Extrinsic Semiconductors

The real power of semiconductors is realized by adding small, controlled amount of specific dopant, or impurity atoms. The doping process can greatly alter the electrical characteristics of the semiconductor. The doped semiconductor called extrinsic semiconductors, which is the primary reason that we can fabricate the various semiconductor devices. The usual doping are:

1. V group atoms having five valence electrons (arsenic, antimony, phosphorus) or
2. III group atoms having three valence electrons (gallium, indium, aluminum, boron).

V group doping atom is known as donor atom because it donates one electron to the conduction band of pure semiconductor. The III group atom, on the other hand, is called acceptor atom because it accepts one electron from the semiconductor atom.

Extrinsic semiconductors can be subdivided into two classes:

(i) n-type semiconductors

(ii) p-type semiconductors.

(i) <u>n-type Extrinsic Semiconductor.</u>

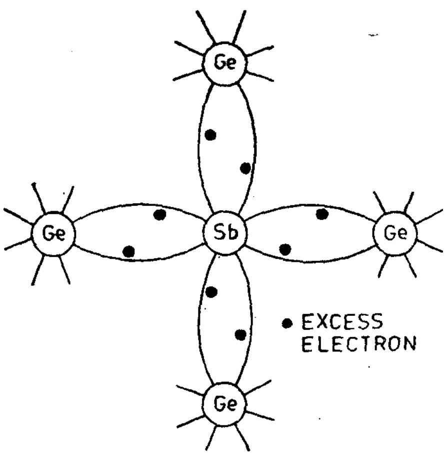

Fig. 5.1 Schematic bond representation for n-type germanium doped with antimony

This n-type is obtained when a V Group material like antimony (Sb) is added to pure semiconductor crystal; each antimony atom forms covalent bonds with the surrounding four germanium atoms with four of its five electrons. The fifth electron is loosely bound to the antimony atom. Hence, it can be easily excited from the valence band to the conduction band, practically every antimony atom introduced one ***conduction electron without creating a positive hole, and makes the pure semiconductor an n-type (n for negative) extrinsic.*** In terms of energy levels, the fifth antimony electron has an energy level (called donor level) just below the conduction band. Usually, the donor level is 0.01 eV below conduction band for germanium and 0.054 eV for silicon. In n-type semiconductor, ***electrons are the majority carriers (n_n)*** while ***holes the minority carriers (p_n), (n_n)*** >>***(p_n)***.

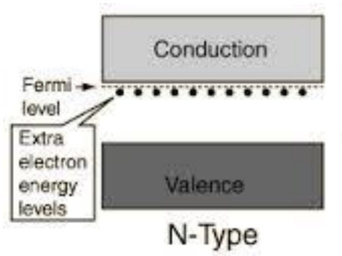

Fig. 5.2 The energy band diagram showing the discrete donor energy state

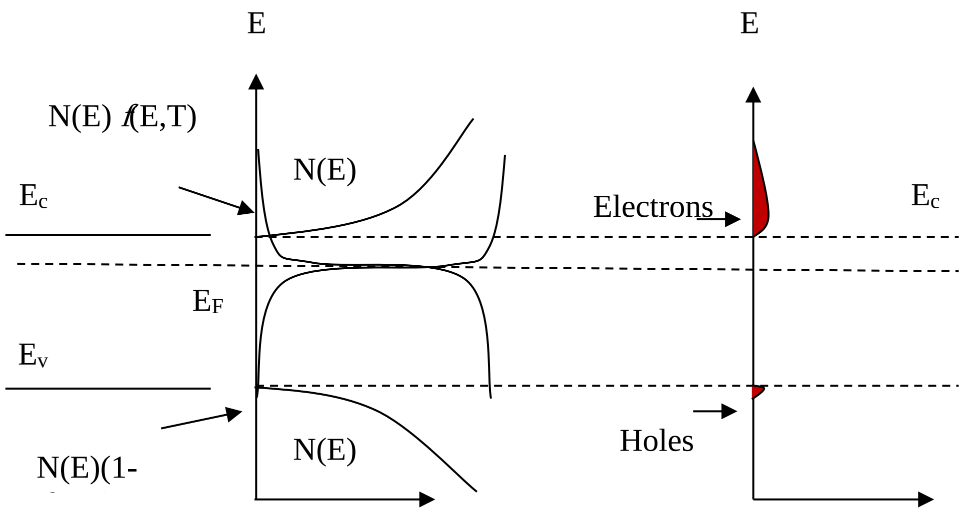

Fig. 5.3 The density of states function N(E), the Fermi-Dirac distribution function f(E), and areas representing electron and hole concentrations for the case when E_F is above the intrinsic Fermi energy.

(ii) p-type Extrinsic Semiconductor.

