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# Boron ion interaction with pnp bipolar power transistor and displacement damage effects on its electrical characteristics

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## Abstract

Bipolar junction transistors used in switching and amplification applications is examined for their electrical performance after irradiation with 60 MeV boron ions of different fluence. Unirradiated device base current is $5.97\times10^{-5}$ A while it is $9.03\times10^{-4}$ A after irradiation with a fluence of $1\times10^{12}$ ions/cm$^2$. For unirradiated device collector current is $1.22\times10^{-3}$ A and is $7.31\times10^{-4}$ A after irradiation to a fluence of $1\times10^{12}$ ions/cm$^2$. Base current increases whereas collector current decreases after irradiation with a fluence of $1\times10^{12}$ ions/cm$^2$. The magnitude of decrease in collector current is approximately same as that of the increase in base current, showing the leakage of the collector current due to irradiation. The output collector gain of the unirradiated transistor is 20.5 after irradiation to a fluence of $1\times10^{12}$ ions/cm$^2$ it has reduced to 0.81. The capacitance measurements for base-emitter junction show that for the unirradiated and irradiated samples, linearity of the curves indicate uniformity of shallow doping concentration. The built in potential (Vbi) for unirradiated device is 2.69 V and after irradiation it is 2.52V. The device is also studied for activation energy, trap concentration and capture cross-section of deep levels are studied using deep-level transient spectroscopy (DLTS) technique. Majority carrier trap level is observed with energy Ev+0.784 eV.

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*Keywords:* Radiation Hardness, Silicon, Linear Energy Transfer, Displacement Damage;

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## 1. Introduction

BJT's have important applications in analog and mixed – signal IC's and BICMOS (Bipolar Complementary Metal Oxide Semiconductor) circuits because of their current drive capability, linearity, and excellent matching characteristics Dinesh et.al. (2008). Ionizing radiation may cause failures in integrated devices (ICs) due to gain degradation of individual devices. Extensive research has been carried out in exploring the effect of radiation-induced damage at the surface of the device.

A comparison of ionizing radiation induced gain degradation in a lateral, substrate and vertical pnp bipolar junction transistors is reported by Schmidt et.al (1995) and Schrimpf et. al. (1995). They have concluded that the effect of ionizing radiation on lateral and substrate pnp structures are different from the effects on vertical pnp structure. Of the three pnps, the lateral pnp suffers the most current gain degradation while the vertical pnp suffers the least current gain degradation due to ionizing radiation. But the heavy ion irradiation effects need to be studied on pnp BJTs as they are important. There are little reports on TID and $D_d$ due to heavy ion irradiations on BJTs. Radiation induced changes in bipolar device characteristics are caused by generation of net positive oxide trapped charge, and an increase in surface recombination velocity due to formation of interface traps. It is also important to study the defects present deep inside the device. Detailed analysis is needed for large spectrum of devices in order to develop radiation hard model.

Wei et.al reported that, base current of irradiated bipolar devices increased with increase in ion fluence and the collector current decreased. This results in a decrease in the current gain ($\beta=I_C/I_B$) Wu et.al.

The operation of BJT devices may depend on the particle energy deposition mechanisms by ionization and non-ionization processes Dinesh et.al. (2008). The radiation-induced damage and its effect on device parameters mainly depend on particle type, energy and fluence, also it may depend on the device technology. Hence the irradiation effect of B-ion impact on BJTs may show significant variations in their characteristics, when compared to Li-ion. There are evidences that the existence of boron ion in galactic cosmic ray (GCR). BJTs are commonly employed in many fields including particle physics experiments, nuclear medicine and space Claude Leroy et.al., (2007). The particle interactions in the bulk or active part of the silicon devices are responsible for the gain degradation resulting from the absorbed dose. Both the ionizing and non-ionizing energy-loss contributes to the absorbed dose (figure 1, $S_e$ and $S_n$ of the table 1).

