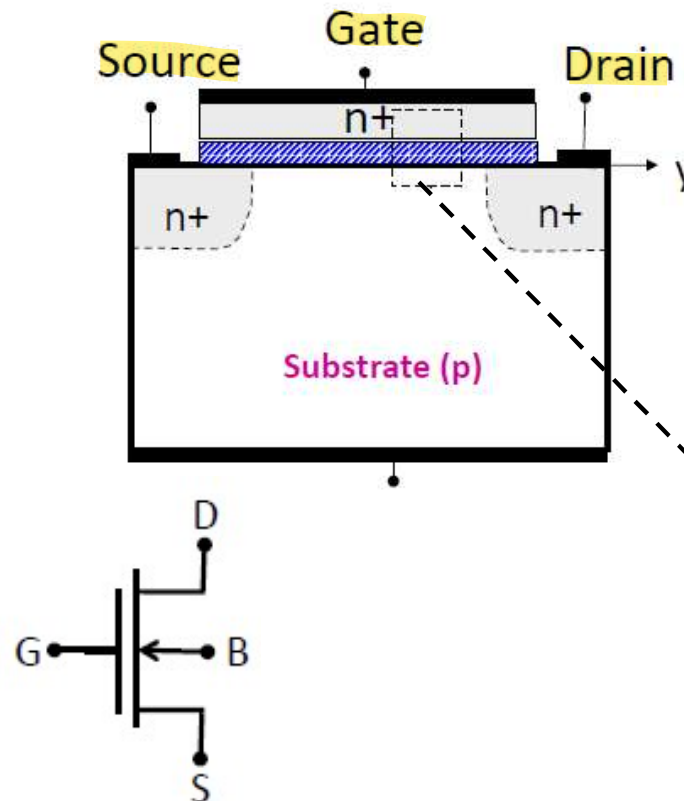
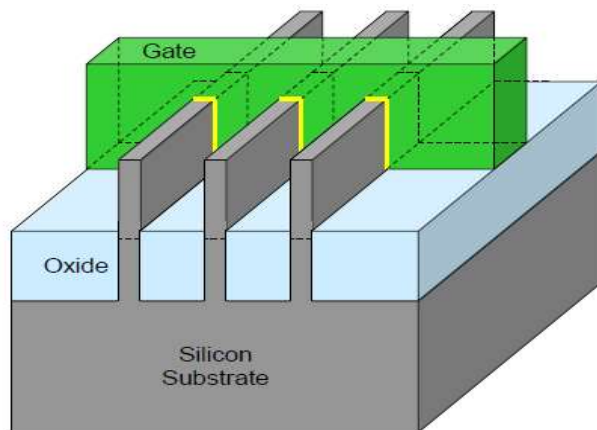
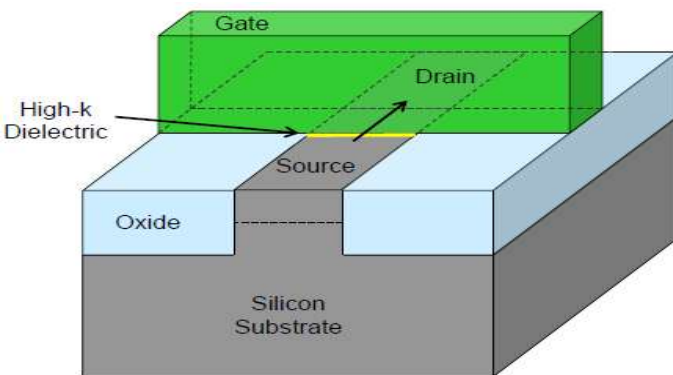


MOS Field-Effect Transistor (MOSFET)

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

Low-power, integration

Digital logic/memory, analog, RF, power...

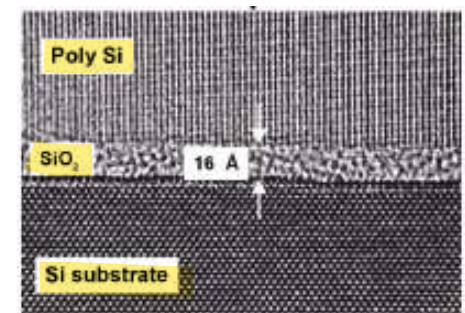


NMOSFET

PMOSFET?

Charge-control

$$J = (Q) \otimes v$$



MOSCAP

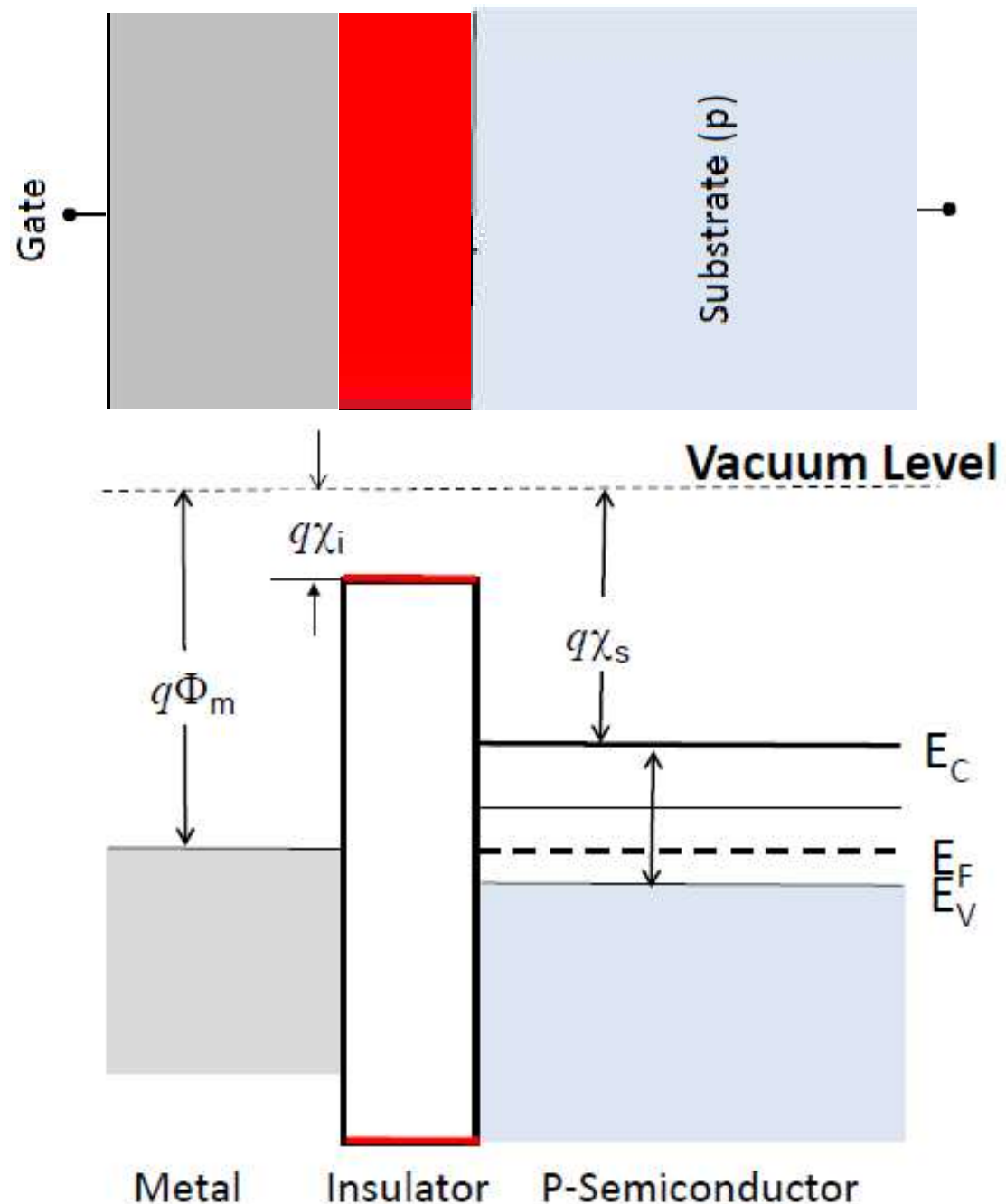
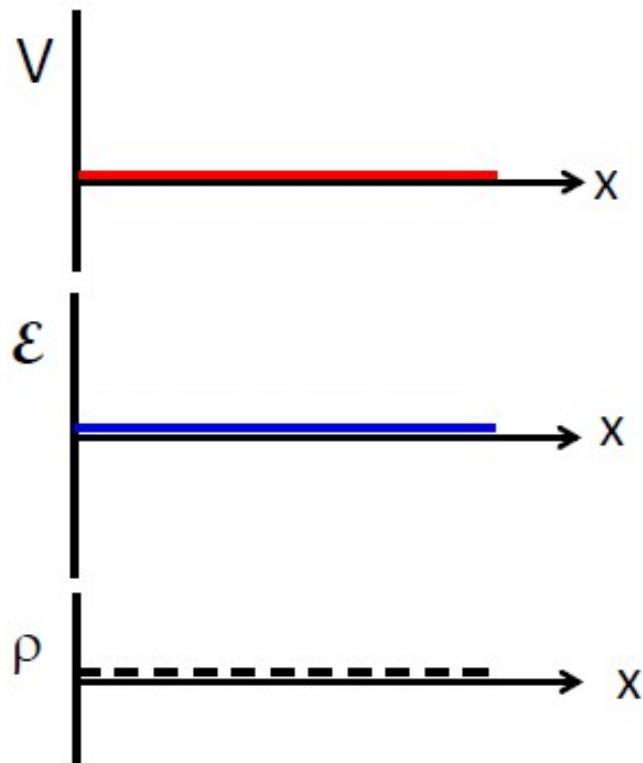
MOS band-diagram – ideal, equilibrium

