# FET Example

An n-channel Si JFET with $N_a = 10^{18}\,cm^{-3}$ in the $p^+$ gate region and $N_d = 10^{16}\,cm^{-3}$ in the channel has $a = 1\,\mu m$. $\mu_n = 1{,}000\,cm^2V^{-1}s^{-1}$. $\frac{Z}{L} = 10$.

What is the pinch-off Voltage?

$$V_p = \frac{q a^2 N_d}{2\epsilon} = \frac{1.6\times10^{-19}C \times 10^{-8} cm^2 \times 10^{16} cm^{-3}}{2\times 11.8 \times 8.84 \times 10^{-14} \frac{F}{cm}} = \underline{7.66\ V}$$

Note: If we take contact potential $V_0$ into account, then threshold Voltage $\underline{V_T = V_p - V_0}$

$V_T = V_p - V_0$

$V_0 =$ $\qquad$ $=$ $\qquad$ $=$

$V_T =$

What is conductance $G_o$?

$G_o =$

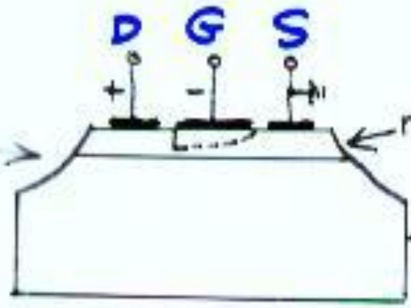
$\rho =$ $=$ $=$

$G_o =$ $= 2 \times 10^{-4}\,cm \times 1.6 \times 10^{-19}\,C \times 10^{3}\,\frac{cm^2}{V\text{-}s} \times 10^{16}/cm^3 \times 10$

$=$

# MESFET

## Deplete Channel with Reverse-Biased Schottky Barrier




Advantages: higher speed, ease of fabrication

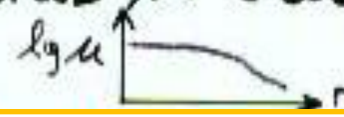
→ $\mu(GaAs) > \mu(Si)$

→ Easy to define pattern for metal deposition
No diffusion involved → can achieve tight geometric tolerances

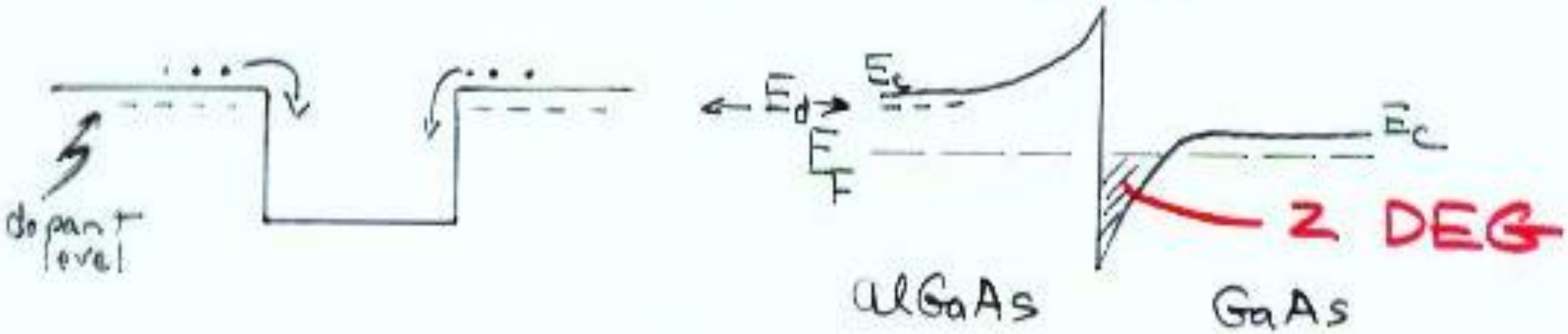
→ Can achieve very short gate lengths

To get $G_0 = 2aZ/\rho L = \frac{2A\sigma}{L} = \frac{2A}{L} ne\mu$ large, aim for and .

