Essentials of MOSFETs

Unit 3: MOS Electrostatics

Lecture 3.1: Energy Band Diagram Approach

Mark Lundstrom

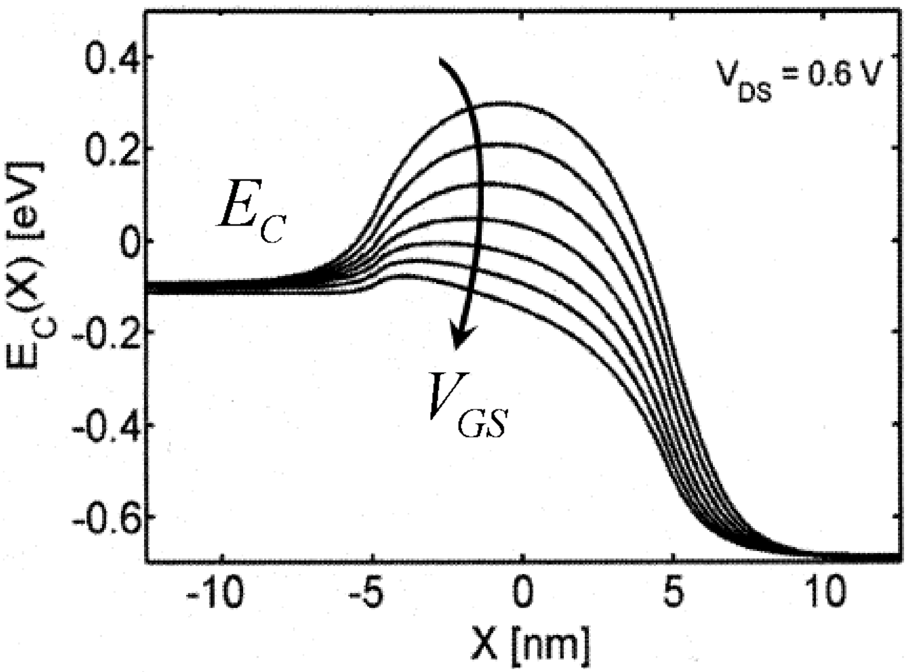
lundstro@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA

Electrostatics

Unit 3: electrostatics

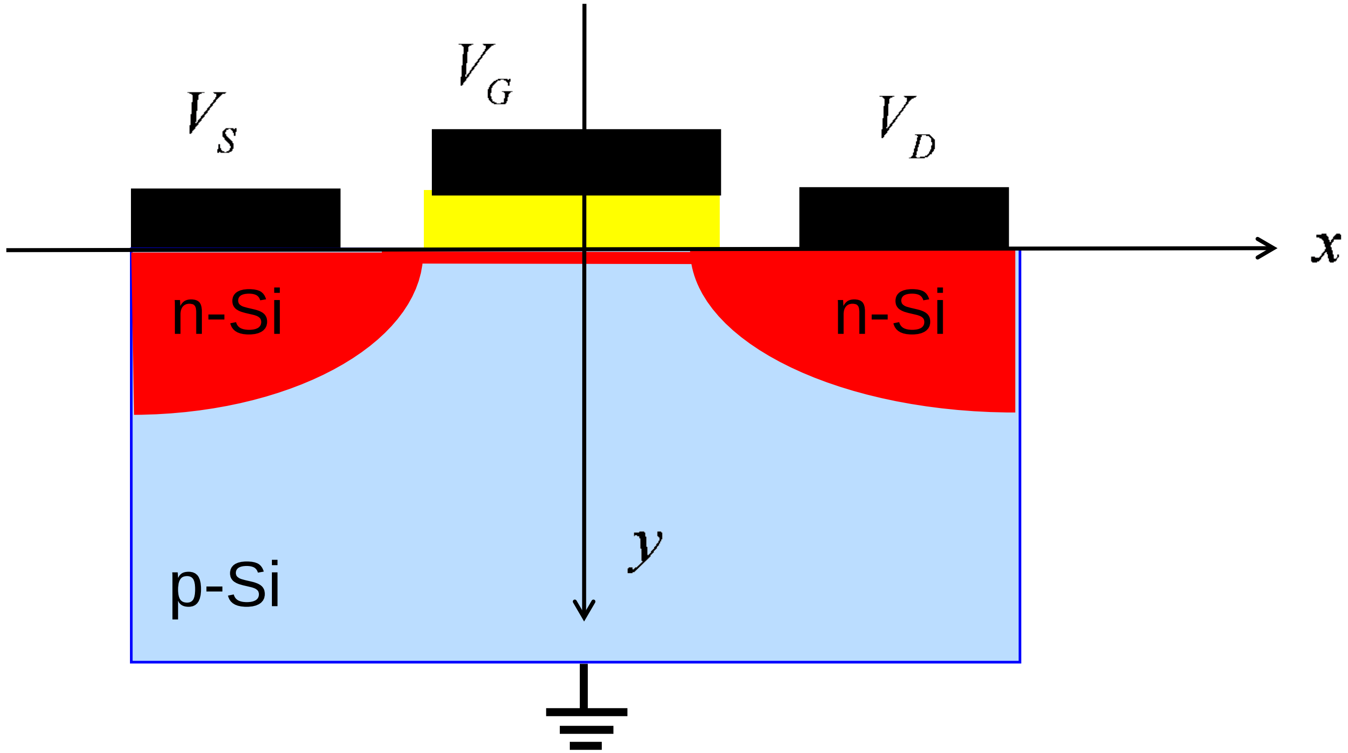
$$I_D/W = \left|Q_n\left(V_{GS},V_{DS}\right)\right|\left\langle \upsilon_x\left(V_{GS},V_{DS}\right)\right\rangle$$

Unit 4: transport



Before developing analytical expressions, we should understand MOS electrostatics from an energy band perspective.

2D energy band diagrams



$$E_C(x,y) = E_{C0} - q\psi(x,y)$$

$$E_V(x,y) = E_{V0} - q\psi(x,y)$$

The potential, *Ψ(x,y)*, in the semiconductor is controlled by the voltages applied to the terminals.

