Threshold voltage of MOS transistor:

- The threshold voltage of a MOS transistor (Vth is V_{GS} required to strongly invert the surface of the substrate under the gate.) is calculated like that of a MOS structure with one slight modification in Q_B.

$$Q_B = \sqrt{2\,q\;N_{sub}\;\varepsilon_{sub}\,|\,2\,\phi_F - V_{SB}\,|}$$

Where V_{SB} is the source to bulk voltage.

- For circuit analysis:

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

Where γ is called body effect coefficient = $\dfrac{\sqrt{2q\;N_{sub}\varepsilon_{sub}}}{C_{ox}}$

V_{T0} = the threshold voltage with $V_{SB}=0$ i.e. with out the body effect.

Depletion mode Versus Enhancement mode MOSFET:

- If a MOSFET is on (i.e. in strong inversion) at zero bias then it is a depletion Mode MOSFET (it is normally ON).
  - We actually have to apply a $V_{GS} < V_{th}$ to turn off the NMOS or a $V_{GS} > V_{th}$ for PMOS .
- If a MOSFET is normally off ➔ it is enhancement mode
  - Then for NMOS we have to apply a $V_{GS} > V_{th}$ to turn it ON or a $V_{GS} < V_{th}$ to turn a PMOS ON.

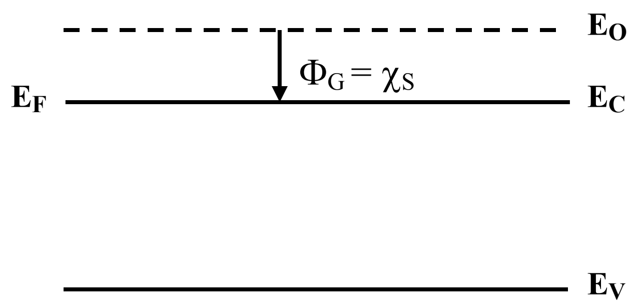
Depletion NMOS ➔ Vth ≤ 0	Enhancement NMOS ➔Vth >0
Depletion PMOS ➔ Vth ≥ 0	Enhancement PMOS ➔Vth < 0

Poly Gate MOSFET:

The gate of MOS transistors is usually made with polycrystalline Si, that is heavily doped (either P or N type).

- In this case Φ_G depends on the type of poly Si

- For N-type poly → the Fermi level is in the conduction band →
  $\Phi_G = \mathbf{E_O} - \mathbf{E_F} = \chi_S$

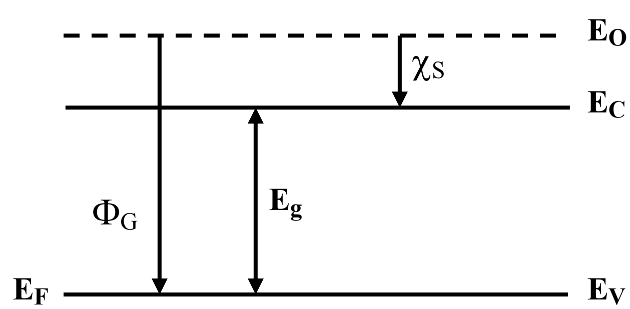


The flat-band voltage V_{FB}:

$$V_{FB} = \Phi_G - \Phi_S = \chi_s - [\chi_s + \frac{E_g}{2q} - \phi_F] \rightarrow$$

$$V_{FB} = -\frac{E_g}{2q} + \phi_F$$

- For P-type poly→ the Fermi level is in the Valence band →
  $\Phi_G = \mathbf{E_O} - \mathbf{E_F} = \chi_S + Eg$



Hence:

$$V_{FB} = \chi_s + \frac{E_g}{2q} - [\chi_s - \frac{E_g}{2q} - \phi_F] \rightarrow$$

$$V_{FB} = \frac{E_g}{2q} + \phi_F$$

Ex1) An MOS transistor is made with a P-type substrate (Na = 10^{16} cm^{-3}) and a heavily doped P-type poly Si gate.
Cox = 2 fF/μm^2 . Calculate Vth and specify the type of the transistor

Sol:
This is an NMOS transistor, since the type of substrate is p-type .

$$V_{th} = V_{FB} + 2\phi_F - \frac{Q_B}{C_{OX}} - \frac{Q_{OX}}{C_{OX}} \quad \left(\frac{Q_{OX}}{C_{OX}} \to 0\right)$$

$$\phi_F = -V_T \ \ln\frac{Na}{n_i} = -0.025\ln\frac{10^{16}}{10^{10}} = -0.345$$

$$V_{FB} = \Phi_G - \Phi_S = \chi_s + Eg - [\chi_s + \frac{E_g}{2q} - \phi_F]$$

$$= - 0.345 + 0.55 = 0.19 \text{ v}$$

$$Q_B = \sqrt{2q \ N_{sub} \ \varepsilon_{sub} |2\phi_F|} = \sqrt{1.6\times10^{-19}\times2\times10^{16}\times8.85\times10^{-14}\times12}$$

$$= - 4.8 \times 10^{-8} \ \ c/cm^2$$

Vth = 0.19 + 0.69 + 4.8 × 10^{-8} = 1.12 V

➔ the type is enhancement NMOS

Ex2) For the same transistor in [Ex1], if the Gate poly is N-type & Q_{ox} = 5x 10^{-8} c/cm^2 Calculate Vth and specify the type of the transistor
Sol:

ϕ_F = -.345 v ,

$$V_{FB} = \chi_s - [\chi_s + \frac{E_g}{2q} - \phi_F]$$

V_{FB} = - 0.89 V , Q_B is the same.

➔

$$\text{Vth} = -0.89 + 0.69 + \frac{4.8\times10^{-8}}{2\times10^{-7}} - \frac{5\times10^{-8}}{2\times10^{-7}} \approx -0.21v$$

➔ the type is Depletion NMOS

Ex3)
For example 2, what is the type of the doping and its concentration required to make Vth = + 0.8v?

Sol.:

We want to increase Vth by about 1v (i.e. make it harder to invert
➔ we need to make it more P-type => i.e. increase Na

- By how much should we increase Na?

Na affects ϕ_F : $|\phi_F| \propto$ ln Na
Na also affects $V_{FB} : V_{FB} \propto \ln Na$
Na affects $Q_B \propto \sqrt{Na}$. This is a bigger dependency

Ignore effects of Na on ϕ_F and V_{FB} =>

we need to increase $\frac{Q_B}{C_{OX}}$ by 1 volt

$\frac{Q_B}{C_{OX}}$ $was \approx 0.23v$

we need it to be = 1.23 v →

$Q_B = 1.23\ Cox = 2.46 \times 10^{-7}\ c/cm^{2}$

$$= \sqrt{2\,q\ \ N_{sub}\ \ \varepsilon_{sub}\,|\,2\,\phi_F\,|} = Na = 2.58x10^{17}\,c/cm^{2}$$

we already have 10^{16} => we need to add $2.58x\ 10^{17} - 10^{16} = 2.48x\ 10^{16}\ cm^{-3}$ more acceptors.