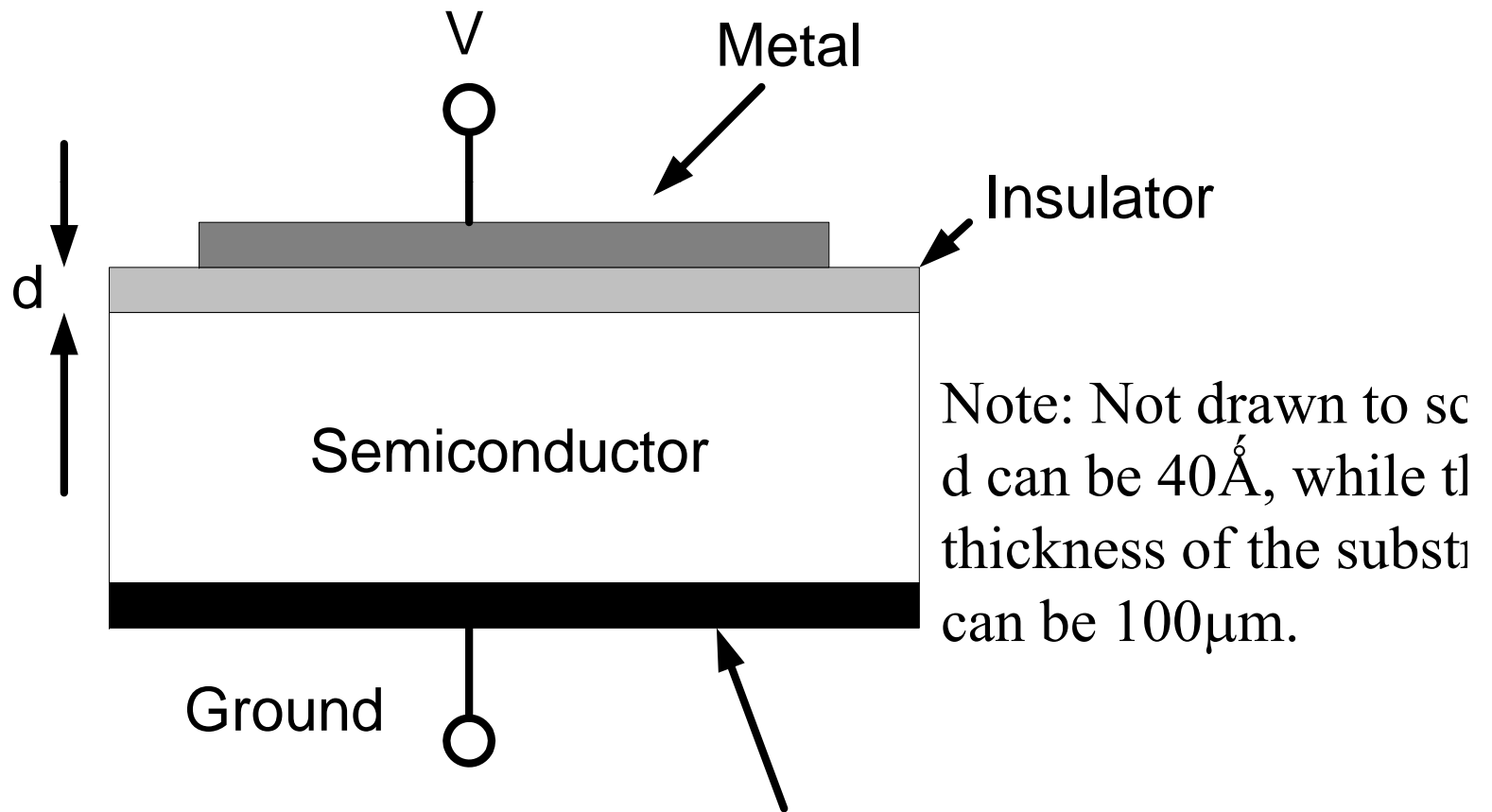


MOSFET

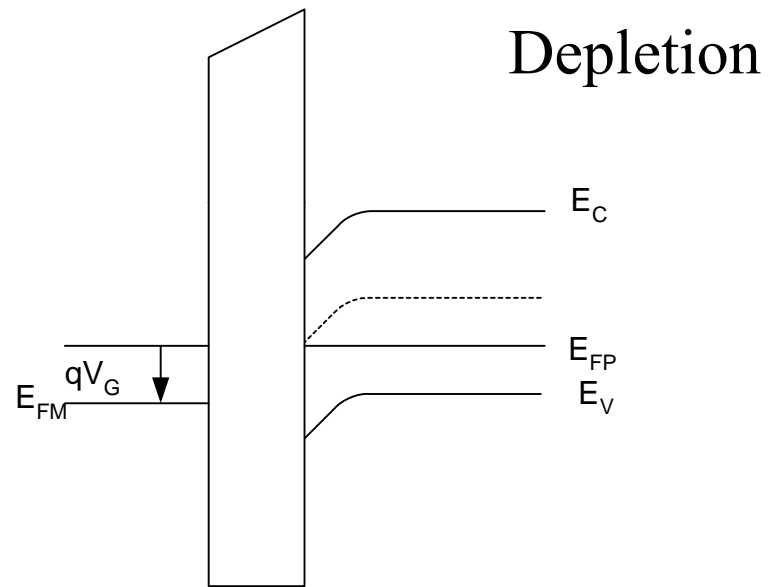
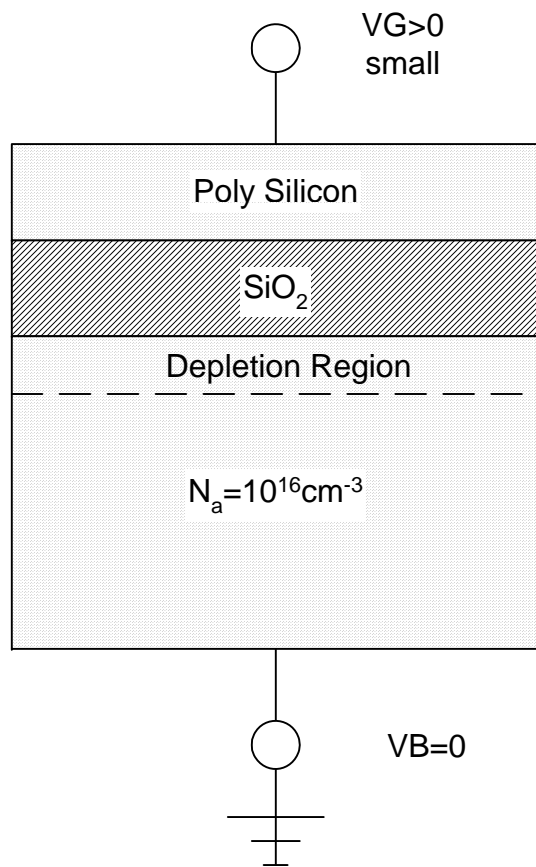
- Metal Insulator Semiconductor (MIS) transistor
- Insulated Gate Field Effect Transistor (IGFET)
- Majority Carrier Device.
- Transistor