But increasing degrades $\mu$ (due to



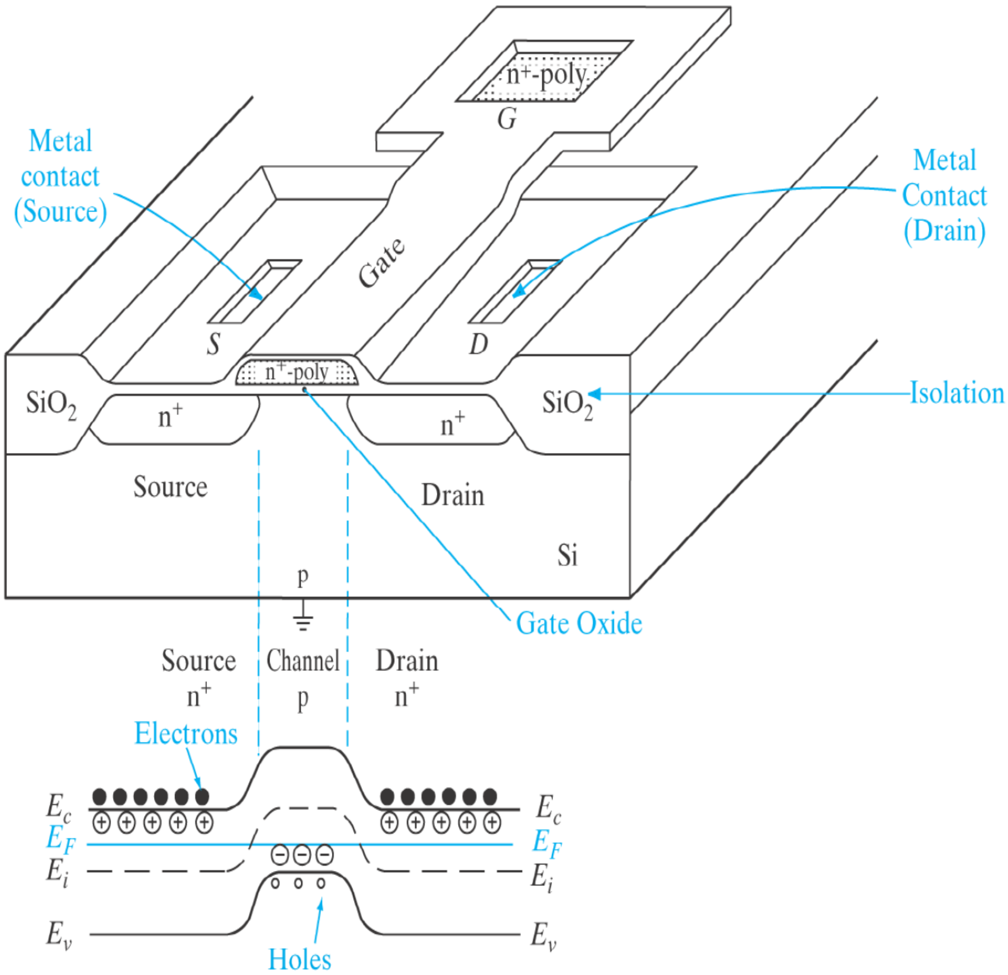

Solution: Put




Can get $10^{12}\ \mathrm{cm}^{-2}$ in < 100 Å layer with $\mu \rightarrow$ 2,000,000! (T = 4°K)

→ Very high

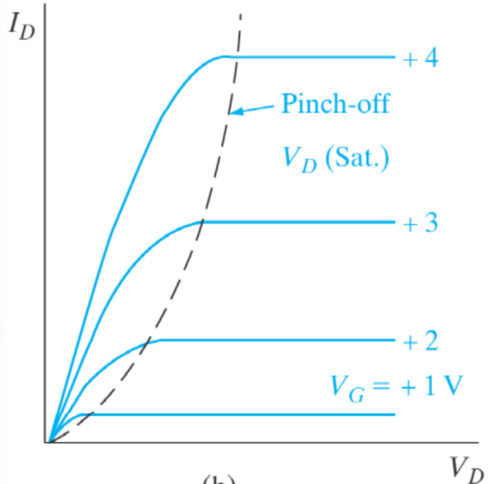
# MOSFET




No current flow without channel between source and drain.

