Essentials of MOSFETs

Unit 3: MOS Electrostatics

Lecture 3.4: Flat-band Voltage

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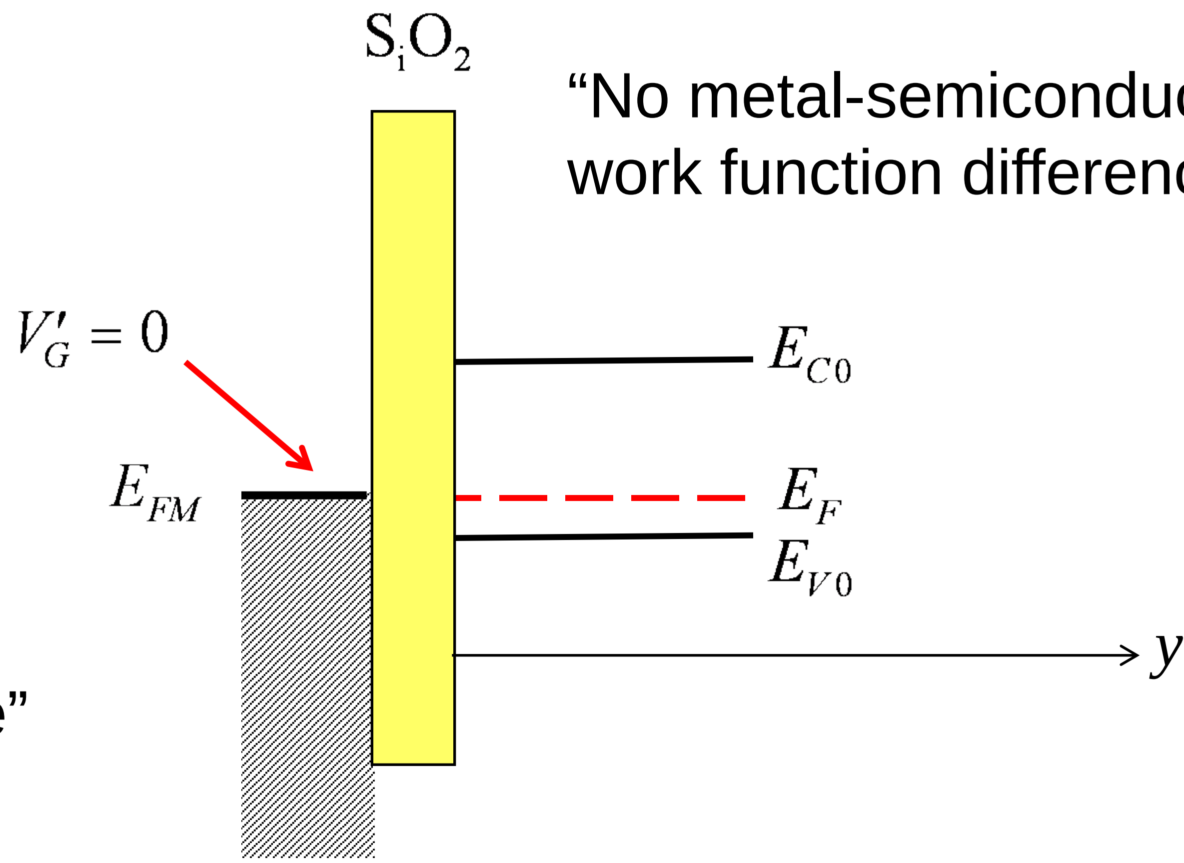
Hypothetical, ideal MOS-C



