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 $Q_B$.

$$Q_B = \sqrt{2qN_{\text{sub}}\varepsilon_{\text{sub}} | 2\phi_F - V_{SB} |}$$

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

- For circuit analysis:

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

Where $\gamma$ is called body effect coefficient $= \frac{\sqrt{2qN_{\text{sub}}\varepsilon_{\text{sub}}}}{C_{ox}}$

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

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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 $\Rightarrow$ 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 $\Rightarrow$ | $V_{th} \leq 0$ | Enhancement NMOS $\Rightarrow$ | $V_{th} > 0$
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<tbody>
<tr>
<td>Depletion PMOS $\Rightarrow$</td>
<td>$V_{th} \geq 0$</td>
<td>Enhancement PMOS $\Rightarrow$</td>
<td>$V_{th} &lt; 0$</td>
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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 $\Phi_G$ depends on the type of poly Si

- For N-type poly $\rightarrow$ the Fermi level is in the conduction band $\rightarrow$
  \[ \Phi_G = E_O - E_F = \chi_S \]

  \[
  \begin{align*}
  E_F & \quad \Phi_G = \chi_S \\
  E_O & \quad E_C
  \end{align*}
  \]

The flat-band voltage $V_{FB}$:

\[
V_{FB} = \Phi_G - \Phi_S = \chi_S - \left[ \chi_S + \frac{E_g}{2q} - \phi_F \right] \rightarrow
\]

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

- For P-type poly $\rightarrow$ the Fermi level is in the Valence band $\rightarrow$
  \[ \Phi_G = E_O - E_F = \chi_S + E_g \]

Hence:

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

\[
V_{FB} = \frac{E_g}{2q} + \phi_F
\]
Ex1) An MOS transistor is made with a P-type substrate \((N_a = 10^{16} \text{ cm}^{-3})\) and a heavily doped P-type poly Si gate. 
\(C_{ox} = 2 \text{ fF/µm}^2\). Calculate \(V_{th}\) and specify the type of the transistor.

\[V_{th} = V_{FB} + 2\phi_F - \frac{Q_B}{C_{ox}} - \frac{Q_{ox}}{C_{ox}}\]

\[\phi_F = -V_T \ln \frac{N_a}{n_i} = -0.025 \ln \frac{10^{16}}{10^{10}} = -0.345\]

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

\[= -0.345 + 0.55 = 0.19 \text{ V}\]

\[Q_B = \sqrt{2q N_{sub} \varepsilon_{sub}} |2\phi_F| = \sqrt{1.6 \times 10^{-19} \times 2 \times 10^6 \times 8.85 \times 10^{-14} \times 12}\]

\[= -4.8 \times 10^{-8} \text{ c/cm}^2\]

\[V_{th} = 0.19 + 0.69 + 4.8 \times 10^{-8} = 1.12 \text{ V}\]

\[\rightarrow \text{ the type is enhancement NMOS}\]

Ex2) For the same transistor in [Ex1], if the Gate poly is N-type & 
\(Q_{ox} = 5 \times 10^{-8} \text{ c/cm}^2\). Calculate \(V_{th}\) and specify the type of the transistor.

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

\[\Phi_{FB} = \Phi_N - \Phi_S = \chi_n - E_n + [\chi_n + \frac{E_n}{2q} - \phi_F]\]

\[= -0.345 + 0.55 = 0.19 \text{ V}\]

\[Q_{ox} = 5 \times 10^{-8} \text{ c/cm}^2\]
\[ \phi_F = -0.345 \text{ V}, \]

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

\[ V_{FB} = -0.89 \text{ V}, \quad Q_B \text{ is the same}. \]

\[ V_{th} = -0.89 + 0.69 + \frac{4.8 \times 10^{-8}}{2 \times 10^{-7}} - \frac{5 \times 10^{-8}}{2 \times 10^{-7}} \approx -0.21 \text{ V} \]

\[ \text{the type is Depletion NMOS} \]

**Ex3)**

For example 2, what is the type of the doping and its concentration required to make \( V_{th} = +0.8 \text{ V} \)?

**Sol.:**

We want to increase \( V_{th} \) by about 1 V (i.e. make it harder to invert)

\[ \Rightarrow \text{ we need to make it more P-type} \Rightarrow \text{i.e. increase Na} \]

- By how much should we increase Na?

Na affects \( \phi_F \): \( |\phi_F| \propto \ln \text{Na} \)

Na also affects \( V_{FB} \): \( V_{FB} \propto \ln \text{Na} \)

Na affects \( Q_B \propto \sqrt{\text{Na}} \). This is a bigger dependency

Ignore effects of Na on \( \phi_F \) and \( V_{FB} \) =>

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

\[ \frac{Q_B}{C_{OX}} \approx 0.23 \text{ V} \]

we need it to be = 1.23 V \[ \Rightarrow \]
\[ Q_B = 1.23 \text{ Cox} = 2.46 \times 10^{-7} \text{ c/cm}^2 \]

\[ = \sqrt{2} q N_{\text{sub}} \varepsilon_{\text{sub}} |2 \phi_F| = N_a = 2.58 \times 10^{17} \text{ c/cm}^2 \]

we already have \( 10^{16} \) => we need to add \( 2.58 \times 10^{17} - 10^{16} = 2.48 \times 10^{16} \text{ cm}^{-3} \) more acceptors.