+ Gate induces - charge under gate and creates channel

(Vary conductance, G)



(b)

Threshold Voltage $V_T$

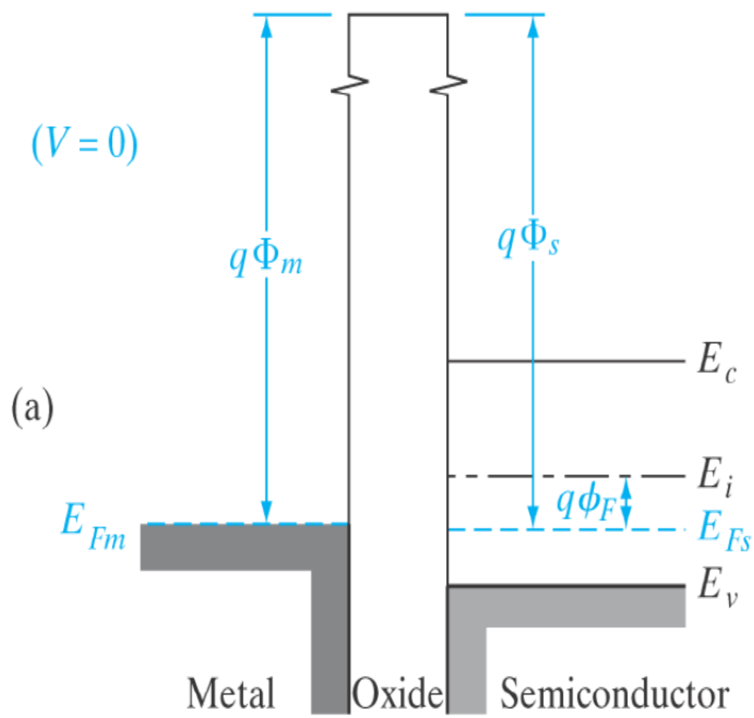
= minimum voltage to induce a channel

Enhancement Mode - Transistor "normally off"

Depletion Mode - Transistor - "normally on"

# MOS Capacitor

Metal and semiconductor are the two capacitor plates.

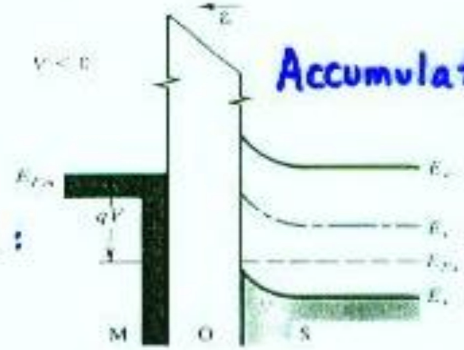



Ideal case: $\phi_m = \phi_s$

→ no field across oxide for $V=0$

("modified" $\phi$ referenced to oxide $E_c$ instead of $E_{vac}$.)

Accumulation



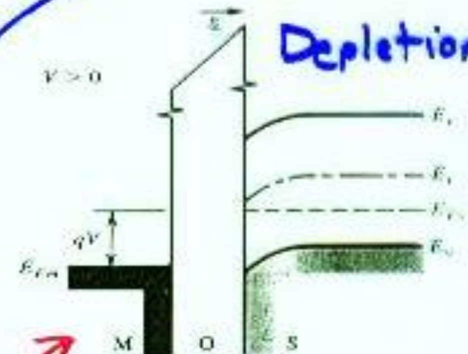
Apply negative V to metal:

- charge on metal

+ charge on semiconductor

- Bands bend up in semiconductor with ⊖V since $-E_F + E_i$ increases (more holes near surface)
- Metal $E_F$ moves up with ⊖V

Depletion



- $\phi_m$ and $\phi_s$ stay the same, so oxide conduction band tilts.