2-D Cross Section of an MIS Capacitor

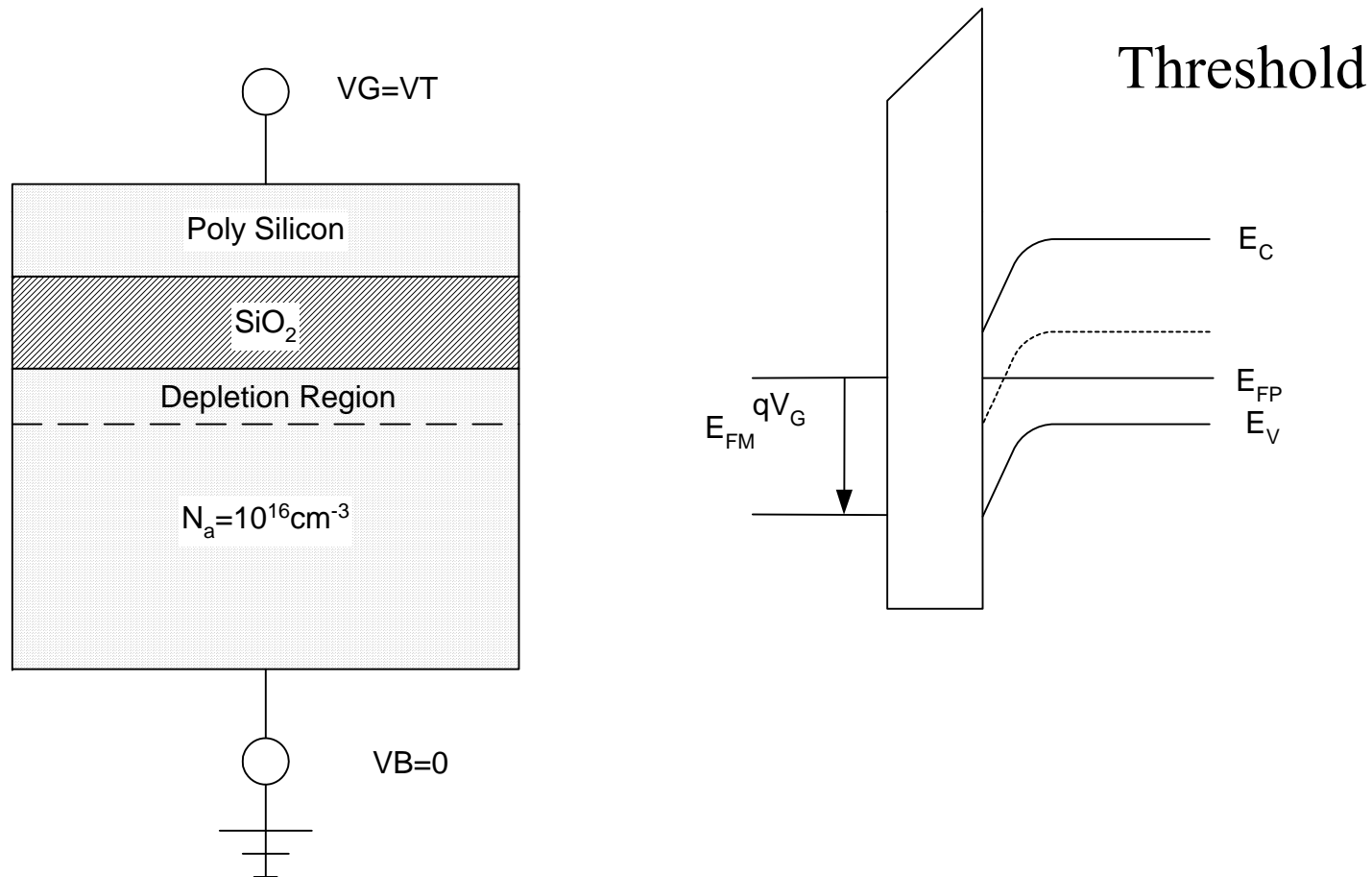


d and t_{ox} are used interchangeably. Ohmic Contact

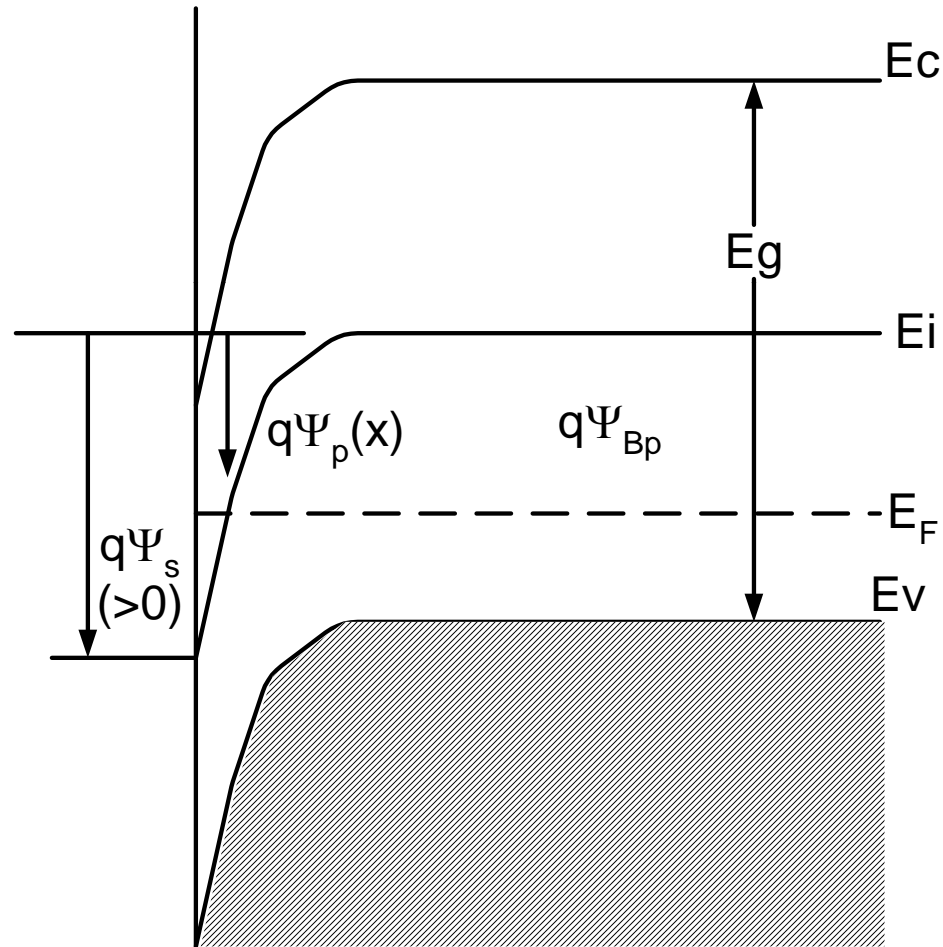
MOS System Under External Bias



MOS System Under External Bias



Detailed EGB for MIS



Basic Charge Model 1

P-Type

Total Charge Concentration

$$\rho = q \cdot (p_p - n_p - N_b)$$

Hole Concentration

Electron Concentration

Net Doping Concentration

Basic Charge Model 2

Far from the surface $\rho=0$

Near the surface: 3-D Poisson's Equation

$$\frac{d^2}{dx^2} \psi + \frac{d^2}{dy^2} \psi + \frac{d^2}{dz^2} \psi = \frac{-\rho}{\epsilon_{si}}$$

Assume no variation in the y or x directions

$$\frac{d^2}{dz^2} \psi = \frac{-q}{\epsilon_{si}} \cdot (p_p - n_p - N_b)$$

Basic Charge Model 3

N-Channel Device the quasi-Fermi level of holes can be assumed to be constant ($\Psi \geq 0$)