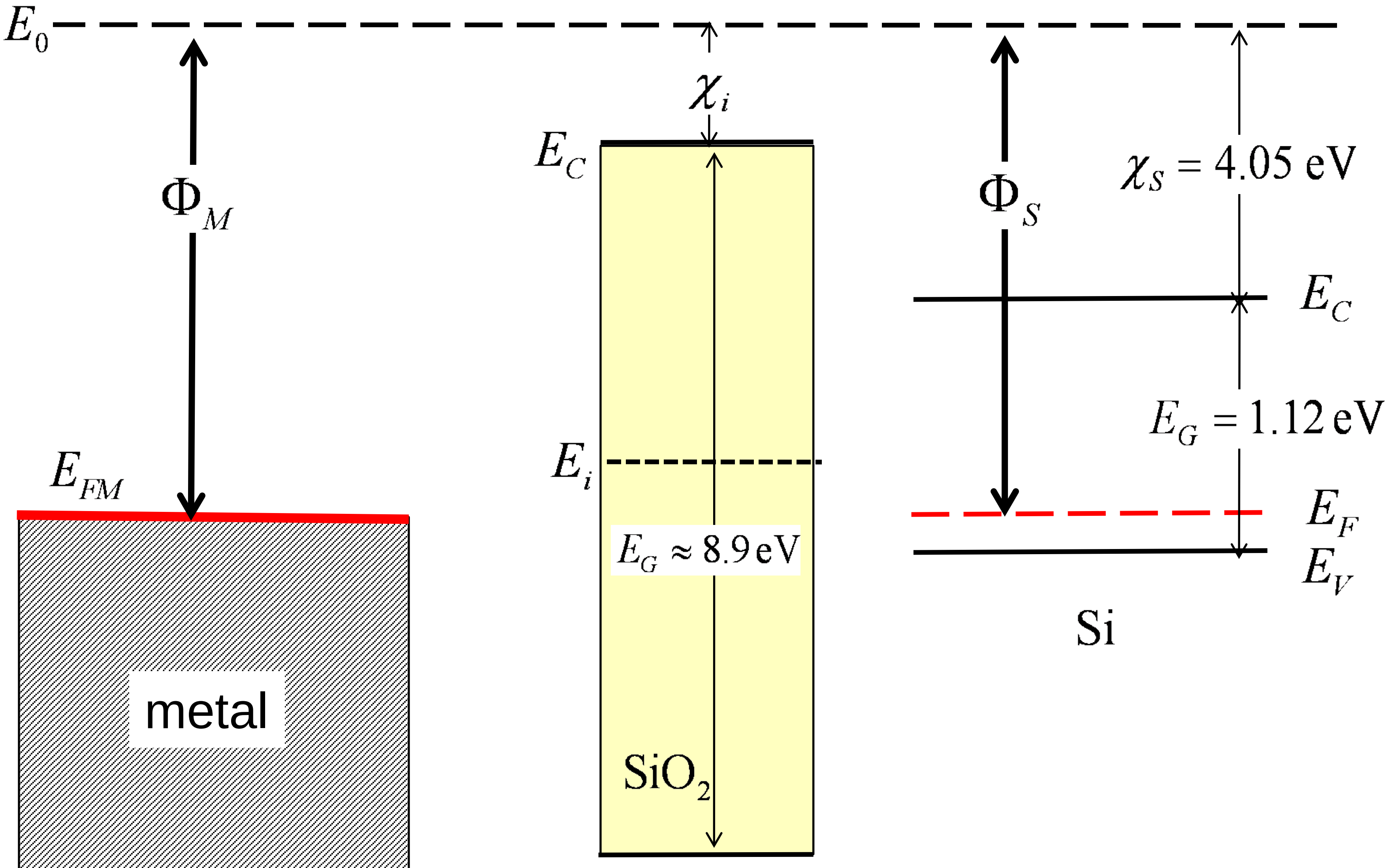
"No metal-semiconductor work function difference."

