Session 1: Solid State Devices

From Atoms to Transistors

Objective

To Understand: how “Diodes,” and “Transistors” operate!
Resistivity is characteristic of the material.

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

Resistivity is characteristic of the material.

\((\rho_{Al} = 10^{-6} \, \Omega \text{cm})\) \quad \text{Cu, Al} \rightarrow SiO_2 \rightarrow SiO_2 \quad (\rho_{SiO_2} = 10^{16} \, \Omega \text{cm})

- Intel Core i7
- Today
- Clock rate 2.66 GHz 3.33 GHz
- 64 bit processor
- 4 cores
- 751M Transistors at 45 nm
- Oregon 32 nm plant
- Price 272-502 $
- 263 mm2 die size
Bohr Atomic Model

wave-particle duality
\[ \lambda = \frac{\hbar}{p} \]

\[ mvr = nh \]

Energy Bands:

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

single atom

2 atoms

N atoms

Pauli exclusion principle

allowed energies

forbidden energies

2N electrons
### Materials

<table>
<thead>
<tr>
<th>Conductor</th>
<th>10⁻²</th>
<th>Semi-conductor</th>
<th>10²</th>
<th>Insulator</th>
<th>ρ[Ωcm]</th>
</tr>
</thead>
<tbody>
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</table>

- **Conduction Band**: Represents the band of states where electrons can move freely.
- **Valence Band**: Represents the band of states that are filled with electrons.
- **Band Gap (Eₐ)**: The energy difference between the conduction and valence bands.

<table>
<thead>
<tr>
<th>Material</th>
<th>Band Gap (Eₐ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.1 eV</td>
</tr>
<tr>
<td>Ge</td>
<td>0.7 eV</td>
</tr>
<tr>
<td>SiO₂</td>
<td>9 eV</td>
</tr>
</tbody>
</table>

**Empty Seat / Filled Seat**

**Electron Distribution**

### Intrinsic Semiconductor

- **Valence Band**: Band of filled orbitals.
- **Conduction Band**: Band of empty orbitals.
- **Filled States**: States that are occupied by electrons.
- **Empty States**: States that are free for electrons.
**Intrinsic Semiconductor**

\[ n_0 \text{ electron density} \]
\[ p_0 \text{ hole density} \]
\[ n_0 = p_0 = n_i \]
\[ n_i = AT^{3/2} e^{-E_U/kT} \]

\[ n_i \bigg|_{T=300^\circ K} = 10^{10} \text{ / cm}^3 \]
\[ n(Si) = 2 \times 10^{23} \text{ / cm}^3 \]

(useless!!!)

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**n-type Semiconductor**

Donor: P, As, Sb

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

\[ N_D \text{ up to } 10^9 \text{ / cm}^3 \]

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

Acceptor: B, Ga, In

\[ n_0 \text{ electron density} \]
\[ p_0 \text{ hole density} \]

\[ p_0 = N_A \]

\[ n_0 p_0 = n_i^2 \]

\[ N_A \text{ up to } 10^{19} / \text{cm}^3 \]

\[ n(Si) = 2 \times 10^{23} / \text{cm}^3 \]

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**Energy Diagrams**

Potential Energy

Kinetic Energy
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 Distribution

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

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

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

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

Empty seat / filled seat

Electronic Structure

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

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

$E_g (\text{SiO}_2) = 9 \text{eV}$

Electrons / Holes: Intrinsic

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

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

$n_0 = \int N(E)f(E) dE$

$p_0 = \int N(E)(1-f(E)) dE$
Electrons / Holes: n-type

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

Electrons / Holes: p-type

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

\[ n_0 = n_e^{(E_f - E_i)/kT} \quad p_0 = n_e^{(E_i - E_f)/kT} \]
Flow of Charge

**Drift**

\[ J = q(n\mu_n + p\mu_p)E \]

\[ \nu_p = \mu_p E \]

\[ \nu_n = \mu_n E \]

**Diffusion**

Charges move to be evenly distributed throughout space

Similar to perfume in room or heat in a solid

[23]

\[ J_n = qD_n \frac{dn}{dx} \]

\[ J_p = -qD_p \frac{dp}{dx} \]

PN Junction

[24]
PN Junction

P-type

n-type

depletion region

$E_C$

$E_V$

$E_f$

PN Junction

P-type

n-type

depletion region

$E_C$

$E_V$

$E_f$

$J_{n-drift}$
**PN Junction – Reverse Bias**

- $V_R$: reverse bias voltage
- $J_{n-drift}$: n-type drift current
- $J_{n-diff}$: n-type diffusion current
- $J_{p-drift}$: p-type drift current
- $J_{p-diff}$: p-type diffusion current
- $E$: electric field
- $E_f$: Fermi level
- $E_C$: conduction band electron energy level
- $E_V$: valence band hole energy level
- $qV_R$: voltage applied to the device
- $R$: resistance

**PN Junction – Forward Bias**

- $V_F$: forward bias voltage
- $J_{n-drift}$: n-type drift current
- $J_{n-diff}$: n-type diffusion current
- $J_{p-drift}$: p-type drift current
- $J_{p-diff}$: p-type diffusion current
- $E$: electric field
- $E_f$: Fermi level
- $E_C$: conduction band electron energy level
- $E_V$: valence band hole energy level
- $qV_F$: voltage applied to the device
- $R$: resistance
PN Junction

Depletion Region, $p^+$-n diode
$R = \rho \frac{l}{w x}$
$R = \rho \frac{l}{w_x}$

$V_G = -2$

$V_D$

$I_D$

$V_{DS}$

$V_P$

$V_G = 0$

$V_G = -2$
Thank you