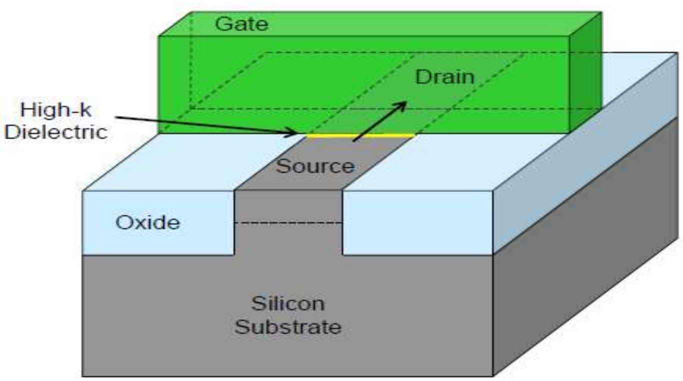
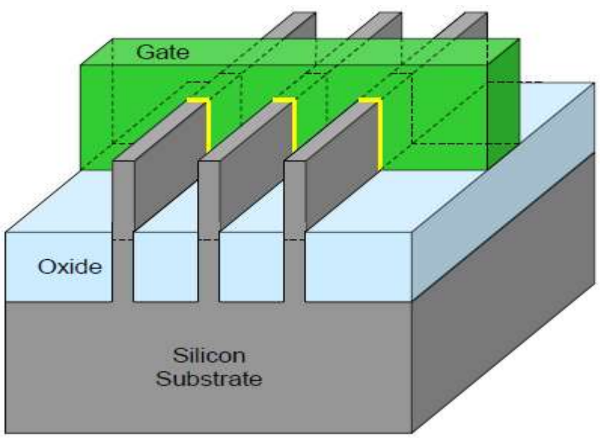
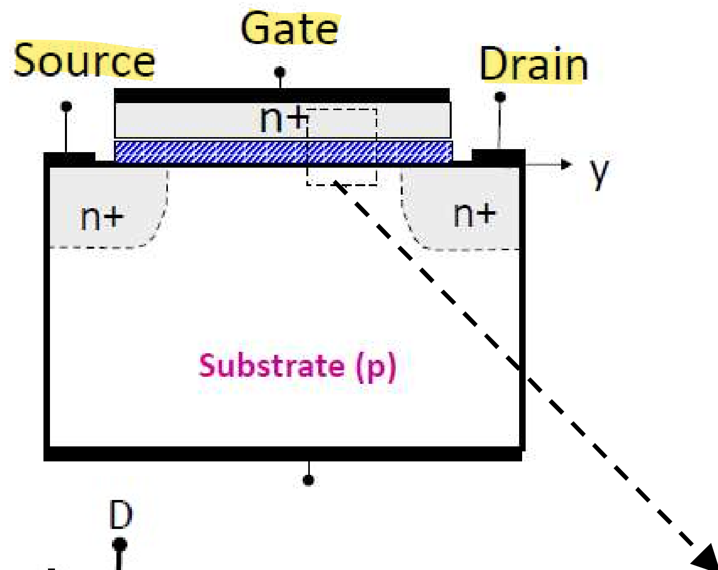
MOS Field-Effect Transistor (MOSFET)

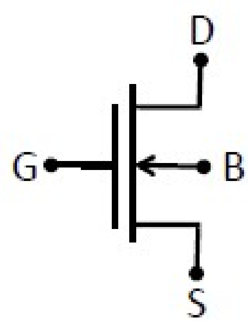
MOS-based devices (MOSFET, FinFET, Power-MOSFET…)

