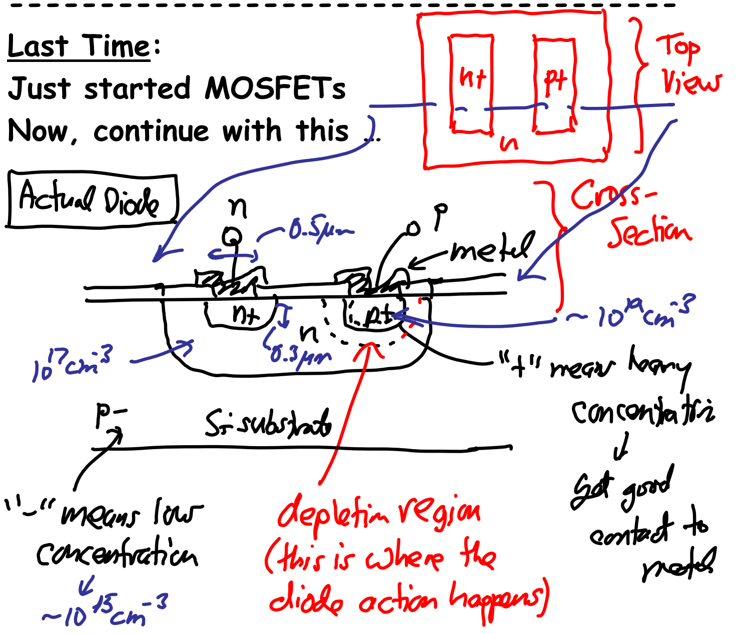
Lecture 13: MOSFETs I

- **Announcements:**
- HW#5 online and due Friday via Gradescope
- Lab#3 next week
  - Materials for Lab#3 online
- Midterm 1 ~2 weeks away, on Friday, Oct. 5, from 5-6:30 p.m., in 277 Cory
- UC Police Dept. slow at giving people access to the lab, for several classes … be patient
- --
- Lecture Topics:
  - MOSFETs
    - Structure and Operation
    - Cutoff
    - Linear Region
- --
- **Last Time:**
- Just started MOSFETs
- Now, continue with this ↓



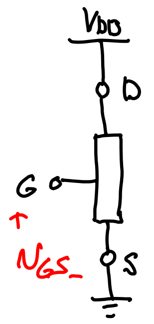
"+" means heavy concentration ↓ get good contact to metal

"-" means low concentration ↓ $\sim 10^{15} cm^{-3}$

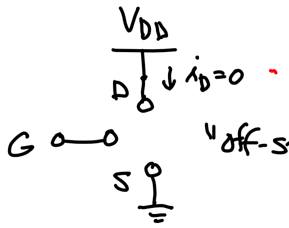
depletion region (this is where the diode action happens)

Transistor Operation → The Basic Goal

Overall Goal: A device for which



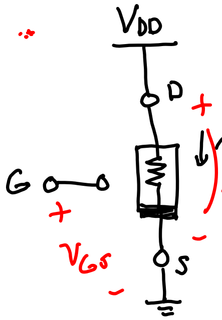
① With $v_{GS} = v_G - v_S$ = small:



"off-state"

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

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

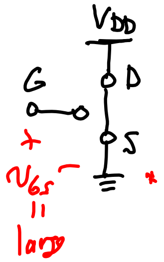


$i_D = f(v_{GS}, v_{DS})$

"on" state

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

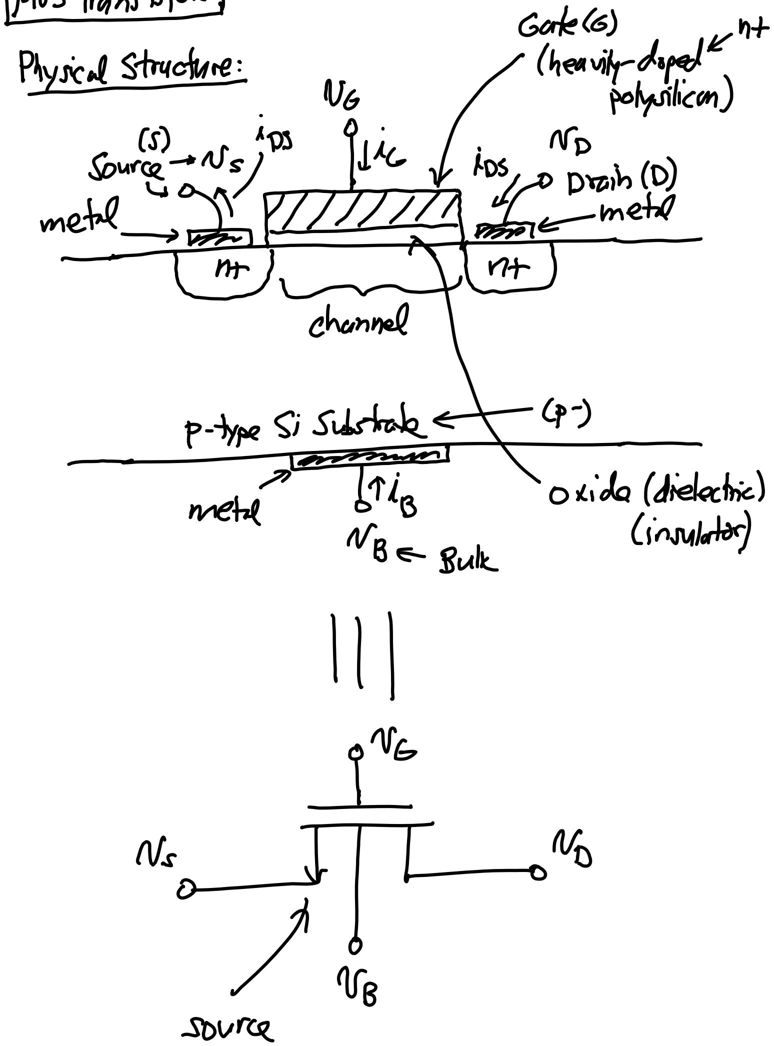
→ for high enough voltage:



