MOS Stack

Lecture 4-5

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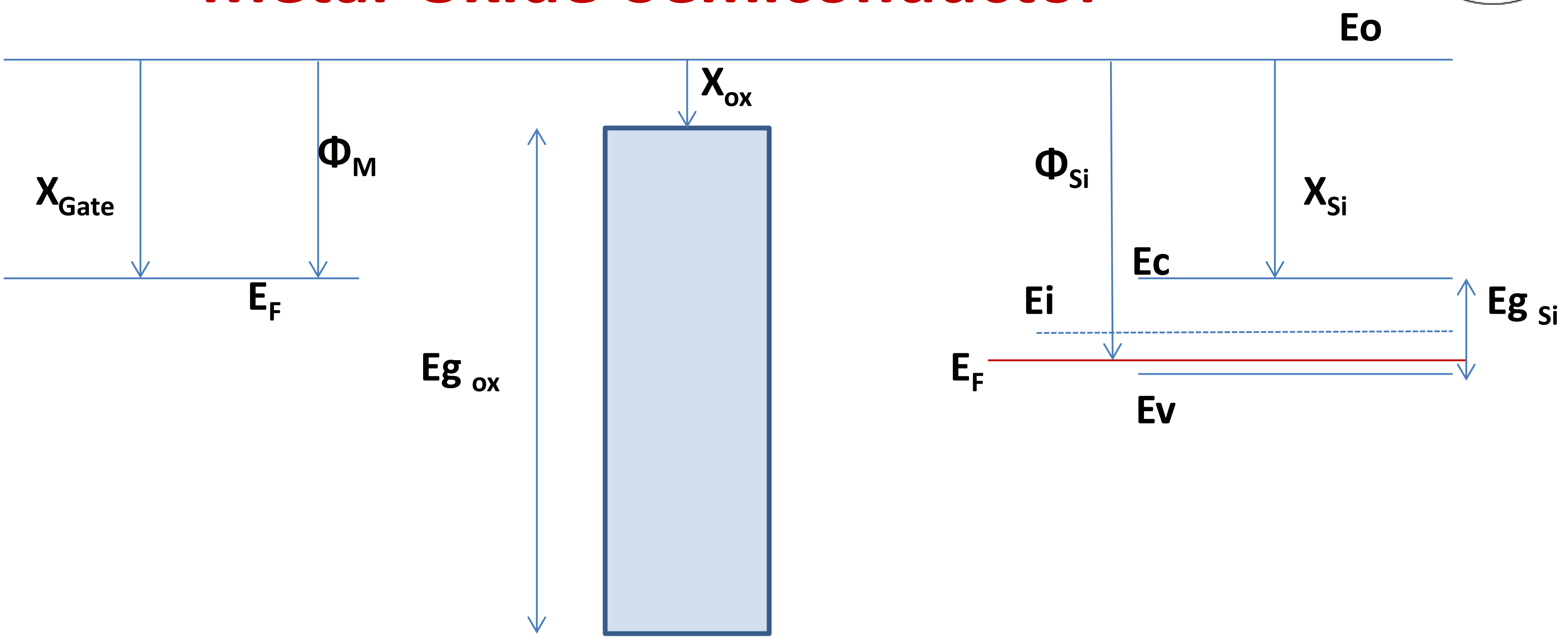
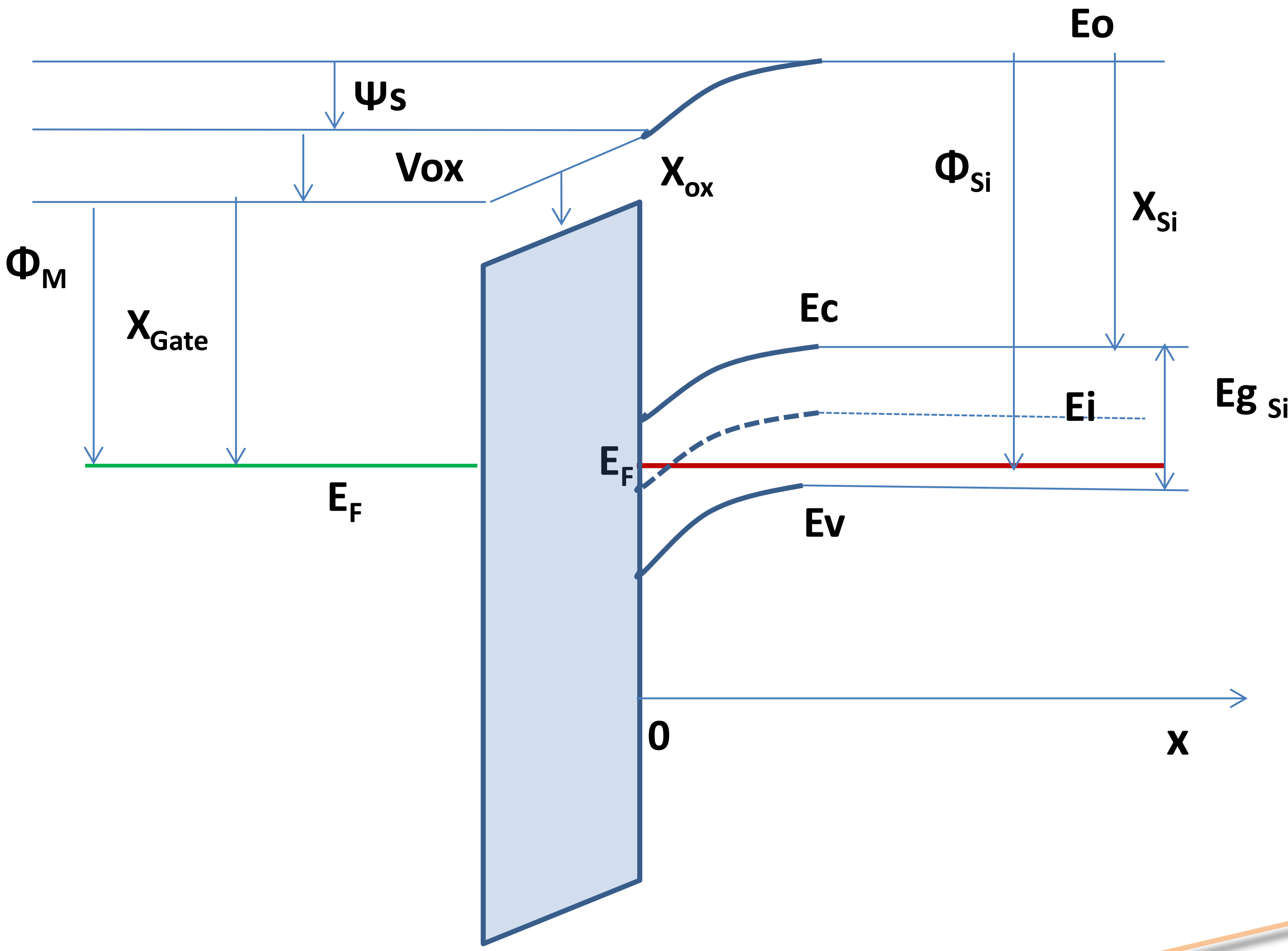
Outline

