EE105 - Fall 2005
Microelectronic Devices and Circuits

Lecture 6

MOS Capacitors

Lecture Material

- Last lecture
  - PN junction
  - Diode currents
- This lecture
  - MOS capacitor
MOS Capacitor

- MOS = Metal Oxide Silicon
- Sandwich of conductors separated by an insulator
- “Metal” is more commonly a heavily doped polysilicon layer n+ or p+ layer
- NMOS $\rightarrow$ p-type substrate, PMOS $\rightarrow$ n-type substrate

\[
\varepsilon_{ox} = 3.9\varepsilon_0 \\
\text{Oxide (SiO}_2\text{) } \\
\text{Very Thin! } \\
t_{ox} \sim 1\text{nm}
\]

\[
\varepsilon = 11.7\varepsilon_0 \\
\text{Body (p-type substrate)}
\]

P-I-N Junction

- Under thermal equilibrium, the n-type poly gate is at a higher potential than the p-type substrate
  \[
  \phi_p = -\frac{kT}{q} \ln \frac{N_a}{n_i} \\
  \phi_n \approx 550\text{mV}
  \]
- No current can flow because of the insulator but this potential difference is accompanied with an electric field
- Fields terminate on charge!
Fields and Charge at Equilibrium

- At equilibrium there is an electric field from the gate to the body. The charges on the gate are positive. The negative charges in the body come from a depletion region.

Good Place to Sleep: Flat Band

- If we apply a bias, we can compensate for this built-in potential

\[ V_{FB} = -(\phi_n - \phi_p) \]

- In this case the charge on the gate goes to zero and the depletion region disappears.
- In solid-state physics lingo, the energy bands are “flat” under this condition.
Accumulation

If we further decrease the potential beyond the “flat-band” condition, we essentially have a parallel plate capacitor.

- Plenty of holes and electrons are available to charge up the plates.
- Negative bias attracts holes under gate.

\[ Q_G = C_{ox}(V_{GB} - V_{FB}) \]

\[ Q_B = |Q_G| \]

Depletion

- Similar to equilibrium, the potential in the gate is higher than the body.
- Body charge is made up of the depletion region ions.
- Potential drop across the body and depletion region.

\[ Q_G(V_{GB}) = -Q_B \]

\[ Q_B = -qN_aX_d(V_{GB}) \]
Inversion

As we further increase the gate voltage, eventually the surface potential increases to a point where the electron density at the surface equals the background ion density

\[ n_s = n_i e^{\frac{q\phi}{kT}} = N_a \quad \Rightarrow \quad \phi_s = -\phi_p \]

At this point, the depletion region stops growing and the extra charge is provided by the inversion charge at surface

Threshold Voltage

The threshold voltage is defined as the gate-body voltage that causes the surface to change from p-type to n-type

For this condition, the surface potential has to equal the negative of the p-type potential

We’ll derive that this voltage is equal to:

\[ V_{th} = V_{FB} - 2\phi_p + \frac{1}{C_{ox}} \sqrt{2q\varepsilon_s N_a (-2\phi_p)} \]
Inversion Stops Depletion

- A simple approximation is to assume that once inversion happens, the depletion region stops growing.
- This is a good assumption since the inversion charge is an exponential function of the surface potential.
- Under this condition:

\[
Q_G(V_{tn}) \approx -Q_{B,\text{max}}
\]

\[
Q_G(V_{GB}) = C_{ox}(V_{GB} - V_{tn}) - Q_{B,\text{max}}
\]

Q-V Curve for MOS Capacitor

- In accumulation, the charge is simply proportional to the applies gate-body bias.
- In inversion, the same is true.
- In depletion, the charge grows slower since the voltage is applied over a depletion region.
**Numerical Example**

- MOS Capacitor with p-type substrate:
  \[ t_{ox} = 20\text{nm} \quad N_a = 5 \times 10^{16} \text{cm}^{-3} \]

- Calculate flat-band:
  \[ V_{FB} = -(\phi_n - \phi_p) = -(550 - (-402)) = -0.95\text{V} \]

- Calculate threshold voltage:
  \[
  C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-13} \text{F/cm}}{2 \times 10^{-6} \text{cm}}
  \]
  \[
  V_{Tn} = V_{FB} - 2\phi_p + \frac{1}{C_{ax}} \sqrt{2q\varepsilon_s N_a (-2\phi_p)}
  \]
  \[
  V_{Tn} = -0.95 - 2(-0.4) + \frac{\sqrt{2 \times 1.6 \times 10^{-19} \times 1.04 \times 10^{-12} \times 5 \times 10^{16} \times 2 \times 0.4}}{C_{ox}} = -0.52\text{V}
  \]

**Num Example: Electric Field in Oxide**

- Apply a gate-to-body voltage:
  \[ V_{GB} = -2.5 < V_{FB} \]

- Device is in accumulation
- The entire voltage drop is across the oxide:
  \[
  E_{ox} = \frac{V_{ax}}{t_{ax}} = \frac{V_{GB} + \phi_n - \phi_p}{t_{ox}} = \frac{-2.5 + 0.55 - (-0.4)}{2 \times 10^{-6}} = -8 \times 10^3 \frac{\text{V}}{\text{cm}}
  \]

- The charge in the substrate (body) consist of holes:
  \[
  Q_B = -C_{ox} (V_{GB} - V_{FB}) = 2.67 \times 10^{-7} \text{C/cm}^2
  \]
Numerical Example: Depletion Region

- In inversion, what’s the depletion region width and charge?

\[ V_{B,max} = \phi_s - \phi_p = -\phi_p - \phi_p = -2\phi_p = 0.8V \]

\[ V_{B,max} = \frac{1}{2}\left(\frac{qN_a}{\varepsilon_s}\right)X_{d,max}^2 \]

\[ X_{d,max} = \sqrt{\frac{2\varepsilon_s V_{B,max}}{qN_a}} = 144nm \]

\[ Q_{B,\text{max}} = -qN_a X_{d,max} = -1.15 \times 10^{-7} \text{C/cm}^2 \]

MOS CV Curve

- Small-signal capacitance is slope of Q-V curve
- Capacitance is linear in accumulation and inversion
- Capacitance in depletion region is smallest
- Capacitance is non-linear in depletion
In accumulation mode the capacitance is just due to the voltage drop across $t_{ox}$.

- In inversion the incremental charge comes from the inversion layer (depletion region stops growing).
- In depletion region, the voltage drop is across the oxide and the depletion region.