1. INTRODUCTION

For efficient devices it is important to characterize the defects in semiconductors so that those defects that are bad are eliminated and those that are useful can be controllably introduced. The high-energy radiation induces changes in the electrical, optical, structural, and other properties of semiconductors. At the present time, the corresponding studies are carried out for a wide variety of semiconductor materials under various conditions of irradiation.

Due to delay in procurement of GaN wafers the work is carried out on the studies of radiations effects (ion beams) on electrical properties of Silicon NPN BJTs. A bipolar junction transistor (BJT) is widely used in discrete circuits as well as in IC design, both analog and digital. Its main applications are in amplification of small signals, and in switching digital logic signals. In a BJT, both majority carriers and minority carriers play a role in the operation of the transistor, hence the term bipolar. Bipolar Junction Transistors (BJTs) have important applications in analog or mixed signal ICs and BiCMOS circuits because of their current drive capability, linearity and excellent matching characteristics. Many of the integrated circuits (ICs) used in space systems, including operational amplifiers, comparators and voltage regulators are to accomplish analog functions.

Si Microelectronic circuits and devices are widely used in both terrestrial and space applications. Si Bipolar junction transistors (BJTs) have important applications in analog or mixed-signal integrated circuits (ICs) and bipolar metal oxide semiconductor (BICMOS) circuits, because of their current drive capability, linearity and excellent matching characteristics[1]. Some of these are extensively used in spacecrafts [2]. The radiation effects on bipolar devices produced by protons, neutrons, electrons and gamma rays have been investigated in the past years [3]. However only a few studies are available on irradiation effects of heavy ions for NPN BJTs . These investigations are valuable to study the effect of radiation on current transport in these devices. Therefore, the investigations on the modifications in semiconductor devices like Bipolar junction transistors (BJTs) under radiations are of both technological importance and scientific interest.

2. THEORETICAL RESUME

2. 1. Radiation Interaction with Matter

The various radiation sources give rise to various radiation particles with wide variation in energy and dose rate. For example, the space environment consists of a low-level constant flux of energetic charged particles (protons, electron and heavy ions), whereas a nuclear explosion may give out strong pulses of neutrons and gamma rays. From the standpoint of radiation interaction with solid material, the various types of irradiation particles can be divided into three groups: (1) photons (x-rays, gamma rays); (2) charged particles (electrons, protons, alpha particles and heavy ions); and (3) neutrons. The interactions of the radiation with solid-material targets depend on the mass, charge state, and kinetic energy of incident particle, and on the atomic mass, atomic number and density of the target material. There are a number of specific types of interaction that can take place for each group of irradiation particle mentioned above. The knowledge of the radiation interaction is essential for interpreting the types and degree of the damage introduced in semiconductor material for a specific radiation environment[4-7].

2.1.1. Photon interactions

Photons interact with matter primarily through (1) photoelectric effect, (2) Compton scattering and (3) pair production. The types of interaction which the photon may undergo depend on the photon energy and atomic number (Z) of the target. In all three cases, the interactions generate energetic secondary electrons.

In the photoelectric process, the photon is completely absorbed by the emitted outer-shell electrons of the target atom. The probability of a photoelectric interaction decreases with increasing photon energy and increases with Z of target. In Compton scattering the high energy incident photon is not completely absorbed because its energy is much higher than the atomic-electron-binding energy of the target atom. The incoming photon gives part of its energy to the electron, and then the scattered photon has lower energy, lower frequency and longer wavelength. The wavelength change in such scattering depends only upon the angle of scattering for a given target particle. The shift of the wavelength increases with the scattering angle. In pair production, a high-energy photon gives up its quantum energy to the formation of a particle-antiparticle pair in its interaction with matter. The quantum energies of the gamma rays are equal to the sum of the mass energies of the two particles (including their kinetic energies).

2.1.2. Charged particle interactions

Charged particles, such as protons and electrons, interact with matter primarily through (1) Rutherford scattering and (2) nuclear interactions. The Rutherford scattering is typically the dominant interaction. In Rutherford (Coulomb) scattering, the charged particles interact with the electric field of the target atom. This interaction can cause both excitation and ionization of the atomic electrons. Additionally, the incident charged particle may transfer recoil energy E to a lattice atom, the so-called primary knock-on atom (PKA). For sufficiently energetic impacts, the recoil energy exceeds material dependent displacement-threshold energy and the PKA leaves its original lattice position, thus a Frenkel (vacancy-interstitial) pairforms.

In nuclear interaction, the incident particle actually interacts with the atomic nucleus. For example, a proton can be absorbed in a target nucleus, and the nucleus then emits an alpha particle. This process is also called spallation. The alpha particles produced in spallation, and the recoil atoms from displacement mentioned above can transform a proton environment into a heavy ion environment. Nuclear interactions can result in elastic or inelastic scattering and transmutation (through fusion or fission).

