Fundamentals of Nanotransistors

Unit 2: MOS Electrostatics

Lecture 2.1: Introduction

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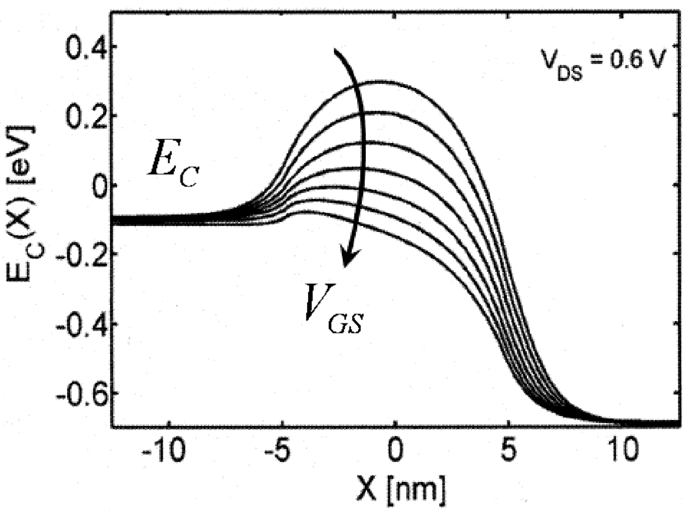
Outline: Unit 2

Lecture 2.1: Introduction

Lecture 2.2: Depletion Approximation
Lecture 2.3: Gate Voltage and Surface Potential
Lecture 2.4: Flatband Voltage
Lecture 2.5: Mobile Charge: Bulk MOS
Lecture 2.6: Mobile Charge: ETSOI
Lecture 2.7: 2D Electrostatics
Lecture 2.8: The VS Model Revisited

Lecture 2.9 Summary

Electrostatics



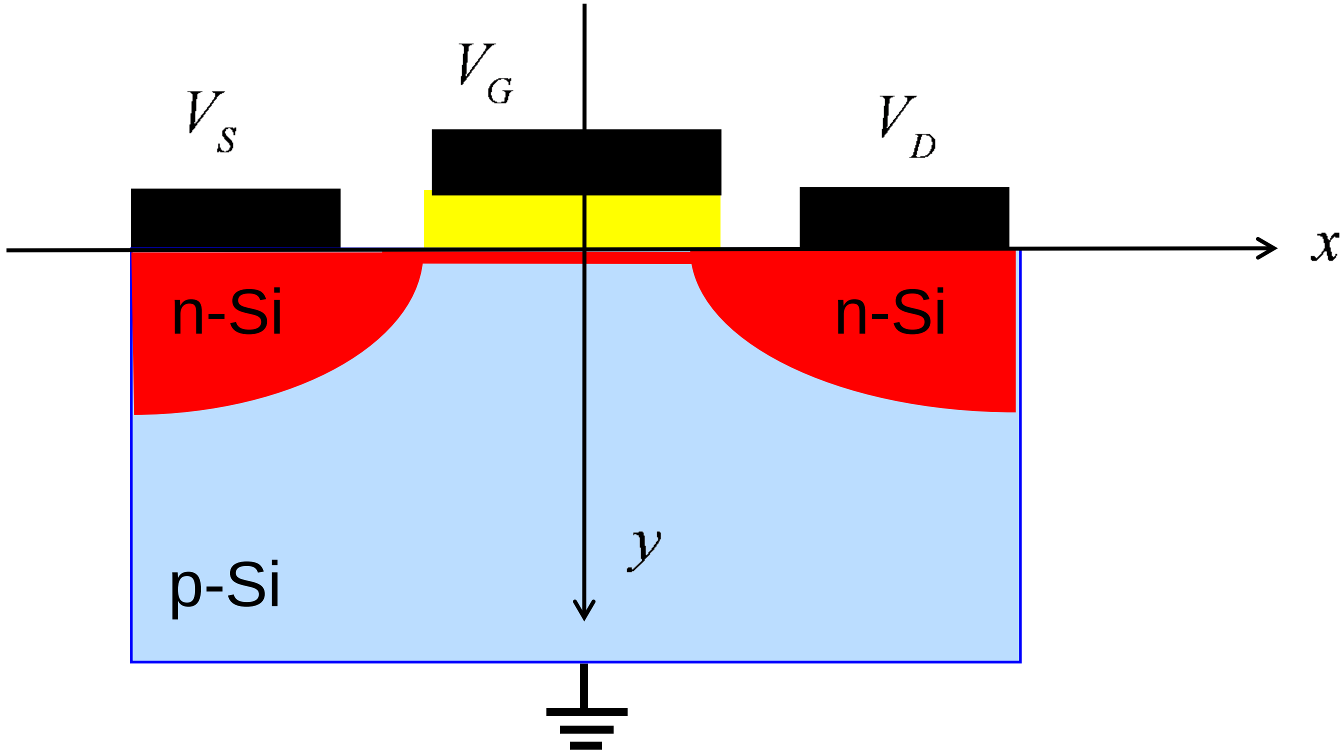
Unit 2: electrostatics

$$I_{DS}/W = -Q_n\left(V_{GS}, V_{DS}\right)\left\langle \upsilon\left(V_{DS}\right)\right\rangle$$