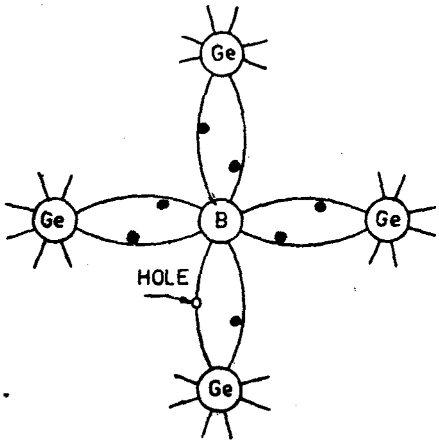

Fig. 5.4 Schematic bond representation for p-type germanium doped with boron

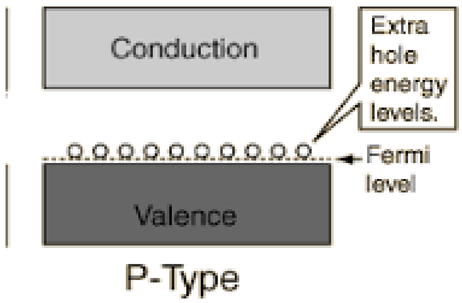

Fig. 5.5 The energy band diagram showing the discrete acceptor energy state

This p-type is obtained when a III Group material like boron (B) is added to pure semiconductor crystal. In this case, the three valence electrons of boron atom form covalent bonds with four surrounding germanium atoms but one bond is left incomplete and gives rise to a hole

Thus, boron which is called an acceptor impurity causes as many positive holes in a germanium crystal as there are boron atoms thereby producing a p-type (p for positive). Accordingly, ***holes form the majority carriers (p_p)*** whereas ***electrons form the minority carriers(n_p)***, ***(p_p)*** >>***(n_p)***. Fermi level shifts nearer to the valence band, the acceptor level lies immediately above the Fermi level. Conduction is by means of hole movement.

law mass of action $n_i^2=n_i\,p_i=n_n\,p_n=n_p\,p_p$

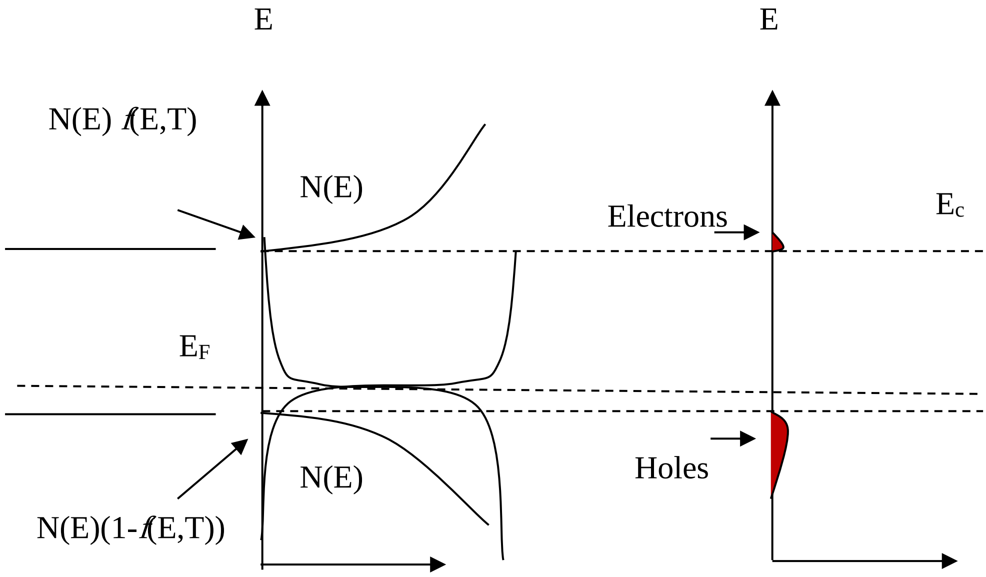

Fig. 5.6 The density of states function N(E), the Fermi-Dirac distribution function f(E), and areas representing electron and hole concentrations for the case when E_F is below the intrinsic Fermi energy.

Majority and Minority Carriers

In a piece of pure semiconductor, no free charge carriers are available at 0°K, as its temperature is raised to room temperature, some of the covalent bonds are broken by heat energy and as a result, electron-hole pairs are produced. These are called thermally-generated charge carriers/

An intrinsic semiconductor can be converted into a:

- p-type semiconductor by the addition of an acceptor impurity***(N_A)*** adds a large number of holes to it. Hence, in p-type holes ***(p_p)***both added ***(N_A)***and thermally-generated ***(p_i)***

$$p_p = N_A + p_i$$

- N-type semiconductor by the addition of an donor impurity***(N_D)*** adds a large number of electrons to it. Hence, in N-type electrons ***(n_n)*** both added ***(N_D)*** and

$$n_n = N_D + n_i$$

thermally-generated ***(n_i)***

Example

Calculate the number of free electrons in pure silicon at ordinary temperatures. If one silicon atom out of every million atoms is replaced by an arsenic atom, how many free electrons per cubic meter are there? If density 2.33×10^3 kg/m^3, atomic weight 28.086, E_g=1.1eV.

