EE 204 - Analog Circuits
Lecture 16

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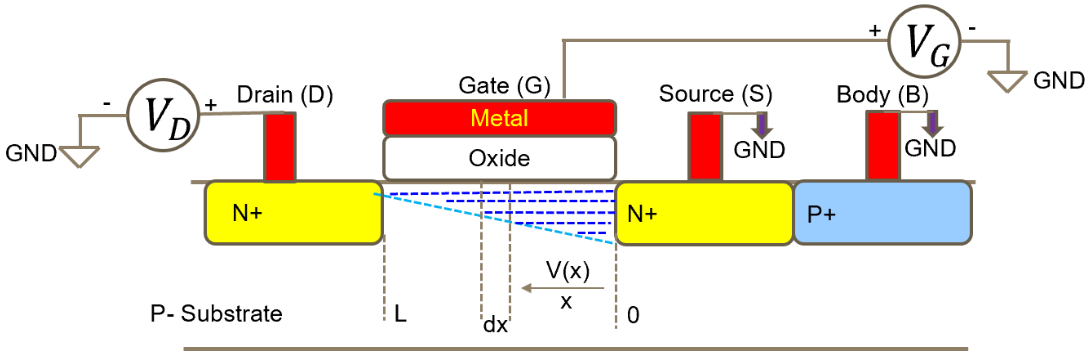
1 Operation of a MOSFET

The operation of a MOSFET is the most important aspect while analysing a MOSFET diagram.

When there are no mobile charges in the channel,

$$Q_{ch} = WC_{ox}(V_{GS} - V_{TH})$$



When there are mobile chargers along channel x, $V(x)$ goes from 0 to V_{DS}

$$Q_d = WC_{ox}(V_{GS} - V(x) - V_{TH})$$

and current through channel would be,

$$I_{DS} = Q_d(x)v$$

where, v is the velocity and

$$v = \mu_n \frac{dV(x)}{dx}$$

On substituting the relations and solving for I_{DS}, we get -

$$I_{DS} = \mu_n \frac{W}{L} C_{ox}(V_{GS} - V_{TH})V_{DS} - \frac{V_{DS}^2}{2}$$

Therefore,

$$I_{DS} \propto \mu_n, \frac{W}{L}, C_{ox} \quad \text{(Device aspect ratio)}$$

$$I_{DS} \propto (V_{GS} - V_{TH})$$

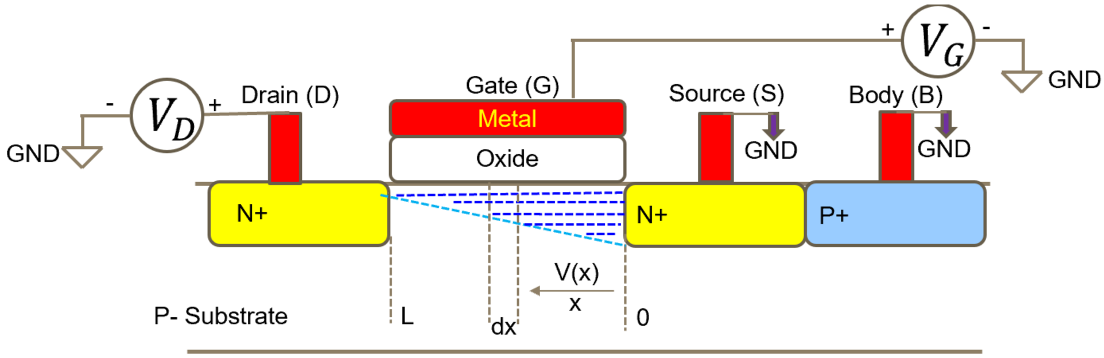
$$I_{DS} \propto V_{DS}$$

1.1 Pinch-Off Voltage

When a positive gate-source voltage (V_{GS}) is applied to an NMOS, it creates a channel that allows current to flow from the drain to the source. As the drain-source voltage (V_{DS}) increases, the channel begins to taper and eventually pinches off. This pinch-off occurs when the drain-source voltage equals the gate-source voltage minus the threshold voltage ($V_{DS} = V_{GS} - V_{TH}$). At this point, the current becomes saturated and remains almost constant.

In simpler terms, pinch-off is a state where the channel of current between the source and drain ends is constricted or "pinched-off", limiting the flow of current. This happens when the voltage difference between the source and drain is high enough.

So, in essence, the pinch-off voltage is defined as the gate-to-source voltage at which drain-to-source current becomes constant.



