Chapter 1

INTERACTION OF RADIATION WITH SEMICONDUCTORS - BASIC THEORY

1.1 Introduction

Early in 1950's it was realized that nuclear and space radiation can pose a serious threat to electronic devices and circuits operating in radiation environment. Paradoxically, the semiconductors which have replaced vacuum tubes are more sensitive to radiation damage. As a result, it has become mandatory to investigate the effect of radiation on the performance of semiconductor devices when they are required to be operated in radiation environment (for example, in spacecraft electronic systems). When semiconductor devices are exposed to radiation, they undergo dramatic changes in their properties. These changes can affect the performance of the devices. In the past two decades, intensive investigations of radiation hardness of variety of semiconductor devices have been carried out in order to analyze the performance changes of the individual devices and to find better design strategies. The study of radiation-induced effects on semiconductor devices has thus become an important and active field of research and development.

In this chapter a description of the radiation environment, general interaction of radiation with matter and with semiconductor material, in particular, is presented.

1.2 Radiation environment

Electronic systems operating in the radiation environment get exposed to electromagnetic radiation and particle radiation. Typically four different radiation environments can be identified (i) Space environments such as that in the Van Allen belts, near and deep space orbits (ii) Nuclear environments encountered near nuclear fusion or fission detonations

(iii) Environments near nuclear facilities such as reactors and experimental setups like accelerators and (iv) Radiation harsh environments encountered during the processing of devices [1].

Space radiation environment can be classified into three groups (i) Solar radiation (ii) Trapped radiation in the earth’s magnetic field and (iii) Galactic cosmic rays.

1.2.1 Solar radiation

The sun is a source of three types of radiation viz., electromagnetic waves, solar wind and solar flare particles [2-4]. The bulk of the energy in the solar electromagnetic spectrum lies between the wavelength limits 0.3 ìm and 4.0 ìm. Only one percent of the energy lies beyond this range. This major portion of the sun’s spectrum is non-ionizing in nature and does not cause radiation damage. UV and X-rays from the sun can produce ionization damage in materials on the surface of space system and do not contribute to total dose absorbed by electronic components. However, solar radiation is a dominating factor in determining the temperature distribution within the space system.

Solar wind is an extension of the solar corona extending to several astronomical units. The interaction of solar wind with the geomagnetic filed determines the boundary of the geomagnetic filed. The solar wind essentially consists of protons (99%) and á- particles (1%). The density of protons is about one to ten per cm^3 and probably, an equal density of electrons. The Solar wind is continually blowing and the thermal energy of protons is in the range 1-10 keV. Solar wind flux is about 10^8 protons/cm^2/sec.

Solar flare is a phenomenon of emission of white light in the neighborhood of sun spot and sudden increase in the intensity of hydrogen á- line (6563 A^o). In an interval of half an hour or more following the appearance of large flares, energetic particles are detected on the earth. The radiation dies away with a time constant of one to three days. The radiation mainly consists of protons and á-particles. á-particles flux is only 2 to 10 percent of proton flux. Other heavy nuclear particles constitute about only 0.1% of total. Solar flare activity follows approximately an eleven-year cycle. Solar flare particles are high-energy particles and the energy of the solar protons lies between 10 MeV and 100 MeV [5].

1.2.2 Trapped radiation

The earth's trapped radiation belts (Figure 1.1) were discovered in 1958 by Van Allen. The geomagnetic dipole field traps the charged particles coming from outer space and holds it for a long time [2,6]. These particles are distributed in space, extending from an altitude of a hundred to about 70,000 km. The space occupied by these particles is in the form of a distorted toroid about the earth, within 30^o of the geomagnetic equator. The geomagnetic field responsible for trapping the charged particles is asymmetric due to solar wind, which mainly consists of protons with few KeV energy.

The region where the geomagnetic field energy density equals the energy of the solar wind forms the boundary of geomagnetic field. On the sun side of the earth, magnetosphere extends upto 12 R_E (radius of the earth $R_E \cong 6378$ km) when the sun is quiet. When the sun is active, it is compressed to 8 R_E. On the night side, a geomagnetic tail is formed in the shape of a cylinder of about 40 R_E radius. Trapped charged particles are continuously under motion between points near the north and the south poles, along a helical path. They also have an east or west drift motion, combined with the north-south helical motion. Electrons and protons are the main constituents of the trapped radiation. Trapped radiation intensity undergoes short term and long term time-dependent changes because of magnetic storms. Average values of particles fluxes are used for radiation dose estimation in space.

Electron distribution in Van Allen belts is concentrated in two zones [2]. The inner zone lie in the range of 1.2 R_E to 2.8 R_E with peak at about 1.4 R_E . The outer zone lies in the range of 3 R_E to 11 R_E and peaks at 4 R_E to 5 R_E. High-energy protons ($E > 40$ MeV) are concentrated closer to the earth and peak at 1.5 R_E. The intermediate energy protons (4 MeV $< E <$ 40 MeV) are concentrated within 4 R_E and peak at 2 R_E. The energy spectrum of proton becomes softer as the distance from the center of earth increases. Several models have been developed to describe the flux and energy of particles trapped in Van Allen belts at various distances [7].

1.2.3 Galactic cosmic rays

Galactic cosmic radiation consists of low flux particles (4 particles /cm^2/sec) of energetic (10^7 to 10^9 eV) bare nuclei which appear to fill our galaxy isotropically. The free space galactic cosmic radiation is composed of about 85% protons, 14% á-particles and about 1% heavier nuclei with an average energy of about 1GeV. The flux of cosmic radiation near the earth decreases as the sun becomes active and reduces to about 2.5 particles/cm^2/sec at solar maximum [4].

