Lecture 15: MOSFETs III

- **Announcements**:
- HW#5 online and due Friday via Gradescope
- Lab#3 this week
  - Prelab due before lab next week
- Midterm 1 on Friday, Oct. 11
  - We have 7-9 p.m., 160 Kroeber Hall
  - Passed out a sample exam today and went through the Midterm Info Sheet
  - For the review session, please post on Piazza specific problems you would like covered
- My Monday Office Hours will move to 5-6 p.m. on Oct. 14 and thereafter
- I will be traveling Friday, Oct. 4, and Monday, Oct. 7, so these lectures will be pre-recorded and put online
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- Lecture Topics:
  - MOSFETs
    - —Structure and Operation
    - —Cutoff
    - —Linear Region
    - —Saturation
    - —Body Effect
    - —CV Curves
- ------------------------------------
- **Last Time**:
- Started saturation region MOS analysis
- Now, continue with this …

③ Saturation Region – ($v_{DS} \geq v_{GS} - V_{TN} \geq 0$)

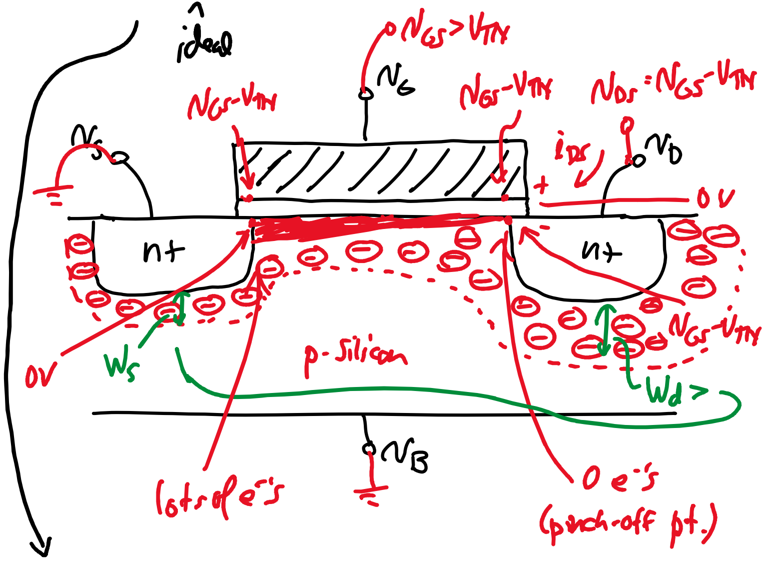
As $v_{DS}\uparrow$ → the voltage across the gate-to-substrate capacitor near the drain:

$$(v_{GS} - V_{TN} - \underset{\overset{\nearrow}{v_D}}{v(x)}) \rightarrow 0$$

↖ @ drain edge

∴ the inversion charge @ drain → 0

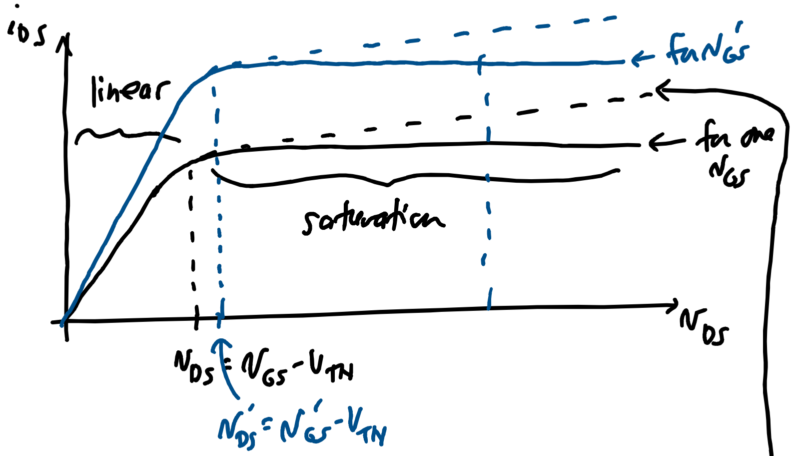
At this point, i_{DS} has reached its ^ideal maximum!