Poisson equation

Goal: Find: $\psi(x,y)$

Solve the Poisson equation: $\nabla \bullet \vec{D}(x,y) = \rho(x,y)$

$$\vec{D} = \varepsilon_S \vec{\mathcal{E}} = \kappa_S \varepsilon_0 \vec{\mathcal{E}}$$

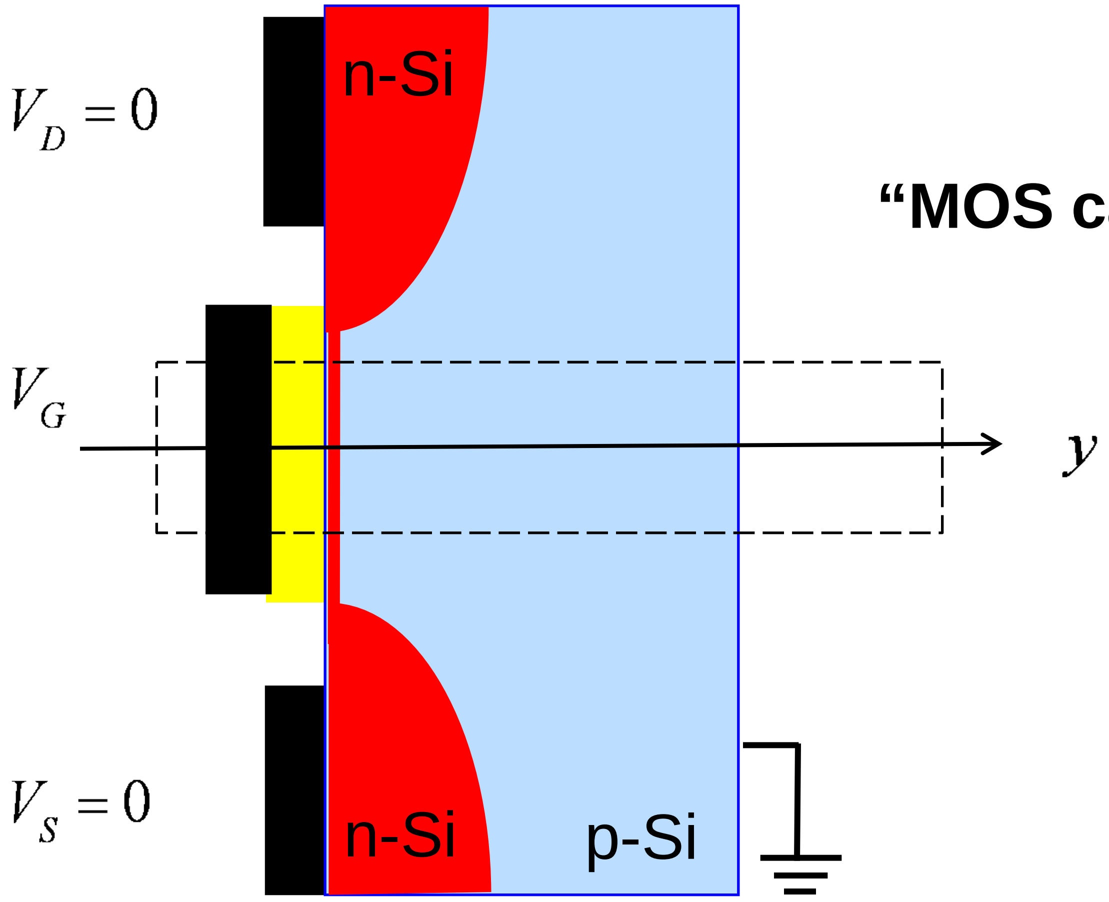
$$\boxed{\nabla^2 \psi(x,y) = -\frac{\rho(x,y)}{\varepsilon_S}}$$

$$\vec{\mathcal{E}} = -\vec{\nabla}\psi$$

$$\rho(x,y) = q\left[p(x,y) - n(x,y) + N_D^+(x,y) - N_A^-(x,y)\right]$$

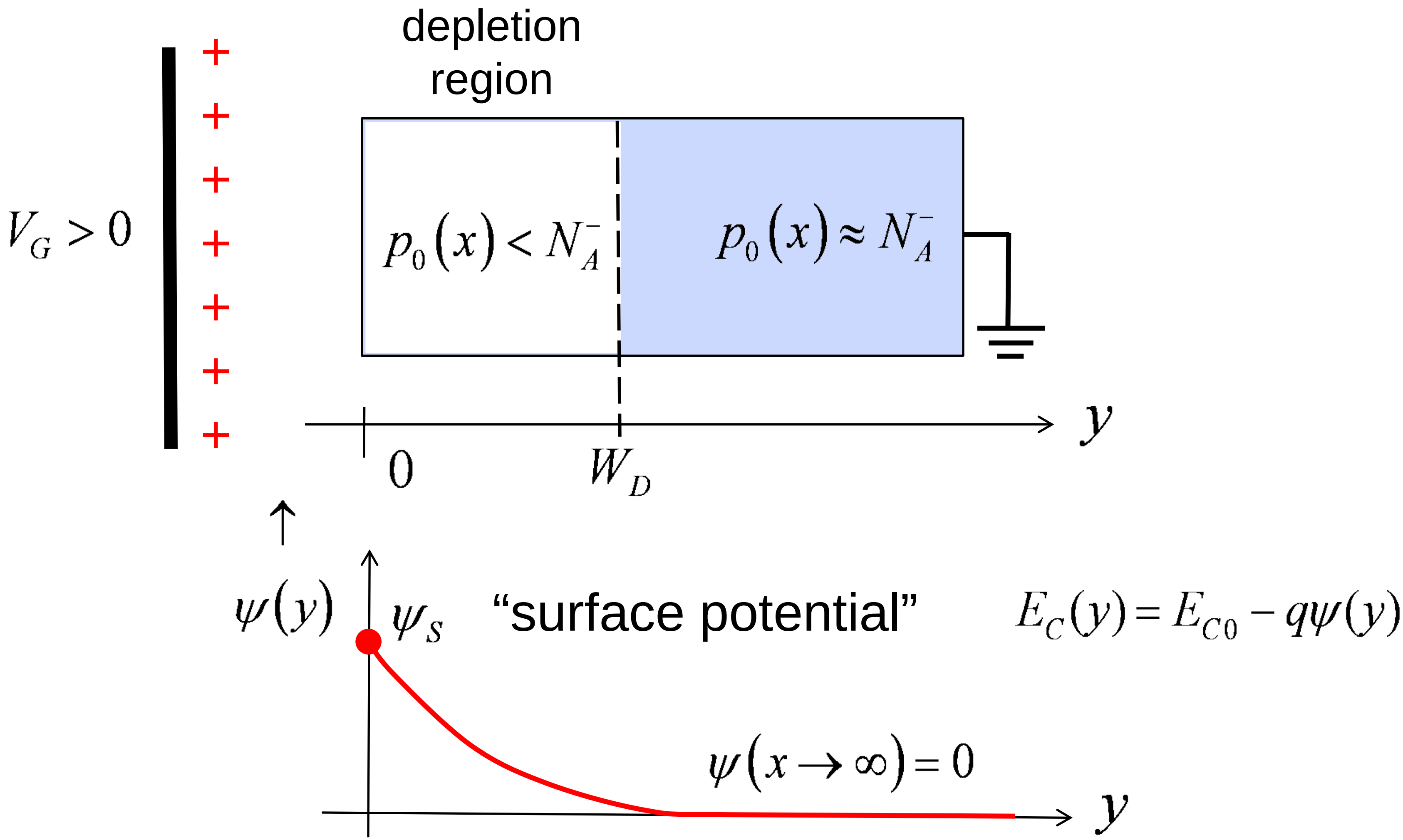
Drawing an energy band diagram provides us with a qualitative solution to the Poisson equation.

