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

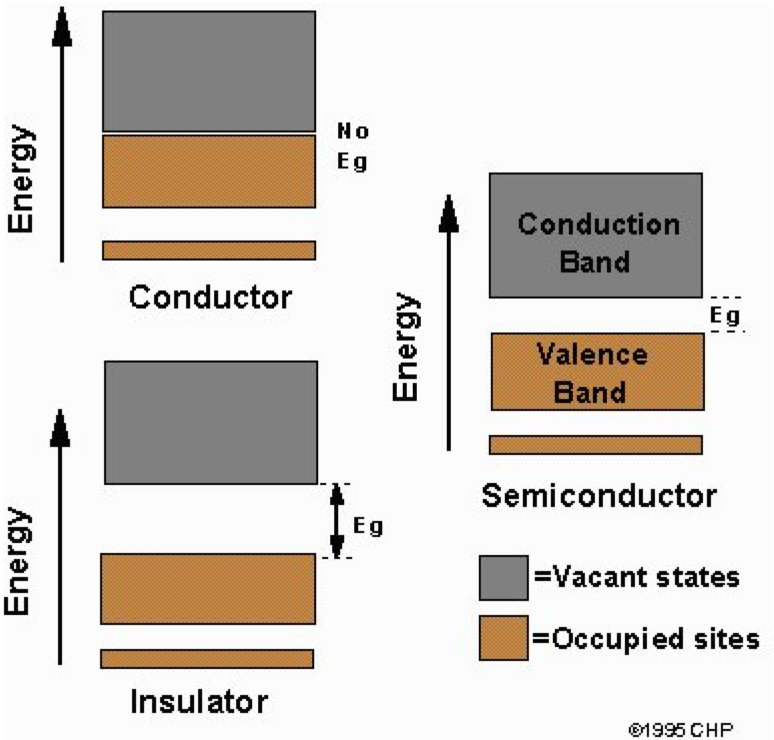
Introduction

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

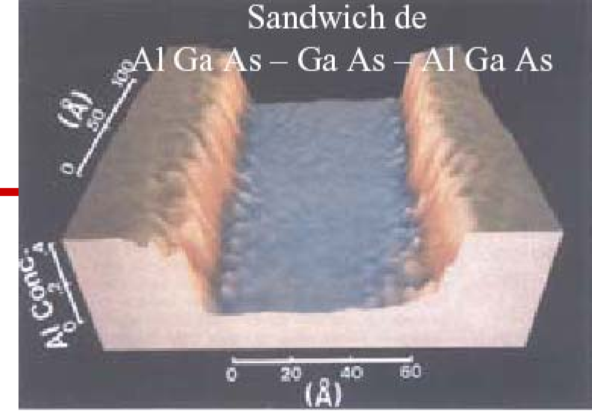
- A semiconductor is something between a conductor and an insulator (actually very similar to insulator)

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

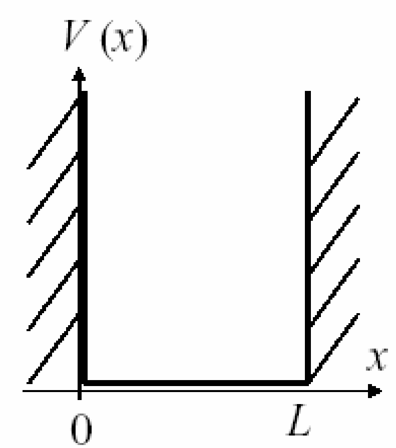
- The “bands” concept comes from Quantum Mechanics



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



$$\hat{H}\psi(x) = E\,\psi(x)$$

$0 \leq x \leq L$

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

$x < 0$ ou $x > L$

$$\psi(x) = 0$$

Wave function

Conditions at boundaries:

$$\psi(0) = \psi(L) = 0$$

Quantum Mechanics "refresher"

- Let's solve the previous equation (where $k = \sqrt{2mE}/\hbar$)

$$\psi''(x) + k^2\psi(x) = 0 \qquad \psi(x) = \alpha \sin(kx) + \cancel{\beta \cos(kx)}$$

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

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

$$n = 1, 2, \ldots$$

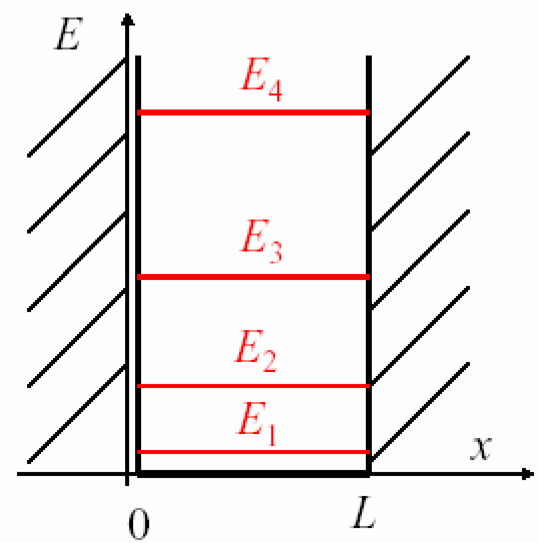
- So the solution in view of the boundary conditions finally takes the form

