Threshold voltage of a MOS device:-

• V_{TO}: It is defⁿ as min gate vtg V_G reqd to cause surface inversion when substrate bias $V_{SB} = 0$.

(For Ideal mos device: $\phi_{GC} - 2\phi_F - \frac{Q_{BO}}{C_{ox}}$; due to process non-linearity: $- \frac{Q_{ox}}{C_{ox}} - \frac{Q_{ss}}{C_{ox}}$)

$$V_{TO} = \phi_{GC} - 2\phi_F - \frac{Q_{BO}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} - \frac{Q_{ss}}{C_{ox}} \quad \text{Volts.}$$

$$= V_1 + V_2 + V_3 + V_4 + V_5.$$

OR

Threshold voltage is that value of gate voltage for which the channel is depleted of majority carriers.

For all practical purposes, we can identify four physical components of V_T:-

1) ϕ_{GC} → work fⁿ diff betⁿ gate & channel.
2) Gate voltage component to change the surface potential.
3) Gate vtg compⁿ to offset the fixed charges in gate oxide and in Si-oxide interface.
4) gate vtg compⁿ to offset depletion region charge.

• V_1 :-

When a MOS device is formed, there exist a contact potential across the MOS device due to work functⁿ difference betⁿ the metal gate and Si substrate.

$V_1 = \phi_{GC}$ → for metal gate.
or ϕ_{ms}

$\phi_{F(substrate)} - \phi_m$

$V_1 = \phi_{GC}$ or ϕ_{ms}

$$V_1 = \phi_{Fsub} - \phi_{Fgate}$$

ϕ_{Fsub}: ϕ_{FP}, ϕ_{FN}

→ for Poly Si gate → doping will be in numerical. ↓ Calculate $\phi_{Fgate} = \phi_m$ from Formula.

ϕ_{Fgate} → Select 0.55 V for metal gate / ~~Poly Si gate~~.

→ V_2 :-

The change in gate vtg reqd to create a ~~depletion~~ inversion layer having thickness x_{dm}

$V_2 = \phi_S - \phi_F$ (refer E.B.D)

$V_2 = -\phi_F - \phi_F$ ∵ $\phi_S = -\phi_F$

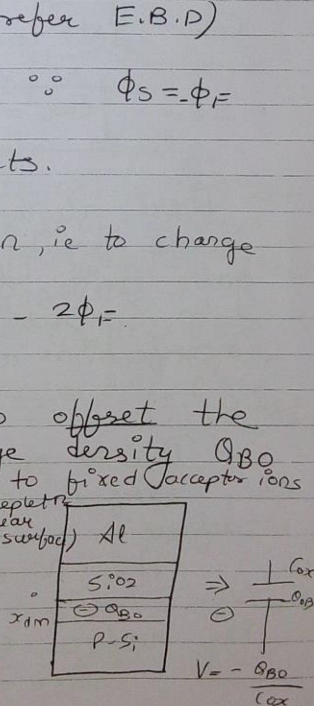
$$V_2 = -2\phi_{Fsub} \text{ Volts.}$$

↓ To achieve surface inversion, ie to change the surface potential by $-2\phi_F$, ext^r gate vtg must be changed.

→ V_3 :-

The gate vtg reqd to offset the effect of depletion charge density Q_{BO} c/cm² is (which is due to fixed acceptor ions located in depletion region near the surface)

$$V_3 = -\frac{Q_{BO}}{C_{ox}} \text{ Volts.}$$



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

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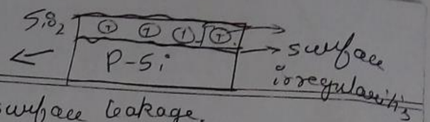
leads to some charges called Surface Charges
→ cause surface leakage.



↦ V_4 :- The gate vtg reqd to offset the effect of this fixed oxide layer charge at interface is

$$V_4 = -\frac{Q_{ox}}{C_{ox}} \quad \text{Volts.}$$

• Due to process non-Linearity, there are a fixed no of oxide layer charges N_{ox}/cm^2

N_{ox} The fixed oxide layer charge density

$$Q_{ox} = q N_{ox} \quad C/cm^2$$

C_{ox} : gate oxide Capacitance per unit area

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

→ There always exists a fixed +ve charge density Q_{ox} at interface betn gate oxide & Si substrate, due to impurities and/or lattice imperfections at the interface.

