Physics of Semiconductors

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1.1 INTRODUCTION

An understanding of the electrical properties of semiconductors is a prerequisite to the study of electronic devices, both bipolar (BJT) and unipolar (MOS). All materials available on the earth are grouped under three categories depending on their ability to conduct electricity through it. They are the following:

- Conductors (silver, copper, aluminium, etc.)
- Semiconductors (germanium (Ge), silicon (Si), aluminium—gallium-arsenide, etc.)
- Insulators (glass, ceramic, bakelite, rubber, air, element sulfur)

1.1.1 Conductors

What makes a material a conductor or an insulator or a semiconductor? We know that any solid has vast number of electrons but all of them do not take part in conduction of current through them. Only the valence electrons (outer-cell electrons) can take part in conduction of current, but they are bound. They participate in the formation of the covalent bond. These covalent bonds of the electrons must be broken to make them free. Since the valence bonds are weak as they are from the outermost shell of the atom, they can be broken easily. In metals, a large number of valence bonds can be broken very easily with or without even supply of external energy. So a large number of electrons become available for conduction of current at room temperature, that is, T _ 300 K.

Silver, copper, aluminium, etc., having plenty of free electrons, are responsible for electrical conduction through them and are called **metals**. The number of available free electrons determines the amount of conduction of electric current through it. If the proportion of free electrons in a material is high, the material conducts large current. They offer very low resistively ($<10^{-8}$ Ωm) to electric current flow.

1.1.2 Insulators

On the contrary, the valence bonds of insulator are very strong and require large energy to break them that at times with that amount of energy the solid material becomes liquid or gets destroyed. In other words, the valence bonds of insulator is so strong that, theoretically even, very few bonds are broken and insignificant conduction of current takes place at T = 300 K. Materials such as glass, ceramic, quartz, bakelite, rubber, air, and the element sulfur are insulators having extremely high resistively ($>10^{10}$ Ωm), that is, they **conduct electric current** rather **poorly**.

1.1.3 Semiconductors

The valence bonds of semiconductor can be broken very easily in its extrinsic form and sufficient numbers of free electrons are made available for conduction of current. To quantify the concentration of carrier, we have to represent the concentration for carrier (electrons) under equilibrium condition including different parameters that affects its concentration by an expression as

$$n_i = N\left(\frac{1}{\text{p}}\right)^{\frac{E}{KT}} \tag{1}$$

where N is the atomic concentration in Si, p is probability that an atom can be hit by a particle, E is bond strength, kT' is the average particle energy at T under equilibrium. Here, E/kT represents number of particle that must converge on their atom and to provide the energy E equal to the bond strength. We know that the probability p is always less than 1. Since $p < 1$, Eq. (1) can be rewritten to suite the better explanation of it as

$$\ln n_i = \ln N - \frac{E}{kT}\ln\left(\frac{1}{\text{p}}\right) \tag{2}$$

The $(1/p)$ in Eq. (2) is more than 1 and so In $\frac{1}{p}$ is a positive quantity. Equation (3) can be approximated as

$$\ln n_i\, 1 - \frac{E}{kT} \tag{3}$$

If we try to plot Eq. (3) for concentration of carriers '*ni*' on log scale on the y axis w.r.t. to the reciprocal of the absolute temperature on the x axis, we get a straight line as indicated in **Fig. 1.1**. What we observe from Fig.1.1 is that the carrier concentration is associated with the bond strength E. As the bond strength of GaAs is 1.41 eV, Si is 1.1 2eV, and Ge is 0.71 eV, the carrier concentration very much depends on the theses energies. For GaAs energy, requirement is more and, hence, a minimum number of carrier concentration is available for it at any temperature w.r.t. the Si and Ge.

