

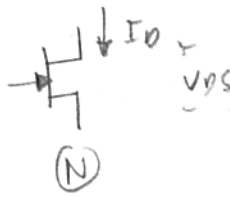
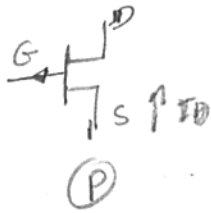
FET / MOSFET

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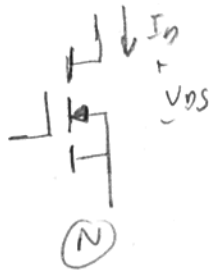
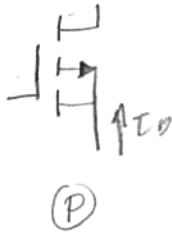
(1)

SYMBOLS

JFET



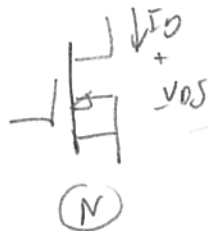
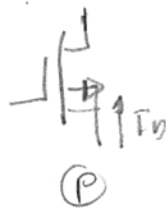
MOSFET
ENHANCEMENT



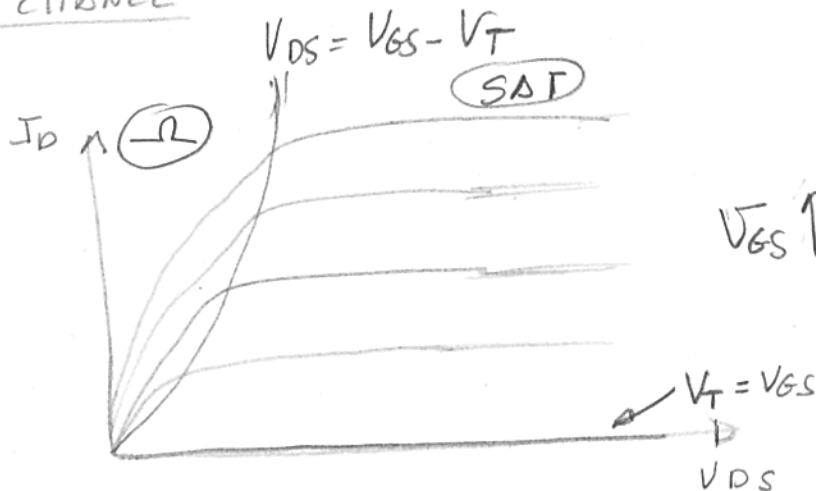
ALSO :



MOSFET
DEPLETION



N CHANNEL



$V_{GS} \uparrow$ (+)

$I_G \approx 0$

HIGH GATE
IMPEDANCE

SAT

$$I_D = \frac{K}{2} (V_{GS} - V_T)^2$$

(-2)

$$I_D = \frac{K}{2} (2(V_{GS} - V_T)V_{DS} - V_{DS}^2)$$

PROPORTIONAL!
 $K \propto \left(\frac{W}{L}\right)$
ALWAYS!

- JFET N CHANNEL

$$V_T < 0 (\approx -3, -4 \text{ Volt})$$

$$V_{GS}|_{\max} = 0 \text{ Volt}$$

- MOSFET N CHANNEL ENHANCEMENT

$$V_T > 0 (\approx 3, 4 \text{ Volt})$$

- MOSFET N CHANNEL DEPLETION

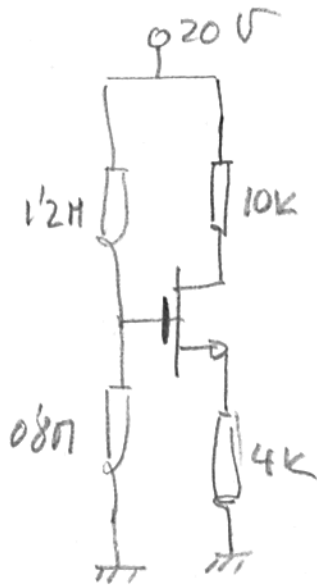
$$V_T < 0 (\approx -3, -4 \text{ Volt})$$

- USUALLY:

SWITCH
OPERATION $\begin{matrix} \nearrow & \text{OFF ZONE} \\ \searrow & \Omega \text{ ZONE} \end{matrix}$

AMPLIFIER $\rightarrow$ SATURATION ZONE
LINEAR
OPERATION

Ex 1



Q point?