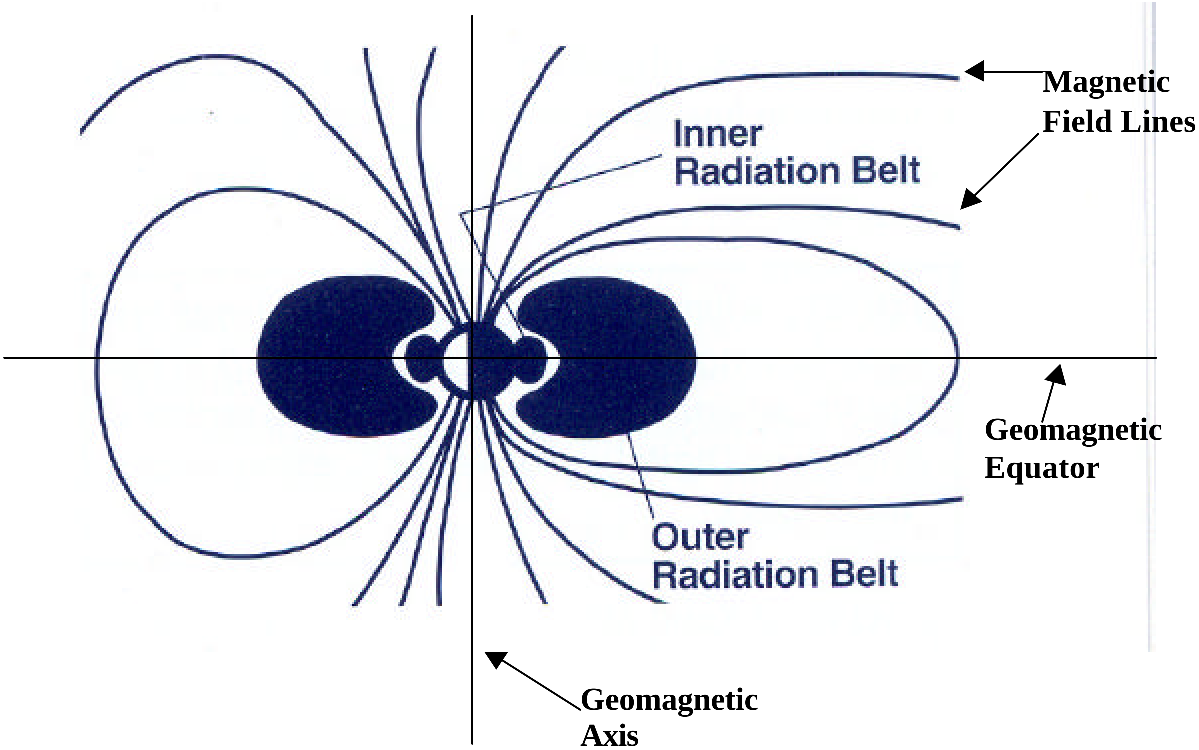

Figure 1.1 Van Allen Belts.

1.3 Interaction of radiation with matter

There are two basic types of radiation which can affect operation of the semiconductor devices: (i) Electromagnetic radiation (X-rays, ã-rays) and (ii) Particle radiation (electron, proton, neutron, heavy ions). When high-energy radiation is incident on a semiconductor material, the nature of the interaction between the impinging high-energy radiation and the target depends on several properties. The relevant high-energy radiation properties are mass, charge, flux/fluence and kinetic energy. The material properties of importance are mass and density. Role of device technology is also important to understand high-energy radiation induced effects. For example, for a given type of radiation, the mechanism of interaction of radiation with bipolar devices is entirely different from that with MOS devices.

Type of interactions

The various types of interactions that occur between the high-energy radiation and target atoms are dependent on the nature of the radiation.

Photons have zero rest mass and are electrically neutral. They interact with target atoms through the photoelectric effect, Compton scattering and pair-production [8]. In all the three cases, the interaction produces energetic free electrons. The energy range in which photoelectric collisions dominate depends on the atomic number Z of the material. The probability of a photoelectric interaction decreases with increasing photon energy and increases with Z. If the incident photon is energetic enough to emit an electron from the K-shell, then most (~80%) of the collisions are with K-shell electrons. In the photoelectric process, the incident photon energy is completely absorbed by the emitted electron (photoelectron). If a K-shell electron is ejected, then an L-shell electron will occupy into the available lower energy state. Depending on the value of Z, either a characteristic X-ray or a low-energy Auger electron is emitted from the L-shell.

In contrast to the photoelectric effect, Compton scattering does not involve complete absorption of the incident photon. In Compton scattering, the photon energy is much greater than the binding energy of atomic electrons (such as those in the K-shell). The incident photons give up a portion of its energy to scatter an atomic electron thereby creating an energetic Compton electron and the lower energy scattered photon continues to travel in the target material. As the photon energy increases, Compton scattering dominates over the photoelectric effect.

The third type of photon interaction namely, pair-production has threshold energy of 1.02 MeV. At this energy, a photon striking a high Z target will be completely absorbed and result in a positron-electron pair production.

Figure 1.2 illustrates the relative importance of the three photon interactions as a function of Z and photon energy [8-9]. The solid line corresponds to equal interaction cross sections for the neighbouring effects. For silicon, (Z = 14) the photoelectric effect dominates at energies < 50 KeV and pair production dominates at energies > 20 MeV. In the intermediate energy range, Compton scattering dominates. Thus over a broad photon

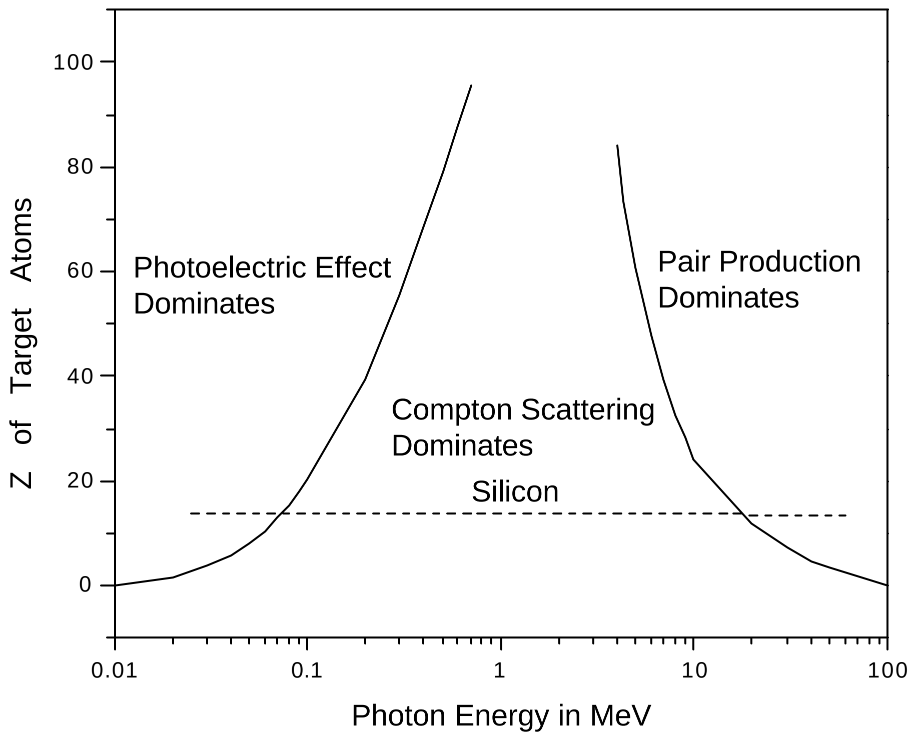

Figure 1.2 Illustration of the relative importance of the photon interactions as a function of Z and photon energy.

energy range, energetic Compton electrons are produced which undergo subsequently charged particle interaction.

