# MOSFET Example:

What is maximum depletion width for ideal MOS capacitor on p-type Si doped with $N_a = 10^{15}\ cm^{-3}$ ?

Solve for $\phi_F =$

$$= 0.0259\ V \ln \frac{10^{15}}{1.5\times10^{10}} = 0.0259\,(8.80)$$

$$= \underline{0.23\ V}$$

Solve for $W_m = 2\sqrt{\dfrac{\epsilon_s \phi_F}{q N_a}}$

For Si, $\epsilon_s = K\epsilon_0 = 11.8 \times 8.85 \times 10^{-14}\,F/cm$

$$W_m = 2\left[\frac{(11.8)(8.85\times10^{-14}\,F/cm)(0.23)V}{(1.6\times10^{-19}\,C)(10^{15}\,cm^{-3})}\right]^{1/2}$$

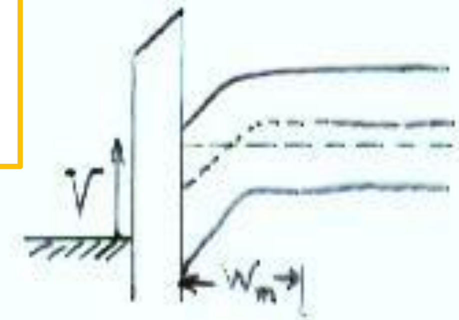
=

=

Lower doping increases $W_m$.

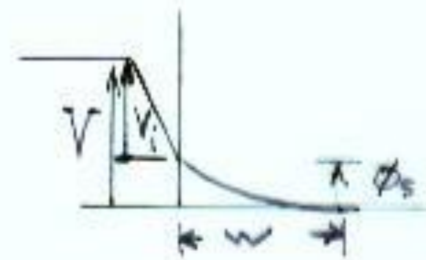
# MOS Capacitance - Voltage

$$Q_d = -qN_aW_m =$$




$$V = V_i + \phi_s$$

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




Applied voltage must be high enough to create $Q_d$ plus the surface potential $\phi_s$ (inverted).

$V_T$ = minimum voltage to achieve strong inversion*

Very Important for MOS transistors

Capacitance-voltage depends on whether accumulation, depletion, or inversion.

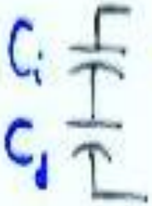
*(real case: add $\phi_m - \phi_s$ term)

V negative: Accumulation — looks like parallel plate capacitor

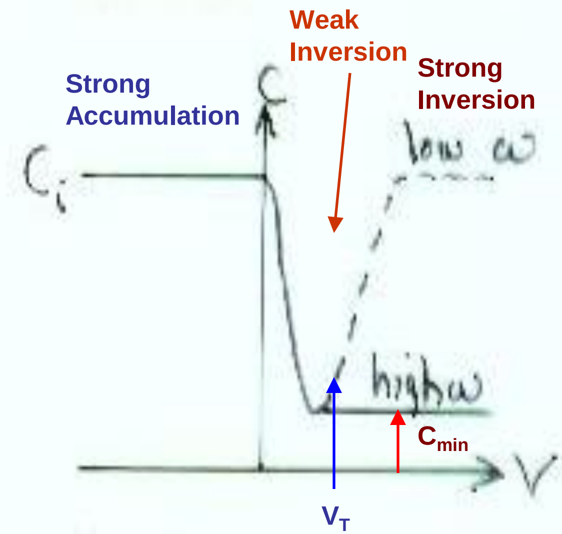
$C_i = \epsilon_i / d$ dominates.

V positive: Depletion — add depletion layer $C_d = \frac{\epsilon_s}{W}$

in series with $C_i$




Total C =

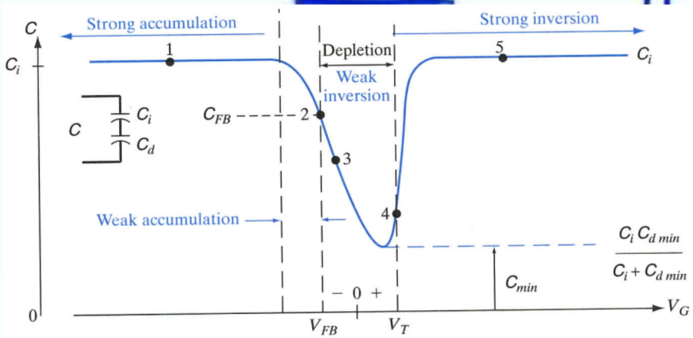



As W grows, $C_d$ decreases → C decreases.

Beyond inversion, charge increases.