$$\mathcal{E}(x) = \frac{1}{q}\frac{dE_i}{dx}$$

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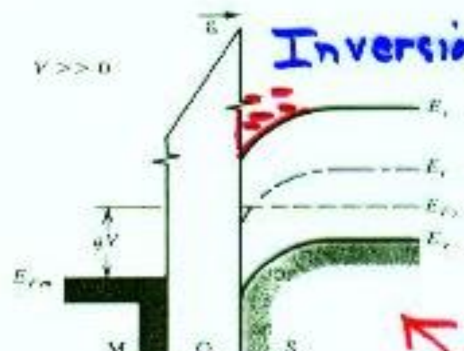
- Bands bend down in semiconductor with ⊕V since $E_F$ closer to $E_i$ and more electrons near surface.
- Metal $E_F$ moves down with ⊕V.
- Very positive voltage to metal: Inversion!

Inversion



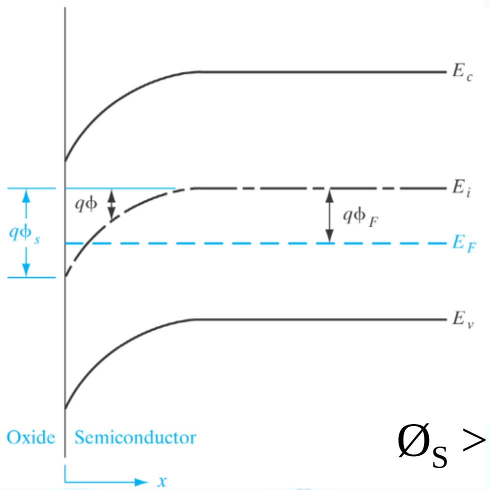
Accumulation: $p = n_i e^{(E_i - E_F)/kT}$

$E_F$ closer to $E_V$: $p$ increases

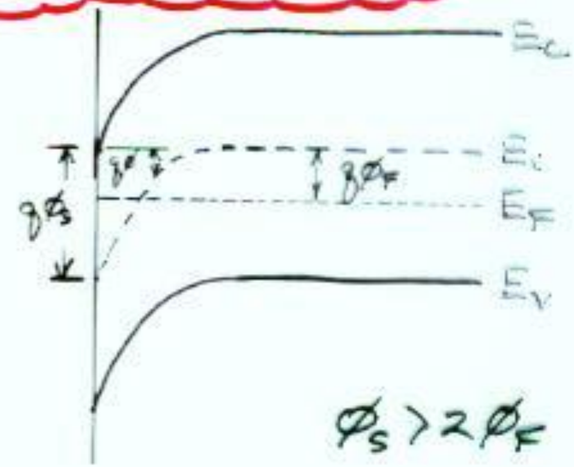
Depletion: $E_F$ farther from $E_V$: $p$ decreases

Inversion: $E_F$ crosses $E_i$: $n > p$

Key to MOS Transistor Action




$\varnothing_S > \varnothing_F$




Definition for strong inversion: Surface as n-type as substrate is p-type

$\phi_s$ (inverted) $= 2\phi_F = 2$ $\boxed{\phantom{xx}}$

Need one $\phi_F$ to bend bands so $E_i = E_F$

Need additional $\phi_F$ to bend bands further so $E_F - E_i = \phi_F$

Electrons: $n = n_i\, e^{(E_F - E_i)/kT} = n_0\, e^{q\phi/kT}$

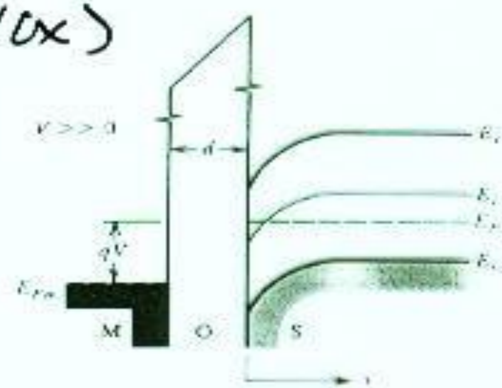
Holes: $p = n_i\, e^{(E_i - E_F)/kT} = p_0\, e^{-q\phi/kT}$

Put $n$ and $p$ in charge density:

$\rho(x) = q(N_d^+ - N_a^- + p - n)$ and

$$\frac{\partial^2 \phi(x)}{\partial x^2} = -\frac{\rho(x)}{\epsilon_s} \quad \text{(poisson's equation)}$$

