Electrical Characteristics of MOS Devices

• The MOS Capacitor
  – Voltage components
  – Accumulation, Depletion, Inversion Modes
  – Effect of channel bias and substrate bias
  – Effect of gate oxide charges
  – Threshold-voltage adjustment by implantation
  – Capacitance vs. voltage characteristics

• MOS Field-Effect Transistor
  – I-V characteristics
  – Parameter extraction
1) Revisit EE143 Week#2 Reading Assignment
   - Introduction to IC Devices, www.icknowledge.com
   - Streetman, Chap 3 Energy Band and Charge carriers in Semiconductors.

2) Visit the Device Visualization Website
   http://jas.eng.buffalo.edu/
   and run the visualization experiments of

   1) Charge carriers and Fermi level,
   2) pn junctions
   3) MOS capacitors
   4) MOSFETs
Work Function of Materials

METAL

\[ E_f \]
\[ E_0 \]
Work function \( = q\Phi \)

SEMICONDUCTOR

\[ E_f \]
\[ E_v \]
\[ E_0 \]

\[ q\Phi_M \] is determined by the metal material

\[ q\Phi_S \] is determined by the semiconductor material, the dopant type, and doping concentration
Work Function ($q\Phi_M$) of MOS Gate Materials

$E_o =$ vacuum energy level  
$E_C =$ bottom of conduction band  
$E_f =$ Fermi level  
$E_V =$ top of conduction band

$q\chi = 4.15\text{eV}$ (electron affinity)

Examples:
Al = 4.1 eV  
TiSi$_2$ = 4.6 eV

$n^+ \text{ poly-Si}$  
($E_f = E_C$)

$p^+ \text{ poly-Si}$  
($E_f = E_V$)
Work Function of doped Si substrate

* Depends on substrate concentration $N_B$

\[ \Phi_s \text{ (volts)} = 4.15 + 0.56 - |\Phi_F| \]

\[ \Phi_s \text{ (volts)} = 4.15 + 0.56 + |\Phi_F| \]

\[ |\Phi_F| = \frac{kT}{q} \ln \left( \frac{N_B}{n_i} \right) \]

\[ q\chi = 4.15 \text{eV} \]

\[ E_o \]

\[ \Phi_s \]

\[ q\Phi_s \]

\[ E_f \]

\[ E_i \]

\[ E_C \]

\[ q\Phi_s \]

\[ E_f \]

\[ E_i \]

\[ E_C \]

\[ |q\Phi_F| \]

\[ n\text{-type Si} \]

\[ p\text{-type Si} \]
The MOS Capacitor

\[ V_G = V_{FB} + V_{ox} + V_{si} \]

Oxide capacitance/unit area

\[ C_{ox} = \frac{\varepsilon_{ox}}{x_{ox}} \] [in Farads/cm²]
Flat Band Voltage

- $V_{FB}$ is the “built-in” voltage of the MOS:
  
  $$V_{FB} \equiv \Phi_M - \Phi_S$$

- Gate work function $\Phi_M$:
  
  Al: 4.1 V; n+ poly-Si: 4.15 V; p+ poly-Si: 5.27 V

- Semiconductor work function $\Phi_S$:
  
  $\Phi_S$ (volts) = 4.15 + 0.56 - $|\Phi_F|$ for n-Si
  
  $\Phi_S$ (volts) = 4.15 + 0.56 + $|\Phi_F|$ for p-Si

- $V_{ox}$ = voltage drop across oxide (depends on $V_G$)
- $V_{Si}$ = voltage drop in the silicon (depends on $V_G$)
A) Accumulation: $V_G < V_{FB}$ for p-type substrate

\[ V_{Si} \approx 0, \text{ so } V_{ox} = V_G - V_{FB} \]

\[ Q_{Si} = \text{charge/unit area in Si} = C_{ox} (V_G - V_{FB}) \]
MOS Operation Modes

• B) Flatband Condition: $V_G = V_{FB}$

No charge in Si (and hence no charge in metal gate)

• $V_{Si} = V_{ox} = 0$

Charge Distribution

M | O | S (p-Si)
C) Depletion: $V_G > V_{FB}$

Depletion Layer thickness

\[ x_d = \sqrt{\frac{2 \varepsilon_S V_{Si}}{qN_B}} \]

\[ V_G = V_{FB} + \frac{qN_B x_d}{C_{ox}} + \frac{qN_B x_d^2}{2 \varepsilon_s} \]

Note: $N_B x_d$ is the total charge in Si/unit area

Charge Distribution

Depletion layer

(For given $V_G$, can solve for $x_d$)
Depletion Mode: Charge and Electric Field Distributions

by Superposition Principle of Electrostatics

\[ \rho(x) \]

\[ \text{Metal} \quad \rightarrow \quad \text{Oxide} \quad \rightarrow \quad \text{Semiconductor} \]

\[ x = x_o + x_d \]

\[ x = 0 \]

\[ x = x_o \]

\[ \pm \rho \]

\[ Q' \]

\[ -Q' \]

\[ E(x) \]

\[ \text{Metal} \quad \rightarrow \quad \text{Oxide} \quad \rightarrow \quad \text{Semiconductor} \]

\[ x = x_o + x_d \]

\[ x = 0 \]

\[ x = x_o \]

\[ = \]

\[ = \]
D) Threshold of Inversion: $V_G = V_T$

$n_{surface} = N_B$ (for p-type substrate)