- MOS Band Diagram
- "Classical" Charge Distribution
- Depletion Approximation
- Potential Drop Equation
- Threshold Voltage (V_{th}) and Flatband Volatge (V_{FB})
- Capacitance Voltage (C-V) Characteristics

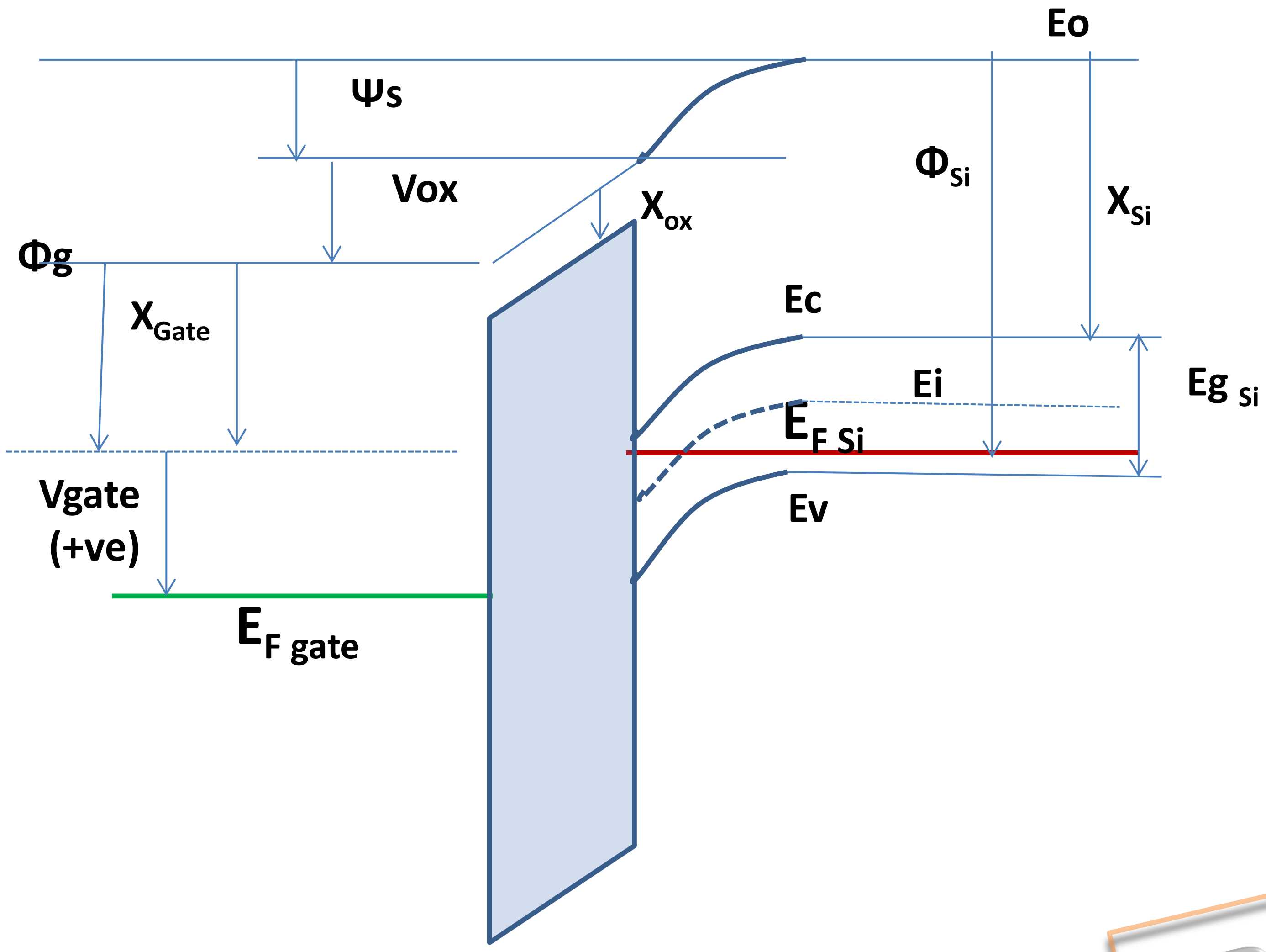
Band Diagram:
Metal-Oxide-Semiconductor



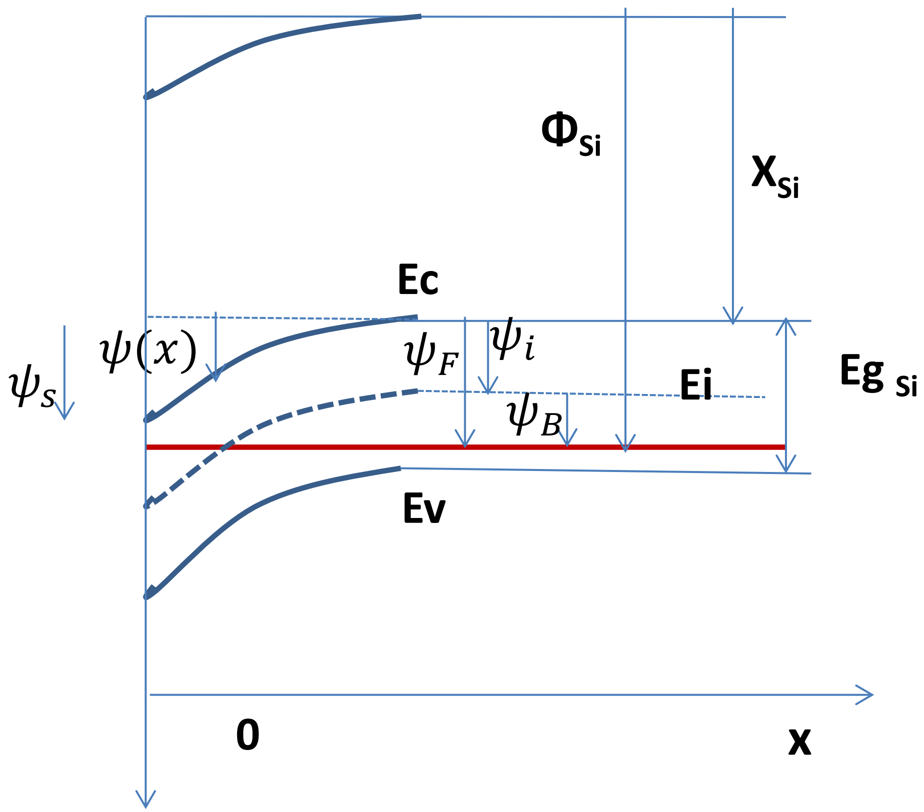
MOS Band Diagram After Contact



Gate Voltage Application



Charge Dependence on Potential



Poisson's Equation for N-MOS Stack

$$\frac{d^2\psi}{dx^2} = -\frac{\rho(x)}{\epsilon}$$

$$= -\frac{q}{\epsilon}\left[p(x) - n(x) + {N_D}^+(x) - {N_A}^-(x)\right]$$

At $x \rightarrow \infty$: Charge Neutrality: $p_0 - n_0 + {N_D}^+ - {N_A}^- = 0$

$p(x) = n_i\, e^{q(\psi_F - \psi_i)/k_BT} = n_i\, e^{q(\psi_B - \psi)/k_BT} = N_A\, e^{-q\psi/k_BT}$

$n(x) = n_i\, e^{q(\psi_i - \psi_F)/k_BT} = n_i\, e^{q(\psi - \psi_B)/k_BT} = ({n_i}^2/N_A)e^{q\psi/k_BT}$

$p_0 \approx N_A\,,\; n_0 = {n_i}^2/p_0 \approx {n_i}^2/N_A$