Solve for $Q(x)$, $\mathcal{E}(x)$, and $V(x)$



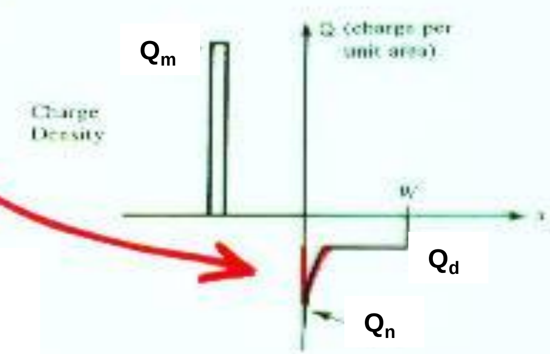

Charge balance: $Q_m = -Q_s$

$= qN_aW - Q_n$

positive $Q_m$ (metal) vs.

negative $Q_s$ (semiconductor)(depletion layer)

and negative $Q_n$ (inversion region)



# MOS Capacitor $\phi$, $\mathcal{E}$, and $Q_s$

$$\frac{\partial^2 \phi}{\partial x^2} = -\frac{\rho(x)}{\epsilon_s} \quad \text{Poisson's Eq. (S+B 6.19)}$$

$$\rho(x) = q\,(N_d^+ - N_a^- + p - n) \quad \text{Charge neutrality}$$

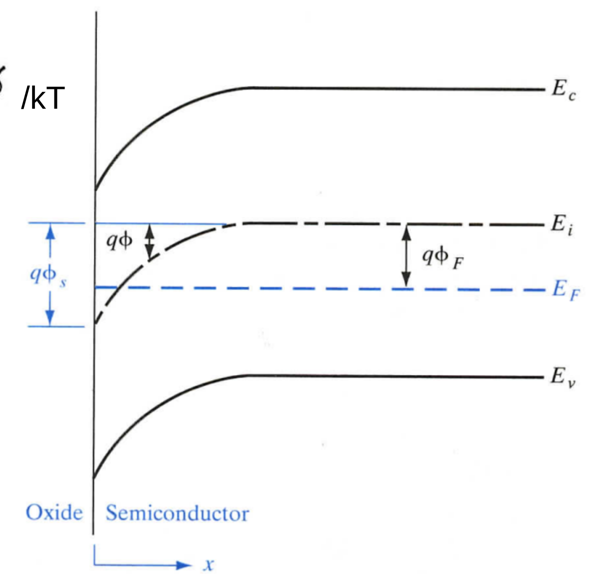
$$n_o = n_i\, e^{(E_F - E_i)/kT} = n_i\, e^{-q\phi_F/kT}$$

at strong inversion

For any band bending depth,

$$n = n_i e^{-q(\phi_F - \phi)/kT} = n_o e^{q\phi/kT}$$

and $p_o = n_i e^{+q\phi_F/kT}$ & $p = p_o e^{-q\phi/kT}$



$$-\frac{\rho(x)}{\epsilon_s} = \frac{-q}{\epsilon_s}\left(n_0 - p_0 + p_0 e^{-q\phi/kT} - n_0 e^{q\phi/kT}\right)$$

$$\frac{\partial^2 \phi}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial \phi}{\partial x}\right) = \frac{-q}{\epsilon_s}\left[p_0\left(e^{-q\phi/kT}-1\right) - n_0\left(e^{q\phi/kT}-1\right)\right]$$