Fermi Potential

The diagram shows the equation $\frac{\Phi_F - \Psi}{U_T}$ in the center. An arrow points from the text 'Fermi Potential' to the Φ_F term in the numerator. Another arrow points from the text 'Intrinsic carrier concentration' to the n_i term in the numerator. A third arrow points from the text 'Thermal Voltage' to the U_T term in the denominator. The equation $p_p = n_i \cdot e$ is positioned between the 'Fermi Potential' and 'Intrinsic carrier concentration' labels, with an arrow pointing from it to the n_i term.

$$\frac{\Phi_F - \Psi}{U_T}$$

$$p_p = n_i \cdot e$$

Intrinsic carrier concentration

Thermal Voltage

$$kT/q$$

Basic Charge Model 4

Application of VS or VD brings electrons out of Equilibrium, denoted by the quasi-Fermi potential Φ_{Fn}

$$\Phi_{Fn} = \Phi_F + V$$

$$n_p = n_i \cdot e^{\frac{\psi - \Phi_F - V}{U_T}}$$

← Channel Voltage

Basic Charge Model 5

The doping concentration N_b is assumed constant in the channel., V_S , V_D , E_{ox} affects vanish

$$V = \Psi = 0$$

$$N_b = n_i \cdot \left(e^{\frac{\Phi_F}{U_T}} - e^{-\frac{\Phi_F}{U_T}} \right)$$

$$\Phi_F \gg U_T \quad \frac{\Phi_F}{U_T}$$

$$N_b = n_i \cdot e^{\frac{\Phi_F}{U_T}}$$

$$\Phi_F = U_T \cdot \ln \left(\frac{N_b}{n_i} \right)$$

Basic Charge Model 6

Electrons

Holes

Fixed depletion charge

$$\frac{d^2}{dz^2}\psi = \frac{q N_b}{\epsilon_{si}} \cdot \left(e^{\frac{\psi - 2 \cdot \Phi_F - V}{U_T}} - e^{-\frac{\psi}{U_T}} + 1 \right)$$

$$\frac{d^2}{dz^2}\psi = \frac{q N_b}{\epsilon_{si}} \cdot G(\psi, 2 \cdot \Phi_F, V)$$

Basic Charge Model 7

$$\frac{d^2}{dz^2} \psi = -\frac{d}{dz} E_Z = -\frac{d}{d\psi} E_Z \cdot \left(\frac{d}{dz} \psi \right) = E_Z \cdot \left(\frac{d}{d\psi} E_Z \right)$$

$$E_Z \cdot d = \frac{q \cdot N_b}{\epsilon_{si}} \cdot G(\Psi, 2 \cdot \Phi_F, V) d\psi$$

$$\int_0^{E_Z} E_Z dE_Z = \int_0^{\Psi} \frac{q \cdot N_b}{\epsilon_{si}} \cdot G(\Psi, 2 \cdot \Phi_F, V) d\psi$$