An energetic ion penetrates a solid it undergoes a succession of binary collisions with target atoms and surrounding electrons, losing energy at each encounter. The transfer of energy from projectile ion to the solid can be conveniently divided into two independent processes, namely electronic energy loss S_e and nuclear energy loss S_n [8]. The former process depicts the interaction of fast ions (MeV) with lattice electrons. An appreciable amount of energy is usually transferred during each electronic collision (so-called inelastic collisions) but the large density of electrons and the high frequency of such collisions cause large amount of energy loss during the slowing down of the incident ion. The later nuclear energy loss process is constituted by collisions between the incident ion and the lattice atoms where conservation of energy and momentum apply (so-called elastic collisions). The rate at which the projectile ion loses energy with penetration depth (x), $S(E)=\frac{dE}{dx}$, is the sum of electronic and nuclear energy-loss terms,

i.e. $S(E)=S_e+S_n$

Electronic energy loss:

An energetic ion passing through a solid interacts simultaneously with many electrons through the attractive Coulomb force. The energy is transferred to the electron by the energetic ion and depending on the proximity of encounter; this energy may be sufficient either for ionization (remove the electron from the atom) or for excitation (raise the electron to a higher-lying shell within the target atom). Electronic energy loss through the inelastic collision is the dominant process at high energy (1MeV/nucleon) and ion paths tend to be quite linear from microns to tens of microns because the ions are not greatly deflected by any single encounter with electron. The theory of electronic energy loss of highly energetic ions in solids was first given by Bohr [9] in 1913. He derived the expression for S_e on the basis of a model which considered the target as a collection of harmonic oscillators whose frequency was determined by optical absorption data. The work was extended to relativistic ions by Bethe [10] and Bloch [11]. They solved the energetic ion energy loss problem quantum mechanically in the first Born approximation. The expression that describes the electronic energy loss of a highly energetic ion in a solid is known as Bohr-Bethe formula and is written as

$$S_e=-\left[\frac{dE}{dx}\right]=\frac{4\pi e^2 Z_p^2 Z_t N_t}{m_e v^2}\left[\ln\left(\frac{2m_e v^2}{I}\right)-\ln\left(1-\frac{v^2}{c^2}\right)-\frac{v^2}{c^2}\right]$$

here v and Z_p e are the velocity and charge of the projectile ion, Z_t and N_t are the atomic numbers and number density of the target atoms, m_e is the electron rest mass and e is the electronic charge. The parameter I represent the average excitation and ionization potential of the target material, and is usually an experimentally determined parameter for each element. For non-relativistic projectile ions only the first term in square brackets of Equation is significant. It is generally valid for different types of ions provided their velocity remains large compared with the velocities of the orbital electrons in the target atoms. It can be seen from this equation that for a given non-relativistic ion, S_e varies as $\frac{1}{v^2}$, or inversely with ion energy. This is due to the fact if the velocity of the ion is low, then it spends a greater time in the vicinity of the electron, and thus transfers greater impulse, and hence larger velocity, to the electron.

To understand how this electronic energy loss is transferred to the crystal lattice, there are two prominent models of microscopic energy transfer from electrons to the lattice atoms: thermal spike model and coulomb explosion model.

Nuclear energy loss:

Ion range in materials where ions have low energy (1keV/nucleon), nuclear energy loss dominates due to the elastic binary collisions between projectile ion and individual target atoms [9]. The derivation of S_n uses two main assumptions: (i) A screened Coulomb potential, and (ii) The impulse approximation.

The electronic energy loss is believed to cause modifications in the materials while the nuclear energy loss is responsible for atomic displacements in the materials. Depending on these energy losses ion beams are used to characterize material as well as to modify them.

2.1.3. Neutron interactions

Neutrons incident on solid material undergo the following nuclear interaction: (1) elastic scattering, (2) inelastic scattering, and (3) transmutation. In elastic scattering, the neutron is not captured but transfers a portion of its energy into an atom of the target material, and can dislodge the atom from its normal lattice position. This process will occur as long as the imparted energy is larger than that required for displacement. The displaced atom (PKA) can in turn cause ionization or further displacement damage. In inelastic scattering, the neutron is captured by the nucleus, and subsequently a lower-energy neutron is emitted. The kinetic energy lost in this process can result in the excited atomic nucleus or displacement. The excited nucleus then returns to its ground state by emitting a gamma ray. In transmutation, the neutron is captured by the atomic nucleus and the nucleus subsequently emits another particle such as a proton or an alpha particle. The remaining atom is hereby transmuted [12].Thus, this process could make the semiconductor device itself radioactive in the long run.

2.2. Radiation damage

In spite of the complicated interaction between radiation and semiconductor materials, in the end there are two essential consequences on semiconductor material concerned. They are (1) displacement damage (atoms dislocated from their normal lattice sites) and (2) ionization (generation of electron hole pairs). In general, energetic particles traveling through semiconductor materials transfer a portion of their energy into ionization and the rest into atomic displacement. The amount of energy that goes into ionization is given by the stopping power, or the Linear Energy Transfer (LET), whereas that going into displacement is given by Non-Ionizing Energy Loss (NIEL) [12].

2.2.1. Displacement damage

The displacement damage is most likely caused by irradiation of neutrons or charged particles, such as protons. An energetic incident particle traversing the material may interacts with a lattice atom via one of the mechanisms mentioned in previous sections to dislodge it from its normal lattice site resulting in a Frenkel (vacancy-interstitial) pair. The recoil atom, or primary knock-on atom (PKA), may travel some distance in the lattice before it comes to rest. If it has sufficient high energy, PKA may introduce further displacements itself. Moreover, in some cases, secondary knock-on atoms can obtain sufficient high energy to dislodge more atoms. The reflected primary particle may also introduce more displacements as long as its kinetic energy is sufficiently high.

