Lecture 13: MOSFETs

- **Announcements**:
- HW#5 online and due Friday via Gradescope
- Lab#3 next week
    - ↳ Materials for Lab#3 online
    - ↳ Prelab due before lab in 2nd week
- Midterm 1 two weeks away, 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
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- Lecture Topics:
    - ↳ MOSFETs
        - —Structure and Operation
        - —Cutoff
        - —Linear Region
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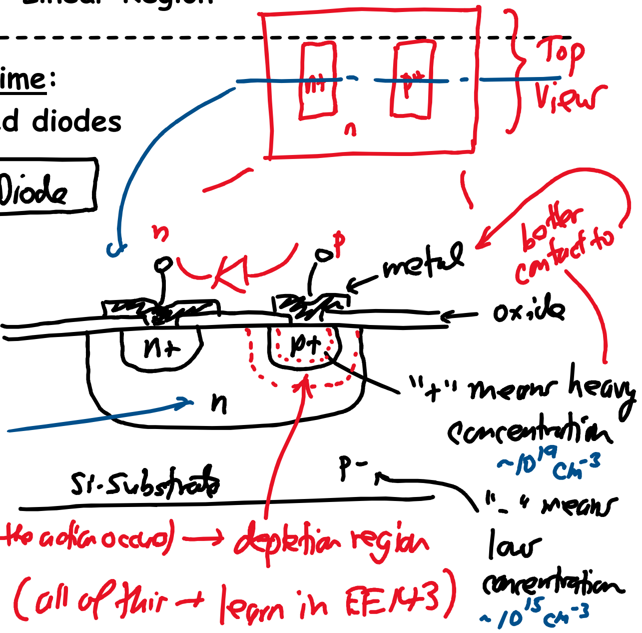
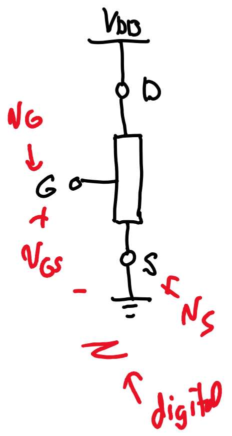
- **Last Time**:
- Finished diodes

Actual Diode

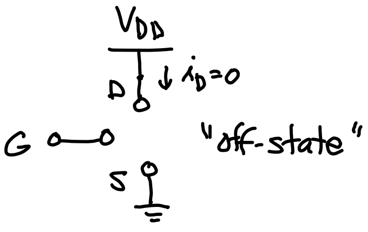


Transistor Operation → The Basic Goal

Overall Goal: A device for which

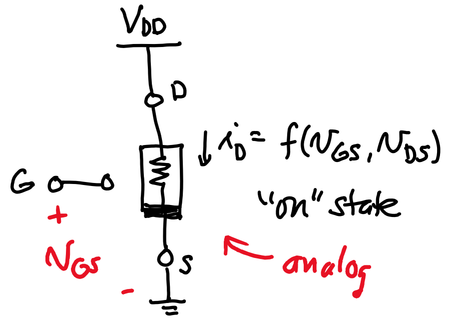


① With $v_{GS} = v_G - v_S$ = small:



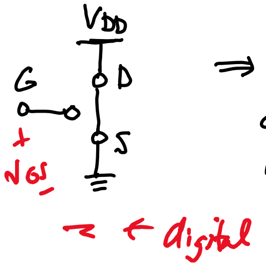
⇒ open ckt. → no current flow from D→S

② With $v_{GS} > V_t \triangleq$ "threshold voltage":



