CHAPTER I

PROCESSES OF INTERACTION OF RADIATION, INDUCED DEFECTS, AND SOURCES USED
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In this chapter, importance of the work carried out in this thesis is mentioned in short. This chapter also discusses different processes of interaction of radiation with the material in general and semiconductors in particular. The effect of interaction of gamma radiation, electrons and heavy ions is discussed in detail. The difference between these processes and its effects on damage production are also discussed. A brief information about the radiation sources used for this work is also given.
1.1 NEED OF THIS WORK:

In last two decades the effects of radiation induced damage in electronic devices is becoming an area of interest. Electronic systems that are normally operated in radiation environment such as in space or near reactors or accelerators cannot avoid radiation. Such devices must be designed to tolerate the effects of radiation. Therefore, it is of extreme importance to study the radiation effects in the electronic materials as well as devices. The data obtained from such studies can be utilized in designing the instrumentation or other data acquisition or processing units which are operated in the above mentioned areas. In case of space applications the data obtained from such studies decide the life of the satellites.

Whenever radiation falls on any material it basically ionizes the target material and due to this disorder is produced in the material. This disorder is often referred as displacement type damage, which is nothing but the displacement of the lattice atoms from their original lattice sites. These displacements can cause changes in the properties of the material which can be mechanical or electrical. However when the ionizing radiation falls on the electronic devices they show degradation in their characteristics. These degradation are seen in the electrical as well as other properties of the device. As the electrical behavior of the device changes there is a possibility of failure of an instrument as this device can be a part of such an instrument. Hence the reliability of the electronic circuitry is very much dependent on the study of these radiation induced degradation of the devices.

The another application of the study of radiation induced defects in devices is to alter device properties. That is to tailor the electrical properties of the devices with the help of intentional addition of defects in the devices. In the case of semiconductor lattice, the defects induced by radiation can alter the energy level diagram of that crystal, by introducing energy trap levels in the forbidden gap. Radiation damage can also be used to alter transport properties such as lifetime of carriers or mobility of carriers can be altered in case of semiconductor.
1.2 INTERACTION OF RADIATION WITH MATERIAL:

Radiation effects start with radiation impinging on the target material. When interaction of radiation with material is considered, the interaction between the impinging particle and target atom is considered. As the impinging particle has high energy, on interaction energy transfer between the target atom and the incident particle take place. The transfer of energy can take place in many ways depending upon the physical parameters of the system. The transferred energy can appear in many ways such as kinetic energy, heat or creation of new particle.

The most likely process to take place is ionization of the target material. In case of ionization the electron takes away most of the kinetic energy as it is light in weight. The electron can get sufficient kinetic energy to further ionize the material that is this electron when strikes with another atom ionizes it. During the ionization process the rest of the atom experiences the recoil and gets displaced from its original position. If the impinging particle can impart sufficient energy which is greater than the threshold energy $E_d$ for displacement, to the atom then the target atom can be displaced on interaction. This displaced atom can act as interstitial atom as it is normally located in between the lattice sites, and the empty lattice site forms the vacancy. Introduction of vacancies and interstitials change the band structure of the material due to change in the bond length and distance between the atoms. There are many process through which the impinging particle can interact with the target atom and it depends on the type of radiation as well as on the target material.

1.2.1. GAMMA RAYS:

Gamma radiation is electromagnetic in nature and cannot produce displacement directly. They transfer their energy to the electrons of the target atom. These electrons in turn can displace the target atoms if their energy is greater than the threshold energy for displacement, $E_d$. Gamma rays are therefore of interest in the study of radiation induced damage in materials. Displacement effects have been studied in various solids for photons energies
above 20 keV. The processes which produce displacement are briefly of three
types, compton scattering, photoelectric effect and production of electron
hole pairs close to the nucleus. The mechanisms of direct energy transfer from
photons to the atomic nucleus are photoelectric effect and compton
scattering.

