EEC 332 - Analog Integrated Circuits

Lecture 4
MOSFET Circuits at DC

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1 The p-Channel MOSFET

To induce a channel for current flow between source and drain, a negative voltage is applied to the gate.

By increasing the magnitude of the negative v_{GS} beyond the magnitude of the threshold voltage V_{tp}, which by convention is negative, a p channel is established , the condition can be described as

$$v_{GS} \leq V_{tp} \tag{1}$$

therefore, v_{OV} can be calculated by

$$v_{OV} \equiv v_{GS} - V_{tp} \tag{2}$$

Saturation mode occurs when

$$v_{DS} \leq v_{OV} \tag{3}$$

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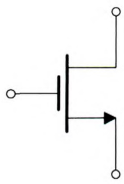
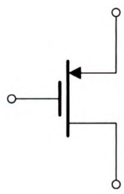
1. Q Compare between n-channel MOSFET and p-channel MOSFET

1. A

	n-channel MOSFET	p-channel MOSFET
Symbol		
polarity of V_t	$V_{tn} \rightarrow$ positive	$V_{tp} \rightarrow$ negative
v_{OV}	$\underbrace{v_{OV}}_{+\text{ve}} \equiv \underbrace{v_{GS}}_{+\text{ve}} - \underbrace{V_{tp}}_{+\text{ve}}$	$\underbrace{v_{OV}}_{-\text{ve}} \equiv \underbrace{v_{GS}}_{-\text{ve}} - \underbrace{V_{tp}}_{-\text{ve}}$
In Saturation	$v_{DS} \geq v_{OV}$	$v_{DS} \leq v_{OV}$

2 MOSFET Circuits at DC

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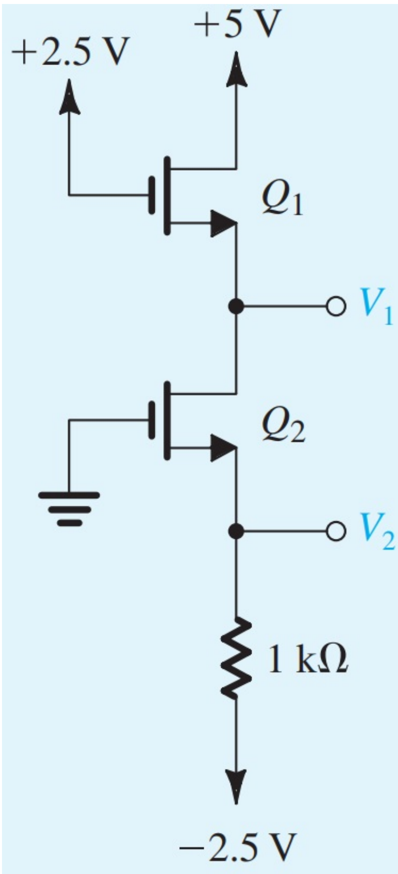
2. Q for the following circuit , find the labeled node voltages. The NMOS transistors have V_t = 0.9 V and $k_n'(W/L) = 1.5$ mA/V^2.



2. A

For Q_2 transistor

$$i_{D2} = \frac{V_2 - (-2.5)}{1000}$$
$$= V_2 + 2.5 \text{ mA} \tag{1}$$

The gate source voltage V_{GS} is $V_G - V_S$ and hence V_{GS} is equal to $(2.5 - V_1)$

The drain current for NMOS Q_1 transistor is.

$$i_{D1} = \frac{1}{2} k_n{}' \left(\frac{W}{L}\right) (v_{GS} - V_t)^2$$
$$= \frac{1}{2} \left(1.5 \times 10^{-3} \frac{\text{A}}{\text{V}^2}\right) [(2.5 - V_1) - 0.9]^2$$
$$= 0.75\,(1.6 - V_1)^2$$

Similarly, The drain current for NMOS Q_2 transistor is.

$$
\begin{aligned}
i_{D2} &= \frac{1}{2}k_n'\left(\frac{W}{L}\right)(v_{\sigma s} - V_t)^2 \\
&= \frac{1}{2}\left(1.5\times 10^{-3}\frac{\mathrm{A}}{\mathrm{V}^2}\right)[(0 - V_2) - 0.9]^2 \\
&= 0.75\,(-0.9 - V_2)^2 \qquad (2)
\end{aligned}
$$