↦ V_5 :-

Due to process non-linearities, there are surface charges present at $Si-SiO_2$ interface.

The no of surface charges is N_{ss} $/cm^2$

The Surface charge density is.

$$Q_{ss} = q N_{ss} \quad C/cm^2$$

The gate vtg reqd to offset the effect of Q_{ss} is

$$V_5 = -\frac{Q_{ss}}{C_{ox}} \text{ Volts.}$$

Hence, total gate vtg reqd to create an inversion layer is the sum of above 5 voltages,

$$V_{TO} = V_1 + V_2 + V_3 + V_4 + V_5$$

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

→ Valid for NMOS & PMOS

→ Threshold voltage of a MOS device for zero substrate bias $V_{SB} = 0$

Q1. For an NMOS Tr, substrate doping density $N_A = 10^{16}/cm^3$, gate oxide thickness $t_{ox} = 500 Å$, no of fixed oxide charges $N_{ox} = 2\times10^{10}/cm^2$, no of surface charges $N_{ss} = 0$. Find V_{TO} if $V_{SB} = 0$.

$n_i = 1.45\times10^{10}/cm^2$, $\epsilon_{si} = 11.7\times8.854\times10^{-14}$ F/cm, $\epsilon_{ox} = 3.97\times8.854\times10^{-14}$ F/cm

Data:-

$N_A = 10^{16}/cm^3$

$t_{ox} = 500 Å$

$N_{ox} = 2\times10^{10}/cm^2$

$N_{ss} = 0$, $V_{SB} = 0$

To find:-

$V_{TO} = ?$

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

- $\phi_{GC} \Rightarrow$

$$\phi_{GC} = \phi_{Fsub} - \phi_{Fgate}$$

$$\phi_{Fsub} = \frac{KT}{q} \ln\left[\frac{n_i}{N_A}\right]$$

$$= 0.026 \ln\left[\frac{1.45\times10^{10}}{10^{16}}\right] = -0.35V$$

Select $\phi_{Fgate} = 0.55V$

$$\therefore \phi_{GC} = -0.35 - 0.55$$
$$= -0.9V$$

- $Q_{BO} = -\sqrt{2q\,\epsilon_{si}\,N_A\,|-2\phi_F|}$ c/cm²

$$= -\sqrt{2\times1.6\times10^{-19}\times11.7\times8.854\times10^{-14}\times10^{16}\times0.7}$$

$$= -48.17\times10^{-9} \text{ c/cm}^2$$

- $Q_{ox} = q N_{ox}$ c/cm²

$$= 1.6\times10^{-19}\times2\times10^{10}$$

$$= 3.2\times10^{-9} \text{ c/cm}^2$$

- $Q_{SS} = q N_{SS}$

$$= 0 \text{ c/cm}^2$$

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

$$= \frac{8.854\times10^{-14}\times3.97}{500\times10^{-8}}$$

$$= 70.3\times10^{-9} \text{ F/cm}^2$$

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

$$= -0.9 - 2(-0.35) + \frac{48.17}{70.3} - \frac{3.2}{70.3} - 0$$

$$\boxed{V_{TO} = 0.44 \text{ Volts}}$$

↳ (For NMOS, V_{TO} is +ve)

Q2 For a PMOS Tr, $N_D = 10^{16}/cm^3$, $t_{ox} = 500°A$, $N_{ox} = 2\times10^{10}/cm^2$, $N_{SS} = 0$, $V_{SB} = 0$. Find V_{TO}.

