5720/6720: Lecture #4

Jan. 17

- HW due
- Lecture notes will be posted online.
- I will put reading assignments in notes (do it before attempting homework)

Ch. 1 reading: 1.1 (ignore graded junctions, forward biased junctions)
1.2 (all)
1.5 (for reference)

Up Until Now: - reviewed MOSFET characteristics at the device level.

Summary of Important Large Signal Concepts & Equations

① **Diodes**: We only care about diodes in that a MOSFET has reverse biased PN junctions for which we want to know the parasitic capacitances.

Built in potential: $\boxed{\Phi_0 = \frac{kT}{q} \cdot \ln\left(\frac{N_A N_D}{n_i^2}\right)}$

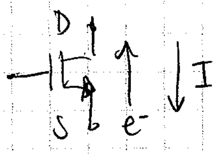
Reverse biased junction capacitance: $\boxed{C_j = \frac{C_{j0}}{\sqrt{1 + V_R/\Phi_0}}}$, where $\boxed{C_{j0} = \sqrt{\frac{q \cdot \varepsilon_S \cdot \varepsilon_0}{2 \cdot \Phi_0} \cdot \frac{N_A N_D}{(N_A + N_D)}}}$

K_S in text

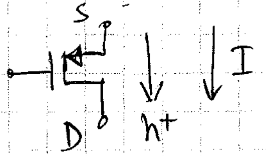
Notes:
- → Units are per unit area.
- → These are small signal equations, valid for a particular bias point.

② **MOSFETs**: MOSFETs are symmetrical devices, designation of drain or source is determined by biasing and direction of current flow.
- carriers flow from source to drain

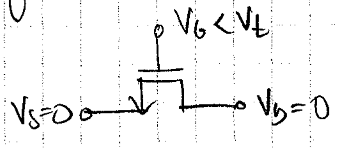
nMOS:



pMOS:

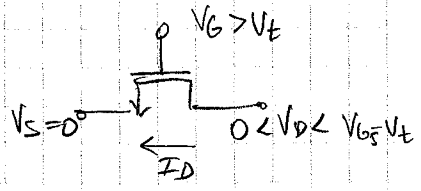


Three important operating regions: 1) Cutoff: $V_{GS} < V_t$, no conductive channel forms



$\boxed{I_D = 0}$ (1)

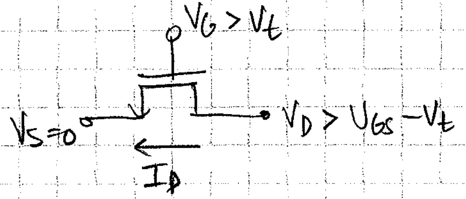
2) Triode: If we increase $V_{GS} > V_t$, conductive channel forms. Now if we raise V_D a current will flow



$\boxed{I_D = \mu_n C_{ox} \frac{W}{L}\left[(V_{GS} - V_t) \cdot V_{DS} - \frac{V_{DS}^2}{2}\right]}$ (2)

- transistor functions like a resistor

3) Active/Saturation: For the same V_{GS}, if we continue to increase V_D, channel pinches off and current does not increase further. (to a first order approx.)



$$\boxed{I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)(V_{GS}-V_t)^2} \quad (3)$$

- transistor acts like a current source.

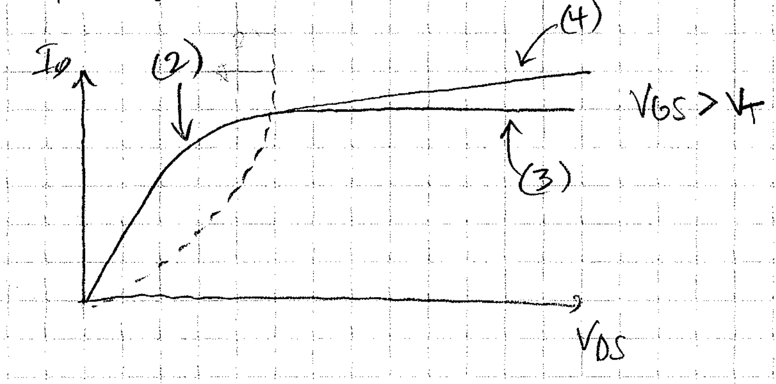
→ In reality, as V_{DS} increases further it does have a small effect on I_D.
- to model these effects we can add a multiplying factor to (3):

$$\boxed{I_D = \frac{\mu_n C_{ox}}{2}\left(\frac{W}{L}\right)(V_{GS}-V_t)^2(1+\lambda \cdot V_{DS})} \quad (4)$$

$\lambda = \frac{1}{V_A}$ don't worry about calculating this.