Solution

$$n_i = \sqrt{N_v N_c}\,\exp(-Eg/2kT) = 1.46\times10^{16}/m^3$$

$$N = \frac{N_{Avo}\times Density}{Atomicweight} = 5\times10^{28}/m^3$$

No. of impurity atom=N_D

$$N_D = \frac{5\times10^{28}}{10^6} = 5\times10^{22}/m^3$$

$$n_n = N_D + n_i = 5\times10^{22} + 1.467\times10^{16}$$

$$n_n = 10^{16}(5\times10^6 + 1.467) \approx 5\times10^{22}$$

Example

Calculate the number of electrons and holes in silicon if Fermi energy is 0.25 below the conduction. At T=300K, the value of $N_c=2.8\times10^{25}/m^3$ and $N_v=1.04\times10^{25}/m^3$.

Solution

If we have the bandgap energy of silicon is 1.12 then the Fermi level will be 0.87 eV above E_v

$$n = N_c \exp(-(E_c - E_F)/kT)$$

$$n = \left(2.8 \times 10^{25}\right)\exp(-(0.25)/0.0259) = 1.8 \times 10^{19}\, m^{-3}$$

$$p = N_v \exp(-(E_F - E_v)/kT)$$

$$p = \left(1.04 \times 10^{26}\right)\exp(-(0.87)/0.0259) = 2.7 \times 10^{10}\, m^{-3}$$

The change in the Fermi level is a function of the donor and acceptor impurity concentration.

Compensated Semiconductor

Compensated Semiconductor is one that contain both donor and acceptor impurities in the same region. During the manufacture of Semiconductor devices n-type material may have to be changed to p-type by addition acceptor impurities N_A and the reverse also required.

If $N_D >> N_A$ n-type

$N_A >> N_D$ p-type

$N_A = N_D$ intrinsic

Neutrality Base: +ve charge= -ve charge

$$p + N_D^+ = n + N_A^-$$

$$n_i^2 = np$$

And if

$$\left|N_D - N_A\right| >> n_i \quad \text{Then it is n-type}$$

$$n_n \approx N_D - N_A$$

if

$$\left|N_A - N_D\right| >> n_i \quad \text{Then it is p-type}$$

$$p_p \approx N_A - N_D$$

Example

Calculate the number of electrons and holes in n-type silicon. At T=300K, if the value of $N_D=10^{22}/m^3$ and $N_A=0$. $n_i=1.5\times10^{16}/m^3$

Solution

$$\left|N_D - N_A\right| >> n_i$$

$$n_n \approx N_D - N_A \approx 10^{22}/m^3$$

$$p_n = \frac{n_i^2}{n_n}$$

$$p_n = \frac{\left(1.5\times10^{16}\right)^2}{10^{22}} = 2.25\times10^{10}/m^3$$

Example

In silicon at ordinary temperatures calculate majority and minority carriers for (i) donor impurities $2.4\times10^{19}/m^3$ (ii) donor impurities $2.4\times10^{19}/m^3$ and acceptor impurities $4.8\times10^{19}/m^3$. Eg=1.12eV.

Solution

(i)

$$n_i = \sqrt{N_v N_c}\exp(-Eg/2kT) = 1.46\times10^{16}/m^3$$

majority carriers

$$n_n = N_D = 2.4\times10^{19}/m^3$$

minority carriers

$$p_n = \frac{n_i^2}{n_n} = \frac{\left(1.46\times10^{16}\right)^2}{2.4\times10^{19}} = 0.896\times10^{13}/m^3$$

(ii)

p-type

$$N_A > N_D$$ is

$$|N_A - N_D| >> n_i$$

$$|N_A - N_D| = |4.8\times10^{19} - 2.4\times10^{19}| = 2.4\times10^{19} / m^3$$

$2.4\times10^{19} > 1.46\times10^{16}/m^3$

$$p_p \approx N_A - N_D = 2.4\times10^{19} / m^3$$

$$n_p = \frac{n_i^2}{p_p} = 0.896\times10^{13} / m^3$$

Example

In silicon at ordinary temperatures calculate majority and minority carriers if doped with $3\times10^{22}/\ m^3$ acceptor impurities and $2.9\times10^{22}/m^3$ donor impurities $E_g=1.1eV$.

Solution

Is

$$|N_D - N_A| >> n_i$$

$$|N_D - N_A| = |2.9\times10^{22} - 3\times10^{22}| = 1\times10^{21} / m^3$$

$n_i = 1.46\times10^{16}/m^3$

$10^{21} >> 1.46\times10^{16}/m^3$

then $p_p = N_A - N_D = 1\times10^{21}/m^3$

$$n_p = \frac{n_i^2}{p_p} = 2.152\times10^{11} / m^3$$

Problems

Q1: Calculate electrons and holes concentration in a germanium sample . If T=300 K, $N_d=5\times10^{19}/m^3$, $N_a=0$. Assume that $n_i=2.4\times10^{19}/m^3$.
(Ans: $5.97\times10^{19}/m^3$, $9.65\times10^{18}/m^3$)

Q2: Calculate holes and electrons concentration in compensated silicon p-type sample. If T=300 K, $N_d=3\times10^{21}/m^3$, $N_a=10^{22}/m^3$. Assume that $n_i=1.5\times10^{16}/m^3$.
(Ans: $7\times10^{21}/m^3$, $3.2\times10^{10}/m^3$)