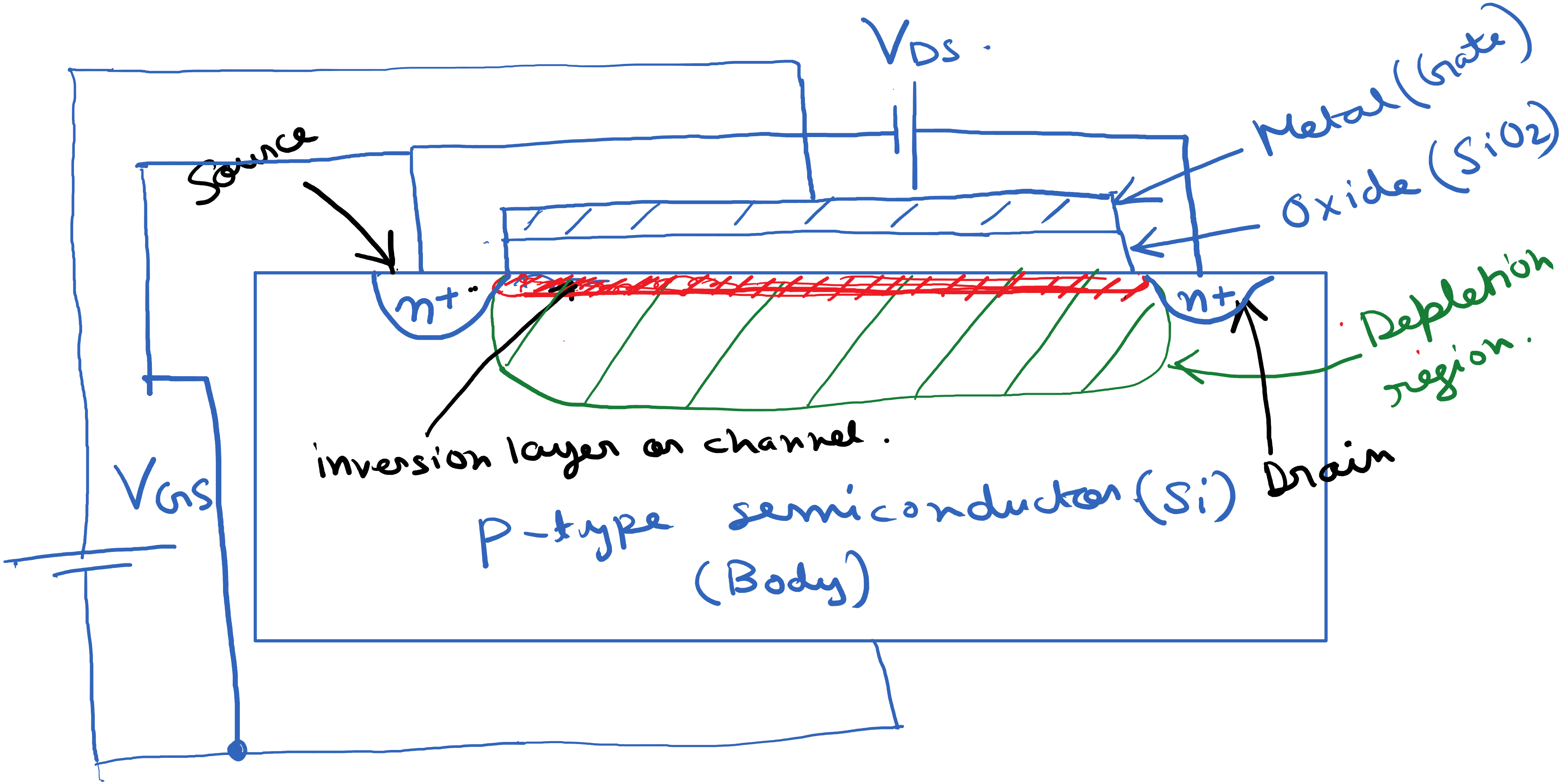
Class - 25

M O S F E T → Transistor.

M → Metal
O → Oxide
S → Semiconductor
F → Field
E → Effect

Metal oxide Semiconductor field effect transistor.

MOSFET → Current between two terminals is controlled by a voltage



VDS.
Metal (Gate)
Oxide (SiO2)
Source
n+.
n+
Depletion region.
inversion layer or channel.
Drain
VGS
P-type semiconductor (Si)
(Body)

The value of V_{GS} at which a very thin layer of mobile electrons is induced at the surface is known as the threshold voltage. (V_{TH} or V_{TN})

The number of mobile electrons at the thin layer near the surface increases when V_{GS} is increased beyond V_{TH}. The number of mobile electrons in this thin layer at the surface is directly proportional to $(V_{GS} - V_{TH})$ and this thin layer is called the inversion layer. or the channel of the MOSFET.

Once the inversion layer starts forming the thickness of the depletion layer doesnot increase anymore with increase in V_{GS}.

Once the inversion layer is formed electrons can easily flow from the source to the drain via the channel. or the inversion layer.

When $V_{GS} = 0$, then no electrons can flow from the source to the drain because there is no. induced channel or inversion layer at the surface of the body. The induced inversion layer comes into picture for $V_{GS} > V_{TH}$ and provides a conductive path for electrons to flow from source to drain.

No current can from drain to source in the absence of the channel because electrons can't flow from p-type semiconductor (Body) to n-type semiconductor (Drain).