- Slightly different from expression in text.

Plot:



→ Another important large signal equation is for body effect, which changes V_t in (2), (3), and (4):

Body effect:
$$\boxed{V_{tn} = V_{tn0} + \gamma\left(\sqrt{V_{SB}+|2\Phi_F|} - \sqrt{|2\Phi_F|}\right)}$$

γ: don't worry about calculating this

→ Final important equation is for charge stored in channel, which can be important when designing switches:

$$\boxed{Q_{ch} = W \cdot L \cdot C_{ox}(V_{GS}-V_t)} \quad \text{where} \quad \boxed{C_{ox} = \frac{\epsilon_{ox}\epsilon_0}{t_{ox}}}$$

t_{ox}: oxide thickness.

PMOS Transistors

→ All preceding equations have been for nMOS.
- exact same equations can be used for pMOS by taking absolute values of everything (V_{GS}, V_t, V_{DS}) and then using common sense to decide in which direction current will flow. (from low voltage to high)

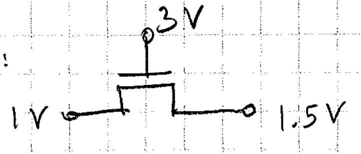
<u>Example</u>: For the following transistors, with $V_{tn} = |V_{tp}| = 1\,V$ and $V_{DD} = 5\,V$:

(a) Denote direction of current flow, and source & drain

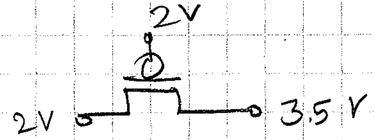
(b) Determine region of operation.

(c) Calculate I_D.

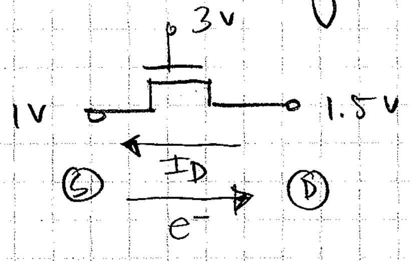
nmos:



pmos:



nmos: (a) Current flows from high to low voltage:



- majority carriers are electrons, which flow from source to drain

(b) $V_{GS} = 3 - 1 = 2\,V$, $> V_{tn} = 1\,V$, so not in cutoff.

$V_{DS} = 1.5 - 1 = 0.5\,V$, $< V_{eff} = V_{GS} - V_t = 2 - 1 = 1\,V$

$\therefore$ in <u>triode</u> region.

(c) $I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_t) V_{DS} - \frac{V_{DS}^2}{2} \right]$

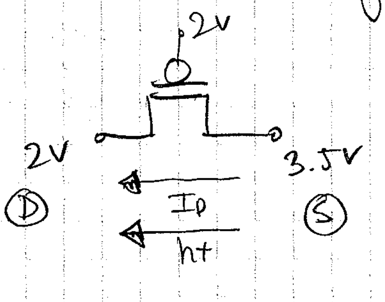
- body effect? $V_B = 0\,V$ (implied since not shown)

$\rightarrow V_{SB} = 1\,V$.

- calculate new V_t using $V_t = \underset{\substack{\uparrow \\ 1V}}{V_{tn0}} + \overset{\text{given}}{\gamma} \left(\sqrt{\underset{\substack{\uparrow \\ 1V}}{V_{SB}} + |2\Phi_F|} - \sqrt{\underset{\substack{\uparrow \\ \text{constant}}}{|2\Phi_F|}} \right)$

- finally, find I_D using this value in equation above.

pmos: (a) Current flows from high to low voltage



- majority carriers are holes, which flow from source to drain.

(b) $|V_{GS}| = 3.5 - 2 = 1.5\,V$, $> |V_{tp}| = 1\,V$, not in cutoff.