Vertical npn transistors exhibit very significant gain degradation, particularly when they are irradiated at low dose rates. In contrast, vertical pnp transistors are relatively hard to ionizing radiation Nowlin et.al., (1992) and Kosier et.al., (1995). Several mechanisms have been proposed which may cause the current gain degradation viz., (1) depletion of the p-type emitter, (2) recombination at the base surface, (3) electron injection into the emitter and (4) surface hole depletion. However, due to competing nature of these mechanisms, it is rather difficult to identify the dominant mechanism. On the other hand, there are relatively less reports on the displacement damage effects in discrete BJTs. Literature reports several npn type transistors have been investigated in the literature for current gain degradation based on these arguments Kulakar et.al., (2003). In general, the pnp type transistors are also expected to exhibit the same type of degradation. However, it appears that there is little experimental evidence to support this. Dale et al. (1988) have studied the high energy electron induced gain degradation in terms of displacement of atoms. Burke (1986), Summers et al. (1986, 1987) and Xapsos et al. (1994) have studied the displacement damage produced by high energy electrons and neutrons. In this work an attempt is made to access the radiation response of vertical discrete pnp transistor 2N6052 manufactured indigenously by Bharath electronics Ltd (BEL) India. Also the objective of this investigation is to reveal the mechanisms due to ionizing and non-ionizing energy deposition and hence degradation of current gain of the pnp BJT.

## 2. Experimental

The investigated devices are manufactured using industrial standards with indigenous technology by Bharath electronics Ltd (BEL) India. This vertical pnp transistor 2N6052, has high-voltage capability, fast switching speeds and low saturation voltages, is selected for irradiation with 60 MeV boron ions, with different fluencies.

The irradiation is carried out using 15 UD 16 MV Pelletron Tandam Vande Graff Accelerator using material science beam line at Inter University Accelerator Center (IUAC), New Delhi India. Decapped transistors are irradiated with 60 MeV boron ions (charge state = +4) under vacuum with un-biased condition (all the leads are grounded) at room temperature. Ion beam current is maintained at 1.0 pnA to get the required fluence [1 pnA (particle nano ampere) = $6.25 \times 10^9$ particles/cm$^2$/s]. The low beam current is selected as it avoids the heating of the transistor during irradiation. To irradiate the sample uniformly, a beam spot of 2 mm$^2$ area is used to scan over a 12 mm × 12 mm area using a magnetic scanner. The fluence is varied from $1\times10^{10}$ to $1\times10^{12}$ ions cm$^{-2}$. I-V characteristics are measured before and after the irradiation using Keithley 2400 source meter with computer interface. The collector characteristics are obtained at constant base current ($I_B$ = 50 μA) by varying collector-emitter voltage $V_{CE}$ from 0.0 to 10.0 V (in step size of 0.01V). From these plots, the collector saturation current ($I_{Csat}$) and the corresponding collector-emitter saturation voltage ($V_{CEsat}$) for various fluences are measured. Gummel plots are acquired by sweeping the base-emitter voltage $V_{BE}$ from 0 V to 1.4 V in steps of 0.01 V at constant collector voltage of 10 V. The device subjected to deep level transient spectroscopy (DLTS) before and after irradiation.

## 3. Results and Discussions

### 3.1. Scattering and Range of Ions in Matter (SRIM) results

SRIM calculations show that the for 60 MeV boron ion, the nuclear energy is much smaller than electronic energy loss (3 to 4 orders of magnitude, given in Table 1), possibly due to smaller elastic scattering cross section Dinesh et.al., (2008). Therefore for electronic excitations maximum energy is deposited. Figure 1 gives the detailed energy loss mechanism through $S_e$ and $S_n$ process. It also depicts the maximum range and linear energy transfer (LET = $S_e$+$S_n$ ) for the corresponding energy of 60 MeV B -ion. The damage caused due to the linear energy transfer [LET = $S_e + S_n \approx 1.422$ MeV/ (mg/cm$^2$)] in the Si target is obtained using Transfer of Ions in Matter TRIM calculations Ziegler et.al., (2008). The results of SRIM calculation are tabulated in Table 1.