$\because$ Q_1 and Q_2 are in series

$$
\begin{aligned}
\therefore\, i_{D1} &= i_{D2} \\
0.75\,(-0.9 - V_2)^2 &= 0.75\,(1.6 - V_1)^2 \\
-0.9 - V_2 &= 1.6 - V_1 \\
V_1 - V_2 &= 2.5\ \mathrm{V}
\end{aligned}
$$

Equate (1) with (2) :

$$
\begin{aligned}
&0.75\,(-0.9 - V_2)^2 = V_2 + 2.5 \\
&0.75\left(0.81 + V_2^2 + 1.8V_2\right) = V_2 + 2.5 \\
&0.6075 + 0.75V_2^2 + 1.35V_2 - V_2 - 2.5 = 0 \\
&0.75V_2^2 + 0.35V_2 - 1.8925 = 0
\end{aligned}
$$

Solve the quadratic equation

$\therefore V_2 = -1.877 \quad$ or $\quad V_2 = 1.37$ V (rejected)

We rejected the positive value because v_{GS} should be greater than V_t for the MOSFET to operate

Thus, the voltage V_2 is -1.877 V

From the equation $V_1 - V_2 = 2.5$ V

$V_1 - V_2 = 2.5$ V

$V_1 = 2.5 - 1.877$

$V_1 = 0.623$ V

Thus, the drain voltage V_1 of Q_2 NMOS transistor is 0.623 V

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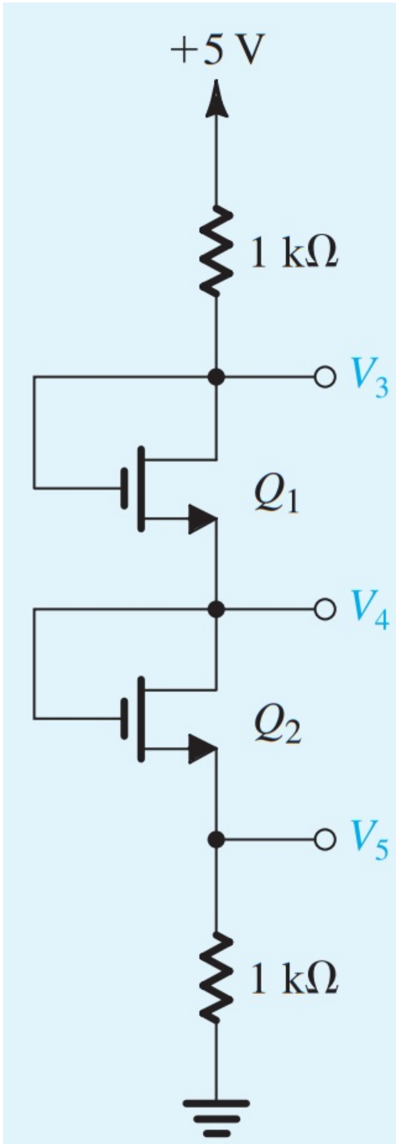
3. Q for the following circuit , find the labeled node voltages. The NMOS transistors have $V_t = 0.9$ V and $k'_n(W/L) = 1.5$ mA/V^2.



3. A

$$\begin{aligned} i_{D1} &= \frac{1}{2}k'_n\left(\frac{W}{L}\right)(v_{GS} - V_t)^2 \\ &= \frac{1}{2}\left(1.5 \times 10^{-3}\frac{\mathrm{A}}{\mathrm{V}^2}\right)[(V_3 - V_4) - 0.9]^2 \\ &= 0.75\,(V_3 - V_4 - 0.9)^2 \end{aligned}$$

$$\begin{aligned} i_{D2} &= \frac{1}{2}k'_n\left(\frac{W}{L}\right)(v_{GS} - V_t)^2 \\ &= \frac{1}{2}\left(1.5 \times 10^{-3}\frac{\mathrm{A}}{\mathrm{V}^2}\right)[(V_4 - V_5) - 0.9]^2 \\ &= 0.75\,(V_4 - V_3 - 0.9)^2 \end{aligned}$$