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\epsilon}\left[N_A\left(e^{-\frac{q\psi}{k_BT}} - 1\right) - \frac{{n_i}^2}{N_A}\left(e^{\frac{q\psi}{k_BT}} - 1\right)\right]$$

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NMOS Stack Charge Eqn.

Multiply both sides by $\left(\frac{d\psi}{dx}\right) dx \;\; (which \; is \; also \; = dx):$

$$\frac{d^2\psi}{dx^2}\frac{d\psi}{dx}dx = \frac{d}{dx}\left[\frac{d\psi}{dx}\right]\frac{d\psi}{dx}dx = \frac{d\psi}{dx}d\left[\frac{d\psi}{dx}\right]$$

$$\frac{d\psi}{dx}d\left[\frac{d\psi}{dx}\right] = -\frac{q}{\epsilon}\left[N_A\left(e^{-\frac{q\psi}{k_BT}} - 1\right) - \frac{{n_i}^2}{N_A}\left(e^{\frac{q\psi}{k_BT}} - 1\right)\right]d\psi$$

Integrate both sides: LHS: from $\frac{d\psi}{dx} = \frac{d\psi_s}{dx}$ at $x = 0$ to $\frac{d\psi}{dx} = 0$ at $x = \infty$

RHS: from $\psi = \psi_s$ at $x = 0$ to $\psi = 0$ at $x = \infty$

$$\left(\frac{d\psi}{dx}\right)^2 = \frac{2K_BTN_A}{\epsilon_{si}}\left[\left(e^{-\frac{q\psi}{k_BT}} + \frac{q\psi}{KT} - 1\right) + \frac{{n_i}^2}{{N_A}^2}\left(e^{\frac{q\psi}{k_BT}} - \frac{q\psi}{KT} - 1\right)\right]$$