The band-gap in semiconductors is a consequence of the periodicity of the lattice. The displacement defects disrupt the periodicity of the lattice resulting in localized states inside the band gap. As a result, these states alter semiconductor device electrical properties. Depending on their energy position, they can act as: (1) Generation centers, (2) Recombination centers, (3) Trapping centers, (4) Compensation centers, (5) Tunnelling centers, and (6) Scattering centers [12].

2.2.2. Ionization

Ionization is primarily caused by the irradiation of photons, such as gamma rays, and charged particles, such as electrons. Since no momentum transfer to the nucleus, the energy required to create an electron-hole pair is relatively small comparing to that for displacement. Ionization occurs when an electron in the valence band is excited into a conduction band. In semiconductors (or conductors), the electrons and holes are free to diffuse and drift (if an electric field is applied). Most of the excited electrons in the conductor band and the holes in the valence band soon undergo recombination and hence no long-term radiation effect observed. However, if an electric field is present, the generated electrons and holes get separated resulting in electric currents. These radiation-induced photocurrents may cause fatal problems, such as the transient upset and current latch up, in semiconductor devices. The ionization goes through the following physical processes: (1) electron-hole pairs generation and initial recombination, (2) charge transport in which positive charges are not very mobile, and some are trapped, while the electrons produced are mobile and removed, (3) hole trapping in the oxide[12].

2.3. Measures of radiation effects

The various radiation environments give rise to a variety of irradiation particles with a wide variation in energy spectrum and dose rate. The space environment consists of a low-level constant flux of energetic charged particles (protons, electrons, etc.), whereas nuclear explosion may give out strong pulses of neutrons and gamma rays. Although the different particles may undergo different interactions with semiconductors and do various damages in semiconductors, the overall radiation-induced performance degradation in semiconductor devices can be inspected by three effects: (1) Single Event Effect (SEE); (2) Total Ionizing Dose (TID) Effects; (3) Displacement Damage Dose Effects.

SEE is the functional disturbance in a device caused by a single energetic particle. Depending upon whether the damage is temporary or permanent, they are classified as soft and hard SEEs. Soft SEE or Soft errors are termed as Single Event Upsets (SEUs). The SEUs normally appear as transient pulses in logic or support circuitry or as bit-flips in memory cells or registers and do not cause severe damage to circuit elements. Several types of potentially destructive hard errors can occur eg. Single Event Latch-up (SEL) resulting in a high operating current above device specifications and must be cleared by a power reset, Single Effect Burnout (SEB) of power MOSFETS, Single Effect Gate Rupture (SEGR), frozen bits, and noise in Charge Coupled Devices (CCDs). TID is the cumulative total absorbed dose by the material and is mainly due to electrons and protons. It is a long-term degradation of electronics due to the ionization caused by the radiation in semiconductor material unlike SEE which is an instantaneous failure mechanism. Displacement damage dose is the absorbed energy by the material as a result of the nuclear interactions which cause lattice defects. Displacement damage dose is the cumulative long-term non-ionizing energy loss damage due to the radiation [12].

2.4. Irradiation studies on Semiconductor devices

Exposure semiconductor devices to ionizing radiation is known to cause a number of effects, which result in the degradation of the device. In bipolar transistors one important parameter is the degradation of the forward current gain [13]. The degradation of gain is derived from degradation of the transport of minority carriers across the base region. Although a number of bipolar junction transistors have been studied for gain degradation, it appears that there are only few response on the actual measurements of gain as a function of fluence/dose of the incident ionizing radiation. In the following a brief literature on several aspects of gain degradation in BJT is reviewed.

The degradation of forward current gain in terms of transport of minority carriers across the base region has been discussed elaborately in ESA reports [I4].

The effect of Gamma-ray, reactor neutrons, electrons and protons on various types of discrete devices has been described in this report.

The minority carrier lifetime damage constant for various types of transistors for reactor neutron, electron and proton irradiation are reported [15]. Brown has exposed 2N1613 npn BJT for proton and electron and effects are reported in terms of gain damage figure [16-17].

Poch and Holmes-Siedle have studied 2N2102 BJT for Gamma ray irradiation [18]. Victor A.J, et. Al have studied the correlation of displacement effects produced by electrons, protons, and neutrons in silicon [6].This study is limited to the degradation of excess carriers lifetime and device electrical parameters directly related to it.

Burke E.A. has studied the energy dependence of proton-induced displacement darnagc in silicon [19]. He has reviewed the calculations of non-ionizing energy deposition in silicon as a function of proton energy between 1-1000 MeV and has made measurements of displacementdamage factors for bipolar transistors.Ratios of proton energy loss to neutron energy loss with experimental ratios of displacement damage factors are also compared.

Summers G.P. et al have measured displacement damage factors K, as a function of collector current for proton irradiation of 2N2222A (npn) and 2N2907 @np) switching transistors and 2N3055 (npn) power transistors over the energy range 5 to 60.3 MeV [20-21].

High-energy electron induced displacement damage in silicon bipolar transistors was studied by Dale C.J. et al [22].

Nichols D.K. et al have studied ten different types of transistors [23]. The total ionizing dose response of these transistors have been measured using gamma rays and 2.2 MeV electron with exposure levels of 750, 1500 and 3000 Gy (Si). Gain measurements are made for a range of collector-emitter voltages and collector currents. Similarly, Xapsos M.A. et al have studied displacement damage produced by the gamma ray and monoenergetic electron beam [24].