$Q = CV = C(V - V_{TH})$

Channel charge: $Q_d(x) = W\ C_{ox}\ (V_{GS} - V(x) - V_{TH})$

$Q_d(0) = W\ C_{ox}\ (V_{GS} - V_{TH})$

$Q_d(L) = W\ C_{ox}\ (V_{GS} - V_{TH} - V_{DS})$

$Q_d(L) = 0$ When $V_{DS} = V_{GS} - V_{TH}$ Pinch off Point

1.2 Beyond Pinch-Off Voltage

In beyond pinch-off region, mathematically,

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

Physically, beyond the pinch-off region, the device enters the saturation region. In this region, the drain-source current (I_{DS}) remains constant despite an increase in the drain-source voltage (V_{DS}). This occurs once V_{DS} exceeds the value of the pinch-off voltage (V_P).

Under these conditions, the device will act like a closed switch through which a saturated value of V_{DS} flows. This behavior is characteristic of MOSFET operation in the saturation region.

$$\int_{x=0}^{x=L_1} I_{DS}(x)\,dx = \int_{V(x)=0}^{V(x)=(V_{GS}-V_{TH})} W\ C_{ox}\ (V_{GS} - \mathrm{V}(x) - V_{TH}).\mu_n\, dV(x)$$

$$I_{DS}.L = \left[\mu_n W\ C_{ox}\ (V_{GS} - V_{TH})V(x) - \frac{V(x)^2}{2}\ \right]_0^{V_{GS}-V_{TH}}$$

$$I_{DS} = \mu_n \frac{W}{L}\ C_{ox}\ \frac{(V_{GS} - V_{TH})^2}{2}$$

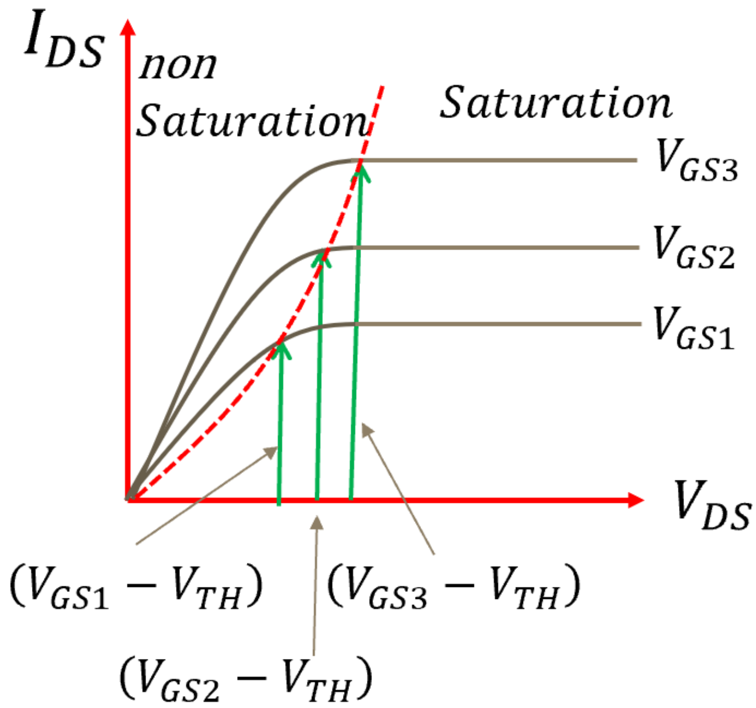
$$I_{DS} = \frac{1}{2}\mu_n \frac{W}{L}\ C_{ox}(V_{GS} - V_{TH})^2$$

$(V_{GS} - V_{TH})$→ Over drive voltage/ V_{dsat}

$(V_{DS} > V_{dsat})$→ for saturation region operation

2 Operating Regions in a MOSFET

Just as in a BJT, we plot I_C vs V_{CE}, in the case of MOSFET, that plot is made between I_{DS} vs V_{DS}.



But being a bit careful, we notice that the regions of saturation is very different in MOSFET as compared to BJT; and the MOSFET operation has only two states in the plot contrary to the three we obtain in the case of a BJT.

The following table helps to summarise the operation regions of a MOSFET and BJT corresponding to the regions marked in their respective plots.