Ideal

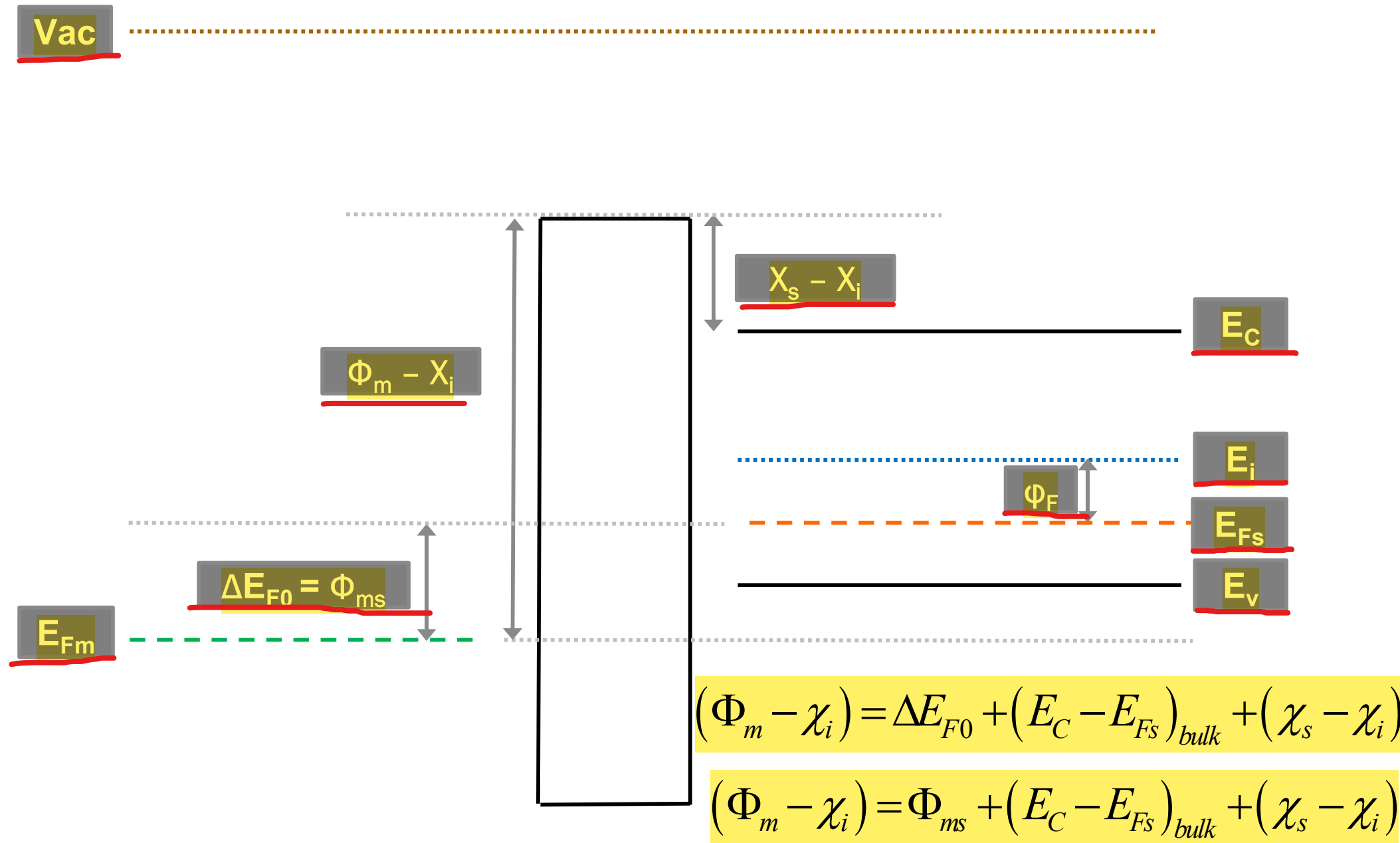
$$\Phi_{ms} = \Phi_m - \Phi_s = 0$$

$$V_{bi} = 0$$

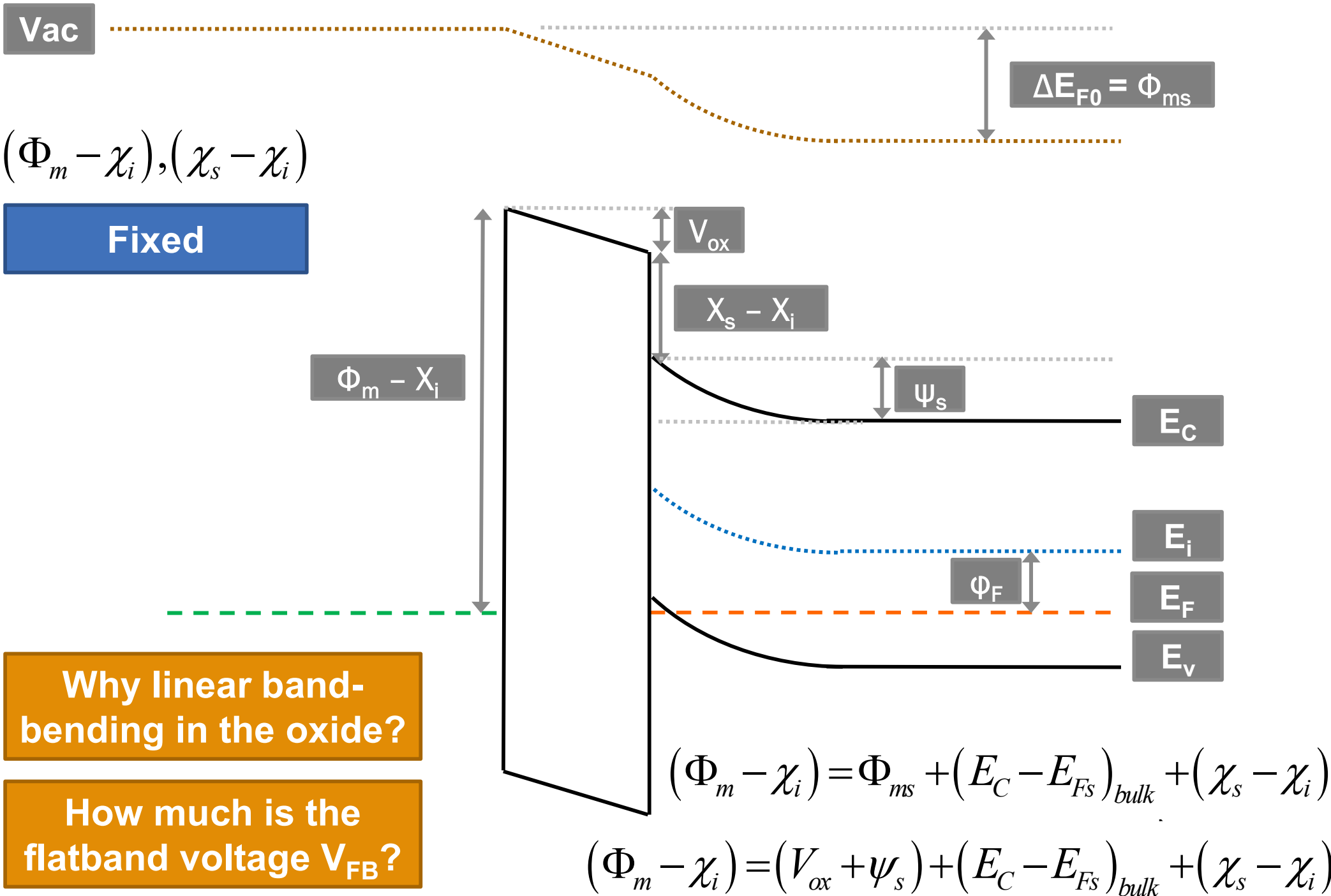
“Flatband” in equilibrium



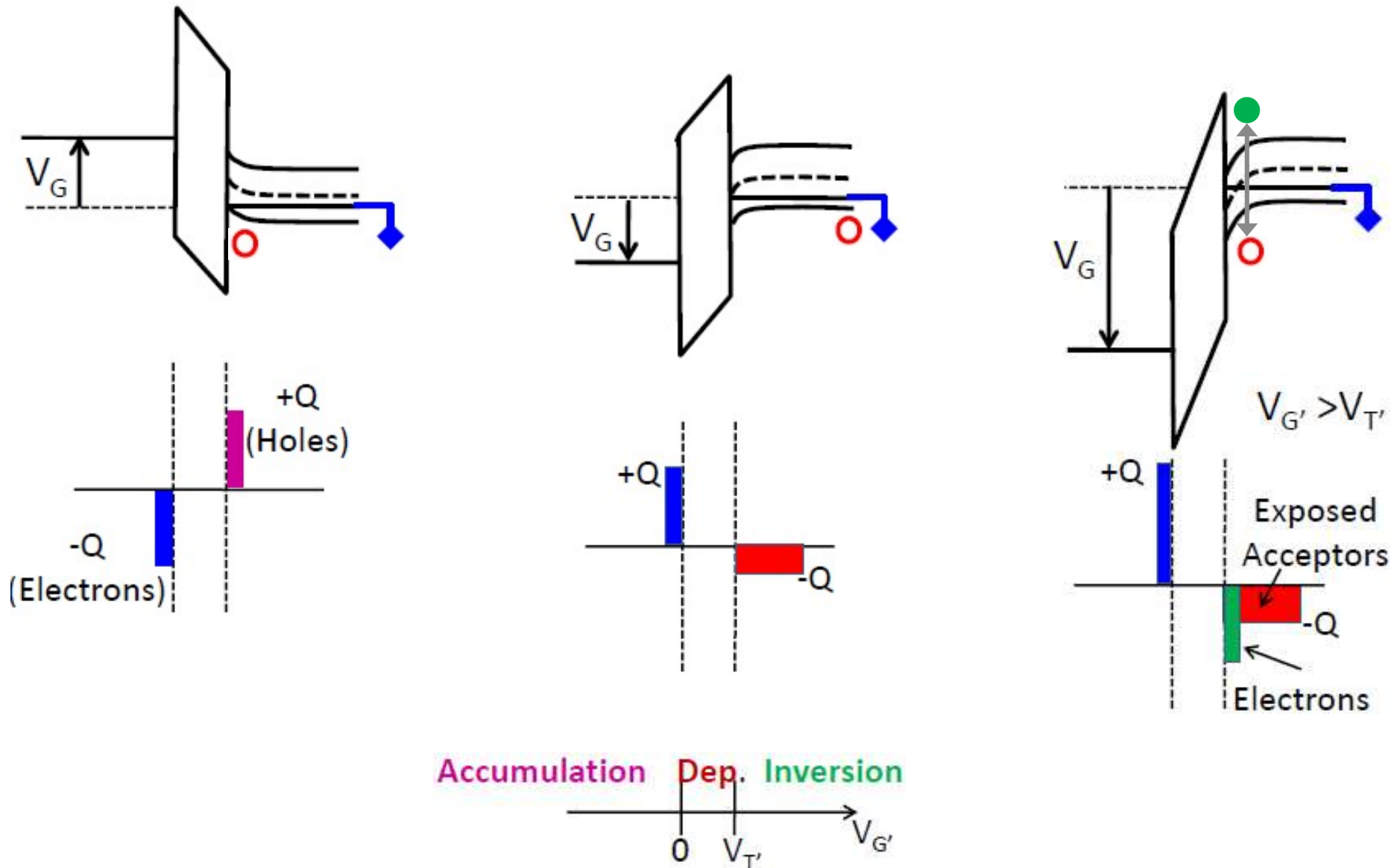
MOS band-diagram – non-ideal, equilibrium