The 1D MOS Capacitor

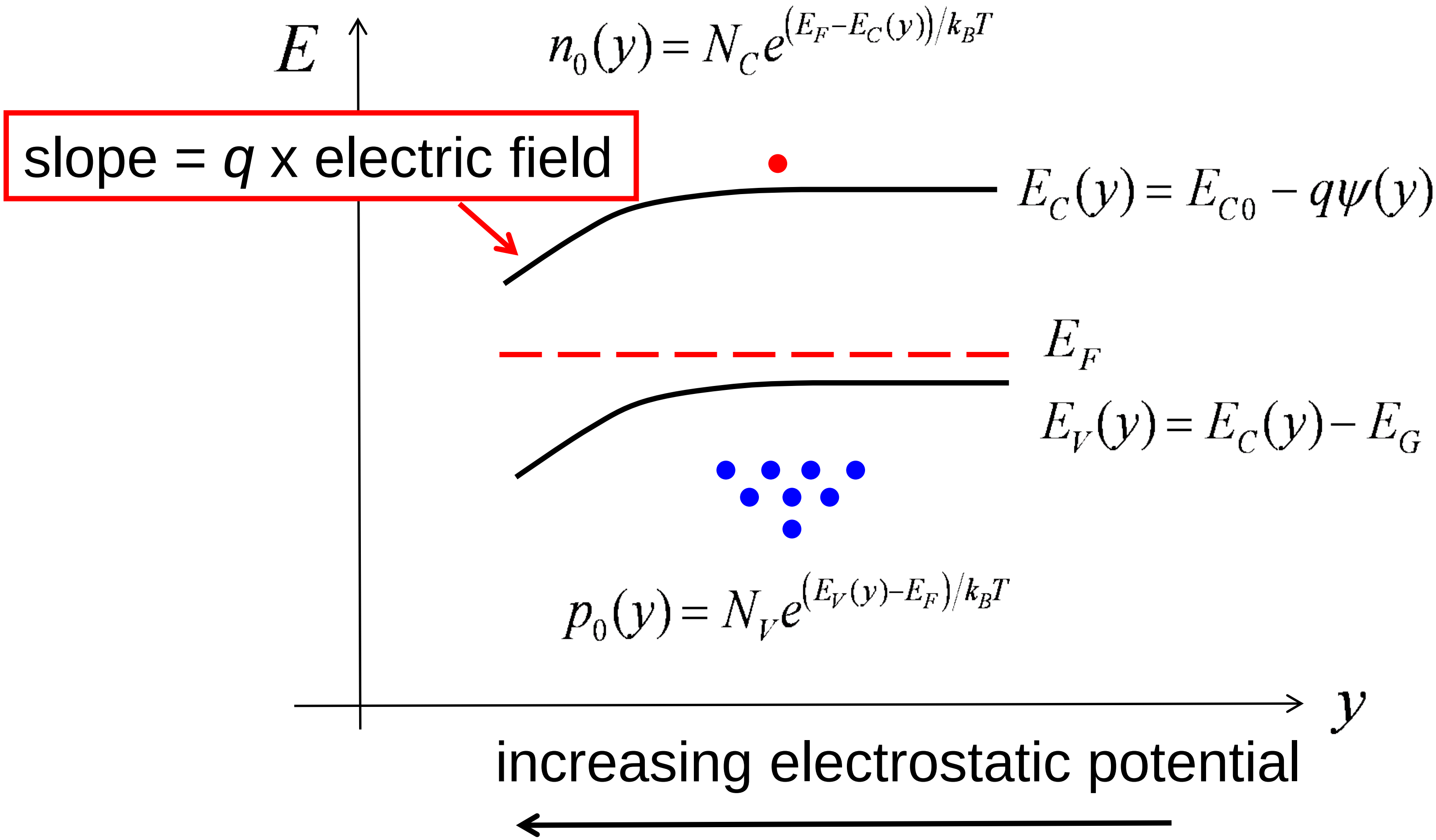


"MOS capacitor"

