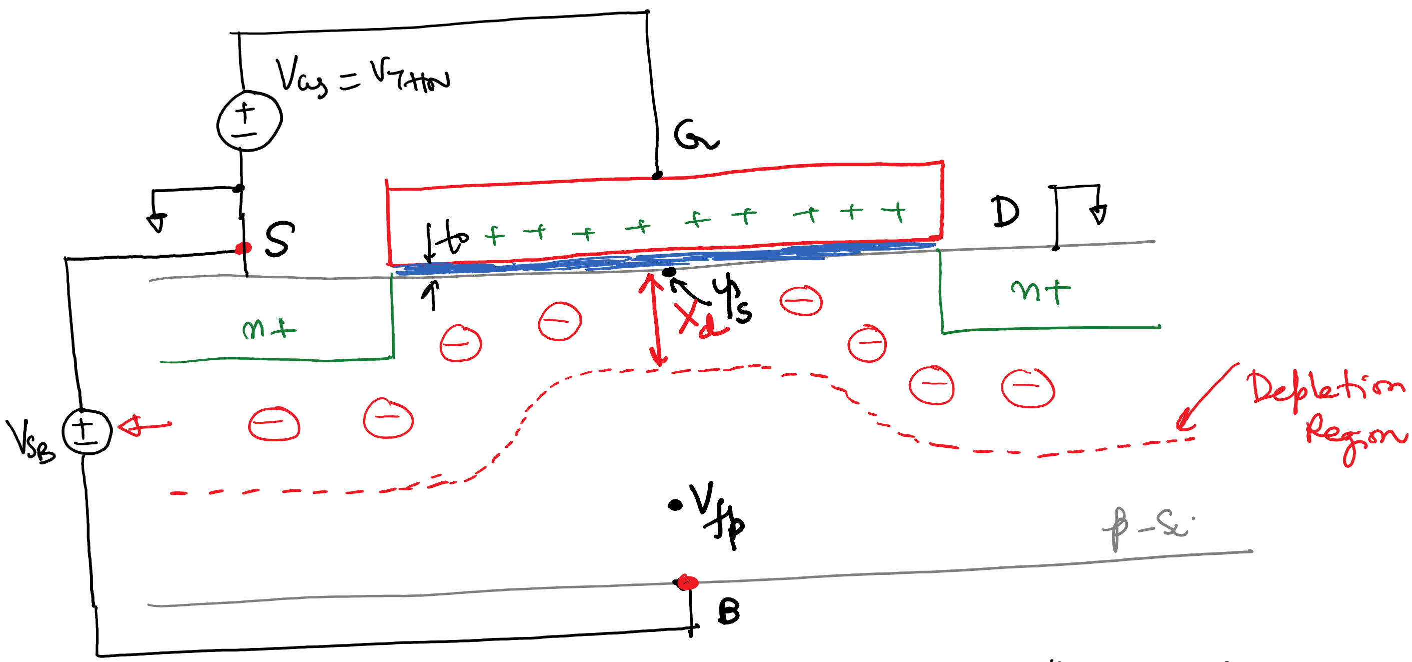
ECE 445 - Lecture 9

Thursday, February 7, 2019 8:05 AM

Threshold Voltage (V_{THN}) : NMOS



When $V_{GS} \simeq V_{THN}$, the Si/SiO$_2$ interface is "inverted"

is created under the gox

↳ a channel of electrons

Thickness of Depletion Region

$$X_d = \sqrt{\frac{2\varepsilon_{si}\,|\psi_s - V_{fp}|}{qN_A}} \longrightarrow (1)$$

