10. Semiconductors

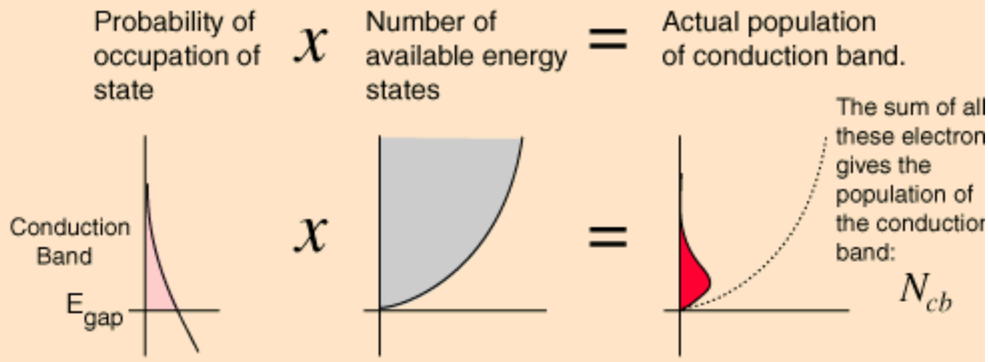
a. Band structure of silicon and GaAs. The W(k) function.

Band Theory of Solids

A useful way to visualize the difference between conductors, insulators and semiconductors is to plot the available energies for electrons in the materials. Instead of having discrete energies as in the case of free atoms, the available energy states form bands. Crucial to the conduction process is whether or not there are electrons in the conduction band. In insulators the electrons in the valence band are separated by a large gap from the conduction band, in conductors like metals the valence band overlaps the conduction band, and in semiconductors there is a small enough gap between the valence and conduction bands that thermal or other excitations can bridge the gap. With such a small gap, the presence of a small percentage of a doping material can increase conductivity dramatically.

An important parameter in the band theory is the Fermi level, the top of the available electron energy levels at low temperatures. The position of the Fermi level with the relation to the conduction band is a crucial factor in determining electrical properties.

Population of Conduction Band for Semiconductor



The population of conduction electrons for a semiconductor is given by

$$N_{cb} = AT^{3/2}e^{-E_{gap}/2kT}$$ Show

where

$$A = \frac{2^{5/2}(m\pi k)^{3/2}}{h^3} = 4.83x10^{21} \ \ electrons / m^3K^{3/2}$$

b. Intrinsic semiconductors: electrons and holes. Electron and hole densities in intrinsic semiconductors at thermal equilibrium. The Fermi level of intrinsic semiconductors. The principle of charge neutrality.

A silicon crystal is different from an insulator because at any temperature above absolute zero temperature, there is a finite probability that an electron in the lattice will be knocked loose from its position, leaving behind an electron deficiency called a "hole".

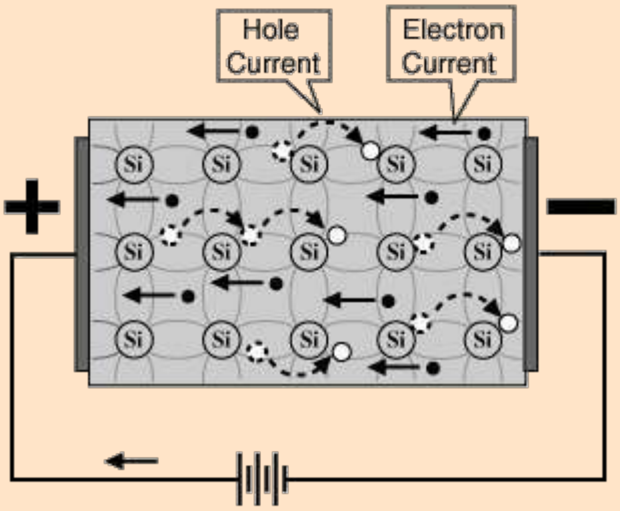
If a voltage is applied, then both the electron and the hole can contribute to a small current flow.

The conductivity of a semiconductor can be modeled in terms of theband theory of solids. The band model of a semiconductor suggests that at ordinary temperatures there is a finite possibility that electrons can reach theconduction band and contribute to electrical conduction.

The term intrinsic here distinguishes between the properties of pure "intrinsic" silicon and the dramatically different properties of doped n-typeor p-type semiconductors.

