Fundamentals of Nanotransistors

Unit 2: MOS Electrostatics

Lecture 2.4: Flatband Voltage

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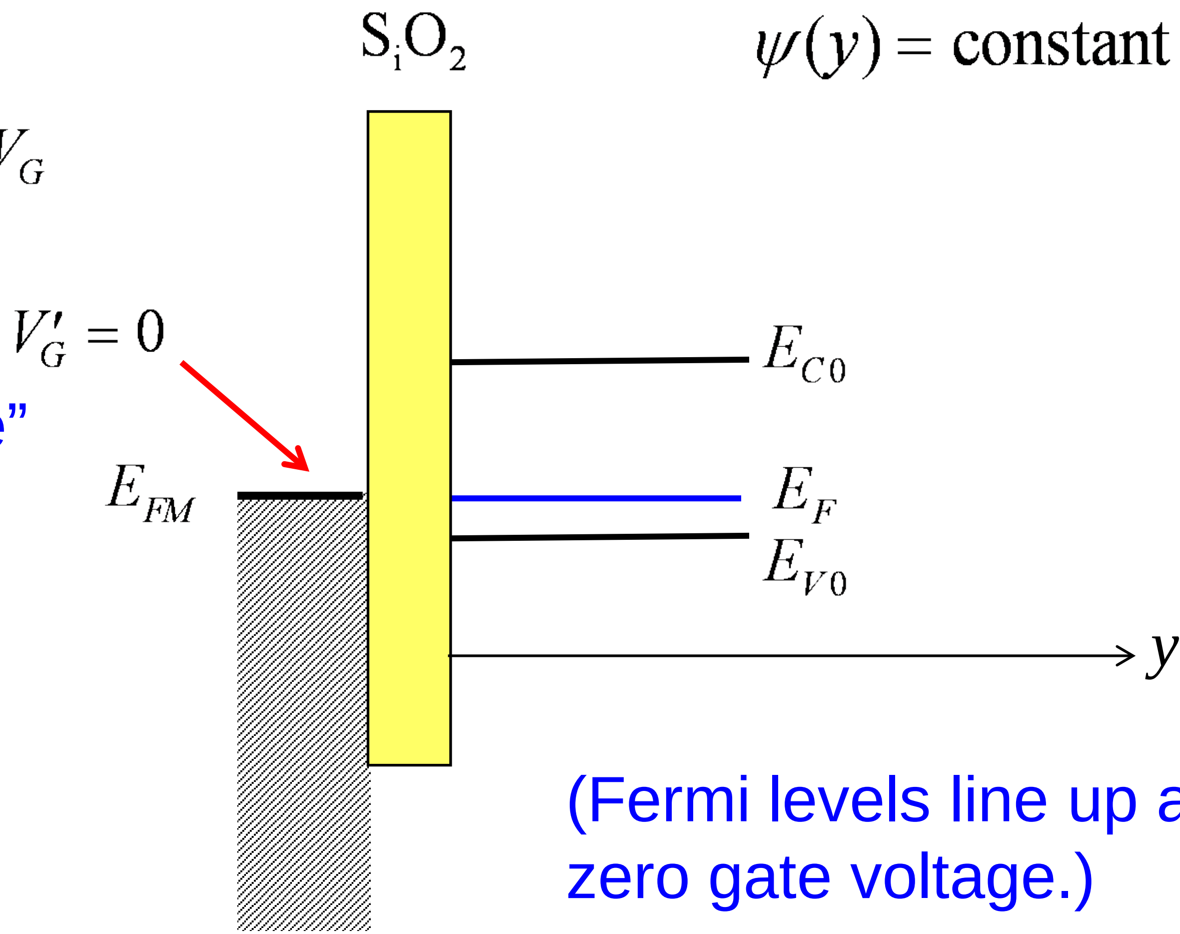
Hypothetical, ideal MOS-C