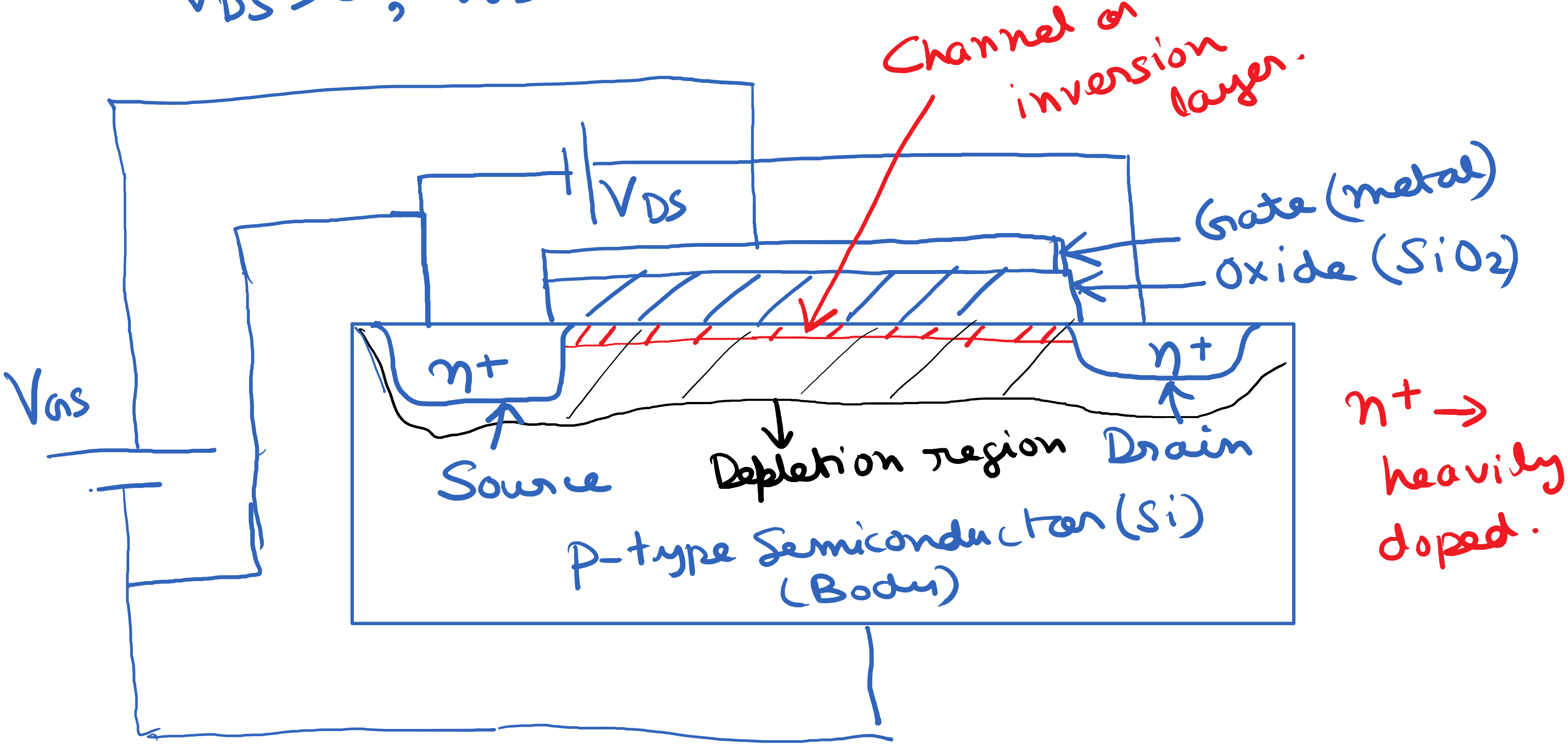
$V_{DS} > 0$, $V_{GS} = 0 \rightarrow$ no current

$V_{DS} > 0$, $0 < V_{GS} < V_{TH} \rightarrow$ no current.

$V_{DS} > 0$, $V_{GS} > V_{TH} \rightarrow$ current flow

$V_{DS} = V_D - V_S$

$V_{GS} = V_G - V_S$.



when V_{GS} is increases beyond V_{TH}, the number of electrons in the induced inversion layer increases. So, the conductivity of the inversion layer also increases. So, the current between drain and source increases with increase in V_{GS}. Thus current between the drain and source can be controlled by increasing the gate voltage.

MOSFET → Source
Drain
Gate
Body → connected to the most negative voltage in the circuit.

No current can actually flow from the metal gate into the p-type semiconductor body because an oxide insulator is present between them. So, the input impedance of a MOSFET at the gate terminal is infinite.

Class-26

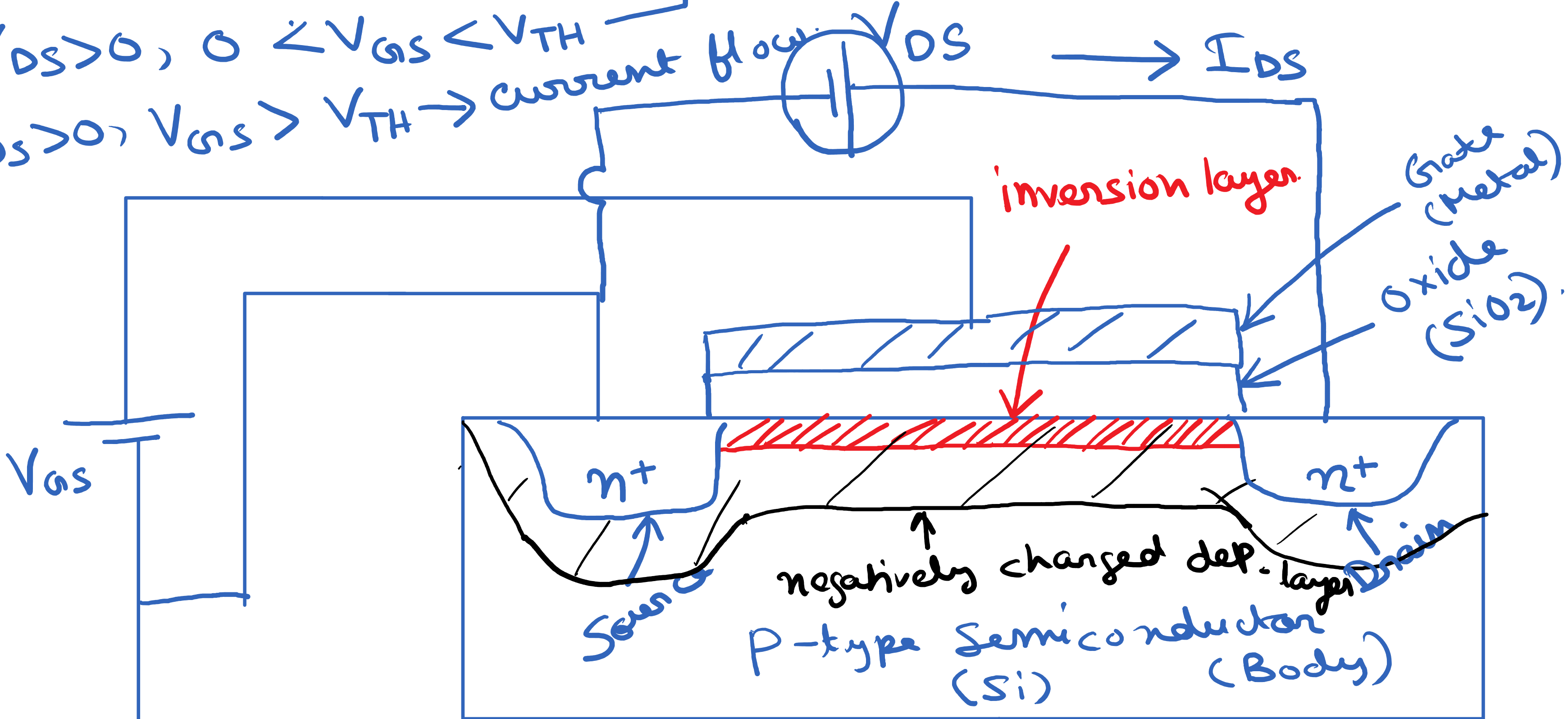
$V_{DS}=0, V_{GS}=0$ → no current flow.