Electrostatic potential vs. position



Band bending

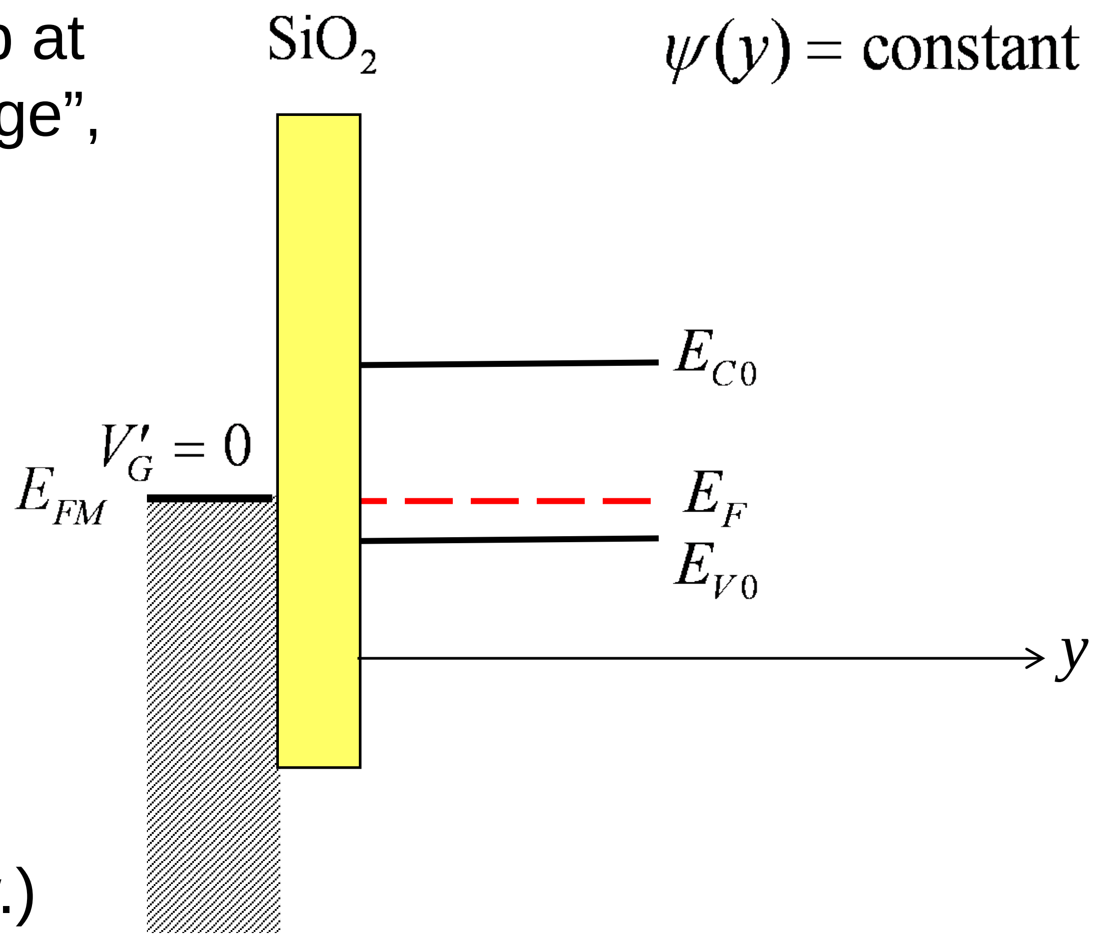


“Flat-band” conditions

Fermi levels line up at the “flat-band voltage”,

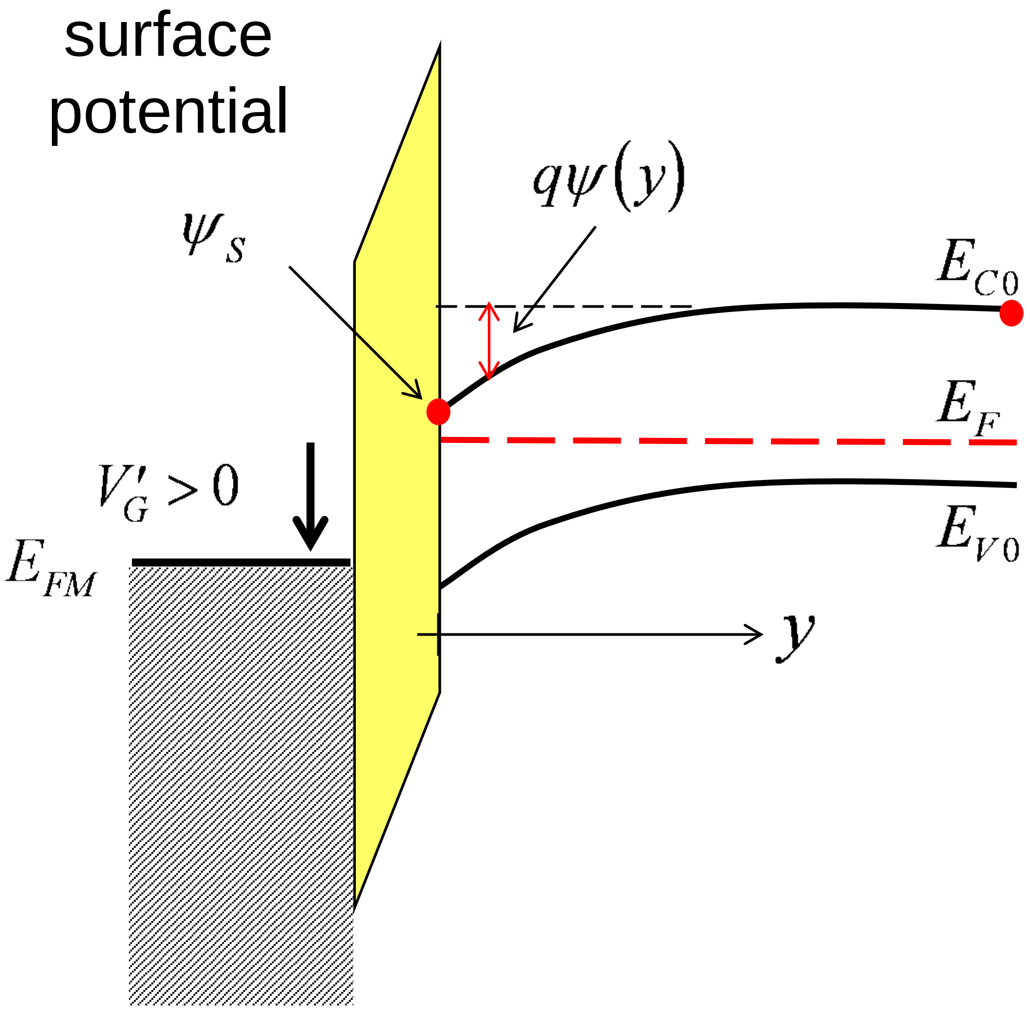
$V_G' = 0$

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



(Ignore metal-semi workfunction differences for now.)