Charged particles incident on a target interact primarily by Rutherford scattering (Coulomb scattering). This interaction can cause both excitation and liberation (ionization) of atomic electrons. Additionally, through Rutherford scattering sufficient energy can be transferred to atoms to displace them from their normal lattice positions. While undergoing this process, the particles loose energy by elastic scattering from the nuclei (Rutherford scattering). Apart from this, the charge particles also loose energy by inelastic collision with the atomic electrons of the material. These reactions occur many times per unit length in the matter and it is their cumulative result which accounts for the two principal effects observed. However, these are by no means the only reaction which can occur. Other processes include emission of Cherenkov radiation, nuclear reactions and bremsstrahlung. As compared to atomic processes, these processes are of rare occurrence [10].

Neutrons which are uncharged, when incident on a target undergo the following nuclear interactions: elastic scattering, inelastic scattering and transmutation. In an elastic collision, the neutron gives up a portion of its energy to an atom of the target material and can dislodge the atom form its lattice position. This process will occur as long as the imparted energy is greater than that required for displacement (~ 25 eV for most material). The displaced atom is referred to as primary recoil (or primary knock-on) which subsequently lose energy to ionization and can also displace other lattice atoms.

Inelastic neutron scattering involves capture of the incident neutron by the nucleus of the target atom and subsequent emission of the neutron at a lower energy. Kinetic energy is lost in this process and the target nucleus is left in an excited state. The excited nucleus returns to its original state by emission of a ã-ray. The Kinetic energy of the emitted neutron is reduced, compared to the incident neutron, by the energy of the ã-ray. Inelastic neutron scattering can also cause displacement of the target atom to occur. The transmutation reaction involves capture of the incident neutron by the target nucleus and subsequent emission of another particle, such as a proton or an alpha particle [11]. The remaining atom is thereby transmuted (converted from one element into another). The dominant processes when silicon is irradiated with fast neutrons (for neutron energy 1 MeV) are the production of displaced atoms and ionization.

1.4 Effects of radiation on semiconductor devices

Radiation effects on semiconductor devices are produced when radiation energy is expended in a semiconductor material. The type of effect produced in a semiconductor material depends on the nature of the radiation particulate. Figure 1.3 shows the effects of different types of radiation particulate on semiconductor devices [12].

The radiation effects on semiconductor material can be broadly classified into: (i) transient effects and (ii) displacement effects.

1.4.1 Transient radiation effects

Transient radiation effects are the manifestations of the interactions of radiation with matter associated with the excitation (including ionization) and de-excitation of electrons. These are temporary effects in semiconductor devices and they usually produce significant changes only in the electrical properties of the devices. The ionization effects are caused by electrons created via photon or other charged particle interaction. The effects are proportional to dose rate or dose of the radiation pulse [1]. Transient effects are significant when devices receive high dose rate.

1.4.2 Displacement effects

The displacement effects usually involve the following occurrences.

(a) A fast nuclear particle entering a material makes a close collision with the nucleus of an atom, imparting to it sufficient energy to displace the atom from its lattice site.

(b) The displaced atom moves through the solid losing energy in collisions with other atoms and displaced atom eventually comes to rest.

(c) The lattice defects so formed may be thermally unstable even at room temperature. Some of them may anneal either annihilating the defect entirely or forming a secondary defect.

(d) The defects influence various macroscopic physical properties, which lead to change in the electrical properties of the material.