$V_{DS}=0, \; 0<V_{GS}<V_{TH}$

$V_{DS}>0, \; 0<V_{GS}<V_{TH}$

$V_{DS}>0, \; V_{GS}>V_{TH}$ → current flow.

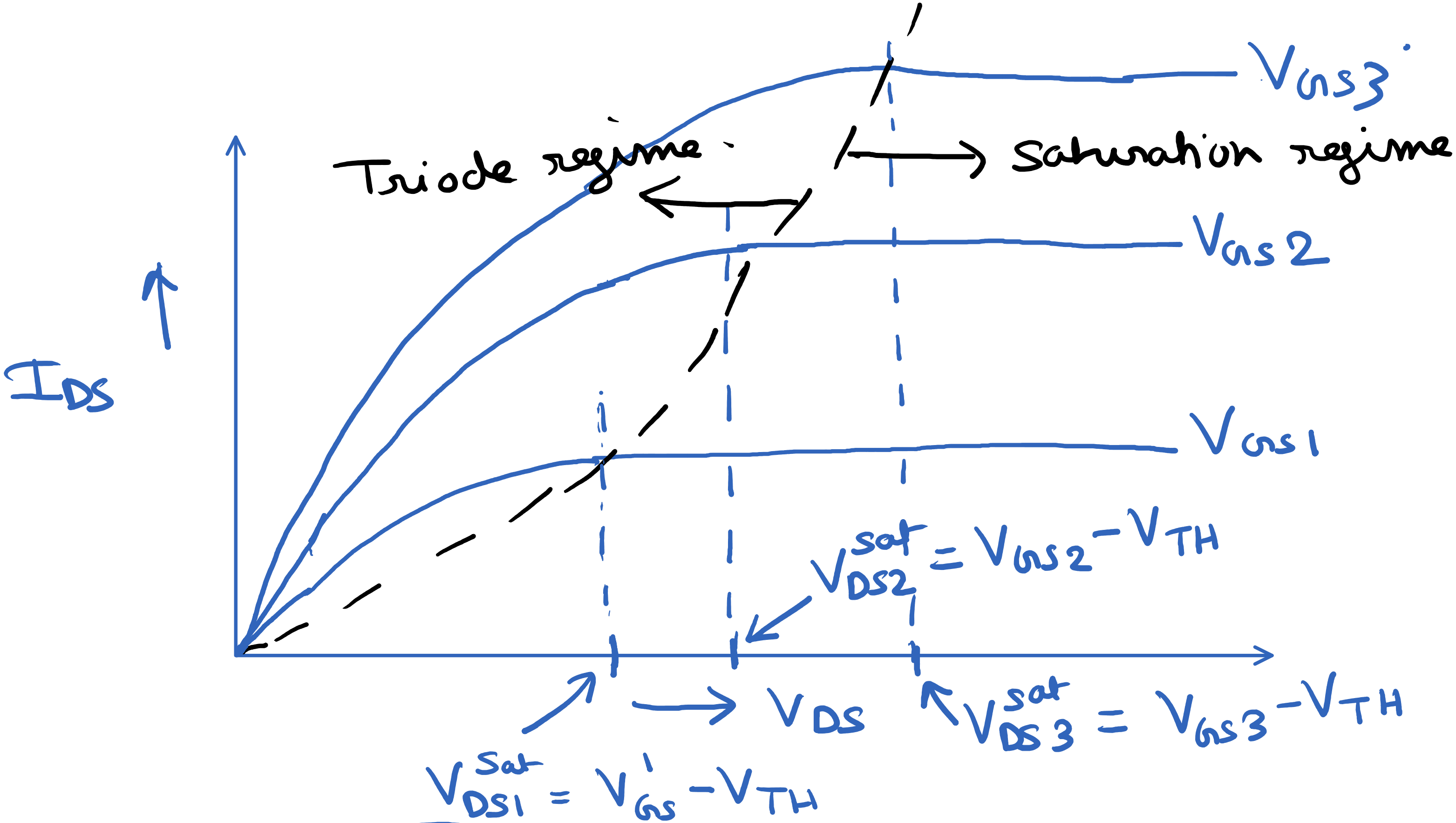
V_{TH} → Threshold voltage.



n-channel MOSFET.

Once the channel is created, that is $V_{GS} > V_{TH}$, then the drain-to-source current increases with increasing V_{GS}. Increasing V_{GS} increases the electric field at the surface and so more electrons are attracted towards the inversion layer.

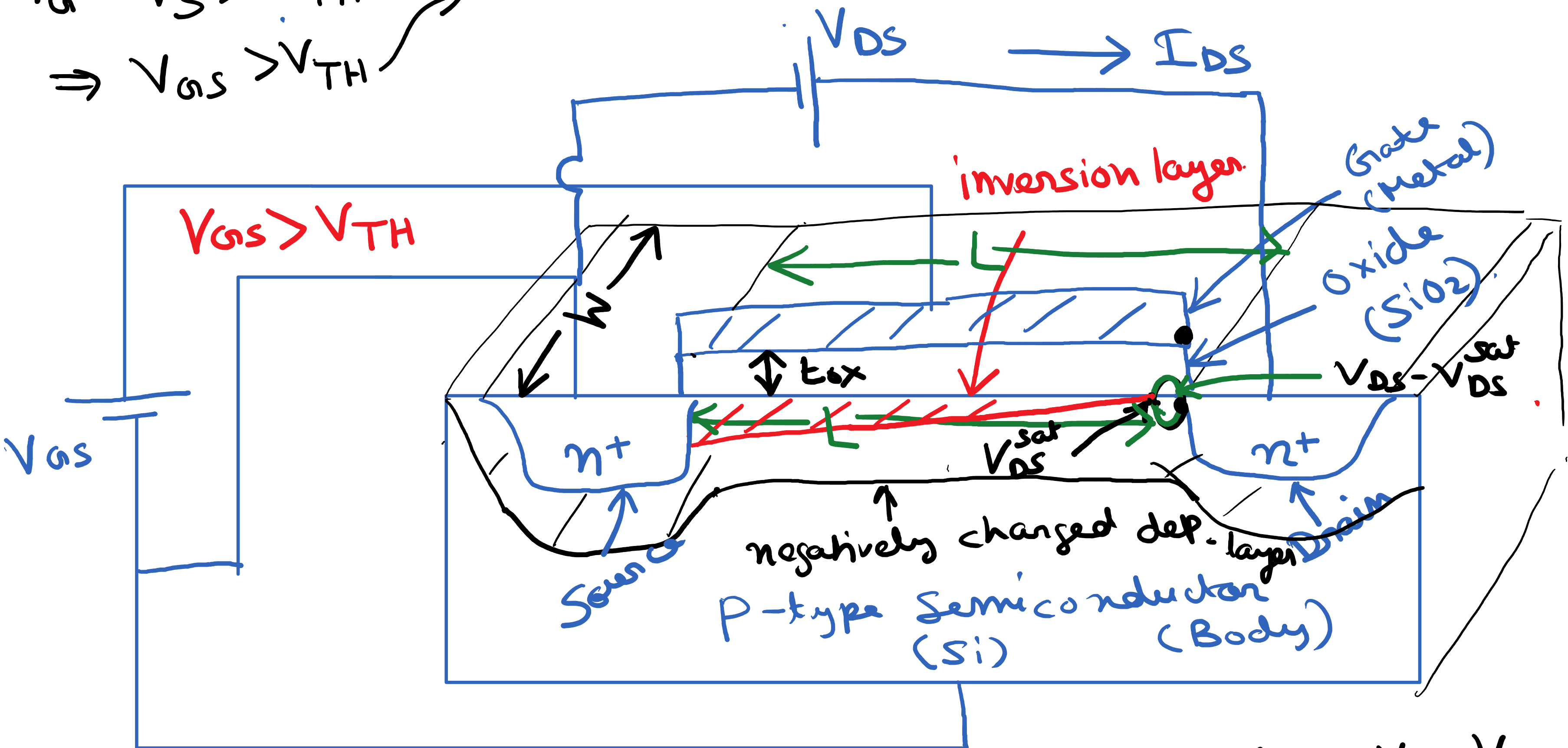
This type of MOSFETs are known as n-channel MOSFET because the inversion layer on the channel contains electrons which are negatively charged.