Low-power, integration → **Digital logic/memory, analog, RF, power…**





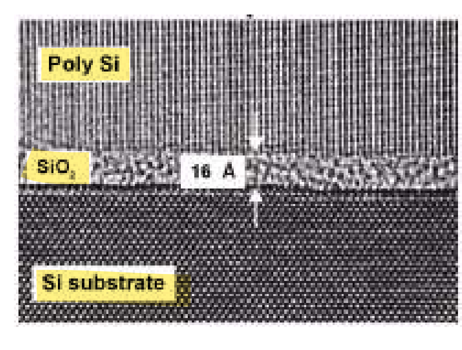




NMOSFET **PMOSFET?**

Charge-control

$$J = Q \otimes v$$



MOSCAP

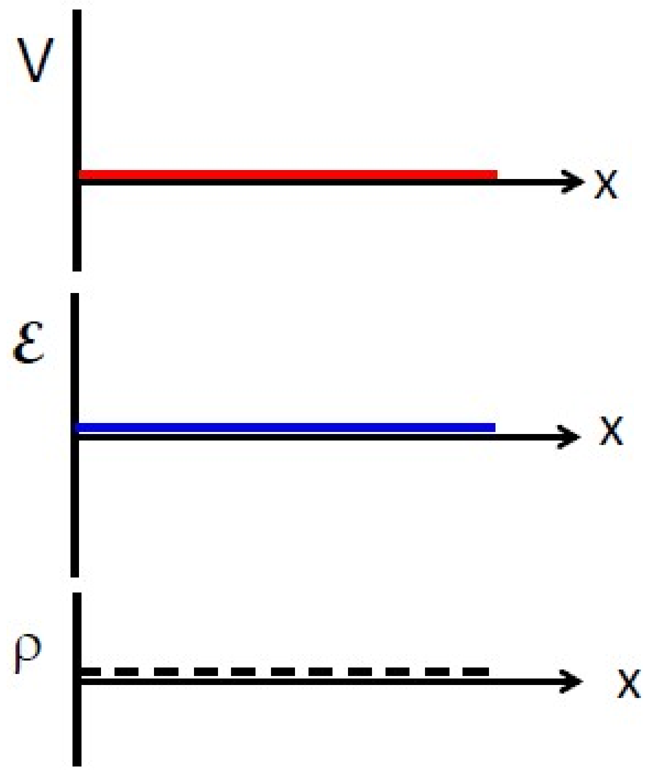
MOS band-diagram – ideal, equilibrium

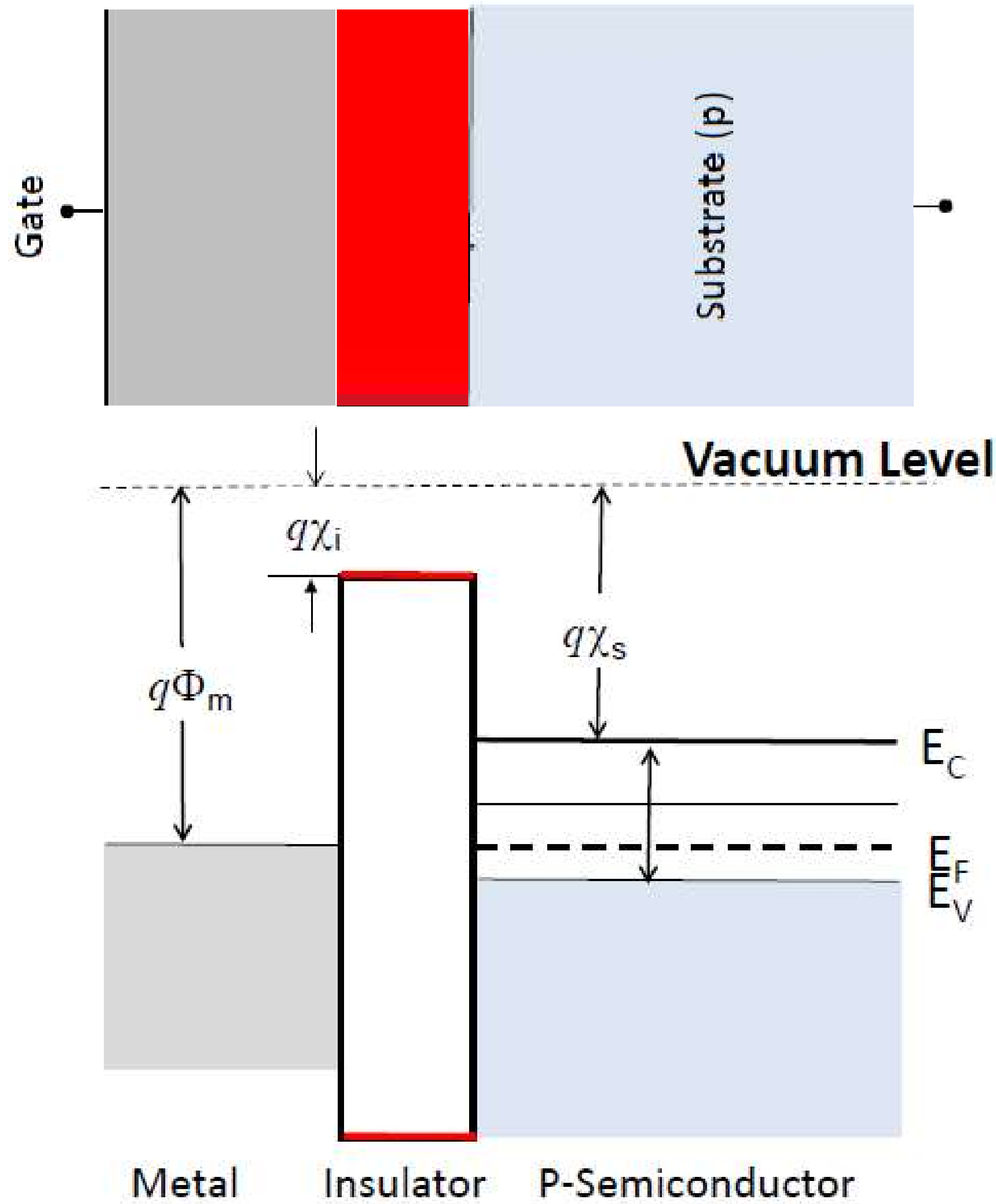
Ideal

$$\Phi_{ms} = \Phi_m - \Phi_s = 0$$

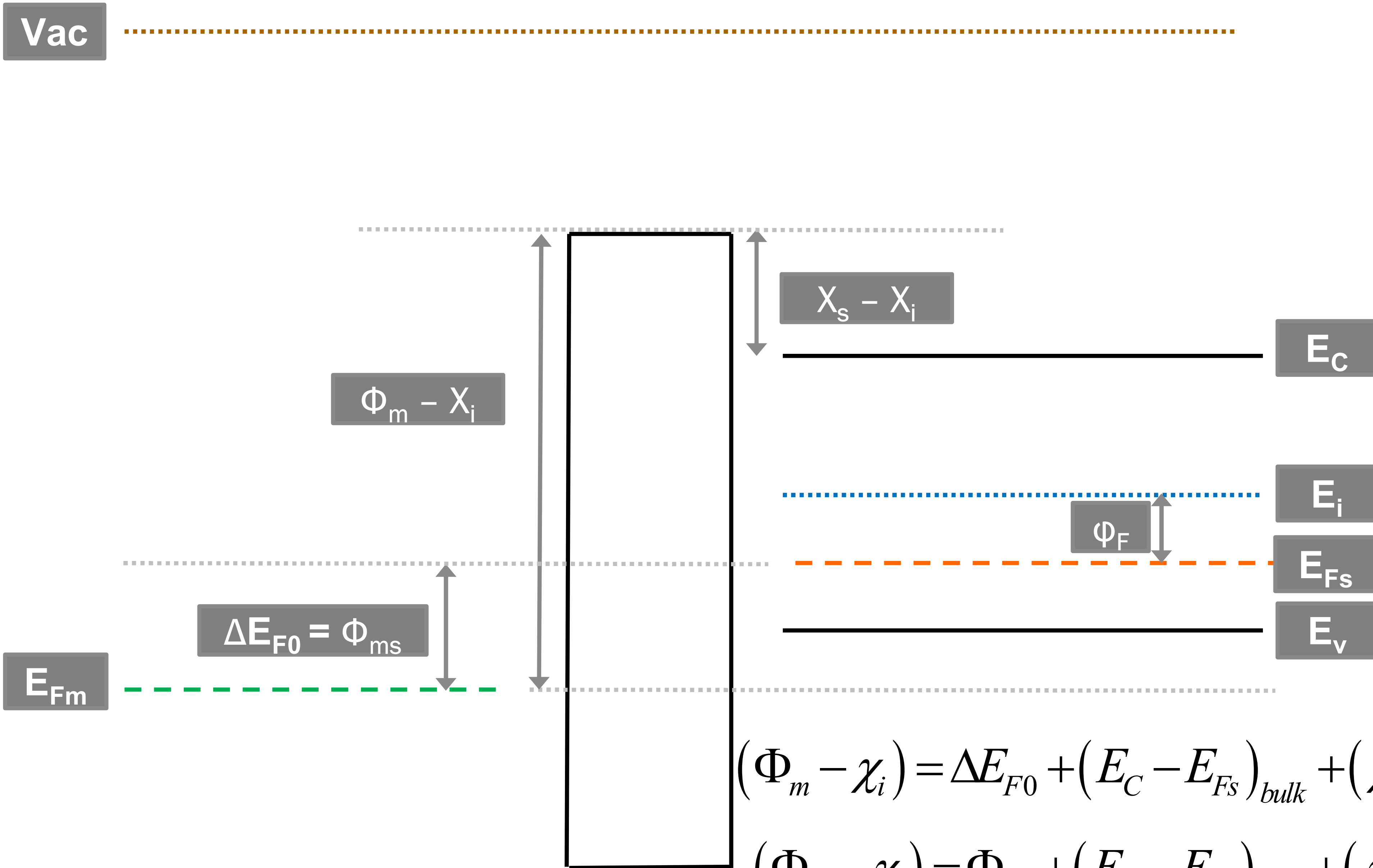
$$V_{bi} = 0$$

“Flatband” in equilibrium





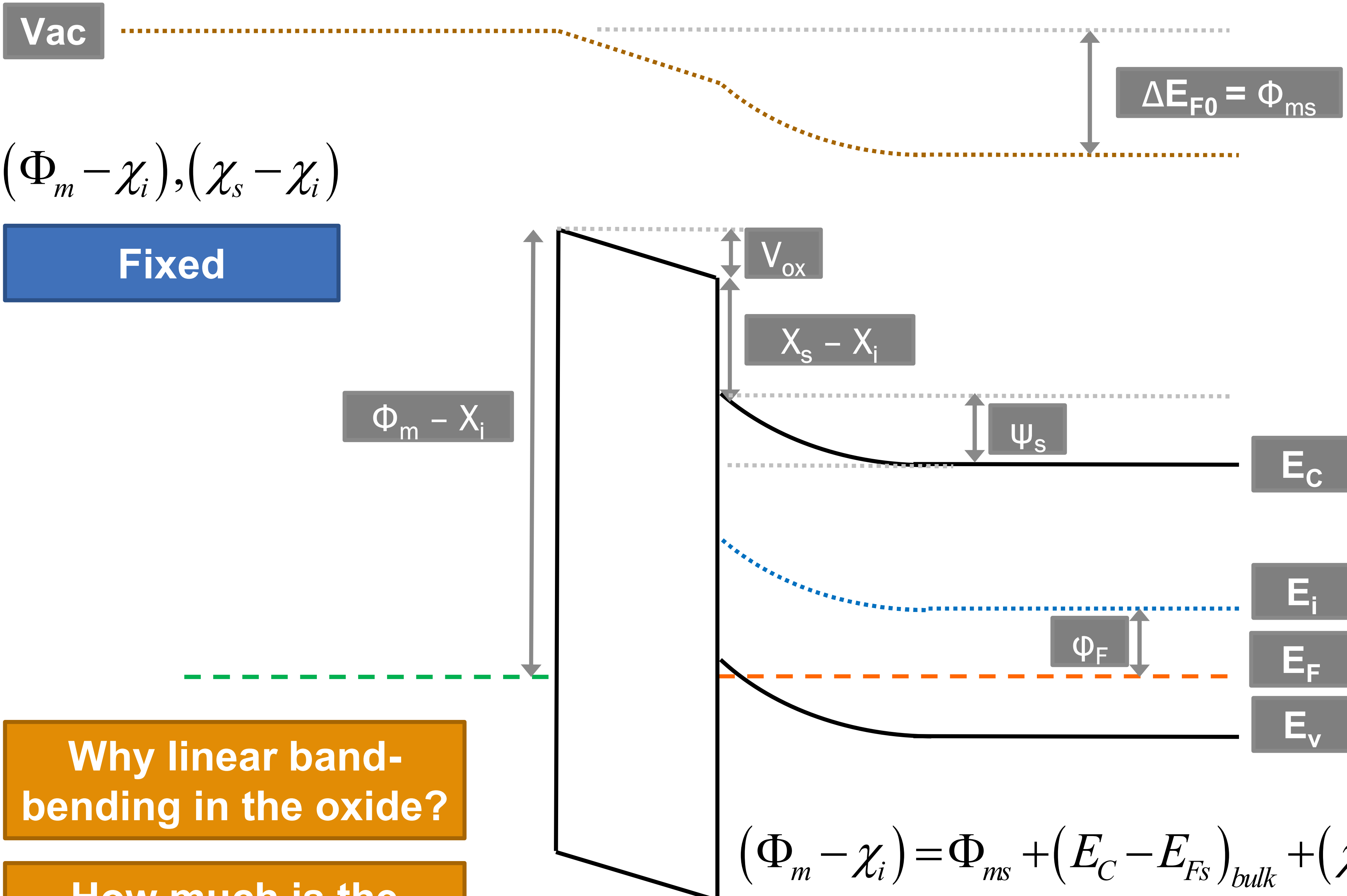