$$\psi(y) = \text{constant} = 0$$

$$E_{FM} = E_{FM}^{0} - qV_G$$



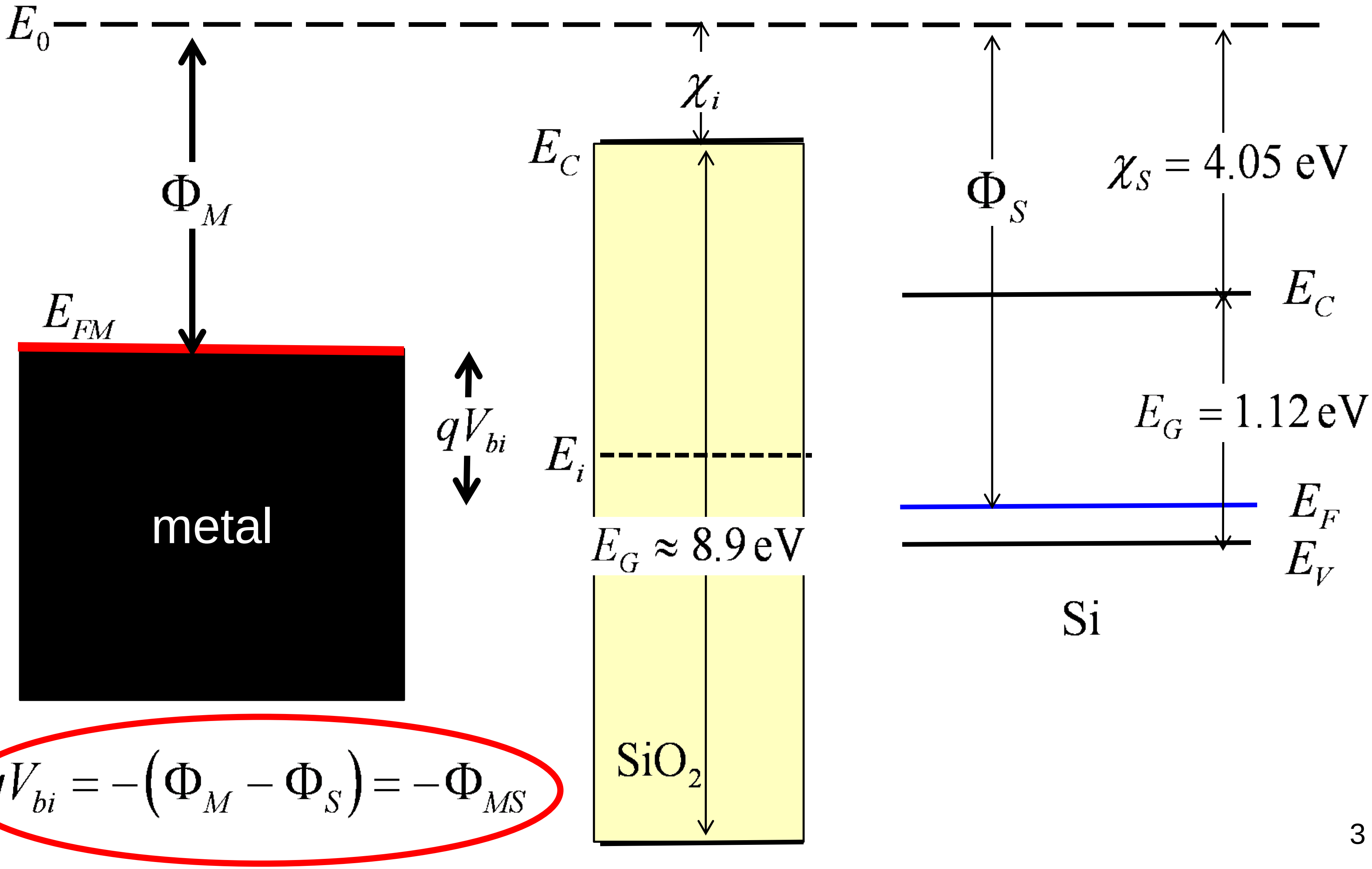
“flatband voltage”

$$V_{FB} = 0$$

No metal-semiconductor workfunction difference.

(Fermi levels line up at zero gate voltage.)