Plug in $v_{GS} - V_{TN} - v_{DS} = 0 \rightarrow v_{DS} = v_{GS} - V_{TN}$ in the i_{DS} equation:

$$\boxed{i_{DS} = \frac{1}{2}\mu_n C_{ox}'' \frac{W}{L}(v_{GS} - V_{TN})^2 \text{ for } v_{DS} = v_{GS} - V_{TN}}$$

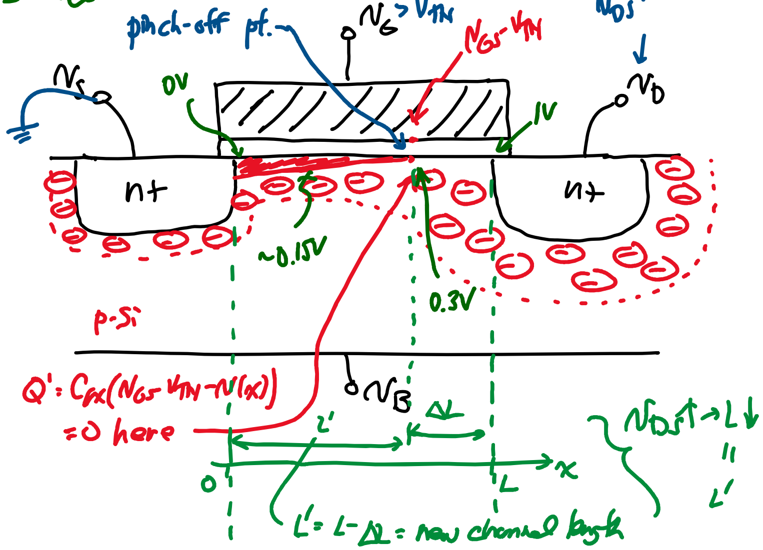
(onset of saturation)



⇒ as $v_{DS}\uparrow \to i_{DS} = \text{const.}$ (ideally) … but, due to 2nd order effects, i_{DS} actually still rises a bit

⇒ **Reason**: channel length modulation

Ex: $v_{GS} = 1V, V_{TN} = 0.7, v_{DS} = 1V \to v_{GS} - V_{TN} = 0.3V \therefore v_{DS} = 1V > v_{GS} - V_{TN}$



Remember:

$$i_{DS} = \frac{1}{2}\mu_n C''_{ox}\frac{W}{L'}(v_{GS} - V_{TN})^2 \to \text{if } \underbrace{L'\downarrow}_{\text{w/ } v_{DS}\uparrow} \to i_{DS}\uparrow$$

$$= \frac{1}{2}\mu_n C''_{ox}\frac{W}{L}\left(\frac{1}{1-\frac{\Delta L}{L}}\right)(v_{GS} - V_{TN})^2$$

$$= \frac{1}{2}\mu_n C''_{ox}\frac{W}{L}\underbrace{\left(\frac{L}{L-\Delta L}\right)}_{=}(v_{GS} - V_{TN})^2$$

