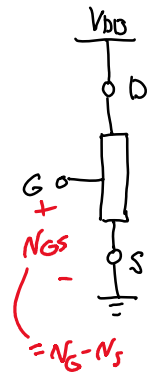
Lecture 15: MOSFETs II

- Announcements:
- HW#5 online and due Friday via Gradescope
- Lab#2 experimental part due next week
- Lab#3 next week
  - Materials for Lab#3 online
  - Prelab due before lab the week of 10/12
  - Experimental part due the week of 10/19
- Note that our Friday lecture this week will be at 12 noon
- ---
- Lecture Topics:
  - MOSFETs
    - Structure and Operation
    - Cutoff
    - Linear Region
    - Saturation
- ---
- Last Time:
- Started MOSFETs
- Now, continue with this …

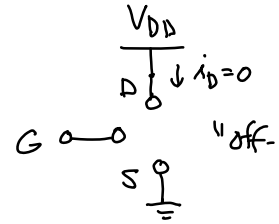
1

Transistor Operation → The Basic Goal

Overall Goal: A device for which



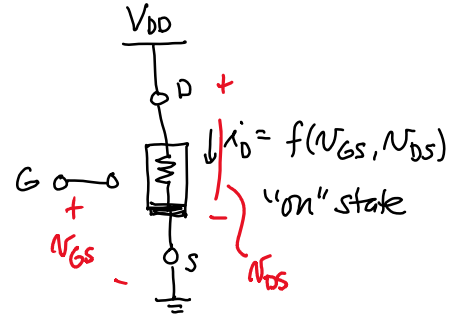
① With $v_{GS} = v_G - v_S$ = small:



"off-state"

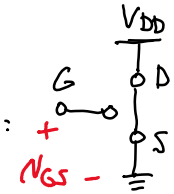
⇒ open ckt. → no current flow from D→S

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



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

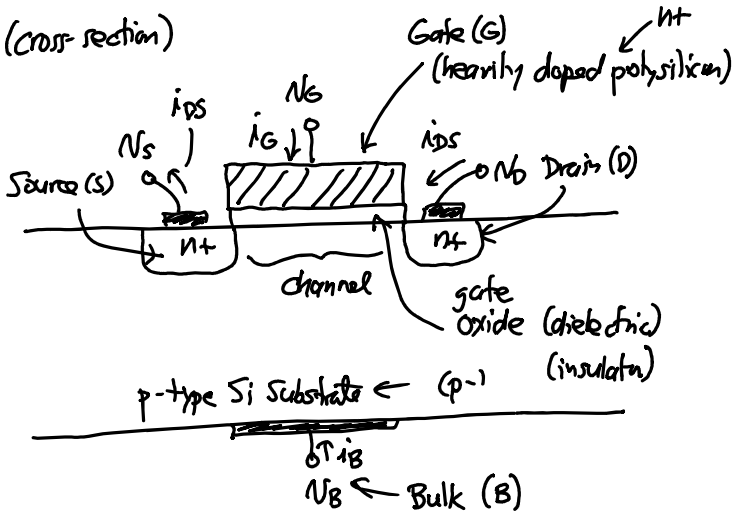
2

Copyright © 2020 Regents of the University of California

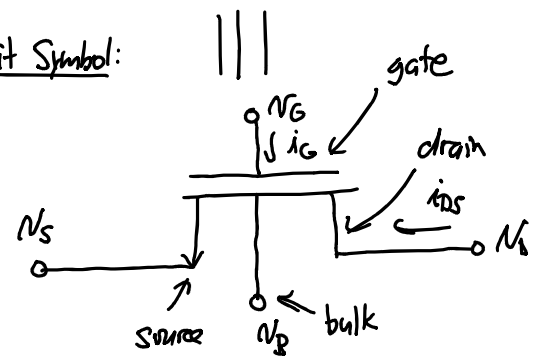
MOS Transistors

Metal Oxide Semiconductor

(cross-section)

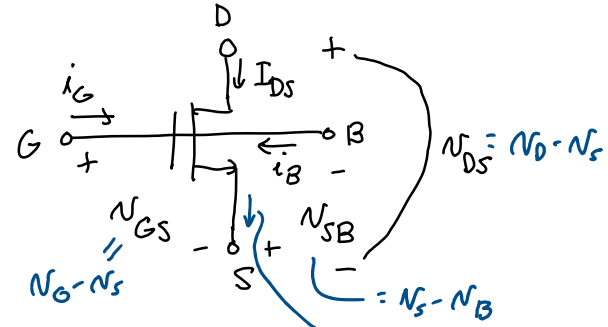


Circuit Symbol:



3

NMOS Transistor Mathematical Model



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

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

(open ckt.)

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

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

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

neg.

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

[v_{DS}: small]

linear w/ v_{DS}!