$V_{FB} = 0$

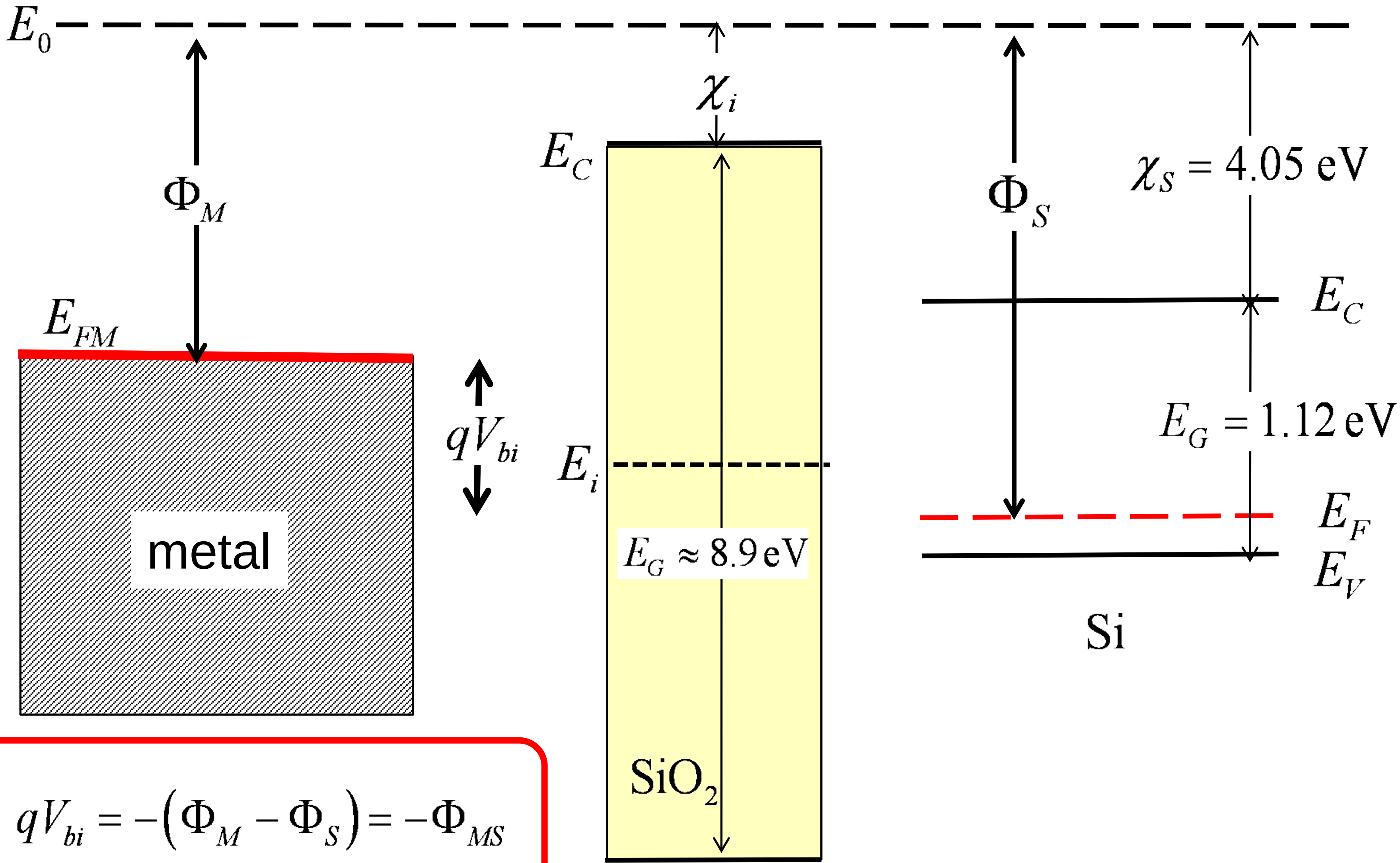
"flatband voltage"

The Fermi level in this "special" metal lines up with the Fermi level in the semiconductor at zero gate voltage.)

