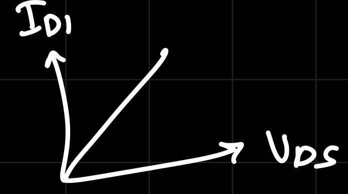
$V_{DS} \uparrow \rightarrow$ Channel conducts $\rightarrow I_D \uparrow$ linearly

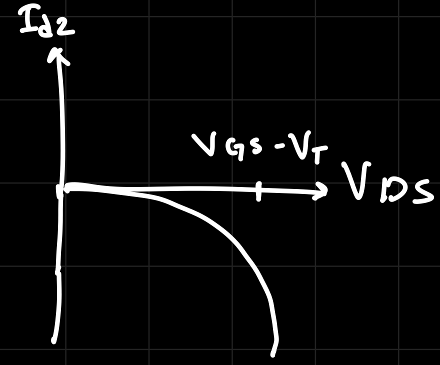
as $V_{DS} >> \rightarrow$ Channel conductivity $\downarrow \rightarrow I_d \downarrow$

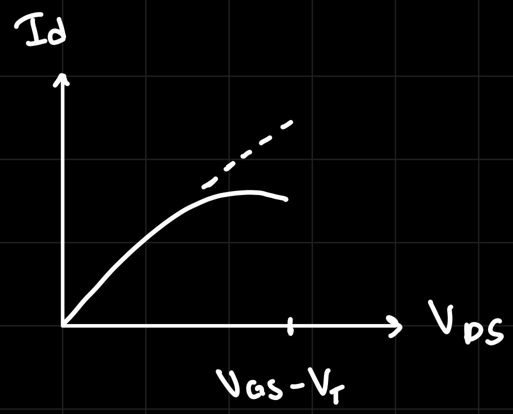
$$I_D = I_{D1} + I_{D2}$$

$$I_{D1} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T) V_{DS}$$



$$I_{D2} = \frac{-1}{2} \mu_n C_{ox} \frac{W}{L} V_{DS}^2$$





for small V_{DS}, $I_D \simeq I_{D1} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T) V_{DS}$

$$R_{DS} = \frac{V_{DS}}{I_{D1}} = \frac{1}{\mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)}$$

This approximation works for $|I_{d1}| >>> |I_{D2}|$

which happens when $(V_{GS} - V_T) >>>> \frac{1}{2} V_{DS}$

> Triode Region

$$R_{DS} = \frac{V_{DS}}{I_{D1}} = \frac{1}{\mu_n C_{ox} \frac{W}{L}(V_{GS}-V_T)} \quad \text{for } V_{DS} \lll 2(V_{GS}-V_T)$$

In a MOSFET in saturation I_D and V_{DS} are independent ✗

↓

wrong assumption because the resistance into Drain → ∞ (const current)

→ pinch off region moves towards SRC terminal

→ for $V_{DS} \gg V_{DS\,sat}$, the net additional potential gets reflected in the depletion region ($\vec{E}$ field)

$$I_{D\,sat} = \mu_n C_{ox} \frac{W}{L}(V_{GS}-V_T)^2$$
(old)

new $I_{D\,sat}$ = ? assuming channel length modulation

↓

$$L \to (L-\Delta L)$$

$$I_D = \frac{1}{2}\mu_n C_{ox} \frac{W}{(L-\Delta L)}(V_{GS}-V_T)^2$$

$$= \frac{1}{2}\mu_n C_{ox} \frac{W}{L} \times \left(1-\frac{\Delta L}{L}\right)^{-1}(V_{GS}-V_T)^2$$

↳ $\frac{\Delta L}{L} \lll 1$

binomial expansion

$$(1+x)^{-1} = 1 - x + \frac{x^2}{2!} + \cdots$$

since $x = -\frac{\Delta L}{L}$ and $x^2 <<<$,

neglecting terms after order = 1

$$(1+x)^{-1} = 1 - x \quad \text{(approx)}$$

$$i_D = \mu_n C_{ox} \frac{W}{L} \times \left(1 + \frac{\Delta L}{L}\right)(V_{GS} - V_T)^2$$

$\Delta L \propto V_{DS}$

$\Delta L = \lambda' V_{DS}$

↳ processed parameter

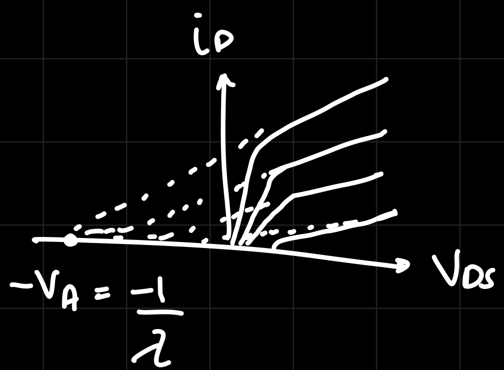
let $\lambda = \frac{\lambda'}{L}$

$$\frac{\Delta L}{L} = \lambda V_{DS}$$

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

now, we observe that $i_D \propto V_{DS}$

similar situation as early effect in BJT



$i_D = 0$

$1 + \lambda V_{DS} = 0$

$\lambda V_{DS} = -1$

$V_{DS} = \frac{-1}{\lambda}$

$V_A = \frac{1}{\lambda}$

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

$$\left[\frac{\partial i_D}{\partial V_{DS}}\right]^{-1} = r_o \quad \text{(resistance)}$$