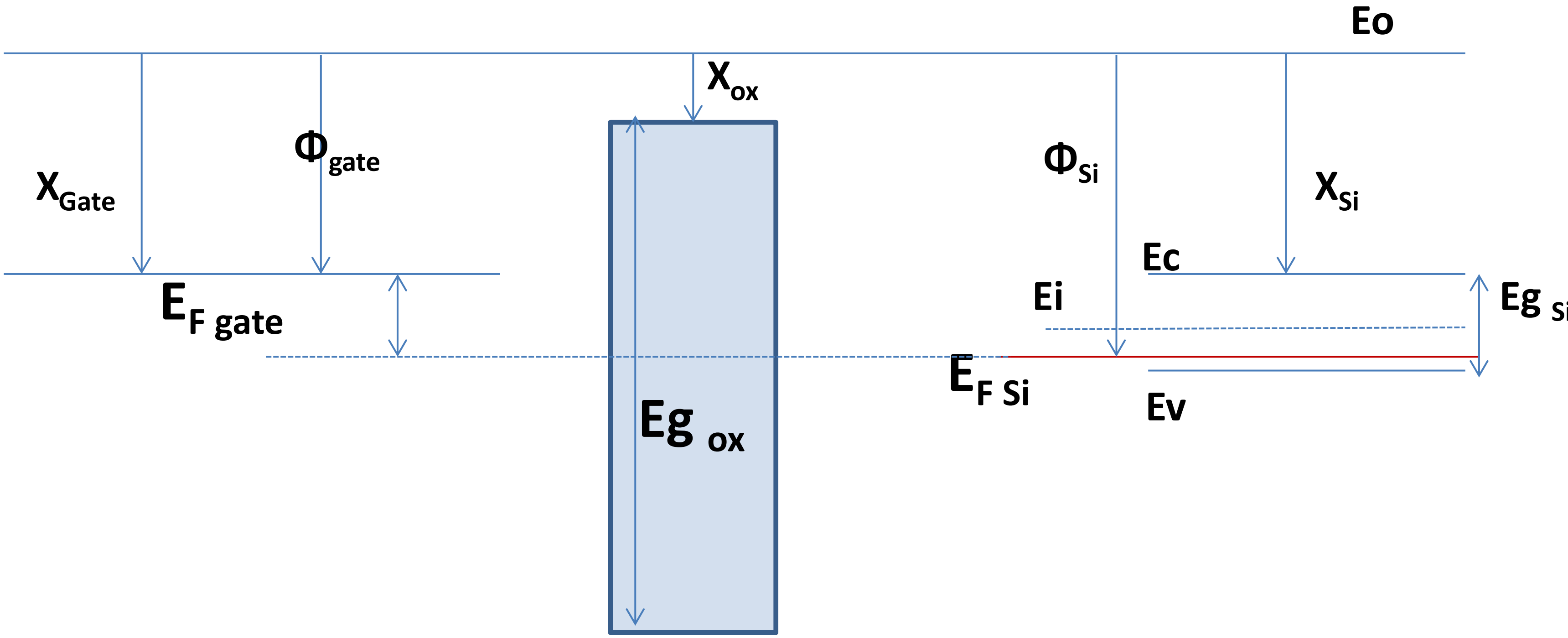
Surface Charge (Q_s)

$$\left(\frac{d\psi}{dx}\right)^2 = Fs^2$$

$$Q_s = -\epsilon_{si}F_s = -\epsilon_{si}\sqrt{\left(\frac{d\psi}{dx}\right)^2}$$

$$Q_s = \pm\sqrt{2\epsilon_{si}K_B T\, N_A}\left[\left(e^{-\frac{q\psi}{k_B T}} + \frac{q\psi}{KT} - 1\right) + \frac{{n_i}^2}{{N_A}^2}\left(e^{\frac{q\psi}{k_B T}} - \frac{q\psi}{KT} - 1\right)\right]^{1/2}$$

Flatband Voltage (V_{FB})