Units 3 and 4: transport

Lecture 1.5

2D energy band diagrams



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

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

Poisson equation

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

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

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

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

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

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

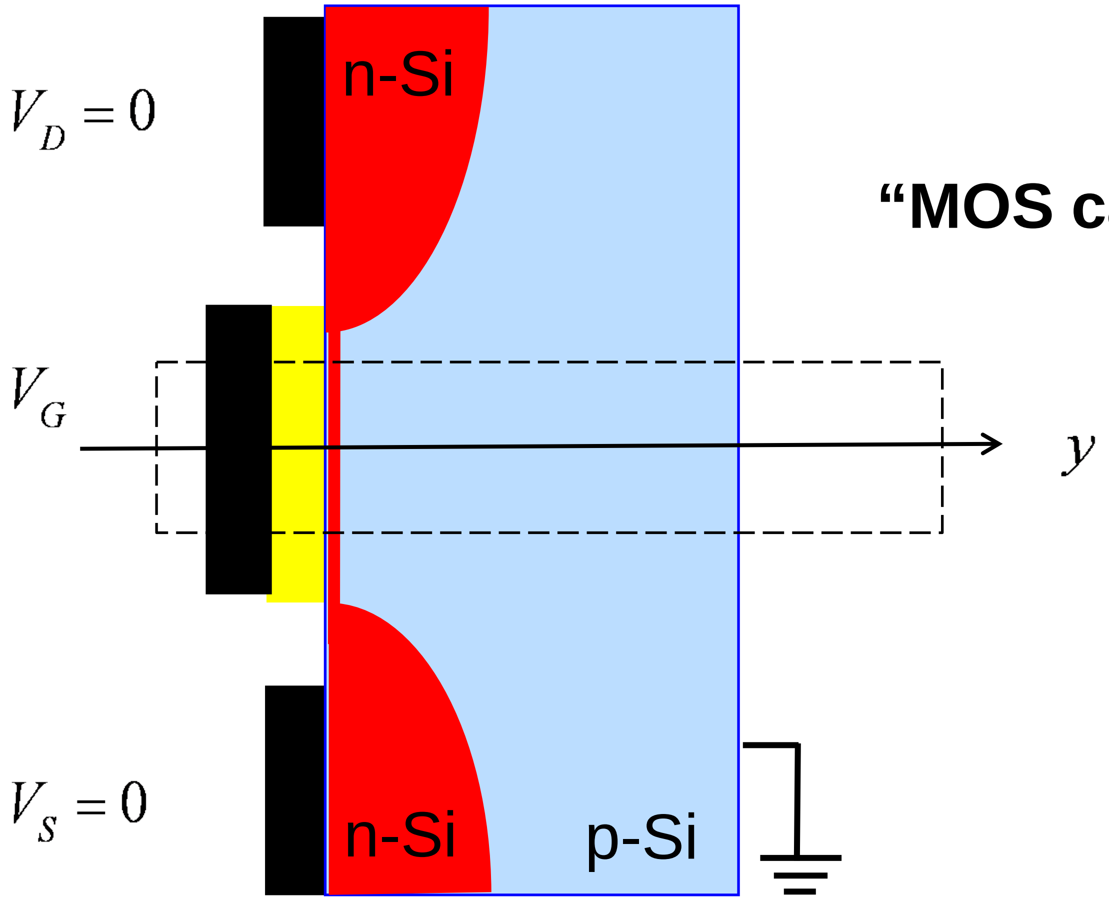
Lecture 2.2: Depletion Approximation

Energy band diagrams

$$\boxed{\begin{aligned} E_C(x,y) &= E_{C0} - q\psi(x,y) \\ E_V(x,y) &= E_{V0} - q\psi(x,y) \end{aligned}}$$

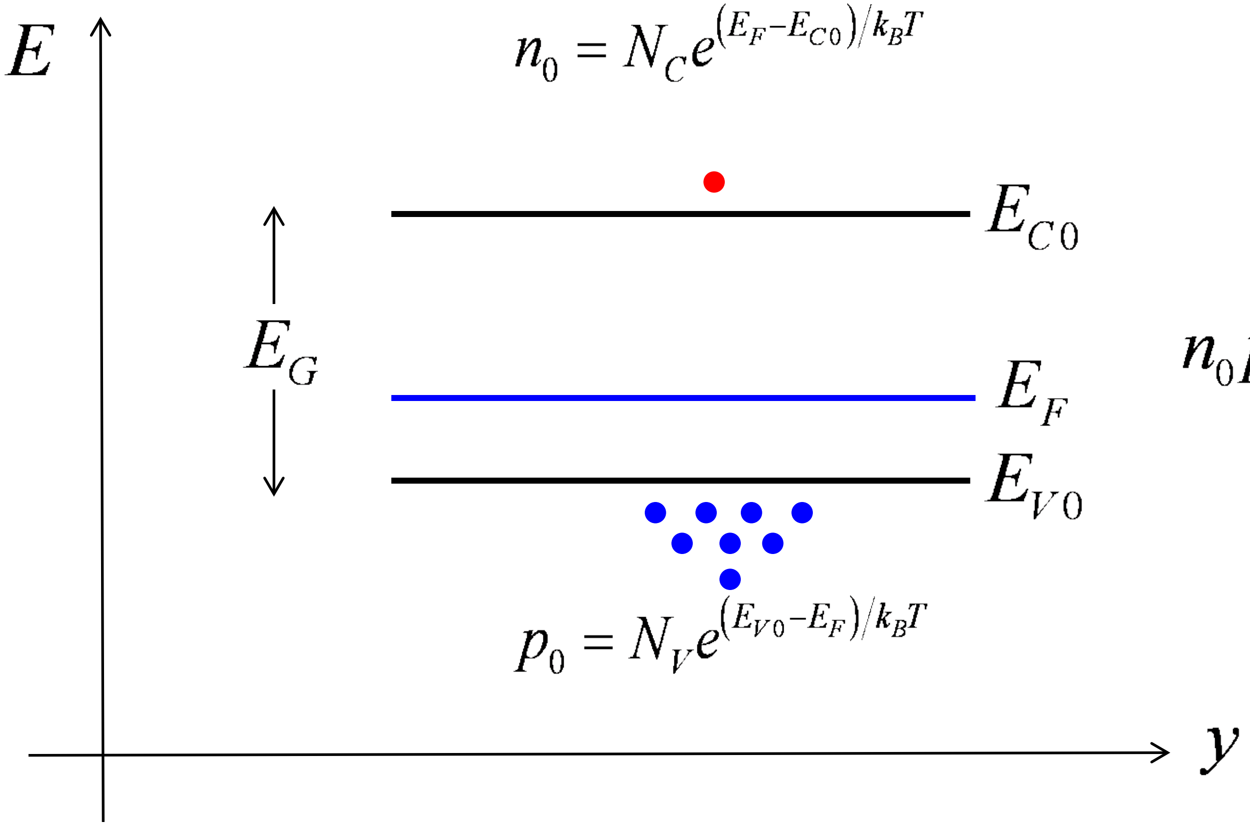
Drawing an energy band diagram provides with a qualitative solution to the Poisson equation.