MOS band-diagram – non-ideal, equilibrium



$$\left(\Phi_m - \chi_i\right) = \Delta E_{F0} + \left(E_C - E_{Fs}\right)_{bulk} + \left(\chi_s - \chi_i\right)$$

$$\left(\Phi_m - \chi_i\right) = \Phi_{ms} + \left(E_C - E_{Fs}\right)_{bulk} + \left(\chi_s - \chi_i\right)$$

MOS band-diagram – non-ideal, equilibrium



$$\left(\Phi_m - \chi_i\right), \left(\chi_s - \chi_i\right)$$

Fixed

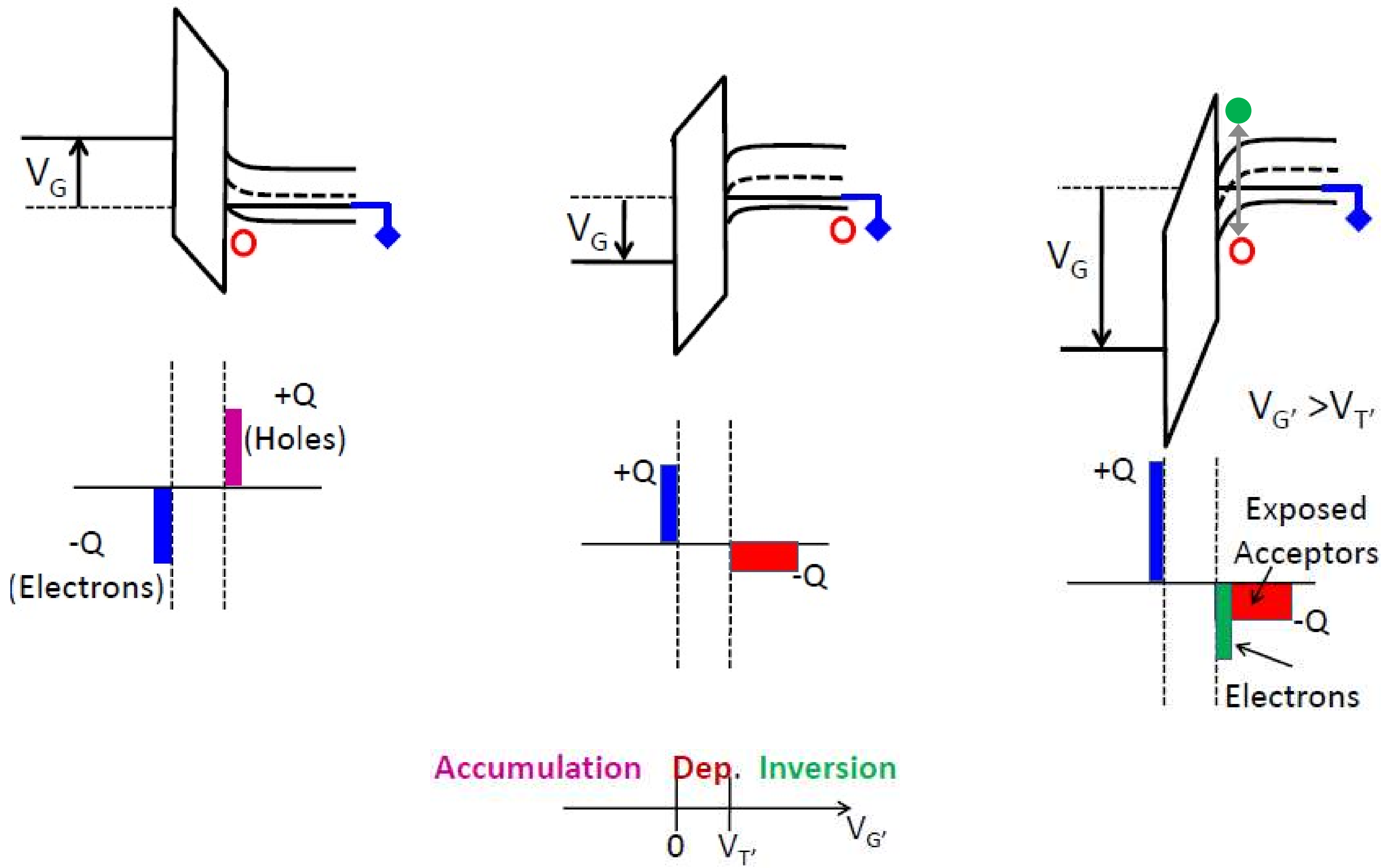
Why linear band-bending in the oxide?