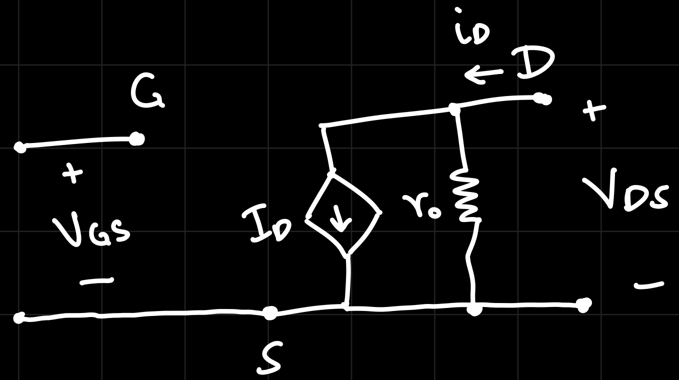
$$= \Big(\underbrace{\tfrac{1}{2}\mu_n C_{ox}\tfrac{W}{L}(V_{GS}-V_T)^2}_{I_{D\,\text{previous}}^{sat}}\lambda\Big)^{-1}$$

$$r_o = \left(\lambda I_{D\,prev}^{sat}\right)^{-1}$$

$$\boxed{r_o = \frac{V_A}{I_{D\,prev}^{sat}}}$$

DC model

Note: $I_{GS} = 0$ ∵ insulator (MO)



Similar to π model of BJT

$$r_o = \frac{V_A}{I_D}$$

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

$$I_D = \frac{i_D}{1+\lambda V_{DS}}$$

$$r_o = \frac{V_A}{I_D} = \frac{V_A}{i_D} \times (1+\lambda V_{DS}) = \frac{V_A}{i_D}\left(1+\frac{V_{DS}}{V_A}\right)$$

PMOS

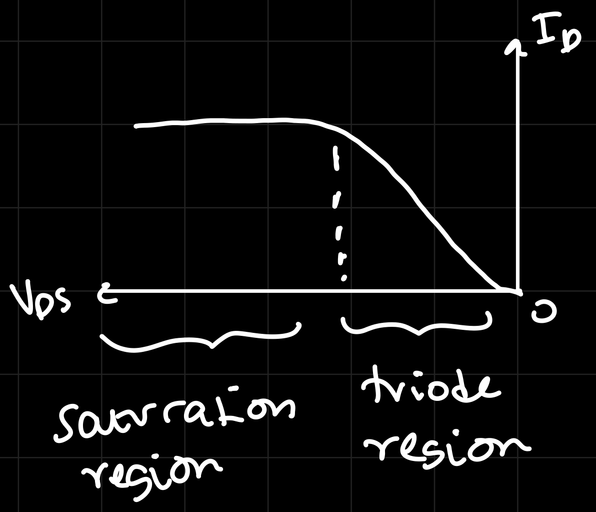
↳ n type substrate

↳ -ve V_{GS} to attract holes

majority carrier ↵

↳ I_D from $S \rightarrow D$

because e^- : $D \rightarrow S$



DC Analysis

(5 steps)

① ASSUME

② ENFORCE (Id equations, $I_G = 0$, V_{DS}? V_{GS}?)

for Triode region:

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

for saturation region:

$$I_d = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)^2$$

④ CHECK

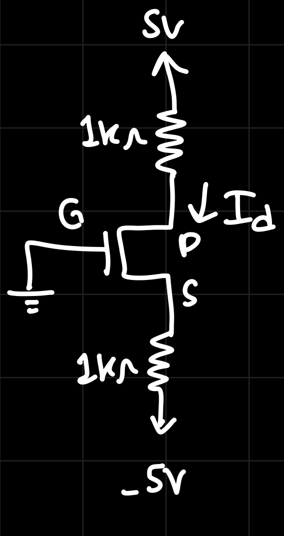
cutoff: $V_{GS} < V_T$

triode: $V_{DS} < V_{GS} - V_T$ and $V_{GS} > V_T$

saturation: $V_{DS} >> V_{GS} - V_T$ and $V_{GS} > V_T$

eg: assume region of operation

↳ saturation



neglecting early effect

$$I_d = \underbrace{\frac{1}{2} \mu_n C_{ox}}(V_{GS} - V_T)^2$$

given $= 0.4\,mA/V^2$ and $V_T = 2V$

$$I_D = 0.4(V_{GS} - 2)^2 \quad — ①$$

$$0 - V_{GS} - 1K(I_D) = -5$$

$$5 - V_{GS} - 1K I_D = 0$$

$$V_{GS} = 5 - 1000 I_D \rightarrow I_D = \frac{5 - V_{GS}}{10^3} \quad \text{--- ②}$$

$$I_D = 0.4(3 - 1000 I_D)^2$$

$$I_D = 0.4(9 + 10^6 I_D^2 - 6000 I_D)$$

$$-5 + 1K I_D + V_{DS} + 1K I_D = +5$$

$$V_{DS} = 10 - (2 \times 10^3 I_D) \quad \text{--- ③}$$

$$\frac{5 - V_{GS}}{10^3} = 0.4(V_{GS}^2 + 4 - 4V_{GS})$$

$$5 - V_{GS} = 400(V_{GS}^2 + 4 - 4V_{GS})$$

$I_d = 1.24mA$ $\qquad$ $3.76V = V_{GS}$

$V_{DS} = 7.52V$

for sat $\rightarrow$ $V_{DS} >> V_{GS} - V_T$ and $V_{GS} > V_T$

Verified ✓