MOIFET (ENHANCEMENT)

$$V_T = 2 \text{ Volt}$$

$$K = 0.5 \text{ mA/V}^2$$

• SATURATION IS ASSUMED :

$$V_G = \frac{20}{1.2 + 0.8} \cdot 0.8 = 8 \text{ V}$$

$$V_{GS} = 8 - I_D \cdot 4$$

$$I_D = \frac{0.5}{2} (V_{GS} - 2)^2$$

$$20 - 4 I_D - V_{DS} = 0$$

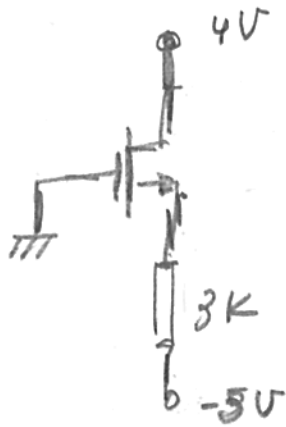
$$I_D = 1$$

$$V_{DS} = 6$$

$$V_{GS} = 4$$

Check : $V_{DS} > V_{GS} - V_T \Rightarrow$ SATURATION IS

EXPECTED

EX 2Q point ?

MOSFET (DEPLETION)

$V_T = -2$

$K = 4 \text{ mA/V}^2$

$$\bullet V_{GS} = +5 - 3 \cdot I_D$$

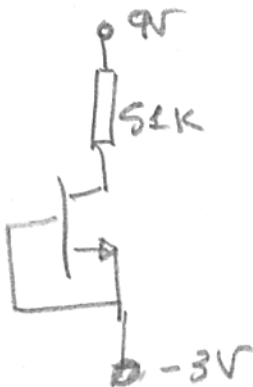
$$\bullet I_D = \frac{4}{2} (V_{GS} + 2)^2$$

$$\bullet 4 - V_{DS} - I_D \cdot 3 + 5 = 0$$

$I_D = 2$

$V_{DS} = 3$

$V_{GS} = -1$

EX 3Q point ?

MOSFET (DEPLETION)

$V_T = -3$

$K = 22 \cdot 10^{-6}$

$$\bullet V_{GS} = 0$$

$$\bullet 9 - 5 I_D - V_{DS} + 3 = 0$$

$$\bullet I_D = \frac{22 \cdot 10^{-6}}{2} (0 + 3)^2$$

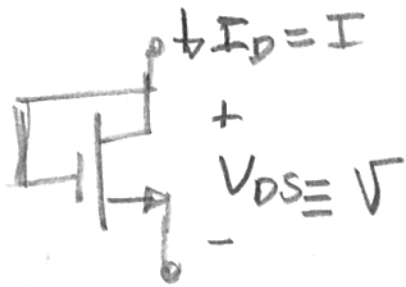
$I_D = 99 \mu\text{A}$

$V_{DS} = 6.95 \text{ Volt}$

• MOSFET Resistor

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: If $V_T > 0$ (enhancement)
Resistor like device

$$\textcircled{1} \quad I_D = \underbrace{I_{DSS}}_{\left(\frac{K}{2}\right)} (V_{GS} - V_T)^2 \quad (\text{MOS SATURATED})$$