Becomes like parallel plate capacitor again, but with opposite charge.

# Calculate major points on a C-V curve




$\epsilon_i / \epsilon_0 = 3.9$ for $SiO_2$

$d = 100\text{Å} = 10^{-6}\,cm$ ; $N_a = 10^{15}$

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

$$C_i = \frac{\epsilon_i}{d} = \frac{(3.9)(8.85\times10^{-14}\,F/cm)}{10^{-6}\,cm} = 3.45 \times 10^{-7}\,F/cm^2$$

$$Q_d = -qN_aW_m = -(1.6\times10^{-19}\,C)(10^{15}\,cm^{-3})(0.387\times10^{-4}\,cm)$$

$$= -0.62\times10^{-8}\,C/cm^2$$

$$V_T = \underbrace{\frac{0.62\times10^{-8}\,C/cm^2}{3.45\times10^{-7}\,F/cm^2}}_{=\,0.018\,V} + 2(0.23\,V) = 0.478$$

at $V_T$:

$$C_d = \frac{\epsilon_s}{W_m} = \frac{(11.8)(8.85\times10^{-14}\,F/cm)}{(0.387\times10^{-4}\,cm)} = \underline{2.70}\times10^{-8}\,F/cm$$

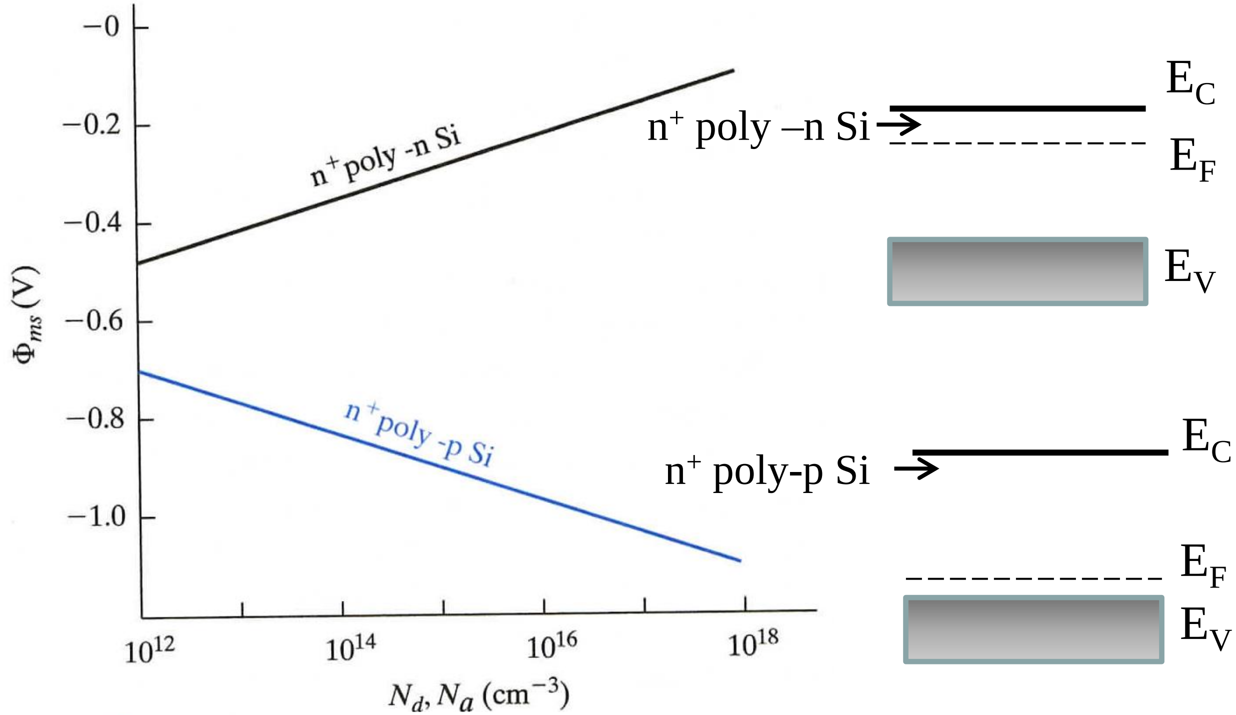
$$C_{min} = \frac{C_i C_d}{C_i + C_d} = \frac{34.5 \cdot 2.70 \cdot 10^{-16}}{(34.5+2.70)\cdot 10^{-8}} = \underline{2.5}\times10^{-8}\,F/cm$$

$C_d$ is close to $C_{min}$ since $C_d$ dominates total C as W grows with depletion

Note: Want low $V_T$ so keep $C_i$ large and d small.

