CHAPTER I

INTRODUCTION

The importance of the semiconductor materials lies in their flexibility of controlling their properties. Conductivity can be varied over several orders of magnitude by changing temperature, optical excitation, and impurity content without altering the bandgap and other basic parameters of the host material [1].

1.1 Semiconductors with shallow and deep level impurities :

For most of the device applications, semiconductors are doped with impurities. In the case of silicon, a IV group element, III or V group elements are used as impurities. These impurities control the type and conductivity properties of silicon. III group impurities act like acceptors and the V group impurities act like donors in silicon. The ionization energies of these impurities are low, and hence the energy levels of these impurities are close to the band edges. Therefore, these impurities are generally referred as shallow level impurities. These shallow level impurities are widely used in the fabrication of semiconductor devices like p-n junctions, Zener diodes, tunnel diodes, transistors, power devices, junction lasers etc. The fundamental properties such as ionization energies and capture cross-sections of these shallow levels are adequately understood in terms of the hydrogenic model in the effective mass approximation [2,3].

The other class of impurities namely deep level impurities, give energy levels deep in the forbidden gap of the semiconductor. Even though the impurities are broadly classified into two groups, namely shallow (<50 meV) and deep levels (>50 meV), depending on their ionization energies [4,5], the exact demarcation is not possible by this criteria. Hjalmarson et.al., [6] have suggested the classification of deep and shallow levels based on their pressure coefficients. According to their scheme, the impurity is called deep impurity if the associated level does not follow the nearby band edge when that edge is perturbed by pressure. The pressure coefficients of deep levels are of the order of 10^{-6}, about two orders of magnitude larger than those of shallow levels.

Generally, deep levels appear in the forbidden gap due to the presence of impurities which do not fit well in the host lattice (such as transition elements), intrinsic impurities (such as interstitials, vacancies) and damage induced by radiation of high energy particles (electrons, protons, neutrons, gamma rays etc.). Deep impurities are distinguished by their multiple charge states and fast diffusion coefficients unlike shallow impurities.

Solid solubility for deep levels are low and often difficult to control. They often form complexes with other impurities and vacancies. They also tend to precipitate at dislocations. Fig.1.1 shows the energy levels of different impurities in silicon [7].