Consider a photon of energy $E_\gamma$ incident on a monoatomic solid, and
assume that any atom receiving energy in excess of $E_d$ is displaced, while
those receiving an energy less than $E_d$ are not. Thus the cross section per atom
$\sigma_d(E_\gamma, E_d)$ for producing a primary displaced atom by a photon of energy $E_\gamma$
is,

$$\sigma_d(E_\gamma, E_d) = \int_{E_d}^{\infty} (d\sigma/dT)(E_\gamma , T) dT$$

However as more than one processes are involved in the displacement,
the cross section $d\sigma/dT$ can be written as,

$$d\sigma/dT = d\sigma^c/dT + d\sigma^{pe}/dT + d\sigma^{pp}/dT \quad (1.2)$$

where $d\sigma^c/dT$ is the cross section for the displacements produced due
to the compton scattering, $d\sigma^{pe}/dT$ is the cross section due to photoelectric
effect and $d\sigma^{pp}/dT$ is the cross section corresponding to the process of pair
production. In the case of photo electric effect the photo electrons are
produced with nearly the same kinetic energy as that of the incident photon
therefore it appears that this process may contribute largely towards the
displacement of atoms. However the cross section for the photo electric effect
decreases rapidly for photon energies beyond 0.1 MeV. Since the
displacement energy, $E_d$, for silicon is around 250 keV, the number of
photoelectrons having energy greater than 250 keV will be extremely small
for any photon energy. Similarly, one would get 0.511 MeV energy photons
through positron annihilation (pair production) which will have very small
cross section for producing photoelectrons of energy greater than $E_d$.
Furthermore, long lived radioisotopes which emit high energy photons to
have appreciable cross section for pair production, are rarely found. For
example widely used Co-60 gamma source emits photons of 1.17 and 1.33
MeV energies and therefore the processes of photoelectric effect and pair production do not contribute much towards displacing the target atoms.

The cross section for the compton scattering is given by the following relation [2];

$$\sigma = \pi r_0^2 Z \frac{(\alpha - 3)(\alpha + 1)}{\alpha^3} \ln (1 + 2\alpha) + \frac{2(5 \alpha^2 + 9\alpha + 1)}{\alpha^2 (1 + 2\alpha)^2} - \frac{8\alpha^2}{3(1 + 2\alpha)^3}$$

In case of compton scattering the energy of the ejected electron varies with the emission angle as per the following relation;

$$T_e = E_\gamma \frac{2\alpha \cos^2(\theta)}{(1 + \alpha)^2 - \alpha^2 \cos^2(\theta)}$$

where, $T_e$ is the energy of the struck electron emitted at an angle $\theta$, with respect to the direction of incident photon of energy $E_\gamma$ and $\alpha = E_\gamma / m_e c^2$. In figure 1.1 the energies of electrons emitted at different angles from 0 to 90 degrees with respect to the incident photon of energy 1.33 MeV are shown. From this graph it can be seen that for Co-60 gamma rays, the electrons emitted beyond 50° are not useful in producing atomic displacements.

The Co-60 gamma source is conveniently available at several places therefore, it is widely used in studies of radiation damage. Since the cross section for the interaction processes are small, high strength source (in the range of kilo curie activity) is necessary to have reasonable time of radiation. The other advantage in using this source is that the radiation dose is almost constant over a irradiation period of tens of hours. Similarly the dose rate can be varied by positioning the sample with respect to the source position.

1.2.2. ELECTRONS :

Energetic electrons with energies around 1 MeV are able to produce displacements by direct interaction through the coulomb potential with the nuclei of the target. Electrons with energy in the range of MeV should be treated using relativistic mechanics. The mass of the nucleus is very much greater than that of the electron, therefore the collision only alters the direction of the electron. If the electron with kinetic energy $E_e$ is deflected
Figure 1.1. In the Compton scattering the variations in the energy of the emitted electrons with emission angle.
through an angle $\theta$, then the energy transferred to the nucleus of mass $M$ is given by:

$$E_{\text{nuc}} = \frac{2m_e}{Mm_e c^2} (E+2m_e c^2) E \sin^2(\theta/2)$$

(1.5)

where, $m_e$ is the electron mass and $c$ is the speed of light. The above equation can also be expressed as:

$$E_{\text{nuc}} = E_{\text{nucm}} \sin^2 (\theta/2)$$

(1.6)

where $E_{\text{nucm}}$ is the maximum possible energy that could be transferred. For practical purposes the $E_{\text{nucm}}$ is taken as:

$$A E_{\text{nucm}} = 560.8 \times (x+2)$$

(1.7)

where $x = E/m_e c^2$. Let $E_{\text{em}}$ be the minimum electron energy to produce displacements then,

$$E_d = 2 \times \frac{m_e}{M} \times \frac{E_{\text{em}}}{m_e c^2} \times (E_{\text{em}}+2m_e c^2)$$

(1.8)

The values of $E_{\text{em}}$ for electrons and gamma rays can be obtained from the plots given in figure 1.2 for different targets of mass numbers upto 200 [1].