Gate voltage and surface potential

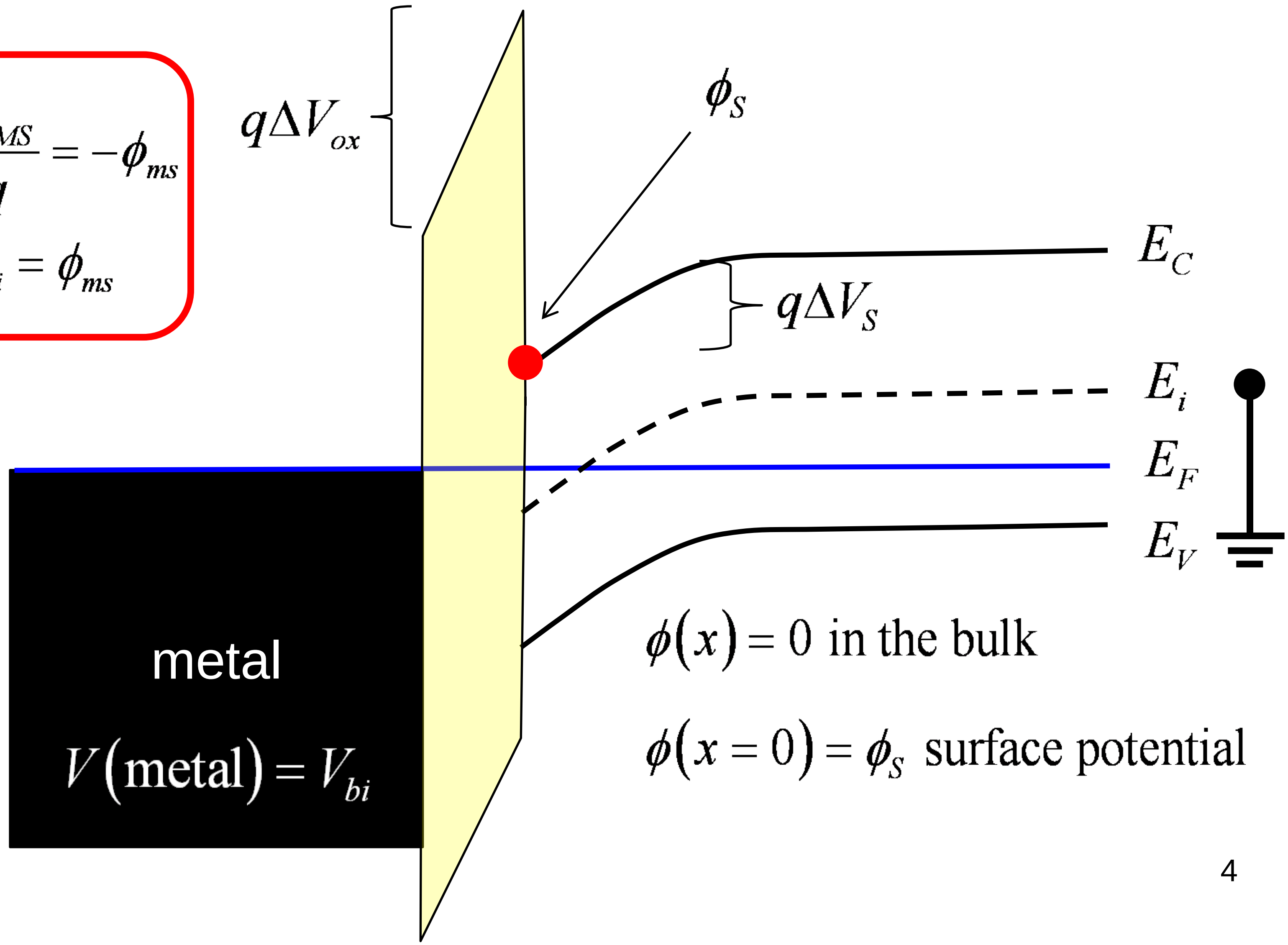


$$qV_{bi} = -\left(\Phi_M - \Phi_S\right) = -\Phi_{MS}$$

Real MOS-C at $V_G = 0$

$$V_{bi} = -\frac{\Phi_{MS}}{q} = -\phi_{ms}$$

$$V_{FB} = -V_{bi} = \phi_{ms}$$



$\phi(x) = 0$ in the bulk

$\phi(x=0) = \phi_S$ surface potential

Example

Aluminum metal and p-type Si

$$N_A = 10^{18}\ \text{cm}^{-3}$$

$$p_0 = N_V e^{(E_V - E_F)/k_B T}\ \text{cm}^{-3}$$

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

$$N_V = 1.83 \times 10^{19}\ \text{cm}^{-3}$$

$$\frac{E_F - E_V}{q} = 0.08\ \text{eV}$$

$$\Phi_M = 4.08\ \text{eV}$$

$$\Phi_S = \chi_S + E_G - \left(E_{FS} - E_V\right)/q$$

$$\chi_S = 4.05\ \text{eV} \qquad E_G = 1.12\ \text{eV}$$

$$\Phi_S = 5.09\ \text{eV}$$

$$\phi_{ms} = \frac{\left(\Phi_M - \Phi_S\right)}{q} = -1.01\ \text{V}$$

$$V_{FB} = \phi_{ms} = -1.01\ \text{V}$$

✓

Gate voltage vs. surface potential

$$V_G' = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

$$V_G = V_G' + V_{FB} = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

$$\boxed{\begin{gathered} V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S \\ V_{FB} = \phi_{ms} \end{gathered}}$$