$$V_{GS3} > V_{GS2} > V_{GS1} > V_{TH}$$

$V_G - V_S > V_{TH}$ → channel is induced at source end.

$\Rightarrow V_{GS} > V_{TH}$



$V_G - V_D > V_{TH} \Rightarrow (V_G - V_S) - (V_D - V_S) > V_{TH} \Rightarrow V_{GS} > V_{DS} - V_{TH}$

If we keep on increasing V_{DS}, the strength of inversion layer will decrease at the drain end. On further decreasing V_{DS}, one point of time would come when the condition $V_{GS} > V_{DS} - V_{TH}$ is not valid any more. In that case, the inversion layer disappears at the drain end. This condition is known pinch-off in case of MOSFET. This happens for $V_{GS} = V_{DS} - V_{TH}$. The value of V_{DS} at which the channel just pinches off at the drain end, that is

$V_{GS} = V_{DS} - V_{TH}$ is satisfied is known as the saturation drain-to-source voltage (V_{DS}^{sat}).

$$V_{DS}^{sat} = V_{GS} - V_{TH}$$

$$I_{DS} = 0 \quad \text{for } V_{GS} < V_{TH} \quad (\text{cut-off regime}).$$

$$I_{DS} = K_n \left[2(V_{GS} - V_{TH}) V_{DS} - V_{DS}^2 \right]$$

for $V_{GS} > V_{TH}$ and $V_{DS} < V_{GS} - V_{TH}$

(Triode regime)

$$I_{DS} = K_n (V_{GS} - V_{TH})^2$$

for $V_{GS} > V_{TH}$ and $V_{DS} \geq V_{GS} - V_{TH}$

(Saturation regime)

$$K_n = \frac{\mu_n W}{2L} C_{ox}$$

$C_{ox} \rightarrow$ oxide capacitance per unit area

$\hookrightarrow \dfrac{\varepsilon_{ox}}{t_{ox}} \rightarrow t_{ox} \rightarrow$ thickness of oxide layer

W = channel width

L = channel length.

V_{GS} fixed, V_{DS} increase.

$$\text{Triode} \xrightarrow[V_{DS}\text{ increase}]{} \text{saturation.}$$

V_{DS} fixed, V_{GS} is varying.

$$\text{cut-off regime} \xrightarrow[V_{GS}\text{ increase}]{} \text{saturation regime} \xrightarrow[V_{GS}\text{ increase}]{} \text{Triode regime.}$$

Class - 27

$$I_{DS} = 0 \quad \text{if} \quad V_{GS} < V_{TH}$$

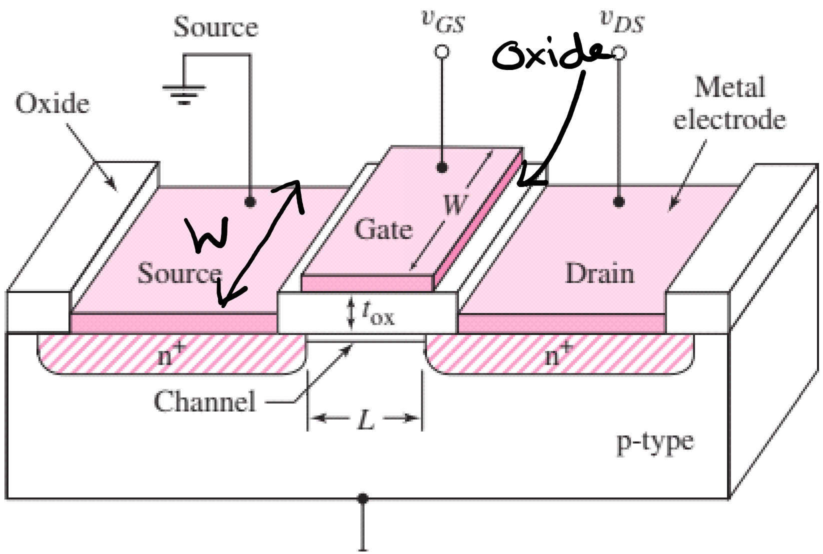
$$I_{DS} = K_n\left[2(V_{GS} - V_{TH})V_{DS} - V_{DS}^2\right]$$

$$\text{if } V_{GS} \geq V_{TH} \text{ and } V_{DS} < V_{GS} - V_{TH}$$

$$I_{DS} = K_n(V_{GS} - V_{TH})^2$$

$$\text{if } V_{GS} \geq V_{TH} \text{ and } V_{DS} \geq V_{GS} - V_{TH}$$

$$K_n = \frac{W \mu_n C_{ox}}{2L}$$



$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{K_{ox}\varepsilon_0}{t_{ox}}$$

