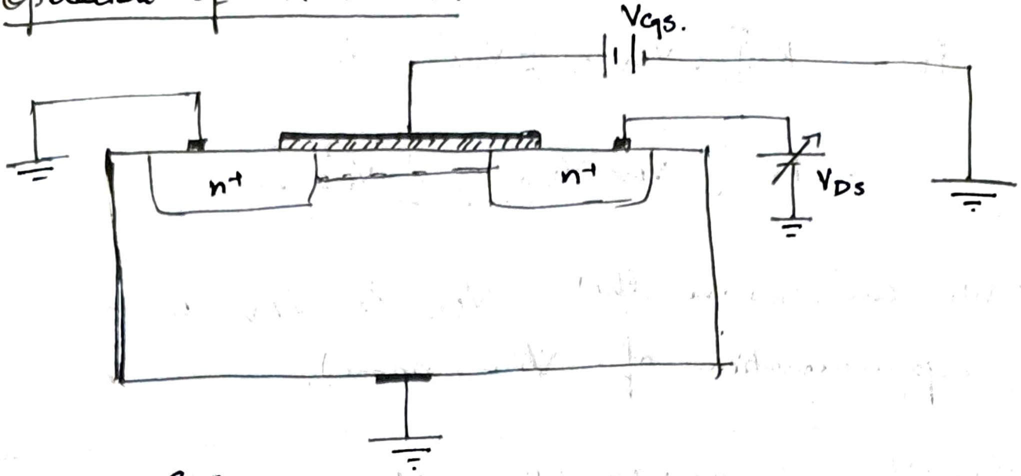
Operation of N-MOSFET :



(from prev week's notes).

When $V_{DS} << V_{ov}$ ($V_{GS} - V_{th}$)

$$I_{DS} = \left[\mu_n C_{ox} \left(\frac{W}{L}\right) V_{ov}\right] V_{DS}.$$

→ $k_n' = \mu_n C_{ox}$ [Process transconductance parameter]

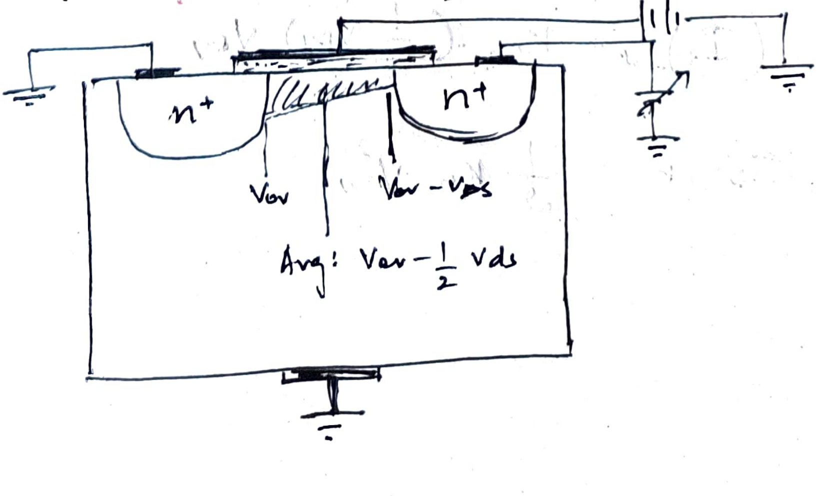
→ $\frac{W}{L}$ = Aspect ratio

→ $k_n = k_n' \left(\frac{W}{L}\right)$ = [Transistor transconductance parameter

⇒ $I_{DS} = k_n (V_{GS} - V_{th}) V_{DS}$.

When V_{DS} ~~<<~~ < $V_{GS} - V_{th}$ [Smaller but significant].

The channel loses its uniformity. The potential at drain is $V_{ov} - V_{DS}$ and that on source is V_{ov}. The approximate voltage taken will be the mean of them = $V_{ov} - \frac{1}{2} V_{DS}$.