Applied gate voltage



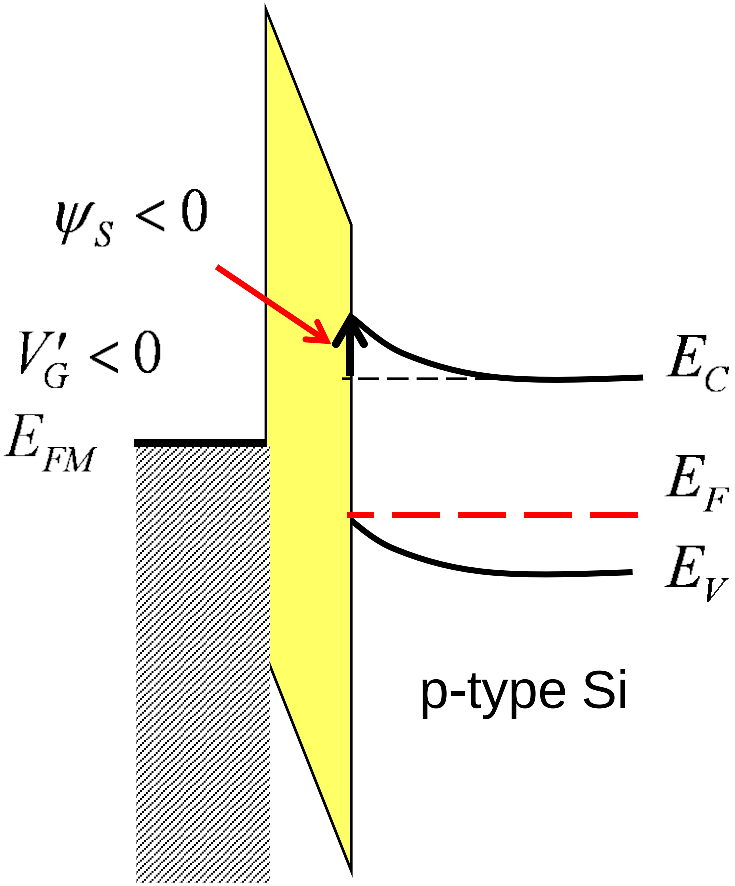
$$E_C(x \to \infty) = E_{C0}$$

$$\psi(y) = 0$$ (arbitrary reference for zero potential)

$$E_C(y) = E_{C0} - q\psi(y)$$

$$\psi(y) = \frac{E_{C0} - E_C(y)}{q}$$

$V'_G < 0$: "accumulation"



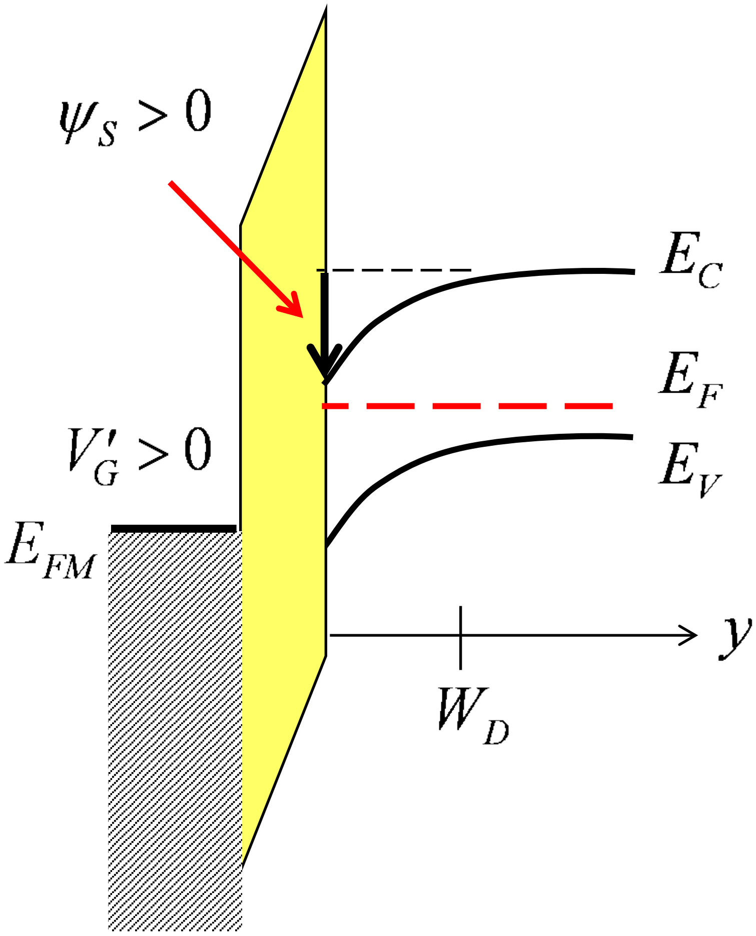
- surface potential < 0
- bands bend up
- hole density increases exponentially near the surface.

$$p_0(y) = N_V e^{\left(E_V(y) - E_F\right)/k_B T}$$

$$Q_S = +q\int_0^\infty \left(p_0(y) - N_A^-\right) dy \ \ \mathrm{C/cm^2}$$

(**accumulation charge** piles up very near the interface)

$V'_G > 0$: "depletion"