→ 3.9 for SiO_2

K_{ox} → relative permittivity of the oxide

t_{ox} → oxide thickness

$$K_n = \frac{W \mu_n C_{ox}}{2L}$$

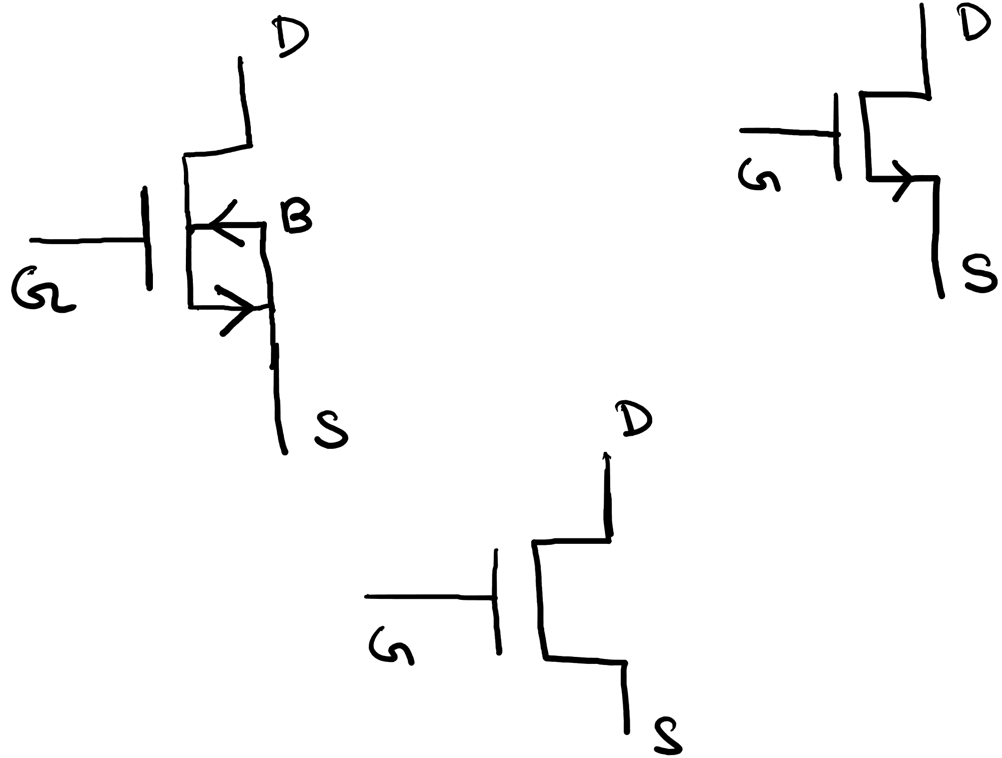
conduction parameter

$$= \frac{k_n W}{2L}$$

process conduction parameter.

$$k_n = \mu_n C_{ox}$$

$\hookrightarrow$ technology parameter. or process parameter.

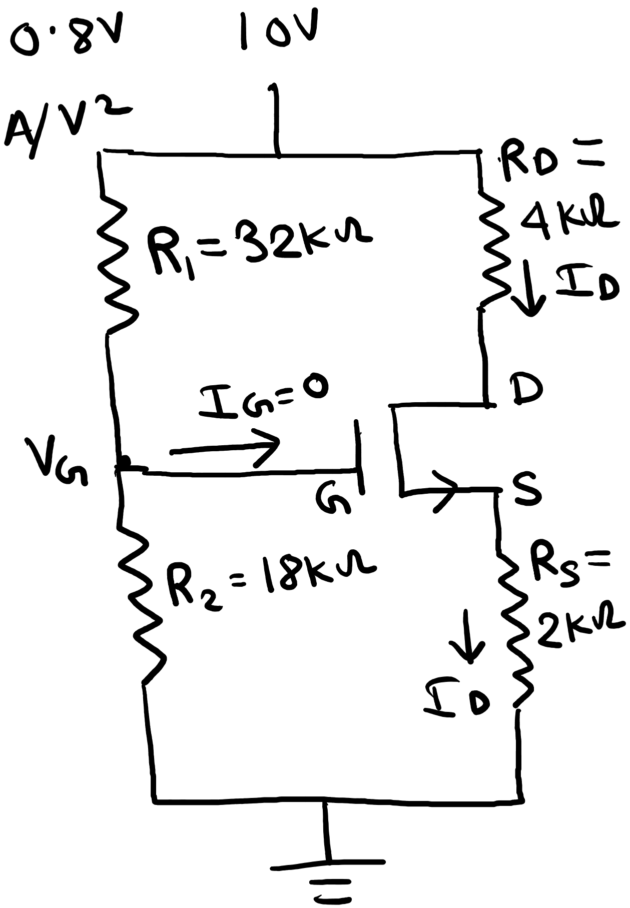


Symbol for n-channel MOSFET.

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

$V_{TN} = 0.8V$

$K_n = 0.5 mA/V^2$



$V_S = I_D R_S = 2 I_D$

$$V_G = \frac{R_2}{R_1 + R_2} \times 10V$$

$$= \frac{18}{18+32} \times 10V = 3.6V$$

$I_D = K_n (V_{GS} - V_{TN})^2$ assuming the MOS is in saturation.

$$= K_n (V_G - V_S - V_{TN})^2$$

$$= 0.5 \times (3.6 - 2 I_D - 0.8)^2$$

$$I_D = 0.5\,(3.6 - 2I_D - 0.8)^2$$

$$\Rightarrow I_D = 3.92 - 5.6I_D + 2I_D^2$$

$$\Rightarrow 2I_D^2 - 6.6I_D + 3.92 = 0$$

$$\Rightarrow I_D^2 - 3.3\,I_D + 1.96 = 0$$

$$I_D = \frac{3.3 \pm \sqrt{3.3^2 - 4\times1.96}}{2}\ mA$$

$$= \frac{3.3 \pm 1.746}{2}\ mA = 2.523mA,\quad 0.77mA.$$

Assuming $I_D = 2.523mA$,

$$V_{GS} = V_G - V_S = 3.6V - 2 \times 2.523V$$
$$= -1.446V < V_{TN}.$$

So, $I_D = 2.523mA$ is not a physical solution.

Let us assume $I_D = 0.77mA$.

$$V_{GS} = V_G - V_S = 3.6V - 2 \times 0.77V$$
$$= 2.06V > V_{TN}$$

So, $I_D = 0.77mA$ is a physical solution.

$$V_{DS} = 10V - I_D(R_S + R_D)$$

$$= 10V - 0.77(2+4)V$$

$$= 5.38V. \quad — (1)$$

$$V_{GS} - V_{TN} = 2.06V - 0.8V$$

$$= 1.26V. \quad — (2)$$

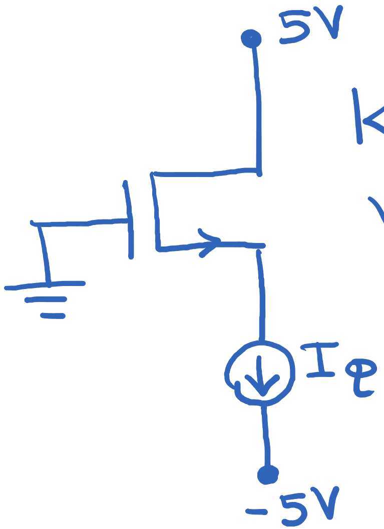
From (1) & (2) $\longrightarrow$ $V_{DS} \geq V_{GS} - V_{TN}$

So, our assumption that the MOSFET is operating in saturation regime is actually valid.