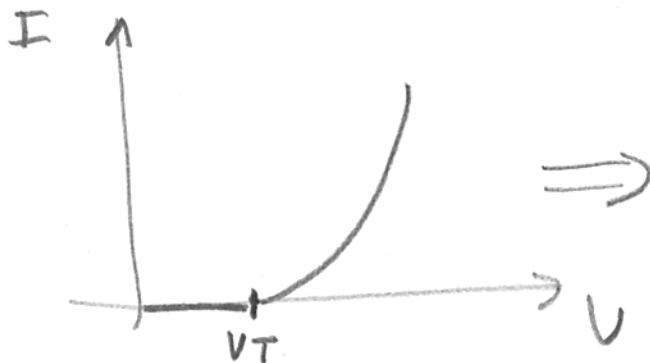
[The device is saturated since

$V_{DS} = V_{GS}$, hence

$$V_{DS} > V_{GS} - V_T \Rightarrow (0 > -V_T)!!!$$

$\uparrow = \uparrow$

So:



$\Rightarrow$ NON LINEAR
(V-I) RESISTOR TYPE
RELATIONSHIP!

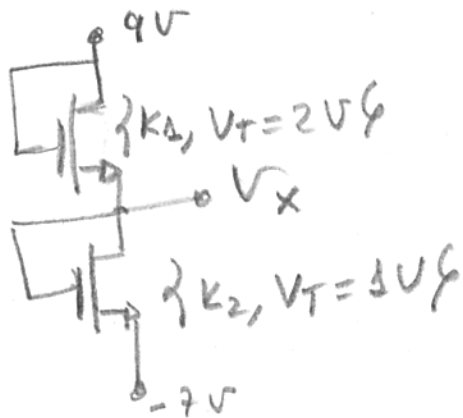
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CMOS VOLTAGE DIVIDER

⑥

It's more suitable to integrate MOSFET than resistors.

EX

• Find $\frac{K_1}{K_2}$ so that ① $V_x = -3V$ and ② $P_{DISIP} = 200\mu W$

• Both MOS behave as resistors

$$\textcircled{1} \cdot I_D = \frac{K_1}{2} \left(\underbrace{9 - (-3) - 2}_{V_{GS} = V_{DS}} \right)^2 = \frac{K_2}{2} \left((-3 - (-7)) - 1 \right)^2 \Rightarrow$$

$$\cdot I_D = K_1 \cdot 50 = K_2 \cdot 45$$

$$\textcircled{2} \quad \underbrace{I_D \cdot (9 - (-3))}_{P_{MOS1}} + \underbrace{I_D \cdot (-3 - (-7))}_{P_{MOS2}} = 200\mu W$$

hence:

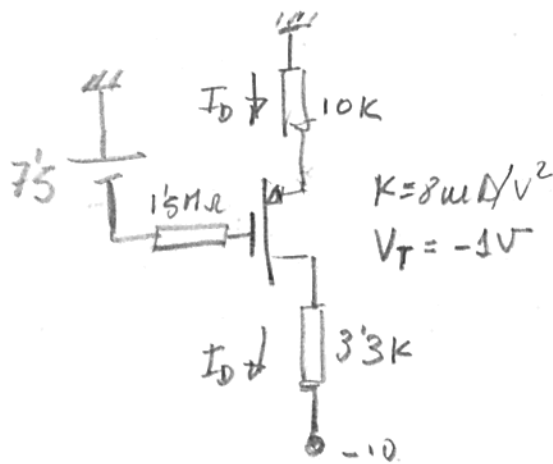
$$I_D = 12.5\mu A$$

$$K_1 = 0.25\mu A/V^2$$

$$K_2 = 2.78\mu A/V^2$$

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P CHANNEL MOSFET



Q point?

