5.1 ACTIVE RF COMPONENTS:

SEMICONDUCTOR BASCS IN RF:

PHYSISCAL PROPERTIES OF SEMICONDUCTORS:

The operation of semiconductor devices is naturally dependent on the physicd behavior of the semiconductors themselves. This section presents a brief introduction to the basic building blocks of semiconductor device modeling, particularly the operation of the pn-junction. In our discussion we will concentrate on the three most commonly used semiconductors: germanium (Ge), silicon (Si), and gallium arsenide (GaAs). Fig 5.1.1 (a) schematically shows the bonding structure of pure silicon: Each silicon atom shares its four valence electrons with the four neighboring atoms, forming four covalent bonds.

In the absence of thermal energy (i.e., when the temperature is equal to zero degree Kelvin [T°K = 0 or F°C = —273.15 , where T'° K = 273.15 + T'°C)) all electrons are bonded to the corresponding atoms and the semiconductor is not conductive. However, when the temperature increases, some of the electrons obtain sufficient energy to break up the covalent bond and cross the energy gap W = *W* - *W* , as shown in Figure 5.1.1(b) (at room temperature *T* -- 300°K the bandgap energy is equal to 1.12 eV for Si, 0.62 eV for Ge, and 1.42 eV for GaAs). These free electrons form negative charge carriers that allow electric current conduction. The concentrator of the conduction electrons in the semiconductor is denoted as n. When an eleckon breaks the covalent bond it leaves behind a positively charged vacancy, which can be occupied by another free electron. These types of vacancies are called holes and their concentration is denoted by *p.*

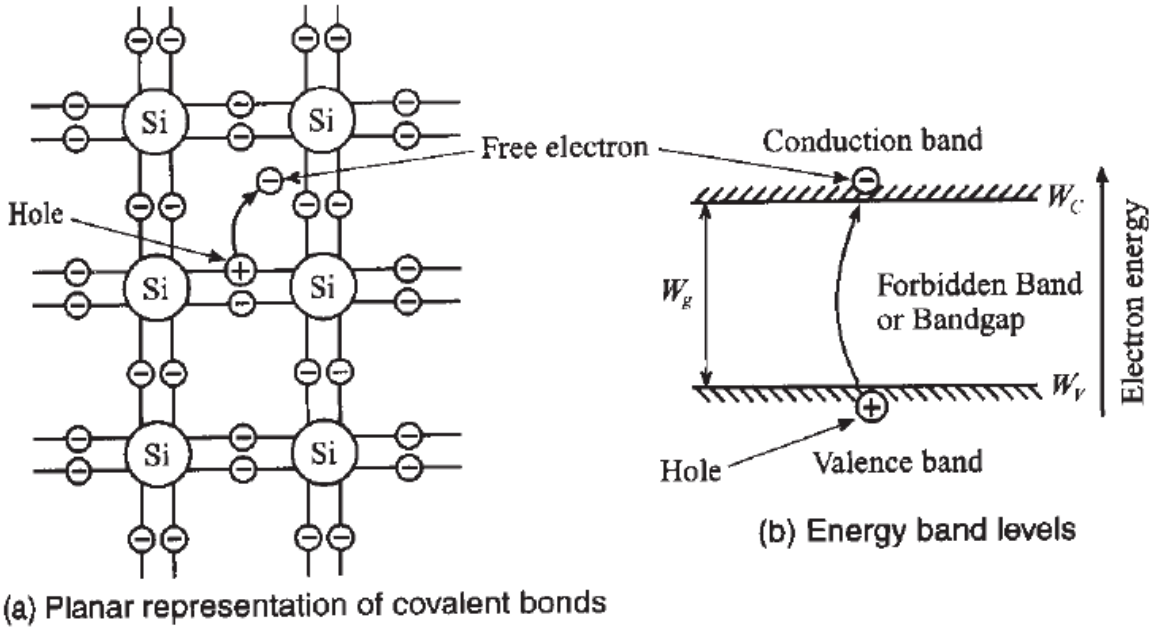

Fig: 5.1.1 Lattice structure and energy levels of silicon

[Source: Reinhold Ludwig and Powel Bretchko,‖ RF Circuit Design – Theory and Applications, Page-273]

Role, they recombine and both charge carriers disappear. In thermal equilibrium we love equal number of recombinations and generations of holes and electrons. The con- centrations obey the Fermi statistics according to

$$n = N_C \exp\left[\frac{W_C - W_F}{kT}\right]$$

$$p = N_V \exp\left[\frac{W_F - W_V}{kT}\right]$$

$$N_{C,V} = 2\,(2\,m^*_{n,p}\,\pi\,k\,T/\,h^2)^{3/2}$$

are the **effective carrier concentration** in the conduction N_C) and valence $N\,q$) bands, respectively. The terms W_C and W_V denote the energy levels associated with the conduction and valence bands and Wp is the **Fermi energy level,** which indicates

the energy level that has a 50% probability of being occupied by an electron. For

intrinsic (i.e., pure) semiconductors at room temperature the Fermi level is very close to the middle of the bandgap. In (6.2), m_n and *mp* refer to the effective mass of elec- trons and holes in the semiconductor that are different from the free electron rest mass due to interaction with the crystal lattice; k is Boltzmann's constant; *h* is Planck's con-

stant; and P is the absolute temperature measured in Kelvin.