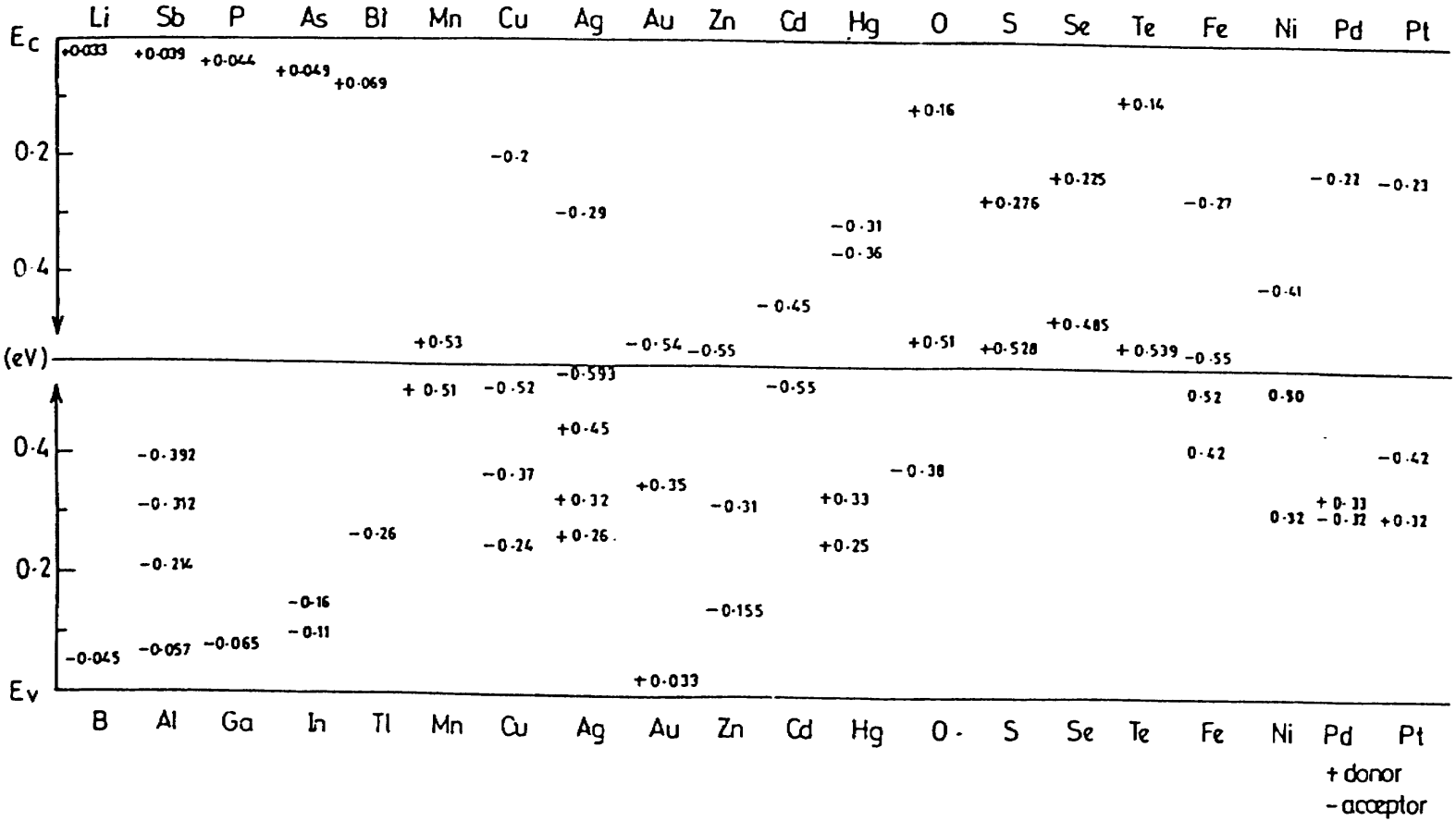

Fig. 1.1. Energy levels of deep and shallow impurities in silicon (After Chen and Milnes [7]).

The presence of deep levels affect the electrical and optical characteristics of the solid state devices. Some time these deep levels may be helpful or some times detrimental. For example, impurities like gold and platinum are used as lifetime killers as these impurities provide additional recombination paths to the carriers and hence reduce the minority carrier lifetime. Thus, by introduction of these impurities, the switching speed of the silicon devices is increased considerably. Radiative recombination centers are useful in giving different colours in light emitting diodes and phosphors. Chalcogens (S,Se and Te) are used in silicon infrared (IR) detectors.

Deep levels are source of low frequency noise in semiconductors. Since deep levels generally act as nonradiative recombination centers, the quantum efficiency of light emitting diodes or the junction lasers is reduced. Presence of deep levels reduce the transfer efficiency and blur the phase transfer process in charge coupled devices [8].

Deep levels may be intentional or unintentional. Therefore, it is necessary to characterise them to have better control over the device performance. Complete characterisation of deep levels needs to find their charge states, energy level, degeneracy ratio, concentration, capture cross-section and chemical identity. It is also desirable to know the defect structure of the complexes and the symmetry of the deep impurity in the host lattice. Ludwig and Woodbury [9] were

the first to report symmetry of various transition metals in silicon from Electron Paramagnetic Resonance (EPR) measurements. Their investigations are source of valuable information in this field. Watkins and Carbett [10,11] have established the microscopic picture of various defect complexes observed in the irradiation studies of silicon.

A number of experimental techniques [12,13,14-16] have been developed over the years for characterisation of deep impurity levels in semiconductors. Sah et.al.,[17] first suggested space charge transient techniques for characterisation of deep impurity levels, and are in wide use at present.

Though significant progress has been made on experimental techniques, theoretical understanding of deep levels has lagged behind. Various theoretical models are developed for better understanding of the deep levels like effective mass theory of Kohn and Luttinger [18], Pseudo potential theory of Pantelides [19], quantum chemical methods based on the crystal field theory of Eremin and Kornienko [20] and cluster model of Deleo et.al.,[21]. But all these theoretical models are able to predict only the trends and not the exact energy levels [22]. The main difficulty is because of the strong electron phonon coupling and the need to consider the complete host band structure rather than the restricted region of the momentum space as in the case of shallow levels. In recent monographs, Jaros [23] and Lannoo and Bourgoin [24] have reviewed the theoretical approaches to

solve the deep level problems.

During the last decade passivation of deep levels by atomic hydrogen has gained momentum because of its technological importance.

As there are several books and review articles [12,13,19,23-27] on both the theoretical and experimental aspects of the subject of deep levels, a brief introduction of deep levels is given. In the present work some deep levels introduced in silicon under different experimental conditions and their passivation by atomic hydrogen are investigated. The impurities chosen are technologically important in device fabrication. Further, the nature of these deep levels not fully understood and the reported data are controvertial to some extent.

1.2 Kinetics of the recombination processes in semiconductors :

Whenever the thermal equilibrium condition ($np=n_i^2$) of a physical system is disturbed, the system tries to restore the equilibrium by different processes like, band-to-band recombination (radiative, or Auger), recombination through deep levels or traps present in the midgap of the depletion region (electron capture, electron emission, hole capture, hole emission). The basic recombination mechanisms are depicted in Fig.1.2.