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

- And the possible energies are

$$E_n = n^2 \, E_1$$

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



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)

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

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

Enrico Fermi (1901-1954)

At absolute zero, fermions will fill up all available energy states below a level E_F called the Fermi energy with one (and only one) particle. They are constrained by the Pauli exclusion principle. At higher temperatures, some are elevated to levels above the Fermi level.

The probability that a particle will have energy E

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

For low temperatures, those energy states below the Fermi energy E_F have a probability of essentially 1, and those above the Fermi energy essentially zero.

The quantum difference which arises from the fact that the particles are indistinguishable.

Paul Dirac (1902-1984)

Fermi-Dirac distribution

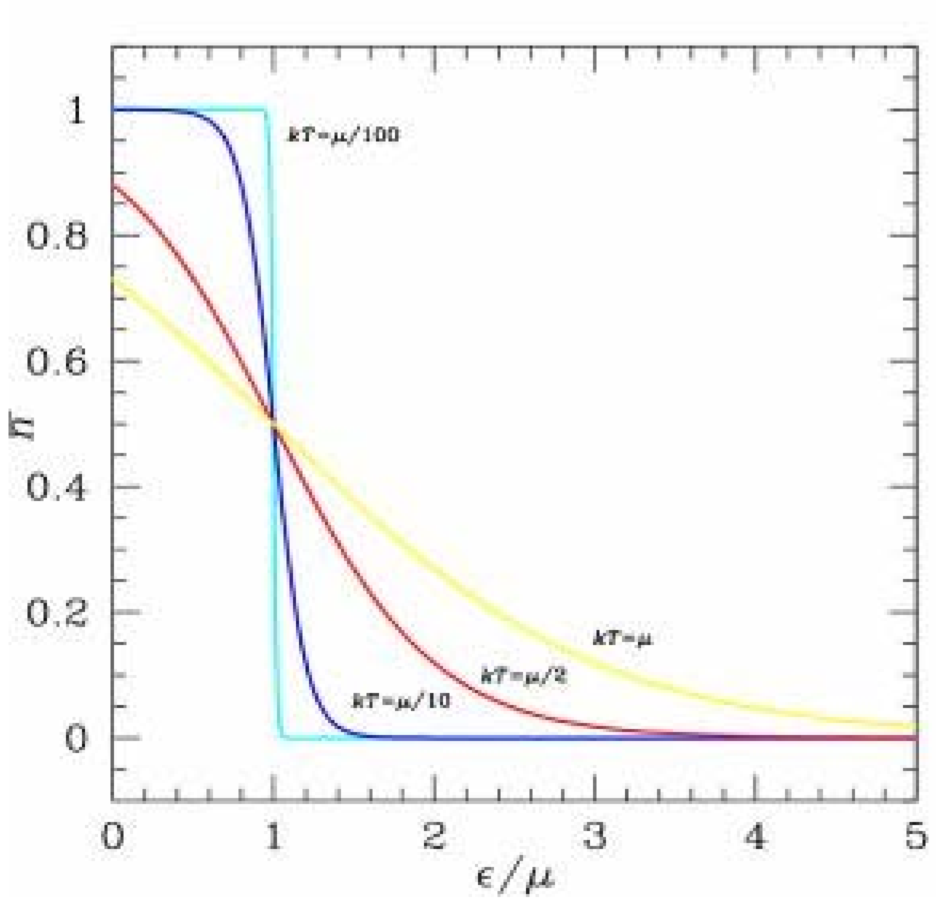
- F-D distribution of the form:

$$E_f = \frac{1}{e^{(\varepsilon-\mu)/(kT)}+1}$$

- Limiting values:

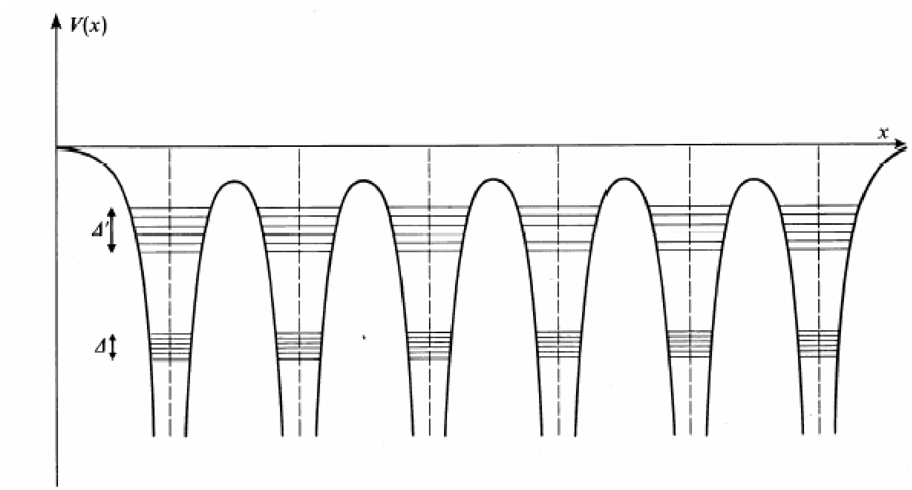
$$\lim_{\varepsilon \to 0} E_f = \frac{1}{e^{-\mu/(kT)}+1} \to 1 \quad (\mu/(kT) >> 1)$$

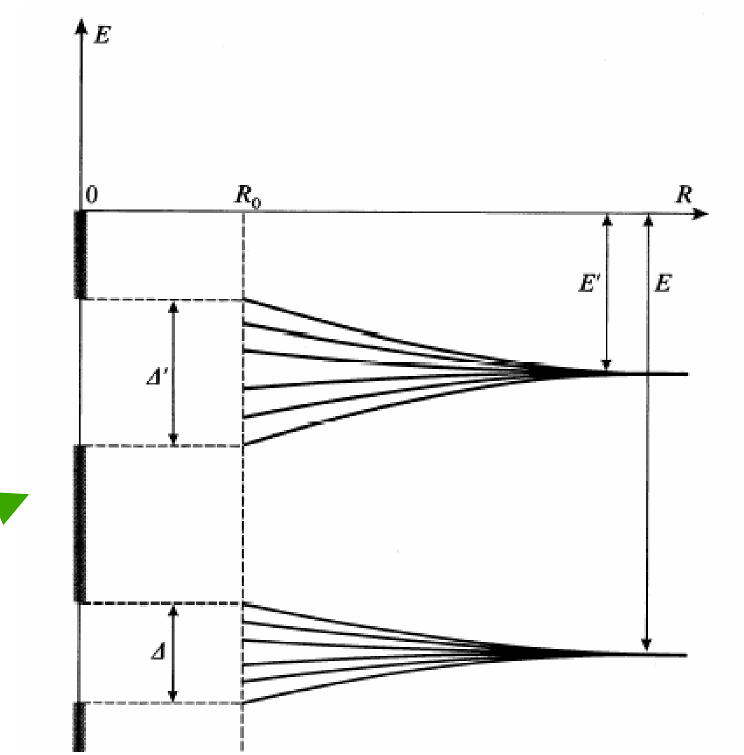
$$\lim_{\varepsilon \to \infty} E_f = 0$$