$$\begin{aligned} \bullet I_D &= \frac{8}{2} (V_{SG} + V_T)^2 \\ \bullet V_{SG} &= -10 \cdot I_D + 7.5 \end{aligned} \quad \Rightarrow \quad \begin{aligned} V_{SG} &= 1.39 \text{ V} \\ I_D &= 0.651 \text{ mA} \end{aligned}$$

$$\text{So: } -10 I_D - V_{SD} - 3.3 I_D + 10 = 0 \Rightarrow$$

$$V_{SD} = -13.3 I_D + 10 = 1.87 \text{ V}$$

NOTICE

N CHANNEL (SAT)

$$I_D = \frac{K}{2} (V_{GS} - V_T)^2$$

P CHANNEL (SAT)

$$I_D = \frac{K}{2} (V_{SG} + V_T)^2$$

SIMILAR BEHAVIOUR IF:

N CHANNEL $V_T > 0$

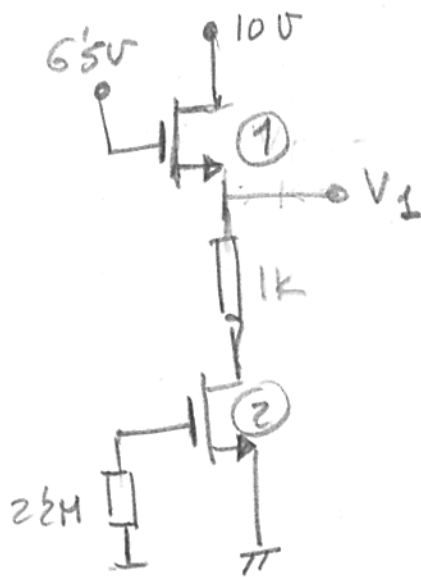
$\Leftrightarrow$

P CHANNEL $V_T < 0$

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Ex



MOSFET

 $V_T = -3V \rightarrow$ depletion $K = 0.444$ FIND Q?

① ($V_{DS} > V_{GS} - V_T$ if saturation)

$\Rightarrow V_{DG} > -V_T$ if saturation.

Since $V_{DG} = 10 - 6.5 = 3.5V \Rightarrow 3.5 > -(-3) \Rightarrow$

① is saturated

$$\bullet I_D = \frac{0.444}{2} (0 + 3)^2 \text{ (MOS ②)} \Rightarrow I_D = 1.998 \mu A$$

$$\bullet 1.998 = \frac{0.444}{2} (V_{GS} + 3)^2 \text{ (MOS ①)} \Rightarrow V_{GS①} = 0 \Rightarrow$$

$$V_1 = 6.5V \Rightarrow V_{D2} = 6.5 - 1.1998 = 4.502 = V_{DS②}$$

$$\bullet V_{DS①} = 10 - V_1 = 10 - 6.5 = 3.5 \text{ Volt}$$

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Small signal model

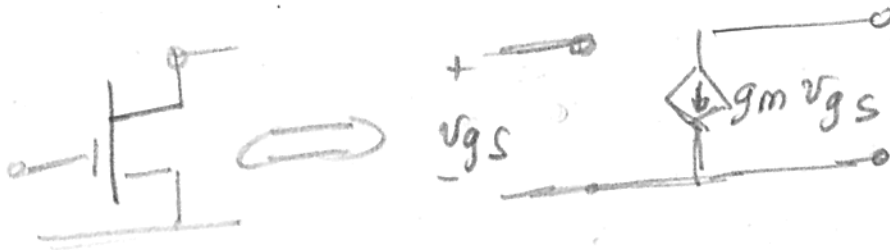
In the saturation zone:

$$I_D = \frac{K}{2} (V_{GS} - V_T)^2 \Rightarrow$$

$$i_d = \frac{K}{2} 2(V_{GS} - V_T) \cdot v_g = K (V_{GS} - V_T) v_g =$$

$$i_d = g_m v_g$$

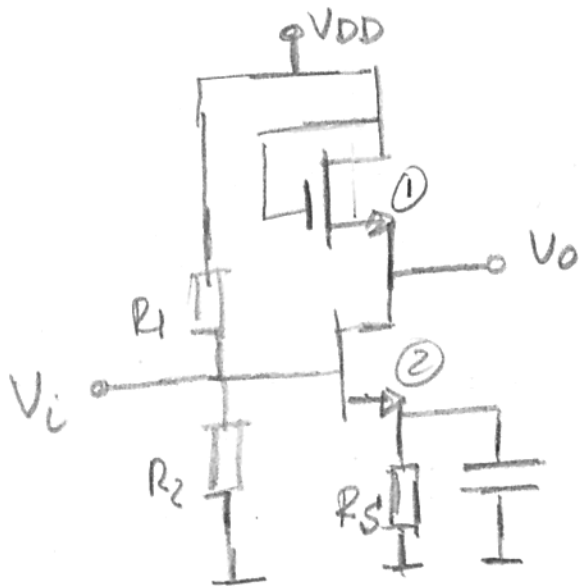
$$g_m = K(V_{GS} - V_T) Q \quad g_m = \sqrt{2KI_D} Q$$

So

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MOS AMPLIFIER WITH ACTIVE LOAD

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- MOS ① behaves as a resistor

$$\boxed{\begin{array}{l} \text{MOS} \\ V_T > 0 \text{ (enhancement)} \end{array}}$$

$$g_{m1} = \sqrt{2k I_{DQ}} = g_{m2}$$

FROM SMALL SIGNAL MODELS

- Let's find the resistance of MOS ① (small signal)



$$V_{DS} = V_{GS} \Rightarrow V_{DS} > V_{GS} - V_T \Rightarrow \text{SATUR}$$

$$\Rightarrow I_D = \frac{k}{2} (V_{DS} - V_T)^2 \Rightarrow$$

$$I_D = \frac{k}{2} (V_{DS|Q} - V_T) \cdot V_{DS} \Rightarrow$$

$$\frac{V_{DS}}{I_D} = r_{\text{small signal}} = \frac{1}{\sqrt{2k I_{D|Q}}} = \frac{1}{g_{m1}}$$

Then :

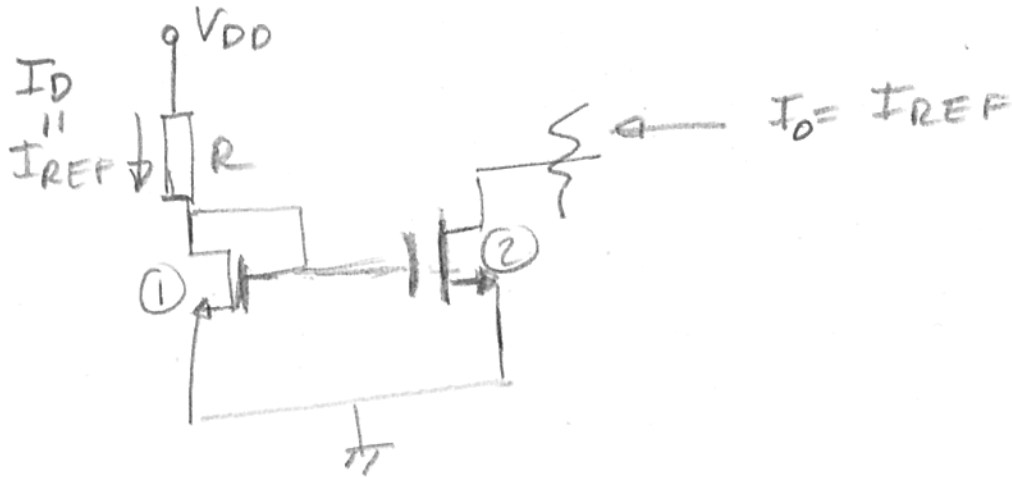
$$V_i \rightarrow \left[R_1 // R_2 \right] \rightarrow \left[g_{m2} V_i \right] \rightarrow \left[\frac{1}{g_{m1}} \right] \Rightarrow V_o = -V_i \cdot \frac{g_{m2}}{g_{m1}}$$

