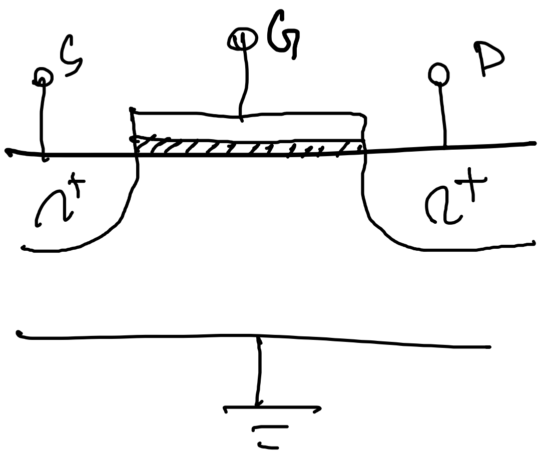
Drain Current equation in three regions of operation:-

Cutoff region : ($V_{GS} < V_{th}$)

* In the cutoff region where the gate to source voltage $V_{GS} < V_{th}$, we don't have the channel formed underneath the gate oxide layer.
* Source and Drain are not electrically connected, there is zero current through the device.



($V_G < V_{th}$)

no channel

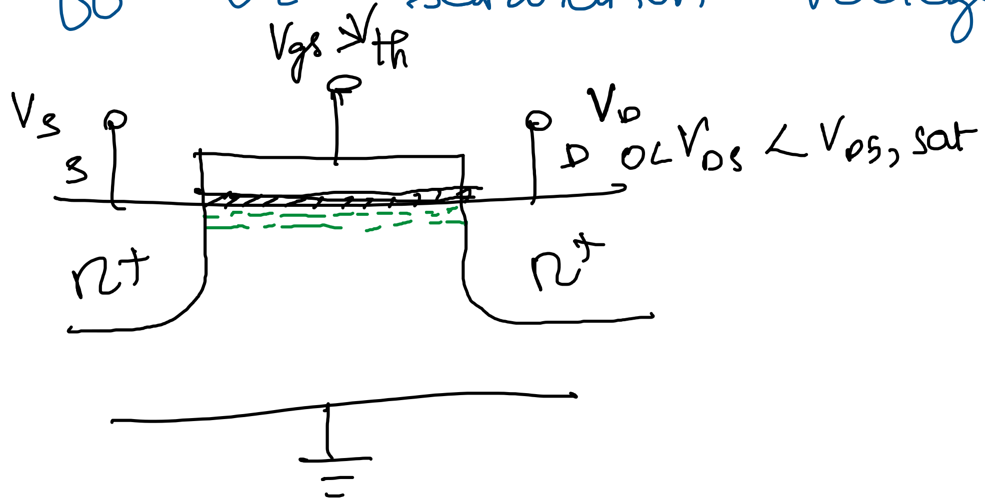
$I_D = 0$

Triode / Linear / Active region :-

$V_{gs} > V_{th}$ and $0 < V_{DS} < V_{DS,sat}$; $V_{DS,sat} = V_{gs} - V_{th}$

* uniform channel is formed underneath the gate oxide layer
* I_D, drain current is a strong fn of V_{gs} and a weak fn of V_{ds}.

* In this region of operation, the gate to source voltage is greater than a threshold voltage but less than the pinch off or saturation voltage.



Eqn for I_D :

$$Q_{channel} = C_g (V_{gc} - V_{TH})$$

$$C_g = \frac{\varepsilon_{ox}}{t_{ox}} WL = C_{ox} WL$$

$$V_{gc} = \frac{V_{gs} + V_{gd}}{2}$$

$V_{gs} \rightarrow$ gate to source voltage

$V_{gd} \rightarrow$ gate to drain voltage

$$V_{gd} = V_{gs} - V_{ds}$$

$$V_{gc} = \frac{V_{gs} + V_{gs} - V_{ds}}{2} = V_{gs} - \frac{V_{ds}}{2}$$

Sub. V_{gc} and C_g in $Q_{channel}$ eqn,

$$\boxed{Q_{channel} = C_{ox} WL \left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)}$$

$$I_D = \frac{Q_{channel}}{t}\ ; \qquad t = \frac{L}{v} \rightarrow \text{velocity}$$

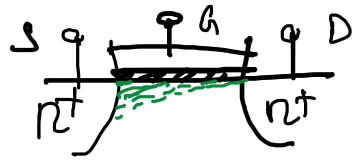
$$v = \mu E\ ; \qquad E = \frac{V_{ds}}{L}$$

$$I_D = \frac{C_{ox} WL \left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)}{\dfrac{L}{\mu \frac{V_{ds}}{L}}}$$

$$\boxed{I_D = \mu C_{ox} \frac{W}{L} \left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right) V_{ds}}$$

Saturation region: $V_{gs} > V_{th}$ and $V_{ds} \geq V_{ds,sat}$

here $V_{ds} = V_{gs} - V_{th}$, Sub. in I_D $\qquad V_{ds,sat} = V_{gs} - V_{th}$



$$I_D = \mu C_{ox} \frac{W}{L} \left(V_{gs} - V_{th} - \frac{V_{gs} - V_{th}}{2}\right) (V_{gs} - V_{th})$$

$$\boxed{I_D = \frac{1}{2} \mu C_{ox} \frac{W}{L} (V_{gs} - V_{th})^2 = \beta (V_{gs} - V_{th})^2}$$