How much is the flatband voltage V_{FB}?

$$\left(\Phi_m - \chi_i\right) = \Phi_{ms} + \left(E_C - E_{Fs}\right)_{bulk} + \left(\chi_s - \chi_i\right)$$

$$\left(\Phi_m - \chi_i\right) = \left(V_{ox} + \psi_s\right) + \left(E_C - E_{Fs}\right)_{bulk} + \left(\chi_s - \chi_i\right)$$

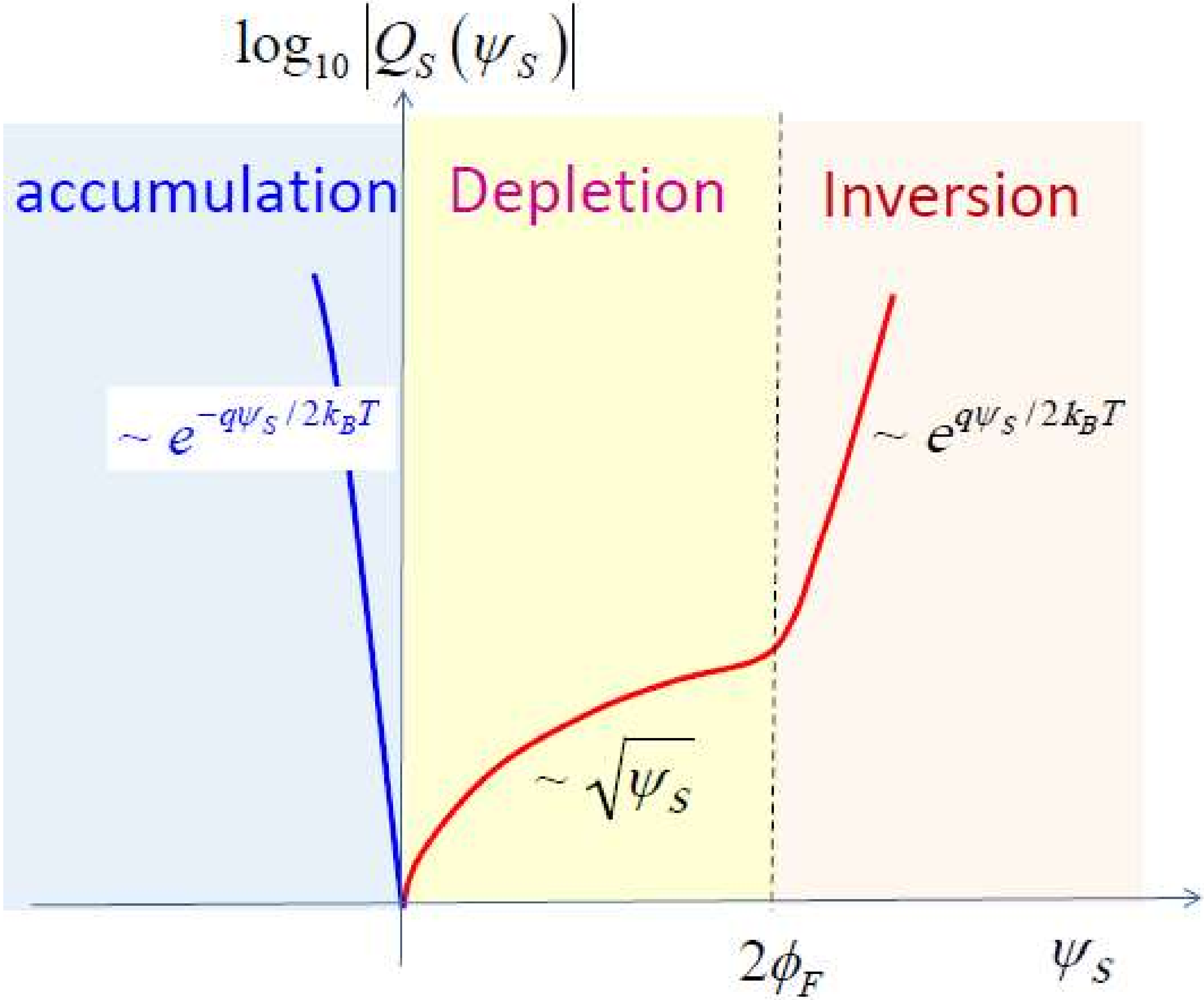
MOS band-diagram – under bias



Where does the excess charge come from?

Which layer forms quicker, accumulation or inversion?

Charge vs. Voltage (Q-V)