Equilibrium energy band diagrams



“MOS capacitor”

Review: energy bands



$$n_0 = N_C e^{\left(E_F - E_{C0}\right)/k_B T}$$

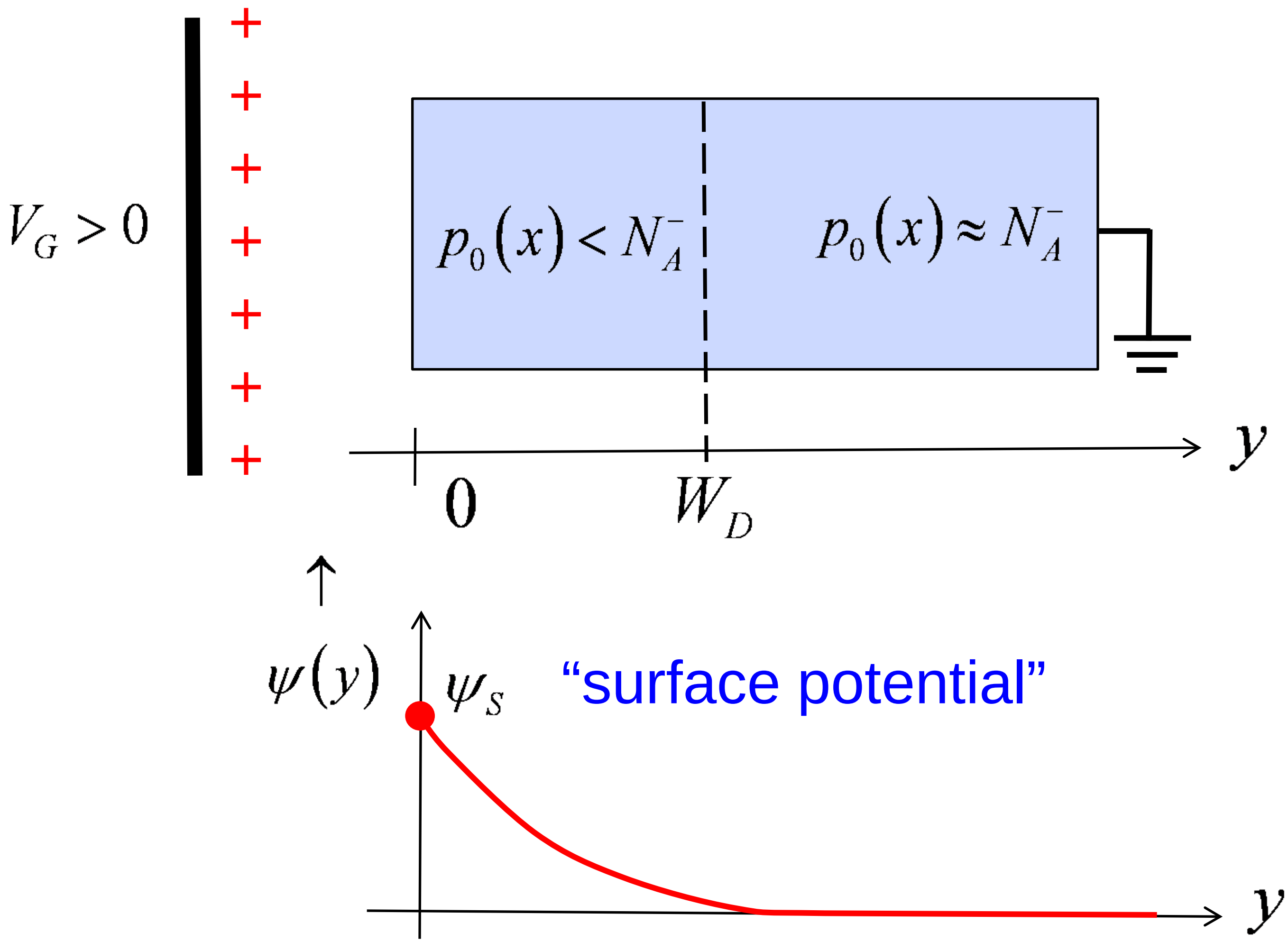
$$p_0 = N_V e^{\left(E_{V0} - E_F\right)/k_B T}$$

$$n_0 p_0 = n_i^2$$

Assumptions:

i) equilibrium, ii) Boltzmann carrier statistics, iii) uniform electrostatic potential