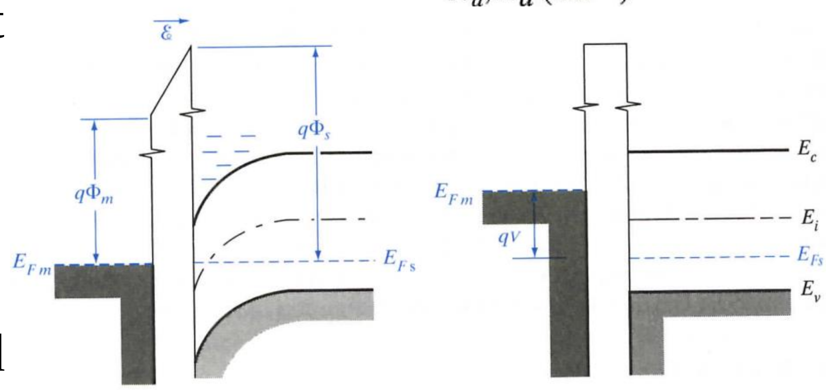
# Effect of Real Surfaces: Work Function Difference

Heavily doped n+ - poly acts as a metal electrode




Work function difference causes Si bands to bend without external bias voltage

Lower metal q $Ø_m$ causes Si bands to bend down in order for $E_{Fm}$ and $E_{Fs}$ to align




(a) Equilibrium $V = 0$

(b) Flat band $V = V_{FB} = \Phi_{ms}$

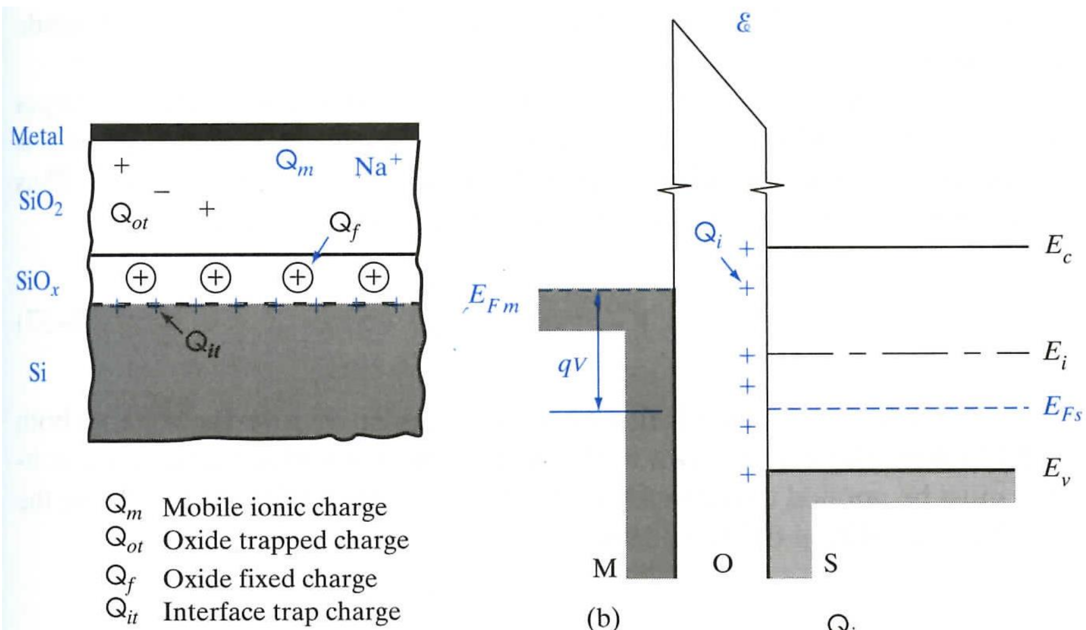
Just to reach flat bands requires negative applied voltage

$V = V_{FB} = \Phi_{ms}$

# Effect of Real Surfaces: Interface Charge

Trapped charge near MOS interface: (1) Traps inside $SiO_2$, (2) Traps at $SiO_2$/Si or $SiO_x$/Si interface (dangling bonds), (3) Mobile ions ($Na^+$)
Can alter applied bias $V_G$; Can vary with applied voltage, time, and temperature

**Eliminating interface traps: a major focus of semiconductor industry**




(a)

(b) $V = V_{FB} = -\frac{Q_i}{C_i}$

Positive interface trapped charge induces negative charges in semiconductor, requiring negative gate voltage to achieve flat band condition

