EECS130
Integrated Circuit Devices

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Course Review
EE130 in one day!
Announcements

• The final exam is scheduled for Friday, December 14, from 12:30 - 3:30 PM in Rm. 277 Cory.
• The review will be held on Wednesday, December 12, from 6:30 - 8:30 PM (room TBA).
• Project reports are due today!
Bond Model of Electrons and Holes (Intrinsic Si)

- Silicon crystal in a two-dimensional representation.

- When an electron breaks loose and becomes a *conduction* electron, a *hole* is also created.
Dopants in Silicon

- As (Arsenic), a Group V element, introduces conduction electrons and creates **N-type silicon**, and is called a **donor**.
- B (Boron), a Group III element, introduces holes and creates **P-type silicon**, and is called an **acceptor**.
- Donors and acceptors are known as dopants.
• Energy states of Si atom (a) expand into energy bands of Si crystal (b).
• The lower bands are filled and higher bands are empty in a semiconductor.
• The highest filled band is the *valence band*.
• The lowest empty band is the *conduction band*.
• Totally filled bands and totally empty bands do not allow current flow. (Just as there is no motion of liquid in a totally filled or totally empty bottle.)
• Metal conduction band is half-filled.
• Semiconductors have lower $E_g$'s than insulators and can be doped.
Density of States

\[ g_c(E) \equiv \frac{\text{number of states in } \Delta E}{\Delta E \cdot \text{volume}} \left( \frac{1}{\text{eV} \cdot \text{cm}^3} \right) \]

\[ g_c(E) \equiv \frac{m_n^* \sqrt{2m_n^*(E-E_c)}}{\pi^2 h^3} \]

\[ g_v(E) \equiv \frac{m_p^* \sqrt{2m_p^*(E_v-E)}}{\pi^2 h^3} \]
There is a certain probability for the electrons in the conduction band to occupy high-energy states under the agitation of thermal energy (vibrating atoms, etc.)
Fermi Function

Probability that an available state at energy $E$ is occupied:

$$f(E) = \frac{1}{1 + e^{(E-E_F)/kT}}$$

$E_F$ is called the **Fermi energy** or the **Fermi level**

There is only one Fermi level in a system at equilibrium.

At $E=E_F$, $f(E)=1/2$
Equilibrium Carrier Concentrations

- Integrate $n(E)$ over all the energies in the conduction band to obtain $n$

$$n = \int_{E_c}^{\text{top of conduction band}} g_c(E) f(E) dE$$

- By using the Boltzmann approximation, and extending the integration limit to $\infty$, we obtain

$$n = N_c e^{-(E_c-E_f)/kT} \quad \text{where} \quad N_c = 2 \left( \frac{2\pi m_n^* kT}{\hbar^2} \right)^{3/2}$$

$N_c$ is called the **effective density of states (of the conduction band)**.
**Drift**

Electron and Hole Mobilities

- *Drift* is the motion caused by an electric field.
Electron and Hole Mobilities

\[ m_p \nu = q \mathcal{E} \tau_{mp} \]

\[ \nu = \frac{q \mathcal{E} \tau_{mp}}{m_p} \]

\[ \nu = \mu_p \mathcal{E} \]

\[ \mu_p = \frac{q \tau_{mp}}{m_p} \]

\[ \nu = -\mu_n \mathcal{E} \]

\[ \mu_n = \frac{q \tau_{mn}}{m_n} \]

• \( \mu_p \) is the hole mobility and \( \mu_n \) is the electron mobility
**Diffusion Current**

\[ J_{n,\text{diffusion}} = qD_n \frac{dn}{dx} \quad J_{p,\text{diffusion}} = -qD_p \frac{dp}{dx} \]

*D* is called the diffusion constant. Signs explained:
Total Current – Review of Four Current Components

\[ J_{TOTAL} = J_n + J_p \]

\[ J_n = J_{n,drift} + J_{n,diffusion} = q n \mu_n \varepsilon + q D_n \frac{dn}{dx} \]

\[ J_p = J_{p,drift} + J_{p,diffusion} = q p \mu_p \varepsilon - q D_p \frac{dp}{dx} \]
Band Diagram: Potential vs. Kinetic Energy