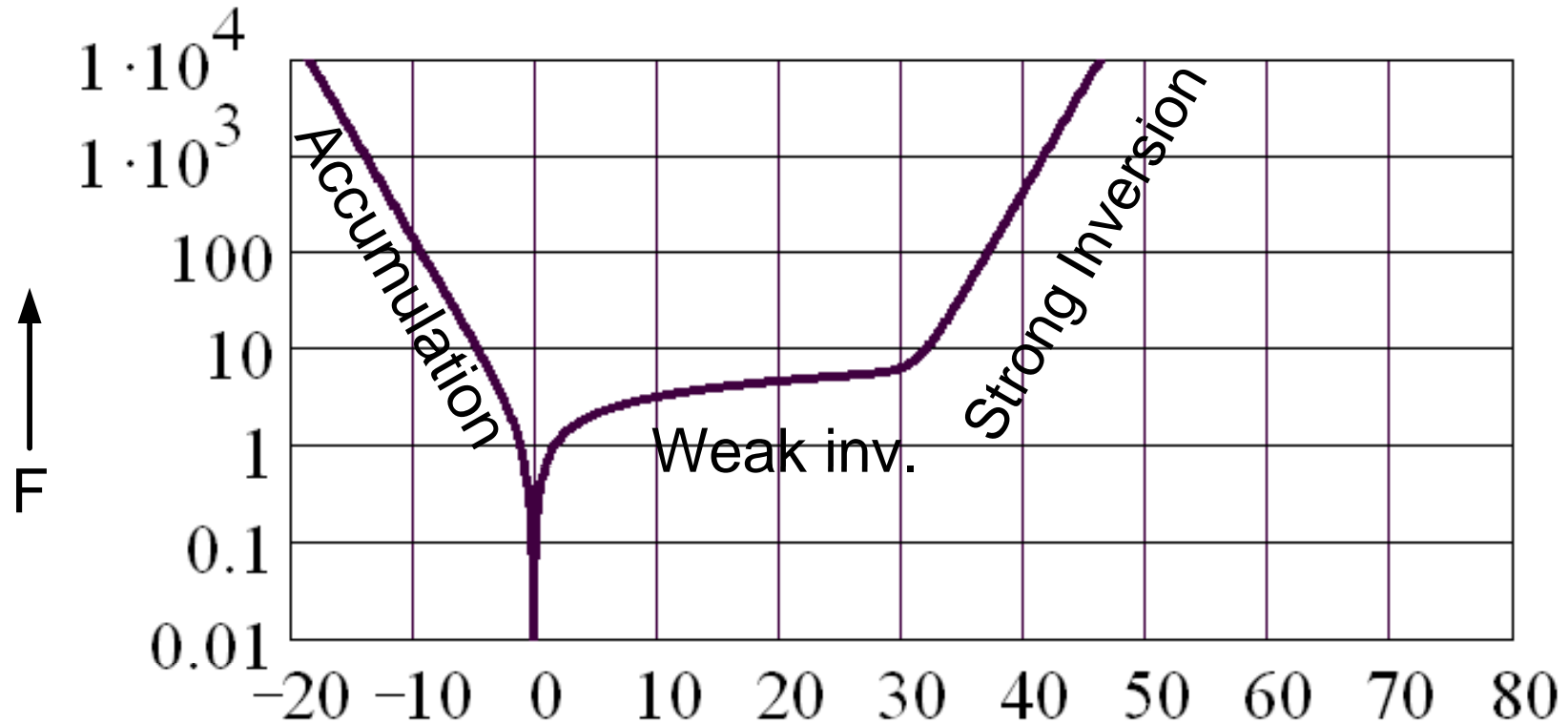
Basic Charge Model 8

$$E_Z = \text{sgn}(\psi) \cdot \frac{U_T}{L_D} \cdot F(\Psi, 2 \cdot \Phi_F, V)$$

$$L_D = \sqrt{\frac{\varepsilon_{\text{si}} \cdot U_T}{2 \cdot q \cdot N_b}}$$