- surface potential > 0
- bands bend down
- space charge density $y < W_D$:

$$p_0(y) = N_V e^{(E_V(y) - E_F)/k_B T} \approx 0$$

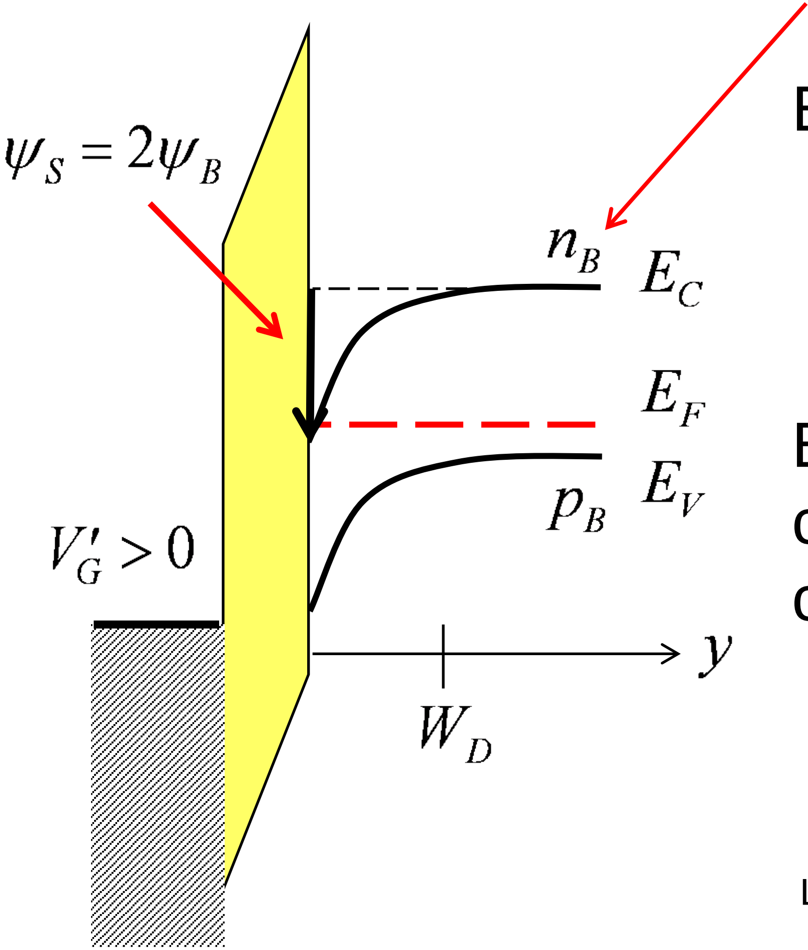
$$n_0(y) = N_C e^{(E_F - E_C(y))/k_B T} \approx 0$$

$$\rho(y) \approx -qN_A^- \quad (y < W_D) \quad \mathrm{C/cm^3}$$

"depletion charge"

$$\rho(y) \approx 0 \quad (y \geq W_D) \quad \mathrm{C/cm^3}$$

$V'_G = V'_T$:   onset of "inversion"



Electron concentration in the bulk:

$$n_B = n_i^2 / N_A \ll p_B$$

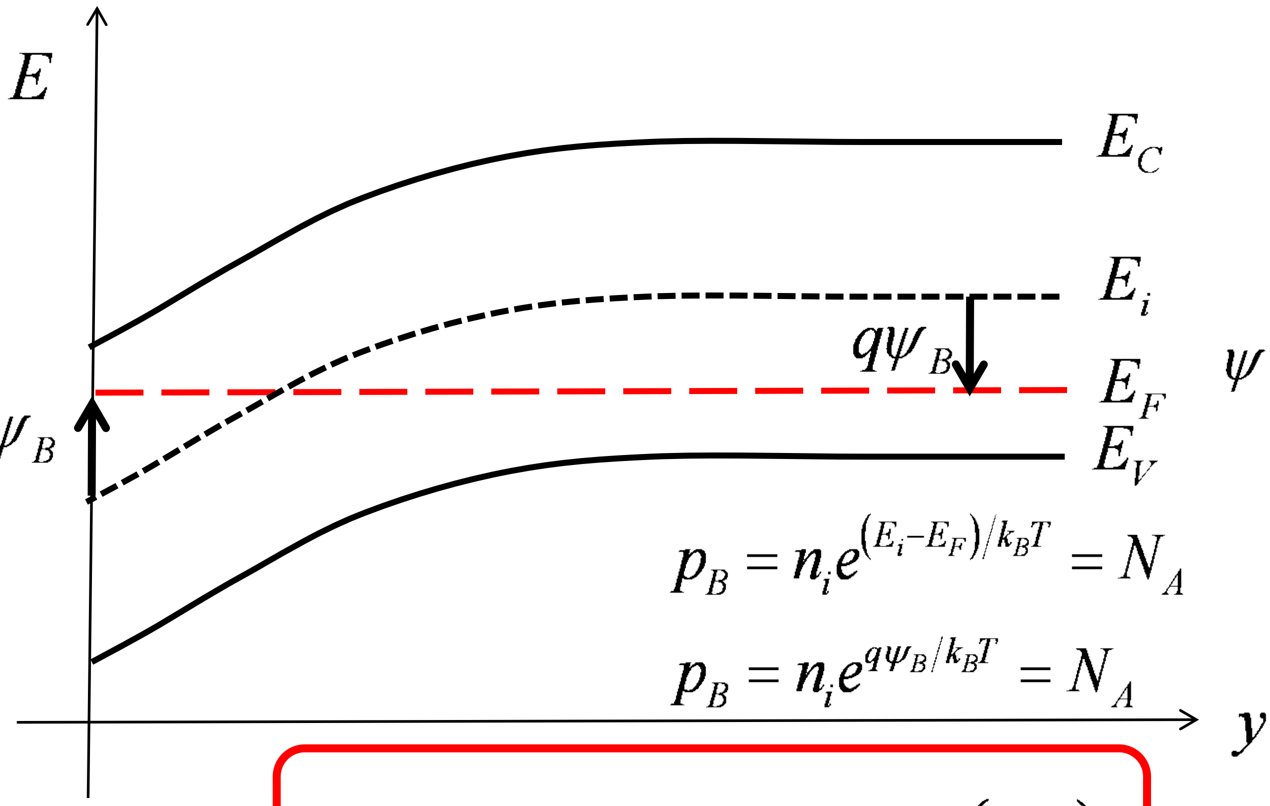
Electron concentration at the surface:

$$n_0(y=0) = N_C e^{(E_F - E_C(0))/k_B T} = n_B e^{q\psi_S / k_B T}$$

Band bending to make electron concentration at the surface = hole concentration in the bulk:

$$n_B e^{q\psi_S / k_B T} = N_A$$ **surface is "inverted"**

Onset of "inversion"



$$n(0) = p_B$$

$$V_G' = V_T'$$

$$q\psi_S = 2q\psi_B$$

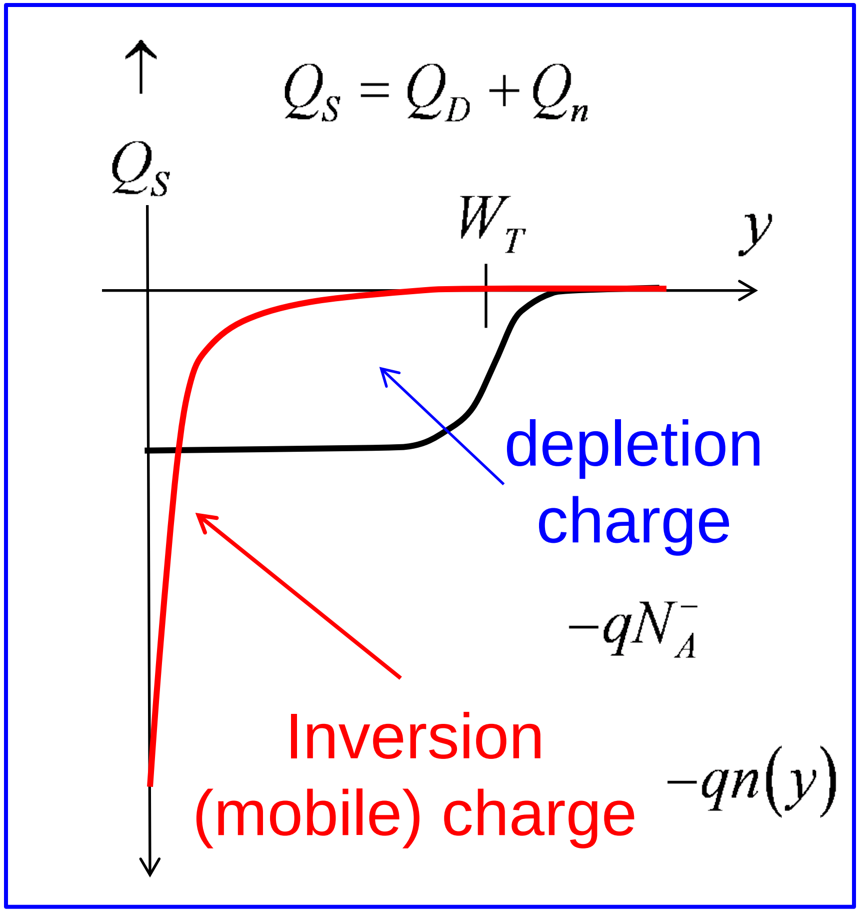
$$\psi(x \to \infty) = 0$$

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

$$p_B = n_i e^{q\psi_B/k_B T} = N_A$$

$$\boxed{\psi_S = 2\psi_B \qquad \psi_B = \frac{k_B T}{q}\ln\left(\frac{N_A}{n_i}\right)}$$

$V'_G > V_T$: “inversion”



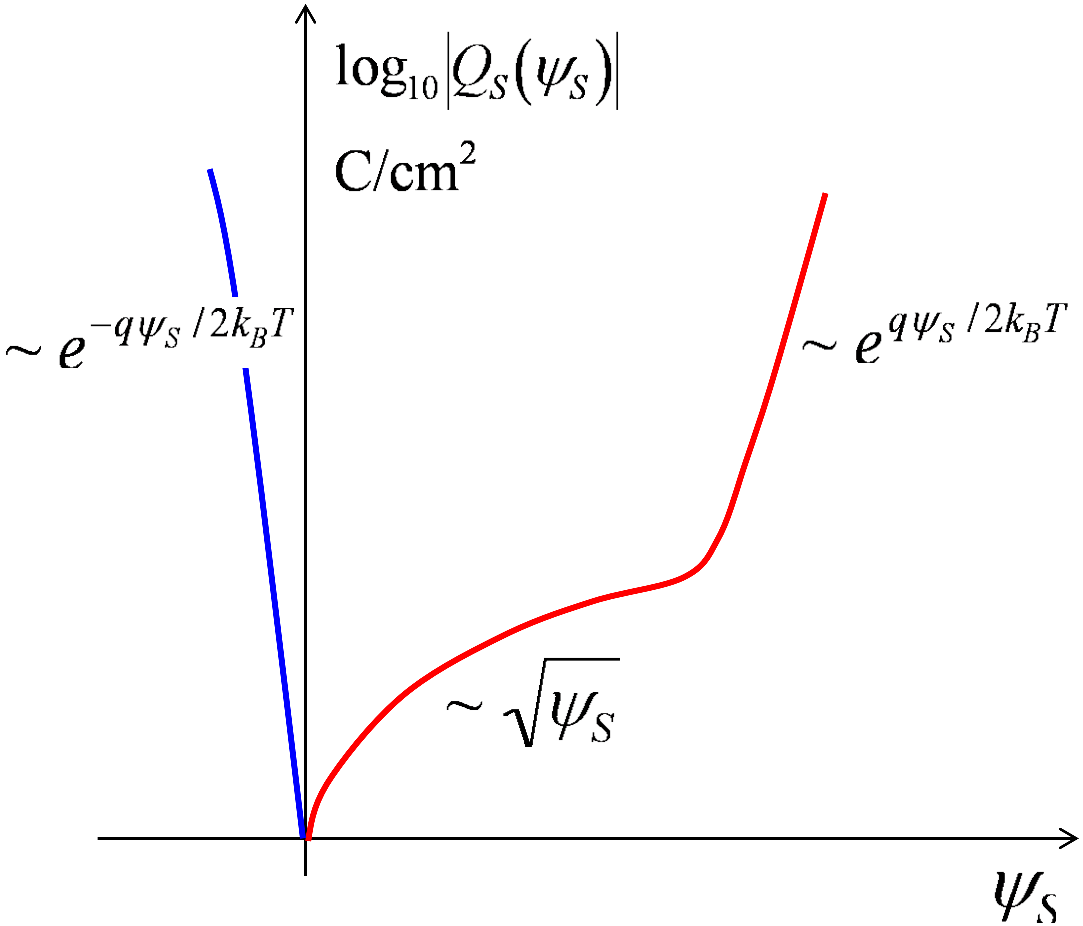
$$\psi_S \approx 2\psi_B \qquad \psi_B = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i}\right)$$