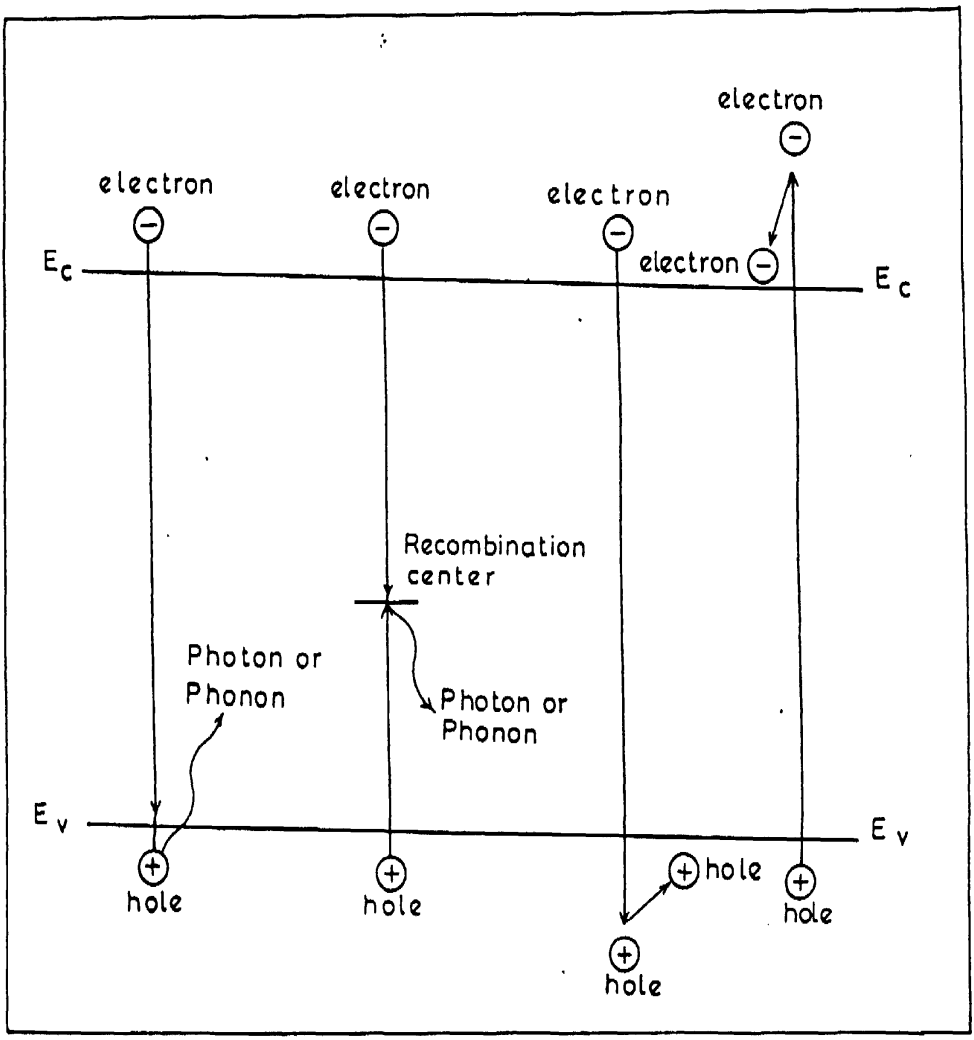

Fig.1.2 Basic recombination mechanisms that determine carrier lifetime in semiconductors.

1.2.1 Carrier lifetime :

In semiconductors electron-hole-pairs (ehps) are generated and recombined continuously. Under thermal equilibrium the generation of ehps is due to thermal process only, and also the rate at which the ehps are generated must be equal to the rate at which they recombine. The equilibrium thermal generation rate 'G_o' is the number of ehps generated per unit volume in unit time from thermal breakage of covalent bonds. G_o is independent of electron-hole concentration and depends on temperature and certain material parameters. The recombination rate is related to the mean time which elapse between the generation of an electron or a hole and its subsequent recombination. This quantity is called as mean carrier lifetime 'τ '. This is an important parameter in device physics.

For determination of lifetime, one has to disturb the equilibrium condition of the semiconductor. This can be done by injecting carriers (generation of ehps) and observing their decay (recombination). The application of external stimuli (thermal or optical) results in generation of ehps. After removing the stimuli, the excess charge carriers will recombine to reach equilibrium. The recovery to equilibrium condition can take place through three recombination processes namely:

(i) band-to-band recombination, in this case an electron drops directly from the conduction band into the valence band,

(ii) recombination through traps, in this case an electron dropping from the conduction band and a hole dropping from valence band recombine at a recombination center present in the bandgap,

(iii) Auger recombination, here the recombination is likely to increase by transferring the energy and momentum released by the recombination of an ehp to a third particle that can either be an electron or a hole. All these processes are schematically illustrated in Fig.1.2.

1.2.2 Minority carrier lifetime :

In the case of low level injection, the change in carrier concentration hardly affects the majority carrier concentration, while the concentration of minority charge carriers change several orders of magnitude. Hence, the recombination lifetime is generally referred to as minority carrier lifetime. But in the case of high level injection, concentration of both the carriers are affected. In such cases the recombination lifetime is called as excess carrier lifetime. In the low level injection the change in carrier concentration Δn is far smaller than the equilibrium majority carrier concentration n_o ($\Delta n << n_o$). In the case of high level injection the change in carrier concentration approaches or even exceeds the majority carrier concentration. In thyristors, operating at high currents where the current densities are of the order of 10 amps/cm^2 or more, the injection level exceeds 10^{16} cm^{-3} even for lifetimes of 1μs in the base region.

1.2.3 Band-to-band recombination :

In this process, electrons in the conduction band and holes in the valence band recombine directly. This transition of electrons from the conduction band to valence band is made possible by emission of photons of energy corresponding to the bandgap i.e., radiative recombination (usually in direct bandgap semiconductors like GaAs) or by transfer of energy to another free electron or hole, i.e., Auger recombination (which is common in indirect bandgap semiconductors like Si and Ge).

The rate of band-to-band recombination is proportional to the concentration of electrons and holes present in the conduction and valence bands. For an n-type semiconductor the band-to-band recombination can be written as,

$$R = a\, n_n p_n \qquad (1)$$

where a is the proportionality constant which depends on the recombination mechanism.

$n_n p_n$ is the total number of electrons and holes in the semiconductor

For low level conditions, where the majority carrier concentration does not change significantly i.e. $n_n = n_{no}$, the net recombination rate can be written as

$$U = R - G_{th} = a\, n_{no}(p_n - p_{no}) \qquad (2)$$

where n_{no}, p_{no} are the equilibrium concentrations of electrons and holes in n-type semiconductor.