Recall: Threshold voltage example

$$V_G' = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

$$V_T' = -\frac{Q_D(2\psi_B)}{C_{ox}} + \psi_S$$

$$V_T' = \frac{5.6 \times 10^{-7}}{1.73 \times 10^{-6}} + 0.96$$

$$= 0.32 + 0.96$$

$$= 1.28 \text{ V}$$

$$V_T = V_{FB} + 1.28 \text{ V} = 0.27 \text{ V}$$ ✓

$$2\psi_B = 0.96 \text{ V}$$

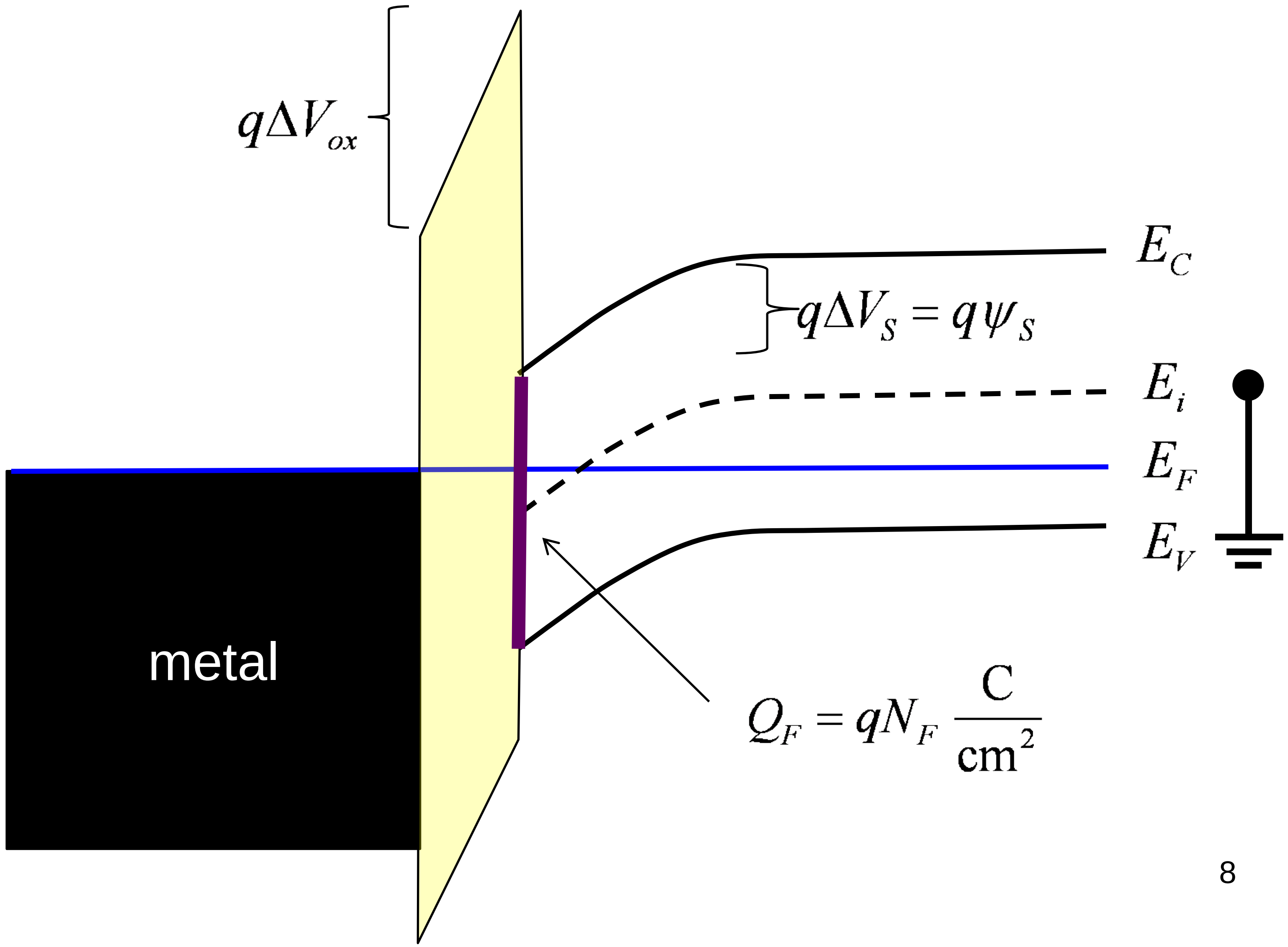
$$W_D = 35 \text{ nm}$$

$$Q_D = -5.6 \times 10^{-7} \text{ C/cm}^2$$

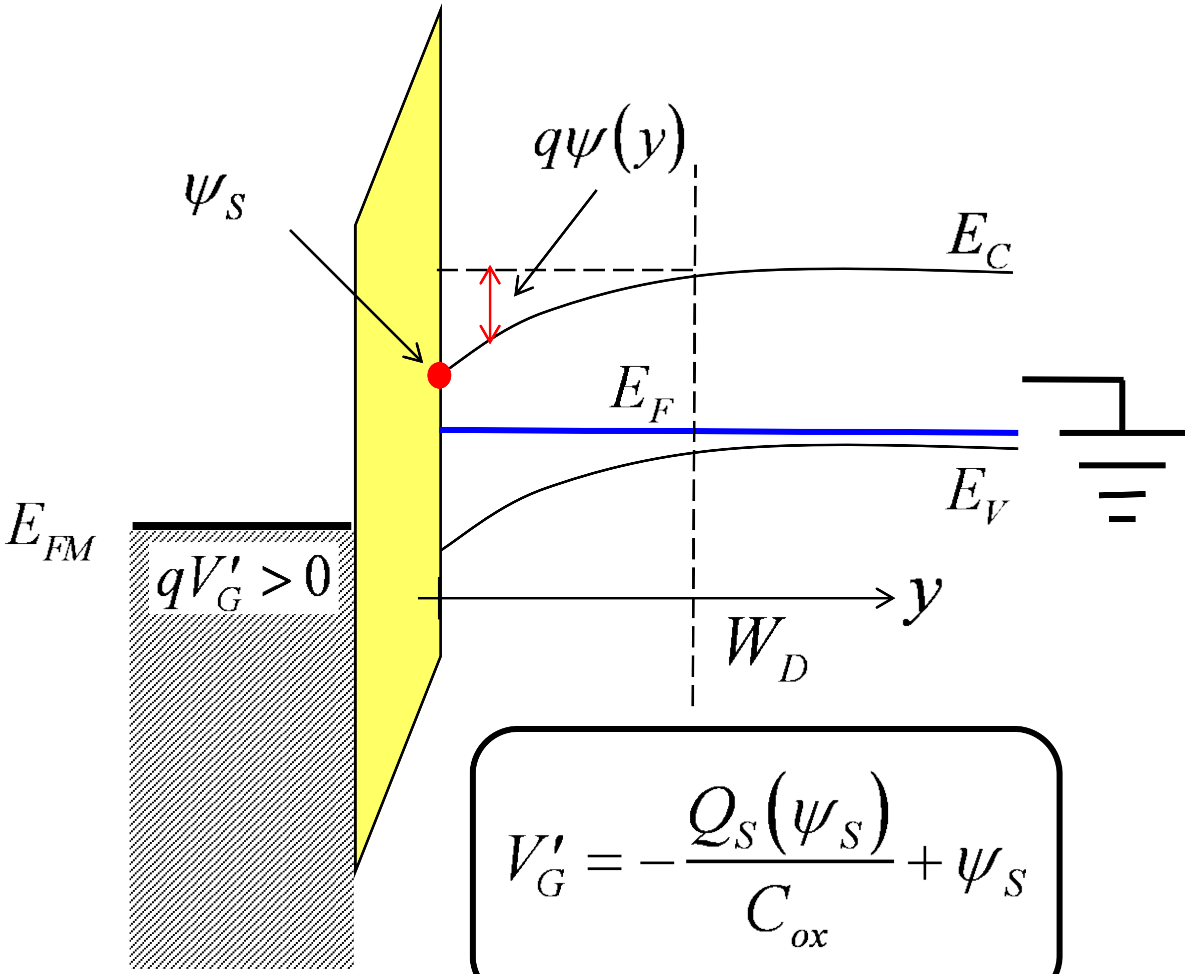
$$C_{ox} = 1.73 \times 10^{-2} \text{ F/m}^2$$