MOS band-diagram – non-ideal, equilibrium



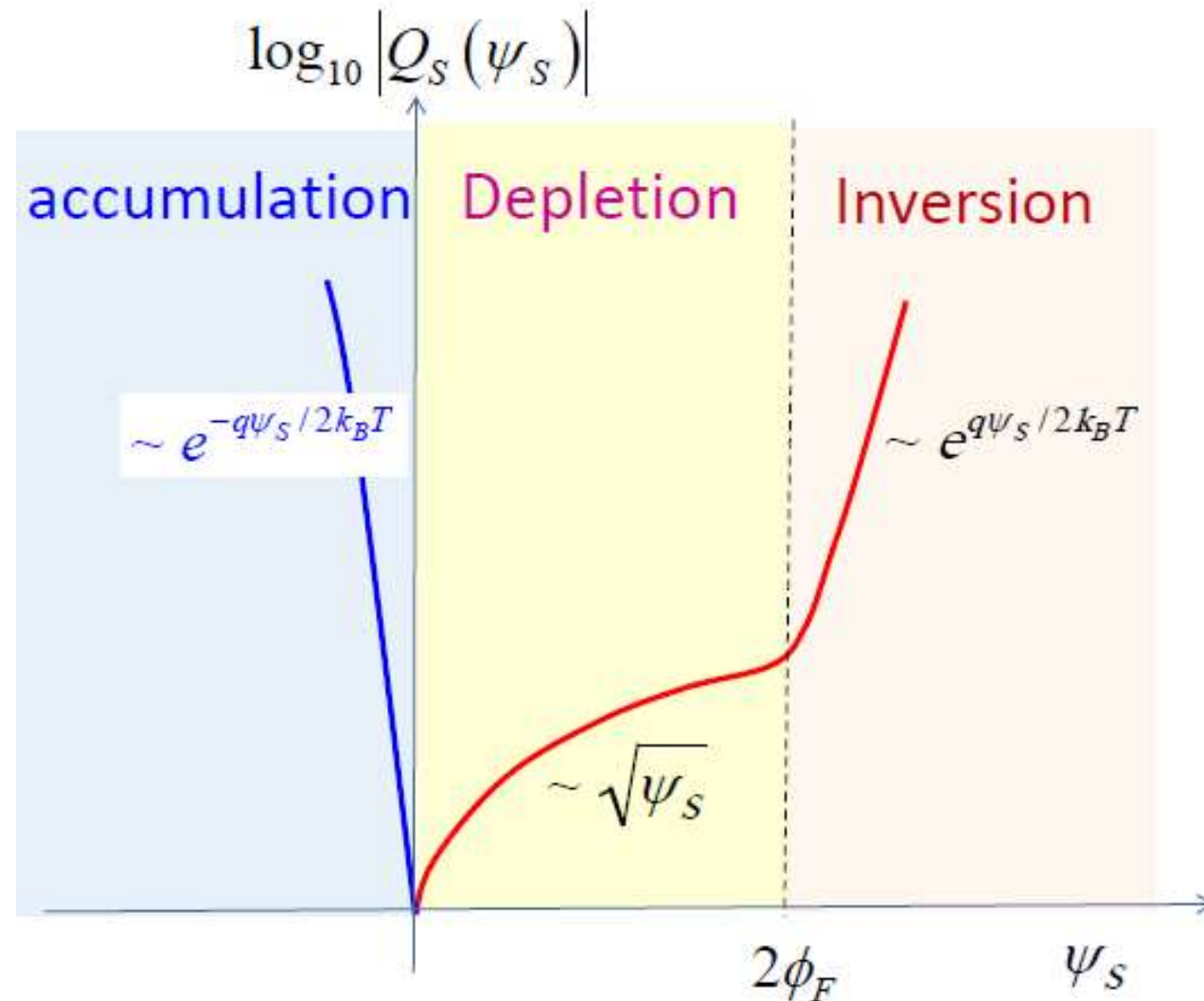
MOS band-diagram – under bias



Where does the excess charge come from?

Which layer forms quicker, accumulation or inversion?

Charge vs. Voltage (Q-V)



