.5x(800aF/um^{2})x14umx10um = 56 fF.
In saturation region: Cgs = (2/3) Cox'WL = 74.67 fF. Cgd = CGDO*W = 5.03x10^{-10}F/m*14um = 7.04 fF.

Problem 9.12

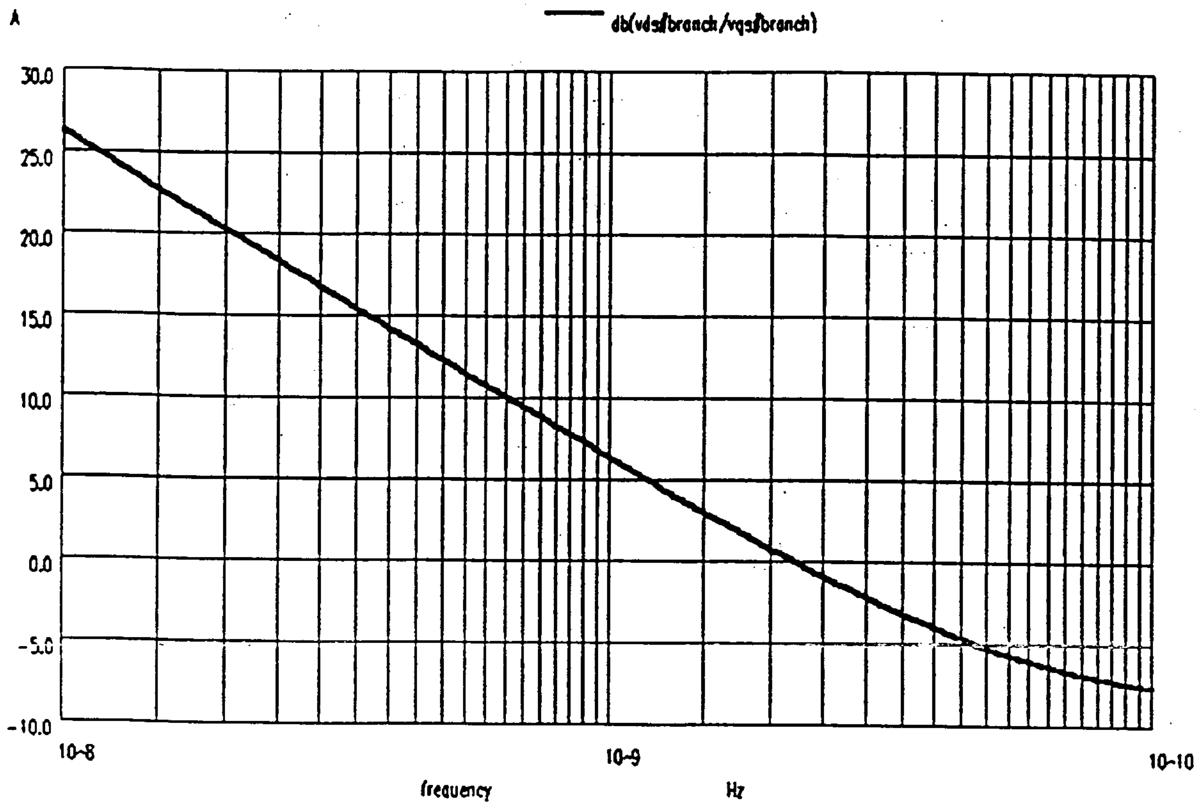
ANS: The circuit, netlist and plots are shown in the following figure and VGS = 1.83v. For n-channel, SPICE simulation gives f_T = 2.2ghz. Notice it is depend on the VGS value. At f_T |id/ig| =1 and at DC |id/ig| = ∞.



The netlist is as following:

```
*** (TurboSim V 1.1) Netlist for C:\TS\P912.CKT
*** Top Level Netlist ***
M1      1 2 0 0 CMOSNB  L=2u W=3u
VDS     1 0     DC 3 AC 0 0
VGS     2 0     DC 1.83 AC 100m 0
***** Spice models and macro models *****
.MODEL CMOSNB NMOS LEVEL=4
**BSIM Model Parameters**
***** End of spice models and macro models *****
.ac DEC 50 100MEGhz 100ghz
.end
```

N-channel SPICE simulation plot:



Problem 9.13

The unity current gain frequency, f_T, of a MOSFET, is given by

$$f_T = \frac{k_p \times W(V_{GS} - V_{THN})}{2\pi \times L \times (C_{gb} + C_{gs} + C_{gd})}$$

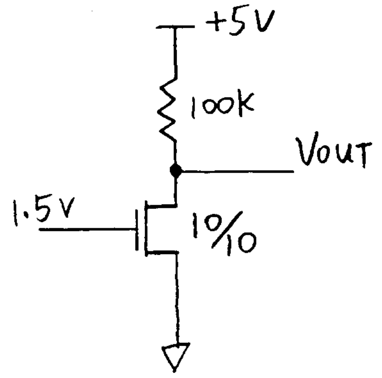
If $V_{GS} - V_{THN}$ is very small, the speed of the circuit will be low.