A resistor for which the current from D→S is a function of applied voltages

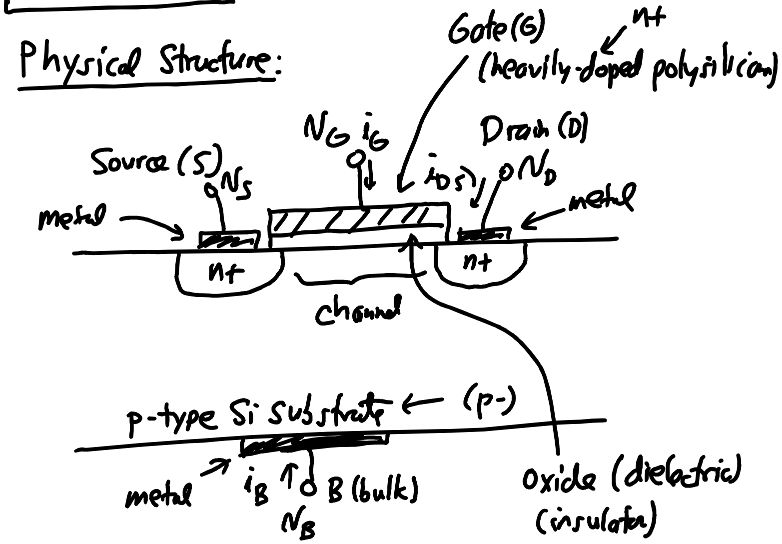
for high enough voltage:



⇒ in effect, we have a switch controlled by voltage at G

MOS Transistor

Physical Structure:



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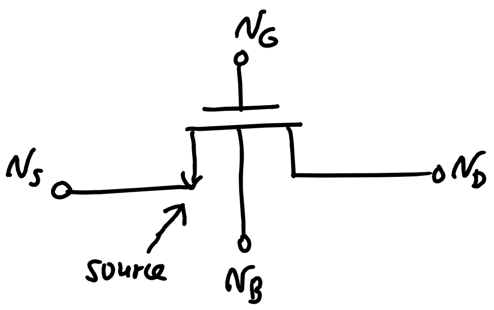
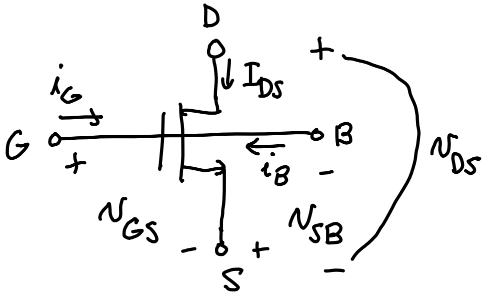


NMOS Transistor Mathematical Model



① **Cutoff Region:** $(v_{GS} \le V_{TN})$ ← threshold voltage (~0.7V)

$i_G = i_B = 0$; $i_{DS} = 0$

② **Linear (or Triode) Region:** $(v_{GS} - V_{TN} \ge v_{DS} \ge 0)$

$i_G = i_B = 0$; $i_{DS} = \underbrace{\mu_n C''_{ox}}_{}\frac{W}{L}\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right)v_{DS}$

$R \sim \frac{v_{DS}}{i_{DS}}$ ~linear

$= K_n\left(v_{GS} - V_{TN} - \frac{v_{DS}}{2}\right)v_{DS}$

$= \underline{K_n\left[(v_{GS} - V_{TN})v_{DS}\right.} - \left.\cancel{\frac{v_{DS}^2}{2}}\right]$ ← if v_{DS} = small

③ **Saturation Region:** $(v_{DS} \ge v_{GS} - V_{TN} \ge 0)$

$i_G = i_B = 0$; $i_{DS} = \frac{1}{2}\mu_n C''_{ox}\frac{W}{L}(v_{GS} - V_{TN})^2(1 + \lambda V_{DS})$