$I_D = 0.77 mA$

$V_{GS} = 2.06V$

$V_{DS} = 5.38V$



$K_n = 0.5\ mA/V^2$

$V_{TN} = 1.2V$

$I_Q = 50 uA$

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

$V_D = 5V,\ V_G = 0V$

$V_D > V_G - V_{TN}$

$\Rightarrow V_{DS} > V_{GS} - V_{TN}$

So, the MOSFET is operating in the saturation regime.

$$I_D = I_Q = 50 uA = 0.05 mA$$

$$\Rightarrow K_n (V_{GS} - V_{TN})^2 = 0.05$$

$$\Rightarrow 0.5(-V_S - V_{TN})^2 = 0.05 \Rightarrow 0.5(V_S - V_{TN})^2 = 0.05$$

$$\Rightarrow (V_S - V_{TN})^2 = 0.1 \quad \Rightarrow V_S - V_{TN} = \pm\sqrt{0.1}V = \pm 0.316V$$

$$V_S = \pm 0.316\,V - V_{TN} = \pm 0.316\,V - 1.2\,V$$

$$= -0.884\,V, \; -1.516\,V.$$

If $V_S = -0.884\,V$, then $V_{GS} = V_G - V_S = -V_S = -0.884\,V$

$\Rightarrow V_{GS} < V_{TN}$.

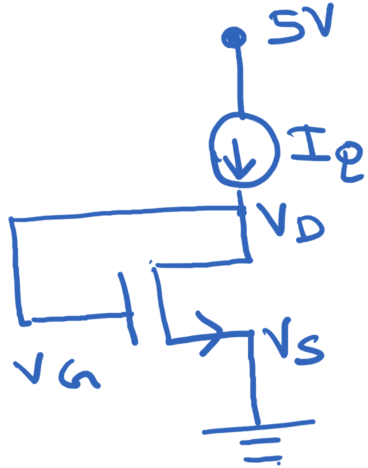
If $V_S = -1.516\,V$, $V_{GS} = V_G - V_S = -V_S = 1.516\,V$.

So, $V_{GS} > V_{TN}$

So, $V_S = -1.516\,V$ is the correct solution.

$$V_{GS} = -V_S = 1.516\,V$$

$$V_{DS} = V_D - V_S = 5V - (-1.576V) = 6.576V.$$



$K_n = 0.5 mA/V^2$

$V_{TN} = 1.2V$

$I_Q = 50 \mu A$

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

$V_{DS} = V_D - V_S > (V_D - V_{TN}) - V_S$

$= (V_G - V_{TN}) - V_S = V_{GS} - V_{TN}$

$\Rightarrow V_{DS} > V_{GS} - V_{TN}$

So the MOSFET must be operating in the saturation regime.

$I_D = I_Q = 50 \mu A = 0.05 mA$

$\Rightarrow K_n (V_{GS} - V_{TN})^2 = 0.05 mA \Rightarrow 0.5 (V_{GS} - V_{TN})^2 = 0.05$

$\Rightarrow (V_{GS} - V_{TN})^2 = 0.1 V^2 \Rightarrow V_{GS} - V_{TN} = \pm\sqrt{0.1}\ V$

$= \pm 0.316V$

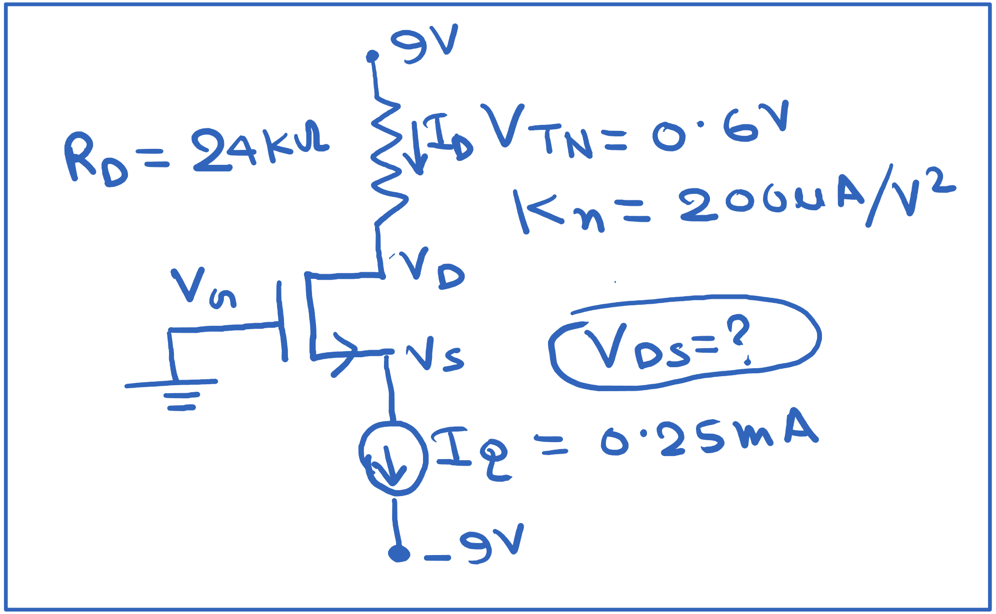
$\Rightarrow V_{GS} = \pm 0.316V + 1.2V = 1.516V, 0.884V$

If $V_{GS} = 0.884V$, then $V_{GS} < V_{TN}$. So, this can't be the physical solution.

If $V_{GS} = 1.576V$, then $V_{GS} > V_{TN}$. So, this must be the physical solution.

Since, the gate and the drain are shorted with each other, therefore, $V_{DS} = V_{GS}$.

So, $V_{DS} = V_{GS} = 1.576V$.



$I_D = I_Q = 0.25mA$.

So, $V_D = 9V - I_D R_D$

$= 9V - 0.25 \times 24$

$= 9V - 6V = 3V$

$V_{DS} > V_{DS} - V_{TN} > V_{GS} - V_{TN}$

$V_{DS} > V_{GS} - V_{TN}$

So, the MOSFET must be operating in the saturation regime.

$I_D = I_Q \Rightarrow K_n (V_{GS} - V_{TN})^2 = 0.25mA$

$\Rightarrow 0.2 (V_{GS} - V_{TN})^2 = 0.25 \Rightarrow V_{GS} - V_{TN} = \pm\sqrt{0.2/0.25}\,V$

$= \pm 0.89V$

$$V_{GS} = \pm 0.89V + V_{TN}$$
$$= \pm 0.89V + 0.6V$$
$$= 1.49V, -0.29V.$$

If $V_{GS} = -0.29V$, then $V_{GS} < V_{TN}$. In this case the MOSFET is in the cut-off regime, which is invalid for this problem.