$\because$ Q_1 and Q_2 are in series

$\therefore$ drain current of Q_1 is equal to the drain current of Q_2

$$\mathbf{0.75}\left(V_3 - V_4 - 0.9\right)^2 = 0.75\left(V_4 - V_5 - 0.9\right)^2$$

$$\frac{V_3 + V_5}{2} = V_4 \qquad (1)$$

For Q_2 transistor :

$$i_{D2} = \frac{V_3 - (0)}{1000}$$
$$= V_5 \text{ mA}$$

$$i_{D1} = \frac{5 - (V_3)}{1000}$$
$$= 5 - V_3 \text{ mA}$$

$$\because i_{D1} = i_{D2}$$

$$\therefore 5 - V_3 = V_5$$

$$V_3 + V_5 = 5$$

Substitute $V_3 + V_5 = 5$ in equation (1)

$$V_4 = \frac{V_3 + V_5}{2}$$
$$= \frac{5}{2} = 2.5 \text{ V}$$

Thus, the drain voltage V_4 of Q_2 NMOS transistor is 2.5 V

$$0.75\,(V_3 - V_4 - 0.9)^2 \text{ mA} = V_5 \text{ mA}$$

$$0.75\,(V_3 - 2.5 - 0.9)^2 = V_5$$

Substitute $V_5 = 0.75\,(V_3 - 3.4)^2$ in $V_3 + V_5 = 5$ V

$$V_3 + V_5 = 5 \text{ V}$$

$$V_3 + 0.75\,(V_3 - 3.4)^2 = 5$$

$$V_3 + 0.75\left(V_3^2 + 11.56 - 6.8V_5\right) = 5$$

$$0.75V_3^2 - 5.1V_3 + V_3 + 8.67 - 5 = 0$$

$$0.75V_3^2 - 4.1V_3 + 3.67 = 0$$

Solve the equation $0.75V_3^2 - 4.1V_3 + 3.67 = 0$ The drain voltage V_3 of Q_1 NMOS transistor is

1.13 V or 4.33 V

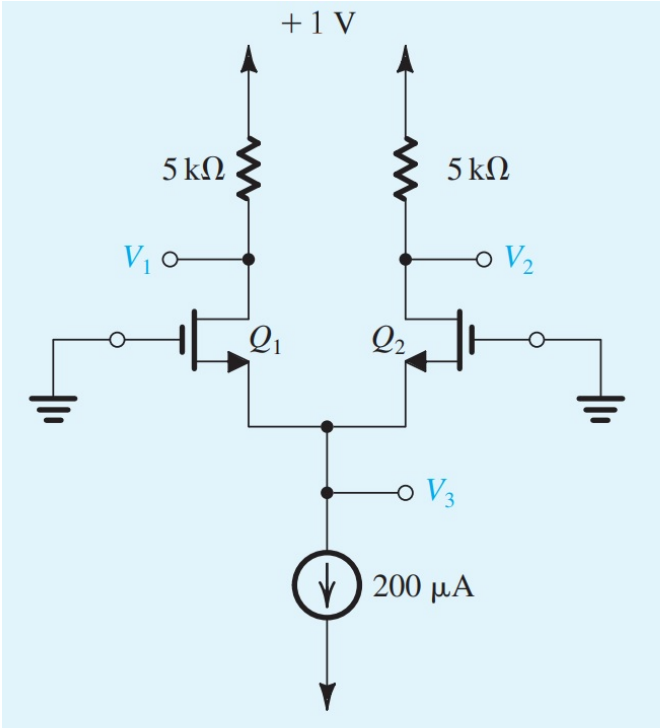
1.13 V is rejected because $V_G > V_S$ for the MOSFET to be $> V_t$.

$$V_3 + V_5 = 5$$

$$V_5 = 5 - V_3$$

$$V_5 = 0.67 \text{ V}$$

Thus, the voltage V_5 is 0.67 V



$\boxed{\text{4. Q}}$ In the circuit of the following figure , transistors and Q_2 have $V_t = 0.5V$, and the process transconductance parameter $k_n' = 400\mu A/V^2$ Find V_1, V_2, and V_3 for each of the following cases:

a) $(W/L)_1 = (W/L)_2 = 10$

b) $(W/L)_1 = 1.5(W/L)_2 = 10$

$\boxed{\text{4. A}}$

a)

Due to the similarity of the circuit :