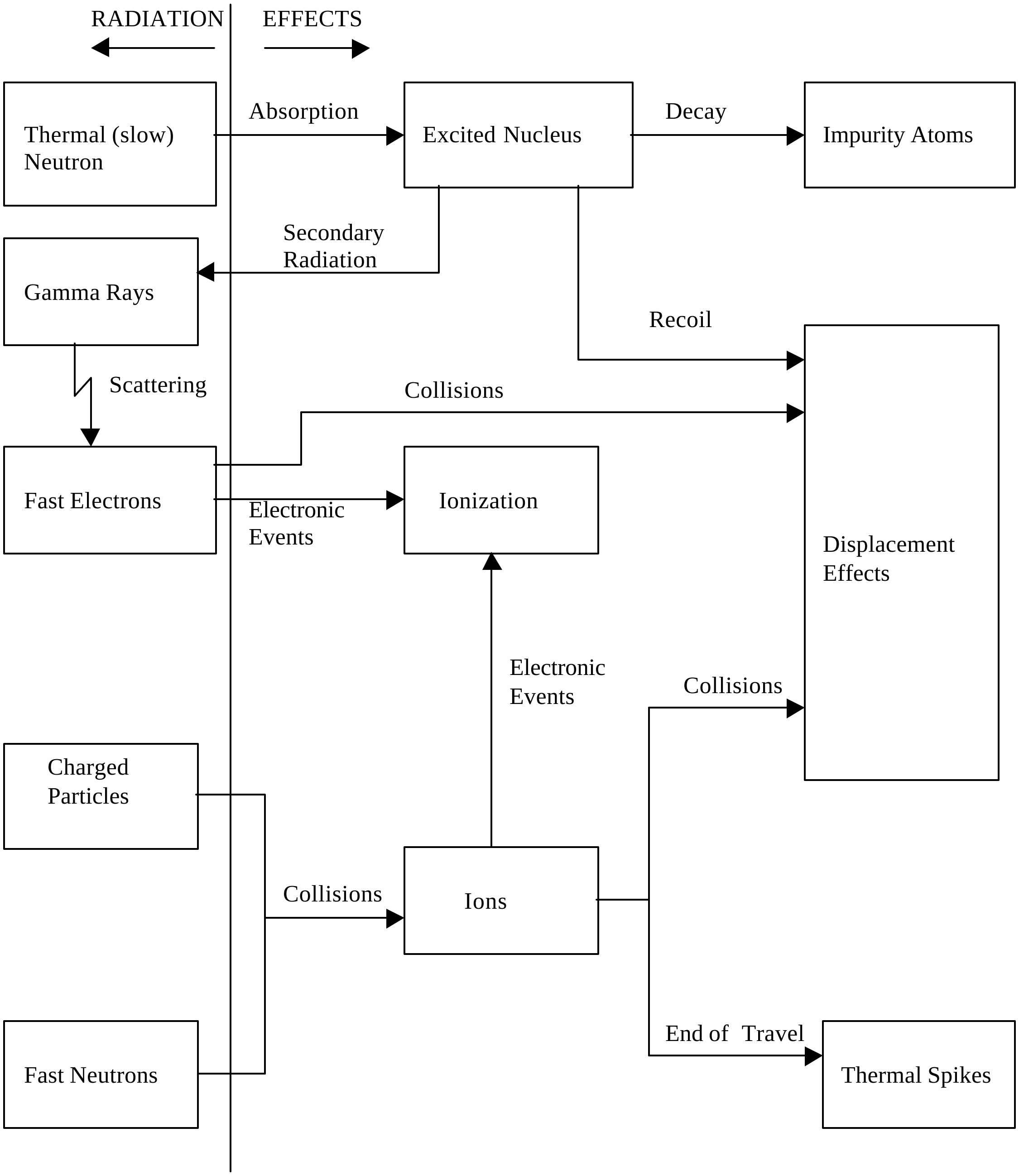

Figure 1.3 Schematic representation of radiation effects.

If the primary radiation is charged (for example high-energy electrons, protons and deuterons), the interaction between the particle and the atom produces a displacement of the atom usually via the coulomb electrostatic force between the nuclear charge of the atom and the moving particle [13]. Since for fast particles the impact parameter must be much less than the average radius of the K-electron orbit in order to produce a displacement, it is inferred that the shielding effect of the orbital electrons is unimportant [14]. A neutron produces displacement by interacting with the nuclear force field and hence interacts only at much shorter impact parameters than do charged primaries.

Gamma ray interacts with atoms by first generating electrons through the photoelectric, Compton or pair-production processes. These secondary electrons produce the atomic displacements. High energy (10 MeV) ã-ray can also produce some displaced atoms as recoils from photo-nuclear reactions. These cause permanent damage to crystal structure in semiconductors.

Apart from transient and displacement effects, other effects which are important in radiation induced studies are the following.

1.4.3 Surface effects

Surface effects, first experienced as a practical design problem on the Telstar satellite, affect the surface layers of transistor and other semiconductor devices [14]. After prolonged exposure to low dose rate electromagnetic (X- and ã-ray) radiation, gas ions and ions of foreign materials formed near the surface of activated transistor are attracted into the surface layer of the semiconductor, thereby upsetting the internal electric fields. Doses of the order of 10^4 to 10^7 rads (Carbon) are required to severely reduce the transistor performance.

1.4.4 Total dose effects

High-energy particles like gamma photon and charged light particles like electron and proton impinging on a material generate electron-hole pairs in the material along their tracks. A fraction of these pairs will recombine, but a fraction will be separated by the electric field. Percentage of non-recombined charges depends on the kind of radiation and material. Following the creation, electrons and holes transport under the applied electric field. These charges will cause total ionizing dose damage. The total dose D is defined as the mean energy absorbed ÄE$_d$ per unit mass Äm of irradiated material [15].

1.4.5 Single event effects

Single Event Effect (SEE) is a phenomenon induced by high-energy protons or heavy ions penetrating through the microelectronic circuits. The high-energy particles impinging on the devices can cause several SEE resulting in device degradation or total failure [15]. SEE's become more significant as the feature dimension of the device decreases. A more detailed description of SEE's is presented in Chapter 7.

1.5 Displacement induced defects in silicon

Energetic photons, charged particles and neutrons incident on silicon material can cause displacement of the target atoms to occur. An atom can be displaced from its lattice site if it receives more energy than a certain threshold value E_d. The threshold energy for displacement is 25 eV for many materials. If the atom receives significantly more energy than E_d, it encounters other atoms in its motion through the lattice and may produce further displacements.

Atomic displacement lead to lattice defects. Displacement induced defects are many times unstable and anneal even at room temperature. Physical manifestation of displacement induced defects in semiconductors are (i) changes in minority carrier lifetime (ii) changes in carrier mobility and (iii) changes in effective doping of semiconductors. Further, scattering of current carriers by the defects depend on whether the defect is charged or not. Therefore the nature of the defect, its charge state are important in predicting the perturbation which the defect will introduce in a material. Various types of defects which can occur in irradiated silicon can be classified into:

1) Simple defects (Isolated, Point)
    Vacancies / Divacancies
    Vacancy-impurity complex
    Interstitials
    Di-interstitials
    Interstitial-impurity complex

2) Defect clusters

Simple defects are also referred to as point, or isolated defects. Regions containing large number of relatively closely spaced defects can also occur and such a grouping is termed a defect cluster. When a displaced atom moves into a non-lattice position, the resulting defect is referred to as an interstitial. The vacancy-interstitial combination is called a close pair, or a Frenkel pair. Two adjacent vacancies from a defect known as the divacancy (a di-interstitial can also occur). Large local groupings of vacancies are also observed in irradiated silicon. Vacancies and interstitials can also form additional type of simple defects when they are adjacent to impurity atoms. Such defects are termed defect-impurity complex. For example, the vacancy-phosphorus pair is a defect that is observed in silicon. Figure 1.4 shows a schematic illustration of three types of simple defects in a lattice structure.

If a displaced atom is given a relative large amount of kinetic energy by an incident particle, the primary knock-on can displace many additional atoms and thereby cause the formation of a region of disorder, or defect cluster. This process occurs for incident neutrons with energy in the MeV range. On the other hand, MeV electrons and photons produce a mixture of isolated defects and small defect clusters.