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

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

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

where ↓

4

Copyright © 2020 Regents of the University of California

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

$i_G = i_B = 0$ 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

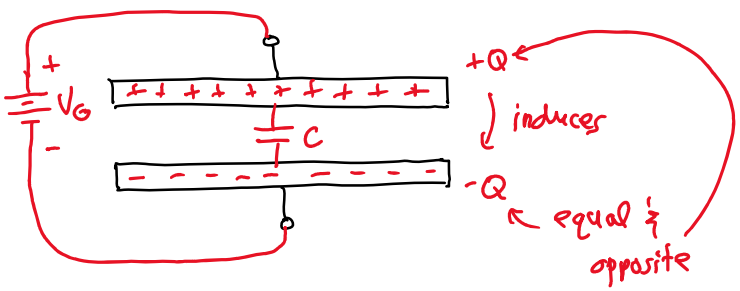
$V_{T0} \triangleq$ threshold voltage w/ $V_{SB} = 0V$

$\gamma \triangleq$ body effect parameter

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

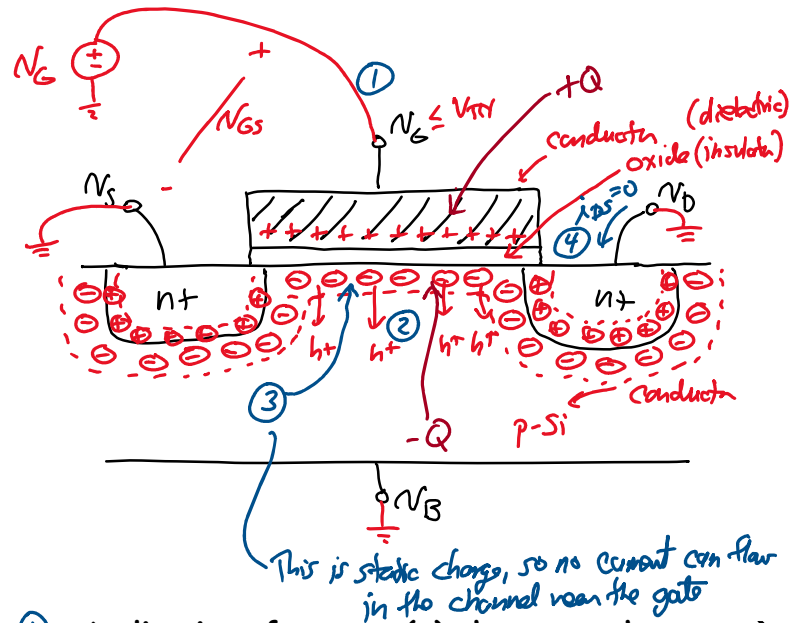
MOS Transistor Regions of Operation

Before starting: reminder of a simple capacitor



$Q = CV_G$

① Cutoff Region - ($v_{GS} \le V_{TN}$) → $V_{TN} \sim 0.6$ or $0.7V$



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 → $i_{DS} = 0$

Copyright © 2020 Regents of the University of California

- 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 $v_{GS} > V_{TN}$

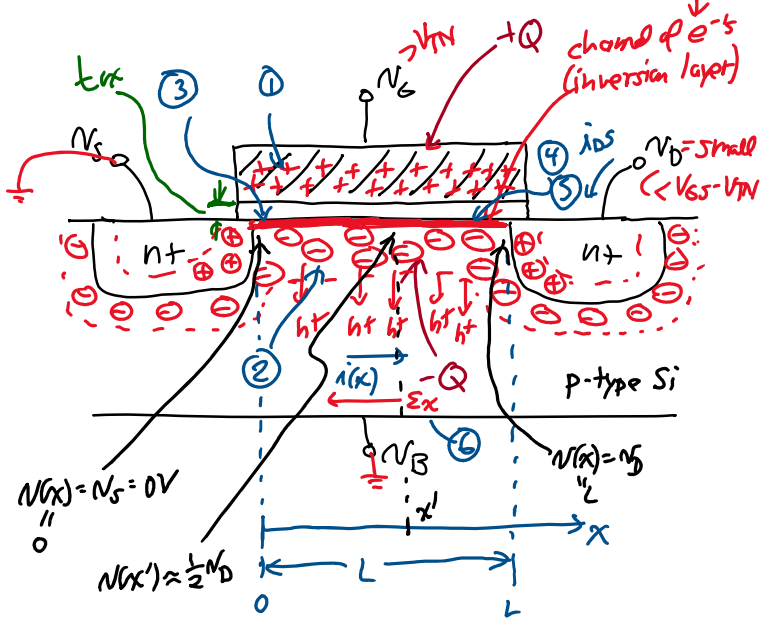
② Linear Region: (or Triode Region)

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

∴ v_{DS} can cause current flow

can move

channel of e-'s (inversion layer)



7

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

$v_x(x)$: velocity of e-'s $\} -\mu_n \mathcal{E}_x$ (electric field; mobility)

Basically given by the charge on the gate-to-substrate capacitor:

$$Q'(x) = -W C''_{ox} (v_{GS} - V_{TN} - v(x)) \quad \} \rightarrow q = CV$$

$-$: e-'s

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

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

ϵ_{ox} = oxide permittivity = $3.9\,\epsilon_0$

t_{ox} = gate oxide thickness [cm]

*

8

Copyright © 2020 Regents of the University of California

*

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

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

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

$$i(x)dx = -\mu_n C_{ox}'' W\left(v_{GS} - V_{TN} - v(x)\right)dv(x)$$

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

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

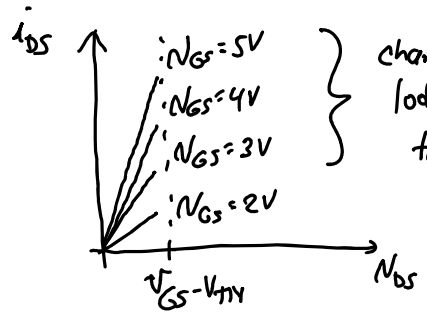
$$i_{DS}L = \mu_n C_{ox}'' W\left[(v_{GS} - V_{TN})v_{DS} - \frac{v_{DS}^2}{2}\right]$$

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

small v_{DS}

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

Linear Region IV Characteristic



characteristic curves look fairly linear for small v_{DS}

9

Copyright © 2020 Regents of the University of California