$= \frac{K_n}{2}(v_{GS} - V_{TN})^2(1 + \lambda V_{DS})$

λ: small ~0.03

where ↓

$K_n = k_n' \frac{W}{L} = \mu_n C_{ox}'' \frac{W}{L}$

$i_G = i_B = 0$ for all regions

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

$\mu_n \triangleq$ e- mobility in the channel

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

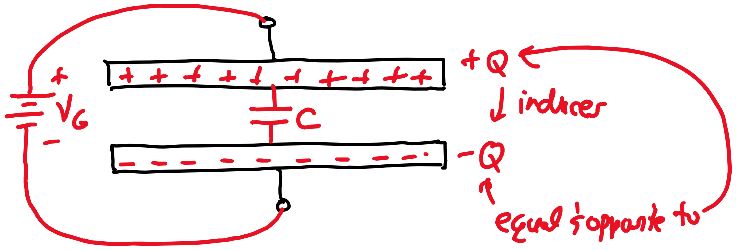
$V_{T0} \triangleq$ threshold voltage w/ $V_{SB} = 0V$

$\gamma \triangleq$ body effect parameter

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

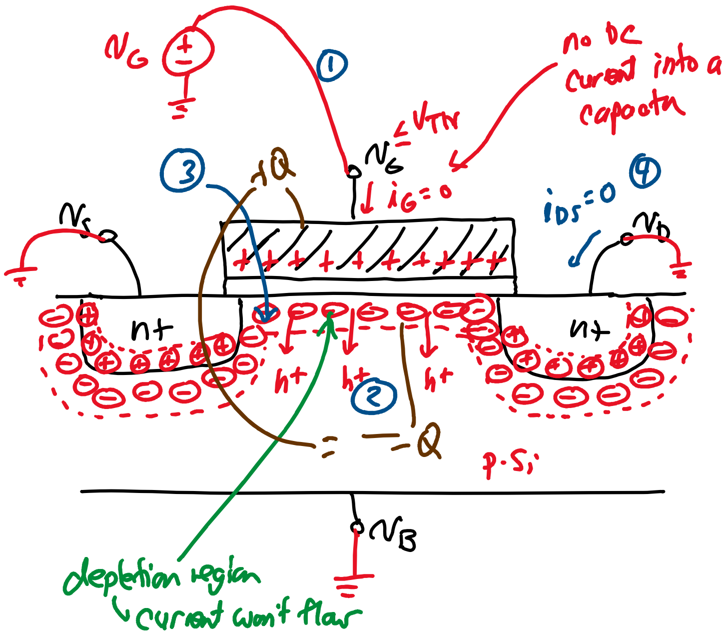
MOS Transistor Regions of Operation

Before starting: reminder of a simple capacitor



$Q = CV_G$

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

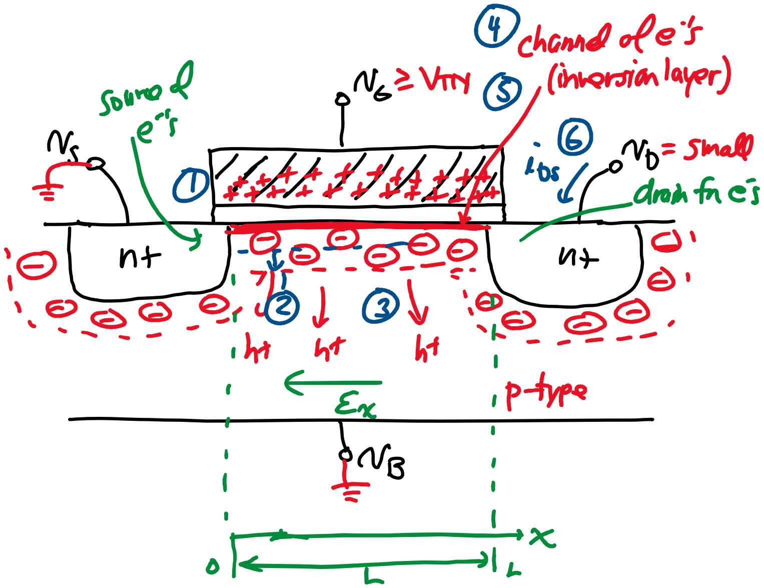
② – The depletion region of fixed (-) charge grows to accommodate

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:

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

e- charge per unit length

velocity of e-'s $\} = -\mu_n E_x$