Semi-Conductor & Diodes

• **Semi-Conductor**
  – Some Quantum mechanics refresher
  – Band theory in solids: Semiconductor, insulator and conductor
  – Doping

• **Diode**
  – p-n junction
  – Diode types
  – applications
Introduction

• In the next few lessons we will discuss electronics components that are semiconductors

• A semiconductor is something between a conductor and an insulator (actually very similar to insulator)

• In Solid State Physics a useful way to illustrate the properties of solids to introduce the concept of “bands”

• The “bands” concept comes from Quantum Mechanics
Quantum Mechanics “refresher”

- A model of bounded electron in a solid consist in representing the “bounding” force by a potential.
- One simple model is to consider a square infinite potential well
- Particle is trapped in the potential well
- Schrodinger’s equation

\[ \hat{H}\psi(x) = E \psi(x) \]

\[ -\frac{\hbar^2}{2m}\psi''(x) = E \psi(x) \]

Conditions at boundaries:

\[ \psi(0) = \psi(L) = 0 \]

Wave function

P. Piot, PHYS 375 – Spring 2008
Let’s solve the previous equation (where $k = \sqrt{2mE/\hbar}$)

$$\psi''(x) + k^2\psi(x) = 0$$

$$\psi(x) = \alpha \sin(kx) + \beta \cos(kx)$$

$$\psi(0) = 0 \Rightarrow \beta = 0$$

$$\psi(L) = 0 \Rightarrow \sin(kL) = 0 \Rightarrow k = k_n = \frac{n\pi}{L}$$

$n = 1, 2, \ldots$

So the solution in view of the boundary conditions finally takes the form

$$\psi_n(x) = \sqrt{\frac{2}{L}} \sin(k_n x)$$

And the possible energies are

$$E_n = n^2 E_1$$

$$E_1 = \frac{\hbar^2 \pi^2}{2mL^2}$$

P. Piot, PHYS 375 – Spring 2008
Case of many electrons

- If we have $N$ electrons and try to trap them in an infinite quantum well, the minimum possible energy of the electron of the “top” electron is given by the Fermi energy (assume $T=0$ K)

$$E_f = \frac{N^2\hbar}{32mL}$$

- At a given temperature, the electron distribution follow the Fermi-Dirac distribution:

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

*Paul Dirac (1902-1984)*

*Enrico Fermi (1901-1954)*
Fermi-Dirac distribution

- F-D distribution of the form:

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

- Limiting values:

\[
\lim_{\epsilon \to 0} E_f = \frac{1}{e^{-\mu/(kT)} + 1} \to 1 \quad (\mu/(kT) \gg 1)
\]

\[
\lim_{\epsilon \to \infty} E_f = 0
\]
Solids Band Theory

- Real potential in a crystal is a series of potential well (not infinite and not simple “square function”)

- The allowed energies for the electron are then arranged as a series of “bands”

- Fermi Energy?
Differences between conductor, semiconductor and insulator

a. Insulator

b. Semiconductor

c. Conductor

Energy of electrons

Conduction Band

Fermi level in gap.

Valence Band

In semiconductors, the band gap is small enough that thermal energy can bridge the gap for a small fraction of the electrons. In conductors, there is no band gap since the valence band overlaps the conduction band.

The large energy gap between the valence and conduction bands in an insulator says that at ordinary temperatures, no electrons can reach the conduction band.
Semiconductor and Fermi Energy

No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.
Semiconductor: Doping

- Addition of an impurity can create additional state within an energy gap.
- Depending on the impurity type:
  - Can add an electron: p type
  - Can add a hole: n type
pn junction

- If p- and n-type semiconductors are in contact (junction), the system behaves very differently from a p or n semiconductor.

- The main characteristic is that current will flow in one direction but not the other.

- Local electron/hole recombination at the junction contact is the underlying mechanism:

_P. Piot, PHYS 375 – Spring 2008_
A bipolar p-n junction: The diode

- If p- and n-type semiconductors are in contact (junction), the system behaves very differently from a p or n semiconductor.

  - **Forward biasing** \( (V_d \geq 0) \), the diode (ideally) acts as a short (i.e. perfect conductor)
  
  - **Reversed bias** \( (V_d < 0) \), diode = open circuit

- Current can only pass in one direction
A bipolar p-n junction: The diode

Assume steady-state regime

- For $V_d < 0$, the diode acts as a **good insulator**: $I_s \sim 1 \text{ pA} - 1 \mu\text{A}$, then the “inverse” current, $I_s$, increase with temperature.