Messenger G.C. and Spratt have studied several silicon and germanium transistors for neutron induced effects [25-26]. On the basis of experimental data and first order theory, they have proposed relation between the minority carrier lifetime and neutron fluence. Similarly, Sanga M.M. and Oldham W.G. have made measurements of minority carrier lifetime in neutron irradiated special uniform-base transistors and np gated diodes [27].

Although a large number of reports on radiation induced effects on BJT's are available in the literature, it appears that there is rather limited experimental data on the flucnce dependence of current gain of the transistor. The main focus of this work is to characterize the radiation response of BJT's which find applications in space systems. The emphasis is on the degradation of forward current gain of the transistors as a function of accumulated dose/ flucnce of different radiations. The transistors have been exposed to Swift Heavy Ions (SHI) to understand the extent and nature of radiation induced changes in the electrical characteristics of the transistors.

2.5. Radiation effects on transistor

The different radiation environments will degrade the electrical properties of a transistor. When a transistor is exposed to ionizing radiation, the base current increases whereas the collector current remains constant. The base current increases because of the increased Shockley-Read-Hall (SRH) recombination in the emitter-base depletion region. The recombination current increases because of two interacting effects:

(1) Increased surface recombination velocity and

(2) Spreading of the emitter- base depletion region.

The increase in surface recombination velocity is proportional to the density of recombination centres at the silicon-insulator interface near the emitter-base junction. The traps with energies near the middle of the silicon band gap are the most effective generation/recombination centres. The recombination rate is maximum when the electron and hole numbers are equal and this condition occurs in the depletion region. The increase in surface recombination velocity is usually a significant factor in determining the amount of radiation-induced gain degradation[28].

The displacement damage also gives rise to generation centers and such centers can play an important role in the reverse-biased base-collector junction. The reverse leakage current at this junction will increase due to the thermal generation of electron-hole pairs at radiation induced centers and the subsequent sweep-out of these carriers by the high electric field. The leakage current can also increase due to generation centers produced at the surface by ionizing radiation.

The radiation induced carrier removal can also alter the properties of a transistor. The width of base- collector depletion region increases under reverse bias condition. This effect gives rise to a decreased punch-through voltage, assuming that the base width is reduced due to carrier removal in the base. In addition, carrier removal in the neutral collector will increase the collector resistance [29-30].

3. MOTIVATION

The radiation effects on the devices can not only cause degradation but also cause the failure of the electronics and electrical systems in the space vehicles or satellites. The major goal is to design devices that can function as intended in harsh radiation environments. This led to the development of the process techniques to fabricate the radiation-hardened devices and development of the reliable and cost-effective radiation hardness assurance test procedures. To simulate the space radiation effects on devices and to qualify a device for reliable functioning in such radiation environments we must depend on the laboratory measurement systems (nuclear radiation sources like gamma etc. and particle accelerators). The radiation dose rate from these sources lies in the range of 50-300 rads/s so that the radiation exposure may take from a few minutes to a few hours to complete [1]. Equivalent radiation exposure in space may take several years. To make these correlations it is required to have deep understanding of the mechanisms that govern the radiation response of the devices.

For practical utility of these devices under such harsh conditions, the understanding of the radiation response mechanisms is more important. Knowledge of the radiation response mechanisms of devices has facilitated the fabrication of radiation hardened devices. Thus, understanding of the basic mechanisms of radiation effects has practical importance for the device manufacturers [31].

4. EXPERIMENTAL DETAILS

4.1. Experimental Methodology

The study include the use of accelerator facility. The primary tool throughout this research is Current-Voltage (I-V) and Capacitance-Voltage (C-V) measurements. A brief account of the above is discussed below.

The entire methodology involves four stages:

1. Fabrication of Schottky interface devices.
2. Pre-characterization of the devices.
3. Irradiation of devices with suitable ion and energy accordingly.
4. Post- characterization of devices.

Irradiation Facilities:

Pelletron Accelerator: The 15 UD Pelletron Accelerator at IUAC, New Delhi belongs to a class of particle accelerators known as tandem Van de Graff accelerator. It is capable of accelerating almost any ion beam from hydrogen to uranium to energies from a few MeV to hundreds of MeV.

4.2. Techniques of Characterization

Current–Voltage (I - V) Characteristics:

A current–voltage characteristic is a relationship between the electric current through a circuit, device, or material, and the corresponding voltage, or potential difference across it. These characteristics are also known as I - V curves, which determine basic parameters of a device and to model its behaviour in an electric circuit [1].

Capacitance–voltage (C-V) Characteristics:

Capacitance–voltage is a technique for characterizing semiconductor materials and devices. The applied voltage is varied, and the capacitance is measured and plotted as a function of voltage. The technique uses a MS junction (schottky barrier) or a p-n junction or a MOSFET to create a depletion region which is empty of conducting electrons and holes but may contain ionized donors and electrically active defects or traps. The depletion region with its ionized charges inside behaves like a capacitor. By varying the voltage applied to the junction it is possible to vary the depletion width. The dependence of the depletion width upon the applied voltage provides information on the semiconductor's internal characteristics, such as its doping profile and electrically active defects densities [1].

4.3. Experimental Procedure

The commercial NPN power transistor 2N3773 procured from BEL, Bangalore, India, was used in our study. The 2N3773 BJTs are mainly used in linear amplifiers and inductive switching applications. The decapped transistors were exposed to 30MeV boron $^{4+}$ and 60MeV oxygen $^{8+}$ ion irradiation at 15UD Pelletron accelerator at Inter university accelerator center (IUAC), New Delhi, India.

