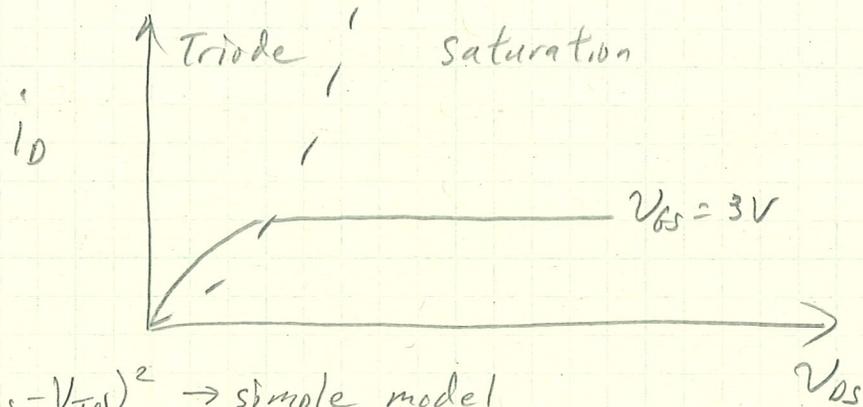


1) More on NMOS Transistors

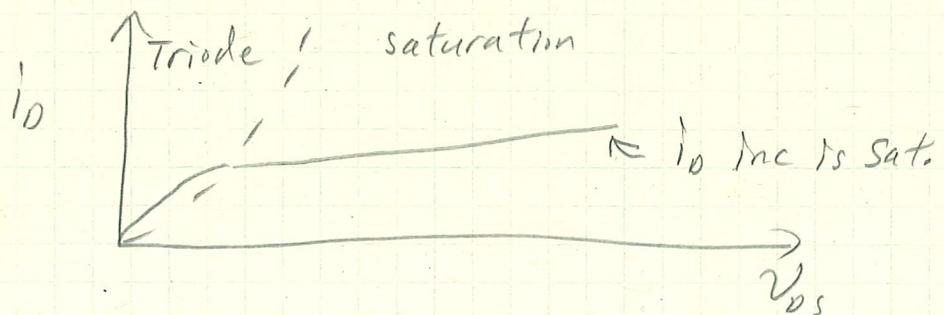
a.

$V_{TN} = 1V$



$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 \rightarrow \text{simple model}$$

Actually:



inc in i_D in Sat mode is called
Channel - Length Modulation

\rightarrow the effective $\frac{W}{L}$ becomes $\frac{W}{L_m - \Delta L}$, which models pinch-off where the length of the conductive inversion layer under the gate oxide decreases as V_{DS} increases

\therefore a more accurate model for i_D in Saturation

$$i_D = \frac{1}{2} k_n' \left(\frac{W}{L} \right) (V_{GS} - V_{TN})^2 (1 + \lambda V_{DS})$$

$\lambda \equiv$ channel-length modulation parameter, $[\lambda] = V^{-1}$
typically: $0V^{-1} \leq \lambda \leq 0.2V^{-1}$

\rightarrow so the effect is usually small

b. When $V_B \neq V_S \rightarrow$ or $V_{SB} \neq 0V$

\rightarrow this results in "substrate sensitivity" or "body effect"

$$\rightarrow V_{TN} = V_{T0} + \gamma (\sqrt{V_{SB} + 2\phi_F} - \sqrt{2\phi_F})$$

where: V_{T0} = zero-substrate bias value for V_{TN} , in V

γ = body-effect parameter, in \sqrt{V}

$2\phi_F$ = surface potential parameter, in V

The Jaeger textbook uses $2\phi_F = 0.6V$, with values of $V_{T0} = 1V$ and $\gamma = 0.75\sqrt{V}$ common

note: when $V_{SB} = 0V$, $V_{TN} = V_{T0} = 1V$ {common value}

\rightarrow Complex digital MOSFET circuits often have $V_{SB} \neq 0V$

c. Capacitances in the MOSFET

\rightarrow several capacitances exist in the MOSFET, which limit high-frequency operation, including:

- ① C_{GC} \rightarrow between the Gate and the channel
- ② C_{GS} \rightarrow " " " " " Source
- ③ C_{GD} \rightarrow " " " " " Drain
- ④ C_{SB} \rightarrow " " Source " " Bulk (substrate)
- ⑤ C_{DB} \rightarrow " " Drain " " Bulk (substrate)

\rightarrow some of these capacitances vary with MOSFET operating mode

d. Cutoff Frequency

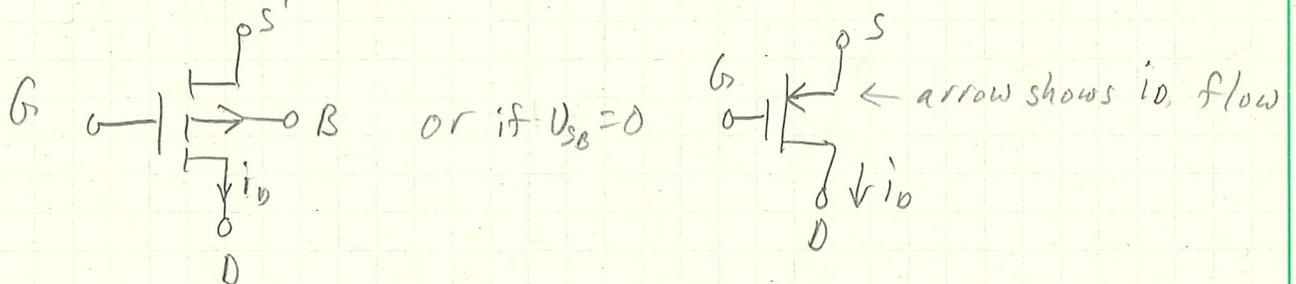
$f_T \equiv$ Cutoff Frequency \rightarrow highest useful frequency of operation for the transistor. It cannot provide amplification above this frequency