Solids Band Theory

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

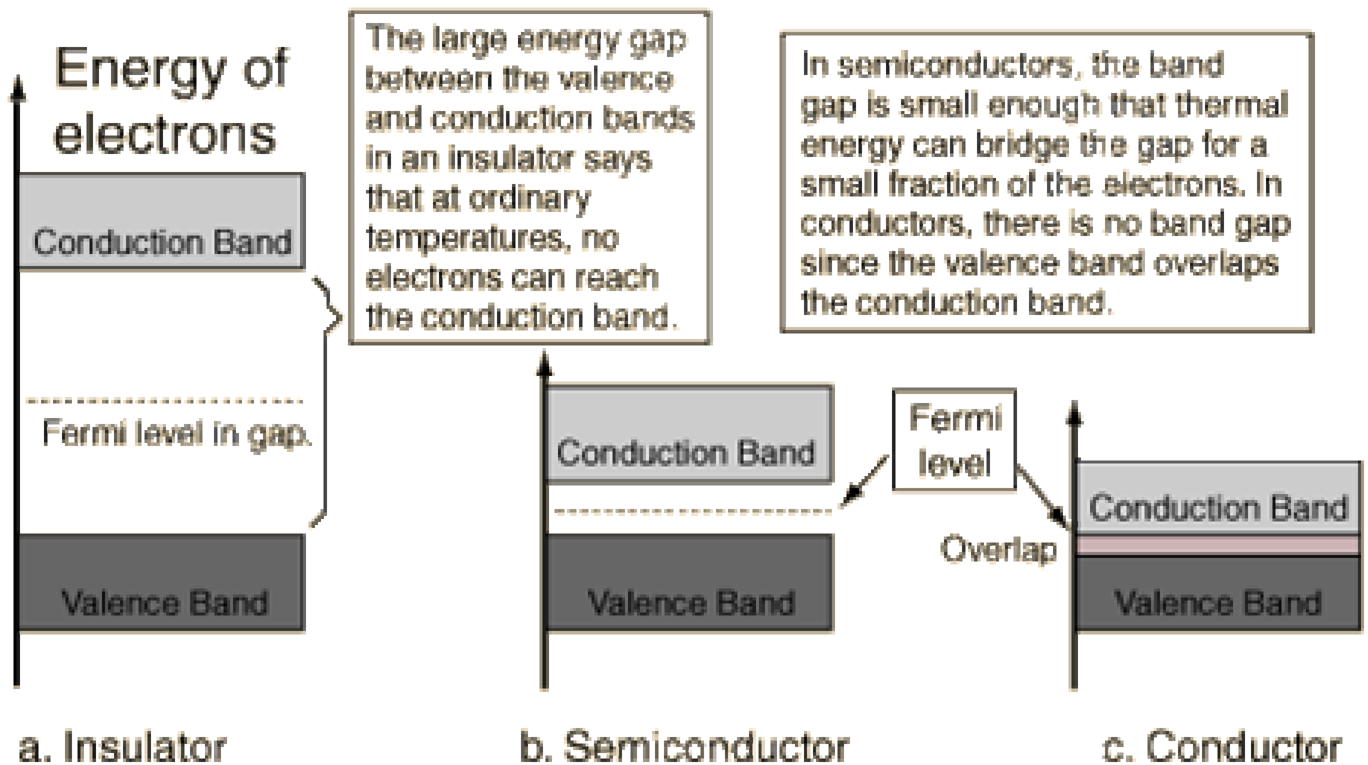




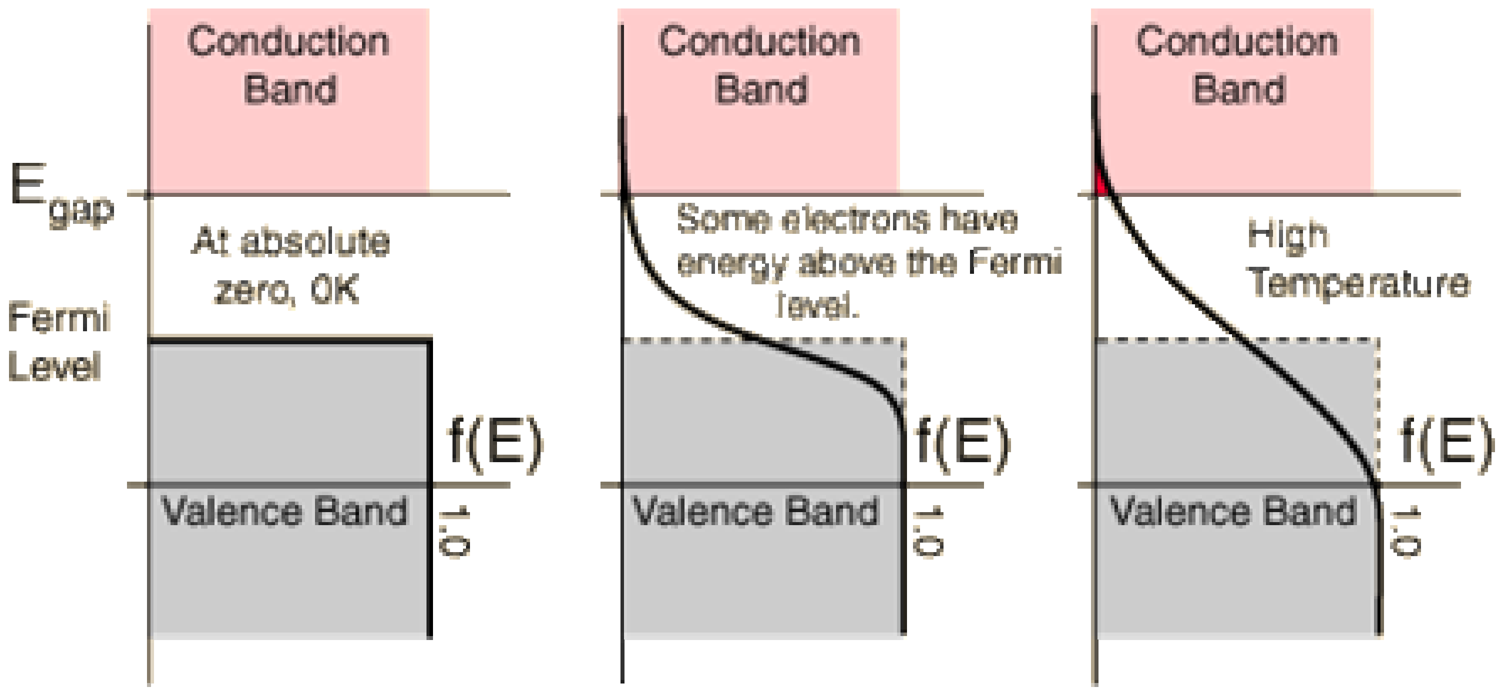
- The allowed energies for the electron are then arranged as a series of "bands"

- Fermi Energy?