The terminals of transistors were grounded during irradiation. Ion beam at room temperature inside a chamber at vacuum ~10^{-6} -10^{-7} mbar. The fluence was varied from 1 x 10^{11} to1 x 10^{12} ions cm $^{-2}$ for different ions . The ion beam current was maintained at ~1 pnA . To irradiate the sample uniformly, a beam spot of 2 mm ^{2} area was scanned over a 10 mm × 10 mm area of sample using a magnetic scanner. Electrical characteristics were performed before and after irradiation using Keithley 2400 source meter and Boonton 7200 capacitance meter. All irradiation experiments and electrical measurements were done at room temperature.

5. RESULTS

The effects of 30MeV Boron and 60MeV Oxygen ion irradiation effects on 2N3773 BJTs . The electronic energy loss, nuclear energy loss and range of the ion in silicon target in case of 30MeV Boron and 60MeV Oxygen ion are estimated from SRIM code and tabulated in Table 1. Figure 1 and 2 illustrates the forward gummel characteristics of 30MeV Boron ion and 60MeV Oxygen ion irradiated transistor respectively.

TABLE 1. SRIM Calculations for 30MeV Boron and 60MeV Oxygen ion Si target

Ion/ energy	**Range (µm)**	**Electronic energy loss (Se) KeV/ µm**	**Nuclear energy loss (Sn) KeV/ µm**	**Ratio (Se)/ (Sn)**
Boron 30MeV	42.79	5.289×10^{2}	3.373×10^{-1}	1.568×10^{3}
Oxygen 60MeV	47.33	9.864×10^{2}	6.315×10^{-1}	1.561×10^{3}

5.1. I-V Characterization:

From Figure 1. and Figure 2. it is clear that both base current and collector current has changed significantly. When compared to collector current, base current has increased significantly, in both boron and oxygen ion irradiation. Particularly at higher voltages (V_{BE} >0.3 V) the change is apparent.There is a drastic increase in base current and moderate decrease in collector current.

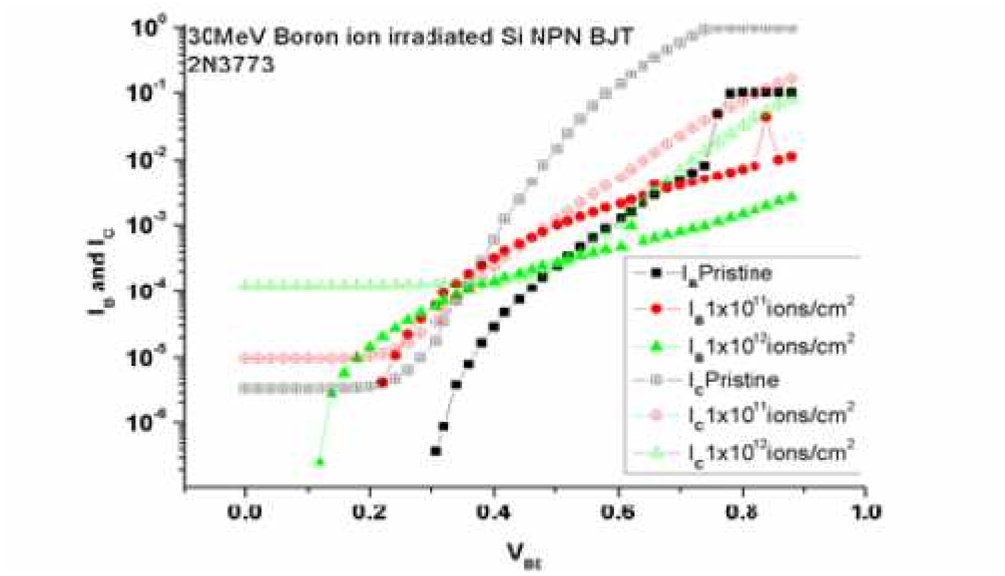

Figure 1. Forward gummel characteristics of 30 MeV Boron ion irradiated 2N3773 Si NPN BJTs