Charge vs. Surface Potential

$$n = n_i e^{(E_F - E_i)/k_B T}$$

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

$$n = n_i e^{(E_F - E_{i0})/k_B T} e^{q\psi/k_B T}$$

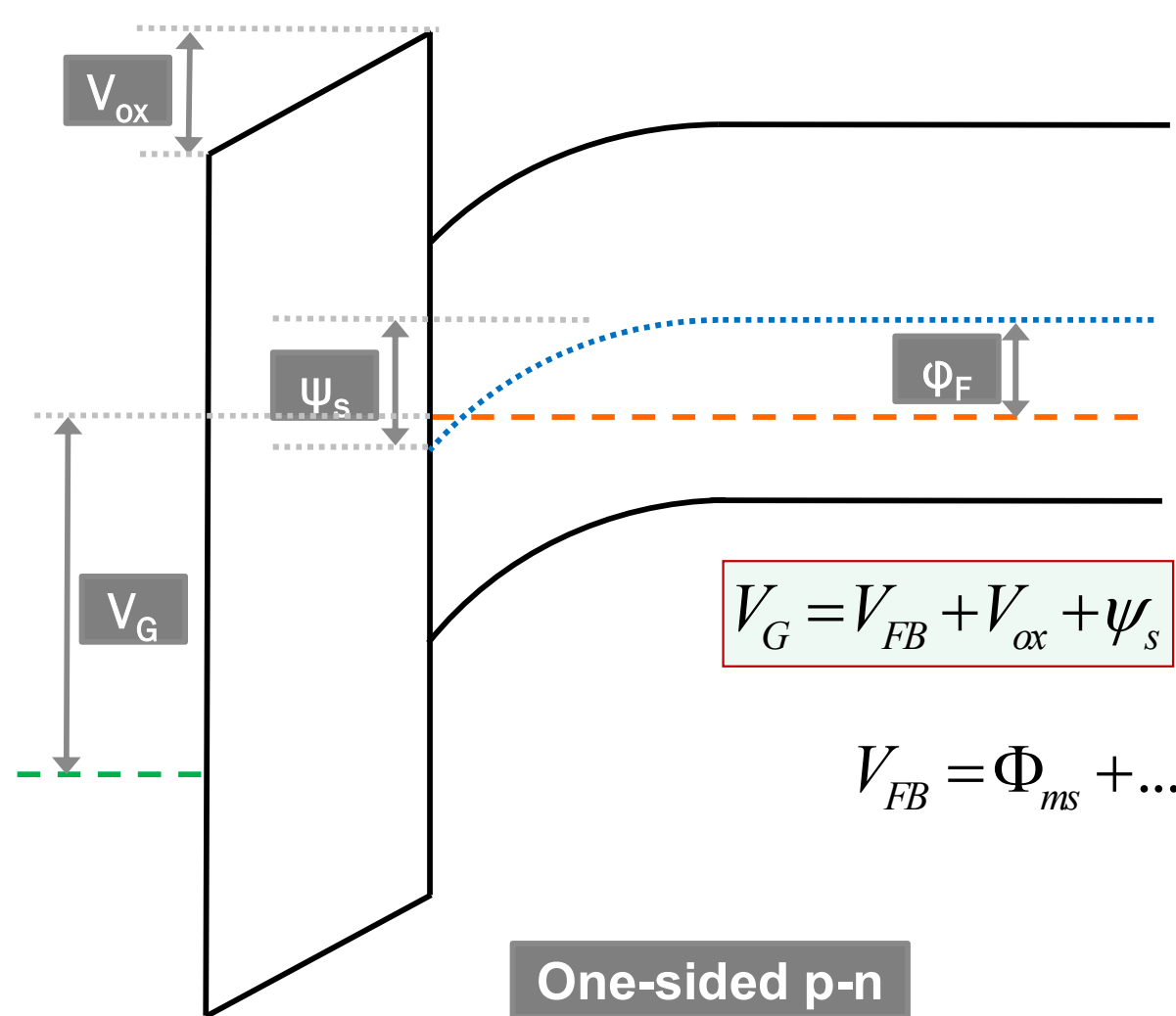
$$n = n_0 e^{+q\psi/k_B T}$$

$$p = p_0 e^{-q\psi/k_B T}$$

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