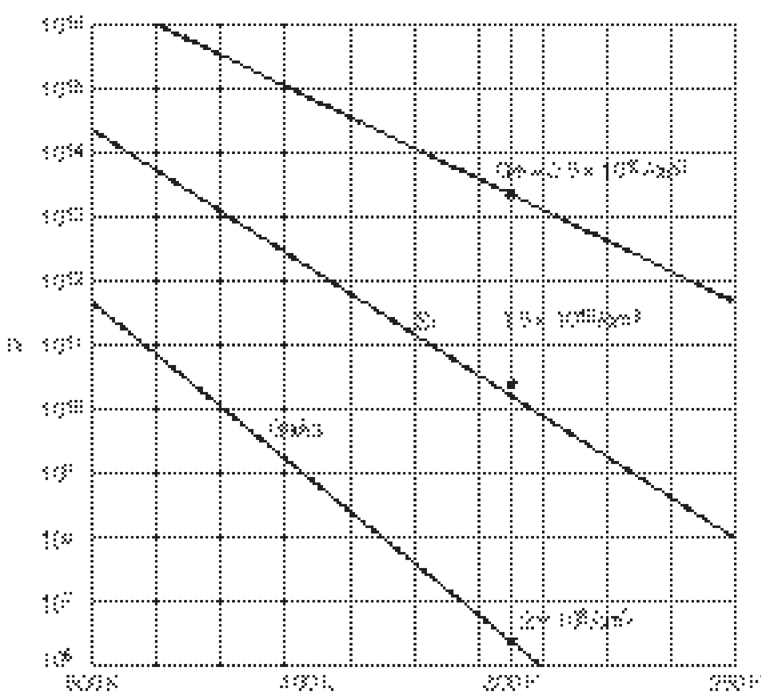


Figure 1.1 *Variation in intrinsic carrier concentration w.r.t. temperature.*

We will be concentrating on Si semiconductor as it is presently dominating the semiconductor manufacturing industry. Table 1.1 presents relevant properties of some of the important elemental semiconductors. If we examine the table carefully, what we observe is that as the atomic number (size of the atom) of the element is increasing its band gap is decreasing. It indicates that the smaller size atoms in any semiconductor are very closely packed. The bonds of the closely packed atoms are very strong. The carbon having very high band gap (E_G = 5.3 eV) is insulator because its atoms are very small in size and, hence, very closely packed inside the crystal structure. The atom size of Si, Ge, and tin (Sn) are much larger than that of the carbon and, hence, they are not so closely packed inside the crystal structure have low band gaps and are called semiconductors. The other revelation of the Table 1.1 is that as the band gap goes on increasing, the resistivity also goes on increasing. The resistivity of the carbon (C) is as high 10^{14} Ω cm where the resistivity of the Sn (semiconductor) is as low as 10^{-4} Ω cm.

Table 1.1 *Properties of elemental semiconductor*

Element	Atomic weight	Band gap (eV)	Resistivity
C	6	5.30	10^{14} Ω cm
Si	14	1.12	10^{5} Ω cm
Ge	32	0.67	10^{2} Ω cm
Sn	50	0.08	10^{-4} Ω cm

Advantages of semiconductor are

1. of much greater density than a gas,
2. reduced ionisation energy (of the order of 1 eV = $1.6 \times 10^{-19} \times 1$ J to produce an electron—hole pair, compared with 5 eV to ionise a solid insulator and 30 eV to ionise a gas),
3. a much greater density of free carriers is produced in a semiconductor,
4. ideal for making the ultra-small, high-speed transistors that implement the modern processor,
5. can be manufactured into large pieces of uniform composition and high quality,
6. larger the crystal (8–12 in. diameter), the more chips can be manufactured at the same time, and the less waste material, thus saving money,
7. of the appropriate hardness so that it can be cut into thin slices without being so brittle that it cracks,
8. readily available and relatively inexpensive, to ensure supply and keep costs down,
9. rapid heating at 20,000°C per second to unlimited temperatures,
10. dopants moved only by 20—30 Å,
11. ultra shallow junctions.

Let us concentrate our discussion on semiconductor because we would be talking, hence forth, regarding devices made of semiconductors and its uses. There are two types of carriers in a semiconductor, namely

- Electrons
- Holes

We have seen in Fig. 1.2 that one electron has gone to the conduction band leaving behind a vacancy. This vacancy is conceptually a positive charge carrier having equal but opposite charge of the electron. This carrier is called **hole**. Hence, the positive charge carrier, the hole, can also move in opposite direction of the electron can contribute to current flow.

The two types of processes occur in a pure or intrinsic semiconductor

- generation and
- recombination

An electron-getting energy in the valence band moves to the conduction band leaving behind a hole in the valence band is called generation process. Although an electron falling back from conduction band to the valence band may though of as recombination process. Under equilibrium, the generation is equal to the recombination.