Integrate $-\frac{\partial \phi}{\partial x} = \mathcal{E}$ from bulk (where $\mathcal{E}=0$) to surface

$$\int_0^{\partial\phi/\partial x}\left(\frac{\partial \phi}{\partial x}\right) d\left(\frac{\partial \phi}{\partial x}\right) = \left(\frac{\partial \phi}{\partial x}\right)^2 \Big/ 2 = \frac{\mathcal{E}^2}{2}$$

$$= \frac{-q}{\epsilon_s}\int_0^{\phi}\left[p_0\left(e^{-q\phi/kT}-1\right) - n_0\left(e^{q\phi/kT}-1\right)\right] d\phi$$

$$= \frac{-q}{\epsilon_s}\left[p_0\left(\frac{-kT}{q}e^{-q\phi/kT}-\phi\right) - n_0\left(\frac{kT}{q}e^{q\phi/kT}-\phi\right)\right]\Bigg|_0^{\phi}$$

$$\frac{\mathcal{E}^2}{2} = \frac{kT p_0}{\epsilon_s}\left[\left(e^{-q\phi/kT} + \frac{q\phi}{kT} - 1\right) + \frac{n_0}{p_0}\left(e^{q\phi/kT} - \frac{q\phi}{kT} - 1\right)\right]$$

$$\mathcal{E}_s = \frac{\sqrt{2}\,kT}{q L_D}\left[\left(e^{-q\phi_s/kT} + \frac{q\phi_s}{kT} - 1\right) + \frac{n_0}{p_0}\left(e^{q\phi_s/kT} - \frac{q\phi_s}{kT} - 1\right)\right]^{1/2}$$

(Surface)

At x = 0 (surface),
$\varnothing = \varnothing_S$

$$L_D = \sqrt{\frac{\epsilon_s kT}{q^2 p_0}}$$ Debye Screening Length

Important Semiconductor Concept!

From Gauss' Law,
integrated space charge / unit area = $Q_s$
= Displacement $D = -\epsilon_s \mathcal{E}_s$

$$\mathcal{E}_s = \frac{\sqrt{2kT}}{q L_D}\left[\left(e^{-q\phi_s/kT} + \frac{q\phi_s}{kT} - 1\right) + \frac{n_o}{p_o}\left(e^{q\phi_s/kT} - \frac{q\phi_s}{kT} - 1\right)\right]^{1/2}$$

(Surface)

$$Q_S = -\,\varepsilon_s\,\mathcal{E}$$

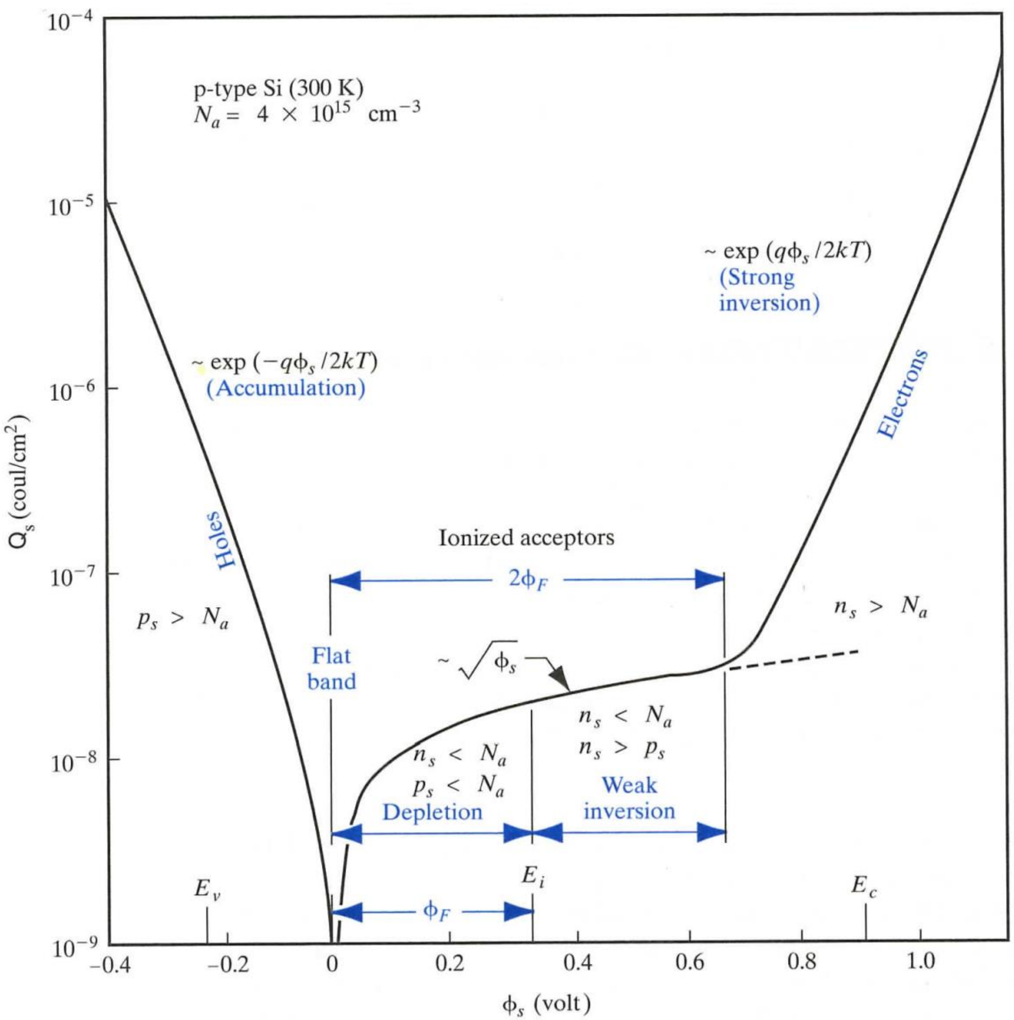
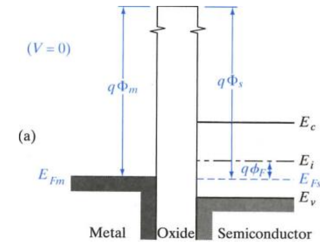
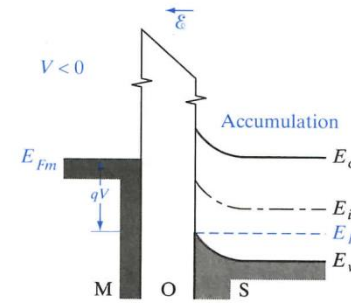



