Session 0: Solid State Physics

From Atom to Transistor
Objective

To Understand: how “Diodes,” and “Transistors” operate!
21 Century Alchemy!

Art of VLSI design is: to put together materials with different resistivity's next to each other to perform a certain task.

Ohm's law

\[ R = \frac{V}{I} \rightarrow \rho = R \frac{A}{L} \]

Resistivity is characteristic of the material

Art of VLSI design is:

to put together materials with different resistivity's next to each other to perform a certain task.

Conductor

Al, Cu

\[ \rho_{Al} \approx 10^{-6} \, [\Omega cm] \]

SiO₂

\[ \rho_{SiO₂} \approx 10^{16} \, [\Omega cm] \]
Periodic Table of Elements

Bohr Atomic Model

wave-particle duality

\[ \lambda = \frac{h}{p} \]

\[ mvr = n\hbar \]

de Broglie standing wave

Energy Bands:

\[ E_4 \]
\[ E_3 \]
\[ E_2 \]
\[ E_1 \]

Abbreviated Periodic Table
Bohr Atomic Model

Single atom:

2 atoms:

N atoms:

Pauli exclusion principle
Materials

1. 2. 3. 4. 5.

$E_G (Si) = 1.1 \text{eV}$  
$E_G (Ge) = 0.7 \text{eV}$  
$E_G (SiO}_2 = 9 \text{eV}$

Conductor $10^{-2}$  
Semi-conductor $10^5$  
Insulator $\rho [\Omega \text{cm}]$

Conduction band  
Valance band  
2N states  

empty seat / filled seat
Intrinsic Semiconductor

Covalent bands

Valance electrons

Si
**Intrinsic Semiconductor**

$n_0$ electron density

$p_0$ hole density

$n_0 = p_0 = n_i$

$n_i \bigg|_{T=300K} = 10^{10} \text{cm}^{-3} \ll n(Si) = 2 \times 10^{23} \text{cm}^{-3}$
**n-type Semiconductor**

Donor: P, As, Sb

- Free electron for each dopant

\[ n_0 = N_D \]

\[ n_0 p_0 = n_i^2 \]

Electron density \( n_0 \) and hole density \( p_0 \) are related.

- \( N_D \) up to \( 10^{19} \text{ cm}^{-3} \)

- \( n(Si) = 2 \times 10^{23} \text{ cm}^{-3} \)
**p-type Semiconductor**

Acceptor: B, Ga, In

\[ n_0 \text{ electron density} \]
\[ p_0 \text{ hole density} \]
\[ n_0 = N_A \]
\[ n_0 p_0 = n_i^2 \]

\( N_A \) up to \( 10^{19} \text{ cm}^{-3} \)

\( n(Si) = 2 \times 10^{23} \text{ cm}^{-3} \)
Energy Diagrams

Kinetic Energy

Potential Energy
Energy Diagrams
Energy Diagrams

\[ E \]

\[ x \]
Density of States

In Stadium: Number of available seats could be a function of distance from the center so ....

\( N \): number of available states for the electrons could be function of “Energy” : \( N(E) \)

Seats are not the same for fans so empty states for electrons!
Fermi Function
Probability of Electron Distribution

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

\( E_F \) is called the Fermi energy or the Fermi level.

If we are 3\( kT \) away from the Fermi energy then we might use Boltzmann approximation:

\[ f(E) \approx e^{-(E-E_F)/kT} \quad \text{if} \quad E - E_F \gg kT \]

\[ f(E) \approx 1 - e^{-(E_F-E)/kT} \quad \text{if} \quad E - E_F \ll -kT \]

\[ N(E) f(E) = \# \text{ of electrons at energy } E \]

\[ N(E)(1 - f(E)) = \# \text{ of holes at energy } E \]
Materials

Conductor $10^{-2}$ Semi-conductor $10^5$ Insulator

Conduction band

Valance band

$E_G (Si) = 1.1\text{eV}$

$E_G (Ge) = 0.7\text{eV}$

$E_G (SiO_2) = 9\text{eV}$

empty seat / filled seat
Electron / Holes : Intrinsic

\[ N(E) f(E) = \text{# of electrons at energy } E \]
\[ N(E)(1 - f(E)) = \text{# of holes at energy } E \]

\[ n_0 = \int_{E_C}^{\infty} N(E) f(E) \, dE \]
\[ p_0 = \int_{E_C}^{\infty} N(E)(1 - f(E)) \, dE \]
Electron / Holes : n-type

