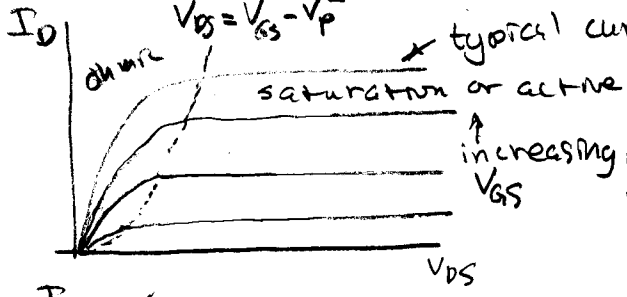
FET summary – stress the active region.

Notes on FETs
12/01/04

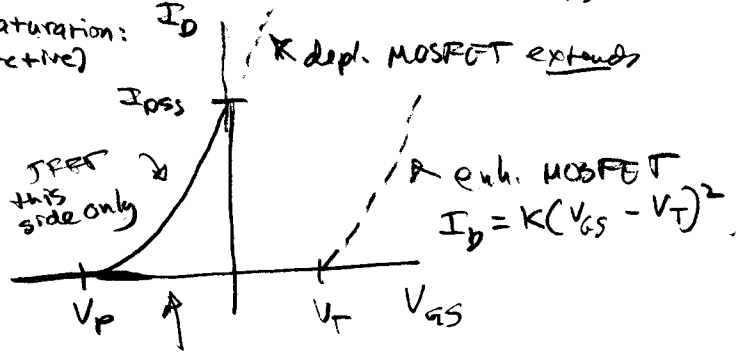
n-channel or p-channel (n-channel shown)
JFET or MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)
↳ depletion or enhancement

$I_G \approx 0$
$I_D = I_S$

$V_{DS} = V_{GS} - V_P$ ← or $V_{DS} = V_{GS} - V_T$ for enhancement mode

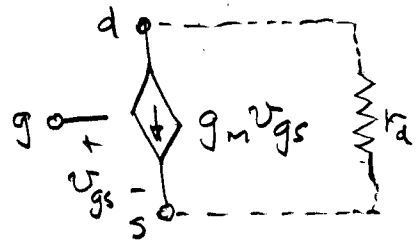


Saturation: (I_D (Active))



$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

small sig. AC model:

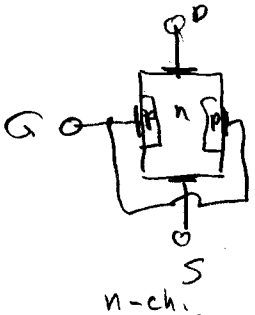


$$g_m = \left.\frac{dI_D}{dV_{GS}}\right|_Q = -\frac{2}{V_P}\sqrt{I_D I_{DSS}}$$

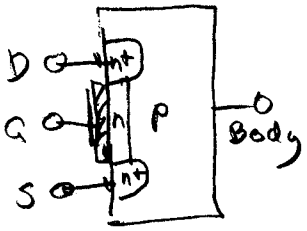
$$\left(= 2K(V_{GS} - V_T)\right)_{\text{ENH. MOSFET}}$$

May add r_d in parallel

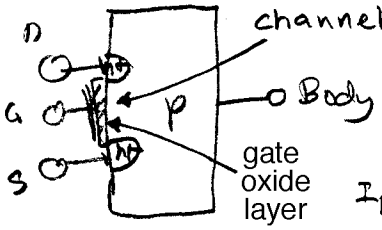
$$r_d = \left.\frac{dV_{DS}}{dI_D}\right|_Q \approx \begin{cases} 100\,\text{K}\Omega\ (\text{JFET}) \\ 10\,\text{K}\Omega\ (\text{MOS}) \end{cases}$$



n-ch. JFET

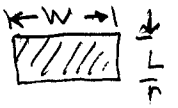


n-ch. depl. MOSFET



n-ch. enh. MOSFET

ENH. MOSFET GATE TOP View

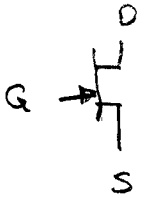


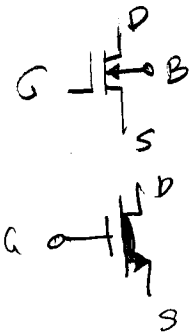
$$I_D = \frac{W \mu_n C_{ox}}{2L}(V_{GS} - V_T)^2$$