G_{th} is the equilibrium thermal generation rate and is given as

$$G_{th} = a n_{no} P_{no} \quad (3)$$

Excess holes present in n-type semiconductor recombine with a decay constant, τ_p, called the recombination lifetime given by

$$\tau_p = 1/ (a n_{no}) \quad (4)$$

Since the calculation is made in terms of minority carriers, τ_p is called the minority carrier lifetime.

In direct-bandgap semiconductors, the band-to-band recombinations are predominant where as in the case of indirect bandgap semiconductors the band-to-band recombination is insignificant compared to other recombination processes.

1.2.4 Recombination - generation through deep impurities :

The probability of direct electron-hole recombination is very small in indirect-bandgap materials. The vast majority of the recombination events in these materials occur via recombination levels within the bandgap. The resulting energy loss due to electron hole recombination is usually given to the lattice as heat rather than emission of photons. Any impurity or imperfection (lattice defect) can serve as a recombination center if it is capable of receiving a carrier of one type and subsequently capturing the opposite type of carrier, thereby annihilating ehp.

Impurities and imperfections in the semiconductor disrupt the perfect periodicity of the crystal lattice which results in the introduction of energy levels in the forbidden gap of the semiconductor. These energy levels act as stepping stones in the transition of electrons and holes between the conduction and valence bands. Hence they influence the lifetime of the carriers in the semiconductor.

For the first time, Schockley and Read [28] and Hall [29] explained the statistics involved in the recombination of electrons and holes in semiconductors through the recombination centers and is known as Schockley-Read-Hall (SRH) statistics. The various possible steps taking place during the recombination and generation for the case of a single midgap level are shown in Fig.1.3 in which arrows represent the electron transitions.

The single level recombination can be described by four different processes, namely electron capture, electron emission, hole capture and hole emission and are denoted by (a),(b),(c), and (d) respectively in Fig.1.3.

The electron capture rate 'r_{nc}' is proportional to the concentration of free carriers 'n' available in the conduction band and to the concentration of empty deep levels ($N_T(1-f)$).

$$r_{nc} = c_n n N_T (1-f) \qquad (5)$$

where $c_n \simeq \sigma_n v_{th}$ is the proportionality canstant known as capture coefficient,

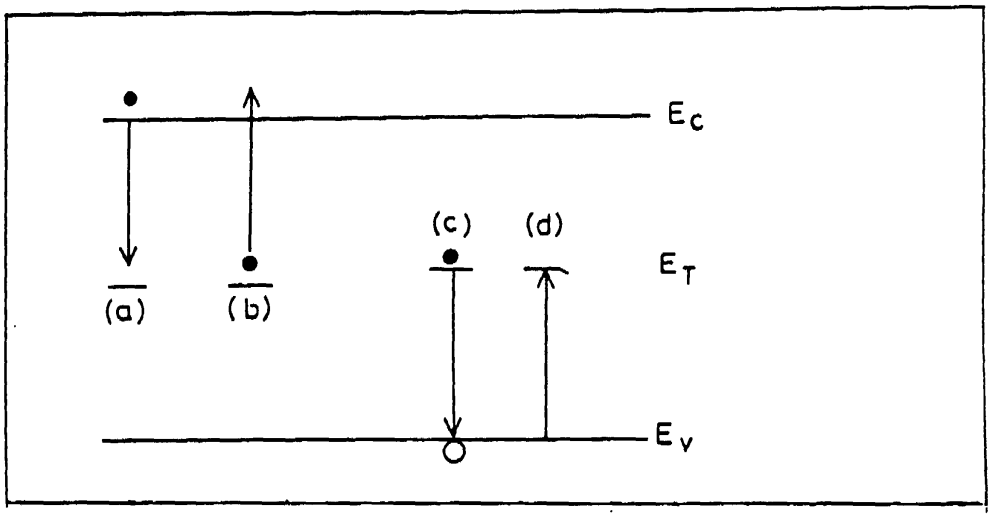

Fig.1.3 Emssion and capture process through deep levels.

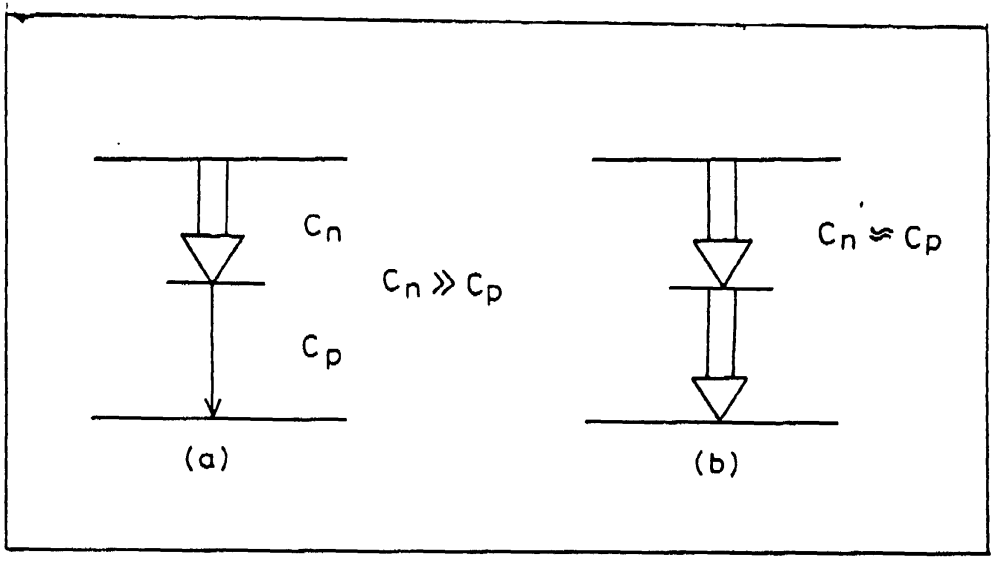

Fig.1.4 Schematic representation of an electron trap, and a recombination center.