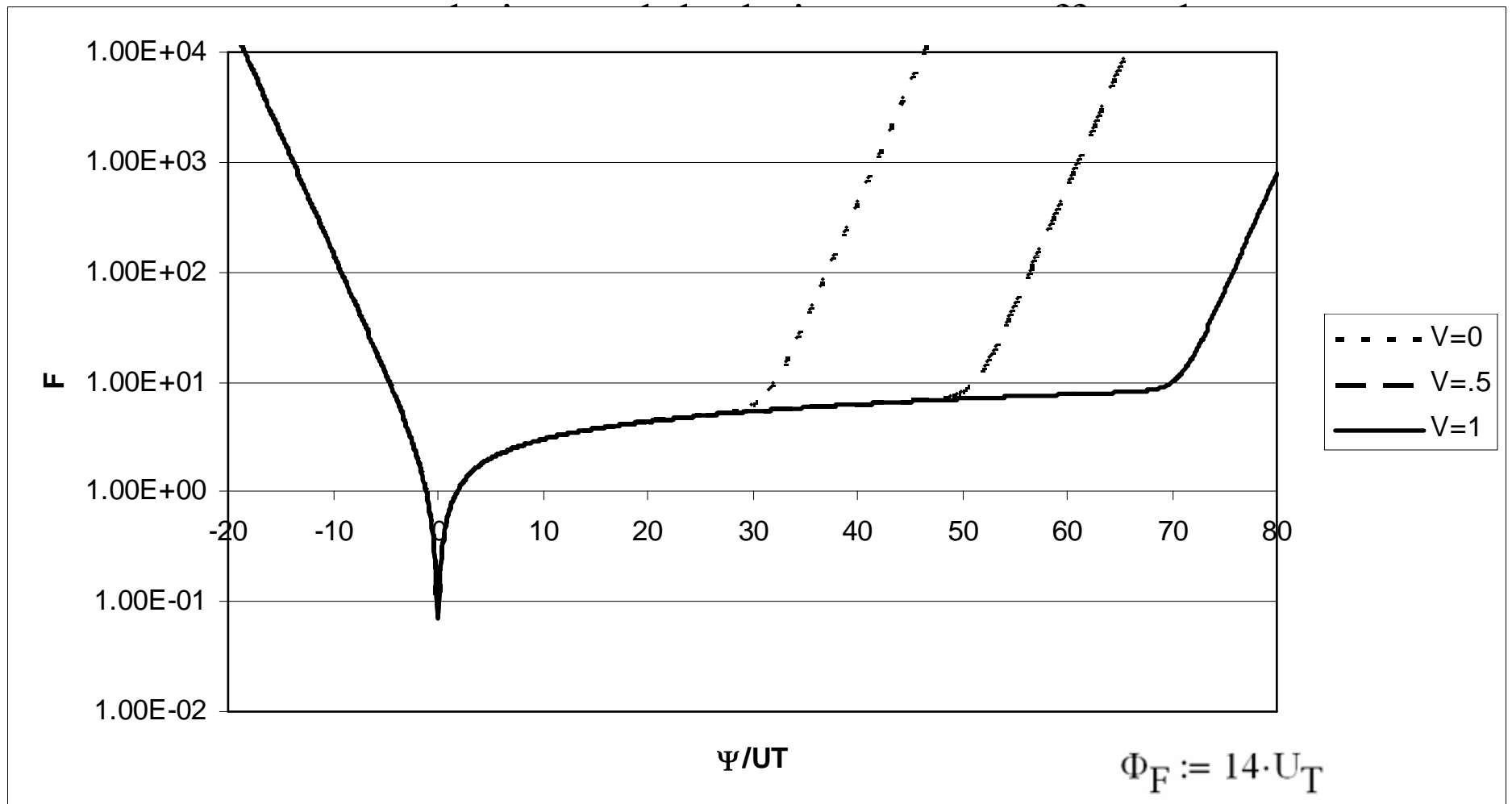
$$F(\Psi, 2 \cdot \Phi_F, V) = \sqrt{\left(e^{\frac{\psi}{U_T}} - 1 \right) \cdot e^{\frac{-(2 \cdot \Phi_F + V)}{U_T}} + e^{\frac{-\psi}{U_T}} - 1 + \frac{\psi}{U_T}}$$

