Lecture 14: MOSFETs II

- **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
- 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
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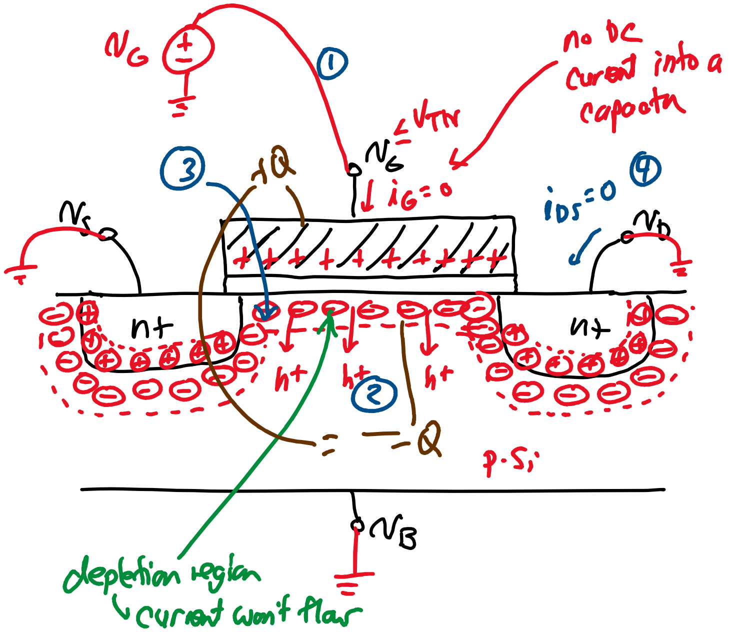
- **Last Time**:
- Started linear region MOS analysis
- Now, continue with this …

① Cutoff Region - ($v_{GS} \le V_{TN}$)



① – Application of v_G puts (+) charge on the gate → this induces (-) charge on the other side of the oxide

② – At this point, the easiest way to create (-) charge in the Si is for the h+ in the p-type substrate to move away from the channel area

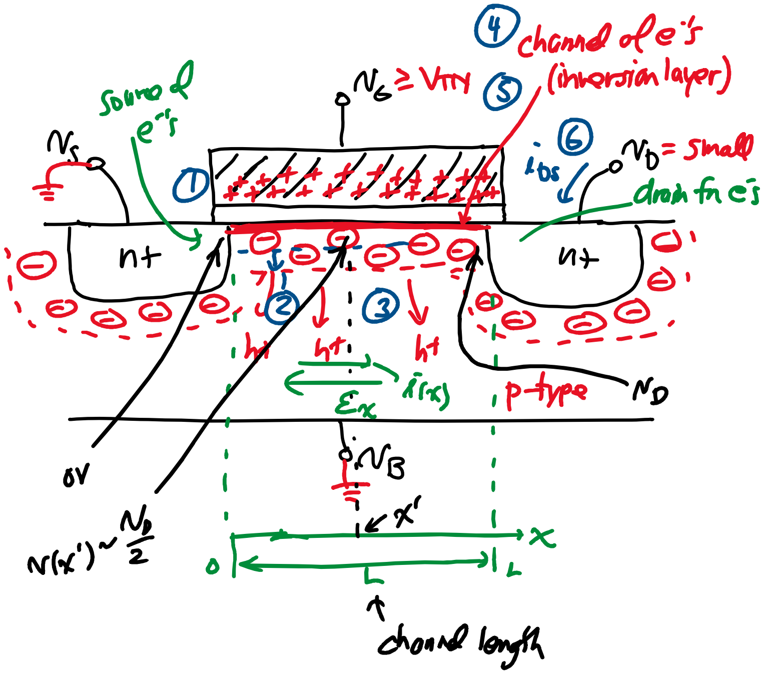
③ – i.e., a (-)ly charged depletion region forms in response to the initial (+) charge on the gate

④ – This is fixed charge that cannot conduct current → $i_{DS} = 0$

- As v_G rises:
  - ① – More (+) charge amasses on the gate
  - ② – The depletion region of fixed (-) charge grows to accommodate
  - ③ – Soon, however the depletion region becomes large enough that it becomes easier to obtain (-) charge (to match the gate's (+) charge) by taking it from the S/D regions!
    - Result: a channel of e-'s forms between the S&D n+ regions → inversion layer
    - This happens when $v_{GS} > V_{TN}$

② Linear Region: (or Triode Region)

$(v_{GS}-V_{TN} \geq v_{DS} \geq 0) \rightarrow$ i.e., v_{DS} = small



⑤ – Channel of e-'s → mobile → silicon in this region now a conductor

⑥ – An E-field generated by v_{DS} gives rise to drift current flow

Derive how much current i_{DS} flows as a function of voltages v_{GS} & v_{DS}:

⇒ the e- drift current at any point in the channel:

$$i(x) = Q'(x)v_x(x)$$

$Q'(x)$: e- charge per unit length

↙ Basically given by the charge on the gate-to-substrate capacitn: $q = CV$

$v_x(x)$: velocity of e-'s $\Big\} = -\mu_n \mathcal{E}_x$

$$Q'(x) = -WC''_{ox}(v_{GS} - V_{TN} - v(x))$$

$-$: e-'s

W: width of channel

$v(x)$: voltage in the channel @ location x → @ D: it's v_D
@ S: it's $v_S = 0V$

$C''_{ox} = \frac{\epsilon_{ox}}{t_{ox}} \triangleq$ oxide capacitance per unit area

where ϵ_{ox} = oxide permittivity $= 3.9\epsilon_o$

t_{ox} = oxide thickness [cm]