σ_n is the electron capture cross section,

v_{th} is the thermal velocity of the conduction band electrons,

N_T is the total concentration of deep levels, and

f is the electron occupancy factor of deep level,

The electron emission rate 'r_{ne}' is proportional to the concentration of deep levels filled by the electrons and is given by

$$r_{ne} = e_n N_T f \tag{6}$$

where e_n is the proportionality constant known as electron emission probability. Here the emission process could be due to thermal or photoionization i.e.,

$$e_n = e_n^t + e_n^o \tag{7}$$

Similarly, the rate equations for the hole capture and emission can be written as

$$r_{pc} = c_p\, p N_T f \tag{8}$$

$$r_{pe} = e_p N_T (1-f) \tag{9}$$

where c_p, e_p are the capture and emission probabilities of holes.

In the absence of external generation and at equilibrium conditions, the emission probabilities for electrons and holes can be derived as follows.

From eqns.5,6,8 and 9, the rate of change of

filled deep level concentration 'n_T' can be written as

$$\frac{dn_T}{dt} = r_{nc} - r_{ne} - r_{pc} + r_{pe} \qquad (10)$$

For an energy level present in the upper half of the bandgap of n-type semiconductor as shown in Fig.1.4, only electron emission and capture processes are dominant i.e., the capture and emission of holes can be neglected and eqn.10 becomes

$$\frac{dn_T}{dt} = r_{nc} - r_{ne} = c_n n p_T - e_n n_T \qquad (11)$$

where p_T, n_T are the concentrations of deep levels filled with holes and electrons

Total deep level concentration 'N_T' is equal to the deep levels filled with electrons and holes i.e.,

$$N_T = n_T + p_T \qquad (12)$$

The rate of change of electron and hole concentrations in the conduction and valence bands can be written as

$$-\frac{dn}{dt} = r_{nc} - r_{ne} \qquad (13)$$

$$-\frac{dp}{dt} = r_{pc} - r_{pe} \qquad (14)$$

Under equilibrium condition

$$\frac{dn_T}{dt} = \frac{dn}{dt} = 0$$

i.e., the electron emission and capture rates must be equal, (i.e., $r_{nc}=r_{ne}$)

$$e_n N_T f = c_n n N_T (1-f) \qquad (15)$$

From eqn.15, the free electron concentration 'n' can be obtained as

$$n = N_c \exp(-(E_C-E_F)/KT) \qquad (16)$$

Using Fermi Dirac statistics, at equilibrium the electron occupancy factor 'f' can be expressed as

$$f = [1+(g_o/g_1)\ \exp((E_T-E_F)/KT)] \qquad (17)$$

where g_o, g_1 are the degeneracies when the deep level is unoccupied and occupied by electrons, and the ratio (g_o/g_1) is called 'the degeneracy ratio'.

For the case, where the transition energy supplied to the electron is by thermal means only, the corresponding electron thermal emission probability 'e_n' and thermal emission time constant τ_n can be obtained from eqns. 13-17, as

$$e_n = 1/\tau_n = \sigma_n\ v_n\ N_C \exp(-(E_C-E_T)/KT) \qquad (18)$$

similar expression holds good for the thermal emission of holes and can be written as

$$e_p = 1/\tau_p = \sigma_p\ v_p\ N_V \exp(-(E_T-E_V)/KT) \qquad (19)$$

σ_n, σ_p are the electron and hole capture cross-sections of the defect

n_1, p_1 are the equilibrium electron and hole densities corresponding to the Fermi level position coincident with the recombination level in the bandgap

Under the condition of space charge neutrality, where $\triangle n = \triangle p$, lifetime can be written as

$$\tau = \frac{\triangle n}{U} = \tau_{po} \frac{n_o + n_1 + \triangle n}{n_o + p_o + \triangle n} + \tau_{no} \frac{p_o + p_1 + \triangle n}{n_o + p_o + \triangle n} = \tau_{SRH} \qquad (22)$$

From the above equation, in heavily doped n- and p-type semiconductors i.e for $n >> p_o$, $\triangle n$, n_1 and $p >> n_o$, n_1, $\triangle p$ for a given density of deep levels, the minority carrier lifetime depends only on the capture rate of minority carriers at the recombination center.

1.2.4.2 Low level injection :

Under low level injection condition, in an n-type semiconductor, the injected electrons are much fewer than the majority carriers i.e., $n_n = n_{no}$ and $n_o >> p_o$, $\triangle n$, then the lifetime, from eqn.22

$$\tau_{LL} = \tau_{po} \left[1 - \exp \frac{E_T - E_F}{KT} \right] + \tau_{no} \left[\exp \frac{2E_i - E_T - E_F}{KT} \right] \qquad (23)$$

i.e., low level injection lifetime 'τ_{LL}' depends on the recombination level (E_T) position in the forbidden gap and the capture cross-section ratio (τ_{no}/τ_{po}) (for Si it is equal to 0.827 (σ_p/σ_n) [30]) and is independent of the concentration

of electrons.