The electron nucleus interaction is through the Coulomb potential, as at high electron energies the atomic electrons can be neglected. The Coulomb interaction gives rise to the Rutherford scattering of the electrons. If the $E_{\text{nucm}}$ is only slightly greater than $E_d$ each collision displacing an atom produces the primary are displacement and hence the damage is also simplest. In this case the cross section is given by;

$$\sigma_d = \left[ \frac{\pi b^2}{4} \right] \frac{E_{\text{nucm}}}{E_d}$$

$$= 5.55 \left( \frac{Z^2}{A} \right) 10^{-24} \text{cm}^2$$

(1.9)

where $b' = 2Ze^2/m_e v^2 (1-v^2/c^2)$

The impinging electrons are slowed down rapidly in the solid as they lose their energy to the electrons of the solid. Therefore, the irradiation damage can be produced only in very thin samples of the order of few millimeters, through which these electrons can pass. Now if the ratio $(E_{\text{nucm}}/E_d)$
Figure 1.2. Minimum electron energy required to produce displacements for target atoms over a mass range up to 200.
is greater than 1 then the primary knock on may produce further
 displacements [3].

As the electrons pass through the medium they lose their energy in
ionizing atoms and radiative collisions. During the interaction with the
material the electron gets deflected many times and therefore it is really
difficult to calculate its range in a material. The empirical relation for the range
of electrons in a material is,

\[ R (\text{mg/cm}^2) = (530 \times E) - 106 \]  (I.10)

where, \( E \) is the energy of the electrons in MeV. This relation holds good
for electron energies from 1 MeV to 20 MeV. The irradiation damage is
produced uniformly by the electrons if the sample thickness is chosen in such
a way that \( \sigma_d \) does not vary much throughout the sample.

In case of semiconductors as the samples are very thin, few \( \mu \text{m} \) thick,
the electrons are known to induce damage uniformly in the wafer.

1.2.3. Heavy Ions

The process of displacement produced by heavy ions is different than
that of the previous two cases. The ions are ionized in the beginning of their
range and then start gaining the electrons in the later part. Therefore, it is
necessary to consider energy loss in the different regions separately. At the
higher energy when the ion enters the medium, it loses some of its electrons
and gets multiply ionized. At this stage the mechanism for energy loss of the
moving ion is through electronic excitation. At higher energies the electrons
of the moving atom can be neglected and the collisions are of Rutherford type
that is due to coulomb interaction. As the kinetic energy of the atom
decreases its degree of ionization also decreases. As the degree of ionization
decreases the energy loss in electronic excitation also reduces. As the moving
atom now becomes neutral the energy is lost in the collision with the target
atom which is of hard sphere type.

At high energies of the order of tens of MeV the moving atom nucleus
directly interacts with the nucleus of the target atom, and this interaction is via
Coulomb potential and thus the scattering is of Rutherford type.
Consider a moving particle of mass $M_j$ and charge $Z_je$ interacts with stationary particle of mass $M_i$ with charge $Z_i e$. Then the cross section is given by:

$$\sigma_d = \pi M_j Z_i^2 Z_2^2 \frac{e^4}{M_i E E_d} \tag{1.11}$$

The mean energy transferred to the struck atom for the case in which the atom is displaced is given as:

$$E_{ad} = E_d \ln \left[ \frac{E_{adm}}{E_d} \right] \tag{1.12}$$

where, $E_{adm} = 4M_1M_2 E / (M_1 + M_2)^2$ The relation 1.12 is valid only when the ratio of $E_{adm}$ to $E_d$ is greater than 1. The Mean free path between collisions in which displacements are produced is given by $L_d = 1/N_0 \sigma_d$ where, $N_0$ is the number of atoms in unit volume. The local energy deposition which is less than $E_d$ results into the thermal spikes, that is the local temperature of the target increases. Assuming that a knock on atom with energy $E_{ad}$ will produce $E_{ad}/2E_d$ further displacements for $E_{ad} > 2E_d$ and will produce only one displacement for $E_d < E_{ad} < 2E_d$, the average total number of displacements $n_d$ produced in a Rutherford collision is,

$$n_d = \frac{1}{2} \left\{ 1 + \ln \left( \frac{E_{adm}}{E_d} \right) \right\} \tag{1.13}$$