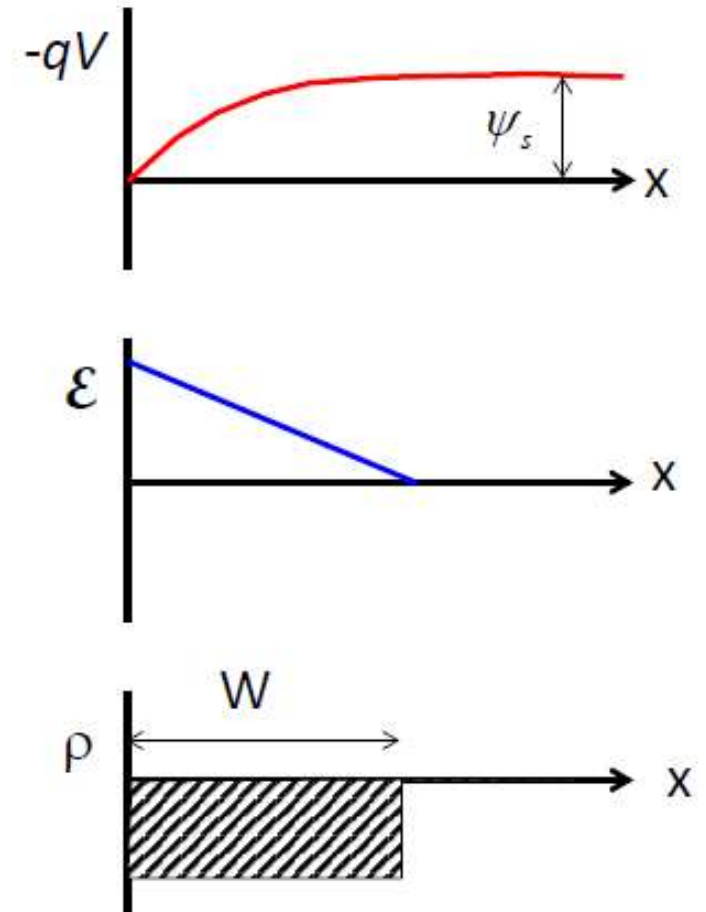
$$\frac{dE}{d\psi} \frac{d\psi}{dx} = -E \frac{dE}{d\psi} = f(\psi)$$

Q-V: depletion



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

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



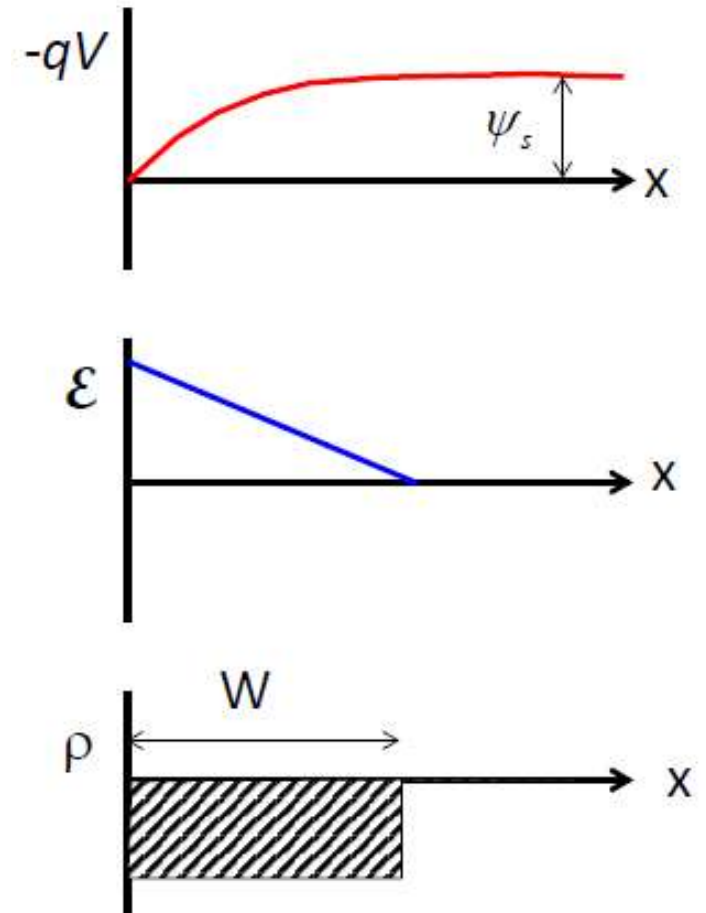
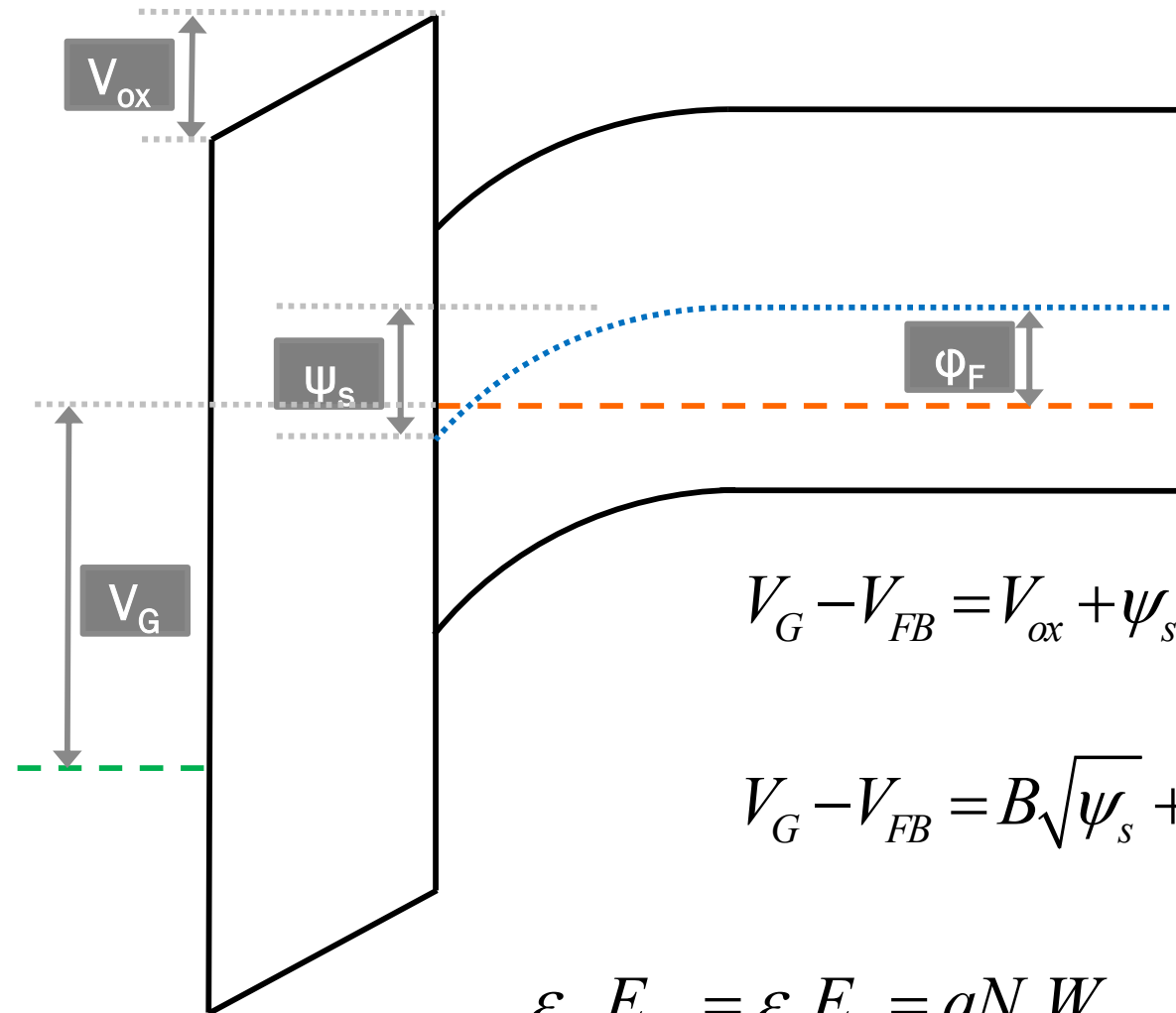
Depletion:

$$\psi_s = \frac{qN_a W^2}{2\epsilon_s}$$

$$Q_s = Q_d = qN_a W \Rightarrow$$

$$Q_d = \sqrt{2\epsilon_s qN_a \psi_s}$$

Q-V: depletion



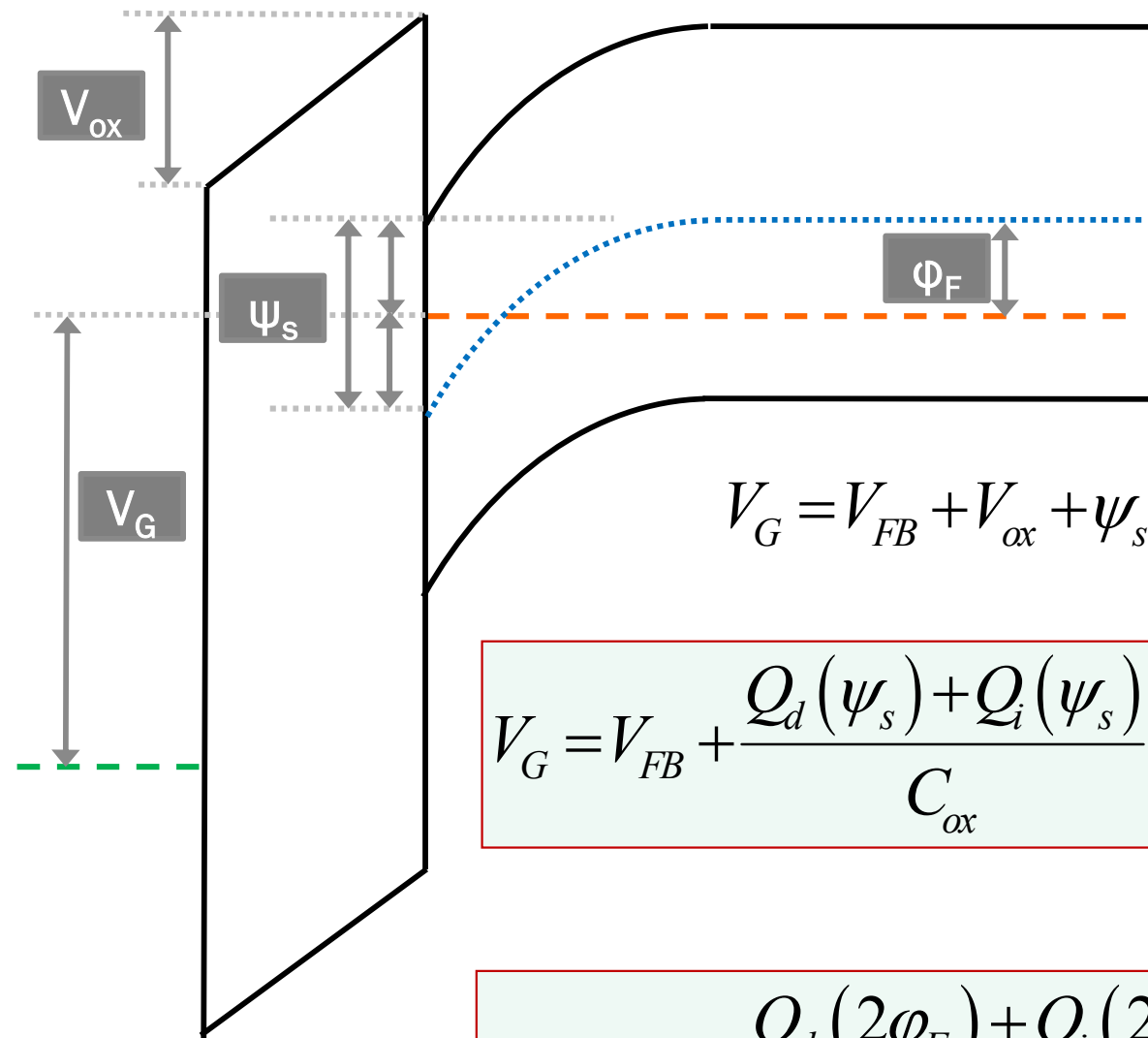
$$\epsilon_{ox} E_{ox} = \epsilon_s E_s = qN_a W$$

Depletion:

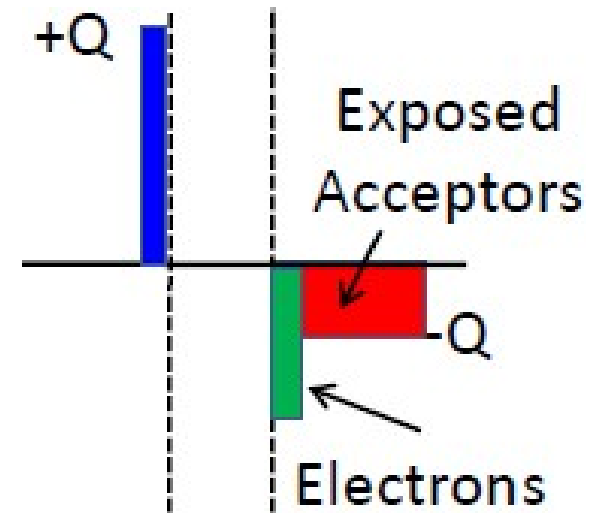
$$E_s = \frac{qN_a W}{\epsilon_s}$$

$$V_{ox} = E_{ox} t_{ox} = \frac{qN_a W}{\epsilon_{ox}} t_{ox} = \frac{Q_d}{C_{ox}} = \frac{\sqrt{2\epsilon_s qN_a \psi_s}}{C_{ox}}$$