The current which will flow in an intrinsic semiconductor consists of both electron and hole current. That is, the electrons which have been freed from their lattice positions into the conduction band can move through the material.

In addition, other electrons can hop between lattice positions to fill the vacancies left by the freed electrons. This additional mechanism is called hole conduction because it is as if the holes are migrating across the material in the direction opposite to the free

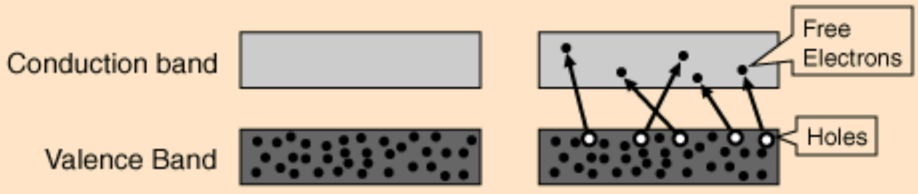


electron movement.

The current flow in an intrinsic semiconductor is influenced by thedensity of energy states which in turn influences the electron density in the conduction band. This current is highly temperature dependent.

Electrons and Holes

In an intrinsic semiconductor like silicon at temperatures above absolute zero, there will be some electrons which are excited across the band gap into the conduction band and which can produce current. When the electron in pure silicon crosses the gap, it leaves behind an electron vacancy or "hole" in the regular silicon lattice. Under the influence of an external voltage, both the electron and the hole can move across the material. In an n-type semiconductor, the dopant contributes extra electrons, dramatically increasing the conductivity. In a p-type semiconductor, the dopant produces extra vacancies or holes, which likewise increase the conductivity. It is however the behavior of the p-n junction which is the key to the enormous variety of solid-state electronic devices.



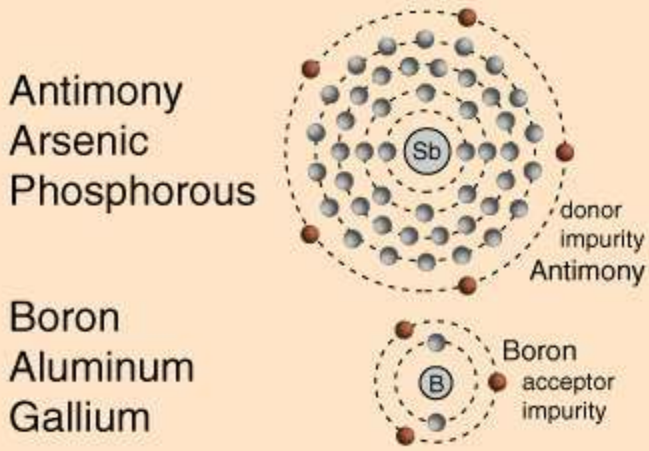
c. Doped semiconductors. Carrier densities and Fermi levels in n -type and p -type semiconductors

The Doping of Semiconductors

The addition of a small percentage of foreign atoms in the regular crystal lattice of silicon or germanium produces dramatic changes in their electrical properties, producing n-type and p-type semiconductors.

Pentavalent impurities

Impurity atoms with 5 valence electrons produce n-type semiconductors by contributing extra electrons.



Trivalent impurities

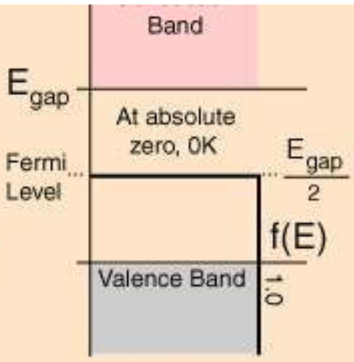
Impurity atoms with 3 valence electrons produce p-type semiconductors by producing a "hole" or electron deficiency.

Fermi Level

"Fermi level" is the term used to describe the top of the collection of electron energy levels at absolute zero temperature. This concept comes from Fermi-Dirac statistics. Electrons are fermions and by the Pauli exclusion principle cannot exist in identical energy states. So at absolute zero they pack into the lowest available energy states and build up a "Fermi sea" of electron energy states. The Fermi level is th surface of that sea at absolute zero where no electrons will have enough energy to rise above the surface. The concept of the Fermi energy is a crucially important concept for the understanding of the electrical and thermal properties of solids. Both ordinary electrical an thermal processes involve energies of a small fraction of an electron volt. But the Fermi energies of metals are on the order of electron volts. This implies that the vast majority of the electrons cannot receive energy from those processes because there are no available energy states for them to go to within a fraction of an electron volt of their present energy. Limited to a tiny depth of energy, these interactions are limited to "ripples on the Fermi sea".