*

$$\star \Downarrow$$

$$i(x) = \left[-W C''_{ox}(v_{GS} - V_{TN} - v(x))\right]\left[-\mu_n \mathcal{E}_x\right]$$

$$\left[\mathcal{E}_x = -\frac{dv(x)}{dx}\right]$$

$$i(x) = -\mu_n C''_{ox} W (v_{GS} - V_{TN} - v(x)) \frac{dv(x)}{dx}$$

$$i(x)\,dx = -\mu_n C''_{ox} W (v_{GS} - V_{TN} - v(x))\,dv(x)$$

$$\int_0^L i(x)\,dx = -\int_0^{v_{DS}} \mu_n C''_{ox} W (v_{GS} - V_{TN} - v(x))\,dv(x)$$

But $i_{DS} = -i(x)$

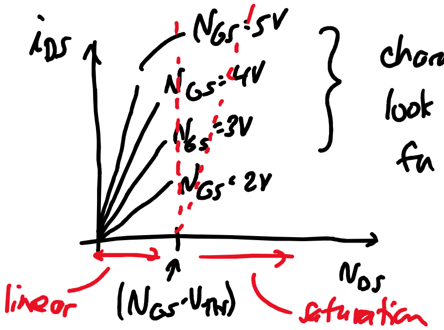
$$i_{DS} L = \mu_n C''_{ox} \overset{W}{\wedge} \left[(v_{GS} - V_{TN}) v_{DS} - \frac{v_{DS}^2}{2}\right]$$

$$\therefore \boxed{i_{DS} = \mu_n C_{ox} \frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right) v_{DS}}$$

(linear region) ↘ small v_{DS}

$v_{DS} < (v_{GS} - V_{TN})$

Linear Region IV Characteristic



} characteristic curves look fairly linear for small v_{DS}

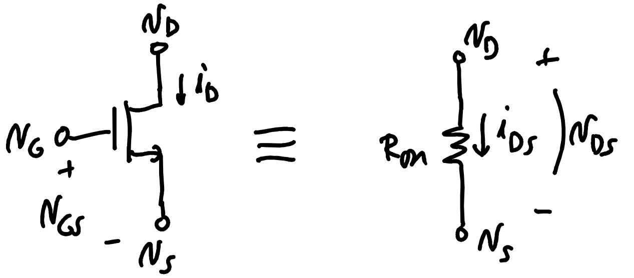
⇒ can define an equivalent small-signal (small v_{DS}) linear resistance for an MOS Xistor in the linear region:

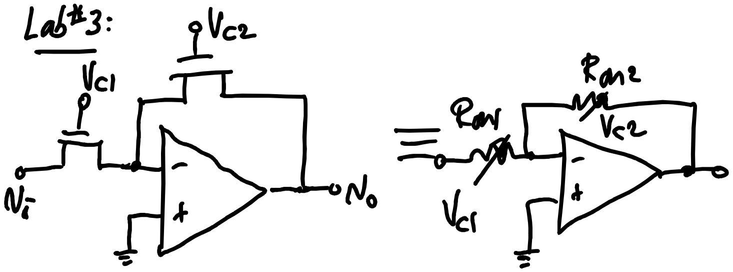
$$\frac{\partial i_{DS}}{\partial v_{DS}} = \mu_n C''_{ox} \frac{W}{L}(v_{GS} - V_{TN} - v_{DS})$$

$$[v_{DS} = \text{small}] \Rightarrow \approx \mu_n C''_{ox} \frac{W}{L}(v_{GS} - V_{TN})$$

$$\boxed{R_{on} = \left[\frac{\partial i_{DS}}{\partial v_{DS}}\right]^{-1} = \frac{1}{\mu_n C''_{ox} \frac{W}{L}(v_{GS} - V_{TN})}}$$

↑ You'll need this for next lab!





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

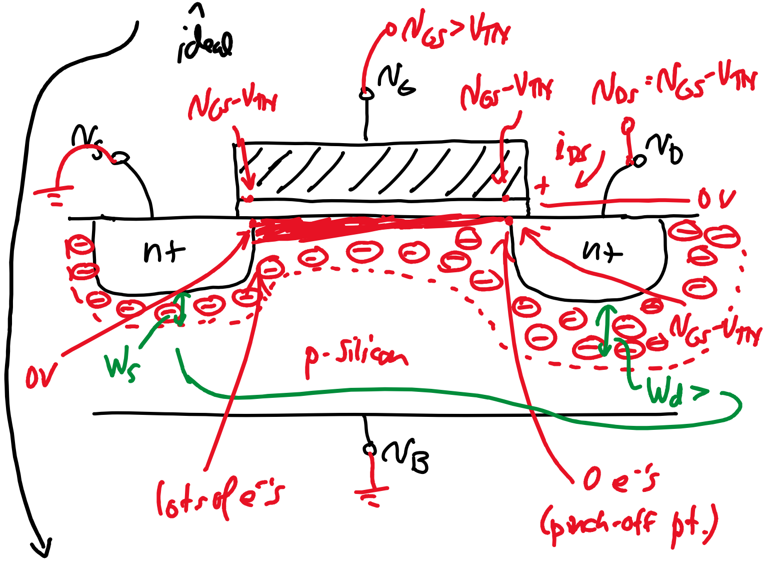
As $v_{DS}\uparrow$ → the voltage across the gate-to-substrate capacitor near the drain:

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

↖ @ drain edge

∴ the inversion charge @ drain → 0

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



Plug in $v_{GS} - V_{TN} - v_{DS} = 0 \to v_{DS} = v_{GS} - V_{TN}$ 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)