It is well-known that the impurity atoms in the silicon lattice have discrete energy levels associated with them, which lie in the band gap between the conduction band minimum and the valance band maximum. In general, any disturbance of lattice periodicity may give rise to energy levels in the bandgap. Radiation-induced defects have such levels associated with them and it is these defects states or centres, that have a major impact on

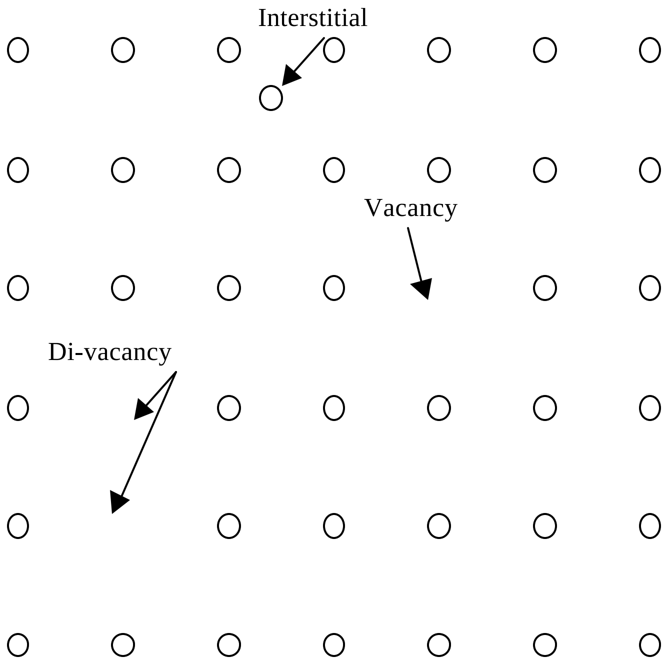

Figure 1.4 Schematic illustration of three types of simple defects in a lattice structure.

the electrical behaviour of semiconductor devices. Thus, the basic phenomena which cause device degradation in a radiation environment are (a) incident particles displace atoms; (b) the resulting defects give rise to new energy levels; (c) these levels alter device electrical properties. Various processes such as generation of charge carriers, recombination, trapping, etc. occur due to the presence of radiation-induced defect centers in silicon bandgap. Figure 1.5 illustrates these processes. These processes are briefly described below.

Generation of electron-hole pair is the thermal generation of electron-hole pairs through a level near midgap. This process can be viewed as the thermal excitation of a bound valance band electron to the defect center and the subsequent excitation of that electron to the conduction band, thereby generating a free electron-hole pair. Alternatively, it can be viewed as hole emission from the center followed by electron emission. Only centers with an energy level near midgap make a significant contribution to carrier generation. An exponential decrease in generation rate occurs as the energy level position is moved from midgap. In addition, emission processes dominate over capture processes at a defect level only when the free carrier concentrations are significantly less than their thermal equilibrium values. Thus, thermal generation of electron-hole pairs through radiation-induced defect centres near midgap is important in device depletion regions [9]. Introduction of such centres increases the leakage current in silicon devices.

Recombination is the recombination of electron-hole pairs. In this process, a free carrier of one sign is first captured at the defect center, followed by capture of a carrier of the opposite sign. Recombination removes electron hole pairs as opposed to the generation process [16]. In general, the recombination rate depends on the defect center (or recombination center) density, the free carrier concentrations, the electron and hole capture cross section and the energy level position. The mean time a minority carrier spends in its band before recombining is referred to as the *recombination life time* $\hat{o}_r$. Radiation-induced recombination centers cause $\hat{o}_r$ to decrease. This is the dominant mechanism for gain degradation in bipolar transistors.

Trapping is the temporary trapping of a carrier at a typical shallow level. In this process, a carrier is captured at a defect center and is later emitted to its band, with no recombination event taking place. In general, trapping of both majority and minority carriers can occur (at separate levels). Radiation-induced traps are responsible for increasing the transfer inefficiency in charged-coupled devices.

Compensation is the compensation of donors or acceptors by radiation-induced centers. In the example shown in Figure (1.5), some of the free electrons available from the donor level are compensated by deep lying radiation-induced acceptors. The result is a reduction in the equilibrium majority carrier concentration. This *carrier removal* process will cause an alteration in any device or circuit property that depends on carrier concentration.

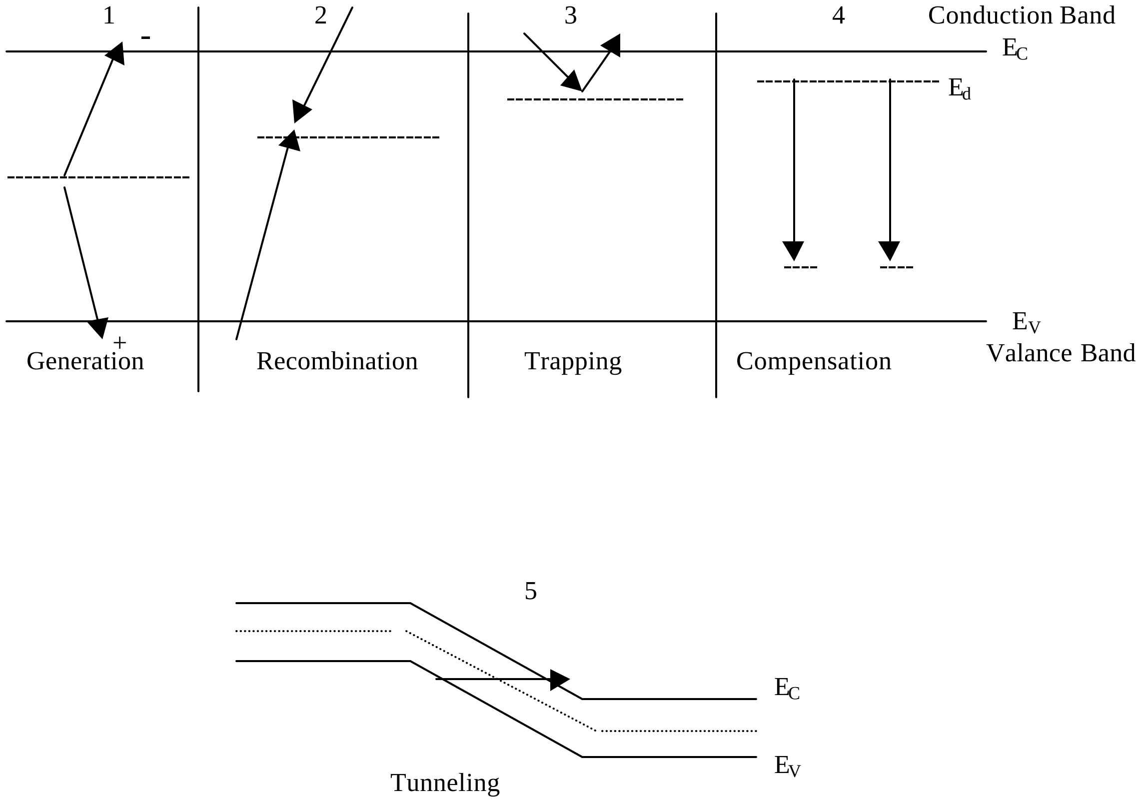

Figure 1.5 Illustration of effects which occur due to the presence of defect centers in the silicon bandgap.