1.2.4.3 High level injection :

For the case of high level injection where the injected carrier concentration is nearly equal to the majority carrier concentration i.e $n>>n_o,p_o,n_1,p_1$ then the lifetime, from eqn.22

$$\tau_{HL} = \tau_{po}+\tau_{no} = \tau_{po}(1+0.827(\sigma_p/\sigma_n) \qquad (24)$$

i.e., the lifetime 'τ_{HL}' is independent of position of the recombination center and the temperature, but directly depends on the capture cross-section ratio (σ_p/σ_n) [30].

1.2.5 Auger recombination :

If the energy released in the recombination process of an electron-hole pair is transferred to a third particle (either an electron or a hole), then the recombination process is called Auger recombination. This process is predominant in heavily doped semiconductor materials. This process is significant in the case of semiconductor power devices where the end regions are heavily doped. Also under high level injection conditions this process is important even though the material is lightly doped. Theoretical investigations by Huldt [31] and Haug[32] on indirect bandgap materials indicate that the Auger process is possible with or without phonon assistance. Auger process can happen either directly from band-to-band or through traps. Auger recombination is measured in the heavily doped materials at low level injection and at

high level injection in high resistivity (lightly doped) silicon [33,34].

Auger lifetimes τ_{nA} and τ_{pA} in the case of heavily doped n-type and p-type silicon is given by

$$\tau_{nA} = 1/(2.8 * 10^{-31} * n_n^2) \quad (25)$$

and

$$\tau_{pA} = 1/(2.8 * 10^{-31} * p_p^2) \quad (26)$$

where n_n, p_p are the majority carrier concentrations in n-type and p-type semiconductors respectively.

But for lightly doped semiconductors under high level injection, where both type of carriers are present, the lifetime is given by

$$\tau_{nAH} = 1/(2.8 * 10^{-31} * g/\Delta n)^2 \quad (27)$$

In indirect bandgap semiconductors, recombination through the deep traps and Auger recombination processes dominate the direct band-to-band recombination process. The effective lifetime τ_{eff} is

$$\tau_{eff} = \frac{\tau_{SRH} + \tau_A}{\tau_{SRH}\, \tau_A} \quad (28)$$

1.3 Thermodynamic analysis of deep levels :

During the process of carrier capture and emission, there are fundamental changes in the ionic character of the defect concerned, as well as an associated adjustment of the

lattice geometry about the defect. Van Vechten and Thurmond [35] have shown that the resulting changes in the lattice around the defect can be accounted by thermodynamic quantities. The entropy factor is considered as one of the important paramenters of a deep level. Knowledge of entropy factor is helpful in understanding the temperature dependence of the deep level with respect to band edges and the nature of its coupling with the host lattice.

Investigations of deep levels suffer from the lack of a clear definition of the term 'energy level'. This energy is an integral part of the Schockley-Read-Hall statistics. It can be treated as a free enthalpy (or the Gibbs free energy) with a temperature dependence or as an enthalpy in which case the entropy property of the center should be considered. Normally thermal measurements give enthalpy and optical measurements give Gibbs free energy.

In thermodynamics, the energy needed to excite an electron from the deep level is referred to as chemical potential; 'u' [36] and is expressed as

$$u \equiv \left[\frac{dE}{dN}\right]_{S,V} \equiv \left[\frac{dG}{dN}\right]_{P,T} \qquad (29)$$

The change in Gibbs free energy is defined as the energy required to excite an electron from a deep level to the conduction band

$$\Delta G = \Delta H - T\,\Delta S \qquad (30)$$

where ΔH is the change in enthalpy

ΔS is the change in entropy

T is the absolute temperature

P is the pressure

V is the Volume.

Using eqn.30, the thermal emission rate (eqn.18) can be written as

$$e_n^t = \sigma_n \, v_n \, N_C \exp(-\Delta G_n/KT) \tag{31}$$

If ΔS is the total entropy change accompanying the electron emission, then

$$e_n^t = \sigma_n \, v_n \, N_C \, X_n \exp(-\Delta H_n/KT) \tag{32}$$

where X_n is the entropy factor and is given by

$$X_n = \exp(\Delta S_n/K) \tag{33}$$

By considering temperature dependence of capture cross-section, eqn.32 can be written as

$$e_n^t = \sigma_n \, v_n \, N_C \, X_n \exp(-\Delta E_n/KT) \tag{34}$$

where ΔE_n is the apparent activation enthalpy and is given by

$$\Delta E_n = \Delta H_n + E_b \tag{35}$$

where E_b is the capture barrier in multi phonon emission (MPE) model.

The entropy change ΔS can be expressed as

$$\Delta S_n = \Delta S_{ne} + \Delta S_{na} \qquad (36)$$

where ΔS_{ne} entropy change due to electronic degeneracy and

ΔS_{na} entropy change due to atomic vibrational energy.

The energy in electronic degeneracy is normally expressed as the ratio of degeneracy factors. Hence 'X_n' can be related to the degeneracy ratio (g_o/g_1) as

$$X_n = \left[\frac{g_o}{g_1}\right] \exp\left[\frac{\Delta S_{na}}{K}\right] \qquad (37)$$

From eqn.32, the slope of the Arrhenius plot ($e_n{}^t/T^2$ Vs. 1/T) gives the activation enthalpy $e\Delta H_n$, if E_b is known. If the emission rate '$e_n{}^t$', capture cross-section σ_o, activation enthalpy ΔE_n, v_n, N_C are known, the entropy factor X_n can be evaluated using eqn.34.