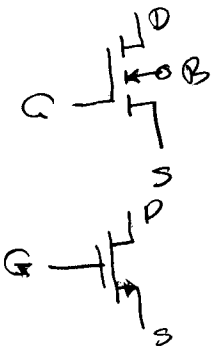
$C_{ox} = C/A$ of oxide layer $= \frac{\epsilon_{ox}}{t_{ox}}$

t_{ox} = oxide layer thickness

μ_n = e^- mobility







(body connected to source)

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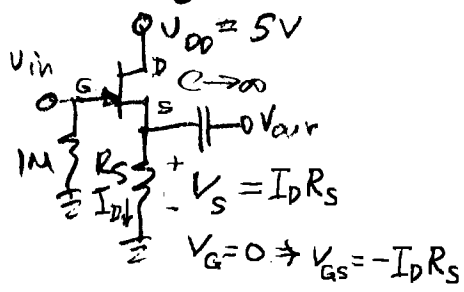
* extra material. Enhancement MOSFET:
possible numbers: $t_{ox} = 55\,\text{nm}$, $\epsilon_{ox} = 3.9 \times 8.85 \times 10^{-12}\ \text{F/m}$
$L \approx 1\,\mu\text{m}$, $W \approx 12\,\mu\text{m}$, $\mu_n = 0.13\ \text{m}^2\text{V}^{-1}\text{s}^{-1}$

Ref.: Neamen, Semiconductor Physics and Devices, p. 495 (McGraw-Hill, 2003)

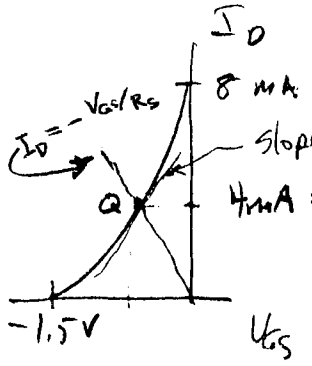
SOURCE FOLLOWER

CIRCUIT

(Bias set by R_S)



JFET CURVE



$\{ V_p = -1.$
$I_{DSS} = 8$

$I_{DQ} = 4$ mA

Find V_{GS_Q} and V_{DS_Q}, verify active region, find R_S

OPERATING POINT

$$I_D = I_{DSS}(1 - V_{GS}/V_p)^2$$

$$I_{DQ} = I_{DSS}(1 - V_{GS_Q}/V_p)^2 = 4\,mA$$

$$(1 - V_{GS_Q}/V_p) = \pm\sqrt{\frac{4\,mA}{I_{DSS}}} = \pm\sqrt{\frac{4\,mA}{8\,mA}} = \pm\sqrt{\frac{1}{2}}$$

$$\frac{V_{GS_Q}}{V_p} = 1 - \sqrt{\frac{1}{2}} = 1 - \frac{1}{\sqrt{2}} \quad \text{(other root} < V_p\text{)}$$

$$V_{GS_Q} = (1 - 0.707)V_p = 0.29 \times -1.5V = -0.44V.$$

Since $V_{G_Q} = 0$, $V_{S_Q} = -V_{GS_Q} = +0.44\,V.$

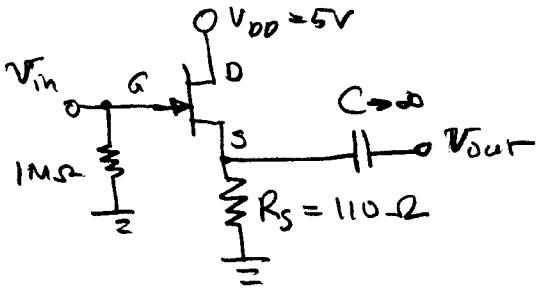
$$V_{DS_Q} = V_D - V_{S_Q} = 5V - 0.44V = 4.56\,V.$$