$i_{D1} + i_{D2} = 200\mu\text{A}$

Therefore Drain current $i_{D1} = i_{D2}$ is $100\mu\text{A}$

$$i_{D1} = \frac{1 - V_1}{5 \times 10^3}\ \text{A} \tag{1}$$

$$\begin{aligned} i_{D1} &= \frac{1}{2} k_n' (W/L)_1 \left(v_G - V_t\right)^2 \\ &= \frac{1}{2}\left(400 \times 10^{-6}\ \text{A/V}^2\right)(10)\left(0 - V_3 - 0.5\right)^2 \\ &= 2\left(V_3 + 0.5\right)^2\ \text{mA} \end{aligned}$$

substitute with $i_{D1} = 100\mu A$ in (1)

$$100 \times 10^{-6}\ \text{A} = \frac{1 - V_1}{5 \times 10^3}\ \text{A}$$

$$0.5 = 1 - V_1$$

$$V_1 = 0.5\ \text{V}$$

Drain voltage of Q_1 NMOS transistor V_1 is 0.5V

Similarly :

Drain voltage of Q_2 NMOS transistor V_2 is 0.5V

$$i_{D1} = 2\left(V_3 + 0.5\right)^2 \ \text{mA}$$

$$100 \times 10^{-6}\ \text{A} = 2\left(V_3 + 0.5\right)^2\left(10^{-3}\right)\text{A}$$

$$\left(V_3 + 0.5\right)^2 = 0.05$$

$$V_3 = -0.723\ \text{V}$$

Source voltage V_3 is -0.723 V

b) $(W/L)_1 = 10$

$(W/L)_2 = 6.66$

$$\begin{aligned} i_{D1} &= \frac{1}{2}k_n'(W/L)_1\left(v_{GS} - V_t\right)^2 \\ &= \frac{1}{2}\left(400 \times 10^{-6}\ \text{A/V}^2\right)(10)\left(0 - V_3 - 0.5\right)^2 \\ &= 2\left(V_3 + 0.5\right)^2\ \text{mA} \\ i_{D2} &= \frac{1}{2}k_n'(W/L)_2\left(v_{GS} - V_t\right)^2 \\ &= \frac{1}{2}\left(400 \times 10^{-6}\ \text{A/V}^2\right)(6.66)\left(0 - V_3 - 0.5\right)^2 \\ &= 1.33\left(V_3 + 0.5\right)^2\ \text{mA} \end{aligned}$$

Divide the two equations :

$$\frac{i_{D1}}{i_{D2}} = \frac{2\left(V_3 + 05\right)^2\ \text{mA}}{1.33\left(V_3 + 0.5\right)^2\ \text{mA}}$$

$$\frac{i_{D1}}{i_{D2}} = 1.5$$

Relation between i_{D1} and i_{D2} is $i_{D1} = 1.5 i_{D2}$

$i_{D1} + i_{D2} = 200\mu\text{A}$

$1.5 i_{D2} + i_{D2} = 200 \times 10^{-6}$ A

$2.5 i_{D2} = 200 \times 10^{-6}$ A

$i_{D2} = 80\mu\text{A}$

Drain current i_{D2} is 80μA

Therefore Drain current i_{D1} is 120μA

We observed that $i_{D1} = \dfrac{1 - V_1}{5 \times 10^3}$ A

$$i_{D1} = \frac{1 - V_1}{5 \times 10^3} \text{ A}$$

$$120 \times 10^{-6} \text{ A} = \frac{1 - V_1}{5 \times 10^3} \text{ A}$$

$$0.6 = 1 - V_1$$

$$V_1 = 0.4 \text{ V}$$

Drain voltage of Q_2 NMOS transistor V_1 is 0.4V

and $i_{D2} = \dfrac{1 - V_2}{5 \times 10^3}$ A

$$i_{D2} = \frac{1 - V_2}{5 \times 10^3} \text{ A}$$

$$80 \times 10^{-6} \text{ A} = \frac{1 - V_2}{5 \times 10^3} \text{ A}$$

$$0.4 = 1 - V_1$$

$$V_2 = 0.6 \text{ V}$$

Drain voltage of Q_1 NMOS transistor V_1 is 0.6V

$$\boldsymbol{i_{D1} = 2\left(V_3 + 0.5\right)^2 \ \text{mA}}$$

$$\boldsymbol{120 \times 10^{-6} \ \text{A} = 2\left(V_3 + 0.5\right)^2 \left(10^{-3}\right) \text{A}}$$

$$\boldsymbol{\left(V_3 + 0.5\right)^2 = 0.06}$$

$$\boldsymbol{V_3 = -0.744 \ \text{V}}$$

Source voltage V_3 is -0.744 V