Lecture 15: MOSFETs III

- Announcements:
- HW#5 online and due Friday via Gradescope
- Lab#3 this week
  - Due week after next (since next week is the first midterm exam)
- Midterm 1: Friday, Oct. 5, from 5-6:30 p.m., in 277 Cory
- Lab Sections on different grading curves
  - Fairer for earlier lab sections
- Will be collecting names and student ID numbers for those who do not yet have access to the lab
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- Lecture Topics:
  - MOSFETs
    - —Channel Length Modulation
    - —Body Effect
  - Bipolar Junction Transistor (BJT)
    - —Regions of Operation
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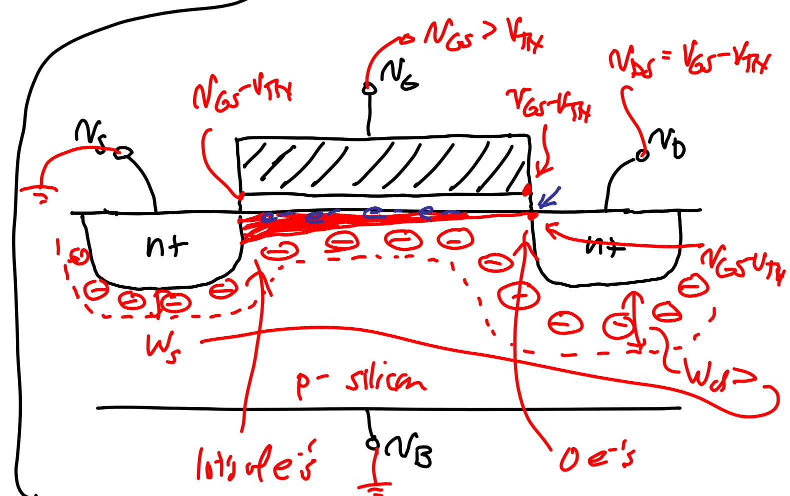
- Last Time:
- Started into channel length modulation
- Now, continue with this …

(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:

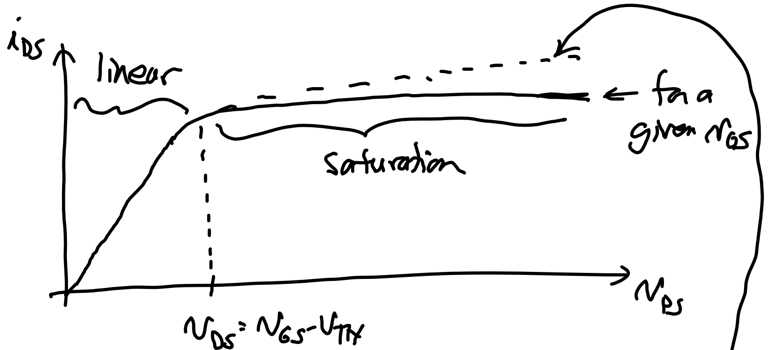
$(v_{GS} - V_{TN} - v(x)) \to 0$ @ the drain edge

At this point, i_{DS} has reached its ideal maximum! { ∴ the inversion charge @ the drain → 0!



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

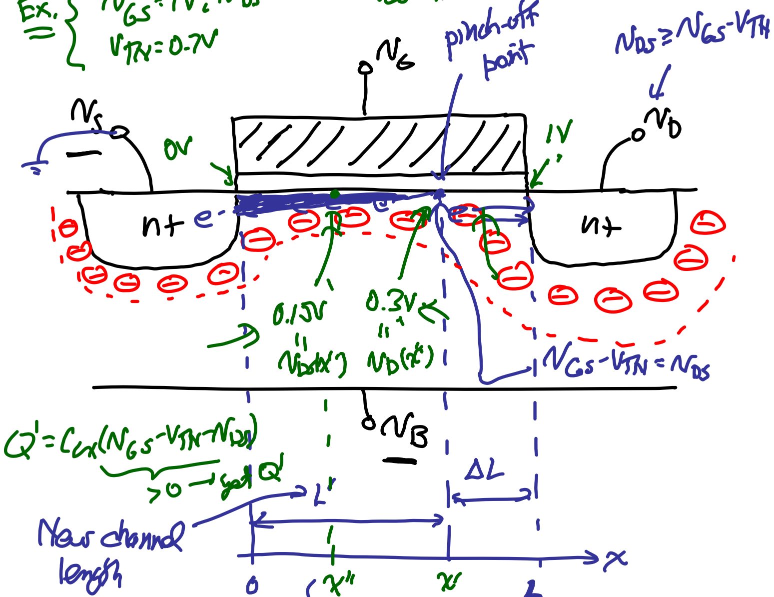
$$i_{DS} = \frac{1}{2}\mu_n C_{ox}'' \frac{W}{L}(v_{GS} - V_{TN})^2 \quad \text{for } v_{DS} = v_{GS} - V_{TN}$$