$N_A \rightarrow$ p-sub Doping Concentration

$\psi_s \rightarrow$ Surface potential of the channel

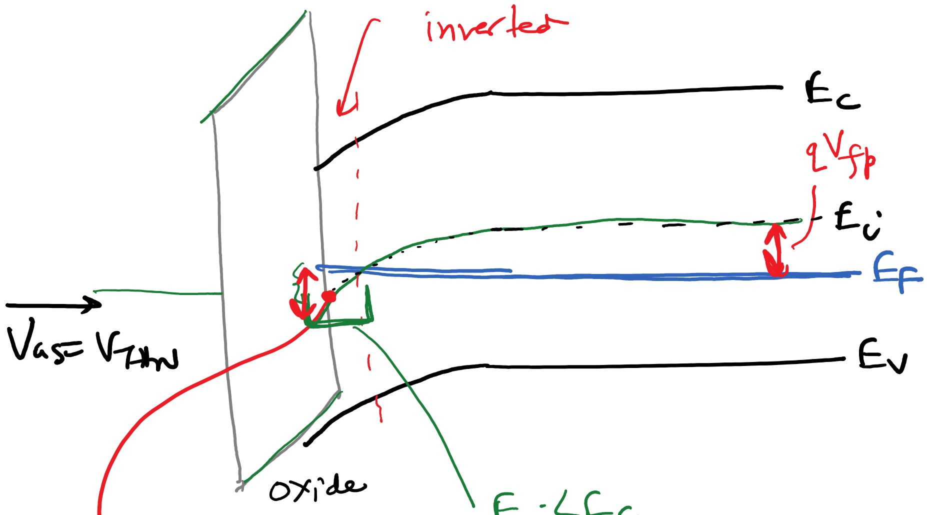
↳ electrostatic potential at Si/SiO$_2$ interface

$V_{fp} \rightarrow$ electrostatic potential of the p-sub (p-type Si)

$$V_{fp} = -\frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right) \longrightarrow -\text{ve number}$$

$\rightarrow V_{fp} = -\frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right) \rightarrow$ -ve number

Energy Diagram:



$q\psi_s = -qV_{fp}$ for inversion $\Rightarrow$ n-type region

In depletion region:

+ve charge on the gate = total charge in the depletion region

$$Q_b' = \boxed{q N_A X_d} = \cancel{q} N_A \sqrt{\frac{2\varepsilon_{si} |\psi_s - V_{fp}|}{\cancel{q} N_A}}$$

charge per unit area

$$= \sqrt{2 \varepsilon_{si} q N_A |\psi_s - V_{fp}|} \longrightarrow (2)$$

Conditions:

(1) $\psi_s = \underbrace{V_{fp}}_{\text{-ve number}} \Rightarrow Q_b' = 0 \Rightarrow$ Flatband $\longrightarrow$ bands are flat

$\hookrightarrow$ MOSFET is at the edge of accumulation

increase V_{GS}

increase V_{GS}

② $\varphi_s = 0 \Rightarrow$ Surface under t_{ox} is depleted of carriers (depletion region)

$V_{GS} \uparrow$

③ $\varphi_s = \underbrace{-V_{fp}}_{\text{+ve number}} \Rightarrow$ By definition, this happens when $V_{GS} = V_{THN} \Rightarrow$ MOSFET is said to be in inversion.

↳ arbitrary definition of V_{THN}

* The value of V_{GS} when $\varphi_s = -V_{fp}$ is arbitrarily defined as the threshold voltage V_{THN}.

↳ φ_s has changed by a total of $2|V_{fp}|$

$\varphi_s = -V_{fp}$ @ $V_{GS} = V_{THN}$

from Eq ② $\Rightarrow$ total $-$ve charge (p.u. area) under gate oxide

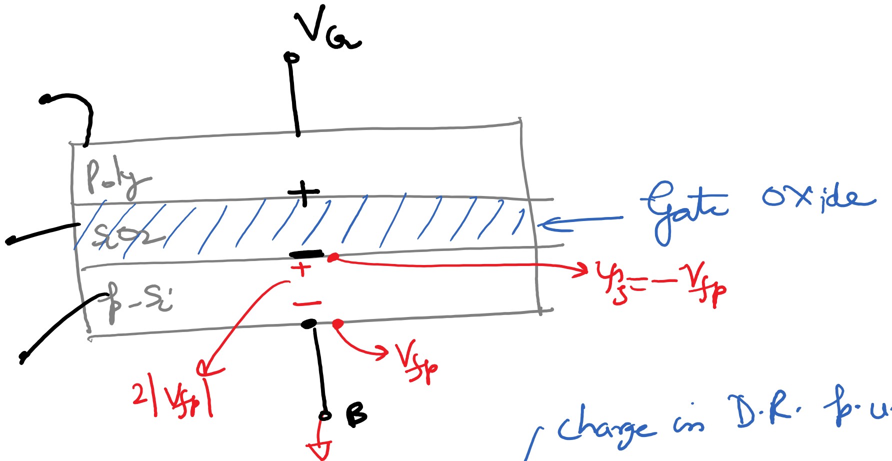
$$Q'_{bo} = \sqrt{2qN_A\varepsilon_{si}|-2V_{fp}|} \longrightarrow ③$$