$|V_{DS}| = 3.5 - 2 = 1.5\,V$, $> V_{eff} = |V_{GS}| - |V_{tp}| = 1.5 - 1 = 0.5\,V$

$\therefore$ in <u>active</u> (saturation) region.

(c) $I_D = \frac{\mu_n C_{ox}}{2}\cdot\frac{W}{L}\left(|V_{GS}|-|V_{tp}|\right)^2\left(1+\underset{\uparrow\text{ given}}{\lambda}|V_{DS}|\right)$

Body effect? $V_B = 5V$ (implied since not shown)

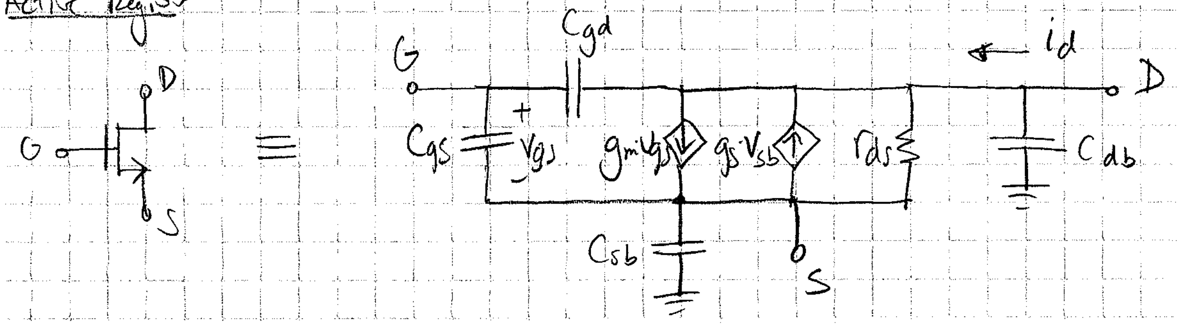
$\rightarrow |V_{SB}| = 5 - 3.5 = 1.5$ V.

- calculate V_t using $|V_t| = |V_{tp0}| + \gamma\left(\sqrt{|V_{SB}|+|2\Phi_F|} - \sqrt{|2\Phi_F|}\right)$
- finally, find I_D.

Small Signal Models

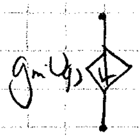
- small signal models depend on what region the transistor is in.

① Active Region

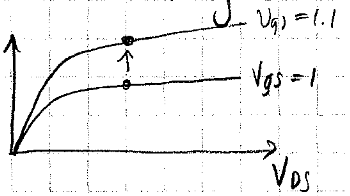


- same model used in 3110, but with extra capacitors and one extra transconductor.

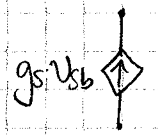
→ let's go through components one at a time and see where they come from



- models change in id for a change in v_{gs}:

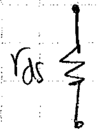


$\therefore g_m = \frac{\partial I_d}{\partial V_{GS}} = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_t) = \sqrt{2\mu_n C_{ox}\frac{W}{L}\cdot I_D}$

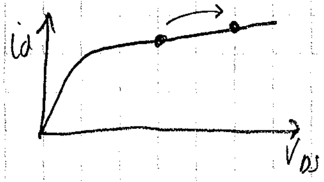


- models change in id due to increase in V_T coming from body effect
  - "back gate" effect
  - note direction is opposite to gm, since increasing V_{SB} reduces I_D.

⇨ $g_s = \frac{\partial I_D}{\partial V_{SB}} = \frac{\partial I_D}{\partial V_T}\,\frac{\partial V_T}{\partial V_{SB}} = \cdots$ (derivation in text) $= \frac{\gamma g_m}{2\sqrt{V_{SB}+2|\Phi_F|}}$



- models finite slope of id - V_{DS} curve (early effect)



$\frac{1}{r_{ds}} = \frac{\partial I_D}{\partial V_{DS}} = \cdots$ (derivation in text) $= \lambda\cdot I_D$

$\rightarrow r_{ds} = \frac{1}{\lambda\cdot I_D}$

↑ can calculate, but will usually be given to you