Hypothetical, ideal MOS-C



Real MOS-C

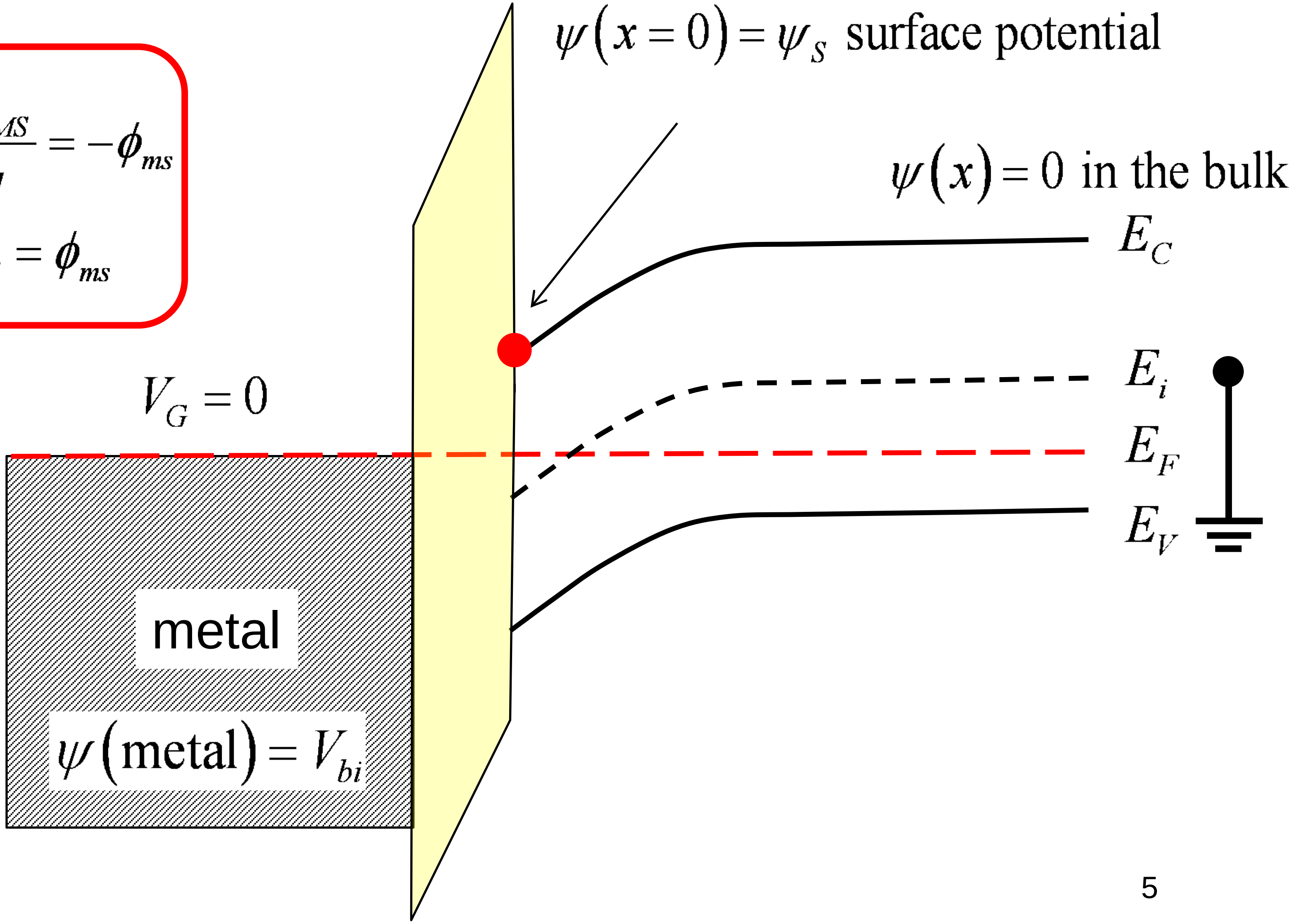


$$qV_{bi} = -\left(\Phi_M - \Phi_S\right) = -\Phi_{MS}$$

Real MOS-C at $V_G = 0$

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

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



Example

Aluminum metal and p-type Si

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

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

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

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

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

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

$$\Phi_S = \chi_S + E_G - (E_F - E_V)/q$$

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