Electrostatic potential vs. position

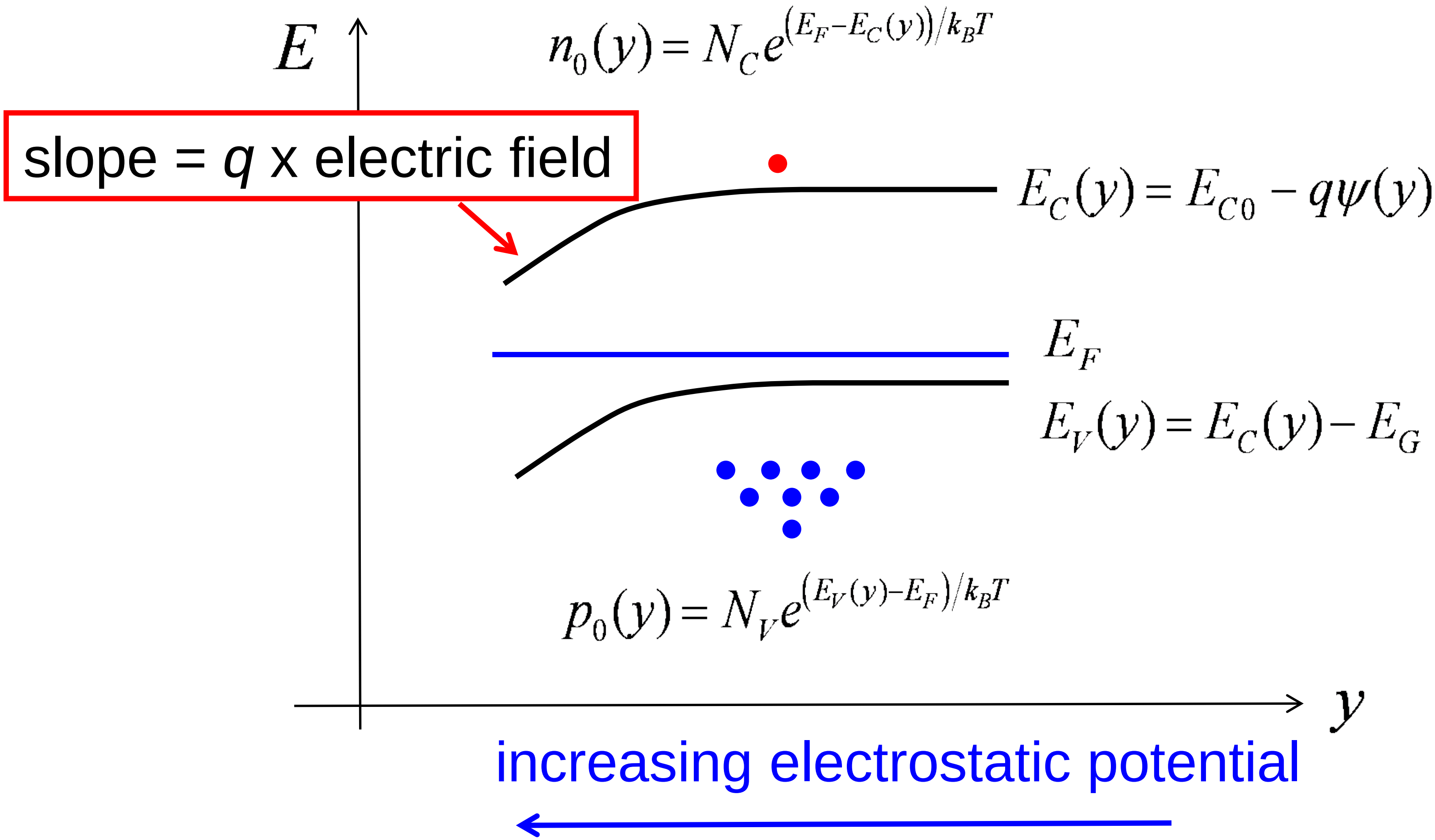


Electrostatic potential and energy bands

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

The energy bands will bend when the electrostatic potential changes with position.