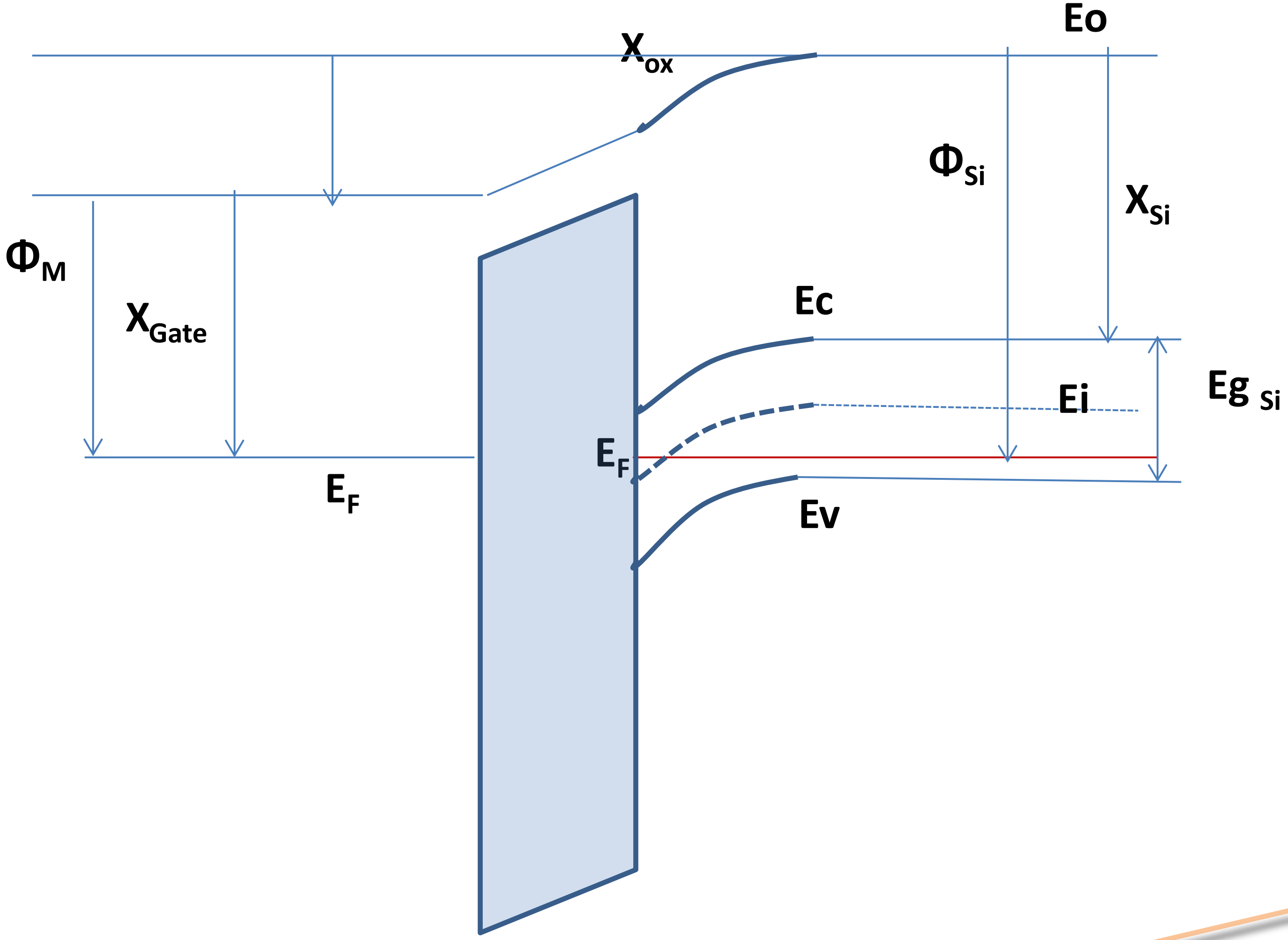
$$V_{FB} = Gate\ Workfunction - Semiconductor\ Workfunction$$

$$qV_{FB} = \Phi_{gate} - \Phi_{Si} = E_{F\,gate} - E_{F\,Si}$$

$$= (X_{gate} + EC_{\ gate} - EF_{\ gate}) \ - \ (X_{Si} + EC_{\ Si} - EF_{\ Si})$$

$$= (X_{gate} + EC_{\ gate} - EF_{\ gate}) \ - \ (X_{Si} + K_B T \ln \frac{N_C}{N_A})$$