Charge vs. Surface Potential

$$n = n_i\, e^{(E_F - E_i)/k_BT}$$

$$n = n_i\, e^{(E_F - E_{i0} + q\psi)/k_BT}$$

$$n = n_i\, e^{(E_F - E_{i0})/k_BT}\; e^{q\psi/k_BT}$$

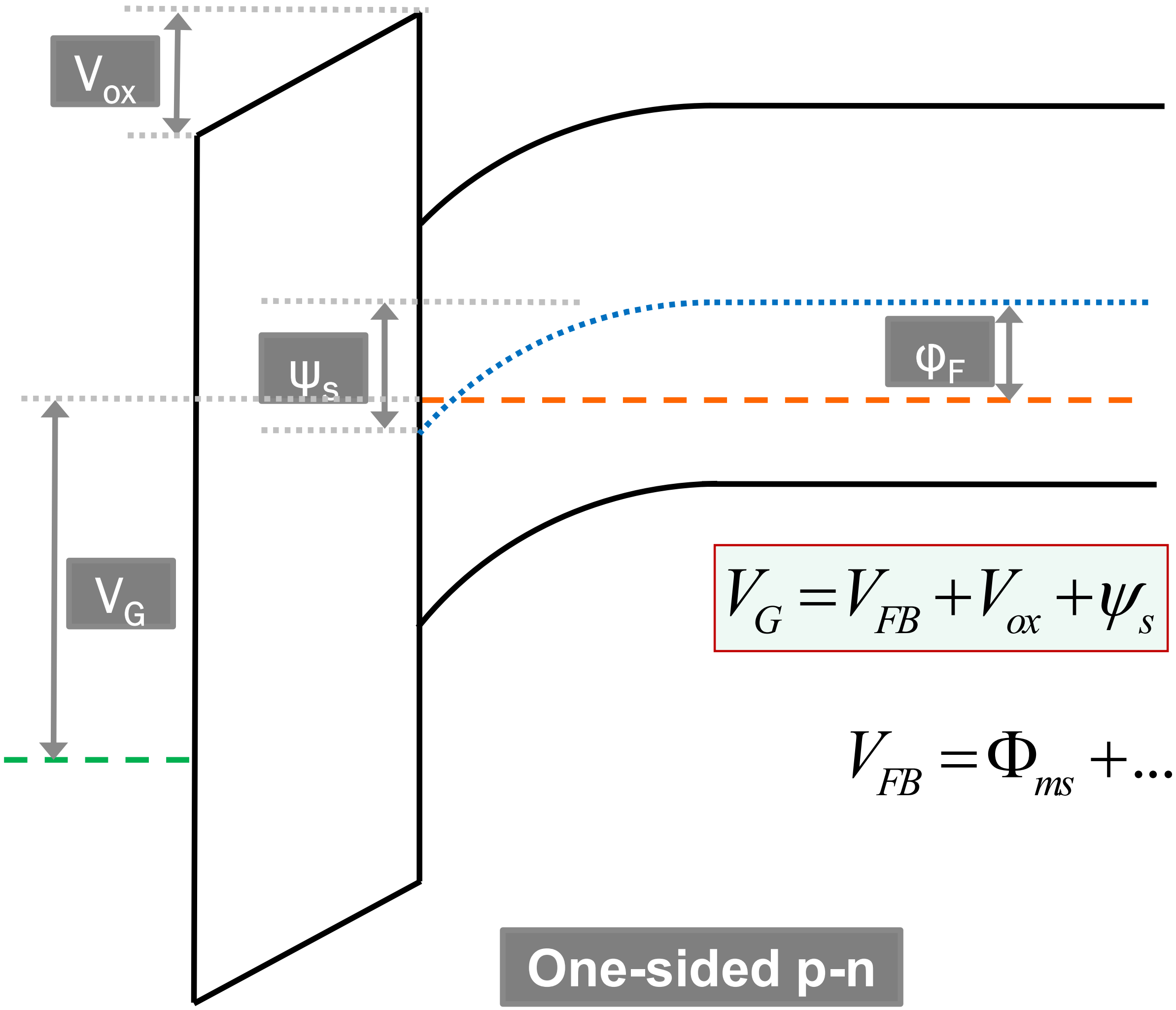
$$\boxed{n = n_0\, e^{+q\psi/k_BT}}$$

$$\boxed{p = p_0\, e^{-q\psi/k_BT}}$$

$$\frac{dE}{dx} = \frac{q\left(p - n + N_d^+ - N_a^-\right)}{\varepsilon_s}$$

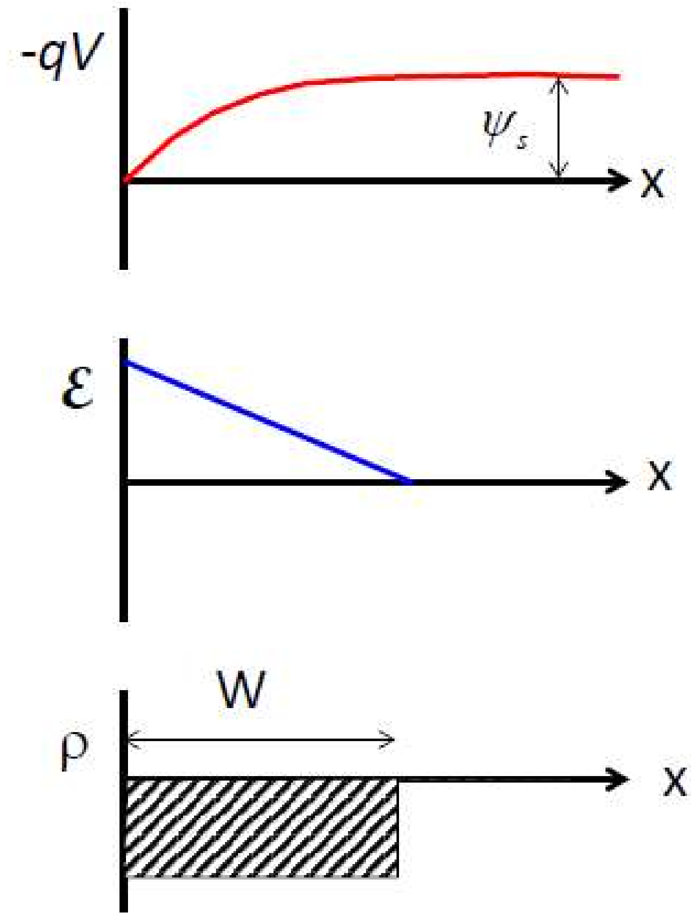
$$\frac{dE}{d\psi}\frac{d\psi}{dx} = -E\frac{dE}{d\psi} = f(\psi)$$