**Figure 6–14**
Variation of space-charge density in the semiconductor as a function of the surface potential $\phi_s$ for p-type silicon with $N_a = 4 \times 10^{15}$ cm$^{-3}$ at room temperature. $p_s$ and $n_s$ are the hole and electron concentrations at the surface, $\phi_F$ is the potential difference between the Fermi level and the intrinsic level of the bulk. (Garrett and Brattain, Phys. Rev., 99, 376 (1955).)

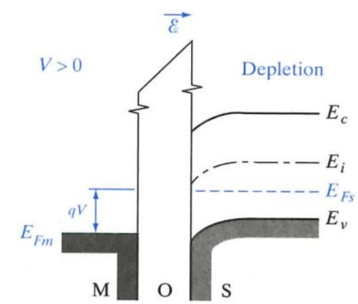
Ø = 0 (flat band): $Q_S = 0$



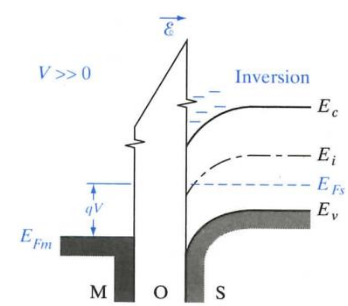

Ø < 0 (accumulation):
$Q_S \sim e^{(-q\,Ø/kT)}$
Increases with neg. Ø




Ø > 0 (depletion):
$Q_S \sim (n_0/p_0)e^{(q\,Ø/kT)}$
$Q_S \sim \sqrt{Ø_s}$
Increases with pos. Ø




Ø >> 0 (inversion):
$Q_S \sim e^{(q\,Ø/kT)}$
Increases with pos. Ø



Voltage: $V = V_i + \phi_s$

across insulator + semiconductor band bending

$$V_i = -\frac{Q_s d}{\epsilon_i} = -\frac{Q_s}{C_i}$$ ← insulator capacitance

$$W = \left[\frac{2\epsilon_s \phi_s}{q N_a}\right]^{1/2}$$ reaches maximum with strong inversion voltage

$$W_{max} = \left[\frac{2\epsilon_s \phi(\text{inv.})}{q N_a}\right]^{1/2}$$

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

We can calculate since we know all terms.