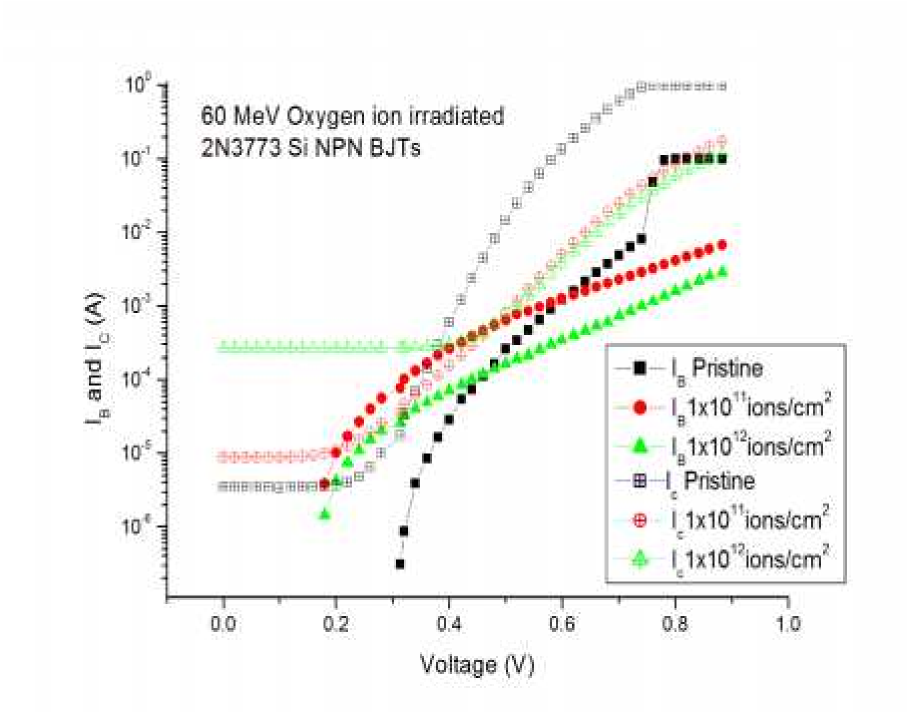

Figure 2. Forward gummel characteristics of 60 MeV oxygen ion irradiated 2N3773 Si NPN BJTs

The dc current gain is shown in Figure 3, in which decrease in current gain for both boron and oxygen ion irradiation can be noticed. The drastic increase in base current contributed to decrease in current gain of the transistor. The degradation in current gain may be explained in terms of both ionization and displacement damage induced by 30MeV boron and 60MeV oxygen ion irradiation. The insulating SiO_2 layer present in the emitter-base region of the transistor under goes ionization damage due to high value of electronic energy loss. When high energetic ions pass through the insulating oxide, they create large number of electron- hole pairs and interface traps at Si/SiO 2 interface which results in the increase of base surface current [32]. The nuclear energy loss causes displacement damage leading to bulk damage in base region of the transistor which increase the recombination centers and reduce the minority carrier life time [33]. Hence the dc current gain undergoes severe degradation inn both boron and oxygen ion irradiated transistor. Also it can be noted that, the extent of gain degradation is almost similar in both the cases.

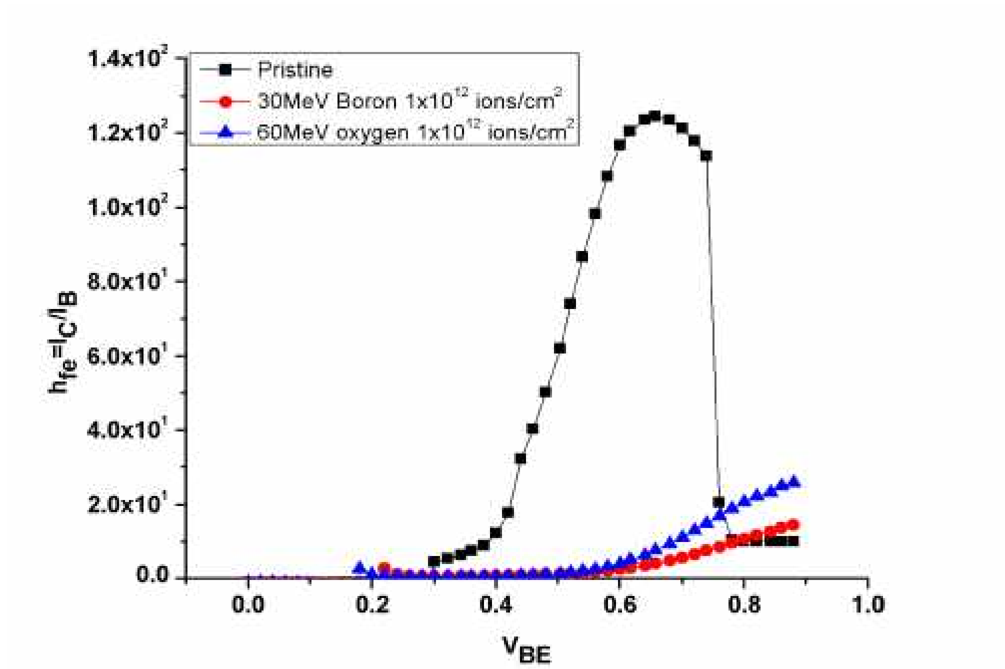

Figure 3. Current gain versus VBE 30 MeV boron and 60 MeV oxygen ion irradiated 2N3773 Si NPN BJTs

The output I_{CE} versus V_{CE} characteristics is shown in Figure 4 for boron and oxygen ion irradiated transistors. It is evident from the figure that the collector saturation current decrease at lower fluence in both cases but moderately increase at higher fluence. Initially the decrease in current is attributed to reduction in minority carrier lifetime because of 30MeV boron and 60MeV oxygen ion induced displacements, vacancies and their complexes.