# Threshold Voltage

$$\boxed{V_T = \Phi_{ms} - (Q_i/C_i) - (Q_d/C_i) + 2\,\varphi_F}$$

| $V_T =$ | $\Phi_{ms}$ | $-\dfrac{Q_i}{C_i}$ | $-\dfrac{Q_d}{C_i}$ | $+\,2\phi_F$ |
|---|---|---|---|---|
| | (−) | (−) | (+) n channel<br>(−) p channel | (+) n channel<br>(−) p channel |

$(kT/q)\ \ln(N_a/n_i)$

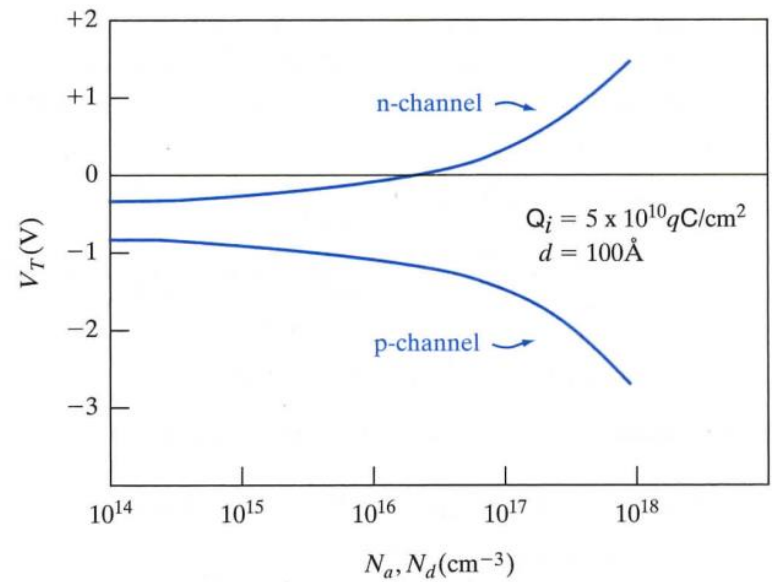
$\Phi_m = \Phi(\text{poly-Si}) = \chi_{Si} + (E_C - E_F) \sim \chi_{Si}$

$\Phi_s = \Phi_{Si} = \chi_{Si} + E_G/2 + kT\ \ln(p_0/n_i)$

$(E_i - E_F)$

Threshold voltage $V_T$ depends on:

- Doping
- interface capacitance $C_i$,
- interface charge $Q_i$,




As substrate p-doping increases, $\Phi_s$ increases, $\Phi_m$-$\Phi_s$ decreases, and $V_T$ decreases

As substrate n-doping increases, $\Phi_s$ decreases, $\Phi_m$-$\Phi_s$ increases, and $V_T$ increases

'Real' Example: Threshold Voltage

n+ poly-Si gate on p-Si substrate with $N_a = 5\times10^{15}\ \text{cm}^{-3}$

(n-Channel MOS transistor) $d(SiO_2) = 100\ \text{Å}$

$Q_i = 4\times10^{10}\ qC/cm^2$

Find $C_i$ and $C_{min}$ (C-V characteristics), $W_m$, $V_{FB}$ and $V_T$

$$\phi_F = \frac{kT}{q}\ln\frac{N_a}{n_i} = 0.0259\ln\frac{5\times10^{15}}{1.5\times10^{10}} = 0.329\ \text{V}$$

$$W_{max} = \quad 2\left[\frac{11.8\times8.85\times10^{-14}\times0.329}{1.6\times10^{-19}\times5\times10^{15}}\right]^{1/2}$$

$$=$$

From Fig. 6-17, $\Phi_{ms} \cong$

$$Q_i = 4\times10^{10}\times1.6\times10^{-19} =$$

$$C_i = \quad = \frac{3.9\times8.85\times10^{-14}}{0.1\times10^{-5}\ \text{cm}} =$$

$$C_i = \quad = \frac{3.9 \times 8.85 \times 10^{-14}}{0.1 \times 10^{-5}\ \text{cm}} =$$

$$V_{FB} = \quad = -0.95 - 6.4 \times 10^{-9} / 3.45 \times 10^{-7}$$

$$=$$

$$Q_d = \quad = -1.6 \times 10^{-19} \times 5 \times 10^{15} \times 4.15 \times 10^{-5}$$

$$=$$

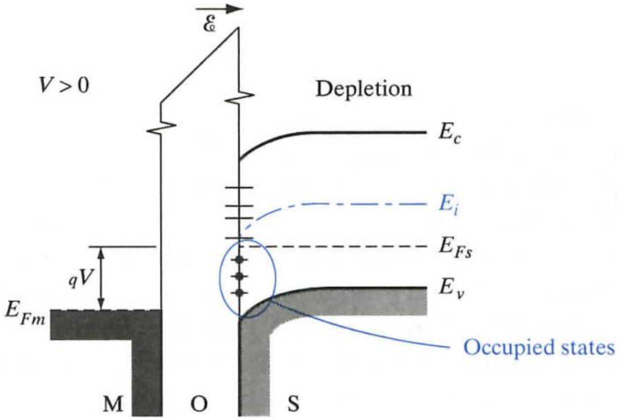
$$V_T = \quad = -0.969 + \frac{3.32 \times 10^{-8}}{3.45 \times 10^{-7}} + 0.658$$