Soln:- $V_{TO} = \phi_{GC} - \phi_F - \frac{Q_{BO}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} - \frac{Q_{ss}}{C_{ox}}$

- $\phi_{GC} = \phi_{Fsub} - \phi_{Fgate}$

$\phi_{Fsub} = \frac{KT}{q} \ln\left[\frac{N_D}{n_i}\right]$

$= 0.35\,V$

Select $\phi_{Fgate} = 0.55V$

$\therefore \phi_{GC} = 0.35 - 0.55V$

$= -0.2\,V.$

- $Q_{BO} = \sqrt{2q\, N_D\, \epsilon_{si}\, |-2\phi_F|}$

$= 48.17\times10^{-9}\ C/cm^2$

- $Q_{ox} = q N_{ox}$

$= 1.6\times10^{-19} \times 2\times10^{10} = 3.2\times10^{-9}\ C/cm^2.$

- $C_{ox} = \epsilon_{ox}/t_{ox} = 70.3\times10^{-9}\ F/cm^2$

- $Q_{ss} = qN_{ss} = 0.$

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

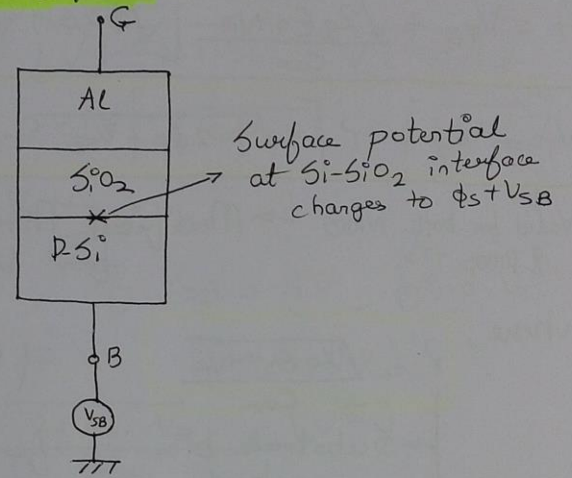
$$= -0.2 - 0.7 - \frac{48.17}{70.3} - \frac{3.2}{70.3} - 0$$

$$\boxed{V_{TO} = -1.63 \text{ Volts.}}$$

↳ For PMOS V_{TO} is -ve.

Note: • Voltage drop across the depletion region at inversion is $-2\phi_F$

↳ Threshold voltage (V_T):
if $V_{SB} \neq 0$.



• Effect of V_{SB}:-

- Surface potential changes to $\phi_s + V_{SB}$
- Depletion charge density change to Q_B

$$Q_{BO} = -\sqrt{2q\epsilon_{si} N_A |-2\phi_F|} \quad c/cm^2$$

$$Q_B = -\sqrt{2q\epsilon_{si} N_A |-2\phi_F + V_{SB}|} \quad c/cm^2$$

- Threshold vtg changes to V_T

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

↳ V_T if $V_{SB} \neq 0$

Note:-

$$V_T = \phi_{GC} - 2\phi_F - \frac{Q_{BO}}{C_{ox}} - \frac{Q_{ox}}{C_{ox}} - \frac{Q_{ss}}{C_{ox}} - \left(\frac{Q_B - Q_{BO}}{C_{ox}}\right)$$

$$V_T = V_{TO} - \frac{Q_B - Q_{BO}}{C_{ox}}$$

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{ V_T of Enhancement type nMOS is +ve
 -||- pMOS is -ve. }

$$V_T = V_{TO} + \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}}\left[\sqrt{|-2\phi_F+V_{SB}|} - \sqrt{|-2\phi_F|}\right]$$

$$V_T = V_{TO} + \gamma\left[\sqrt{|-2\phi_F+V_{SB}|} - \sqrt{|-2\phi_F|}\right]$$

Valid for both Nmos & Pmos Tr's. → Modified Threshold voltage for $V_{SB} \neq 0$.

where, $\gamma = \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}}$ $(V^{\frac{1}{2}})$

- → Substrate bias co-eff / body factor
- +ve for Nmos Tr
- -ve for Pmos Tr
- → Range of γ: $0 < |\gamma| < 1$

Note

- ϕ_F: -ve → nmos; +ve → pmos
- Q_{BO} & Q_B: -ve → nmos; +ve → pmos
- V_{SB}: -ve → pmos; +ve → nmos.

Note :- Since V_{TO} ↑ses, the effect of Substrate bias is to degrade the device performance / characteristics.

Q3. w.r.t Q_1, find threshold vtg V_T if $V_{SB} = 2V$.