$$f_T = \left(\frac{1}{2\pi}\right) \frac{g_m}{C_{GC}} = \left(\frac{1}{2\pi}\right) \frac{\mu_n}{L^2} (V_{GS} - V_{TN})$$

since the MOSFET designer selects W and $L \rightarrow \frac{W}{L}$, he/she can tailor f_T , i_D , and R_{on} by selecting appropriate values for W and L

2) PMOS Transistors

\rightarrow Complementary to NMOS Transistors



with PMOS: $V_S \geq V_D$, $V_{SG} \geq 0$, i_D enters Source and leaves Drain

V_{TP} = PMOS threshold voltage

$V_{TP} < 0$, $V_{TP} = -1V$ typical

with $V_{SB} \neq 0$: $V_{TP} = V_{T0} - \gamma(\sqrt{|V_{BS} - 2\phi_F|} - \sqrt{2\phi_F}) \rightarrow$ Body Effect

Cutoff: $V_{GS} - V_{TP} \geq 0$: $i_D = 0A$

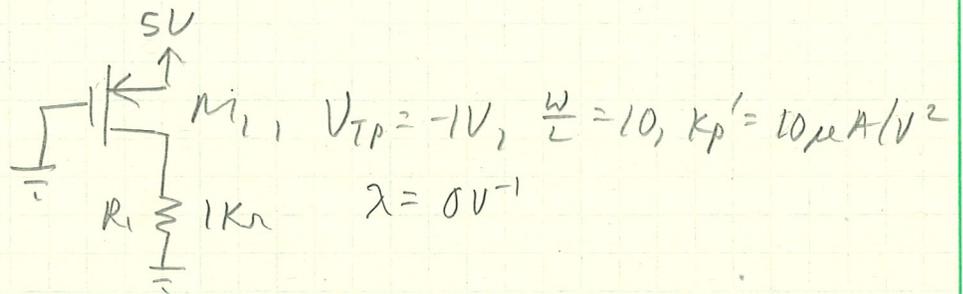
Triode: $V_{GS} - V_{TP} \leq 0$ and $|V_{DS}| \geq |V_{GS} - V_{TP}|$

$$i_D = K_p' \left(\frac{W}{L}\right) (V_{GS} - V_{TP} - \frac{V_{DS}}{2}) V_{DS}$$

Saturation: $V_{GS} - V_{TP} \leq 0$ and $|V_{DS}| \geq |V_{GS} - V_{TP}|$

$$i_D = \frac{1}{2} K_p' \left(\frac{W}{L}\right) (V_{GS} - V_{TP})^2 (1 + \lambda |V_{DS}|)$$

Example PMOS circuit



$$V_{GS} = -5V$$

$$V_{GS} - V_{TP} = -5 - (-1) = -4V < 0V \therefore M_1 \text{ is on}$$

Assume saturation mode

$$\begin{aligned} \therefore i_D &= 0.5 K_P' \left(\frac{W}{L}\right) (V_{GS} - V_{TN})^2 \\ &= 0.5 (10 \times 10^{-6}) (10) (-5 - (-1))^2 \\ &= 0.8 \text{ mA} \end{aligned}$$

$$\begin{aligned} V_D &= 0 + i_D R_1 \\ &= 0.8 \times 10^{-3} (1000) \\ &= 0.8V \end{aligned}$$

$$V_{DS} = 0.8 - 5 = -4.2V$$

$$|-4.2| > |-5 - (-1)| \therefore \text{in Saturation (Barely!)}$$

What is R_{on} for M_1 ?

$$R_{on} = \frac{V_{SD}}{i_D} = \frac{4.2}{8 \times 10^{-4}} = 5250 \Omega$$

If R_1 were much larger, M_1 would have been in the Triode mode

Example w/ f_T

What is f_T for a NMOS Transistor with

$L = 10\mu\text{m}$, $V_{TN} = 1\text{V}$, $V_{GS} = 5\text{V}$, and $\mu_n = 1400\text{ cm}^2/\text{V}\cdot\text{s}$?

$$L = 10\mu\text{m} = 10 \times 10^{-6}\text{ m} = 10 \times 10^{-4}\text{ cm}$$

$$f_T = \left(\frac{1}{2\pi}\right) \frac{\mu_n}{L^2} (V_{GS} - V_{TN})$$

$$= \left(\frac{1}{2\pi}\right) \left(\frac{1400}{(10 \times 10^{-4})^2} (5-1)\right)$$

$$= 891\text{ MHz}$$