Band bending

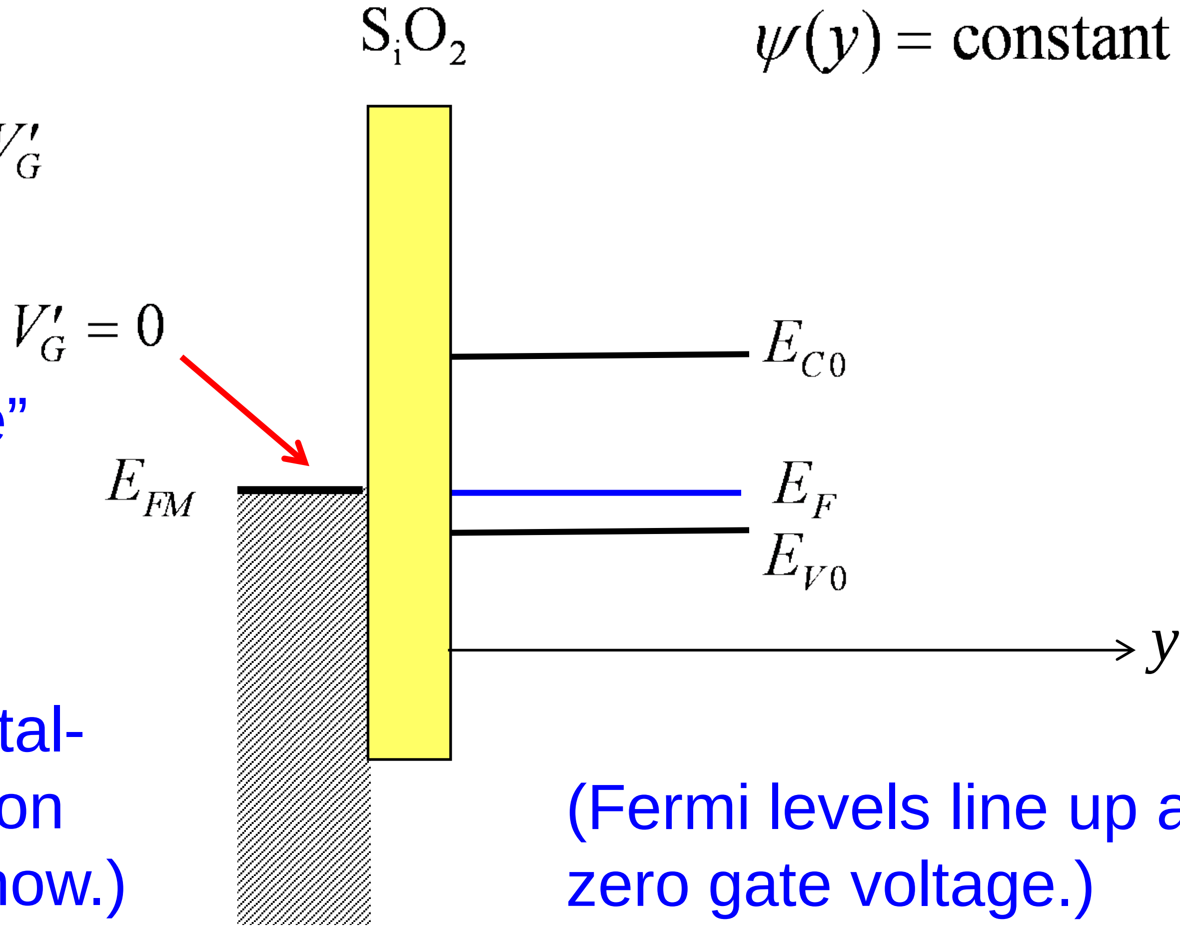


"Flatband" conditions

$$E_{FM} = E_{FM}^{0} - qV_G'$$

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

"flatband voltage"

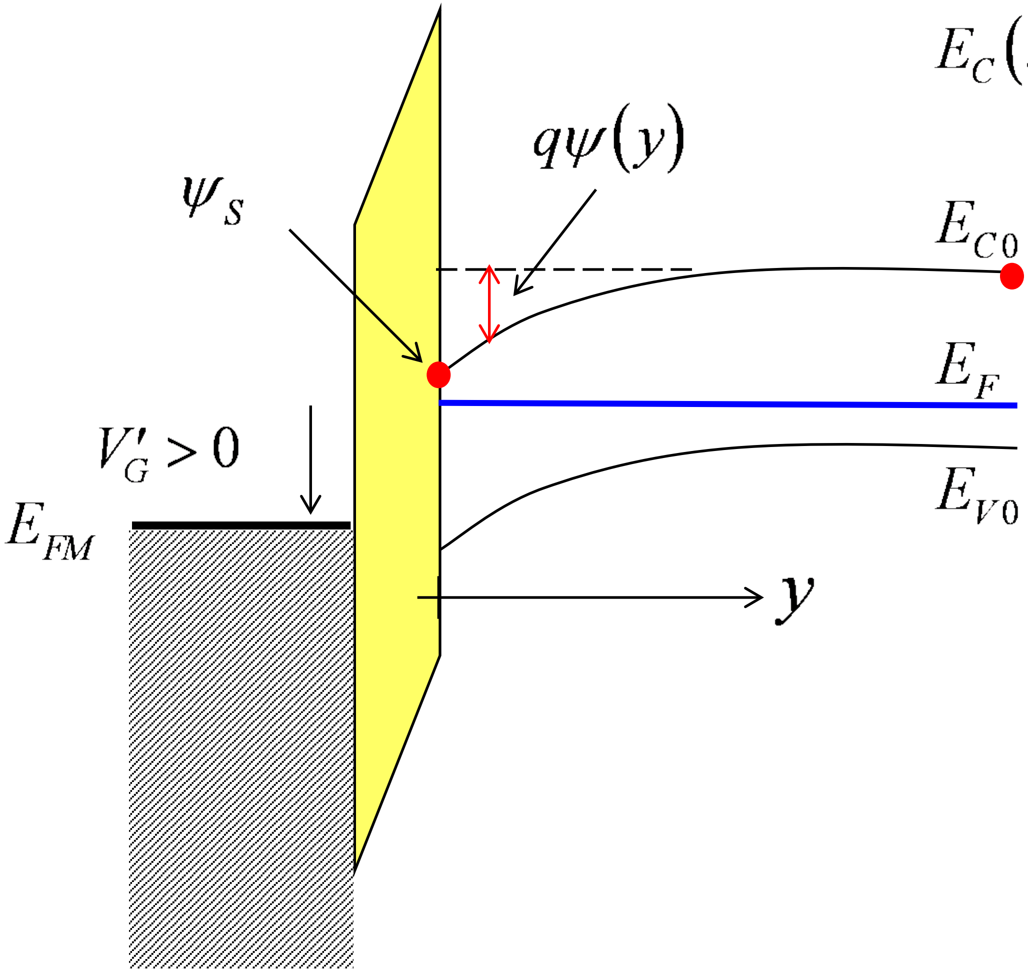


(V'_G: Ignore metal-semi workfunction differences for now.)

(Fermi levels line up at zero gate voltage.)

Applied gate voltage

surface potential



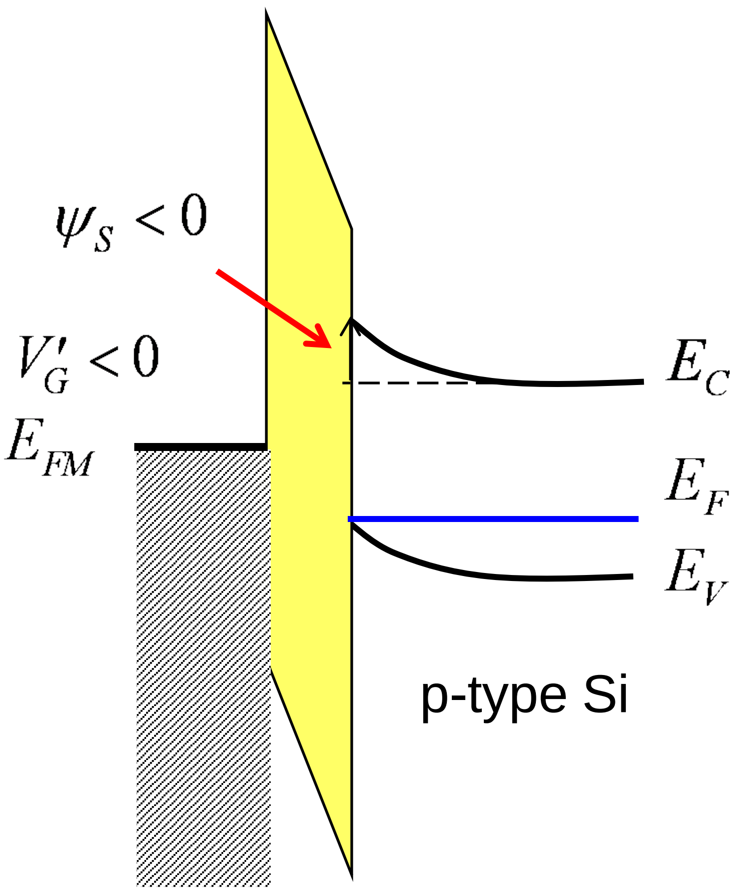
$$E_C(x \to \infty) = E_{C0}$$

$$\psi(y) = 0$$ (arbitrary reference)