Q-V: inversion



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

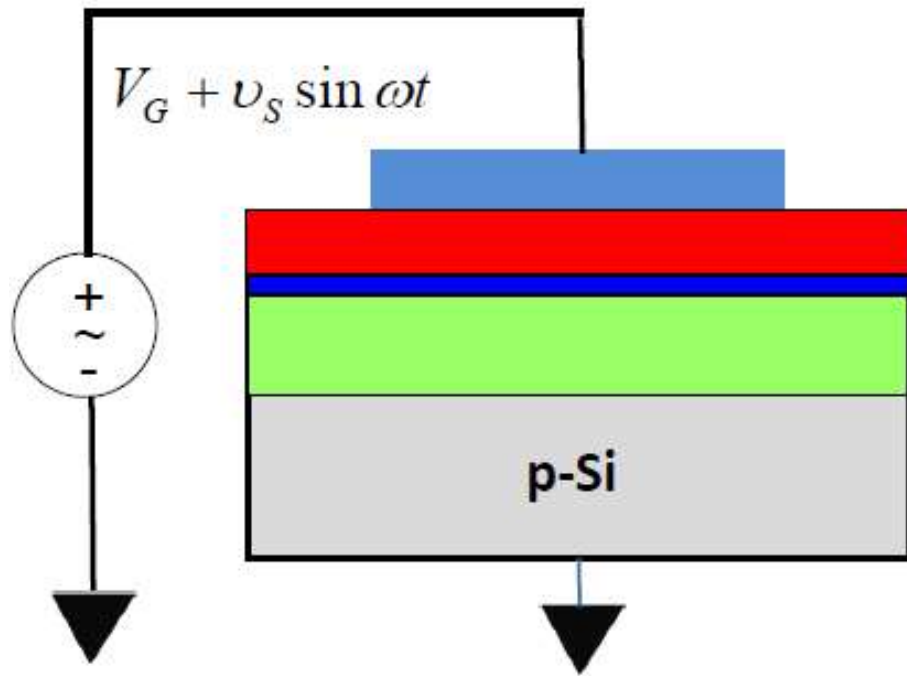


$$Q_i = C_{ox} (V_G - V_T)$$

‘Textbook’ threshold

$$V_T = V_{FB} + \frac{Q_d(2\phi_F) + Q_i(2\phi_F)}{C_{ox}} + 2\phi_F \approx V_{FB} + \frac{Q_d(2\phi_F)}{C_{ox}} + 2\phi_F$$

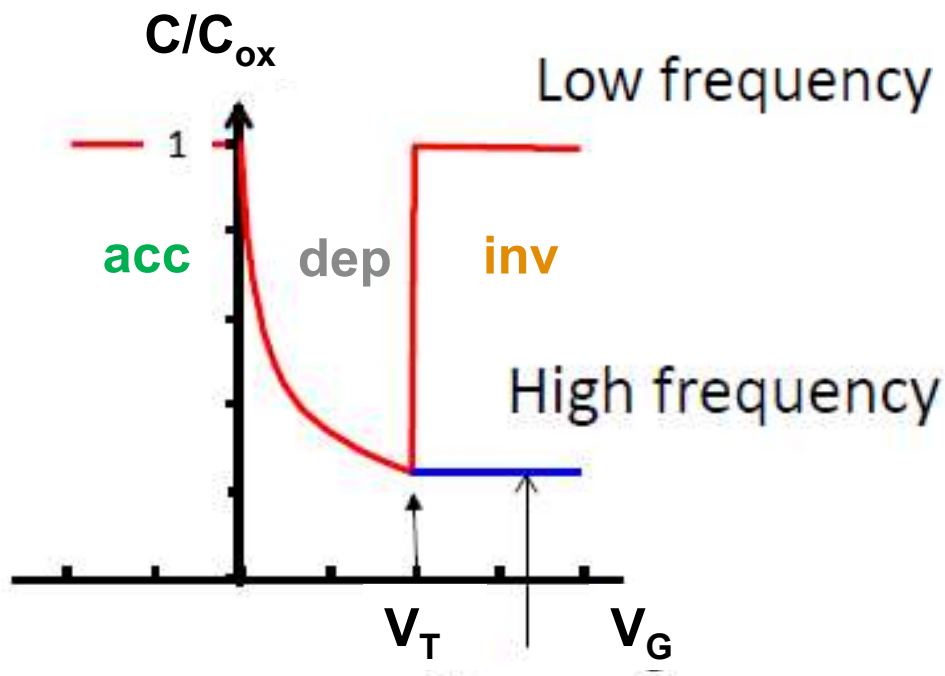
Capacitance vs. Voltage (C-V) – ideal



Small-signal capacitance

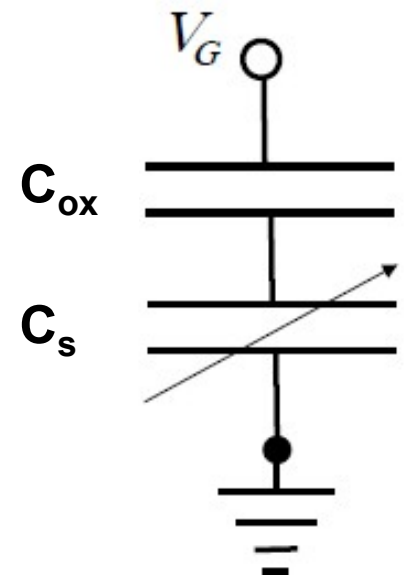
$$C_G \cong \frac{dQ_G}{dV_G} = \frac{d(-Q_s)}{dV_G}$$

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



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

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

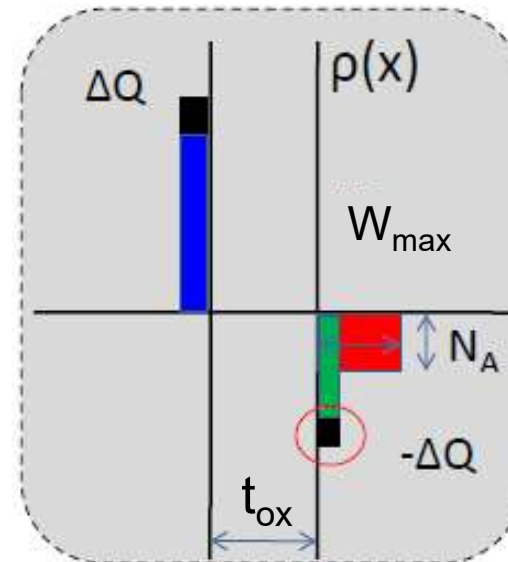
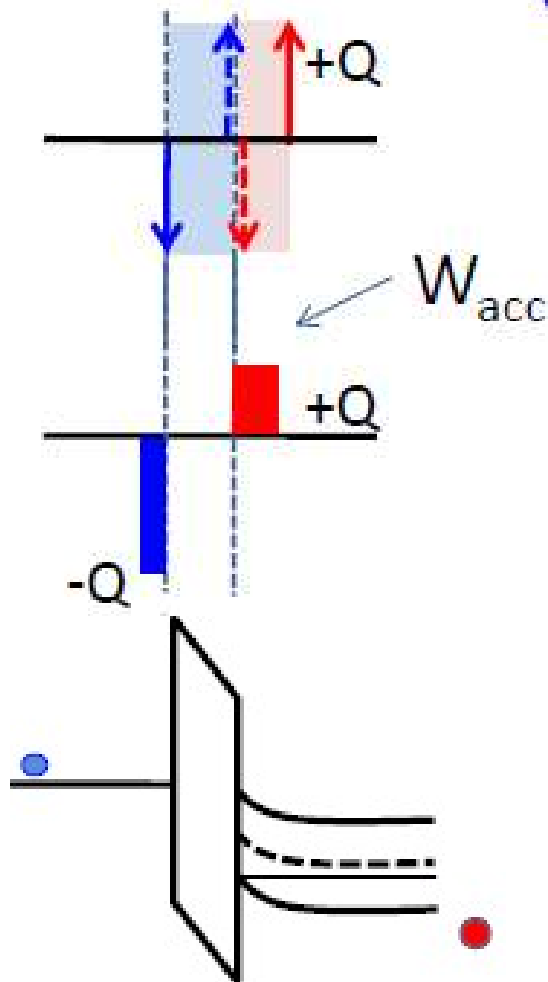