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BASIC CURRENT MIRROR

(CURRENT SOURCE)



$$\text{MOS ①: } \begin{cases} V_{GS} = V_{DS} \Rightarrow I_D = \frac{K_1}{2} (V_{DS} - V_T)^2 \\ V_{DD} - I_D \cdot R - V_{DS} = 0 \end{cases} \Rightarrow$$

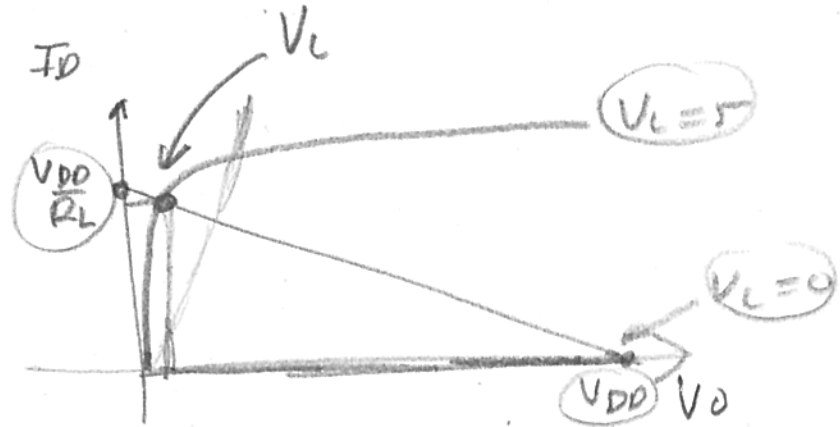
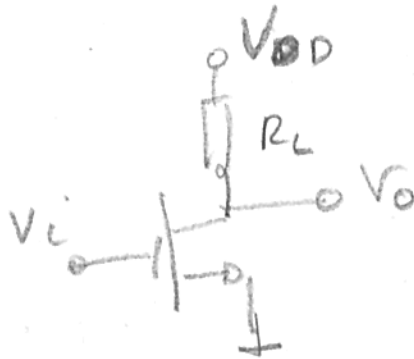
$$\{ I_D, V_{DS} = V_{GS} \}$$

Hence $I_O = \frac{K_2}{2} (V_{GS①} - V_T)^2$ if saturated

Then I_O is referenced $\left(\frac{K_2}{K_1}\right)$ to I_{REF}

MOSFET AS A SWITCH

BASIC CIRCUIT



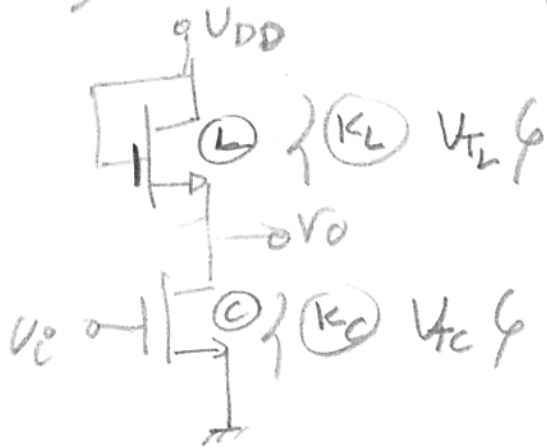
$$V_i = (5V/0V)$$

$$\text{LOAD LINE: } V_{DD} - I_D R_L - V_o = 0$$

As it can be seen:

$$\left. \begin{array}{l} V_i = 5V \Rightarrow V_o \downarrow \downarrow \\ V_i = 0V \Rightarrow V_o = V_{DD} \end{array} \right\} \Rightarrow \text{SWITCHING!}$$

② R_L may be replaced by a MOS LOAD



• L MOS : SATURATION ($V_{DS} = V_{GS} \Rightarrow V_{DS} > V_{GS} - V_T$)

$$I_D = \frac{K_L}{2} (V_{DD} - V_O - V_{TL})^2 \quad (\text{SATURATED})$$

• C MOS