- For $V_d >> \sim 0.7$, current increase quickly and linearly w.r.t. $V_d$’
  \[ \Rightarrow I_d \text{ is not proportional to } V_d: \text{ (there is a threshold voltage } \sim V_o) \]

- For $V_d \in [0,\sim V_o]$: **exponential** increase of current
  \[ I_d \cong I_s \left[ \exp \left( \frac{V_d}{\eta V_T} \right) - 1 \right] \]
  \[ V_T = k \cdot T/e \]
  \[ k = 1,38 \times 10^{-23} \text{ J/K} = \text{ Boltzmann constant} \]
  \[ e = 1.6 \times 10^{-19} \text{ Coulomb, } T \text{ temperature in } \degree \text{Kelvin} \]
  \[ I_s = \text{inverse current} \]
Operational Limits

- **Maximum reverse voltage**

  \[ V_{\text{max}} \text{ typically 10-20 Volts} \]

  ! Can lead to diode destruction!

  \[ V_{\text{max}} = \text{« P.I. V » (Peak Inverse Voltage) or « P.R.V » (Peak Reverse Voltage)} \]

- **Power limitation**

  A diode can only withstand a certain power and we should make sure \[ V_d I_d = P_{\text{max}} \]

- **Temperature can strongly influence diode operation**
This diode is designed to operate around \( V_z \), the reverse breakdown voltage (which is a well-defined value for these diodes).

**Characteristics**

- \( V_Z \): Zener Voltage (by definition: \( V_Z > 0 \))
- \( I_{\text{min}} \): minimum current (absolute value) where the I-V characteristic becomes linear (this is the Zener Domain)
- \( I_{\text{max}} \): maximum possible current (due to power)

Typical values: \( V_Z \approx 1-100 \, V \), \( I_{\text{min}} \approx 0.01-0.1 \, mA \)

_P. Piot, PHYS 375 – Spring 2008_
Light emitting diodes (ou LED)

**Principle**: The current flow induce light emission

- Work under **direct biasing** ($V > V_o$)
- light intensity $\propto$ current $I_d$
- ! Do not work for Si diode

$V_o \neq 0.7V$ ! (GaAs (red): $\sim 1.7V$; GaN (blue): 3V)

Big business! Nowadays higher light intensity makes diode suitable for lighting applications
Common diode types

**Schottky diode**

Schottky diode is a diode with a very low threshold voltage $V_o$ along with a very fast response time.

**« Varicap » diode**

The varicap diode is a diode with variable capacitance. It uses a variation of $C_t$ with $V_d$ in reverse bias operation.

**Photodiode**

Under reverse bias, the diode produces an electric current proportional to the light intensity.
Application: Clipping

- The purpose of Clipping is to protect circuit either by avoiding a certain sign of current or by limiting the maximum voltage.

**Parallel Clipping**

\[ V_g \quad (\text{diode // charge}) \]

\[ R_g \]

\[ V_e \quad Z_e \quad \text{Circuit to be protected} \]

\[ \Leftrightarrow V_e \text{ cannot be much higher than } V_o \]

**Series Clipping**

\[ V_g \quad V_{e(t)} \quad Z_e \quad \text{Circuit to be protected} \]

\[ \Leftrightarrow I_e \text{ cannot be negative} \]
How do we find $V$ and $I$ across a diode??

- Consider the circuit we want to compute $I_d$ and $V_d$

$V_a \quad V_d \quad R_L \quad V_R \quad I_d, V_d, ?$

$\Rightarrow I_d$ and $V_d$ obey Kirchhoff’s law

$\Rightarrow I_d$ et $V_d$ follows the diode characteristics $I(V)$ of the other component

$\Rightarrow$ So the operating point has to satisfy the two aforementioned conditions
How do we find V and I across a diode??

Kirchoff’s law: \[ I_d \rightarrow \frac{V_{al} - V_d}{R_L} \]

\( I(V) \) diode characteristics

Knowing \( I_d(V_d) \) one can **graphically find the operating** point of a diode (actually of any components)

Can also attempt an analytical estimate but need a function to describe the I-V curve

\( P. \ Piot, \ \text{PHYS 375 – Spring 2008} \)