Further, if the degeneracy ratio (g_o/g_1) is known, it is possible to determine as to which band the defect is pinned. If the total entropy change for a band-to-band transition ΔS_{CV} is close to ΔS_{pa}, the energy level is pinned to the conduction band since the entire entropy of the gap can be accounted for by the hole emission transition. On the other hand, if ΔS_{na} is close to ΔS_{CV}, the level is pinned to the valence band. However, in general, it is difficult to seperate the electronic and vibrational contributions to entropy.

1.3.1 Non radiative capture at deep levels :

Capture cross-section is another important parameter of deep levels. Study of capture cross-section of deep levels as a function of temperature, appears to be a powerful tool to get insight into the defect-phonon interaction. It helps to measure the exact energy position of the deep levels in the forbidden bandgap. During carrier capture, the energy of the carrier must be given up, generally the energy loss is non radiative in the case of deep levels. Auger, cascade and multiphonon emission (MPE) processes are the three processess that have been identified as capture mechanisms from the temperature dependence of capture cross-section in various systems.

In the Auger process, the energy released by the capture of one free carrier is used to excite another carrier. The process is weakly temperature dependant and generally high concentration of carriers is necessary for the Auger effect to compete significantly with other recombination processes.

The cascade model suggested by Lax [37] was originally used to explain the large capture cross-section (10^{-12}-10^{-15} cm^2) exhibited by some shallow coulombic attractive centers. In this model, it is assumed that the impurity level has several excited states which are closely spaced. The electron looses its energy by dropping to a series of excited states emitting one phonon at each step. The capture cross-section varies as T^{-4} -T^{-1}, depending on the

temperature (T) and the number of phonons involved. This model has been successful in explaining the temperature dependant capture cross-section of shallow levels in Si and Ge.

Henry and Lang [38] suggested an alternative and most successful mechanism called 'multi phonon emission (MPE)' mechanism, to explain the non-radiative capture and its temperature dependence. According to this, when the localised electronic state is strongly coupled to the lattice, the energy dissipated in the process of capture is in the form of a burst (multi phonon) of phonons i.e., violent local vibration in the sourroundings of the local defect. Fig.1.5 illustrates the electron lattice interaction. Prior to the electron capture, the equilibrium position of the level is in the upper half of the gap. For sufficiently large vibrations, the level can cross into the conduction band and capture an electron. After capture, the lattice near the defect relaxes to lower the equilibrium position of the level in the gap. The capture is followed by a violent lattice vibration near the defect. This vibration rapidly damps down to the amplitude of thermal vibrations. During this damping the localised energy propagates away from the defect in the form of lattice phonons. This process is also explained by the Configuration-Coordinate (C-C) diagram (Fig.1.6), where the total (electronic + elastic) energy is plotted as a function of lattice coordinates (Q). The lattice equilibrium position is at Q=0, when the electron is in the conduction band. For sufficiently large vibrations the carriers in the bandgap can

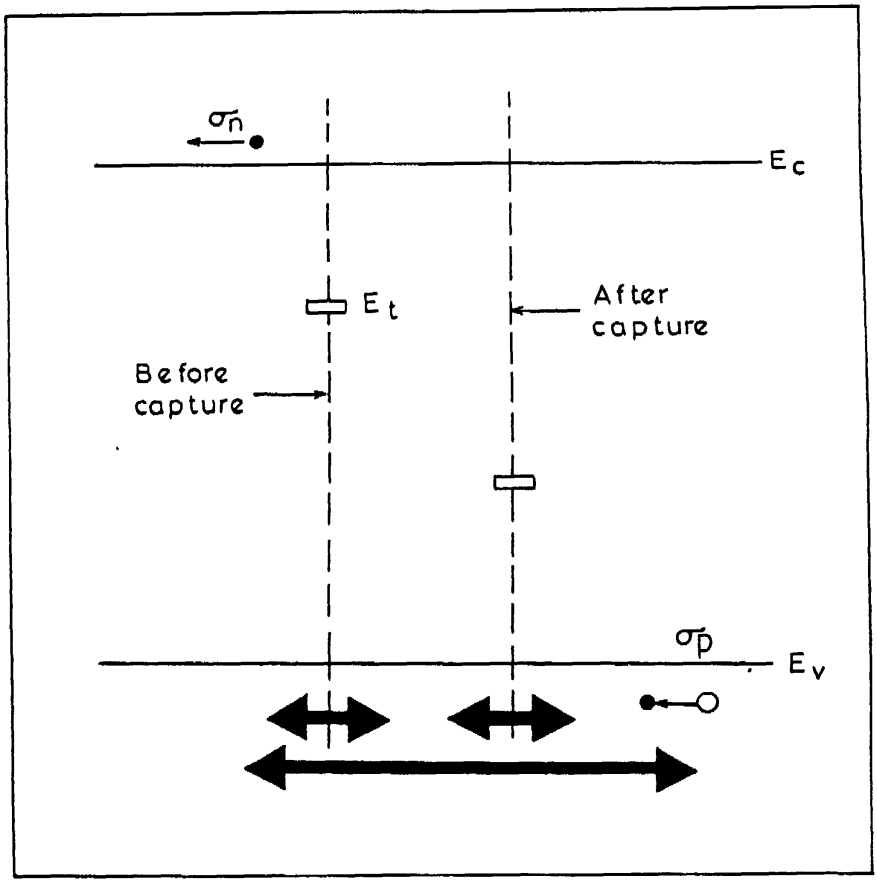

Fig.1.5 Non-radiation capture of an electron by multiphonon emission (Henry and Lang [38])