Soln:- $V_{TO} = 0.44V$ (Refer Q_1)

$$\gamma = \frac{\sqrt{2q\epsilon_{si}N_A}}{C_{ox}}$$

$$\gamma = \frac{\sqrt{2\times1.6\times10^{-19}\times 8.854\times10^{-14}\times 11.7\times10^{16}}}{70.3\times10^{-9}}$$

$\gamma = 0.819 \quad V^{1/2}$

$V_T = V_{T0} + \gamma \left[\sqrt{|-2\phi_F + V_{SB}|} - \sqrt{|-2\phi_F|} \right]$

$V_T = 0.44 + 0.819 \left[\sqrt{|0.7+2|} - \sqrt{|0.7|} \right]$

$V_T = 1.10$ Volts.

Q4. w.r.t Q(2), if $V_{SB} = -1V$, find V_T

Soln:- $V_T = -1.632\,V$ (Refer Q2)

$\gamma = -\frac{\sqrt{2q\,\epsilon_{si}\,N_D}}{C_{ox}} \quad (V^{\frac{1}{2}})$

$\gamma = -0.819 \quad V^{1/2}$

$V_T = V_{T0} + \gamma \left[\sqrt{|-2\phi_F + V_{SB})} - \sqrt{|-2\phi_F|} \right].$

$V_T = -2.01$ Volts

Q. Find depletⁿ layer width (x_d), depletion charge density Q_{BO}, flat band vtg V_{FB} threshold voltage V_{TO} with $V_{SB} = 0$ & body factor γ.

Given:- $t_{ox} = 400°A$ → gate oxide thickness

Substrate acceptor doping $N_A = 1.5 \times 10^{16}/cm^3$

N_D → Donor doping concⁿ $N_D = 10^{18}/cm^3$

N_{ox} → density of singly charged the surface ions is $5 \times 10^{10}/cm^2$.

⇒ $n_i = 1.45 \times 10^{10}/cm^3$, $\epsilon_{ox} = 0.345 \times 10^{-12} F/cm^2$

$\epsilon_{si} = 11.7\epsilon_0 = 1.035 \times 10^{-12} F/cm^2 = \epsilon_{ox} \times 3.97$

For n-channel MOSFET

Soln:- i) $$x_d = \sqrt{\frac{2\epsilon_{si}|-2\phi_F|}{qN_A}}$$

$$\phi_{Fsub} = \frac{KT}{q} \ln\left(\frac{n_i}{N_A}\right)$$

$$\phi_{Fsub} = -0.36V = \phi_F =$$

- $$x_d = \sqrt{\frac{2\epsilon_{si}|-2\phi_F|}{qN_A}}$$

$$x_d = 24.91\ \mu m.$$

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

$$Q_{BO} = -59.8 \times 10^{-9}\ F/cm^2$$

- $$V_{FB} = \phi_{GC} - \frac{Q_{ox}}{C_{ox}}.$$

- $$\phi_{GC} = \phi_{Fsub} - \phi_{Fgate}$$

⇒ let $\phi_{Fgate} = 0.55V$.

$\therefore \quad \phi_{GC} = -0.36 - 0.55$
$= -0.91\,V.$

- $Q_{ox} = q\,N_{ox} = 8 \times 10^{-9}\ F/cm^2$
- $C_{ox} = \dfrac{\epsilon_{ox}}{t_{ox}} = 86.25\ nF/cm$
- $V_{FB} = \phi_{GC} - \dfrac{Q_{ox}}{C_{ox}}$

$$= -0.91 - \frac{8}{86.25} = 1V.$$

$Q_{ss} = 0$

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

$$= -0.91 - 2(-0.36) + \frac{59.8}{86.25} - \frac{8}{86.25}$$

$$\boxed{V_{TO} = 0.41\ \text{Volts}}$$

- Body factor :- (γ)

$$\gamma = \frac{\sqrt{2q\,\epsilon_{si}\,N_A}}{C_{ox}}$$

$$\boxed{\gamma = 0.817\ V^{1/2}}$$

$t_{ox} = 500°A$, $N_A = 10^{16}/cm^3$