$=> V_{Si} = 2|\Phi_F|$

This is a definition for onset of strong inversion

$$V_G = V_T = V_{FB} + \frac{\sqrt{2 \varepsilon_s (2|\Phi_F|)qN_B}}{C_{ox}} + 2|\Phi_F|$$
E) Strong Inversion: $V_G > V_T$

$x_{d_{max}} = \sqrt{\frac{4\varepsilon_S|\Phi_F|}{qN_B}}$

$x_{d_{max}}$ is approximately unchanged when $V_G > V_T$

$V_{ox} = \frac{qN_B x_{d_{max}} + |Q'_n|}{C_{ox}}$

$Q'_n \approx -C_{ox}(V_G - V_T)$
Biasing Conditions for p-type Si

Energy band diagram:
- $V_G = V_{FB}$
- $V_G < V_{FB}$
- $V_T > V_G > V_{FB}$
- $V_G > V_T$

Charge diagram:
- Flat band
- Accumulation
- Depletion
- Inversion

Name
Flat band
Accumulation
Depletion
Inversion

Exposed acceptors
Electrons

Professor N Cheung, U.C. Berkeley
MOS Band Diagrams (n-type Si)

Decrease $V_G$ (toward more negative values)
-> move the gate energy-bands up, relative to the Si

- **Accumulation**
  - $V_G > V_{FB}$
  - Electrons accumulate at surface

- **Depletion**
  - $V_G < V_{FB}$
  - Electrons repelled from surface

- **Inversion**
  - $V_G < V_T$
  - Surface becomes p-type
Total Charge Density in Si, $Q_s$

\[ Q_{\text{acc}} = -C_{\text{ox}} (V_G - V_{FB}) \]

\[ Q_{\text{dep}} = -qN_A W \]

\[ Q_{\text{inv}} = -C_{\text{ox}} (V_G - V_T) \]

\[ Q_s = Q_{\text{acc}} + Q_{\text{dep}} + Q_{\text{inv}} \]
Voltage drop = area under E-field curve

*For simplicity, dielectric constants assumed to be same for oxide and Si in E-field sketches*
Suggested Exercise

Most derivations for MOS shown in lecture notes are done with p-type substrate (NMOS) as example.

Repeat the derivations yourself for n-type substrate (PMOS) to test your understanding of MOS.
p-Si substrate (NMOS)

Accumulation (holes)  \( V_{FB} \)

depletion  \( V_T \)

strong inversion (electrons)  \( V_G \) (more positive)

n-Si substrate (PMOS)

\( V_G \) (more negative)

Strong inversion (holes)  \( V_T \)

depletion  \( V_{FB} \)

Accumulation (electrons)
MOS Capacitance Measurement

- $V_G$ is scanned slowly
- Capacitive current due to $v_{ac}$ is measured

$$i_{ac} = C \frac{dv_{ac}}{dt}$$

$$C = \left| \frac{dQ_{GATE}}{dV_G} \right| = \left| \frac{dQ_s}{dV_G} \right|$$
MOS C-V Characteristics (p-type Si)

Ideal C-V curve:

\[
C = \left| \frac{dQ_s}{dV_G} \right|
\]

slope = \(-C_{ox}\)

accumulation  depletion  inversion
Capacitance in Inversion (p-type Si)

**CASE 1:** Inversion-layer charge can be supplied/removed quickly enough to respond to changes in the gate voltage. → Incremental charge is effectively added/subtracted at the surface of the substrate.

\[ \Delta Q \]

Time required to build inversion-layer charge = \( 2N_A \tau_o/n_i \), where \( \tau_o = \text{minority-carrier lifetime at surface} \)

\[
C = \left| \frac{dQ_{\text{inv}}}{dV_G} \right| = C_{ox}
\]
Capacitance in Inversion (p-type Si)

**CASE 2:** Inversion-layer charge cannot be supplied/removed quickly enough to respond to changes in the gate voltage.

→ Incremental charge is effectively added/subtracted at a depth $W_d$ in the substrate.

\[
\frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_{dep}}
\]

\[
= \frac{1}{C_{ox}} + \frac{W_{dm}}{\varepsilon_{Si}}
\]

\[
= \frac{1}{C_{ox}} + \sqrt{\frac{2(2\psi_B)}{qN_A\varepsilon_{Si}}} \equiv \frac{1}{C_{min}}
\]
Capacitor vs. Transistor C-V
(or LF vs. HF C-V)

p-type Si:

MOS transistor at any $f$
MOS capacitor at low $f$, or
quasi-static $C-V$

MOS capacitor at high $f$

$V_{FB}$
$C_{FB}$
$V_T$
$C_{min}$
$C_{max} = C_{ox}$

accumulation
depletion
inversion

$V_G$
C-V Characteristic

a) accumulation: \( C_{ox} \)

b) flatband: \( \sim C_{ox} \) (actually a bit less)

c) depletion: \( C_{ox} \) in series with the \( C_{depl} \)

d) threshold: \( C_{ox} \) in series with the minimum \( C_{depl} \)

e) inversion: \( C_{ox} \) (with some time delay!)
Small signal charge response $\Delta Q$ due to $\Delta VG$

**Accumulation**

\[ C = C_{ox} \]

**Depletion**

\[ \frac{1}{C} = \frac{1}{C_{ox}} + \frac{x_d}{\varepsilon_s} \]

**Inversion**

Low frequency

\[ C = C_{ox} \]

High frequency

\[ \frac{1}{C} = \frac{1}{C_{ox}} + \frac{x_{d_{max}}}{\varepsilon_s} \]