$$V_{FB} = -1.01 \text{ V}$$

Charge at the oxide-semiconductor interface



Voltage drop across the oxide



$$\boxed{V'_G = -\frac{Q_S(\psi_S)}{C_{ox}} + \psi_S}$$

$$V_G = \Delta V_{ox} + \Delta V_{Si}$$

$$\Delta V_{Si} = \psi_S$$

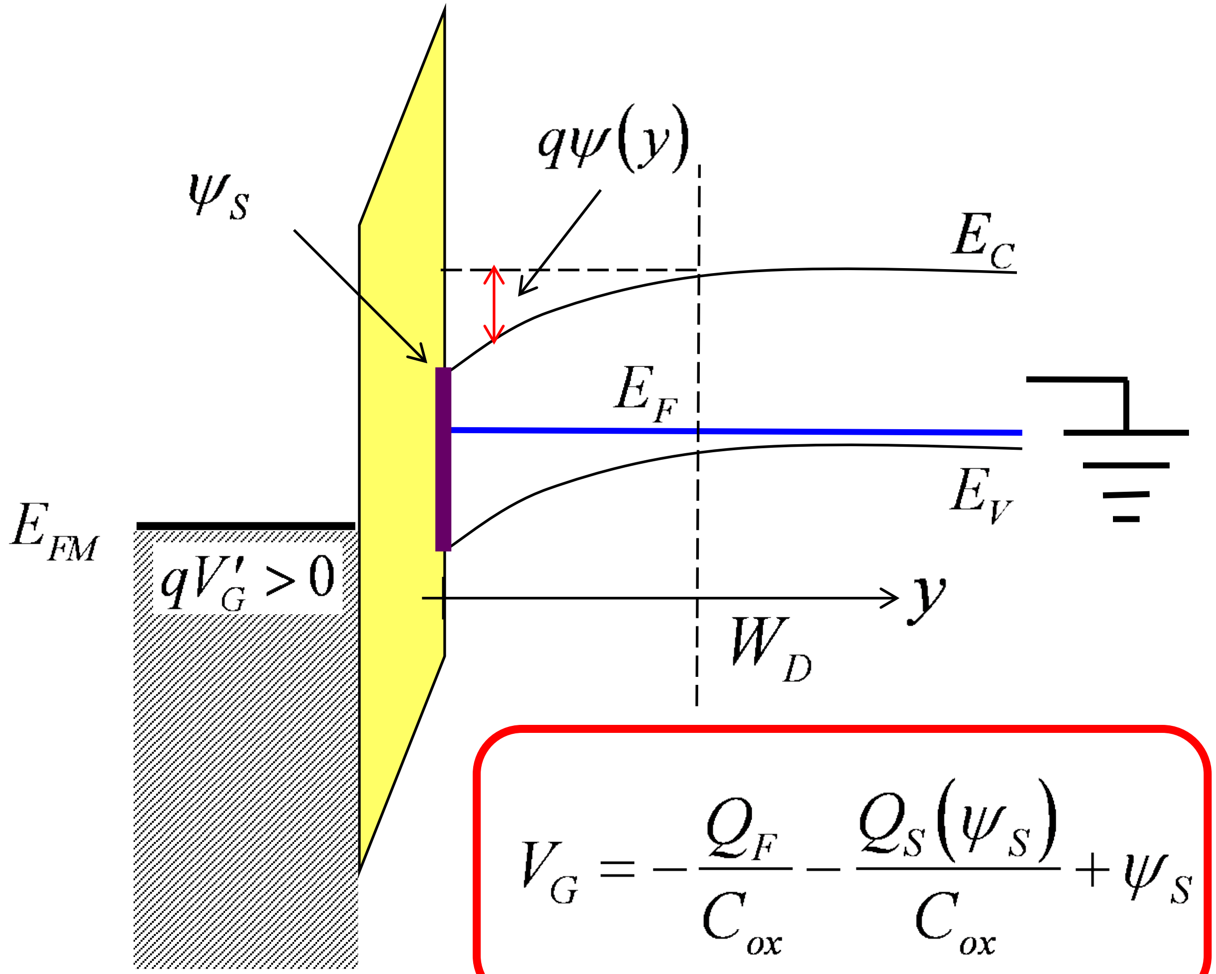
$$\Delta V_{ox} = \mathcal{E}_{ox} t_{ox}$$

$$\varepsilon_{ox}\mathcal{E}_{ox} = -Q_S(\psi_S)$$

$$\Delta V_{ox} = -Q_S(\psi_S)\frac{t_{ox}}{\varepsilon_{ox}}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \ \text{F/cm}^2$$

Voltage drop across the oxide: with Q_F



$$V_G = -\frac{Q_F}{C_{ox}} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

$$V_G = \Delta V_{ox} + \Delta V_{Si}$$

$$\Delta V_{ox} = \mathcal{E}_{ox} t_{ox}$$

$$\varepsilon_{ox}\mathcal{E}_{ox} = -Q_F - Q_S(\psi_S)$$

$$\Delta V_{ox} = \frac{-Q_F - Q_S(\psi_S)}{C_{ox}}$$

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \ \text{F/cm}^2$$

Flatband voltage again

$$\boxed{\begin{gathered} V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S \\ \\ V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}} \end{gathered}}$$

Recall: Threshold voltage example

$$V_T = V_{FB} - \frac{Q_D(2\psi_B)}{C_{ox}} + 2\psi_B$$

$$V_T = 0.27 \text{ V}$$

$$Q_F = qN_F = 1.6\times10^{-8} \text{ C/cm}^2$$

$$\frac{Q_F}{C_{ox}} = 0.01 \text{ V}$$

$$V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}}$$

$$V_T = 0.26 \text{ V} \quad \checkmark$$

$$2\psi_B = 0.96 \text{ V}$$

$$W_D = 35 \text{ nm}$$

$$Q_D = -5.6\times10^{-7} \text{ C/cm}^2$$

$$C_{ox} = 1.73\times10^{-6} \text{ F/cm}^2$$

$$\phi_{ms} = -1.01 \text{ V}$$

$N_F = 10^{11} \text{ cm}^{-2}$ (positive charges)

Wrap up

1) The flatband voltage in a real MOS-C is non-zero.

$$V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}}$$

2) The gate voltage relation is:

$$V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S$$

3) **Next:** Understand the inversion (mobile charge)