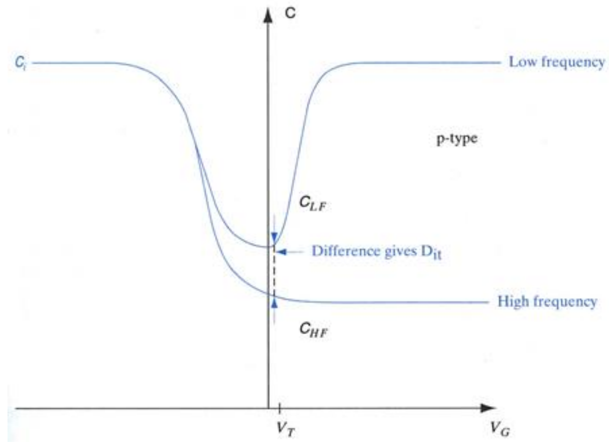
$$=$$

$$C_d = \quad = \frac{11.8 \times 8.85 \times 10^{-14}}{4.15 \times 10^{-5}} =$$

$$C_m = \quad = \frac{3.45 \times 10^{-7} \times 2.5 \times 10^{-8}}{3.45 \times 10^{-7} + 2.5 \times 10^{-8}} =$$

# MOS C-V analysis: can measure insulator d, doping, and $V_T$ from C-V plots



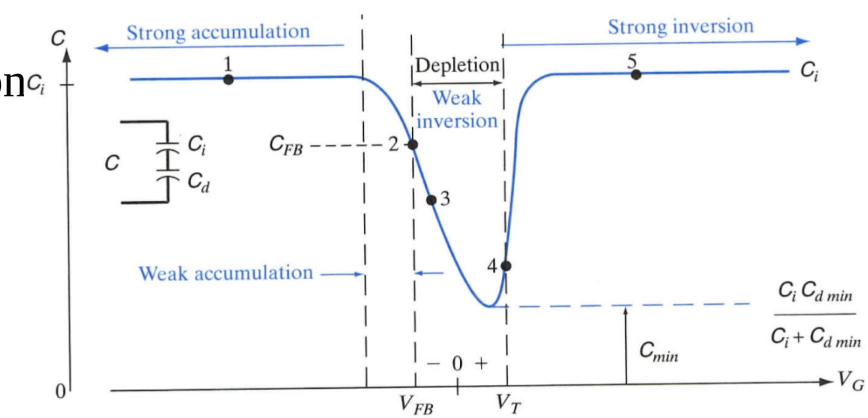

**Substrate type**:
P-type if C(hi-ω) large for $V_G < 0$ and small for $V_G > 0$
Opposite for N-type

Detailed derivation shows:

$D_{it} = (1/q)\,[(C_iC_{LF}/C_i - C_{LF}) - (C_iC_{HF}/C_i - C_{HF})]\ \mathrm{cm}^{-2}\,\mathrm{eV}^{-1}$

**Get insulator d** from:
$C_i = \varepsilon_i/d$ in accumulation or strong LF inversion since know $\varepsilon_i$ ($SiO_2$) = $3.9\ \varepsilon_0$

**Get $C_{dmin}$** from:
LF C-V and
$C_{min} = C_iC_{dmin}/(C_i + C_{dmin})$




**Get $N_a$** from: $f(C_{dmin})$ (Streetman eq. 6-39), which gives:

$\varphi_F = (kT/q)\ln(N_a/n_i)$
$Q_d = -2(\varepsilon_s N_a\,\varphi_F)$
$\Phi_s$, $\Phi_{ms}$, $L_D = \sqrt{(\varepsilon_s(kT/q^2p_0)}$
and $C_{debye} = \varepsilon_s/L_D$

**Can show**:
$C_{FB} = (1/C_{debye}) + (1/C_i)$
to get $V_{FB}$ and $Q_i$ from
$V_{FB} = \Phi_{ms} - (Q_i/C_i)$

And finally:
$V_T = \Phi_{ms} - (Q_i/C_i) - (Q_d/C_i) + 2\,\varphi_F$

**Can calculate what $V_T$ should be from C-V plot**