Q-V: depletion



$$\boxed{V_G = V_{FB} + V_{ox} + \psi_s}$$

$$V_{FB} = \Phi_{ms} + \ldots$$

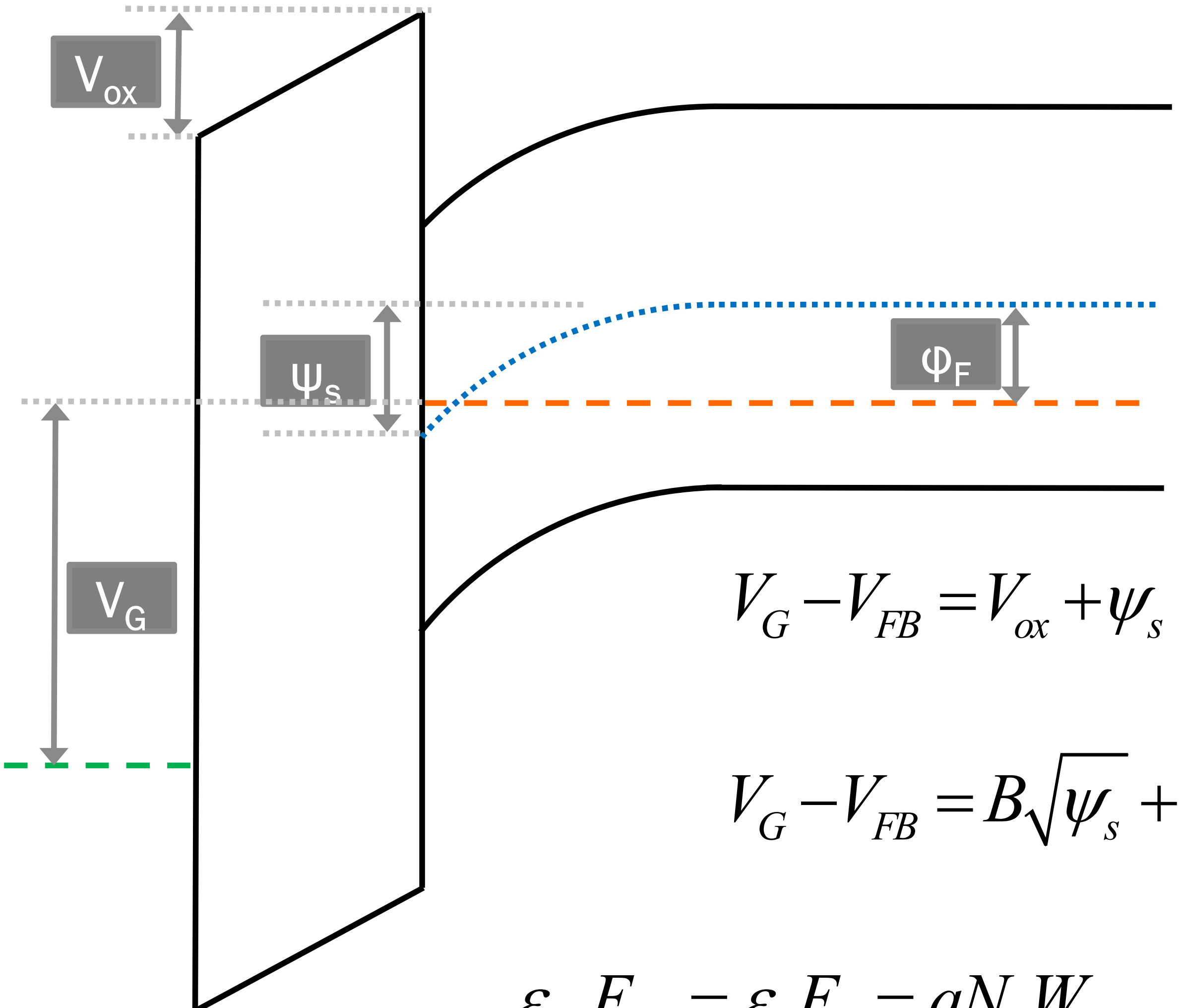


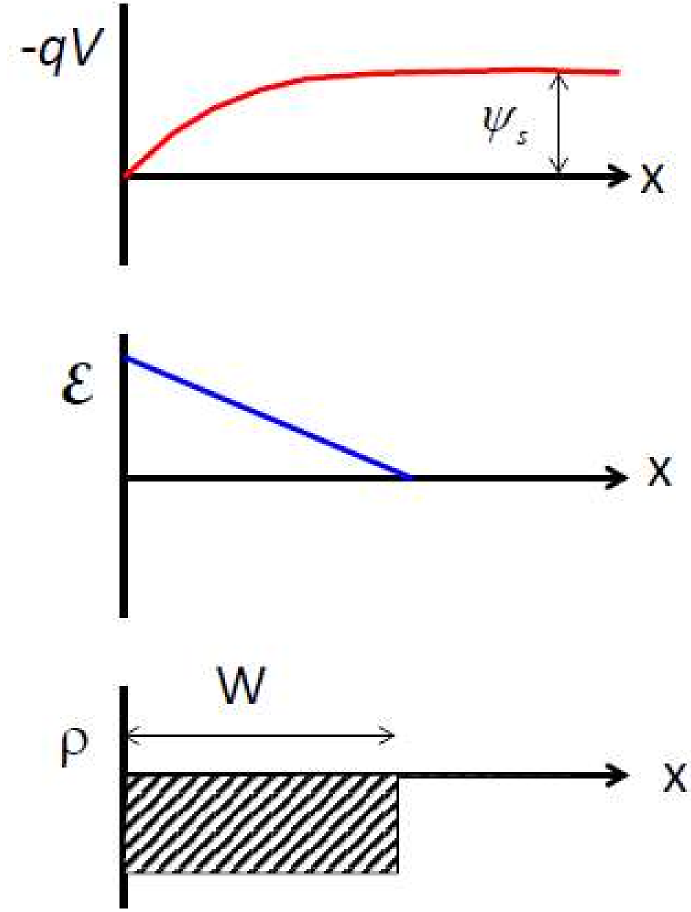
One-sided p-n

Depletion:

$$\psi_s = \frac{qN_a W^2}{2\varepsilon_s} \qquad Q_s = Q_d = qN_a W \Rightarrow \boxed{Q_d = \sqrt{2\varepsilon_s q N_a \psi_s}}$$

Q-V: depletion





$$V_G - V_{FB} = V_{ox} + \psi_s$$

$$V_G - V_{FB} = B\sqrt{\psi_s} + \psi_s$$

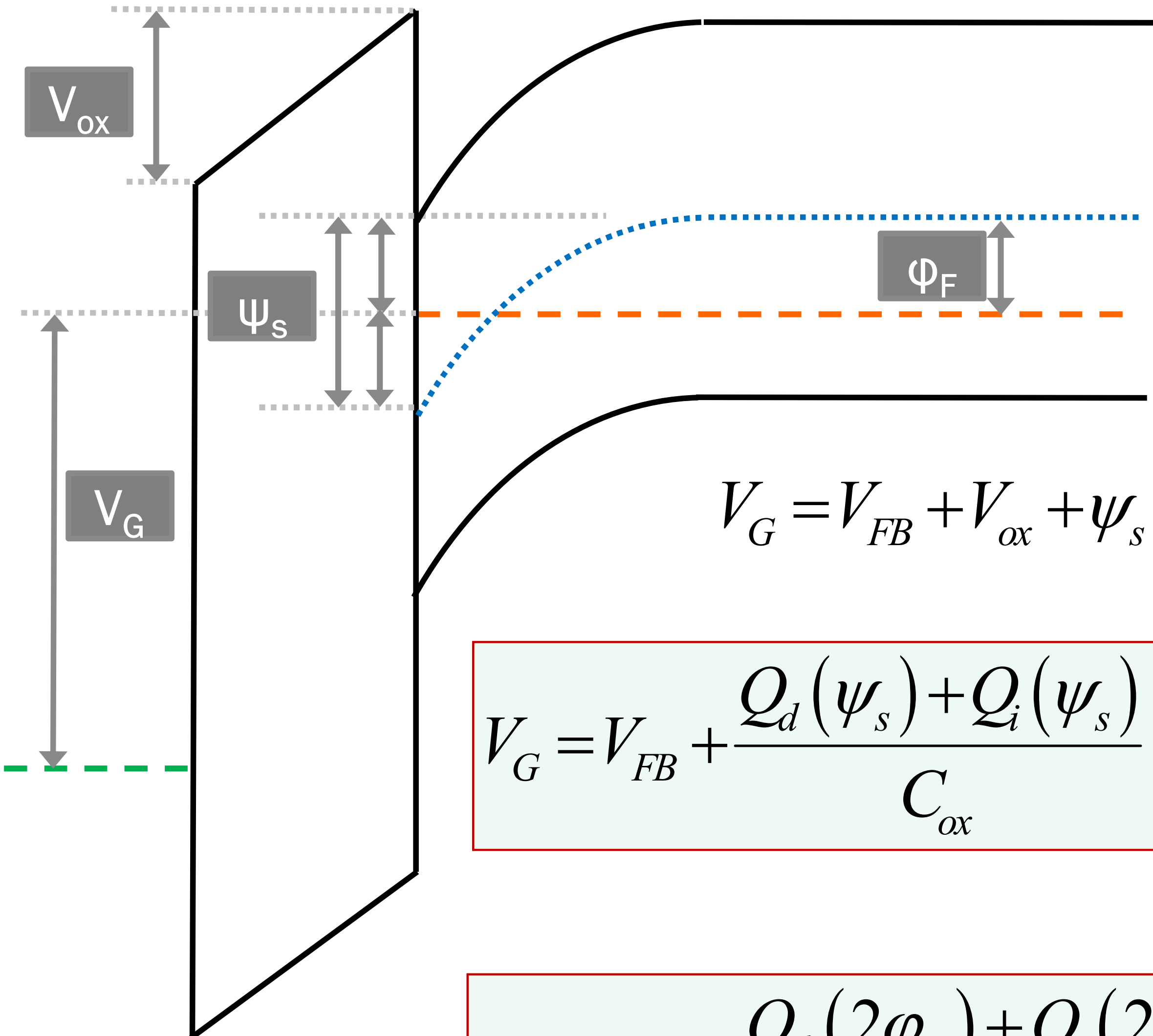
$$\varepsilon_{ox} E_{ox} = \varepsilon_s E_s = qN_a W$$

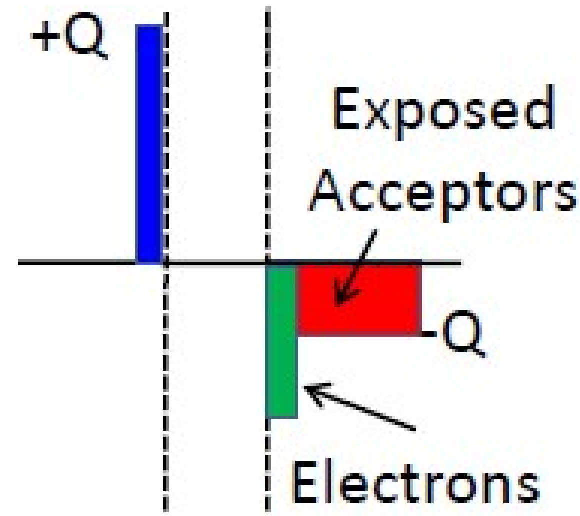
Depletion:

$$E_s = \frac{qN_a W}{\varepsilon_s}$$

$$\boxed{V_{ox} = E_{ox} t_{ox} = \frac{qN_a W}{\varepsilon_{ox}} t_{ox} = \frac{Q_d}{C_{ox}} = \frac{\sqrt{2\varepsilon_s qN_a \psi_s}}{C_{ox}}}$$