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

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

$V'_G < 0$: "accumulation"



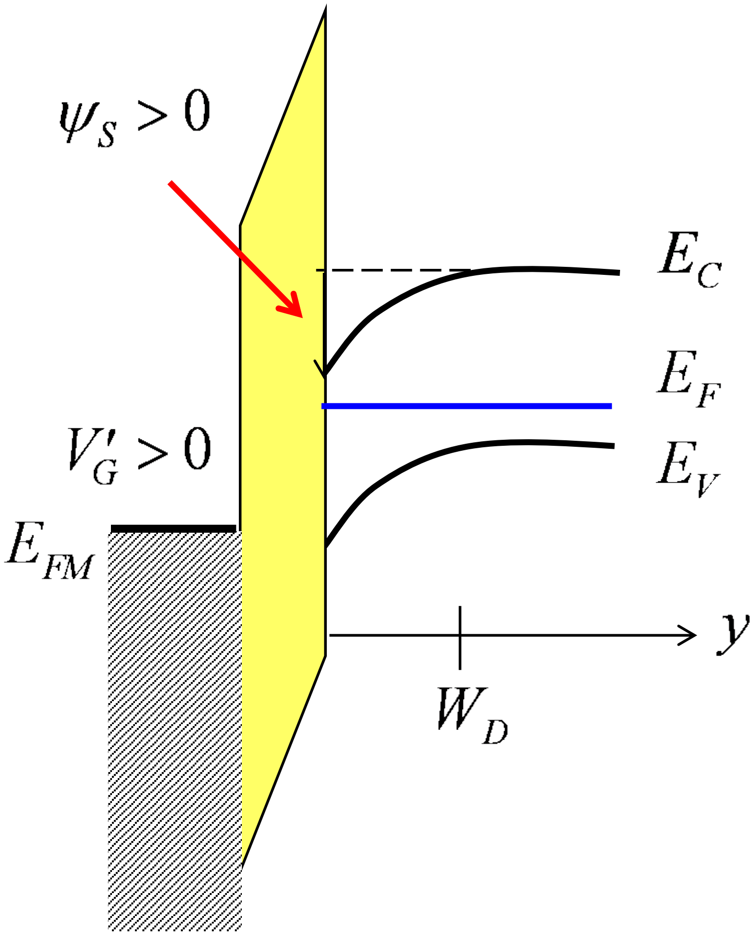
- bands bend up
- surface potential < 0
- hole density increases exponentially near the surface.

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

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

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

$V'_G > 0$: "depletion"



- bands bend down
- surface potential > 0
- space charge density:

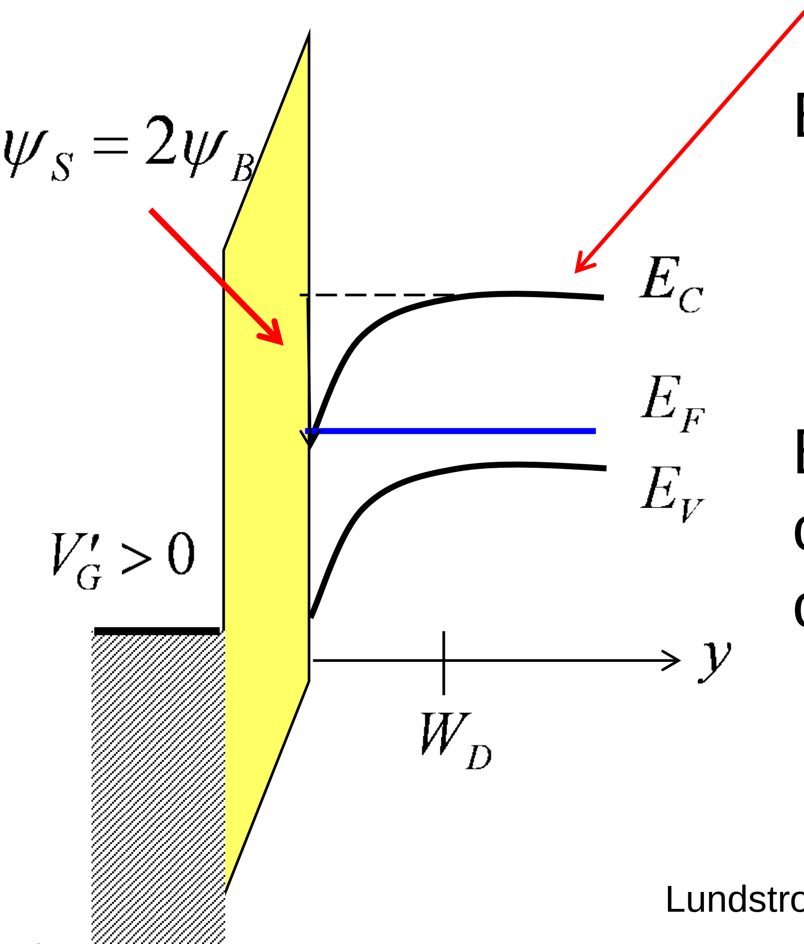
$$p_0(y) = N_V e^{(E_V(y)-E_F)/k_B T} \approx 0$$

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

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

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

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



Electron concentration in the bulk:

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

Electron concentration at the surface:

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

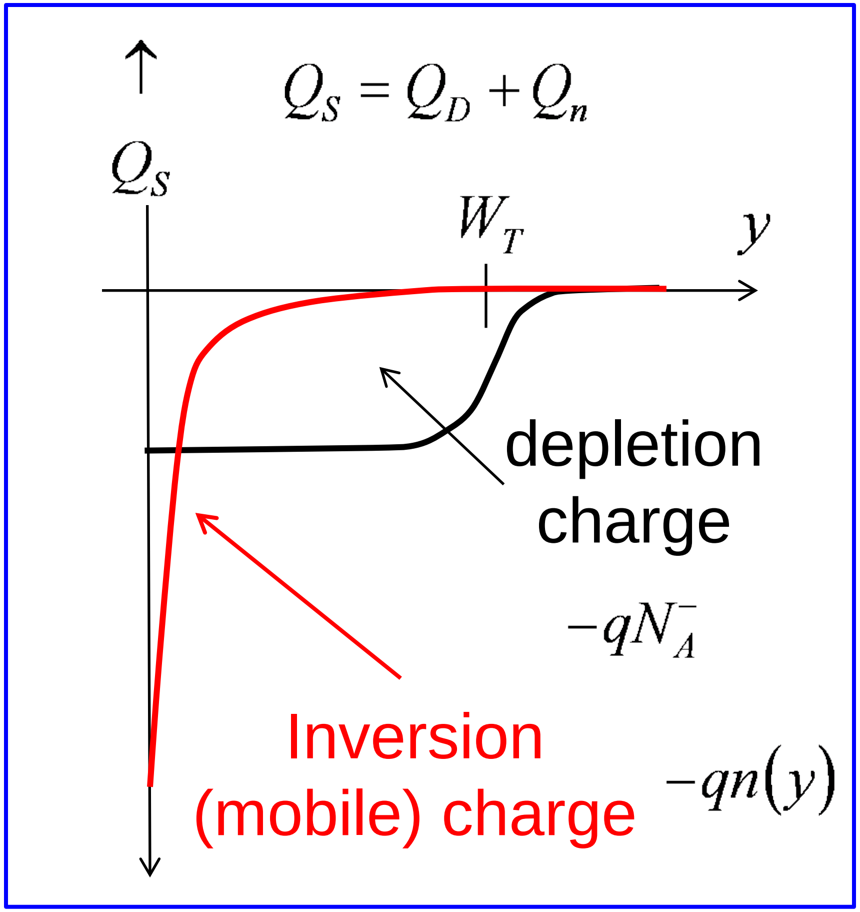
$$n_0(y=0) = n_B e^{q\psi_S / k_B T}$$

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

$$n_B e^{q\psi_S / k_B T} = N_A$$

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

$V'_G > V_T$: "inversion"



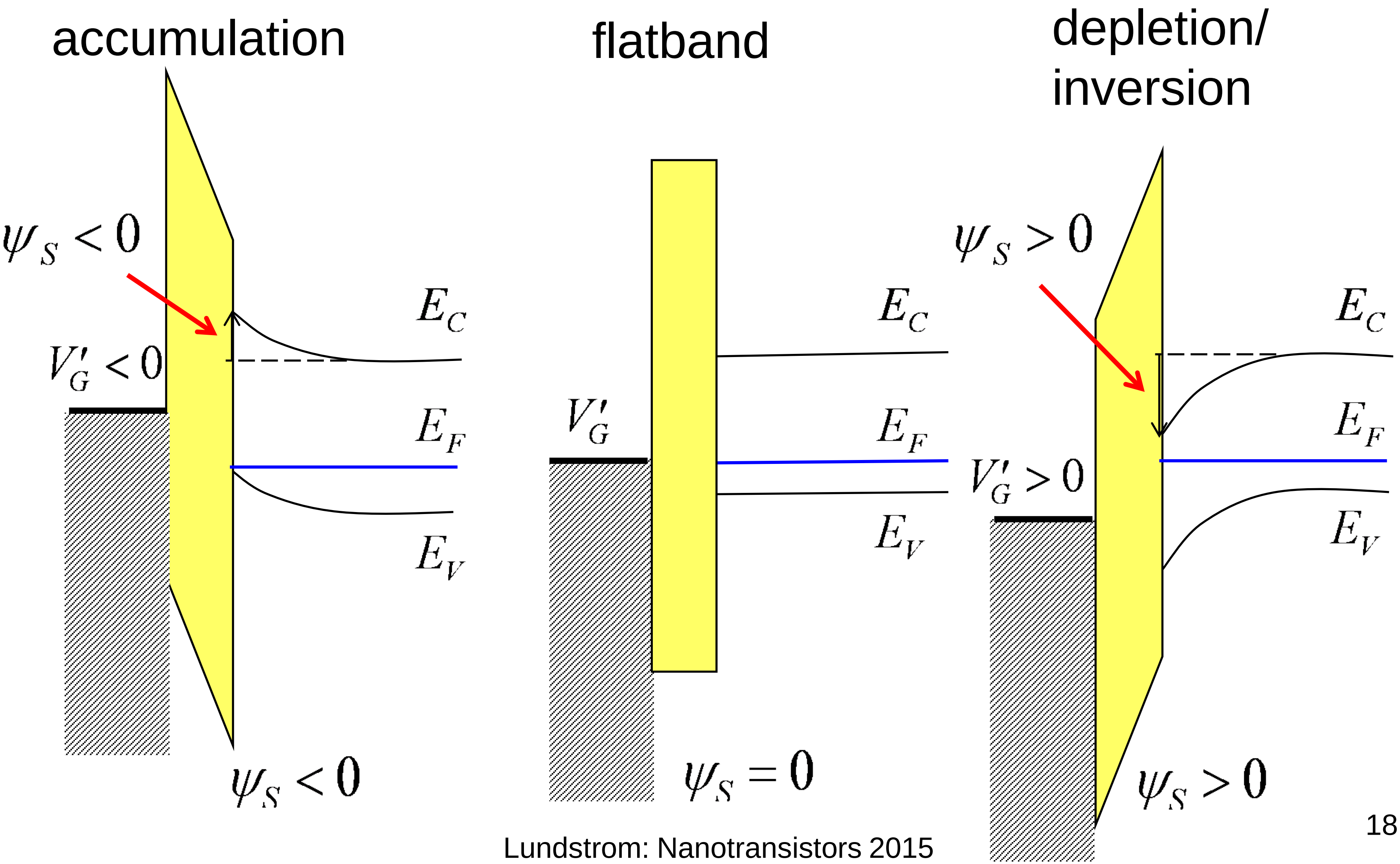
$$\psi_S = 2\psi_B \qquad \psi_B = \frac{k_B T}{q}\ln\left(\frac{N_A}{n_i}\right)$$