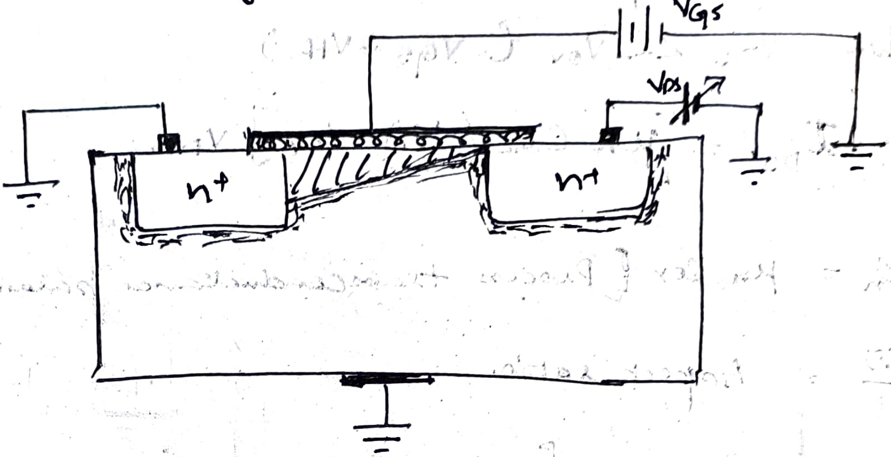


$$i_{DS} = k_n[(V_{ov} - \frac{1}{2}V_{DS})]V_{DS}$$

$$= k_n[V_{ov}V_{DS} - \frac{1}{2}V_{DS}^2]$$

(We can observe that $V_{DS} << V_{ov}$ is an approximation of the same).

When V_{DS} is greater than V_{ov}.



The channel enters a state of pinch-off, i.e, the channel is barely present on the drain. Any excess voltage beyond the overdrive voltage will contribute to the formation of a depletion layer, causing the channel current to be saturated, as it is when $V_{DS} = V_{ov}$.

In this case

$$(I_D)_{sat} = k_n \cdot (\frac{1}{2}V_{ov})V_{ov}$$

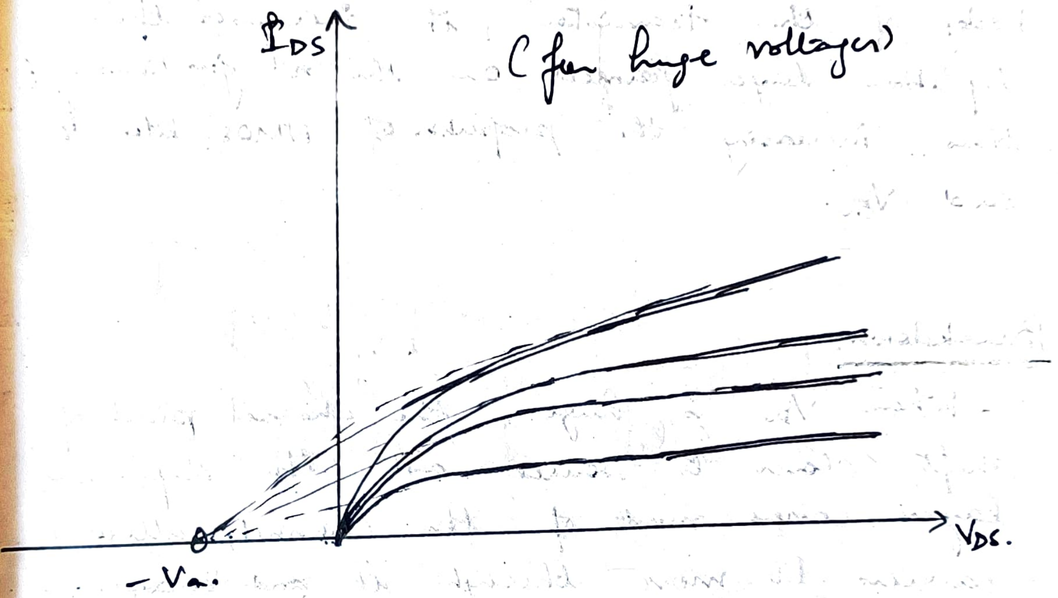
$$\Rightarrow (I_D)_{sat} = \frac{1}{2}k_n V_{ov}^2$$