If $V_{GS} = 1.49V$, then $V_{GS} > V_{TN}$. So, $V_{GS} = 1.49V$ must be the correct solution.

$$V_{GS} = 1.49V.$$

$$V_{GS} = V_G - V_S = -V_S$$

$\hookrightarrow 1.49V$

$$\Rightarrow -V_S = 1.49V \Rightarrow V_S = -1.49V.$$

$$V_{DS} = V_D - V_S = 3V - (-1.49V)$$

$$= 4.49V.$$

Class - 28

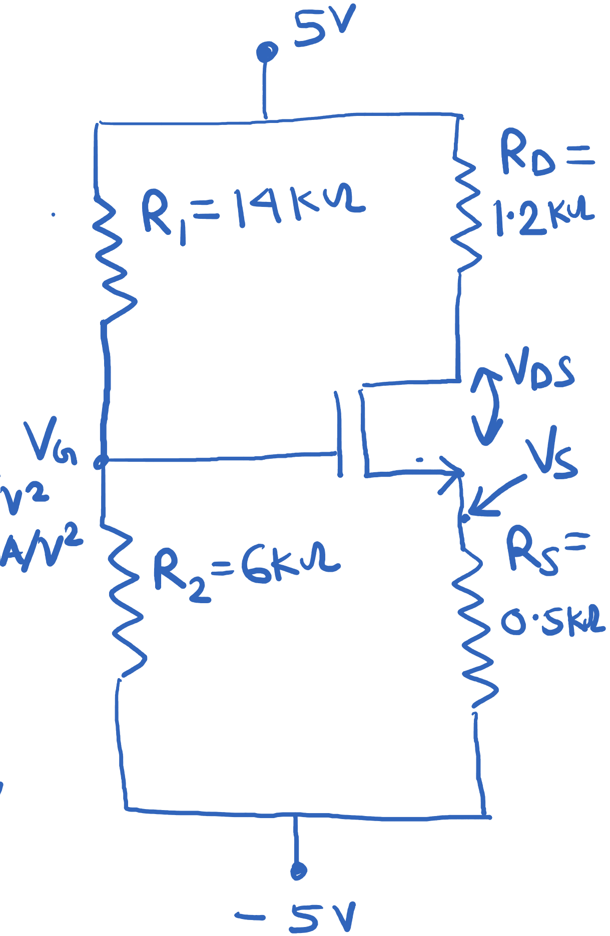
$V_{GS}, I_D, V_{DS} = ?$

$\frac{W}{L} = 25$, $K_n' = 25\,\mu A/V^2$, $V_{TN} = 1V$

A: $K_n = \frac{\mu_n C_{ox} W}{2L}$ $\quad K_n' = \mu_n C_{ox}$

$K_n = \frac{K_n' W}{2L} = \frac{75 \times 25}{2}\,\mu A/V^2 = 937\,\mu A/V^2$

$= 0.937\,mA/V^2$



$P.D = 5V - (-5V) = 10V.$

$V_G = \frac{R_2}{R_1+R_2} \times 5V + \frac{R_1}{R_1+R_2} \times (-5V)$

$= \frac{6}{6+14} \times 5V + \frac{14}{6+14} \times (-5V) = -2V$

$V_S = -5 + I_D R_S = (-5 + 0.5 I_D)\,V$

$$V_{GS} = V_G - V_S = -2V - (-5 + 0.5 I_D)$$

$$= 3 - 0.5 I_D$$

Let us assume that the MOSFET is operating in the saturation regime.

$$I_D = K_n (V_{GS} - V_{TN})^2 = 0.937(3 - 0.5 I_D - 1)^2$$

$$= 0.937(2 - 0.5 I_D)^2$$

$$= 3.748 - 1.874 I_D + .234 I_D^2$$

$$\Rightarrow I_D^2 - 12.28 I_D + 16.01 = 0$$

$$I_D = \frac{12.28 \pm \sqrt{12.28^2 - 4 \times 16.01}}{2} = 10.79\ mA,\ 1.48\ mA$$

$I_D = 10.79\ mA,\ 1.48\ mA.$

$V_{GS} = 3 - 0.5 I_D$

If $I_D = 10.79\ mA$, then $V_{GS} = (3 - 0.5 \times 10.79)\ V$

$= (3 - 5.4)\ V$

$= -2.4\ V.$

So, I_D must be equal to $1.48\ mA$.

Saturation condition $\left.\right\}$ $V_{DS} > V_{GS} - V_{TH}$

$$V_{DS} = [5V - (-5V)] - I_D \overset{0.5k\Omega}{R_S} - I_D \overset{1.2k\Omega}{R_D}$$

$= 10V - I_D \times 1.7 = 10V - 1.48 \times 1.7\ V$

$= 7.484\ V.$

$$V_{GS} = 3V - 0.5 I_D = 3V - 0.5 \times 1.48V.$$

$$= 3V - .74V$$

$$= 2.26V.$$

So, $V_{DS} > V_{GS} - V_{TN}$ is actually valid.

So, the MOSFET must be operating in saturation.

$V_{GS} = 2.26V$

$V_{DS} = 7.484V.$

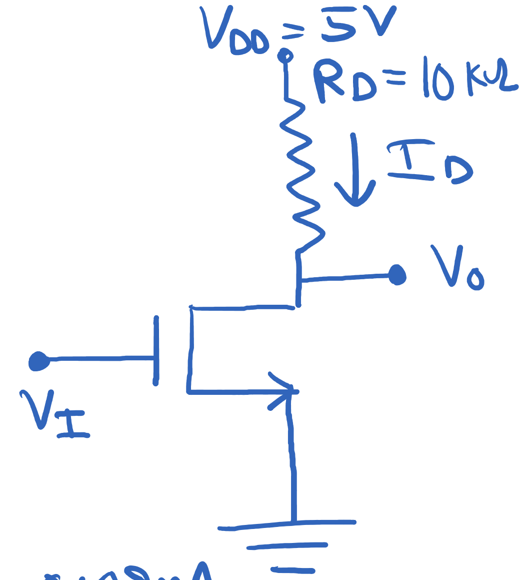
$I_D = 1.48mA$

$V_{TN} = 0.8\,V$

$K_n' = 30\,\mu A/V^2$.

$V_o = 0.1\,V$ when $V_I = 4.2\,V$.

Determine the value of $\frac{W}{L}$ for the transistor.



A:

$$I_D = \frac{V_{DD} - V_o}{R_D} = \frac{5V - 0.1V}{10\,k\Omega} = \frac{4.9}{10}\,mA = 0.49\,mA$$

$V_{GS} = V_I = 4.2\,V$, $V_{DS} = V_o = 0.1\,V$, $V_{GS} - V_{TN} = 3.4\,V$.

$V_{DS} \leq V_{GS} - V_{TN}$. So, the MOSFET is operating in triode regime.