$4.56 = V_{DS_Q} \overset{?}{>} V_{GS} - V_p = -0.44 + 1.5 = 1.06\,V$

Active - Ok

$$R_S = -\frac{V_{GS_Q}}{I_{D_Q}} = \frac{0.44V}{4\,mA} = 110\,\Omega$$

Source follower voltage gain

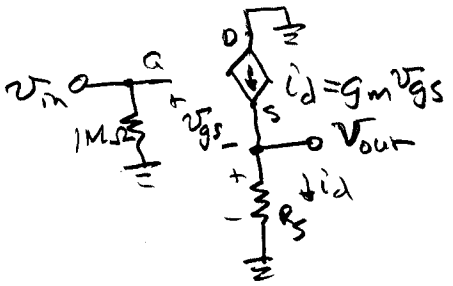


For JFET $V_p = -1.5V$

$I_{DSS} = 8mA$

$I_{DQ} = 4mA$

S.S. AC circuit: (ignore r_d)



$$g_m = -\frac{2}{V_p}\sqrt{I_{DQ} I_{DSS}}$$

$$= -\frac{2}{-1.5V}\sqrt{4mA \times 8mA}$$

$$= 7.5\,mS$$

$$A_V = \frac{v_{out}}{v_{in}}$$

$$v_{out} = i_d R_S$$

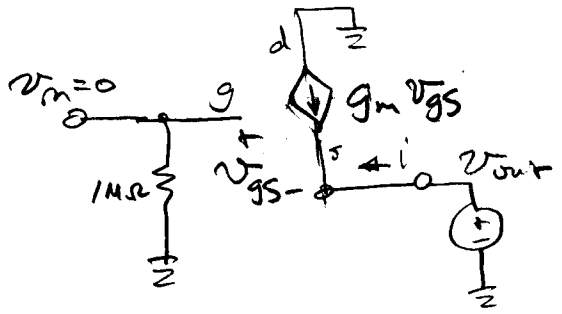
$$v_{in} = v_{gs} + v_{out} = v_{gs} + i_d R_S$$

$$A_V = \frac{i_d R_S}{v_{gs} + i_d R_S} = \frac{R_S}{\frac{v_{gs}}{i_d} + R_S} = \frac{R_S}{\frac{1}{g_m} + R_S} = \frac{110\Omega}{133\Omega + 110\Omega}$$

$$= 0.45$$

Can be improved using a current source in place of R_S, as was done in lab.

Output impedance: $v_{in} = 0$. Apply source at v_{out}



Find:

R_{eff} = Effective resistance looking into source.

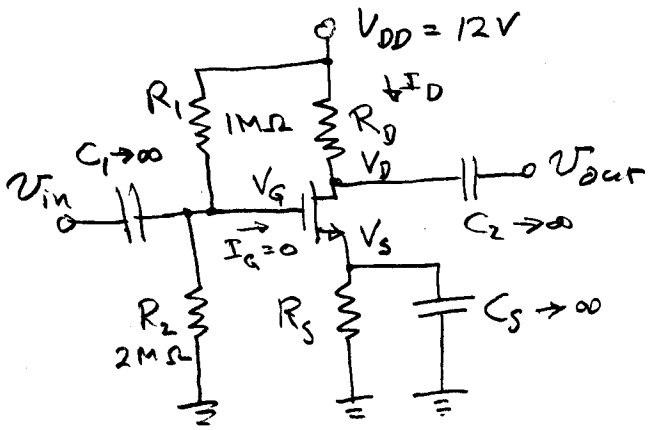
$$= \frac{v_{out}}{i} \qquad \text{but} \begin{cases} i = -g_m v_{gs} \\ v_{out} = -v_{gs} \end{cases}$$

$$= \frac{-v_{gs}}{-g_m v_{gs}} = \frac{1}{g_m}$$

$R_{out} = R_{eff} \| R_s = 133\Omega \| 110\Omega = \underline{\underline{60\Omega}}$.