Differences between conductor, semiconductor and insulator



Semiconductor and Fermi Energy

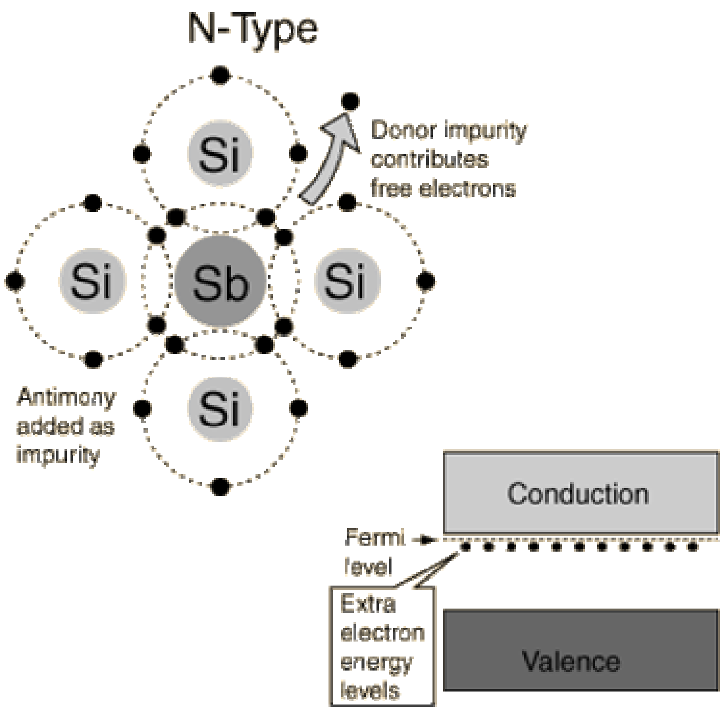


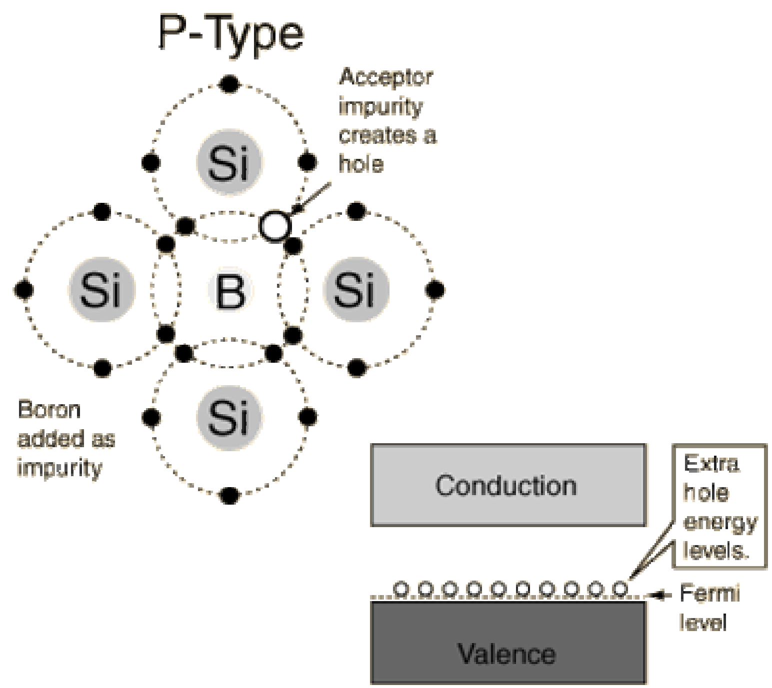
No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

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



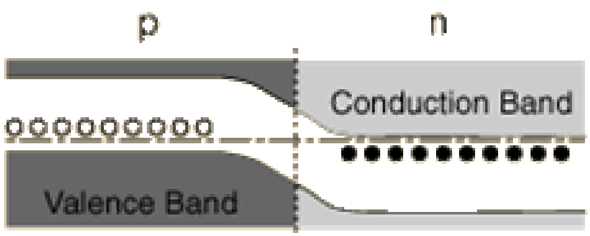


pn junction

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

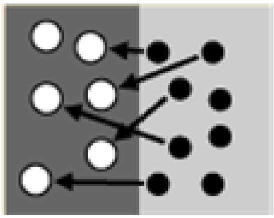
- The main characteristic is that current will flow in one direction but not the other