$E_c$ represents the electron potential energy:

$$P.E. = E_c - E_{\text{reference}}$$
Introduction to Device Fabrication

Oxidation

Lithography & Etching

Ion Implantation

Annealing & Diffusion
Reverse-Biased PN Junction

(a) Equilibrium ($V_A = 0$)

(c) Reverse bias ($V_A < 0$)

Exponential

Constant

$V_A$
Forward Biased PN Junction

(a) Equilibrium ($V_A = 0$)

$E_c$

$E_F$

$E_i$

$E_v$

$I_n$ →

$I_f$ →
Effect of Bias on Electrostatics

Note: simply replace $V_{bi}$ with $V_{bi}-V_A$
Carrier Concentrations at Equilibrium

**p-side**
- \( p_{p0} \)
- \( n_{p0} \)

**n-side**
- \( n_{n0} \)
- \( p_{n0} \)

\[ p_{p0}(-x_p) = N_A \]
\[ n_{p0}(-x_p) = \frac{n_i^2}{N_A} \]
\[ n_{n0}(x_n) = N_D \]
\[ p_{n0}(x_n) = \frac{n_i^2}{N_D} \]
Carrier concentration profile under bias

\[ p_n = p_{n0} + \Delta p_n(x) \]

\[ n_p = n_{p0} + \Delta n_p(x) \]
The Junction Law

$p_n$ product at the edge of the depletion when junction is biased:

$$p_n = n_i^2 e^{qV_A / kT}$$
Excess Carrier Concentrations at $-x_p, x_n$

**p-side**

\[
p_p(-x_p) = N_A
\]

\[
n_p(-x_p) = \frac{n_i^2 e^{qV_A/kT}}{N_A} = n_{p0} e^{qV_A/kT}
\]

\[
\Delta n_p(-x_p) = \frac{n_i^2}{N_A} \left( e^{qV_A/kT} - 1 \right)
\]

**n-side**

\[
n_n(x_n) = N_D
\]

\[
p_n(x_n) = \frac{n_i^2 e^{qV_A/kT}}{N_D} = p_{n0} e^{qV_A/kT}
\]

\[
\Delta p_n(x_n) = \frac{n_i^2}{N_D} \left( e^{qV_A/kT} - 1 \right)
\]
\[ J_{total} \]

\[ J_{pN} \]

\[ J_{nP} \]

N-side \hspace{1cm} 0 \hspace{1cm} P-side

\[ J_{total} \]

\[ J_{nN} \]

\[ J_{pP} \]

N-side \hspace{1cm} 0 \hspace{1cm} P-side

x
Ideal MS Contact: $\Phi_M > \Phi_S$, n-type

Band diagram instantly after contact formation:

Equilibrium band diagram:

Schottky Barrier:

$\Phi_{Bn} = \Phi_M - \chi$

Question: how are $V_{bi}$ and $\Phi_{Bn}$ related?
Effect of Interface States on $\Phi_{\text{Bn}}$

- Ideal MS contact:
  \[ \Phi_{\text{Bn}} = \Phi_M - \chi \]

- Real MS contacts:
  - A high density of allowed energy states in the band gap at the MS interface pins $E_F$ to the range 0.4 eV to 0.9 eV below $E_c$.
**Ideal MOS Capacitor**

- Oxide has zero charge, and no current can pass through it.
- No charge centers are present in the oxide or at the oxide-semiconductor interface.
- Semiconductor is uniformly doped
- \[ \Phi_M = \Phi_S = \chi + (E_C - E_F)_{FB} \]
Ideal MOS Capacitor

At Equilibrium:

![Diagram of an Ideal MOS Capacitor at Equilibrium]
Ideal MOS Capacitor
Under Bias

- Let us ground the semiconductor and start applying different voltages, $V_G$, to the gate

- $V_G$ can be positive, negative or zero with respect to the semiconductor

- $E_{F,\text{metal}} - E_{F,\text{semiconductor}} = - q V_G$

- Since oxide has no charge (it’s an insulator with no available carriers or dopants), $\frac{d E_{\text{oxide}}}{dx} = \frac{\rho}{\varepsilon} = 0$; meaning that the $E$-field inside the oxide is constant.
Ideal MOS Capacitor – n-type Si
MOS C-V characteristics

• The measured MOS capacitance (called gate capacitance) varies with the applied gate voltage
  – A very powerful diagnostic tool for identifying threshold voltage, oxide thickness, substrate doping concentration, and flat band voltage.
  – It also tells you how close to an ideal MOSC your structure is.