The process of generation is proportional to temperature, that is, $G = f(T)$ and the process of recombination is proportional to the product of the electron and hole. So if we equate these two

$$G = f(T) = R = np = n_i^2$$

It means that at any temperature, the product of electron and hole concentration remains constant. Since electrons and holes are generated and recombine in pairs, the number of holes must be equal to the number of electrons. Since, $n = p$, then $n^2 = p^2 = n_i^2$, so, $n = p = n_i^2$ in an intrinsic semiconductor. The n_i is called the intrinsic carrier concentration. The n_i is function of material and the temperature both. For example, Si having 1.12 eV band produces carriers at room temperatures [I1]300 K and 500 K as

$$ni\ (\text{Si, 300K}) = 1.5 \times 10^{10}/\text{cm}^3;\ ni\ (\text{Si, 500K}) = 2.5 \times 10^{14}/\text{cm}^3$$

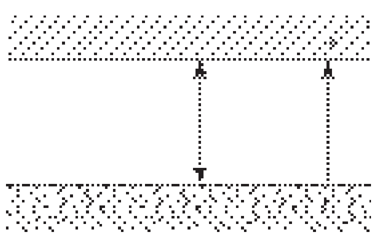


Figure 1.2 *Energy band diagram of semiconductor.*

The energy band gap at 0 K of Ge and Si are 0.785 and 1.21 eV, respectively. The forbidden energy gap decreases with increasing temperature leading to increasing conductivity. It is found that E_G decreases at a rate of 3.6×10^{-4} eV/K in the case of Si, that is,

$$E_G\ (\text{T}) = 1.21 - 3.6 \times 10^{-4}\ \text{T}$$

Similarly in the case of Ge, the energy gap decreases at the rate of 2.24×10^{-4} eV/K.

Example

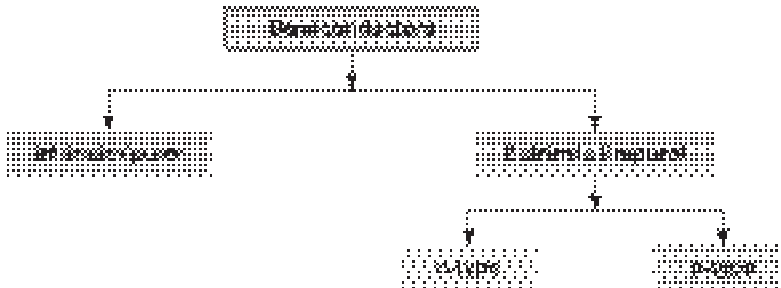
Find the band gap of Si and Ge at room temperature(300 K).

$$E_G\ (\text{Si, 300K}) = 1.21 - 3.6 \times 10^{-4} \times 300 = 1.21 - 0.1 = 1.1\ \text{eV}$$

$$E_G\ (\text{Ge, 300K}) = 0.785 - 2.24 \times 10^{-4} \times 300 = 0.71 - 0.0669 = 0.718\ \text{eV}$$

The Ge having less band gap ($E_G = 0.72$ eV) has more carriers (at least 1,000 times) than that of the Si at room temperature (300 K).

The semiconductor has become very important only because its conductivities can be changed to several orders of magnitude by introducing controlled amount of impurities. Adding of controlled impurities is called doping and the resulting material is called doped semiconductor. The doped semiconductor is called the extrinsic semiconductor. The extrinsic semiconductor is of two types:



The type of the material depends on the type of the impurity introduced. If pentavalent element impurity is introduced into the tetravalent element, the resulting material is called n-type. Here, the ‘n’ stands for negative-charge carriers. The pentavalent element has five electrons in its outermost orbit. The four electrons of the tetravalent element cover the four electrons from all around of the fifth valent element and the fifth electron is left bound loosely to its parent atom. This fifth electron can be detached with very small amount of energy. Hence, each impurity atom is supplying one loosely bound electron and was given the name n-type material. Similarly, if controlled impurity of trivalent element is introduced into the tetravalent element, each trivalent element introduces one hole which is loosely bound to the parent atom. This loosely bound hole can be made free with very small amount of energy. This is the reason it is called p-type material. Here, the ‘p’ stands for positive-charge carriers. The group V elements are called donor, because it can donate one electron and group-III elements are called acceptor because it can accept one electron.

Now again we go back to the discussion of concentration of charge carriers as in Eq. (3). Since we cannot calculate the value of probability p and, hence, exact numbers of carrier concentration cannot be calculated. Only an approximate behaviour can be predicted by the above-mentioned mathematical model. To have better picture of carrier concentration at any temperature, we must consider the band model.

Band model is more appropriately called energy band model. What energy band model does? It tries to analyze population of electrons in terms energy possessed by electrons. Electrons are distributed over a range of energy at a given temperature. What we have to do is to find out a way how electrons are distributed over energy at a given temperature? If there is some way of finding this distribution, we can very easily separate what part of electrons that is free and the other part that is not free at any temperature.

Solids having conductivity between metals and insulators are called semiconductors. Semiconductor materials, used in manufacturing solid-state devices and ICs, are of two types, namely,

- Elemental semiconductor
- Compound semiconductor

Important elemental semiconductor materials are from Group IV of periodic table such as

- Silicon (Si)
- Germanium (Ge)
- Diamond (C)