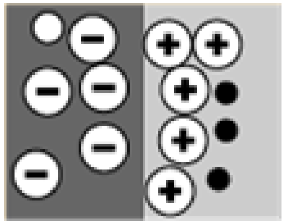
p-n junction



Energy bands at equilibrium

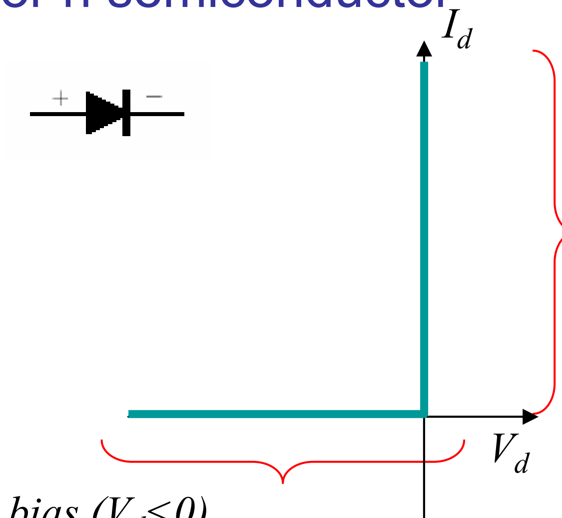
- Local electron/hole recombination at the junction contact is the underlying mechanism:

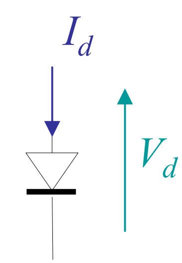




A bipolar p-n junction: The diode

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

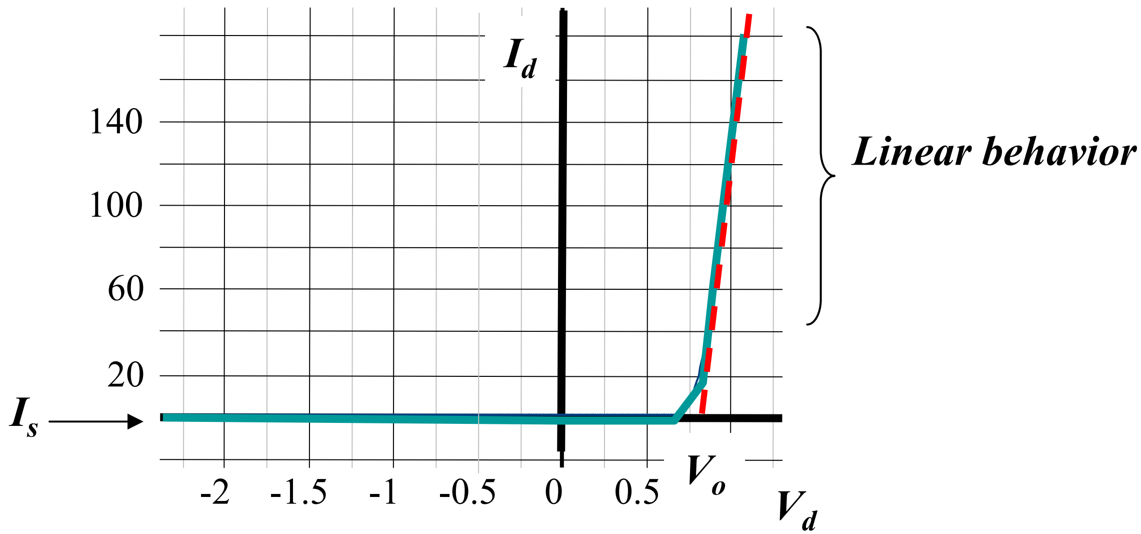




- Current can only pass in one direction

A bipolar p-n junction: The diode

assume steady-state regime



- For $V_d < 0$, the diode acts as a **good insulator** : $I_s \sim 1\ pA - 1\mu A$,
  → the "**inverse**" current, I_s, increase with temperature

- For $V_d >> \sim 0.7$, current increase quickly and linearly w.r.t. V_d"
  → I_d **is not proportional** to V_d: (there is a threshold voltage~ V_o)

- **for**: $V_d \in [0, \sim V_o]$: **exponential** increase of current

$$\boxed{I_d \cong I_s \left[\exp\left(\frac{V_d}{\eta V_T} \right) - 1 \right]}$$

$V_T = k \bullet T/e$
k = 1,38 10^{-23} J/K= Boltzmann constant
e= 1.6 10^{-19}Coulomb, T temperature in °**Kelvin**
I_s = *inverse current*