Problem 9.14

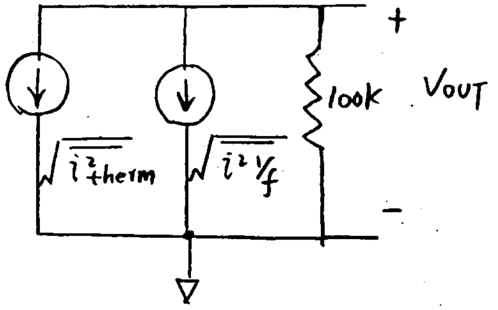
ANS: a) With VGS around Vthn, as we can see from figure 9.10, that Vthn decreases with increasing temperature. With VGS >>Vthn, as we can from figure 9.11, that Vthn will increase as the temperature goes up.

b) For the case Vthn around a few hundred millivolts, if the temperature goes up, since Vthn will decrease, the MOSFET designed to be cutoff may turn on because Vthn decreases and the MOSFET designed to be in saturation VDS>VGS-Vthn may get into the triode region as VDS<VGS-Vthn as Vthn decrease. In addition, if we design to let MOSFETs operating in subthreshold region for low power consideration, since the drain current is exponentially related to the VGS-Vthn, any changes in Vthn can cause significant changes in the drain current and mismatch problems.

Problem 9.16



$\Longrightarrow$



$$I_D = \frac{k'_{pN}}{2}\frac{W}{L}(V_{GS}-V_{THN})^2 = \frac{50\mu A/V^2}{2} \times \frac{10\mu m}{10\mu m} \times (1.5v-0.83v)^2 \approx 11.2\ \mu A$$

$$\left\{\begin{aligned} \sqrt{\overline{i^2_{therm}}} &= \sqrt{6kT\sqrt{2\beta \cdot I_D}} = \sqrt{6\times1.38\times10^{-23}\times300\times\sqrt{2\times50\mu A/V^2\times\frac{10}{10}\times11.2\mu A}} \\ &\approx 0.91\ pA/\sqrt{Hz} \\ \sqrt{\overline{v^2_{therm}}} &= 0.91pA/\sqrt{Hz} \times 100k = 91\ nV/\sqrt{Hz} \end{aligned}\right.$$

$$\left\{\begin{aligned} \sqrt{\overline{i^2_{1/f}}} &= \sqrt{\frac{KF \cdot I_D^{AF}}{f \cdot C'_{ox} \cdot L^2}} = \sqrt{\frac{10^{-25}\times(11.2\times10^{-6}A)^{1.3}}{f\times800\,aF/\mu m^2\times(10\mu m)^2\times10^{-18}}} \\ &\approx 0.677\ nA/\sqrt{f} \\ \sqrt{\overline{v^2_{1/f}}} &= 0.677\,nA/\sqrt{f} \times 100\,k = 67.7\mu V/\sqrt{f} \end{aligned}\right.$$

$$\left\{\begin{aligned} \sqrt{\overline{i^2_{100k}}} &= \sqrt{\frac{4kT}{R}} = \sqrt{\frac{4\times1.38\times10^{-23}\times300}{100\times10^3}} = 0.41\ pA/\sqrt{Hz} \\ \sqrt{\overline{v^2_{100k}}} &= 0.41pA/\sqrt{Hz} \times 100\,K = 41\,nV/\sqrt{Hz} \end{aligned}\right.$$

Problem 9.16 (cont.)

$$\overline{v_{ON}^2} = \int_1^{1000} \left[(91\times10^{-9})^2 + (41\times10^{-9})^2 + (67.7\times10^{-6})^2 \cdot \frac{1}{f} \right] df$$

$$\approx 3.2\times10^{-8}\ V^2$$

$$\therefore \sqrt{\overline{v_{ON}^2}} = 1.79\times10^{-4}\,V = \underline{\underline{179\,\mu V}}$$