• Measurement of C-V characteristics
  – Apply any dc bias, and superimpose a small (15 mV) ac signal (typically 1 kHz – 1 MHz)
MOSC with n- and p-type substrate

\[ C_G \]

\[ V_G \]

p-type

n-type
Qualitative discussion: n-MOSFET

\[ V_G > V_T; \quad V_{DS} \approx 0 \]

- \( I_D \) increases with \( V_{DS} \)

\[ V_G > V_T; \quad V_{DS} \text{ small, } > 0 \]

- \( I_D \) increases with \( V_{DS} \), but rate of increase decreases.

\[ V_G > V_T; \quad V_{DS} \approx \text{pinch-off} \]

- \( I_D \) reaches a saturation value, \( I_{D,\text{sat}} \)
- The \( V_{DS} \) value is called \( V_{DS,\text{sat}} \)

\[ V_G > V_T; \quad V_{DS} > V_{DS,\text{sat}} \]

- \( I_D \) does not increase further, saturation region.
Band Diagram at various $V_{ds}$

![Band Diagram](image)
Quantitative $I_D$-$V_{DS}$ Relationships – 1st attempt

“Square Law”

$$I_D = \frac{Z\mu_n}{L} C_{ox} \left[ (V_G - V_T) V_{DS} - \frac{V_{DS}^2}{2} \right] \quad 0 < V_{DS} < V_{DS,sat}; \quad V_G > V_T$$

$I_D$ will increase as $V_{DS}$ is increased, but when $V_G - V_{DS} = V_T$, pinch-off occurs, and current saturates when $V_{DS}$ is increased further. This value of $V_{DS}$ is called $V_{DS,sat}$, i.e., $V_{DS,sat} = V_G - V_T$ and the current when $V_{DS} = V_{DS,sat}$ is called $I_{DS,sat}$.

$$I_{D,sat} = \frac{Z \mu C_{ox}}{2L} (V_G - V_T)^2 \quad V_D > V_{DS,sat}; \quad V_G > V_T$$

Here, $C_{ox}$ is the oxide capacitance per unit area, $C_{ox} = \varepsilon_{ox} / x_{ox}$
$I_D-V_{DS}$ characteristics expected from a long channel ($\Delta L << L$) MOSFET (n-channel), for various values of $V_G$.
Threshold and Subthreshold

\[ I_D = \mu_{\text{eff}} C_G \frac{W}{L'} (V_{GS} - V_T) V_{DS} \]

\[ = \frac{V_{DS}}{R_{CH}} \]

slope gives mobility

mobility degradation at high \( V_{GS} \)

\( V_{DS} \) small

actual

intercept gives \( V_T \)

subthreshold conduction
Velocity Saturation

\[ \nu = \frac{\mu_s \varepsilon}{1 + \frac{\varepsilon}{\varepsilon_{sat}}} \]

\[ \varepsilon \ll \varepsilon_{sat} : \nu = \mu_s \varepsilon \]

\[ \varepsilon \gg \varepsilon_{sat} : \nu = \mu_s \varepsilon_{sat} \]

- velocity saturation has large and deleterious effect on the \( I_{on} \) of MOSFETS
**$V_t$ Roll-off**

- $V_t$ roll-off: $V_t$ decreases with decreasing $L_g$.
- It determines the minimum acceptable $L_g$ because $I_{off}$ is too large if $V_t$ becomes too small.

*K. Goto et al., (Fujitsu) IEDM 2003*  
65nm technology. EOT=1.2nm, $V_{dd}=1V$
Energy-Band Diagram from Source to Drain

- **L dependence**

- **V<sub>ds</sub> dependence**

![Diagram showing energy-band from source to drain with annotations for long and short channel, and V<sub>ds</sub> dependence with log(I<sub>ds</sub>) vs V<sub>gs</sub> graph.]