$V_{GS} = 4.2V, \quad V_{DS} = 0.1V, \quad I_D = 0.49\, mA.$

$$I_D = K_n\left[2(V_{GS} - V_{TN})V_{DS} - V_{DS}^2\right]$$

$$= K_n\left[2(4.2 - 0.8)\,0.1 - 0.1^2\right]V^2$$

$$0.49\, mA = K_n \times 0.67 V^2.$$

$$\Rightarrow K_n = \frac{0.49\, mA}{0.67\, V^2} = 0.731\, mA/V^2.$$

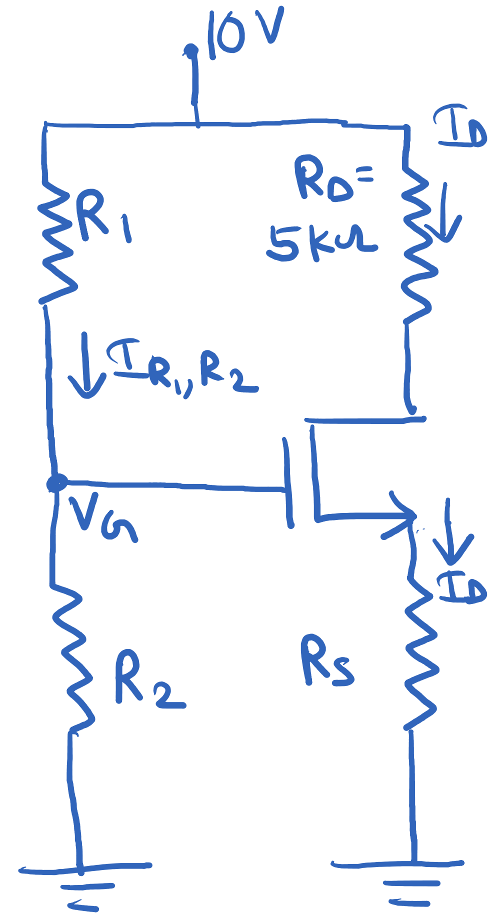
$$\Rightarrow k_n' \times \frac{W}{2L} = 0.731\, mA/V^2$$

$$\Rightarrow W/L = 0.731\, mA/V^2 \times \frac{2}{k_n'} = 0.731\, mA/V^2 \times \frac{2}{0.03\, mA/V^2}$$

$$= 48.75$$

$V_{TN} = 1.2V$, $k_n' = 60\mu A/V^2 = 0.06 mA/V^2$

Design the circuit, that is choose R_1, R_2 and R_S along with W/L, such that $V_{DSQ} \cong 5V$ and the current through R_1 and R_2 is approximately 5% of the drain current. The voltage across R_S is approximately equal to the V_{GS} of the MOSFET.



$V_{TN} = 1.2V$, $k_n' = 60\,\mu A/V^2$

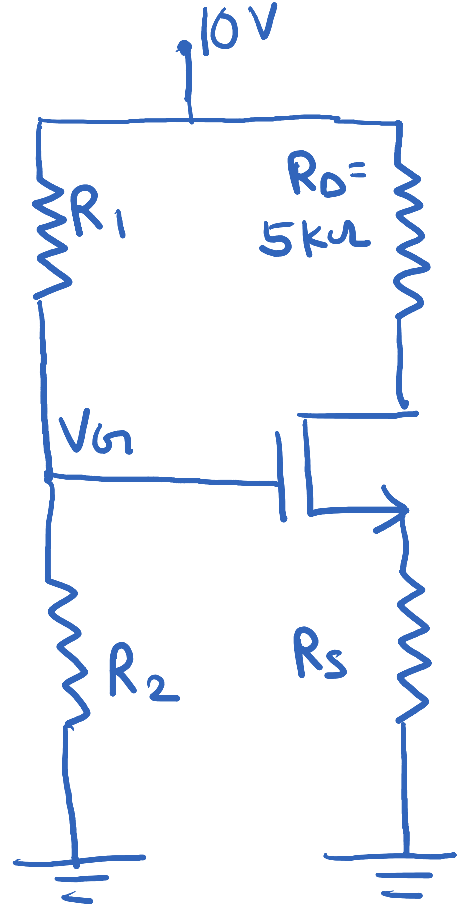
$$I_D = \frac{V_{RS}}{R_S} \simeq \frac{V_{GS}}{R_S}$$

Also, $$I_D = \frac{10V - V_{DSQ}}{R_D + R_S} = \frac{10V - 5V}{R_D + R_S}$$

$$= \frac{5V}{5K\Omega + R_S}$$

We choose $R_S = 5K\Omega$.

$$I_D = \frac{5V}{5K\Omega + 5K\Omega} = 0.5mA.$$



$$V_{GS} \cong V_{R_S} = I_D R_S = 0.5\,mA \times 5\,k\Omega = 2.5\,V.$$

$V_{GS} \cong 2.5V$

$V_{DSQ} \cong 5V$

$V_{TN} = 1.2V.$

So, the MOSFET is operating in saturation.

$$V_{DSQ} > V_{GS} - V_{TN}.$$

$$I_D = K_n (V_{GS} - V_{TN})^2 = K_n (2.5V - 1.2V)^2$$

$$= 1.69 K_n V^2$$

$$\Rightarrow K_n = \frac{0.5\,mA}{1.69\,V^2} = 0.295\,mA/V^2$$

$$K_n = 0.295 \ mA/V^2$$

$$k_n' = 0.06 \ mA/V^2.$$

$$\frac{k_n'}{2}\frac{W}{L} = K_n \Rightarrow \frac{W}{L} = \frac{K_n}{k_n'} \times 2$$

$$= \frac{0.295}{0.06} \times 2$$

$$= 9.833$$

$$\frac{W}{L} = 9.833.$$

$$I_{R_1,R_2} = 5\% \text{ of } I_D = \frac{5}{100} I_D = \frac{I_D}{20}.$$

$$= \frac{0.5\,mA}{20} = 0.025\,mA.$$

$$I_{R_1,R_2} = \frac{10V}{R_1+R_2} = 0.025\,mA$$

$$\Rightarrow R_1 + R_2 = \frac{10V}{0.025\,mA} = 400\,k\Omega$$

$$V_G = \frac{10V}{R_1+R_2} \times R_2 = V_{GS} + V_{R_S} = 2.5V + 2.5V = 5V.$$

$$\Rightarrow R_2 = \frac{5V}{10V} \times (R_1+R_2) = \frac{1}{2} \times 400\,k\Omega = 200\,k\Omega.$$

$$R_1 + R_2 = 400\,k\Omega$$

$$\Rightarrow R_1 = 400\,k\Omega - R_2$$

$$= 400\,k\Omega - 200\,k\Omega$$

$$= 200\,k\Omega.$$

$$\left.\begin{aligned} R_1 &= R_2 = 200\,k\Omega \\ R_S &= 5\,k\Omega \\ \frac{W}{L} &= 9.833. \end{aligned}\right\} \text{Ans.}$$