Basic Charge Model 9



$$\Phi_F := 14 \cdot U_T \quad \frac{\psi}{U_T}$$

Notice that as the channel voltage increases, it takes more surface potential to reach strong inversion, and



Apply Gauss's Law

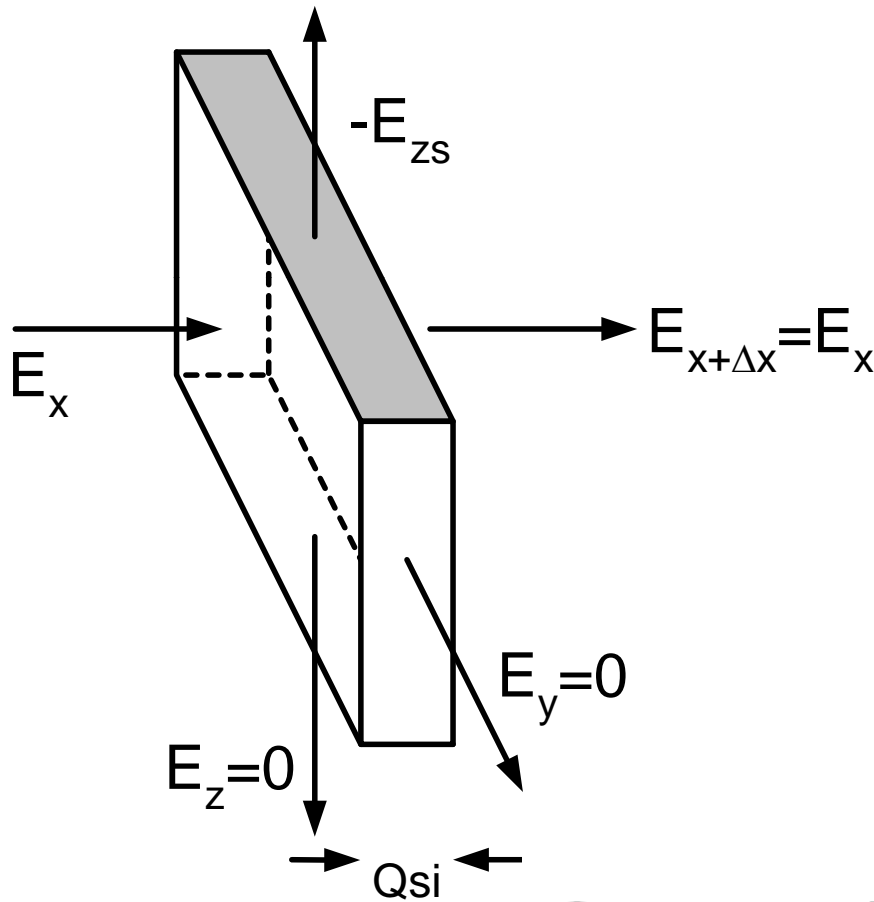
$\Psi_s < 0$ Accumulation of Holes

$\Psi_s = 0, F = 0$, Flatband

$0 < \Psi_s \ll 2\Phi_F + V$ Weak inversion

(There is a small concentration of electrons.)