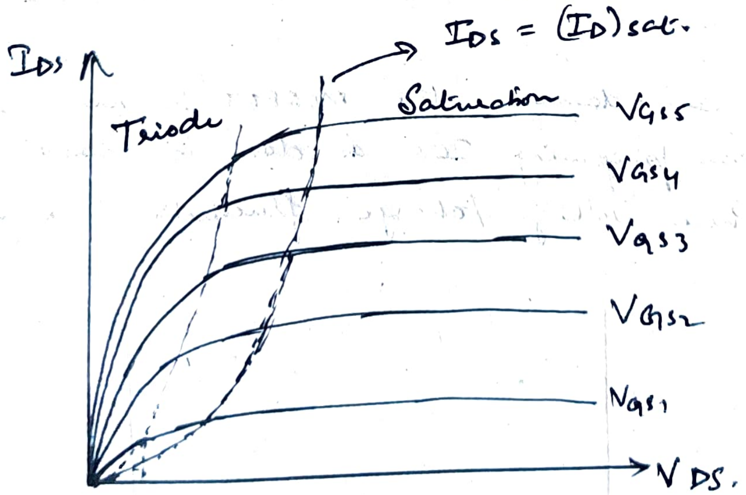
Note:

When V_{DS} increases over a certain limit, the depletion layer provides carriers for current transfer, increasing the saturation current value.

$$i_{DS} = (i_D)_{sat}\left[1 + \lambda V_{DS}\right]. \qquad \lambda \propto \frac{1}{L}.$$

When we plot the graphs for various V_{GS}, we can extend the linear slopes and find them meeting on the x-axis at $V = -V_A$ (early voltage), just like the case with BJT.





Characteristic graph for N-MOS.

The three modes of a MOSFET are:

- Cut-off: $V_{GS} < V_{th}$
- Triode (linear): $V_{GS} > V_{th}$

  $V_{DS} < V_{GS} - V_{th}$
- Saturation: $V_{GS} > V_{th}$

  $V_{DS} \geq V_{GS} - V_{th}$

Body effect:

When a -ve voltage is applied on the body of the transistor, it increases the depletion layer formed on the n^+ junctions and thus, increasing the properties of NMOS like I_{DS} and V_{th}.

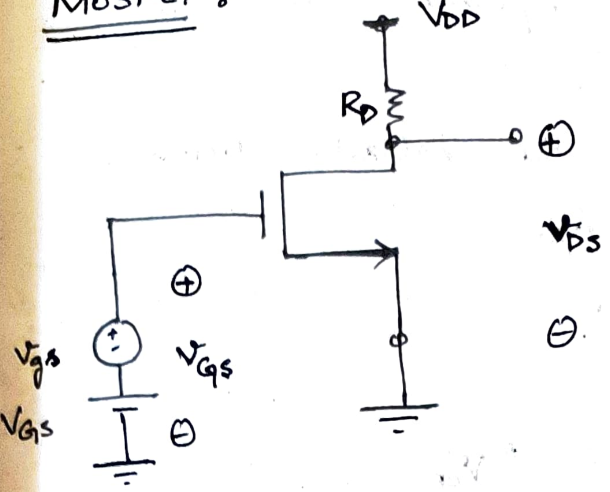
Breakdown:

When V_{DS} is huge, the channel pinch off shifts closer to source and the depletion layer covers most of the channel, allowing carriers to move through it ~~and carrying~~ causing ~~an~~ ~~overshoot~~ overshoot in current.

Note: This can damage the MOSFET in some cases. Hence, even preparing ICs is done in conditions ~~[illegible]~~ where voltage/charge fluctuation is very low.