At higher temperatures a certain fraction, characterized by the Fermi function, will exist above the Fermi level. The Fermi level plays an important role in the band theory of solids. In doped semiconductors, p-type and n-type, the Fermi level is shifted by the impurities, illustrated by their band gaps. The Fermi level is referred to as the electron chemical potential in other contexts.

In metals, the Fermi energy gives us information about the velocities of the electrons which participate in ordinary electrical conduction. The amount of energy which can be given to an electron in such conduction processes is on the order of micro-electron volts (see copper wire example), so only those electrons very close to the Fermi energy can participate. The Fermi velocity of these conduction electrons can be calculated from the Fermi energy.



Context of Fermi level for a semiconductor

$$v_F = \sqrt{\frac{2E_F}{m}}$$ Table

This speed is a part of the microscopic Ohm's Law for electrical conduction. For a metal, the density of conduction electrons can be implied from the Fermi energy.

The Fermi energy also plays an important role in understanding the mystery of why electrons do not contribute significantly to the specific heat of solids at ordinary temperatures, while they are dominant contributors to thermal conductivity and electrical conductivity. Since only a tiny fraction of the electrons in a metal are within the thermal energy kT of the Fermi energy, they are "frozen out" of the heat capacity by the Pauli principle. At very low temperatures, the electron specific heat becomes significant.

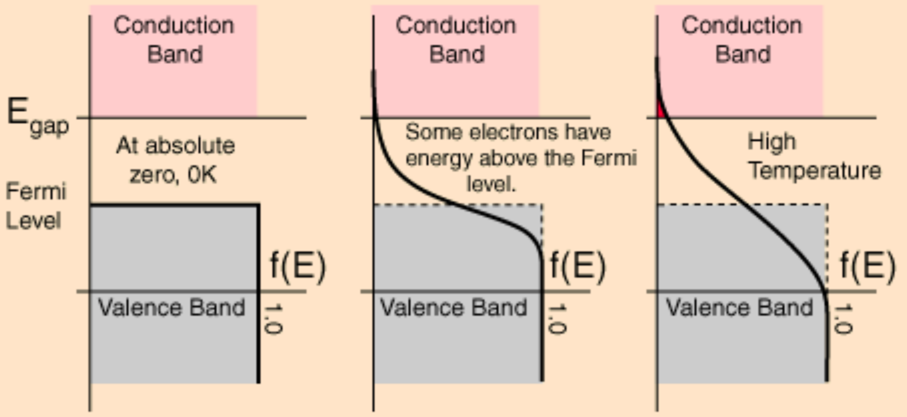
Fermi Function

The Fermi function f(E) gives the probability that a given available electron energy state will be occupied at a given temperature. The Fermi function comes from Fermi-Dirac statistics and has the form

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

The basic nature of this function dictates that at ordinary temperatures, most of the levels up to the Fermi level E_F are filled, and relatively few electrons have energies above the Fermi level. The Fermi level is on the order of electron volts (e.g., 7 eV for copper), whereas the thermal energy kT is only about 0.026 eV at 300K. If you put those numbers into the Fermi function at ordinary temperatures, you find that its value is essentially 1 up to the Fermil level, and rapidly approaches zero above it.

The illustration below shows the implications of the Fermi function for the electrical conductivity of a semiconductor. The band theory of solids gives the picture that there is a sizable gap between the Fermi level and the conduction band of the semiconductor. At higher temperatures, a larger fraction of the electrons can bridge this gap and participate in electrical conduction.



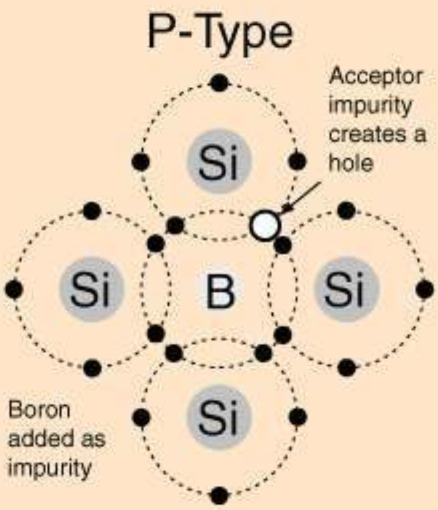
No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

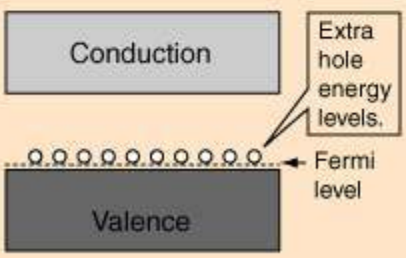
At high temperatures, some electrons can reach the conduction band and contribute to electric current.