Potential Drop Equation: No Applied Gate Voltage

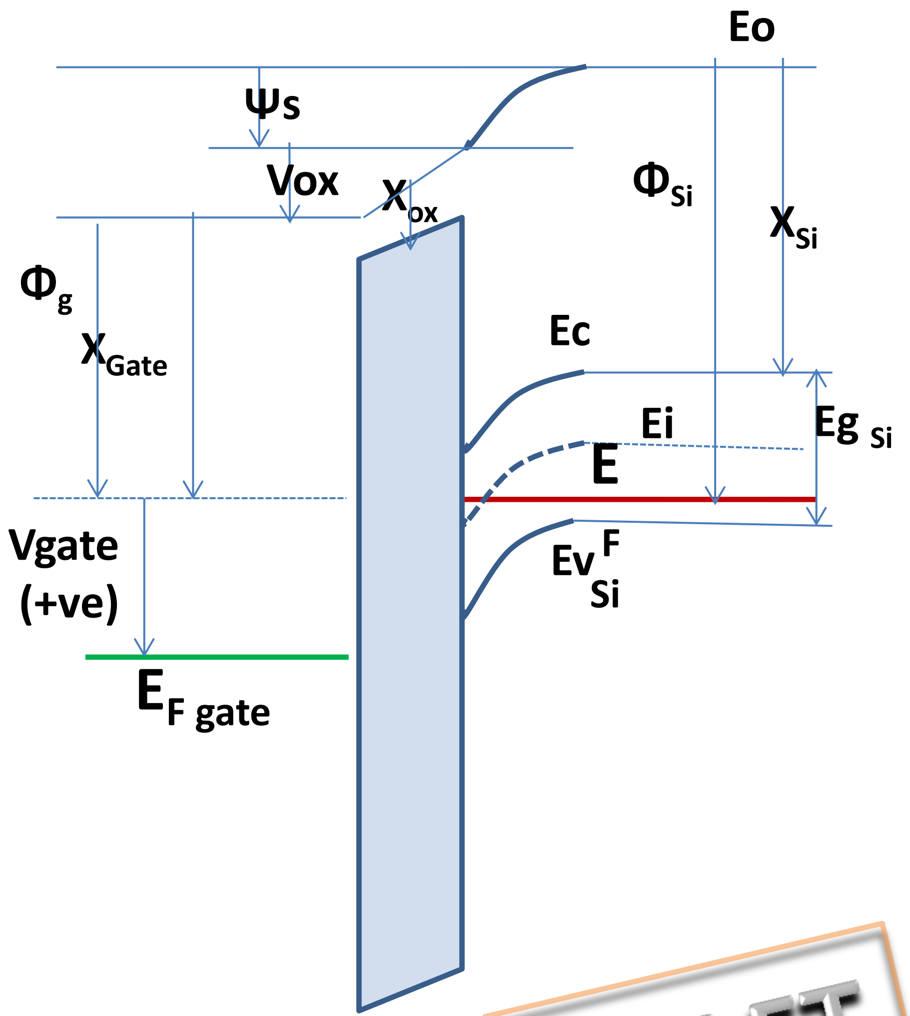


Potential Drop Equation: Applied Gate Voltage

$$V_g + (\Phi_{si} - \Phi_g) = V_{ox} + \Psi_s$$

$$V_g - VFB = V_{ox} + \Psi_s$$

$$V_{ox} = -\frac{Q_s}{C_{ox}}$$



In Inversion:

$$Q_s = Q_{dep} + Qin_v$$

$$Q_{dep} = -qNAWde_p = -\sqrt{2\varepsilon_{si} q N_A \Psi_s}$$

In Strong Inversion:

$$Q_{inv} \approx -\sqrt{\frac{2\varepsilon_{si} K_B T\, n_i^2}{N_A}}\, e^{q\psi_s/2KBT}$$

In-between: use Q_s equation

In Depletion: $Q_s \approx Q_{dep}$

Threshold Voltage (V_{th}) under Depletion Approximation

At $0 > \Psi_s \geq 2\,\Psi_{Bulk}$:

- No free carriers (i.e. no inversion electrons)
- Only depletion charges from ionized dopants

At $\Psi_s \geq 2\,\Psi_{Bulk}$:

- No more changes in surface potential
- Fixed Q_{dep}
- Only changes in inversion electrons
- V_{gate} at $\Psi_s \geq 2\,\Psi_{Bulk}$ is called Threshold Voltage (V_{th})

Using: $V_{gate} = V_{FB} - \frac{Q_s}{C_{ox}} + \Psi_s$

At "Onset" of Strong Inversion: $V_{th} = VFB - \frac{Q_{dep}}{C_{ox}} + 2\Psi_{Bulk}$

$$= VFB + \frac{\sqrt{2\varepsilon_{si} q N_A (2\Psi_{Bulk})}}{C_{ox}} + 2\Psi_{Bulk}$$

Inversion Charge(V_{th}) under Depletion Approximation

In Strong Inversion ($V_g > V_{th}$):

$$V_{gate} = VFB - \frac{Q_{dep} + Q_{inv}}{C_{ox}} + 2\Psi_{Bulk} = V_{FB} - \frac{Q_{dep}}{C_{ox}} + 2\Psi_{Bulk} - \frac{Q_{inv}}{C_{ox}}$$

$$V_{gate} = V_{th} - \frac{Q_{inv}}{C_{ox}}$$

$$\rightarrow \boldsymbol{Q_{inv} = -Cox(Vgate - Vth)}$$

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Capacitance-Voltage (C-V) Characteristics
Small Signal: $C_C(Vg) = dQ_C/dV_C$