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

⇒ Reason: channel length modulation

Ex. $\begin{cases} v_{GS}=1V,\ v_{DS}=1V \\ V_{TN}=0.7V \end{cases}$ → $v_{GS}-V_{TN}=0.3V$ → ∴ $v_{DS}=1V > v_{GS}-V_{TN}$



∴ L → L' (i.e., it gets smaller)

∴ $i_{DS} = \frac{1}{2}\mu_n C_{ox}'' \frac{W}{L'}(v_{GS}-V_{TN})^2$ → if $L\downarrow \rightarrow i_{DS}\uparrow$ (w/ $v_{DS}\uparrow$)

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

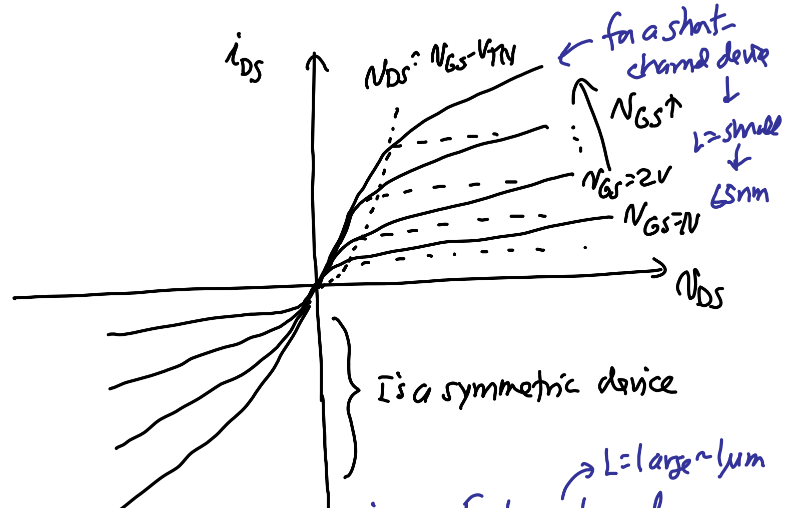
$= \frac{1}{2}\mu_n C_{ox}'' \frac{W}{L}\left(\frac{L}{L-\Delta L}\right)(v_{GS}-V_{TN})^2$

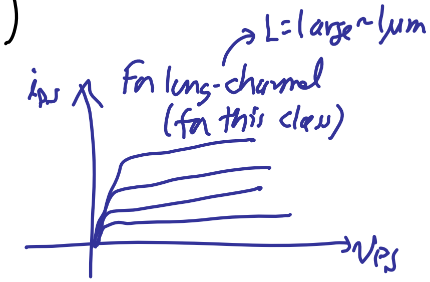
$\Delta L = f(v_{DS})$ → $= 1+\lambda v_{DS}$

saturation

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

$\lambda \triangleq$ channel length modulation parameter
$(0.001\,V^{-1} \leq \lambda \leq 0.1\,V^{-1})$





Body Effect (Substrate Sensitivity)

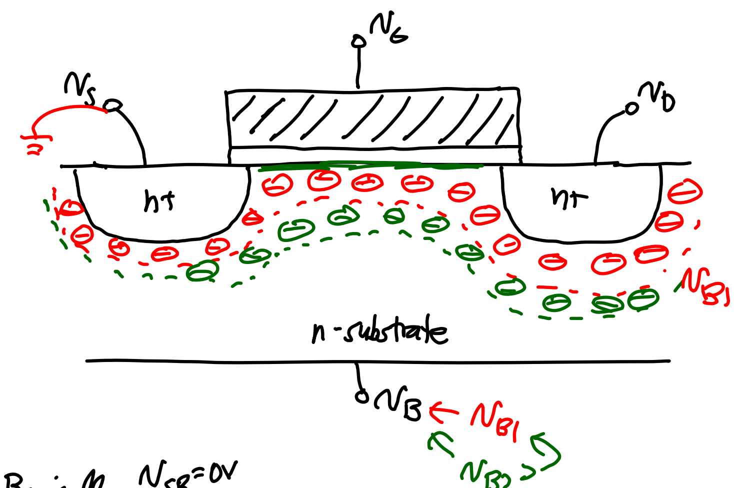
⇒ threshold voltage, V_{TN}, is a function of substrate bias voltage: v_{SB}

⇒ 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: $v_{SB}=0V$

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

where $V_{TO} \triangleq$ 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:

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

↳ $V_{TO}=(+)$ → enhancement mode NMOS

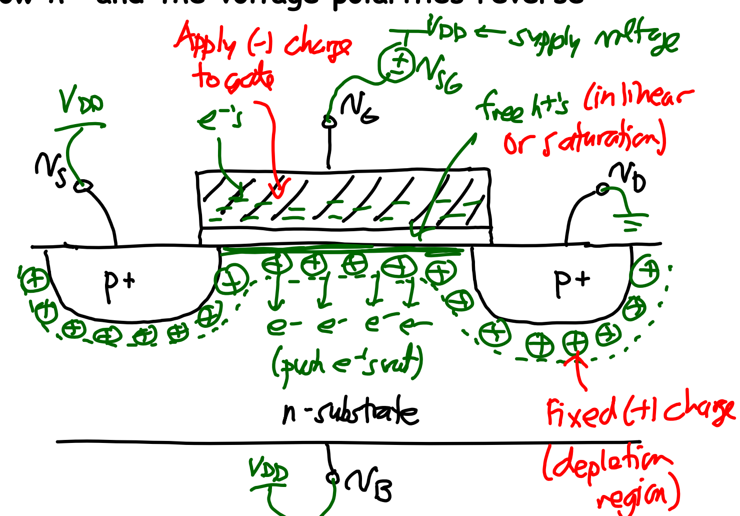
$V_{TO}=(-)$ → depletion-mode NMOS (but out of the scope of this class)

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

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

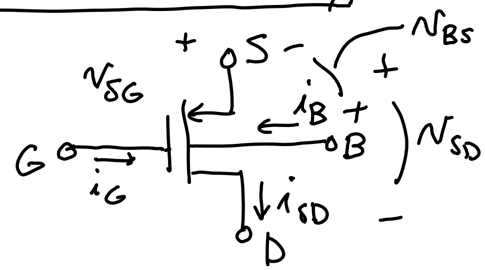
PMOS Transistors

- 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 PMOS

PMOS Transistor Model Summary



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

$$i_{SD} = 0$$

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

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

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

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

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

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

Where for all regions:

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

$$i_G = 0 \text{ and } i_B = 0$$

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

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

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

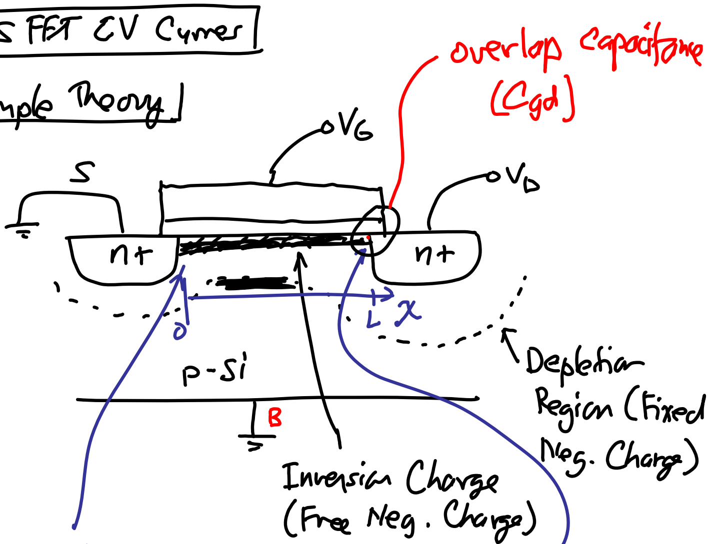
$V_{TO} \triangleq$ threshold voltage w/ $V_{SB} = 0V$

$\gamma \triangleq$ body effect parameter

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

MOS FET CV Curves

Simple Theory

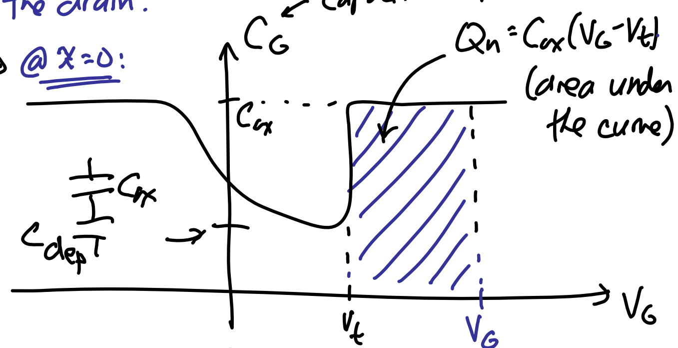


$Q'(x=0) = C_{ox}(V_{GS} - V_{TN})$

$Q'(x=L) = C_{ox}(V_{GS} - V_{TN} - V_{DS})$

Thus, the inversion charge thins down towards the drain.

@ $x=0$:



$C_G = \frac{dQ}{dV} = \frac{dQ_n}{dV}$ ← when inversion charge can keep up w/ the frequency