Q-V: inversion





$$V_G = V_{FB} + V_{ox} + \psi_s$$

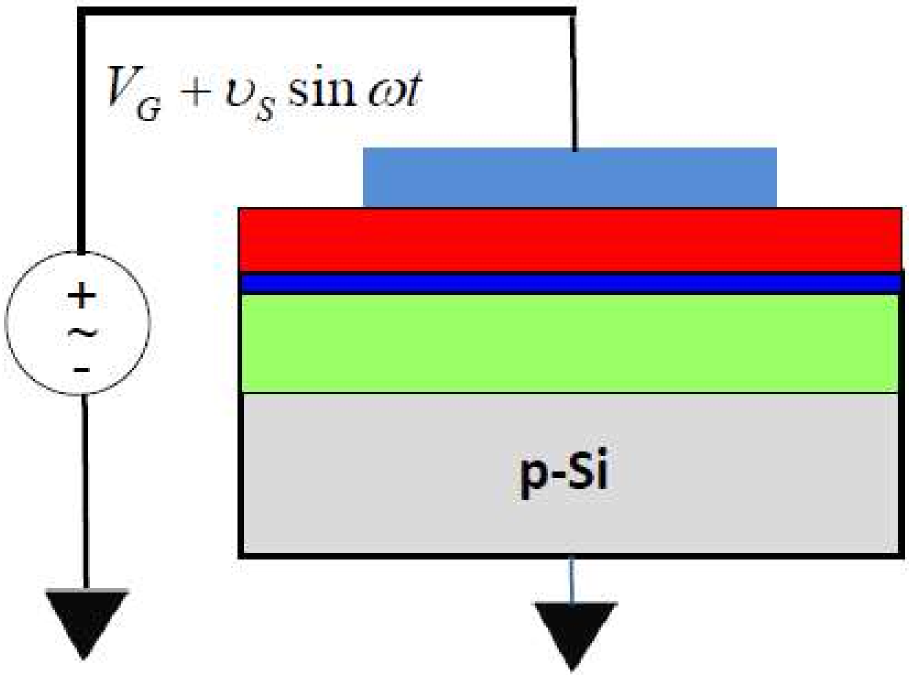
$$\boxed{Q_i = C_{ox}\left(V_G - V_T\right)}$$

$$\boxed{V_G = V_{FB} + \frac{Q_d\left(\psi_s\right) + Q_i\left(\psi_s\right)}{C_{ox}} + \psi_s}$$

'Textbook' threshold

$$\boxed{V_T = V_{FB} + \frac{Q_d\left(2\varphi_F\right) + Q_i\left(2\varphi_F\right)}{C_{ox}} + 2\varphi_F \approx V_{FB} + \frac{Q_d\left(2\varphi_F\right)}{C_{ox}} + 2\varphi_F}$$

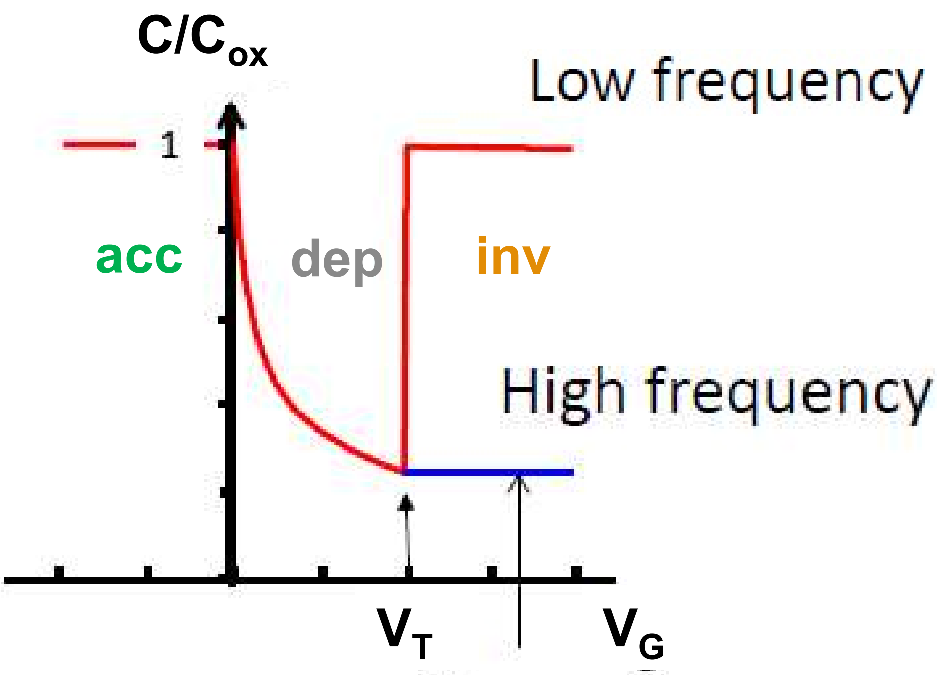
Capacitance vs. Voltage (C-V) – ideal



Small-signal capacitance

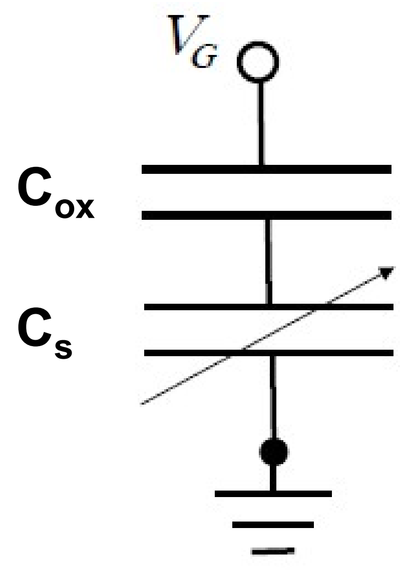
$$C_G \cong \frac{dQ_G}{dV_G} = \frac{d(-Q_s)}{dV_G}$$

$$V_G = \psi_s - \frac{Q_s}{C_{ox}} \Rightarrow \frac{dV_G}{d(-Q_s)} = \frac{d\psi_s}{d(-Q_s)} + \frac{1}{C_{ox}}$$