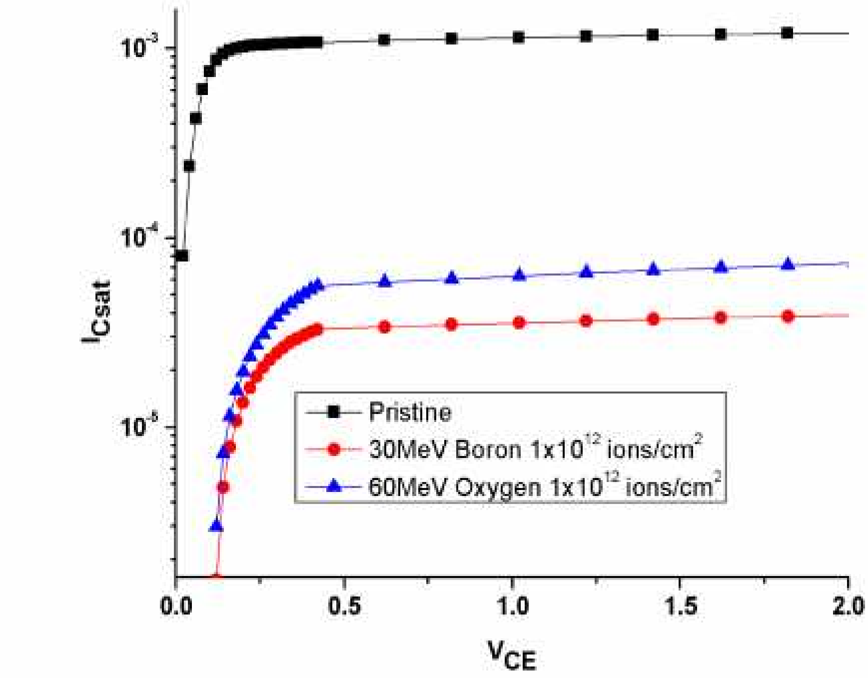

Figure 4. Output collector current characteristics at IB= 50µA before and after 30MeV Boron and 60MeV Oxygen ion irradiated 2N3773 Si NPN BJTs

5.2. C-V Characterization:

The variation of capacitance along with the applied reverse bias voltage in emitter-base configuration is as shown in the Figure 5 The value of capacitance at zero bias voltage is 550pf for unirradiated transistor and it reduces to 300pf and 125pf for 30MeV boron and 60MeV oxygen ion irradiated transistors for the fluence of 1×10^{12} ions/cm ^{2} . The capacitance –voltage characteristics show clear degradation as the bias voltage is increased. The reduction in carrier density may have caused the decrease in capacitance [34].

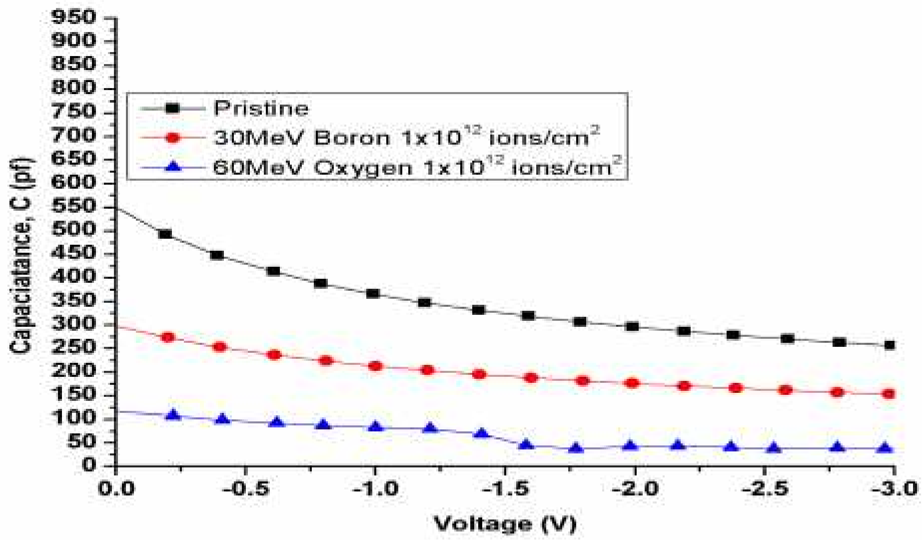

Figure 5. Capacitance-voltage characteristics of 30 MeV boron and 60MeV Oxygen ion irradiated 2N3773 Si NPN BJTs

6. CONCLUSION

The commercial BJTs 2N3773 has been subjected to SHI ions - 30MeV boron and 60MeV oxygen ion irradiation at different fluences from 1×10^{11} to1×10^{12} ions cm $^{-2}$. In both cases base current and collector current has changed significantly. When compared to collector current, base current has increased significantly, in both boron and oxygen ion irradiation. Particularly at higher voltages (V_{BE} >0.3 V) the change is apparent. There is a drastic increase in base current and moderate decrease in collector current. The electrical degradation observed in both the cases was almost similar. Both ionization and displacement damage induced defects and their complexes were responsible for the observed degradation. The value of capacitance at zero bias voltage is 550pf for unirradiated transistor and it reduces to 300pf and 125pf for 30MeV boron and 60MeV oxygen ion irradiated transistors for the fluence of 1×10^{12} ions/cm ^{2}. The capacitance–voltage characteristics indicated the clear degradation as the bias voltage is increased. The reduction in carrier density may have caused the decrease in capacitance.

In addition to this work, the defect characterization in GaN and its compounds due to electron irradiation is in progress to investigate their role for the material's electrical and optical properties.

REFERENCES:

[1] D.K. Schroder, "Semiconductor Material and Device Characterization", Third Ed. John Wiley & Sons, New Jersey, (2006).

[2] C.M Dinesh, Ramani, M.C Radhakrishna, R.N Dutt, S.A Khan, D Kanjilal, Nucl. Instr. and Meth. B 266, (2008)

[3] ChaomingLiu, XingjiLi, HongbinGeng, ZhimingZhao, DezhuangYang, ShiyuHe, Nucl. Instr and Meth. A 624, 671–674 (2010)

[4] W.R. Dawes, Jr., F.B. McLean, P.A. Robinson, Jr., and J.J. Silver, "Hardening Semiconductor Components against Radiation and Temperature". Noyes Data Corporation (1989).