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

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

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

Gate voltage vs. surface potential

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

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

$$V_{FB} = \phi_{ms} = \Phi_{MS}/q$$

Recall: Threshold voltage example

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

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

$$V_T' = 1.28 \text{ V}$$

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

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

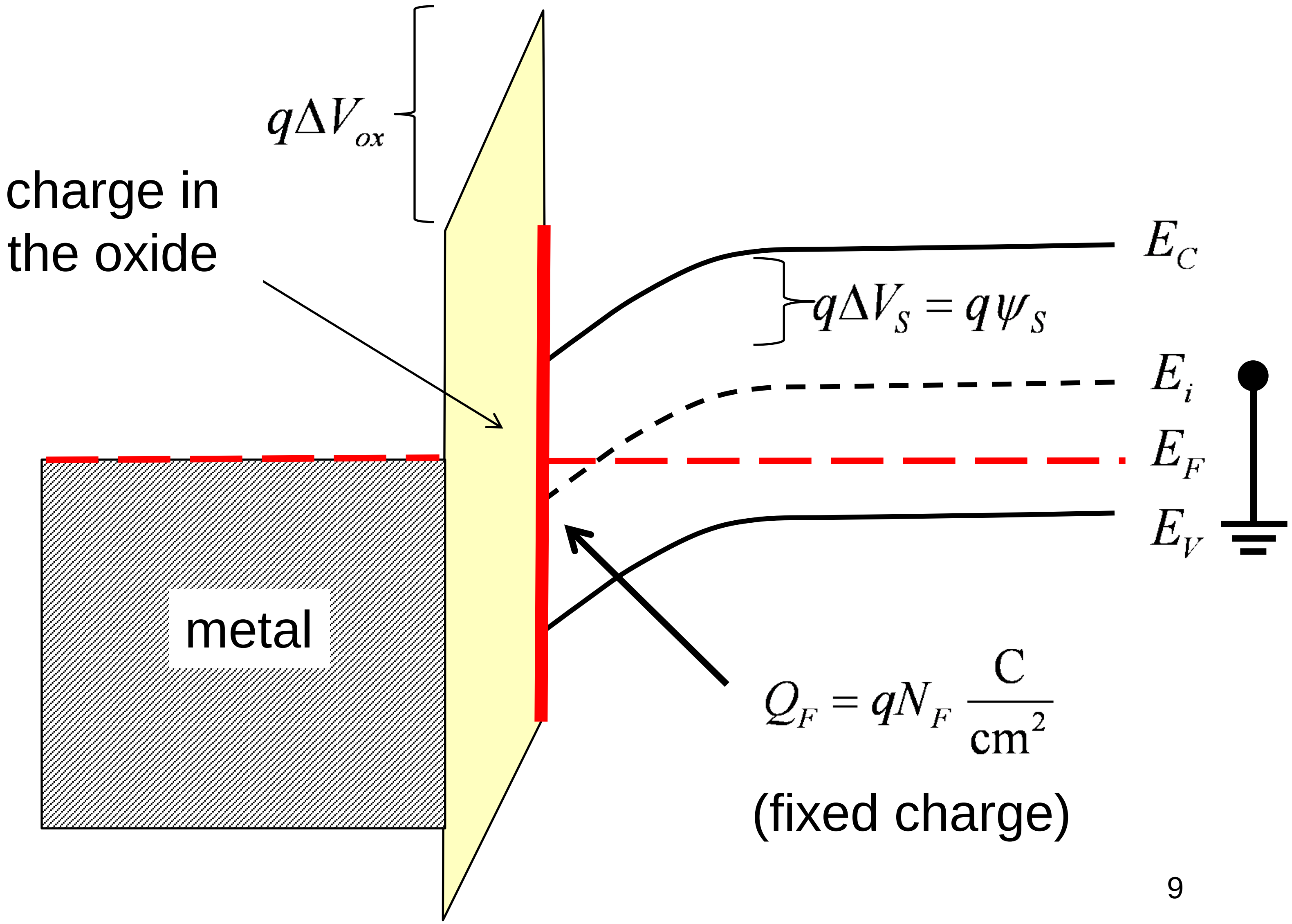
$$Q_D = -5.6 \times 10^{-7} \text{ C/cm}^2$$