Note that although the Fermi function has a finite value in the gap, there is no electron population at those energies (that's what you mean by a gap). The population depends upon the product of the Fermi function and the electron density of states. So in the gap there are no electrons because the density of states is zero. In the conduction band at 0K, there are no electrons even though there are plenty of available states, but the Fermi function is zero. At high temperatures, both the density of states and the Fermi function have finite values in the conduction band, so there is a finite conducting population.

P-Type Semiconductor

The addition of trivalent impurities such as boron, aluminum or gallium to an intrinsic semiconductor creates deficiencies of valence electrons,called "holes". It is typical to use B_2H_6 diborane gas to diffuse boron into the silicon material.





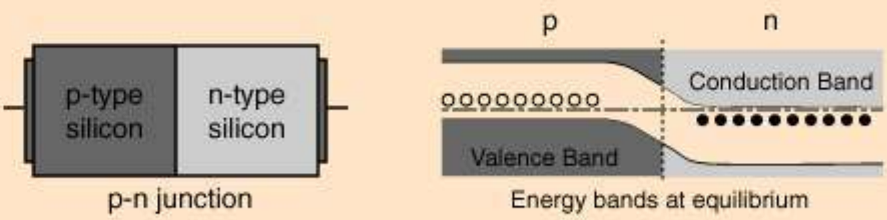
N-Type Semiconductor

The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH_3).

d. Carrier transport in semiconductors: drift and diffusion. Carrier generation and recombination in semiconductors e. The p-n junction and the p-n-p, n-p-n transistor

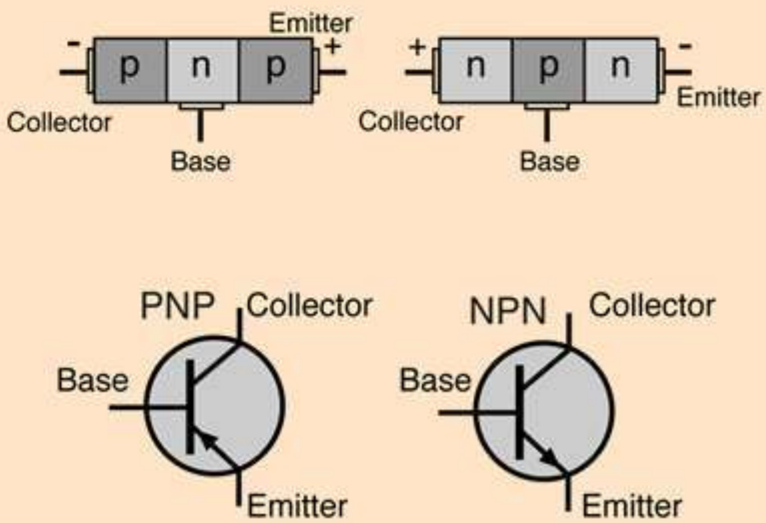
P-N Junction

One of the crucial keys to solid state electronics is the nature of the P-N junction. When p-type and n-type materials are placed in contact with each other, the junction behaves very differently than either type of material alone. Specifically, current will flow readily in one direction (forward biased) but not in the other (reverse biased), creating the basic diode. This non-reversing behavior arises from the nature of the charge transport process in the two types of materials.



The open circles on the left side of the junction above represent "holes" or deficiencies of electrons in the lattice which can act like positive charge carriers. The solid circles on the right of the junction represent the available electrons from the n-type dopant. Near the junction, electrons diffuse across to combine with holes, creating a "depletion region". The energy level sketch above right is a way to visualize the equilibrium condition of the P-N junction. The upward direction in the diagram represents increasing electron energy.

The Junction Transistor



A bipolar junction transistor consists of three regions of doped semiconductors. A small current in the center or base region can be used to control a larger current flowing between the end regions (emitter and collector). The device can be characterized as a current amplifier, having many applications for amplification and switching.