\[ N(E) f(E) = \text{# of electrons at energy } E \]

\[ N(E)(1 - f(E)) = \text{# of holes at energy } E \]

\[ n_0 = \int_{E_C}^{\infty} N(E) f(E) dE \]

\[ p_0 = \int_{E_C}^{\infty} N(E)(1 - f(E)) dE \]

\[ n_0 \gg p_0 \]
Electron / Holes: p-type

\[ N(E) f(E) = \# \text{ of electrons at energy } E \]
\[ N(E)(1 - f(E)) = \# \text{ of holes at energy } E \]

\[
\begin{align*}
    n_0 &= \int_{E_C}^{\infty} N(E) f(E) \, dE \\
p_0 &= \int_{E_C}^{\infty} N(E)(1 - f(E)) \, dE
\end{align*}
\]

\( p_0 \gg n_0 \)
Fermi Energy

intrinsic

n-type

p-type

\[ E \]

\[ E_{C} \]

\[ E_{V} \]

\[ n_{0} \]

\[ p_{0} \]
Fermi Energy

1. n-type p-type
2. \( E_F \) n-type
3. p-type
4. n-type
5. \( E_F \)
**Flow of Charge**

**Drift**

- Electric field
- Drift

**Electric field**

$E_c$  
$E_v$

$J \propto \mathcal{E}$

**Diffusion**

Charges move to be evenly distributed throughout space. Similar to perfume in room or heat in a solid

$J_n = qD_n \frac{dn}{dx}$

$J_p = -qD_p \frac{dp}{dx}$
PN Junction
PN junctions

\[ E_{Cp} \quad E_{Cn} \]
\[ E_{Fp} \quad E_{Fn} \]
\[ E_{Vp} \quad E_{Vn} \]
PN junctions

Depletion region

\[ qV_{bi} \]

\( E_{cp} \)
\( E_{cp} \)

\( E_{fp} \)
\( E_{fp} \)

\( E_{vn} \)
\( E_{vn} \)
PN junctions

- depletion region
- $J_{n_{diff}}$
- $J_{n_{drift}}$
- $J_{p_{diff}}$
- $J_{p_{drift}}$
- $E_{Cp}$
- $E_{Fn}$
- $E_{Cn}$
- $E_{Fp}$
- $E_{Vp}$
- $E_{Vn}$
- $qV_{bi}$
PN junctions, Reverse Biased

\[ V_R \]

\[ J_{n_{\text{drift}}} \quad J_{n_{\text{diff}}} \]

\[ E_{Fp} \quad qV_R \quad E_{Fn} \]

\[ J_{p_{\text{diff}}} \quad J_{p_{\text{drift}}} \]
PN junctions, Forward Biased

$V_F$  

$p$  

$n$  

depletion region

$J_{n_{drift}}$  

$J_{n_{diff}}$

$E_{Fp}$  

$qV_F$  

$E_{Fn}$

$J_{p_{diff}}$  

$J_{p_{drift}}$
Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions.
Under normal operating conditions, the BJT may be viewed electrostatically as two independent pn junctions.
BJT Electrostatics

pnp

Emitter $W_B$ Base Collector

$V_E$ $V_C$

$E_{CE}$ $qV_C$

$E_{FE}$ $qV_E$

$E_{VE}$
Junction FET

Source

Gate

Drain

Gate

p+

n

p+

2a

W

L
JFET

\[ R = \rho \frac{L}{Wx} \]
JFET

\[ R = \rho \frac{L}{W x} \]

\[ V_D > 0 \]
$R = \rho \frac{L}{Wx}$

$V_D \sim 0$
JFET

\[ R = \rho \frac{L}{Wx} \]

\[ V_D \sim 0 \]
JFET

\[ R = \rho \frac{L}{Wx} \]

\[ V_G = -2 \]

\[ V_D \]

\[ V_G = -2 \]

\[ V_G = 0 \]

\[ V_D = \]
The potential barrier to electron flow from the source into the channel region is lowered by applying $V_{GS} > V_T$. 

$V_G = 0$

$V_G > 0$

$V_G = V_T$
Qualitative Theory of the NMOSFET

1. When $V_{GS} > V_T$, $V_{DS} ≈ 0$

2. When $V_{GS} > V_T$, $V_{DS} > 0$

3. When $V_{DS} > V_{GS} - V_T$

   $V_{DS_{sat}} = V_{GS} - V_T$