[5] E.G. Stassinopoulos, and J.P. Raymond, "The Space Radiation Environment for electronics," Proc. of the IEEE, col. 76, p1423 (1988).

[6] A. Holmes-Siedle and L. Adams, "Handbook of Radiation Effects". Oxford University Press (1993).

[7] G. Messenger and M. Ash, "The Effect of Radiation on Electronic System"s. Van Nostrand Reinhold Company (1986).

[8] J. Linhard and M. Scharff, Phys. Rev. 124, 128 (1961).

[9] N. Bohr, Phil. Mag. 25, 10 (1913).

[10] H.A. Bethe, Ann. Physik 5, 325 (1930).

[11] F. Bloch, Ann. Physik 16, 287 (1933).

[12] Krzysztof Iniewski, "Radiation Effects in Semiconductors" (CRC Press Taylor & Francis Group).

[13] Radiation Design Handbook, European Space Agency- PSS - 01 - 609, 1903, Section 7.

[14] G.J Brucker, W.J Dennehy and A.G Holmes-Siedle. "Ionization and Displacement Damage in Silicon Transistors", JEEE Trans. Nucl.Sci.,Vol. NSI2, N0.5, 66 (1965).

[15] R.R Brown., "Proton and Elechon Permanent Damage in Silicon Semiconductor Devices", Boeing Report D2-90570 (1964).

[16] R.R Brown, and W.E Home, "Space Radiation Equivalence for Effects on Bipolar Transistors", NASA CR-814, US Department of Commerce, Washington D.C. (1967).

[17] W.J Pouch and A.G Holmes-Siedle, "A Prediction and Selection System for Radiation Effects in Planar Transistors", IEEE Trans. Nucl. Sci. Vol. NS-15, No. 6, 213 (1968).

[18] A.J Victor, "Correlation of Displacement Effcts Produced by Elechons, Protonsand Neutrons in Silicon", IEEE Trans. Nucl. Sci.. Vol. NS-22, 2663 (1975).

[19] E.A Burke, "Energy Dependence of Proton Induced Displacement Damage in Silicon", IEEE Trans. Nucl. Sci. Vol. NS-33, 1276 (1986).

[20] G.P Summers, E.A Wolicki, M.A Xapsos, P Marshall, C. I Dale, M.A Gehlhausen. and R.D Blice. "Energy Dependence of Displacement Damage Factors for Bipolar Transistors", IEEE Trans. Nucl. Sci., Vol, NS-33, 1282 (1986).

[21] G.P Summm., E.A Burke., C.J Dale, E.A Wolicki, P.W Marshall. and Gehlhausen M.A. "Correlation of Panicle-Induced Displacement damage in Silicon". IEEE Trans. Nucl. Sci., Vol. NS-34, 1 134 (1987).

[22] C.J Dale., P.W Marshall, E.A Burke, P.G Summers, and E.A Wolicki. "High Energy Electron Induced Displacement Damage in Silicon", lEEE Trans. Nucl. Sci., Vol. 35, 1208 (1988).

[23] D.K Nichols., W.E Price and M.K Gauthier. "A Comparison of Radiation damage gamma ray and 2.2 MeV Electrons", IEEE Trans. Nucl. Sci., in T m i s t o r s from Val. NS-29, 1970 (1982).

[24] M.A Xapsos, G.P Summers, C.C Blatchley, C.W Colerico, E.A Burke S.R Messenger and P Shapiro, "Gamma Ray and Electron Displacement Damage Studies of Semiconductors", IEEE Trans. Nucl. Sci. Vo1.41, 1945 (1994).

[25] G.C Messenger, "Displacement Damage In Slllcon and Germanium crystals" . Nucl Sci Vol. NS-12, 53 (1965)

[26] C Messenger and M.S Ash., "The Effect of Radtation on Elechonic Systems", Van Nostrand Reinhold Company, New York (1986)

[27] M.M Sanga and W G Oldharn., "Measurement of Neutral Base Lifetime In Neutron-inadlated Transistors", IEEE Trans Nucl Sci Vol. NS- 266 (1990)

[28] J. Leszczynski, Nat. Nanotechnol. 5, 633 (2010).

[29] P. Ruden, Nat. Mater. 10, 8 (2011).

[30] G. L. Miller, D. V Lang, and L. C. Kimerling, Annu. Rev. Mater. Sci. 7, 377 (1977).

[31] J. R. Schwank, Basic Mechanisms of Radiation Effects in the Natural Space Environment (Technical Report, Sandia National Laboratories).

[32] Xingji Li , HongbinGeng , MujieLan , ChaomingLiu , DezhuangYang and ShiyuHe Physica B 405 1489– 1494 (2010).

[33] Chaoming Liu , XingjiLi, Hongbin Geng, Zhiming Zhao, Dezhuang Yang, and Shiyu He Nucl. Instrum. Methods Phys. Res. Sect. A 624 671–674 (2010).

[34] C.M. Dinesh, Ramani , M.C. Radhakrishna , R.N. Dutt , S.A. Khan and D. Kanjilal Nuclear Instruments and Methods in Physics Research B 266 1713–1718 (2008).