$$\Delta L = f(v_{DS}) \to \underbrace{1 + \lambda v_{DS}}$$

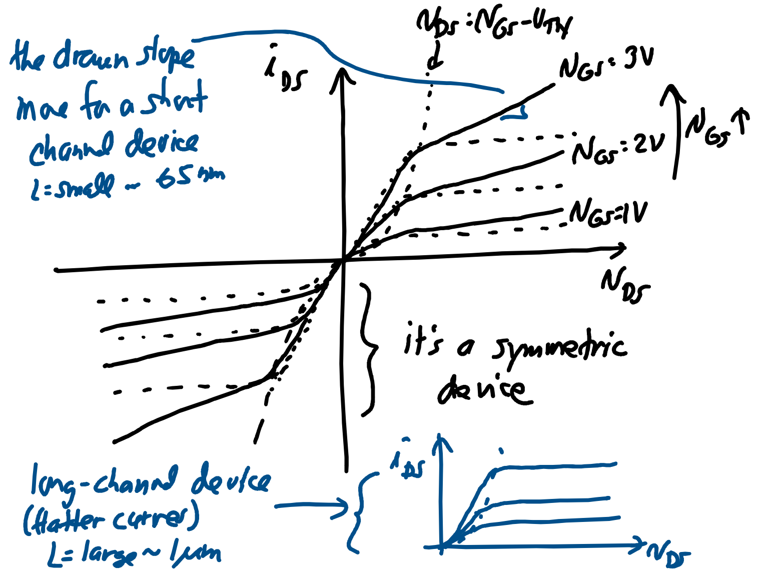
model the v_{DS} dependence

$$\therefore \boxed{i_{DS} = \frac{1}{2}\mu_n C''_{ox}\frac{W}{L}(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})}$$

(beyond the onset of saturation)

$\lambda \triangleq$ channel length modulation parameter

$(0.001V^{-1} \leq \lambda \leq 0.1V^{-1})$



Body Effect (Substrate Sensitivity)

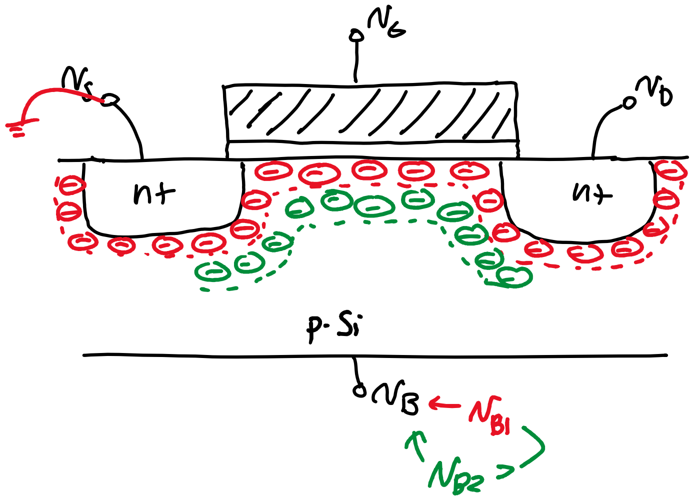
⇒ threshold voltage, V_{TN}, is a function of the substrate bias voltage: V_{SB}

→ Reason: (simple version)

as $V_{SB}\uparrow$ → max. channel depletion region gets larger (i.e., it can hold more charge)

↳ need more V_{GS} to invert the channel

↳ $V_{TN}\uparrow$



Basically: V_{TN} when $V_{SB}=0V$

$$V_{TN}=V_{T0}+\gamma\left(\sqrt{V_{SB}+2\phi_f}-\sqrt{2\phi_f}\right)$$

Where $V_{T0}\triangleq$ value of V_{TN} for $V_{SB}=0V$ [V]

$\gamma\triangleq$ body effect parameter [$\sqrt{V}$]

$2\phi_f\triangleq$ surface potential parameter [V]

For a typical NMOS transistor:

$-5V\le V_{T0}\le 5V$ → but usually 0.7V

↳ V_{T0}: (+) → enhancement mode NMOS

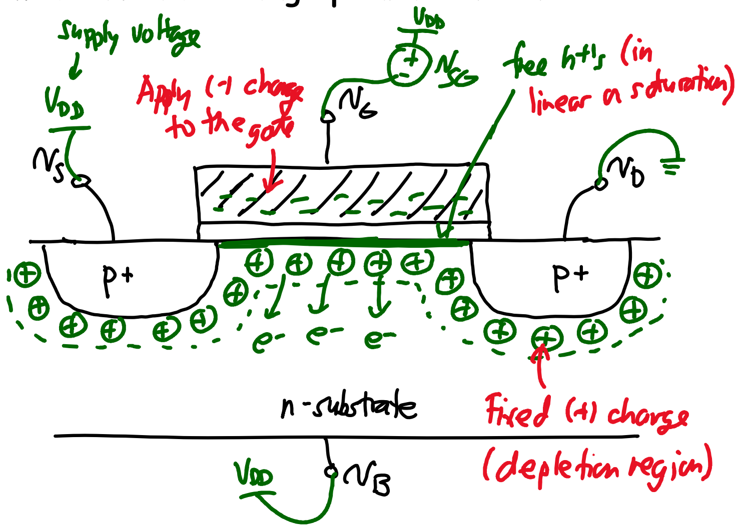
V_{T0}: (−) → depletion mode NMOS (but out of the scope of this class)