* If the source is not at ground

$$Q'_b = \sqrt{2qN_A\varepsilon_{si}|-2V_{fp} + V_{SB}|} \longrightarrow ④$$

at inversion

Contact potential:



* potential across the gate oxide

$$V_{ox} = \frac{Q_b'}{C_{ox}'} \longrightarrow (5)$$

charge in D.R. p.u. area

capacitance p.u. area

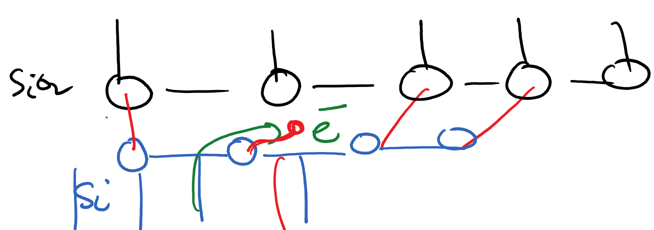
$$C_{ox}' = \frac{\varepsilon_{ox}}{t_{ox}}$$

Gate voltage

$$V_G \triangleq V_{ox} + 2|V_{fp}|$$

$$V_G \triangleq \frac{Q_b'}{C_{ox}'} - 2V_{fp}$$

* Extra charge due to surface states, Q_{ss}'



dangling states at the surface

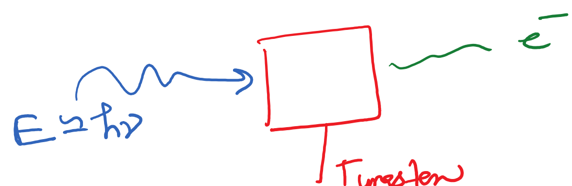
* surface states at the Si/SiO_2 interface

↳ dangling bonds / defects
↳ electrons gets trapped in these states

$$V_G \triangleq \frac{Q_b' - Q_{ss}'}{C_{ox}'} - 2V_{fp} \longrightarrow (6)$$

Work function ⇒ Contact potential

↳ Energy required to take an electron from an atom and take it to ∞



work function ⇒ ΔE

Electron Energy = $h\nu - \Delta E$

* We need to account for the contact potentials between the gate and the substrate (gate & substrate can be different material)

$$V_{ms} = (V_a - \cancel{V_{ox}}) + (\cancel{V_{ox}} + V_{fp})$$

$$= V_a - V_{fp} \longrightarrow \text{contact potential} = \text{substrate potential}$$

Contact potential difference b/w Gate & substrate

for doped polysilicon gate

for doped polysilicon gate

$$V_{ms} = \underbrace{\frac{kT}{q} \ln\left(\frac{N_{D,poly}}{n_i}\right)}_{\text{contact potential of poly gate}} - \left(\underbrace{-\frac{kT}{q} \ln\left(\frac{N_A}{n_i}\right)}_{\text{Substrate potential}}\right)$$

$$V_{THN} = V_G - V_{ms}$$

accounting for the difference of contact potentials

$$\Rightarrow V_{THN} = \frac{Q_b' - Q_{ss}'}{C_{ox}'} - 2V_{fp} - V_{ms}$$

D.R. charge @ $V_{SB}=0$

D.R. charge

$$= -V_{ms} - 2V_{fp} + \frac{(Q_{bo}' - Q_{ss}')}{C_{ox}'} - \frac{(Q_{bo}' - Q_b')}{C_{ox}'}$$

$$\boxed{V_{THN} = \overbrace{-V_{ms} - 2V_{fp} + \frac{Q_{bo}' - Q_{ss}'}{C_{ox}'}}^{V_{THN0}} + \underbrace{\frac{\sqrt{2q\varepsilon_{si}N_A}}{C_{ox}'}\left[\sqrt{|2V_{fp}+V_{SB}|} - \sqrt{2|V_{fp}|}\right]}_{\text{additional voltage needed for inversion when } V_{SB}>0}}$$