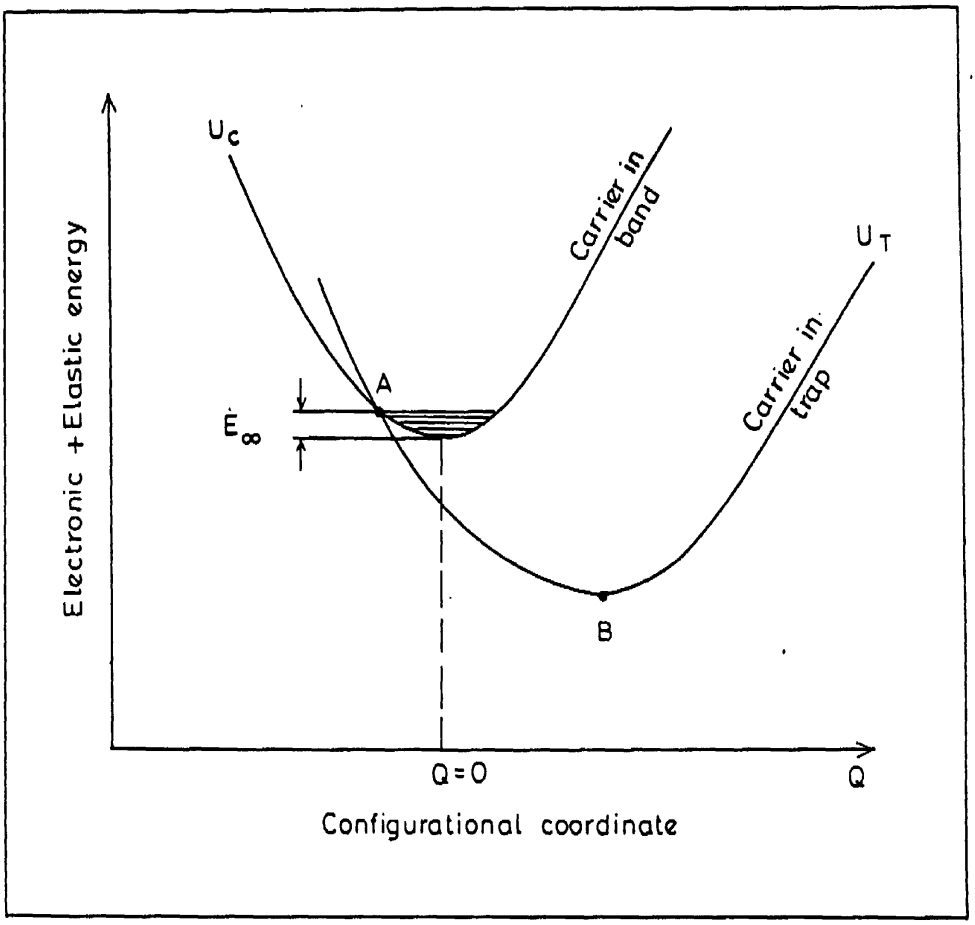

Fig.1.6 Configurational coordinate diagram for a non radiative capture.

be captured by the deep level at the cross over point A. The lattice then relaxes to point B with emission of large number of phonons. The multi phonon emission gives rise to a temperature dependant capture cross-section given by.

$$\sigma_n^t(T) = \sigma_o \exp(-E_o/KT) \quad (38)$$

where E_o is the activation energy for the capture. This type of capture occurs in some deep levels in GaAs and GaP [38]. Gibb et.al.,[39] suggested an intermediate state model which explains the temperature dependant capture cross-section and is an extention of the cascade model. In this model, the elctron is first captured by a cascade process down to an energy state E_1. The subsequent transition from the first excited state E_1 to ground state E_2 ($E_e<E_1$) is accompanied by multi phonon emission. The thermally activated capture cross-section is given by

$$\sigma_n^t(t) = A^* T^{-2} \exp(E_1/KT) \quad (39)$$

where A^* is the temperature independant factor.

This mechanism has been used to explain the temperature dependant capture cress-section of chalcogens [40,41].

1.4 Introduction of Deep levels in semiconductors :

Deep levels in semiconductors can be introduced by variety of ways. Prominent of these are solid state diffusion of intentional or unintentional impurities, irradiation of the

semiconductor with high energy particles such as electrons, protons,neutrons, gamma rays etc,.

Deep levels can be introduced in silicon by diffusion of materials of group II or VI impurities. In general all elements which replace an atom of the host lattice and belong to the periodic table groups closests to the semiconductor create deep impurity levels.

Another method in which energy levels can be introduced into the forbidden gap of the semiconductor is by exposing it to the high energy radiation (electrons, protons, neutrons, gamma rays etc.). The high energy particles can displace atoms from their normal position in the semiconductor lattice, resulting in the formation of a vacancy and an interstitial atom. These in turn will rapidly form more complex lattice defects which behave much like impurities introduced into the semiconductor. They will have energy levels within the forbidden gap and can act as acceptors, donors and recombination centers.

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