$\Psi_s > 2\Phi_F + V$ Strong Inversion



$$Q_{si} = -\epsilon_{si} \cdot E_z = \frac{-\epsilon_{si} \cdot U_T}{L_D} \cdot \frac{U_T}{L_D} \cdot F(\Psi, 2 \cdot \Phi_F, V)$$

We need to relate the Gate Voltage (V_G) to the Surface Potential (Ψ)

The Electric Field at the upper face:

$$E_{OX} = \frac{V_G - \Phi_{ms} - \Psi_s}{t_{OX}}$$

Metal Semiconductor Workfunction

Fixed oxide Charge

$$Q_{si} + Q_{fc} = -\epsilon_{OX} \cdot E_{OX} = -C_{OX} \cdot (V_G - \Phi_{ms} - \Psi_s)$$

$$C_{OX} = \frac{\epsilon_{OX}}{t_{OX}}$$

Surface potential

Capacitance

$$W_m = 2 \left[\frac{\epsilon_s kT \ln(N_a / n_i)}{q^2 N_a} \right]^{\frac{1}{2}}$$

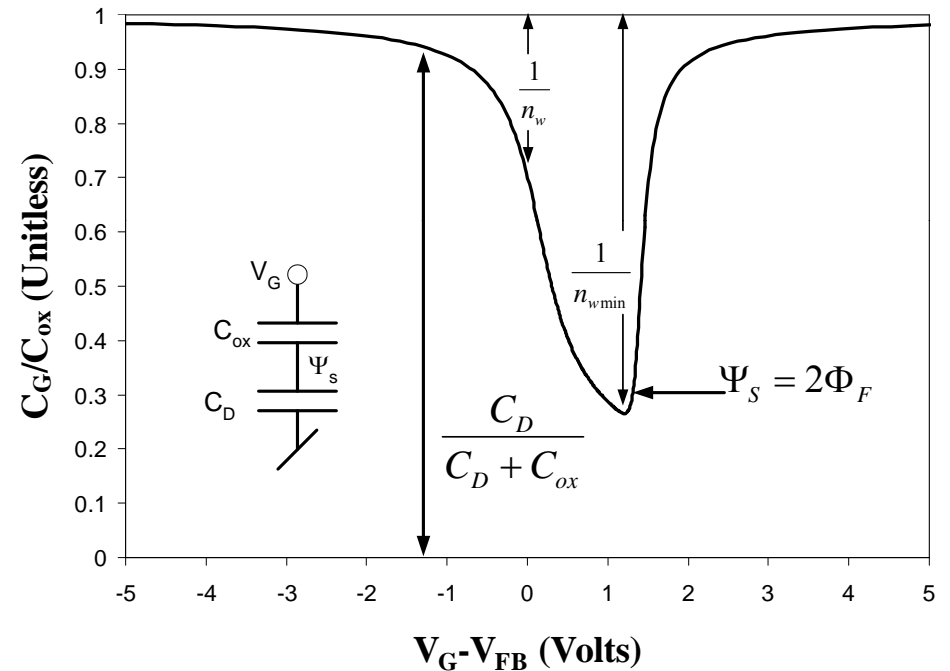
$$\phi_F = \frac{kT}{q} \ln(N_a / n_i)$$

$$Q_d = -2(\epsilon_s q N_a \phi_F)^{\frac{1}{2}}$$

$$V_T = -\frac{Q_d}{C_i} + 2\phi_F$$

$$C_i = \frac{\epsilon_i}{d}$$

$$C_d = \frac{\epsilon_s}{W}$$



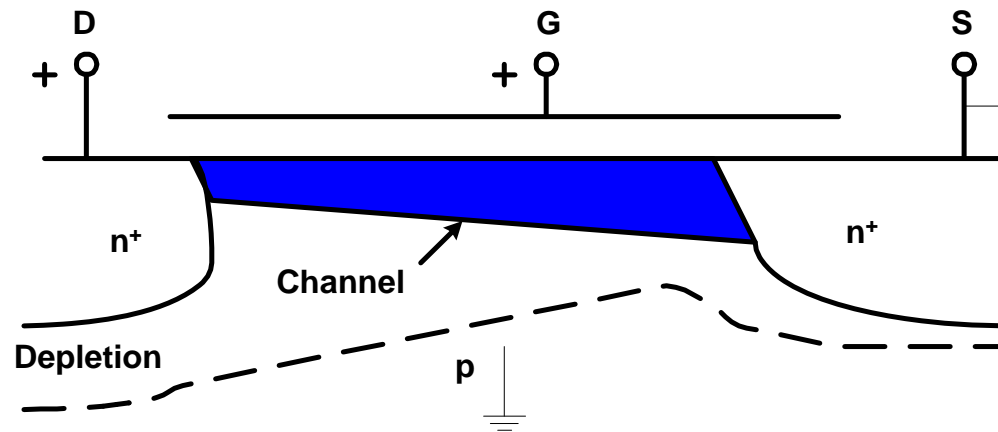
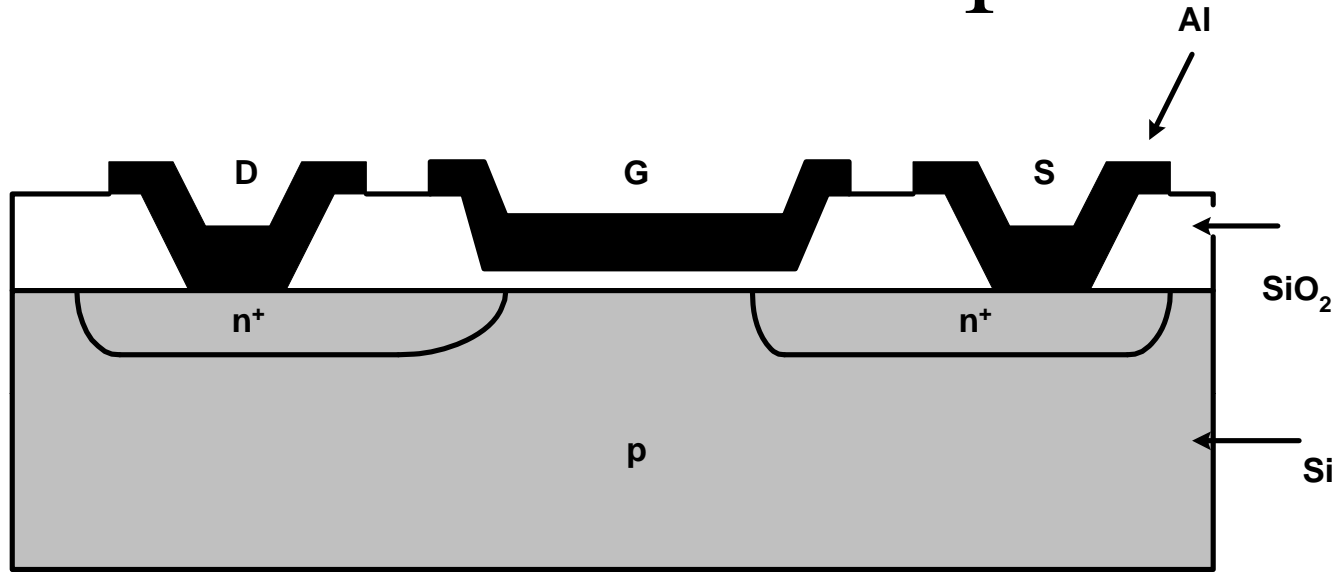
Basic MOSFET operation

