Course [redacted] ε

- Q_s : extends on the semiconductor
- insulator : no charges (ideal)
- metal : $\vec{E} = 0$ $\Rightarrow$ charges only at surface
- Gauss Law :

$$\frac{\partial E}{\partial x} = \frac{\rho(x)}{\varepsilon} \Rightarrow E = \frac{Q}{\varepsilon}$$

total charge density (*)

dielectric constant

- Electric field is discontinuous
but $\vec{D}$ normal must be continuous :

$$\varepsilon_s \cdot E_s = \varepsilon_{ox} \cdot E_{ox} \quad , \text{ at interface}$$

- Capacitance per unit area :

$$C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}}$$

dielectric constant

thickness of oxide

(*) Other ways of looking at this : #1

·) $\varepsilon = F/m =$

$$C[F] = \frac{Q[C]}{V}$$

thus

$$\varepsilon \cdot \underbrace{\frac{V}{cm}}_{|\vec{E}|} = \frac{Q}{cm^2} \quad \text{charge density}$$

$$\Rightarrow |\vec{E}| = \frac{Q_s}{\varepsilon}$$

or

$$C = \frac{\varepsilon . A}{t}$$

$$Q = C . V$$

thus:

$$\frac{Q}{A} = \underbrace{\frac{\varepsilon}{t} . V}_{|\vec{E}|}$$

$$\Rightarrow Q_s = \varepsilon . |\vec{E}|$$

$\therefore$ the dielectric constant links the amount of charges to an electric field !

Exercise 1 :

Consider MOS structure : $x_{ox} = 4.5nm$

$\phi_{bi} = 1V$

$\phi_{ox} = 0.42V$ at zero bias

calculate ϕ_s , Q_s , E_s , E_{ox} :

$$E_{ox} = \frac{\phi_{ox}}{x_{ox}} = \frac{0.42V}{4.5 \times 10^{-7} cm} = 9.3 \times 10^{5} V/cm$$

$$E_s = \frac{\varepsilon_{ox} . E_{ox}}{\varepsilon_s} = \frac{3.9}{11.7} \times 9.3 \times 10^5 = 3.1 \times 10^5 V/cm$$

$$Q_s = \varepsilon_s E_s = 11.7 \times 8.85 \times 10^{-14} F/cm \times 3.1 \times 10^5 V/cm = 3.2 \times 10^{-7} C/cm^2$$

$$\phi_s = \phi_{bi} - \phi_{ox} = 0.58V$$

Depletion approximation :

* Note that :

Just as previously, the conduction band E_C followed the shape of the potential with a negative sign : $E_c(x) \sim -\phi(x)$

$\Rightarrow$ Now the same happens but :

- E_c is no longer continuous.
- $\phi(x)$ is continuous.

$\Rightarrow$ the larger the difference in workfunction, the larger x_d.

We don't know x_d :

$$\underbrace{Q = V.C}$$

$$\phi_{bi} = \phi_s - \frac{Q_s}{C_{ox}}$$

$$= \frac{q N_A . x_d^2}{2\varepsilon_s} + \frac{q N_A x_d}{C_{ox}}$$

quadratic equation :

$$\Longrightarrow \quad \therefore \; x_d \simeq \frac{\varepsilon_s}{C_{ox}} \left(\sqrt{1 + \frac{4\phi_{bi}}{\gamma^2}} - 1 \right)$$

γ : body factor coefficient

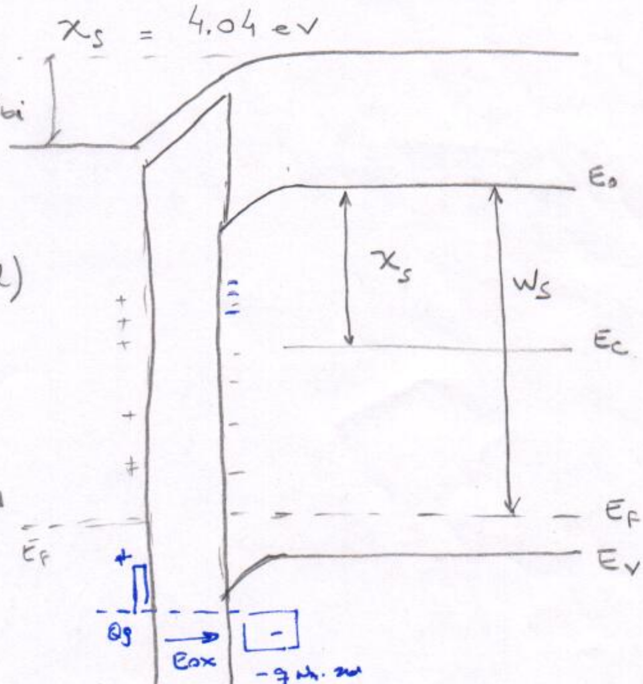
$$\gamma = \frac{1}{C_{ox}} \sqrt{2\varepsilon_s \, q \, N_A} \quad \left[V^{1/2} \right] \Rightarrow N_A \uparrow, \; x_d \downarrow, \; C \uparrow \Rightarrow \gamma \uparrow$$

$\Rightarrow \gamma$: relative magnitude of the depletion region capacitance and the oxide capacitance.