Contact potential difference

definition of inversion

surface state

$$\boxed{V_{THN} = V_{THN_0} + \gamma\left(\sqrt{|2V_{fp}| + V_{SB}} - \sqrt{|2V_{fp}|}\right)}$$

$$V_{THN_0} = -V_{ms} - 2V_{fp} + \frac{Q_{bo}' - Q_{ss}'}{C_{ox}'}$$

$$\gamma = \frac{\sqrt{2q\varepsilon_{si}N_A}}{C_{ox}'} \Rightarrow \text{Body factor}$$

$\rightarrow V_{THN_0}$ ...

$$\gamma = \frac{\sqrt{2q\varepsilon_{si}N_A}}{C_{ox}'} \Rightarrow \text{Body factor}$$

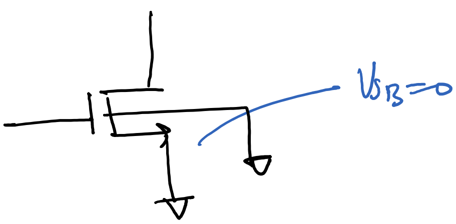
$V_{THN} = V_{THN_0}$ @ $V_{SB} = 0$

↳ Body effect

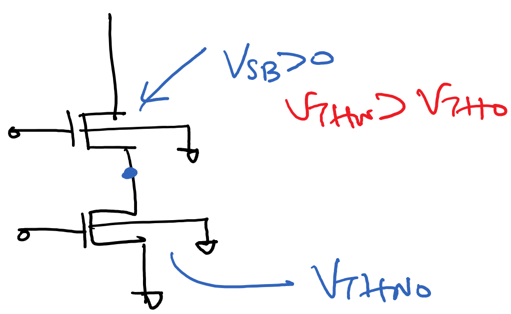
$$V_{THN_0} = -V_{ms} - 2V_{fp} + \frac{Q_{bo}'}{C_{ox}'} - \frac{Q_{ss}'}{C_{ox}'}$$

$V_{FB} = -V_{ms} - \frac{Q_{ss}'}{C_{ox}'}$ is called the flatband voltage

for $V_{GS} = V_{FB} \Rightarrow$ bands are flat



$V_{THN} = V_{THN0}$



$$V_{THN} = V_{THN_0} + \gamma\left(\sqrt{|2V_{fp}| + V_{SB}} - \sqrt{|2V_{fp}|}\right)$$

$$V_{fp} = -\frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

$$\frac{\sqrt{2q\varepsilon_{si}N_A}}{C'_{ox}}$$

$$V_{FB} - 2V_{fp} + \frac{Q'_{bo}}{C'_{ox}}$$

$$C'_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$-V_{ms} - \frac{Q'_{ss}}{C'_{ox}}$$

$$\sqrt{2\varepsilon_{si}\, q\, N_A\, |2V_{fp}|}$$

$$\frac{kT}{q}\ln\left(\frac{N_A N_{D,poly}}{n_i^2}\right)$$

In practice, if we use typical values of poly doping (N_D, poly) etc we get $-ve$ V_{THN}

↳ not acceptable

⇒ Threshold Voltage Adjust implants

Ex. implant the channel region with B^+ ions

↳ BF_2

↳ increase V_{THN} by a factor of

$$\frac{Q_c'}{C_{ox}'}$$ ← implanted charge density

$$V_{THN_0} = V_{FB} + \frac{Q_{bo}' - Q_{ss}' + Q_c'}{C_{ox}'}$$

↳ adjusts V_{THN} to a desired range of values.