The major source of energy loss at higher energies is electronic excitation. In this energy range the moving atom is stripped off all its electrons, and the energy loss is due to Rutherford collisions of the electrons of the solid with the nucleus. and the rate of energy loss is given by:

$$\frac{dE}{dR} = \frac{4\pi N_0 e^4 Z_i Z_2^2}{2E} \frac{M}{m_e} \ln \frac{4E}{m_i I} \tag{1.14}$$

where $I$ is the average ionization potential of the target atom. As the energy of the ion reduces it starts gaining the electrons and hence the effective charge of the ion changes and is denoted by $Z_2$ effective. This effective charge is given as:

$$Z_2 \text{effective} = 0.9 \times 10^2 \ (E/A)^{1/2} Z_2^{1/3} \tag{1.15}$$

As the energy of the ion further decreases it approaches towards charge neutrality and then experiences collision which is of hard sphere type.
The energy at which the ion becomes neutral can be calculated. If the velocity of the ion is \( v \) then the electrons of the lattice with velocity much less than \( v \) can at most transfer energy \(~ m_e v^2 \) to the electrons of the atom, if this energy is less than the atom's ionization potential then the atom remains neutral. Assuming a minimum ionization energy of the atom as 2 eV, the value of \( E_n \) at which the atom becomes neutral is

\[
E_n = \frac{1}{2} M v^2 = \frac{1}{2} M \times \frac{1}{m_e}
\]

\[
= \frac{1840}{2} \text{ A eV} \approx 920 \text{ keV} \tag{1.16}
\]

The hard sphere collisions basically give rise to the atomic displacements. MeV energy ions can penetrate a few microns in the target before coming to rest. The property of ions to produce displacements in the end of range region is utilized to introduce defects in specific areas. In case of semiconductors this property is used to tailor the characteristics of devices.

I.3 RADIATION SOURCES:

I.3.1 GAMMA SOURCE:
In the present work the Co-60 gamma source of the Department of Chemistry, University of Pune, was used. The strength of this source was 10 kilo curie and the dose rate could be varied from 10 kRad/hr to 360 kRad/hr. The Dose rate was measured using a standard Fricke dosimeter.

I.3.2 ELECTRON SOURCE:

The electron beam was obtained from the electron accelerator called as Microtron of Department of Physics, University of Pune [4]. This is an 8 MeV race track Microtron, a side view and a top view showing various parts of the accelerator are shown in photographs I.1 (a) and (b) respectively. The control system of the machine is housed in a separate room and all the operations of the machine are carried out remotely from the control console, a view of the same is shown in photograph I.2. It is an eight orbit machine with energy gain per orbit variable from 800 keV to 1000 keV. The machine is operated at pulse width of 2 \( \mu \)s, repetition rate variable from 50 PPS to 250 PPS, and pulse current of about 10 mA. Most of the parts of this accelerator were obtained from the Berkeley, California, and some parts were fabricated in the University
Photograph 1.1 (a). Photograph showing side view and top view of Race-Track Microtron.

Photograph 1.1 (b). Control console of Race-Track Microtron.
of Pune workshop. This accelerator can provide electron beam in the energy range 0.5 MeV to 1 MeV and 6 MeV to 8 MeV [5].

1.3.3 HEAVY ION SOURCE:

For the present work the main source of ions used was the Pelletron accelerator. As shown in figure 1.3, the 15 UD Pelletron ion accelerator consists of ion source, focusing lenses, mass analyzer, accelerating column, irradiation chamber, arrangement for ion dose measurement and hi-vacuum system. This accelerator is a vertical tandem accelerator. Negative ions from the ion source are preaccelerated, mass analyzed and injected at energy of 250 to 350 keV into the accelerator. At the terminal they are stripped to various charge state \((q)\) by foil or gas stripper. These positive ions then get repelled by the terminal to gain further energy which is then energy analyzed by the analyzer magnet (1.8 m in radius) and can be delivered in seven beam lines by using a switching magnet.