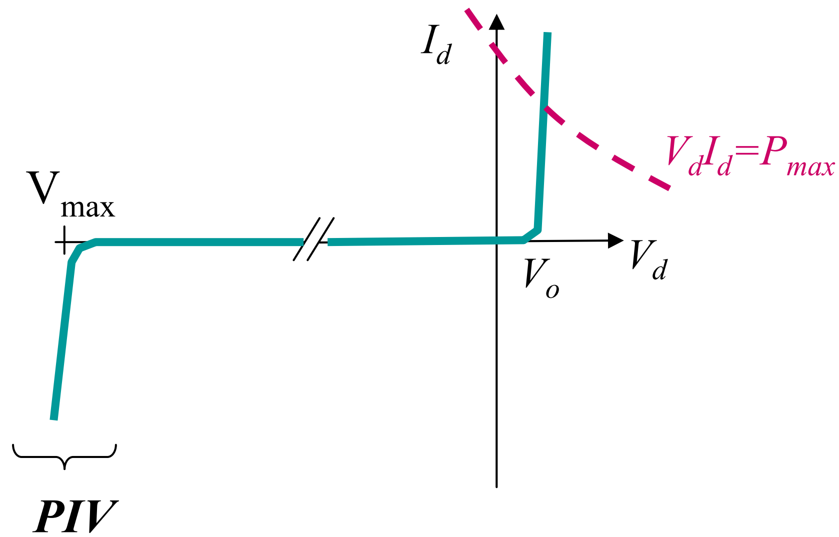
Operational Limits

- **Maximum reverse voltage**

  V_{max} typically 10-20 Volts

  ! Can lead to diode destruction!

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



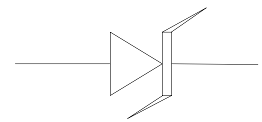
- **Power limitation**

  A diode can only withstand a certain power and we should make sure $V_dI_d=P_{max}$

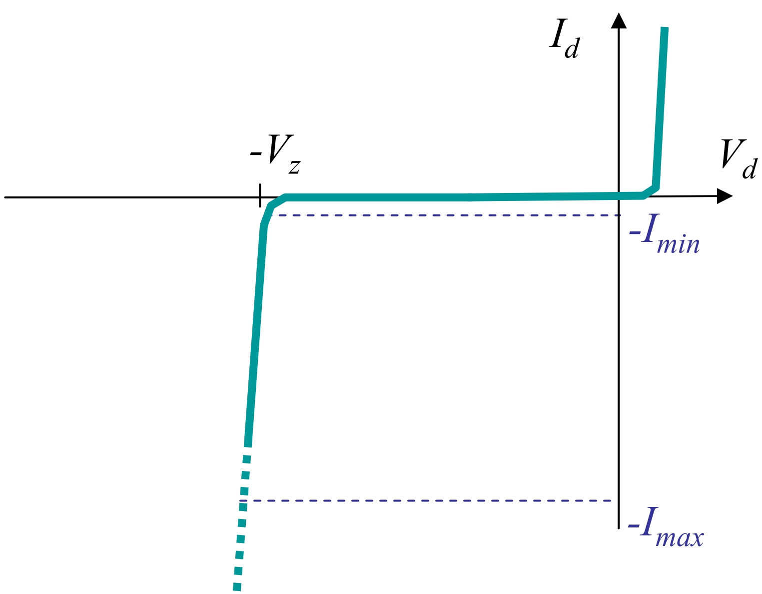
- **Temperature can strongly influence diode operation**

Zener Diode

This diode is designed to operated around Vz, the reverse break down voltage (which is a well defined value for these diodes)



- **Characteristics**



***V_Z* :** Zener Voltage (by definition: $V_Z > 0$)

***I_{min}* :** min current (absolute value) where the I-V characteristic becomes linear (this is the Zener Domain)

***I_{max}* :** maximum possible current (due to power)

Typical values : V_Z~1-100 V , I_{min} ~0,01- 0,1mA

Zener from Clarence Melvin Zener (1905-1993) Bell Labs

Common diode types

Light emitting diodes (ou LED)

- **Principle :** The current flow induce lgith emission

  Work under **direct biasing ($V > V_o$)**

  light intensity $\propto$ current I_d

  ! Do not work for Si diode

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

Big business! Nowdays higher light intensity makes diode suitable for lighting applications