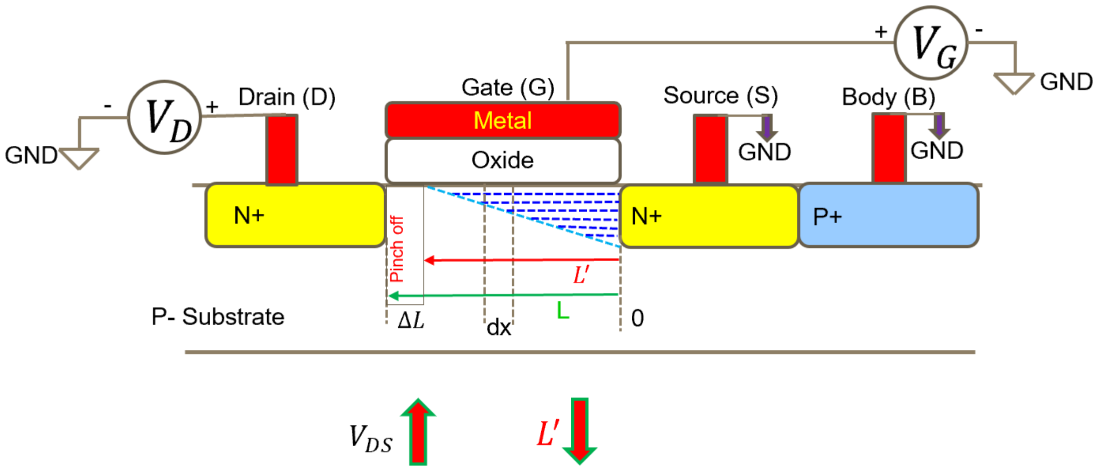
	Bipolar transistor	MOSFET
Device as switch or resistor	Saturation $V_{CE} < 0.3\text{V}$	Linear Triode $V_{DS} < (V_{GS} - V_{TH})$
Device useful amplification	Active $V_{CE} > 0.3\text{V}$	Saturation $V_{DS} \geq (V_{GS} - V_{TH})$

3 Channel Length Modulation Effect

Channel-length modulation, is a phenomenon that occurs in MOSFETs as a result of changes in the length of the conducting channel between the source and the drain terminals.

This effect has important implications for the behavior of MOSFETs, especially when they are used for amplification or switching applications.

When a voltage is applied to the gate to turn the MOSFET on, the channel between the source and the drain opens, and current flows through the channel. However, the channel length is not constant but can vary due to several factors, including manufacturing variations and applied voltages.



3.1 Effects of Varying Channel Length

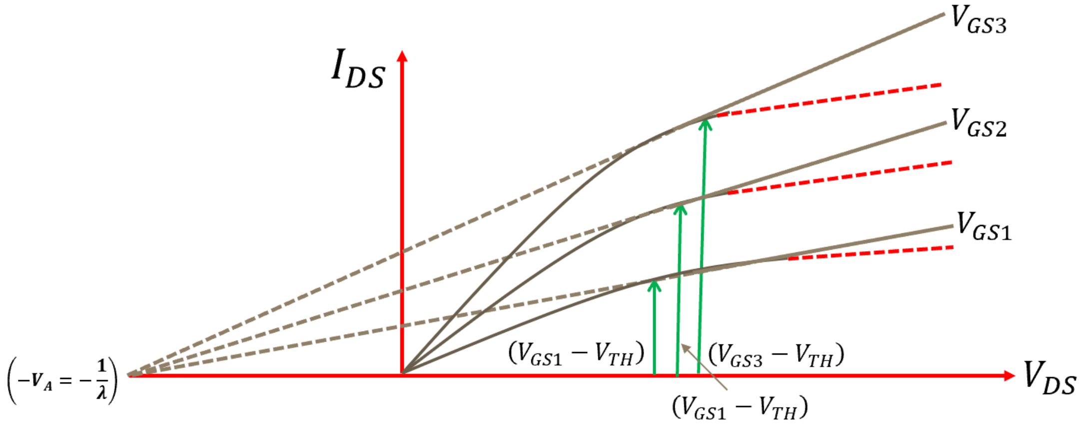
- **Voltage Dependence** : The channel length is influenced by the voltageacross the drain and source terminals (V_{DS}). When V_DS increases, the depletion region around the drain also increases, which effectively shortens the channel length
- **Impact on Output Characteristics** : The variation in channel length due to V_DS affects the output characteristics of the MOSFET. Specifically, it causes a change in the output current (I_{DS}) concerning V_{DS}.

The new I_{DS} that we get by solving with channel length modulation in consideration is the following:

$$I_{DS} = \frac{1}{2}\mu_n \frac{W}{L} C_{ox}(V_{GS} - V_{TH})^2(1 + \lambda\, V_{DS})$$

where, λ is the channel length modulation co-efficient.

The new I_{DS} vs V_{DS} looks like the following:



I_{DS}
V_{GS3}
V_{GS2}
V_{GS1}
$\left(-V_A = -\frac{1}{\lambda}\right)$
$(V_{GS1} - V_{TH})$
$(V_{GS3} - V_{TH})$
$(V_{GS1} - V_{TH})$
V_{DS}