In an intrinsic semiconductor the number of free electrons produced by thermalexcitation is equal to the number of holes (i.e. n = *p* -- n_i). Therefore, electron and hole concentrations are described by the concentration law

$$np = n_i^2$$

where a; is the intrinsic concentration. Equation (6.3) is true not only for intrinsic butalso for doped semiconductors, which are discussed later in this section.

$$n_i = \sqrt{N_C N_V}\exp\left[-\frac{W_C - W_V}{2kT}\right] = \sqrt{N_C N_V}\exp\left[-\frac{W_g}{2kT}\right]$$

Classical electromagnetic theory specifies the electrical conductivity in a materid to be $a = JZE$, where is the current density and ñ is the applied electric field. The conductivity in the classical model (Drude model) can be found through the carrier con- centration N, the associated elementary charge q, the drift velocity v_d , and the applied

electric field ñ:

$$\sigma = \frac{q\,N\,v_d}{E}$$

In semiconductors, we have both electrons and holes contributing to the conductivity ofthe material. At low electric fields the drift velocity v_d of the carriers is proportional to the applied field strength through a proportionality constant known as **mobility** q .

$$\sigma = qn\mu_n + qp\mu_p$$

where q , *qp* are the mobilities of electrons and holes, respectively. For intrinsic semi-conductors we can simplify (6.6) further by recalling that n = *p* - *n* , that is,

$$\sigma = qn_i(\mu_n + \mu_p) = q\sqrt{N_C N_V}\exp\left[-\frac{W_g}{2kT}\right](\mu_n + \mu_p)$$

It is desired to find the conductivities for the intrinsic materials of Si, Ge, and GaAs as a function of temperature. To make the compu-tations not too difficult, we assume that the bandgap energy and the mobilities for holes and electrons are temperature independent over the range of interest —50°C ñ *T* ñ 200°C in Fig 5.1.2 .

Solution: As a first step it is convenient to combine into one parameter O_0(F) all factors without the exponential term is given by,

$$\sigma_0(T) \quad q\sqrt{N_C N_V}(\mu_n + \mu_p)$$

where electron and hole mobilities are found from Table E-1:Jim = 1350(Si), 3900(Ge), 8500(GaAs)

Up 480(Si), 1900(Ge), 400(GaAs)

$$N_{C,V}(T) = N_{C,V}(300°\text{K})\left(\frac{T}{300}\right)^{3/2}$$

This leads to the form

$$\sigma = \sigma_0(T)\exp\left(-\frac{W_g}{2kT}\right) = q(\mu_n + \mu_p)\sqrt{N_C N_V}\left(\frac{T}{300}\right)^{3/2}\exp\left(-\frac{W_g}{2kT}\right)$$

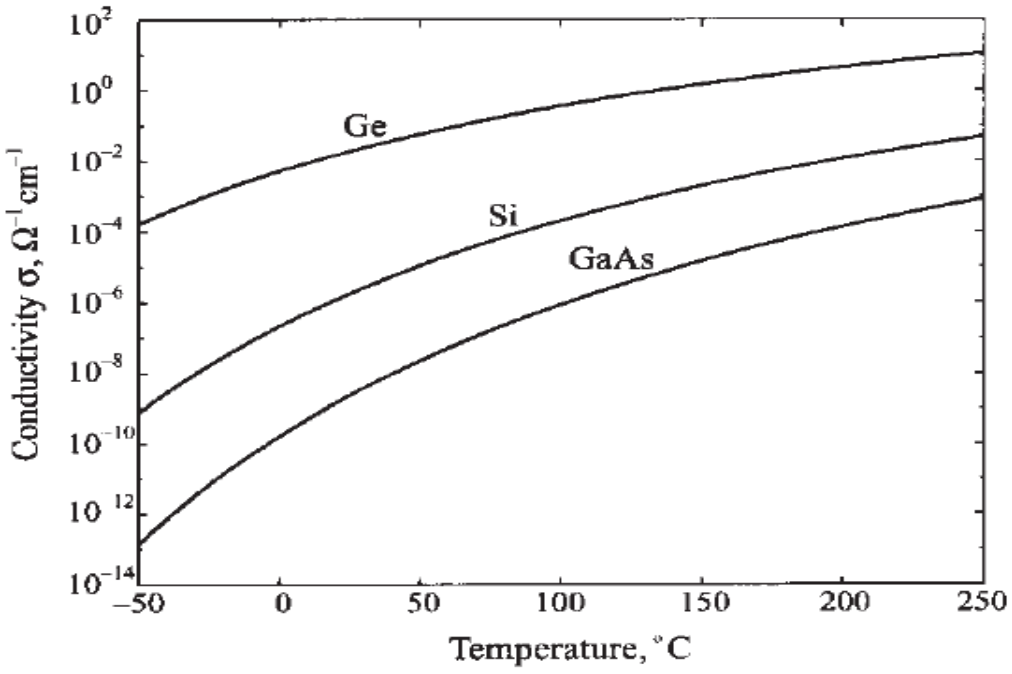

Fig: 5.1.2 Conductivity of Si, Ge, GaAS in the range from -50° C to 250° C

[Source: Reinhold Ludwig and Powel Bretchko,‖ RF Circuit Design – Theory and Applications, Page-276]