$0\le\gamma\le 3\sqrt{V}$ → typically, $0.5\sqrt{V}$

$0.3V\le 2\phi_f\le 1V$ → for us, generally 0.6V

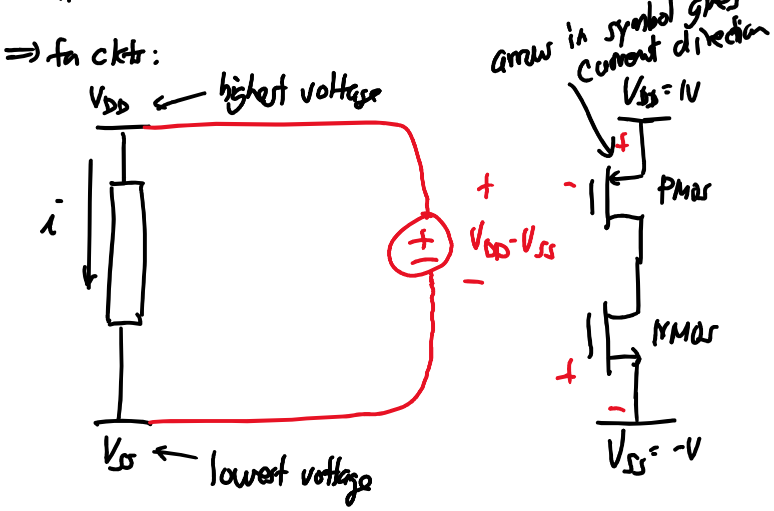
PMOS Transistors

- Basically, the reverse of NMOS transistors
- Physics basically the same, but the carriers are now h+ and the voltage polarities reverse

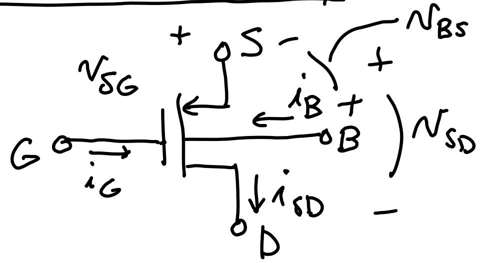


V_{TP} = (-) for an enhancement mode PMOS

⇒ for ckts:



PMOS Transistor Model Summary



① Cutoff Region: $(v_{SG} \le -V_{TP})$

$$i_{SD}=0$$

② Linear (or Triode) Region: $(v_{SG}+V_{TP} \ge v_{SD} \ge 0)$

$$i_{SD}=k_p\left(v_{SG}+V_{TP}-\frac{v_{SD}}{2}\right)v_{SD}$$

$$=\mu_p C_{ox}''\frac{W}{L}\left(v_{SG}+V_{TP}-\frac{v_{SD}}{2}\right)v_{SD}$$

③ Saturation Region: $(v_{SD} \ge v_{SG}+V_{TP} \ge 0)$

$$i_{SD}=\frac{1}{2}\mu_p C_{ox}''\frac{W}{L}(v_{SG}+V_{TP})^2(1+\lambda v_{SD})$$

$$=\frac{k_p}{2}(v_{SG}+V_{TP})^2(1+\lambda v_{SD})$$

where for all regions:

$k_p = k_p' \frac{W}{L} = \mu_p C_{ox}'' \frac{W}{L}$

$i_G = 0$ and $i_B = 0$

$V_{TP} = V_{T0} - \gamma\left(\sqrt{V_{BS} + 2\phi_f} - \sqrt{2\phi_f}\right)$

$\mu_p \triangleq$ h^+ mobility in the channel

$C_{ox}'' \triangleq$ gate oxide per unit area

$V_{T0} \triangleq$ threshold voltage w/ $V_{SB} = 0V$

$\gamma \triangleq$ body effect parameter

$2\phi_f$ = built-in surface potential $\approx 0.6V$