Transistor Amplifier:

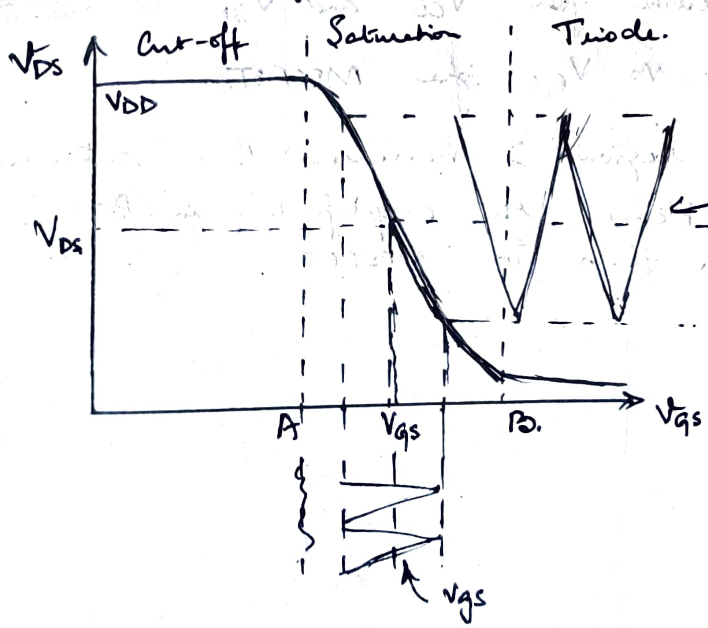
MOSFET:



Notation:

$$\underbrace{v_{DS}}_{\text{Mix of AC and DC}} = \underbrace{V_{DS}}_{\text{Purely DC}} + \underbrace{v_{ds}}_{\text{Purely AC.}}$$

Characteristic of a MOSFET (v_{DS} vs v_{GS}):



The MOSFET can be used as an amplifier in the saturation region, since the slope is linear in that region.

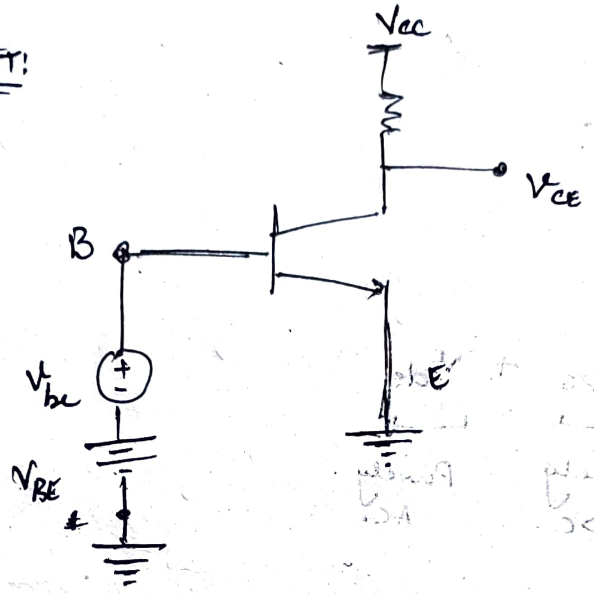
A DC voltage V_{GS} is applied on the gate, and a ~~small~~ DC voltage V_{DS} is observed.

A small AC voltage v_{gs} is then applied.

<u>Note:</u> When signal amplitude increases, the linearity ~~might~~ not remain intact.

Hence, the middle of the saturation region is generally chosen as V_{GS}.

<u>BJT:</u>

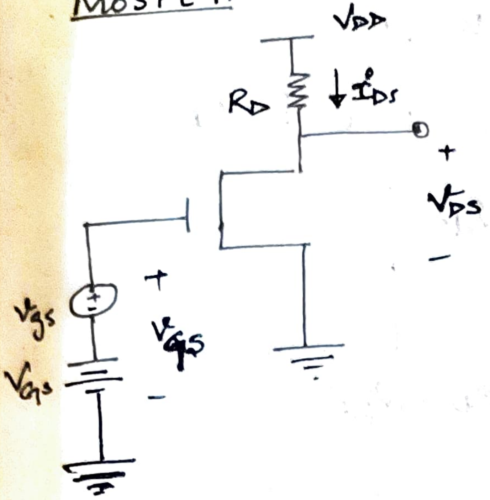


The characteristic for V_{CE} and V_{BE} is similar to that of V_{DS} vs V_{GS} for MOSFETs.