The energy of the accelerated particle beam available depends on the charge state \((q)\) of the ion and the terminal potential \(V_t\).

\[
E = (q+1) V_t \text{ MeV} \tag{1.17}
\]

The terminal potential \(V_t\) is normally in the range 10 MV to 15 MV. The charge state of the particle depends on the ion species. For material science work mainly Light Ion Beam Room Scattering Chamber (LIBR) and Materials Science Beam lines are available. In LIBR a chamber of 375 mm diameter and 300 mm height is provided at -30° beam line. A remotely controlled target ladder is inserted from the top lid of the chamber which has a linear movement of 70 mm. The targets are pasted on the ladder. The workable vacuum of \(10^{-7}\) torr is available. The material Science beam line is at 45° and provides similar facilities like LIBR. Most of the present work was carried out at LIBR, the detailed description of the experimental facility is given in Chapter VI.

1.4 RADIATION INDUCED DEFECTS:

In a regular periodic lattice the discrete allowed energy levels of individual atoms are altered and merge into very dense bands. In case of semiconductors there are two bands well separated by the band gap. At
Figure I.3. A schematic diagram of Pelletron - an ion accelerator.
absolute zero, one of these bands is completely filled with electrons and is known as valence band and the other is completely empty which is known as conduction band. These two bands are well separated and the energy difference between these two bands is called as the energy band gap or forbidden gap.

In case of intrinsic semiconductor the density of energy levels in the band gap is negligibly small. Only at finite temperature some of electrons from valence band are excited to conduction band and are available for conduction. In case of extrinsic semiconductor, the periodicity of the lattice is interrupted by the added impurity atoms hence an energy level is added into the forbidden gap. These energy levels can capture electrons or holes depending upon the impurity type. On introduction of column V element in the silicon lattice the energy level is created near the conduction band and is known as donor level as it can donate electron to the conduction band. Whereas introduction of group III element introduces energy level near the valence band and is known as acceptor level as it captures electrons from valence band [6].

The radiation produces defects in the solid through atomic displacements. The simplest type of defect is produced when the lattice atom is dislodged from its position and is placed in an interstitial position. Due to this also the energy of the crystal is raised by an amount $E_i$, which is energy of formation of interstitials. In a similar way $E_v$ is the energy of formation of vacancy. A vacancy is created when the lattice site is vacant. These defects are called as point defects. The atoms surrounding the vacant site can jump into the vacancy if they have sufficient thermal energy to do so. Some time clustering of point defects is also seen such as line defects, divacancies or diinterstitials. Due to such defects in the solid the properties of the solid change. In case of semiconductor the electrical properties of the material change due to either introduction of scattering centers or due to introduction of the new energy states in the energy gap.

The high energy radiation produces defect complexes in semiconductor material which reduce minority carrier lifetime, change majority carrier density,
and reduce mobility of carriers. The vacancy and interstitial defects are mobile even at liquid nitrogen temperature. The interstitial silicon are not electrically active and also do not form stable and electrically active complexes. However, the vacancies and their complexes are effective recombination and trapping centers. These include A centre (Oxygen impurities), E centre (n type dopants) and divacancy. Whenever a trapping centre traps a charge and becomes a charged ion it adds to the coulomb scattering of rest of the carriers, which causes reduction in mobility and diffusion constant. The E centre is located ~ 0.4 eV below the conduction band and acts as an effective trapping centre, whereas the divacancies introduce defect level at around 0.35eV above the valence band and acts as effective trapping as well as recombination centres. The A center is located ~ 0.17 eV below the conduction band edge, in float zone type silicon the concentration of A centers is less as there are less oxygen impurities. It has been reported in literature that a large fraction of the radiation induced defects in semiconductor can be annealed above 450°C.

In the Chapters II through IV the effect of radiation induced defects on devices has been studied whereas Chapter 5 reports studies on defects using technique of Hall measurement.
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