Tunneling is the tunneling of carriers through a potential barrier by means of defect levels. This defect assisted (also called trap assisted) tunneling process can cause device currents to increase in certain situations.

In summary, radiation-induced levels in the bandgap can give rise to five processes: generation, recombination, trapping, compensation and tunneling. In principle, any combination or all of these processes can occur through the same level. The role that a particular level plays depends on carrier concentration, temperature and the device region in which it resides.

1.6 High-energy radiation induced effects on bipolar junction transistors

Bipolar Junction Transistors (BJT) consist of a pair of closely spaced *p-n* junctions in a single semiconductor structure. The order can be *npn* or *pnp*. These devices in both discrete and integrated form are essential components in many electronic systems, especially in applications such as in amplifiers, which require a high current gain or considerable *drive* current. When these are exposed to high-energy radiation, the most striking and common effect of radiation is the current gain degradation. The action of a transistor as a current amplifier may be explained with reference to Figure 1.6.

The transistor consists of relatively large volumes of the same type semiconductor material, the emitter and the collector, separated by the base, which is a thin layer of the opposite type semiconductor material. With bias voltages applied as shown in the figure, conduction carriers will be injected from the emitter into the base with a velocity

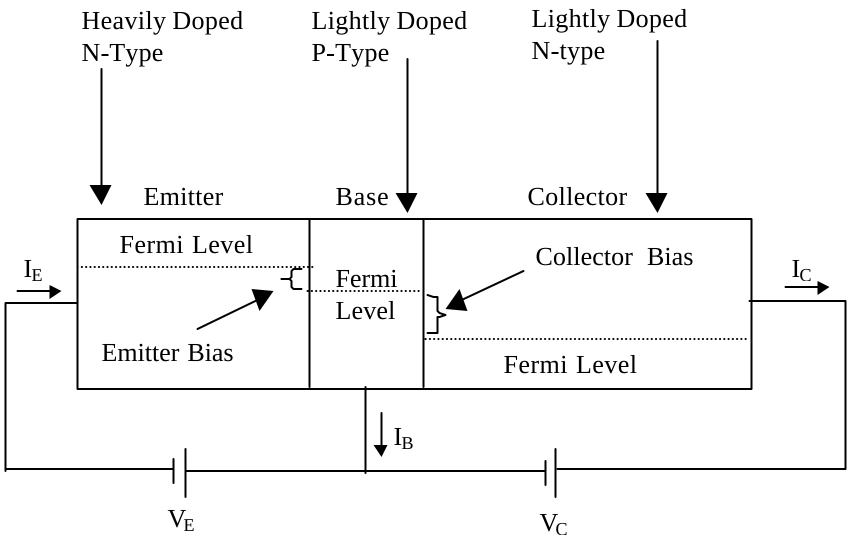

Figure 1.6 Transistor action.

determined by the applied field. Once in the base volume of the transistor, the carriers are termed *minority carriers*. Approximately, 98 to 99 % of those injected carriers enter the collector region by diffusing across the base, and an apparent current amplification takes place. The base thickness and the minority carrier's lifetime in the base region determine in part the electrical characteristics of the transistor. The base thickness remains constant for moderate particle fluences, while the life-time of the minority carriers is shortened by the radiation-induced crystal-lattice defects, which act as trapping and recombination centers for the carriers. Changes in the crystal surface, such as those which occur due to ion trapping (surface effects) also influence the behaviour of the device. As the amplification of the transistor is directly a function of the number of carriers traversing the base region, any loss of carriers via radiation-induced defects constitute a loss in the device gain.

In an intrinsic semiconductor, diffusion of carriers in the absence of external field or radiation will maintain an equilibrium condition with respect to carrier density. If this equilibrium is upset, the induced disturbance will decay exponentially toward the original equilibrium condition represented by an equation of the form

$$n = n_i + \Delta n \ \exp\left(\frac{-t}{\tau}\right) \tag{1.1}$$

where n is the carriers/cm^3 at time t, n_i is the initial condition, Δn is the induced carriers, and τ is the carrier lifetime. It is this carrier lifetime or *minority carrier lifetime* which is of great importance in radiation induced study. The carrier lifetime is that length of time in which the induced equilibrium disturbance decays to 1/e of its original value.

The process by which it takes place is termed *recombination*, which takes place when a hole and an electron meet and recombine. The concept of recombination center is required to account for experimentally measured values of lifetimes in semiconductor material. The recombination center captures and removes from the free carrier stream the carriers that happen to pass. It holds the carrier until such a time as an opposite carrier appears in the valence band below, whereupon the electron drops and recombines with the hole in the valance band.

The recombination center thus provides for permanent loss of the carrier. The recombination center is located at a defect, which creates an energy state in the middle of the forbidden energy gap. The defect may be located in the bulk volume of the crystal, such as impurity atoms or radiation damage induced lattice deformations. The surface of the crystal also represents a defect extended enough to warrant the term *surface recombinations*, which account for irregularities in lifetime behaviour at the crystal surfaces.

The *trap*, in contrast to the recombination center, removes the carrier only temporarily from the conduction band. The trap is produced by defects (impurity or radiation-induced) which create shallow localized states close to the edges of the forbidden gap. After capturing a carrier the trap will return the carrier to the conduction band with much higher probability than allow a recombination. The trap retains the carrier for periods ranging from 10^{-8} s to several days before returning to the conduction band, thereby introducing phase distortions in the signal processed by the transistors.

1.6.1 Mechanism of degradation of forward current gain

The term *gain* refers to either of the two separate parameters in a bipolar transistor. Common-base current gain (h_{FB} or α) is the ratio of collector current and emitter current and has a value less than unity. Common-emitter current gain (forward current gain h_{FE} or â) is the ratio of collector current and base current. Typical values of â ranges from 50 to 2000.

There are several factors which combine to determine transistor current gain (â): emitter efficiency, surface recombination velocity, recombination in the emitter field region, recombination in the base region and conductivity modulation [17]. Of these the recombination in the emitter field region and in the base region are the two dominant factors, which influence the transistor current gain.

When BJT's are exposed to radiation, the gain of the transistor decreases as the accumulated dose or fluence increases. The main cause for gain degradation is the displacement of atoms in the bulk of the semiconductor. This bulk damage produces an increase in the number of recombination centers and therefore reduces minority carrier lifetime. Another cause for gain degradation is the ionization in the oxide passivation layer, particularly that part of the oxide covering the emitter-base junction. The gain degradation can be represented by the equation

$$Ä\left(\frac{1}{â}\right) = \frac{1}{â} - \frac{1}{â_{0}} \qquad (1.2)$$

where $â_0$ and â are the gain values before and after irradiation.