- n-channel
 - A positive voltage is applied to the gate thus attracting electrons which form a channel between the two n^+ source and drain regions
- p-channel
 - A negative voltage is applied to the gate thus attracting hole which form a channel between the two p^+ source and drain regions

Basic MOSFET operation

- n-channel
 - Requires a gate voltage more positive than V_T to create an electron channel.
- p-channel
 - Requires a gate voltage more negative than V_T to create an electron channel.

Basic MOSFET operation



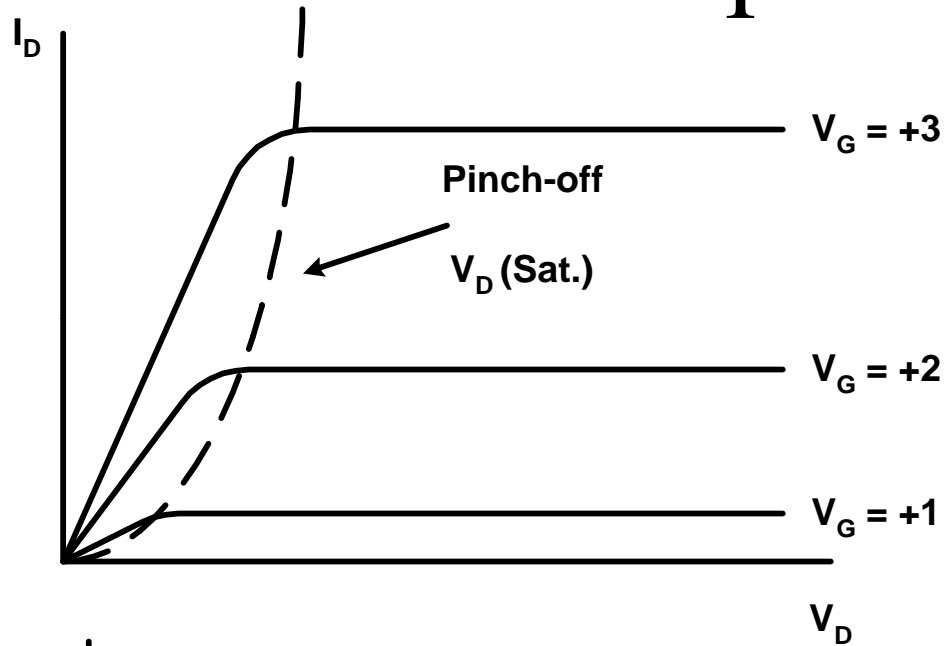
Basic MOSFET operation

- depletion mode
 - Already have a channel with zero gate voltage and a negative voltage is required to turn it off.
- enhancement mode
 - Requires a gate voltage larger than V_T to induce a channel.

Basic MOSFET operation

- PMOS
 - a p-type channel is created in a n-type substrate.
- NMOS
 - an n-type channel is created in a p-type substrate.

Basic MOSFET operation



Examples

- Solve Example 8-1 except $N_a=1 \times 10^{17} \text{cm}^{-3}$
- Solve Example 8-2 except use a 50\AA SiO_2 layer.