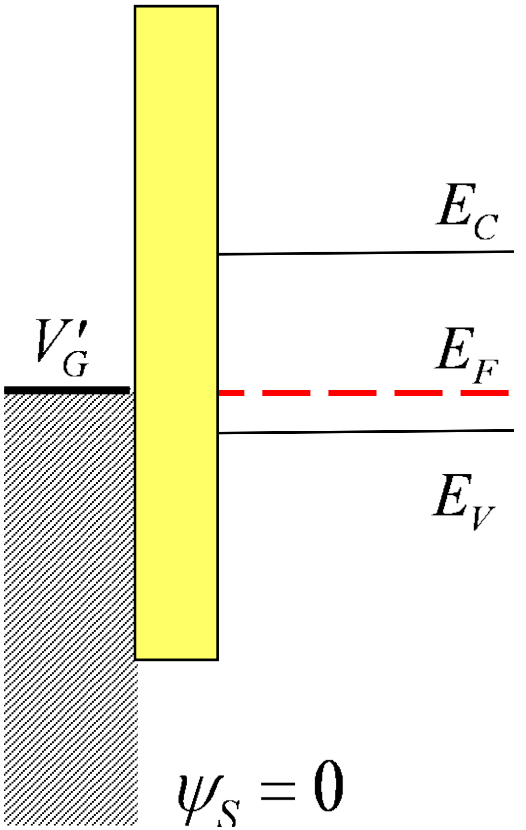
Hard to bend the bands further.

$$W_T = \sqrt{2\varepsilon_S (2\psi_B)/qN_A}$$

Electron charge piles up very near to the surface.

Total charge in semiconductor vs. surface potential





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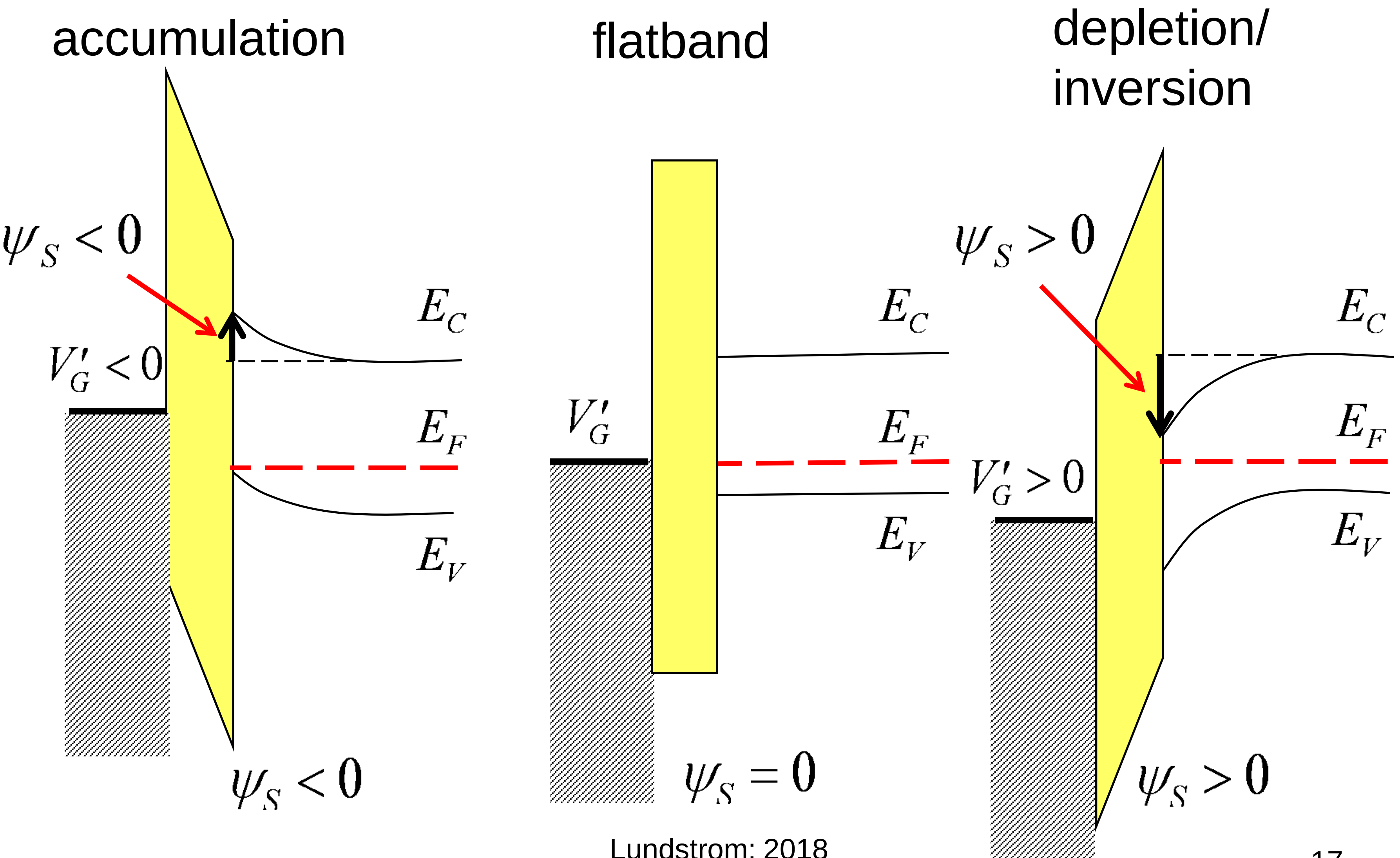
Exercise

Re-do the previous two slides for an n-type semiconductor.

Summary



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Next topic

Our goal is to solve the Poisson equation for $\psi(x, y)$.

In general, a numerical solution is required, but

In depletion, we can solve the problem analytically using the **depletion approximation**.