Exercise :

Consider MOS structure :

- W gate : $W_M = 4.54\,eV$
- 4.5 nm SiO_2
- p-type $N_A = 6 \times 10^{17}\,cm^{-3}$



calculate E_{ox} and Φ_S (surface potential)

$$W_S = \chi_s + (E_F - E_V) + E_g$$

$$W_S = \chi_s + \underbrace{E_g + KT \ln \frac{N_A}{N_V}}_{E_g + E_F - E_V = E_c - E_F}$$

since $(E_F - E_V) = -KT \ln\left(\frac{N_A}{N_V}\right)$

$$\therefore W_S = 4.04 + 1.12 + 0.026 . \ln \frac{6 \times 10^{17}}{3.1 \times 10^{19}} = 5.06\,eV$$

$$\therefore \phi_{bi} = \frac{1}{q}(W_S - W_M) = 5.06 - 4.54 = 0.52\,V$$

$$C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}} = \frac{3.9 \times 8.85 \times 10^{-14} F/cm}{45 \times 10^{-7}\ cm} = 7.7 \times 10^{-7} F/cm^2$$

$$\gamma = \frac{1}{C_{ox}} \sqrt{2 \varepsilon_s q N_A} = \frac{\sqrt{2 \times 1.04 \times 10^{-12} F/cm \times 1.6 \times 10^{-19} C \times 6 \times 10^{17} cm^{-3}}}{7.7 \times 10^{-7} F/cm^2} =$$

$$\gamma = 0.58\ V^{1/2}$$

$\varepsilon_s = 11.7 \times 8.85 \times 10^{-7} F/cm$

thus:

$$x_d = \frac{\varepsilon_s}{C_{ox}} \left(\sqrt{1 + \frac{4 \phi_{bi}}{\gamma^2}} - 1 \right) =$$

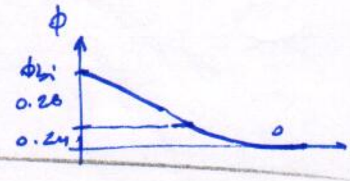
$$= \frac{1.04 \times 10^{-12} F/cm}{7.7 \times 10^{-7} F/cm^2} \cdot \left(\sqrt{1 + \frac{4 \times 0.52}{0.58^2}} - 1 \right) = \mathbf{23\,nm}$$

$$E_{ox} = \frac{q N_A x_d}{\varepsilon_{ox}} = \frac{1.6 \times 10^{-19} C \cdot 6 \times 10^{17} cm^{-3} \times 2.3 \times 10^{-6} cm}{3.45 \times 10^{-13} F/cm}$$

$$= 6.4 \times 10^5\ V/cm$$ $\Rightarrow$ thus $\phi_{ox} = E_{ox} \cdot x_{ox} = 6.4 \times 10^5 \frac{V}{cm} \times 4.5 \times 10^{-7} cm = 0.28V$

$$\phi_s = \frac{q N_A x_d^2}{2 \varepsilon_s} = \frac{1.6 \times 10^{-19} C \cdot 6 \times 10^{17} cm^{-3} \times (2.3 \times 10^{-6})^2}{2 \times 1.04 \times 10^{-12} F/cm} = 0.24V$$

$\Rightarrow \phi_{bi} = 0.24V$



MOS under bias:

- $\phi_{bi} \longrightarrow \phi_{bi} + V$

- presence of the oxide blocks the current $\Rightarrow$ electrostatics are similar to that of a pn diode or Schottky diode

$$\Rightarrow \quad \phi_{bi} + V = \phi_s(V) - \frac{Q_s(V)}{C_{ox}}$$

Exercise: Consider an MOS structure with: #4

- Poly-Si gate $W_M = 4.04\ eV$
- SiO_2 oxide : 4.5nm at $V = -0.5V$
- p-type $N_A = 6 \times 10^{17}\ cm^{-3}$

Compute Q_s, x_d ($V = -0.5V$) & V_{Th}, Q_i (for $V = 2V$). How about the carrier density?

1) $\phi_{bi} = 1\ V$, $C_{ox} = 7.7 \times 10^{-7}\ F/cm^2$

2) previously : $\gamma = 0.58 V$

Depletion charge : $Q_s = -\frac{1}{2}\gamma^2 . C_{ox} \left(\sqrt{1 + 4\frac{\phi_{bi} + V}{\gamma^2}} - 1\right)$

$$= -\frac{1}{2} \cdot (0.58)^2 \cdot 7.7\times10^{-7}\ F/cm^2 \cdot \left[\sqrt{1 + 4\frac{1.0 - 0.5}{(0.58)^2}} - 1\right] = -2.1\times10^{-7}\ C/cm^2$$

$$x_d = \frac{Q_s}{-q \cdot N_A} = \frac{-2.1\times10^{-7}}{-1.6\times10^{-19} \times 6\times10^{+17}} = 22\ nm$$

3) $\phi_{sth} = 2\frac{kT}{q}\ln\frac{N_A}{n_i} = 2 \times 0.026 \times \ln\frac{6\times10^{17}}{1.02\times10^{10}} = 0.93\ V$

$$V_{th} = \overset{-\phi_{bi}}{V_{FB}} + \phi_{sth} + \gamma\sqrt{\phi_{sth}}$$

$$= -1V + 0.93 + 0.58 \cdot \sqrt{0.93} = 0.49V$$

$\therefore V > 0.49V$

$\Rightarrow$ inversion

for $V = 2V$:

$$Q_i = -C_{ox} \cdot (V - V_{th}) = -7.7\times10^{-7}\ F/cm^2 \times (2 - 0.49) = -1.2\times10^{-6}\ C/cm^2$$

$$\therefore n_i = \frac{-1.2\times10^{-6}\ C/cm^2}{-1.6\times10^{-19}} = 7.5\times10^{12}\ cm^{-2}$$