A major change in the electrical properties of a semiconductor can be initiated by introducing impurity atoms. This process is called doping, as shown in Figure 5.3(a). To achieve o-type doping (which supplies additional electrons to the conduction band) we introduce atoms with a larger number of valence electrons than the atoms in the intrinsic semiconductor lattice that they

substitute. For instance, the implantation of phosphorous (P) atoms into Si introduces loosely bound electrons into the neutral crystal lattice, as shown in Figure 5.3(b).

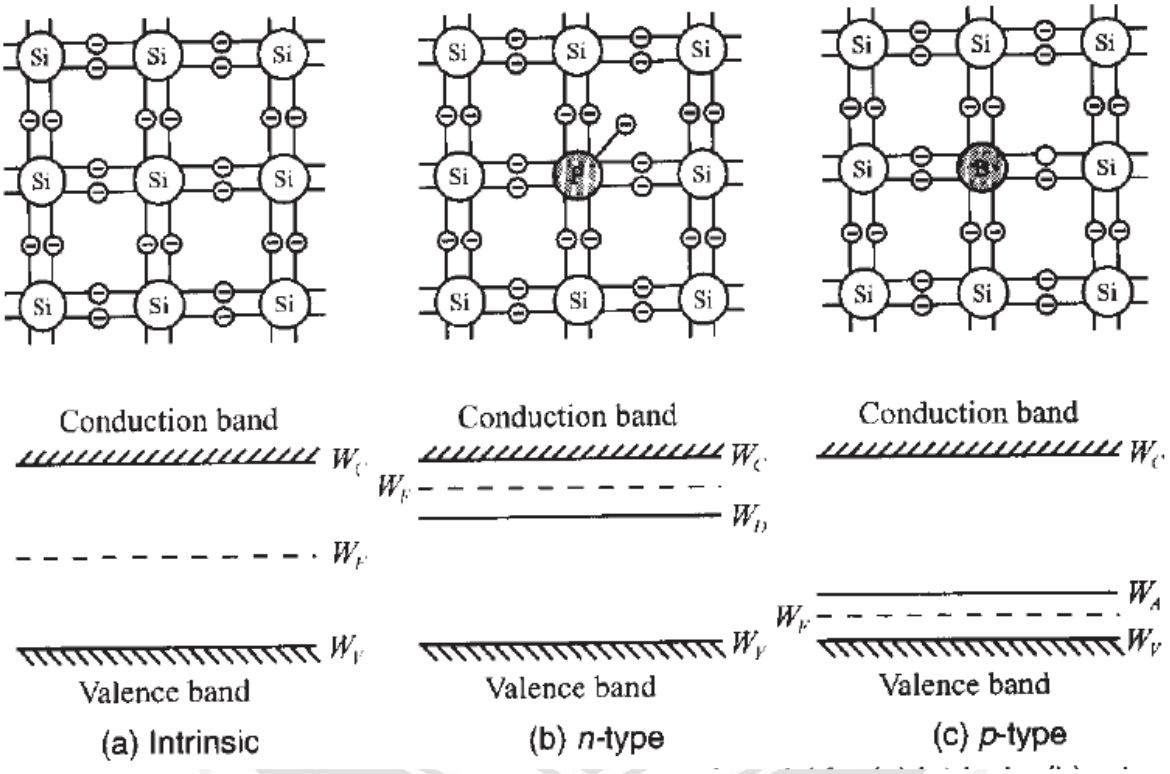

Fig: 5.3 Lattice structure and energy bang model for (a) intrinsic (b) n-type (c) p-type

[Source: Reinhold Ludwig and Powel Bretchko,‖ RF Circuit Design – Theory and Applications, Page-277]

It is intuitively apparent that the energy level of this "extra" electron is closer to the conduction band than the energy of the remaining four valence electrons. When the temperature is increased above absolute zero, the loosely bound electron separates from the atom, forming a free negative charge and leaving behind the fixed positive ion of phosphorous, as shown in Figure 5.3(c). Thus, while still maintaining charge neutrality, the atom

has donated anelectron to the conduction band without creating a hole in the valence band. This results in an increase in the Fermi level since more electrons are located in the conduction band. Contrary to the intrinsic semiconductor *(n ¡, p,*) we now have an n-type semicon- ductor in which the electron concentration is related to the hole concentration as

$$nq = N_D + p$$