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

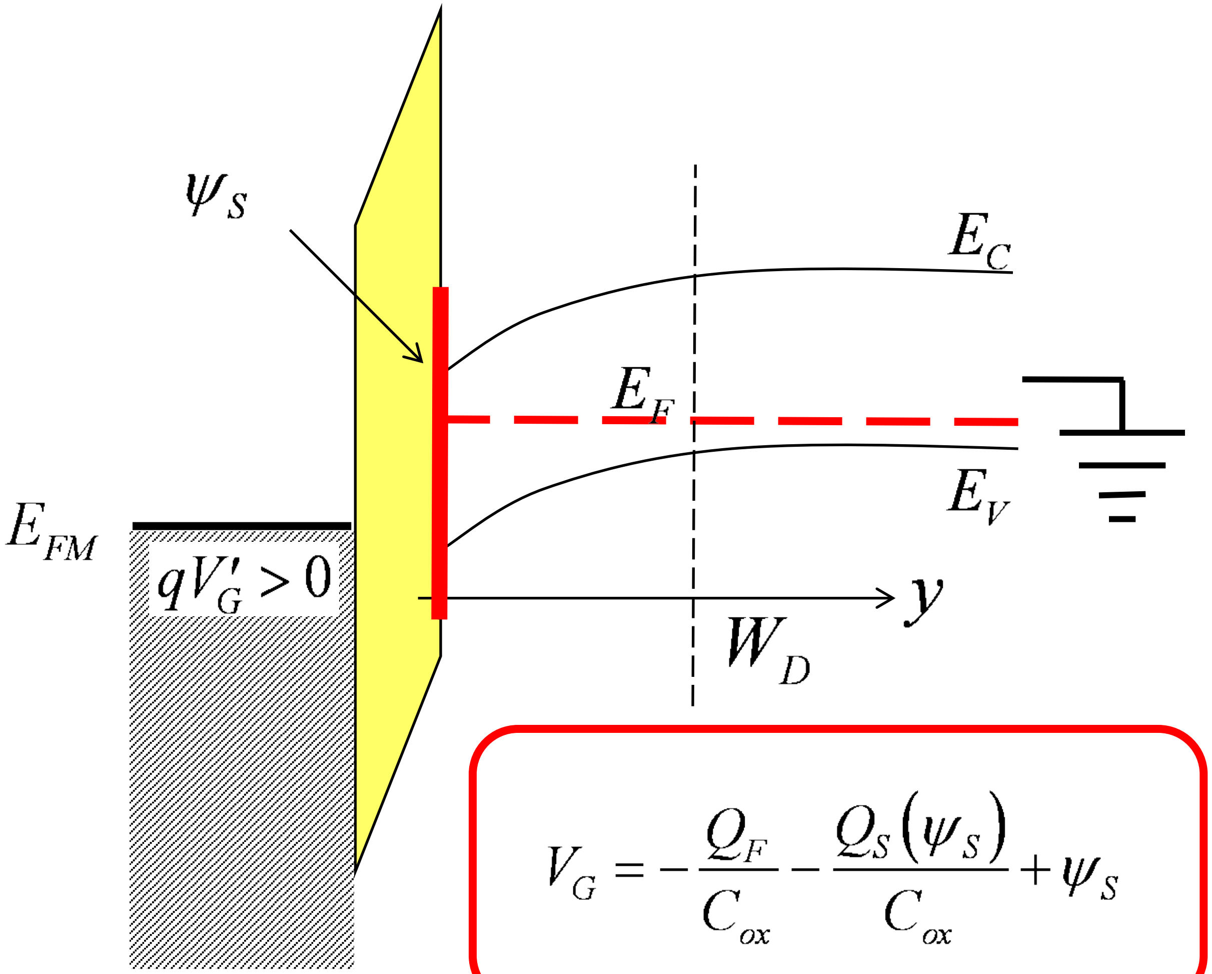
$$V_{FB} = -1.01 \text{ V}$$

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

Charge at the oxide-semiconductor interface



Volt drop across the oxide at fixed surface potential



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

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

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

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

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

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

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Flat-band voltage again

$$\boxed{\begin{gathered} V_G = V_{FB} - \frac{Q_S(\psi_S)}{C_{ox}} + \psi_S \\[2em] V_{FB} = \phi_{ms} - \frac{Q_F}{C_{ox}} \end{gathered}}$$

Recall: Threshold voltage example

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

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

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

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

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

$$V_T = 0.26 \text{ V}$$ ✓

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

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

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

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

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

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

Summary

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

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

2) The gate voltage relation is:

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

Next topic

Measuring the small signal capacitance as a function of DC bias voltage is a powerful technique for characterizing MOS structures.

Understanding MOS CV characteristics is the subject of the next lecture.