Enhancement-mode MOSFET bias & common source amplifier

Based on Example 9.6 in text (p. 596)



{ enh. mode
n-channel MOSFET
$K = 0.25\ mA/V^2$
$V_T = 2V$

Q-point:
$I_{DQ} = 4\ mA$
$V_{DS_Q} = 6V$

R_1 & R_2 are given - as shown. Find R_S, R_D, verify "active" region operation.

$I_S = I_D$ (since $I_G = 0$)

$$V_{DS_Q} = V_{DD} - I_{D_Q}(R_D + R_S)$$
$$6V = 12V - 4mA(R_D + R_S)$$
$$(R_D + R_S) = \frac{6V}{4mA} = 1500\,\Omega \qquad (1)$$

Find V_{GS_Q}: $I_{DQ} = K(V_{GS_Q} - V_T)^2$

$$4mA = 0.25\,mA/V^2\,(V_{GS_Q} - 2V)^2$$
$$V_{GS_Q} - 2V = \pm 4V \Rightarrow V_{GS_Q} = \underline{6V} \quad (+ \text{ chosen, } - \text{ below } V_T)$$

Find V_{S_Q}: $V_G = V_{DD}\frac{R_2}{R_1 + R_2} = 12V \cdot \frac{2}{3} = \underline{8V}$

$$V_{GS_Q} \equiv V_{G_Q} - V_S \Rightarrow V_S = V_G - V_{GS_Q} = 8V - 6V = \underline{2V}$$

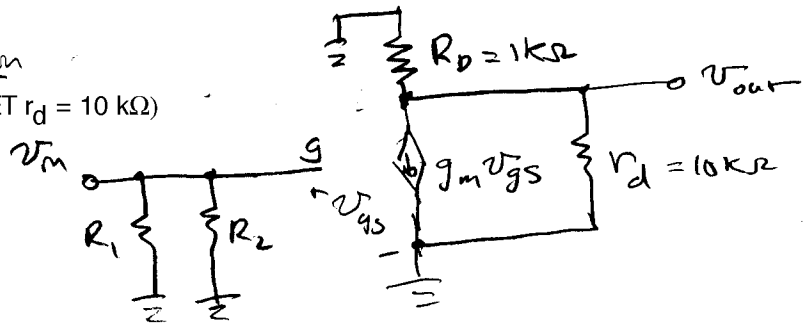
Find R_S, R_D: (use eqn. (1) above)

$$R_S = \frac{V_{S_Q}}{I_{D_Q}} = \frac{2V}{4mA} = \underline{500\,\Omega}, \quad R_D = 1500 - R_S = \underline{1000\,\Omega}$$

Active? $V_{DS_Q} \overset{?}{\geq} V_{GS_Q} - V_T$ $\quad 6V \overset{?}{\geq} 6V - 2V = 4V$ $\quad \underline{OK}$.

Find G_{vm}

(Assume MOSFET r_d = 10 kΩ)



$$v_m = v_{gs}$$

$$v_{out} = -g_m v_{gs} (r_d \| R_D)$$

$$A_v = -g_m (r_d \| R_D)$$

$$g_m = 2K (V_{GSQ} - V_T) = 2 \times 0.25\,mA/V^2 (6V - 2V)$$

$$= 2\,mS$$

$$A_v = -2\,mS \times 0.909\,k\Omega = -1.8$$