Gain degradation is often analyzed by plotting the change in reciprocal gain Ä(1/â), versus radiation fluence. The term Ä(1/â) is known as the *gain damage figure* [18]. The effects of bulk and surface damage can be separated as follows

$$\text{Ä}\left(\frac{1}{\text{â}}\right) = \text{Ä}\left(\frac{1}{\text{â}}\right)_b + \text{Ä}\left(\frac{1}{\text{â}}\right)_s \tag{1.3}$$

where the suffixes ‘b’ and ‘s’ refers to the bulk and surface contributions respectively. However, while the bulk contributions may be reasonably predicted from analysis of minority carrier lifetime behaviour, the surface contribution is highly dependent upon process factors.

1.6.2 Displacement damage constant

The effect of atomic displacement in bulk silicon is to reduce the minority carrier lifetime which in turn reduces the current gain. The reduction in lifetime may be represented by the following equation

$$\frac{1}{\text{ô}} - \frac{1}{\text{ô}_0} = K_{\text{ô}}\boldsymbol{j} \tag{1.4}$$

where $K_{\text{ô}}$ ($cm^2 s^{-1}$) is known as the *minority carrier lifetime damage constant* for a given type and resistivity of silicon at a given radiation energy; ö is the fluence and ô_0 and ô are the initial and post-irradiation lifetime values. The value of $K_{\text{ô}}$ can be experimentally determined and adjusts for variables such as particle spectrum, particle type and device construction. $K_{\text{ô}}$ shows wide variations from device to device and a particular $K_{\text{ô}}$ is only usable in the degradation region in which it is determined. Further, values of $K_{\hat{o}}$ cannot account for the many different doping techniques adopted in transistor manufacturing process to obtain the right transistor characteristics. $K_{\hat{o}}$ also cannot account for emitter efficiency changes due to irradiation and surface recombination. Thus it is a difficult task to predict the value of $K_{\hat{o}}$ as there are a various complication factors which depend on device geometry such as

(i) The effectiveness of a given recombination center on lifetime depends upon the charge state of that center. This in turn is controlled by the minority carrier equilibrium pertaining to that point. A diffused junction device contains depletion regions near the junctions. In these regions, the electric fields are high and carriers are swept out rapidly. The material here resembles an intrinsic semiconductor and recombination rates certainly alter these rates. The actual field and hence carrier equilibria vary with the applied bias voltage.

(ii) The nature of the manufacturing techniques commonly used for transistors. In a diffusion transistor, the base and emitter regions are formed by the diffusion of dopants into the substrate silicon. Thus, the dopant concentration profile (and hence the Fermi level) in the base is far from uniform and varies by order of magnitude. In an ion-implanted device, different dopant concentration profiles will also be found. In addition, the implantation itself is likely to cause defects in the silicon, which are removable by annealing.

(iii) When current flows in the transistor, the Fermi level is altered by the presence of excess carriers injected at the emitter-base junction and effectively depends upon the operating level of the transistor.

1.6.3 Influence of base width

In bipolar devices, base width is also an important factor which has significant influence upon gain degradation by bulk damage. Assuming that the surface recombination and emitter efficiency remain constant, the gain damage figure caused by bulk damage can be shown to be [18]

$$Ä\left(\frac{1}{â}\right)=\frac{W^{2}}{2D_{b}}K_{ô}\boldsymbol{j} \qquad (1.5)$$

where W is the base width and D_b is the minority carrier diffusion constant in the base. This equation demonstrates the strong dependence of the gain damage figure upon base width. Thus, it is necessary to measure or calculate this term for devices under consideration. The value of W itself cannot be measured easily; however, the cut-off frequency ‘$f_{á}$’ (the frequency at which common-base current gain ‘á’ falls to one-half of its low frequency value, say at 1Hz) bears a close relation to W. By using this dependence, Messenger et al have derived the following equation for the effect of bulk damage on transistors [17, 20-25]

$$Ä\left(\frac{1}{â}\right)=\frac{K_{ô}}{2\,ð\,f_{á}}\boldsymbol{j} \qquad (1.6)$$

Although the cut-off frequency $f_{á}$ is included in the equation for gain prediction, an alternative parameter 'f_T' (the gain bandwidth product) is more easily measured and also most commonly quoted for transistors. It is the product of common-emitter gain 'â' and the frequency of measurement when the frequency lies on the descending part of the gain frequency curve.

It is often convenient to express transistor damage as a *gain damage factor* also called *displacement damage factor* (K) without normalizing for base width, f_T, etc. Thus,

$$\frac{1}{â} - \frac{1}{â_0} = Ä\left(\frac{1}{â}\right) = K\ \boldsymbol{j} \qquad (1.7)$$

where K is the *displacement damage factor* expressed in cm^2/particles. From the equation (1.7), we can calculate the K as follows.

$$K = \left(\frac{1}{\boldsymbol{j}}\right)\left(\frac{1}{â} - \frac{1}{â_0}\right) \qquad (1.8)$$

From equation (1.6) and (1.8) we then have

$$K_ô = 2ð\, K\ f_T \qquad (1.9)$$

The frequency '$f_{á}$' and 'f_T' are not exactly equal, 'f_T' being slightly lower than $f_{á}$. The ratio between them depends on the doping profile. For ideal step junctions, $f_{á}$ = (1.22).f_T; for diffused junctions, the ratio is 1.33. Thus, in practice the error introduced by using 'f_T' in the prediction of Ä(1/â) is not often significant and in any case, error is on the side of safety. In recent publications, ‘f_T’ has been used in place of ‘$f_{á}$’ for diffused transistors without any correction factors [26-27].

1.6.4 Effect of surface recombination on gain degradation

There are two basic mechanisms involved in the surface linked effects of total-dose on the gain degradation of bipolar transistors: (a) accumulation of positive trapped charges in the oxides, and (b) the accumulation of interface states at the silicon-silicon dioxide interface [28-29]. The interactions of these two mechanisms with the factors of polarity, emitter technology, base doping density, emitter bias and dose rate can account for most of the observed effect. Figure (1.7) depicts the base-emitter junction of *npn* device before and after irradiation. The fringing fields point from the emitter to the base (they point in the opposite direction in *pnp* devices). In the post-irradiation case, the positive oxide charges and surface states are shown. The fields are modified by the presence of the charges.

