THRESHOLD VOLTAGE OF MOS TRANSISTOR

$V_T =$ Work function between Gate & channel + Surface charge between the oxide & bulk Si + Potential to change the surface potential to strong inversion

$$V_T = \underbrace{[\phi_{GC}] + [-\frac{Q_{ox}}{C_{ox}}]} + \underbrace{[-2\phi_F - \frac{Q_B}{C_{ox}}]}$$

① $V_{FB} = \phi_{GC} - \frac{Q_{ox}}{C_{ox}}$: Flat the Energy band

② $V_{IC} = -2\phi_F - \frac{Q_B}{C_{ox}}$: Inverse the channel

Components of V_T :

1) $\phi_{GC} = \Phi_G - \phi_C$ = work function between Gate & channel

2) $-\frac{Q_{ox}}{C_{ox}}$ = surface charge between the oxide and bulk silicon due to impurities and imperfections at the interface and must be overcome

3. $-2\phi_F$ = voltage needed to change the surface potential to strong inversion

4) $-\frac{Q_B}{C_{ox}}$ = voltage needed to offset the induced depletion layer charge

Note: ϕ_F is the Fermi potential

n_i = intrinsic concentration $pn = n_i^2$

For p-type mat'l ($p \gg n$) ; $\phi_{FP} = \frac{kT}{q} \ln(\frac{n_i}{p}) < 0$

" n-type " ($n \gg p$) : $\phi_{FN} = \frac{kT}{q} \ln(\frac{n}{n_i}) > 0$

$Q_B = ?$ $Q_B = qN_A X_d$ where X_d = depletion region width

Assume step p-n junction

$$X_d = \left(\frac{2\epsilon_{Si}|\phi_s - \phi_F|}{qN_A}\right)^{1/2}$$

$$\Rightarrow Q_B = -2\sqrt{2qN_A \epsilon_{Si} |\phi_s - \phi_F|}$$

Note: ϕ_s is the surface potential and for strong inversion & $V_{SB}=0$

$\phi_s = -\phi_F$

When $V_{SB} = 0$, the depletion region consists of a fixed negative charge written as

$$Q_{B0} = -\sqrt{2q\epsilon_{Si}N_A|-2\phi_F|}$$

If $V_{SB} \neq 0$

$$Q_B = -\sqrt{2q\epsilon_{Si}N_A(|-2\phi_F| + V_{SB})}$$

$$\Rightarrow V_T = \phi_{GC} - \frac{Q_{ox}}{C_{ox}} - 2\phi_F - \frac{Q_B}{C_{ox}}$$

$$= V_{FB} - 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{B0}}{C_{ox}} + \frac{Q_{B0}}{C_{ox}}$$

$$= \left(V_{FB} - 2\phi_F - \frac{Q_{B0}}{C_{ox}}\right) - \frac{Q_B - Q_{B0}}{C_{ox}}$$

$$= V_{T0} + \gamma\left(\sqrt{|2\phi_F| + V_{SB}} - \sqrt{2|\phi_F|}\right)$$

Where: $V_{T0} = \phi_{GC} - \frac{Q_{ox}}{C_{ox}} - 2\phi_F - \frac{Q_{B0}}{C_{ox}} = V_{FB} - 2\phi_F - \frac{Q_{B0}}{C_{ox}}$

$\gamma = \sqrt{2q\epsilon_{Si}N_A} / C_{ox}$

Example 2.3

Known $t_{ox} = 22$ Å (1 Å $= 10^{-10}$ m $= 10^{-8}$ cm)

$N_A = 3\times10^{17}\ \text{cm}^{-3}$

determine C_{ox} and γ

$\left.\begin{array}{l}\epsilon_{ox} \approx 4\epsilon_0 \\ \epsilon_{Si} \approx 12\epsilon_0\end{array}\right\}\ \epsilon_{Si} \approx 3\epsilon_{ox}$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{4\epsilon_0}{t_{ox}} = \frac{(4)(8.85\times10^{-14}\ \text{F/cm})}{(22\times10^{-8}\ \text{cm})} = 1.61\times10^{-6}\ \text{F/cm}^2$$

$$\gamma = \sqrt{2q\epsilon_{Si}N_A} / C_{ox} = 0.196\ V^{1/2} \qquad = \frac{\sqrt{(F\cdot V)(\frac{F}{cm})(\frac{1}{cm^3})}}{\frac{F}{cm^2}}$$

Example 2.4

Known $N_A = 3\times10^{7}\ \text{cm}^{-3}$ $N_D = 10^{20}\ \text{cm}^{-3}$ for gate

$t_{ox} = 22$ Å & $2\times10^{10}\ \text{cm}^{-2}$ positive charged ions per area at Oxide-Si interface

determine V_{T0}

$$\phi_{FP} = \frac{KT}{q}\ln\left(\frac{n_i}{N_A}\right) = 0.026\ln\left(\frac{1.45\times10^{10}}{3\times10^{17}}\right) = -0.438\ \text{V}$$

Assume the polysilicon gate has the doping of the source/drain because of implantation of these areas.

$$\phi_G\ (\text{gate}) = \frac{KT}{q}\ln\left(\frac{N_D}{n_i}\right) = 0.026\ln\left(\frac{10^{20}}{1.45\times10^{10}}\right) = 0.589\ \text{V}$$

For n-doping $\phi_{GS} < 0$

$$\phi_{GC} = -(\phi_F - \phi_G) = -0.438 - 0.589 = -1.027\ \text{V}$$

$\epsilon_{ox} = 4\epsilon_0$

$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$

$Q_{BO} = -\sqrt{2q\epsilon_{Si}N_A|-2\phi_F|}$

$\Rightarrow \frac{Q_{BO}}{C_{ox}}$

$$\Rightarrow V_{TO} = \phi_{GC} - 2\phi_F - \frac{Q_{BO}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}$$

$$= -1.027 + 0.876 + 0.183 - 0.002 = +0.03\ \text{V}$$

How are larger thesholds achieved ?

A p+ implant makes V_{TN} larger