The active region is narrower than saturation in BJT. Hence, the amplification in BJT is much larger than in MOSFET.

Gain for a small signal:

<u>MOSFET:</u>



$$I_{DS} = \frac{1}{2}(k_n)\left[V_{GS} - V_{th}\right]^2$$

$$V_{DS} = V_{DD} - I_{DS} R_D.$$

$$i_{DS} = \frac{1}{2}k_n\left[v_{GS} - V_{th}\right]^2$$

$$= \frac{1}{2}k_n\left[(V_{GS} - V_{th}) + v_{gs}\right]^2$$

$$= \frac{1}{2}k_n\left[(V_{GS} - V_{th})^2 + 2(V_{GS} - V_{th})v_{gs} + v_{gs}^2\right].$$

when $v_{gs} \ll V_{GS} - V_{th}$, $v_{gs}^2 \ll$ rest term.

$$\approx \frac{1}{2}k_n^2(V_{GS} - V_{th})^2 + k_n(V_{GS} - V_{th})v_{gs}.$$

$$\approx I_{DS} + i_{ds}.$$

$$\Rightarrow i_{ds} = k_n(V_{GS} - V_{th})v_{gs}$$

$$= g_m v_{gs}.$$

where $g_m = \dfrac{i_{ds}}{v_{gs}} = k_n(V_{GS} - V_{th}) = \dfrac{2I_{DS}}{V_{GS} - V_{th}}$

$=$ Transconductance gain

$$v_{DS} = V_{DD} - i_{DS} R_D$$

$$= V_{DD} - [I_{DS} + i_{ds}] R_D$$

$$= (V_{DD} - I_{DS} R_D) + (-i_{ds} R_D)$$

$$= V_{DS} + v_{ds}.$$

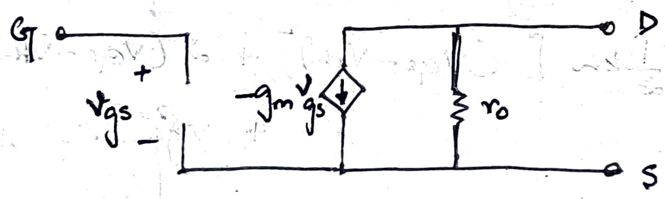
$$\Rightarrow v_{ds} = -i_{ds} R_D$$

$$= -\cancel{v_{gs}}\, g_m R_D \cdot v_{gs}.$$

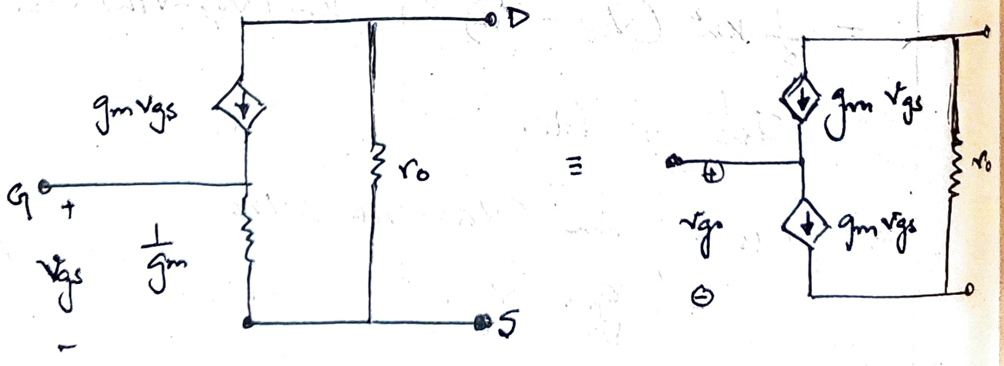
$$\Rightarrow \frac{v_{ds}}{v_{gs}} = -g_m R_D.$$

Small signal equivalent model:

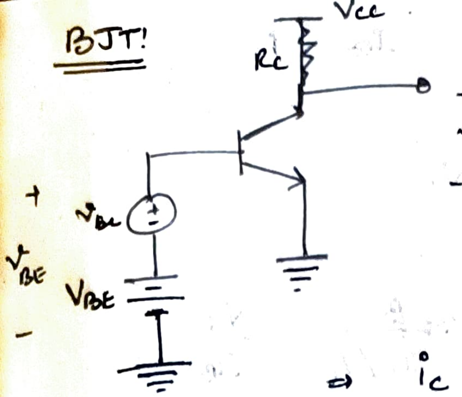
π - Model:



T - Model:



BJT!



$$I_C = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

$$V_{CE} = V_{CC} - I_C \cdot R_C.$$

$$v_{BE} = V_{BE} + v_{be}.$$

$$\Rightarrow \quad i_C = I_S \cdot e^{v_{BE}/V_T}$$

$$= I_S \, e^{(V_{BE} + v_{be})/V_T}$$

$$= \left[I_S \, e^{V_{BE}/V_T}\right]\left(e^{v_{be}/V_T}\right)$$

$$\left[\text{for } v_{be} \ll V_T \;,\; e^{v_{be}/V_T} \approx 1 + \frac{v_{be}}{V_T}\right]$$

$$i_C = I_C \left(1 + \frac{v_{be}}{V_T}\right)$$

$$\Rightarrow \quad i_C = I_C + \frac{I_C}{V_T} \cdot v_{be} = I_C + i_c$$

$$\Rightarrow \quad i_c = \frac{I_C}{V_T} v_{be} = g_m v_{be}$$

$$\Rightarrow \quad g_m = \frac{i_c}{v_{be}} = \frac{I_C}{V_T}$$

$$v_{CE} = V_{CC} - i_C \cdot R_C$$

$$= V_{CC} - I_C R_C - i_c R_C$$

$$= V_{CE} + v_{ce}$$

$$\Rightarrow \quad v_{ce} = -g_m \cdot R_C \cdot v_{be}$$

$$\Rightarrow \quad \frac{v_{ce}}{v_{be}} = -g_m R_C.$$

$$i_B = \frac{i_C}{\beta} = \frac{I_C + i_c}{\beta} = I_B + i_b$$

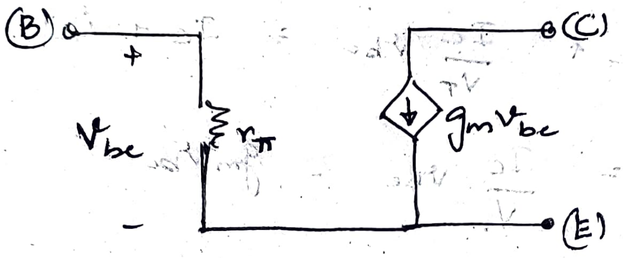
$$\Rightarrow i_b = \frac{i_c}{\beta} = \frac{g_m}{\beta} v_{be}$$

$$\Rightarrow r_\pi = \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = \frac{\beta}{I_C/V_T} = \frac{V_T}{I_B}$$

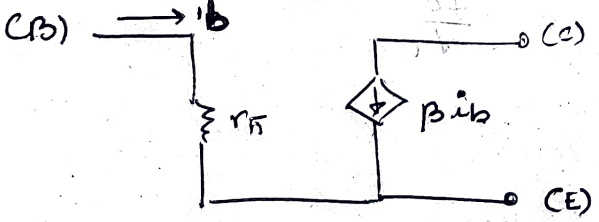
Illy, $r_e = \frac{v_{be}}{i_e} = \frac{\alpha}{g_m} = \frac{V_T}{I_E}$

Equivalent model:

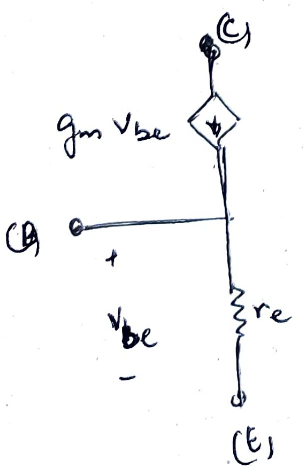
π- Model:



(or)



T- Model:



or