Hard to bend the band further.

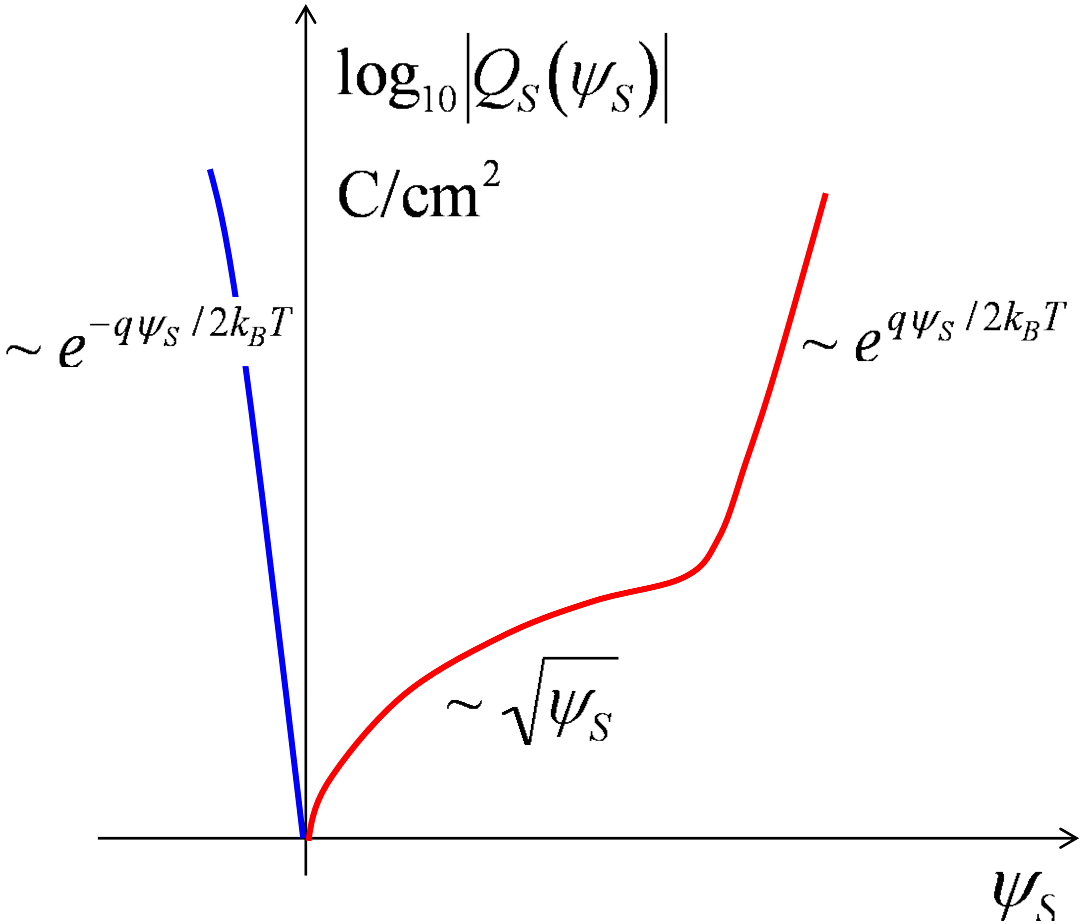
$$W_T = \sqrt{2\varepsilon_S\left(2\psi_B\right)/qN_A}$$

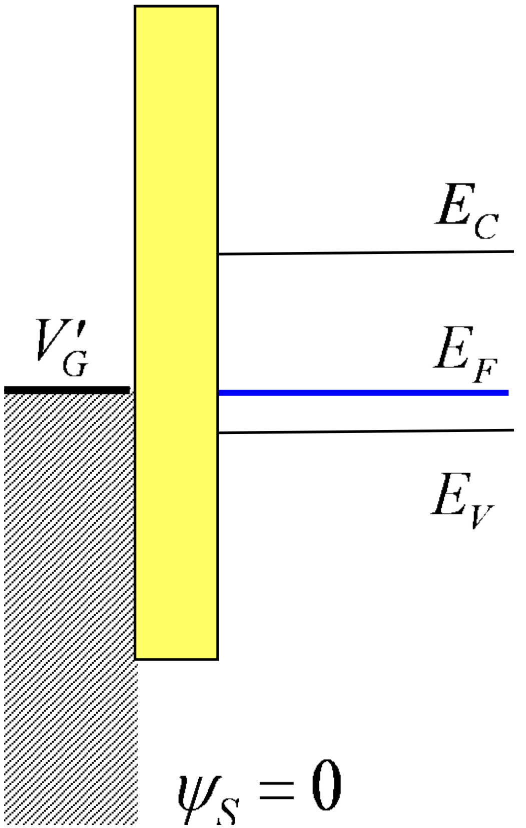
Electron charge piles up very near to the surface.

1D MOS electrostatics



MOS electrostatics





Exercise

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

Next: Lecture 2.2

The 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**.