Ideal C-V: accumulation, inversion

$$C_{s,acc} = \frac{\epsilon_s}{W_{acc}} \gg C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$$

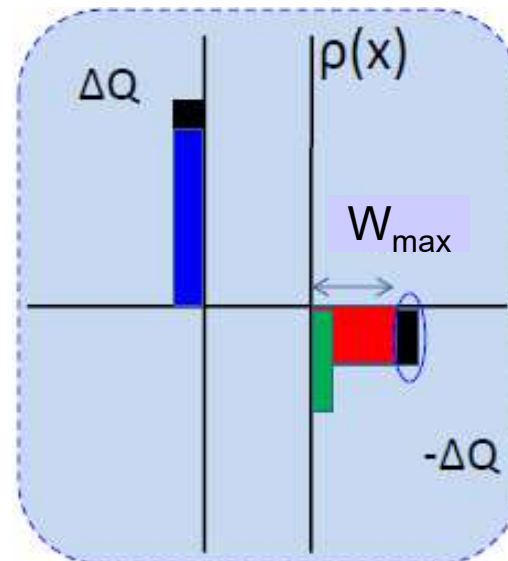
$$C_{s,inv} = \frac{\epsilon_s}{W_{inv}} \gg C_{ox}$$

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



HF

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

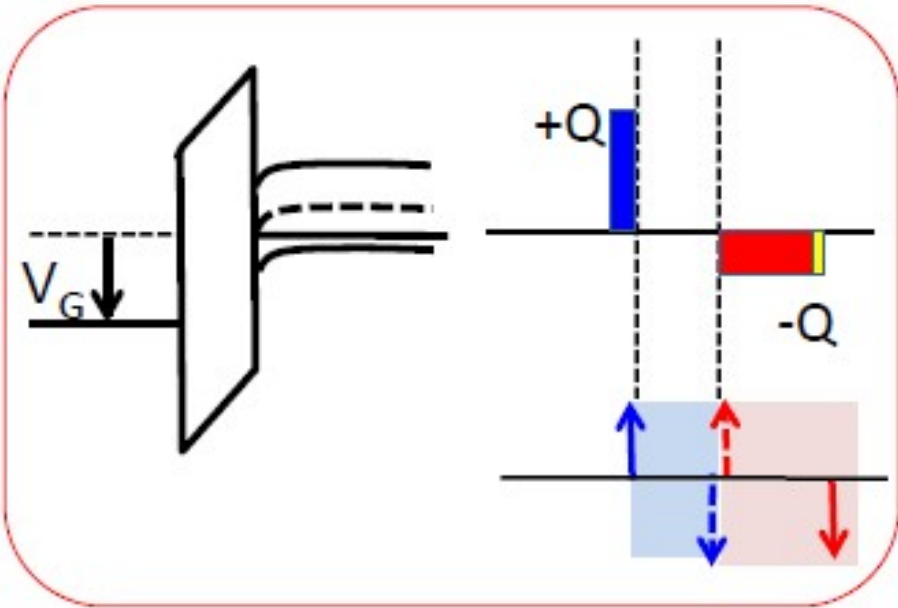


LF

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

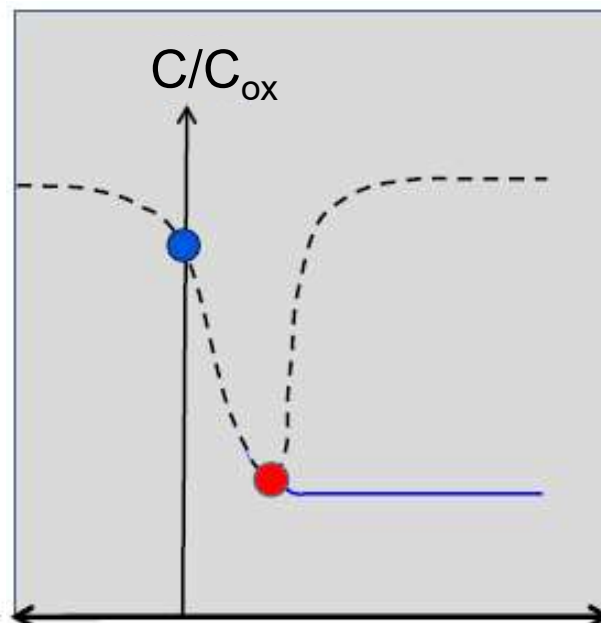
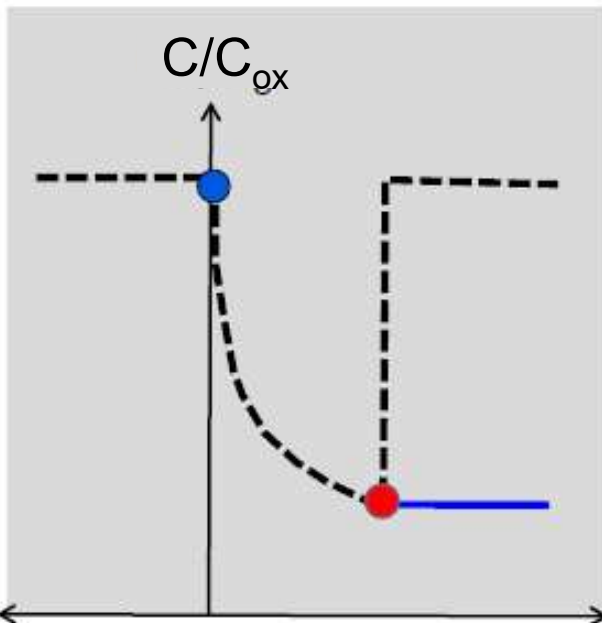
Why are the electrons slow?

Ideal C-V: depletion



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

$$V_G = V_{ox} + \psi_s = \frac{qN_a W}{C_{ox}} + \frac{qN_a W^2}{2\epsilon_s}$$



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

How do you calculate C_{FB} ?