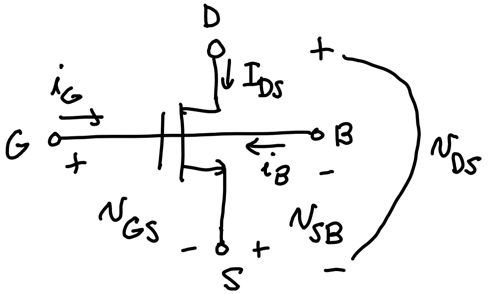
⇒ in effect, we have a switch controlled by voltage at G

MOS Transistors

Physical Structure:



NMOS Transistor Mathematical Model



① Cutoff Region: $(v_{GS} \leq V_{TN})$ ← threshold voltage

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

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

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

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

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

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

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

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

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

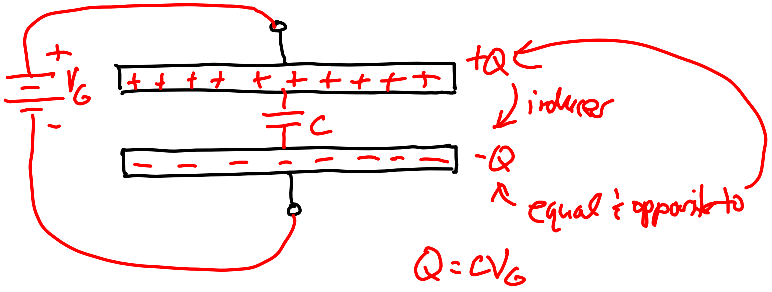
$V_{T0} \triangleq$ threshold voltage w/ $V_{SB} = 0V$

$\gamma \triangleq$ body effect parameter

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

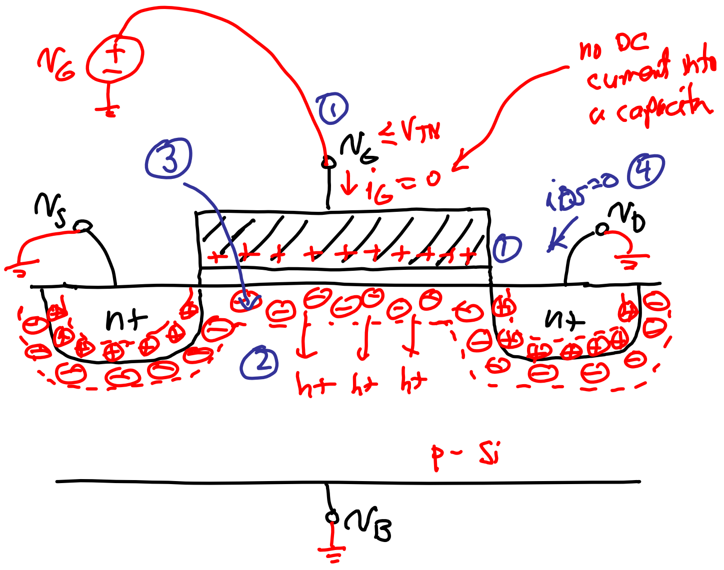
MOS Transistor Regions of Operation

Before starting: reminder of a simple capacitor



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

$V_{TN} \sim 0.6$ to $0.7V$

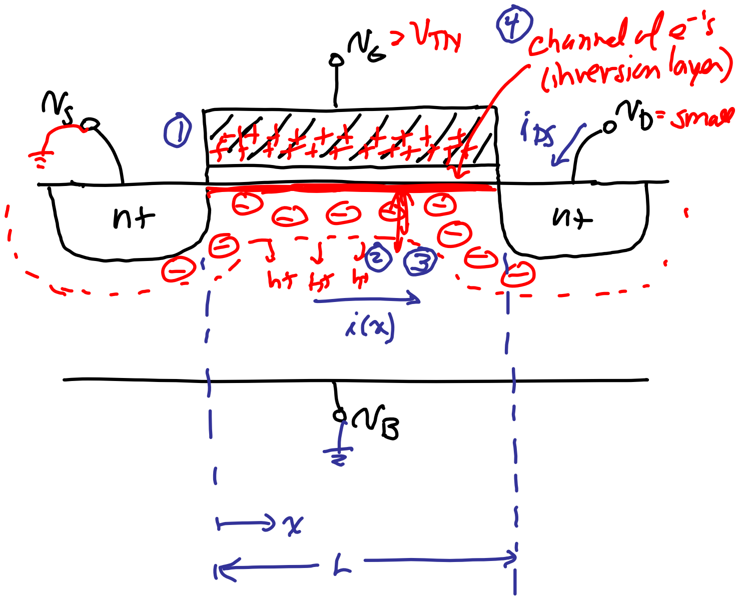


1. Application of v_G puts (+) charge on the gate → this induces (-) charge on the other side of the oxide
2. At this point, the easiest way to create (-) charge in the Si is for the h+ in the p-type substrate to move away from the channel area
3. i.e., a (-)ly charged depletion region forms in response 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!
  - ④ – **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



- Channel of e-'s → mobile → silicon in this region now a conductor
- An E-field generated by v_{DS} gives rise to drift current flow

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

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

$$i(x) = Q'(x)\,v(x)$$

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

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