The buildup of positive trapped charges in the oxides at the emitter-base junction will deplete lowly doped *p*-type base regions. As a result, the total depleted surface area in *npn* transistors increases. This increase in the depleted surface causes an increase in the surface recombination current. The recombination reaches a maximum in forward biased junctions where the electron and hole concentrations are equal (called cross-over condition). The location of the cross-over, as well as the width of the depletion region at the surface is dependent on the surface potential. The surface potential in turn is dependent on the distribution of charges in oxide and at the interface, and the junction

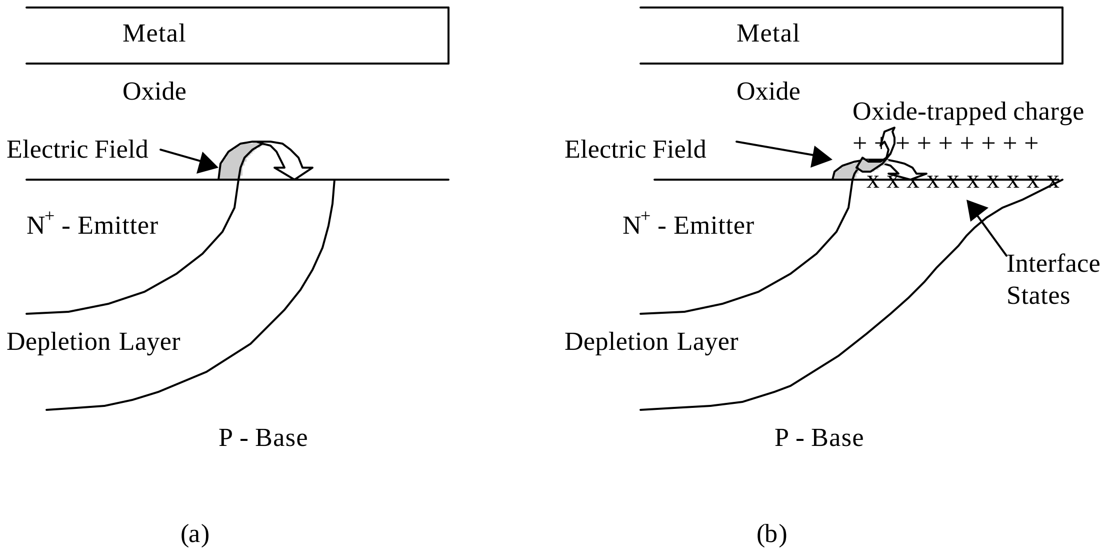

Figure 1.7 Magnified cross-section of the base-emitter junction of an *npn* transistor. (a) Pre-irradiation. (b) Post-irradiation.

bias conditions. The surface recombination rate per unit area for a distribution of trap levels at the surface of a forward biased junction can be theoretically estimated [28, 30]. The recombination rate is maximum where the number of electrons is equal to number of holes, which occurs at the surface within the depletion region. Since there is more recombination in the device, more base current will flow at a given base-emitter voltage. Further, this recombination occurs at the periphery of the emitter. As oxide charge increases, the position of the cross-over moves out further into the base until the entire base region becomes inverted.

The buildup of interface traps at the silicon-silicon dioxide interface increases the surface recombination velocity. These traps do not contribute surface current when they lie over undepleted surfaces, but they are effective recombination centers when they lie over depleted surfaces. Consequently, there is an interaction between the positive trapped oxide charge and the interface traps. As positive oxide charge increases (particularly over a *p*-type region), the surface depletion region increases, exposing more recombination sites due to interface traps. Thus, while oxide charges and interface traps may increase sublinearly or even linearly with total dose, base current may increase superlinearly with total dose. For example, if the total dose is doubled, the excess base current more than doubles.

In addition, the oxide charges and interface traps interact with the fringing electric fields of the junction in the oxide. The positive trapped oxide charge shields the fringing electric fields in the oxide. Therefore, as positive oxide charge accumulates, the fields change, and subsequent accumulation of positive oxide charge occurs under different field conditions. The fields will also tend to concentrate the positive oxide charges and the interface states in the direction of the field (assuming the buildup of interface traps occurs due to a two-state H^+ process). Specifically, the damage will accumulate over the base side of the junction in *npn* devices, but over the emitter side of the junction in *pnp* devices. In other words, the oxide charges and interface states accumulate in spatially non-uniform distribution.

Both mechanisms cause in increase in base current through recombination. The collector current is unchanged. Therefore, the current gain decreases. The base current in a bipolar transistor can be expressed [13]

$$I_B = \frac{I_S}{\beta_{pk}} \exp\left(\frac{V_{BE}}{kT}\right) + I_{SS} \exp\left(\frac{V_{BE}}{n\,kT}\right) \qquad (1.10)$$

where I_S is the collector saturation current, β_{pk} is the peak pre-irradiated current gain, V_{BE} is the base-emitter junction bias, I_{SS} is a surface saturation current, and n is an ideality factor characterizing the recombination. The first term in the equation (1.10) is proportional to emitter area. The second term is directly proportional to emitter perimeter. As the total dose increases, value for n increases from 1 to 2 [31].

1.7 Thermal annealing

It is well known that most radiation-induced defects are permanent. Annealing of defects occurs when a vacancy and an interstitial atom combine. For less massive destruction of the silicon crystal structure, such as that produced by electrons and protons, annealing of certain number of defects could occur at room temperature. However, for some radiation-induced defects, the semiconductor material must be heated to temperatures in excess of 150 ^{o}C to produce significant annealing. In general, the radiation-induced defects may be considered permanent damage. A very slow annealing is experienced when irradiated devices are allowed to rest for several months at room temperature. However, a major fraction of the defects induced during irradiation will remain.

1.7.1 Thermal annealing of bulk damage

Radiation-induced displacement defects (bulk damage) in silicon do not anneal easily because the vacancies and interstitials created by the radiation are usually complexed with an impurity atom (oxygen or dopant). The defects that concern us most are those that are stable at room temperature, e.g. the ‘A’ centre (complex of a vacancy with oxygen) and the centres designated ‘E’ (phosphorus vacancy), ‘J’ (di-vacancy) and ‘K’ (divacancy-oxygen complex). These centres are completely stable at temperature below 200^{0} C. But the damage often anneals between 200 and 450^{0} C completely [18].

1.7.2 Thermal annealing of surface effects

The thermal annealing of the surface effects in bipolar transistor slightly different from that of displacement related defects. Interface states anneal out at temperature in the 100 to 200^{0} C range and trapped charges could be removed between 150 to 300^{0} C. Some relaxation may occur even at room temperature.

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