$$\boxed{\frac{1}{C_G} = \frac{1}{C_s} + \frac{1}{C_{ox}}}$$

$$C_s \cong \frac{d(-Q_s)}{d\psi_s}$$

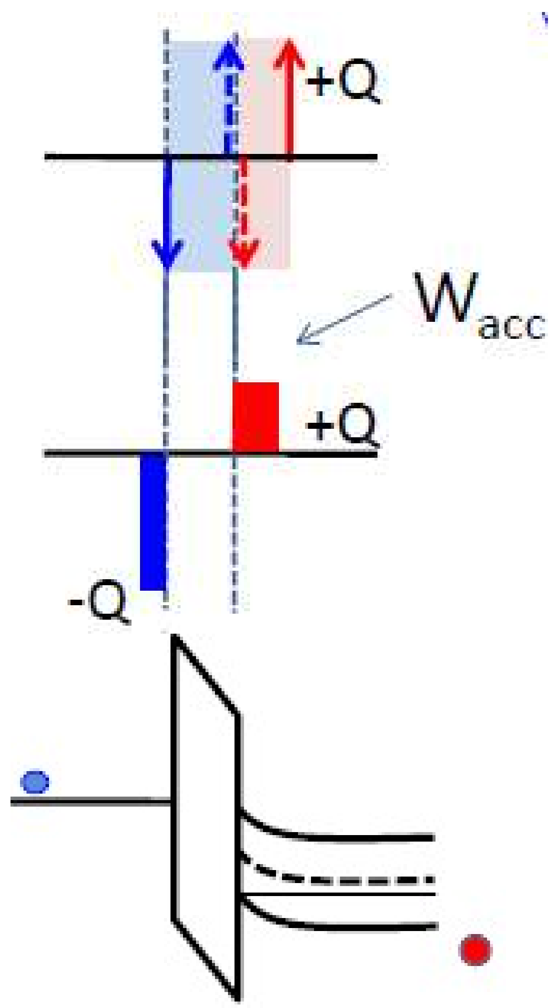


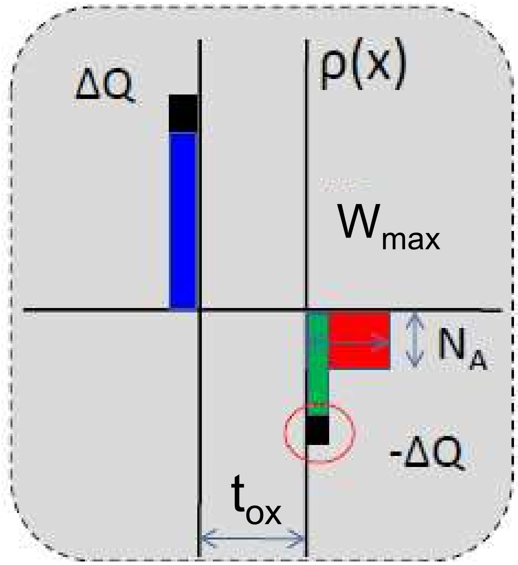
Ideal C-V: accumulation, inversion

$$C_{s,acc} = \frac{\varepsilon_s}{W_{acc}} \gg C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$$

$$C_{s,inv} = \frac{\varepsilon_s}{W_{inv}} \gg C_{ox}$$

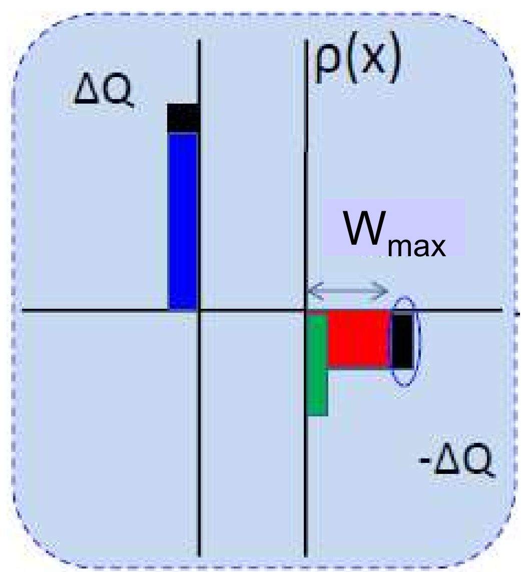
$$\frac{1}{C_G} \approx \frac{1}{C_{ox}}$$





HF

$$\frac{1}{C_G} \approx \frac{1}{C_{ox}}$$

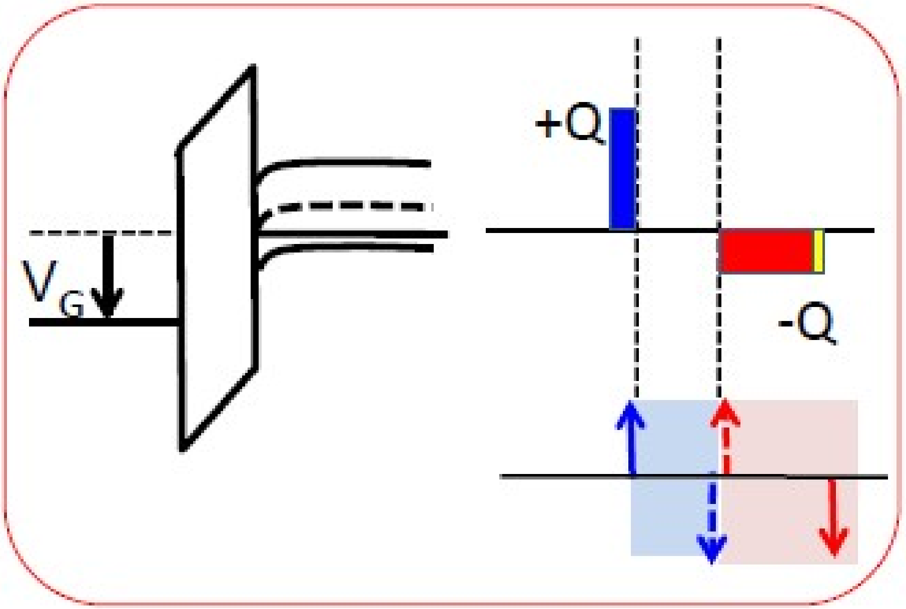


LF

$$\frac{1}{C_G} = \frac{1}{C_{s,\min}} + \frac{1}{C_{ox}}$$

Why are the electrons slow?

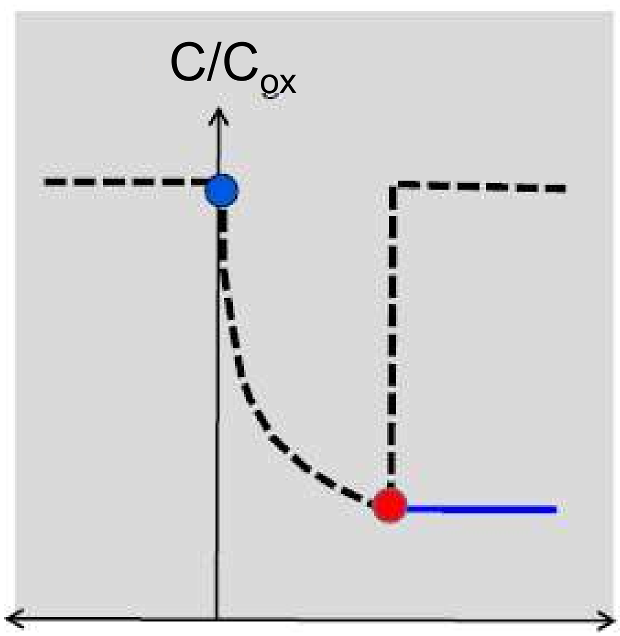
Ideal C-V: depletion

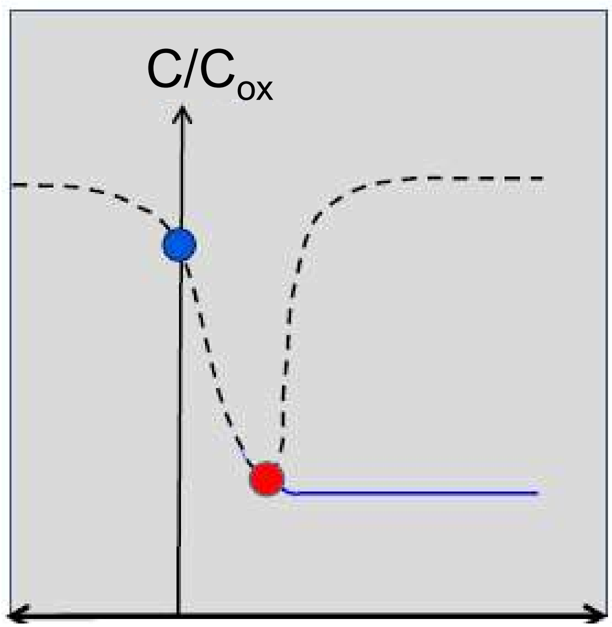


$$C_G = \frac{C_{ox}C_s}{C_{ox}+C_s} = \frac{C_{ox}}{1+C_{ox}/C_s} = \frac{C_{ox}}{1+C_{ox}W/\varepsilon_s}$$

$$V_G = V_{ox} + \psi_s = \frac{qN_aW}{C_{ox}} + \frac{qN_aW^2}{2\varepsilon_s}$$

$$C_{s,\min} \Leftarrow W_{\max} = \sqrt{\frac{2\varepsilon_s \cdot 2\varphi_F}{qN_a}}$$





How do you calculate C_{FB}?