Common diode types

Schottky diode

Shottky 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

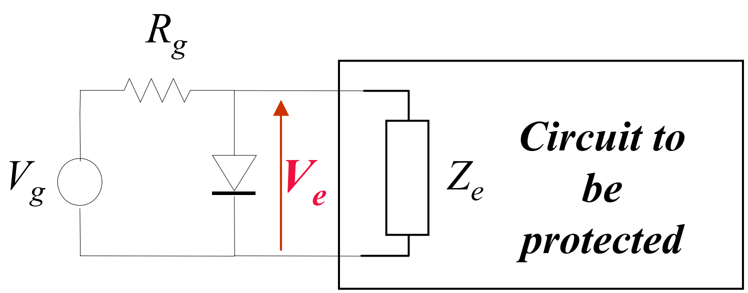
Under reverse bias, the diode produces an electric current proportional to the **light intensity**

Application: Clipping

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

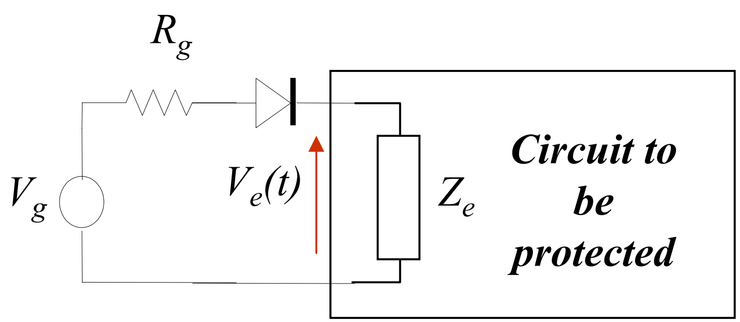
Parallel Clipping

(diode // charge)



$\Leftrightarrow$ V_e cannot be much higher than V_o

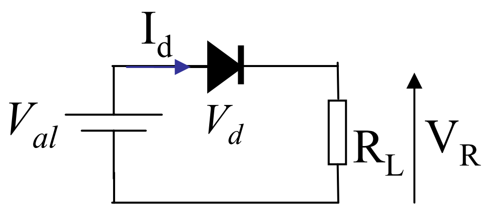
Series Clipping



$\Leftrightarrow$ I_e 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



I_d , V_d, ?

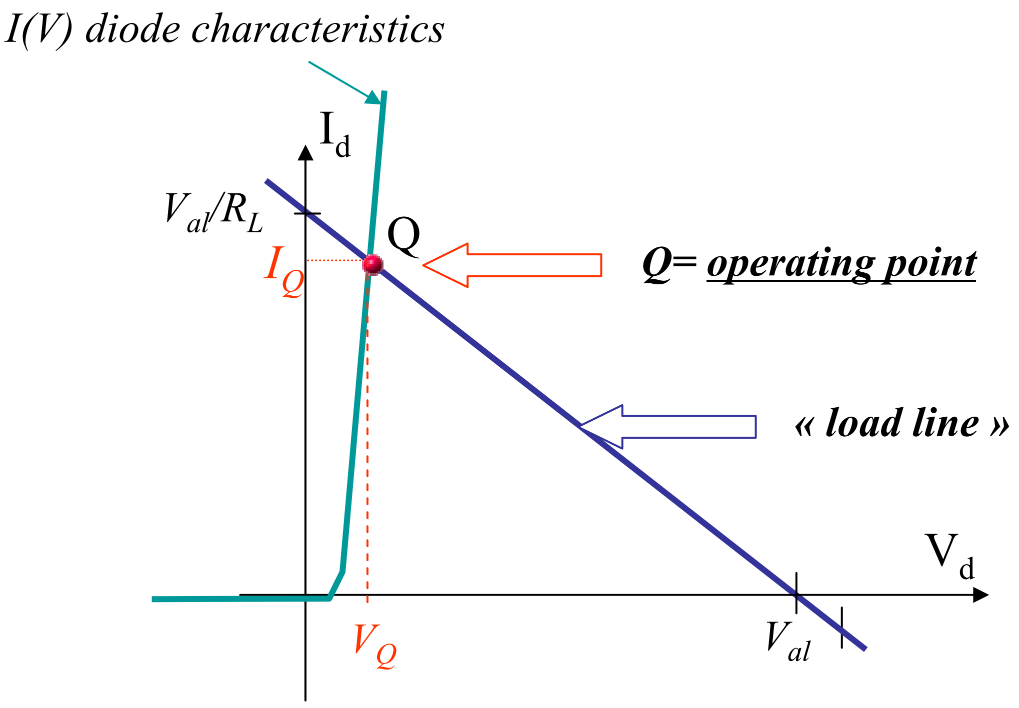
➔ I_d and V_d obey **Kirchhoff**'s law

➔ I_d et V_d follows the diode characteristics **I(V)** of the other component

➔ So the operating point has to satisfy the two aforementioned conditions

How do we find V and I across a diode??

■ Kirchoff's law: $\cdots \rightarrow I_d = \dfrac{V_{al} - V_d}{R_L}$



➔ 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