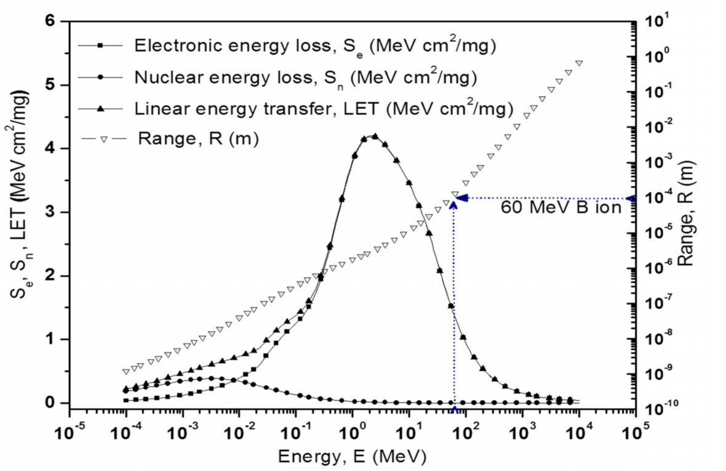

Fig.1. Variation Of Se, Sn , LET and Range for different Energy.

The use of non ionising energy loss (NIEL) in predicting the effect of 60 MeV Boron ion in silicon transistor is important. NIEL is due to atomic displacement by incident particle with it traverses silicon material, and product of the NIEL and the particle fluence gives the displacement damage energy along the track. Finding a linear relationship between NIEL and experimental damage co-efficient suggests a method of calculating the radiation response of silicon device in a complex space radiation environment.

The product of the NIEL (MeV cm$^2$ g$^{-1}$) and the particle fluence (ions cm$^{-2}$) gives the displacement damage dose (in rad). NIEL for a given ion in a given target can be calculated by using SRIM (Stopping power and Range of Ion in Matter) and TRIM (Transfer of Ions in Matter) data by using an algorithm given by Messenger et. al. (1999). NIEL for a given ion is calculated using the formula,

$$\text{NIEL=M (Total displacements produced by the ion)}\left(\frac{1}{\rho}\right)$$

Where $M = \frac{1}{10^6}\left(\frac{T_d}{0.4} + 2\right)$

$T_d = 21$eV (threshold energy required for Silicon atom displacement), $\rho = 2.32$ gcm$^{-3}$ (density of Silicon)

Total displacements produced by the ion in a given range of target can be estimated by using TRIM program and the range can be calculated by using SRIM program. NIEL for 60 MeV boron ions is presented in the Table 1.1. Xingji Li et. al. (2010) reported that bipolar junction transistors are a basic type of electric devices, which are commonly used in spacecraft. It is of significance to examine their response to radiation of high energy protons and heavy ions.

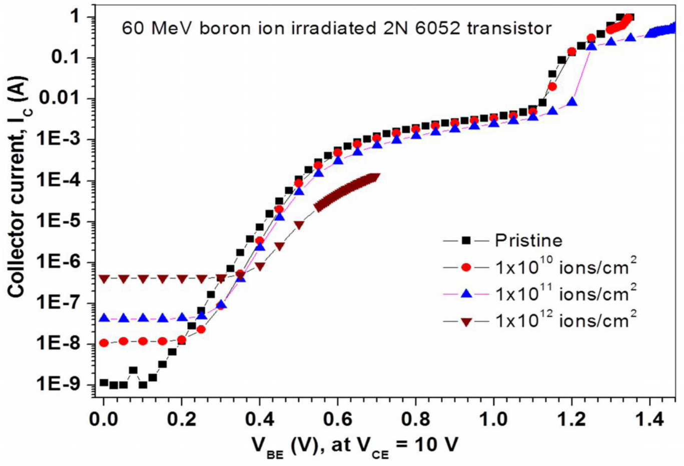

Fig. 2. Variation of collector IC current for different $V_{BE}$ at constant $V_{CE}$ for 60 MeV $B^{4+}$ Ion Irradiated 2N 6052.

It is shown that the current gain of the NPN BJTs is markedly degraded under the exposure of protons and Br ions with different energies. There are two competing mechanisms responsible for the current gain degradation, including the ionization and displacement damage Messenger et.al., (1999).

Table 1. SRIM simulation results for 60 MeV boron ion irradiation on silicon.

| Parameter | Value |
|---|---|
| Energy (MeV) | 60 |
| Range, R (µm) | 116.34 |
| $S_e$ (MeV cm$^2$/mg) | 1.422 |
| $S_n$ (MeV cm$^2$/mg) | 7.892 x10$^{-4}$ |
| Average Displacements/ion | 2220.2 |
| Average Replacements/ion | 171.7 |
| Average Vacancies/ion | 2049.2 |
| NIEL up to R (MeV cm$^2$/g) | 4.481 |
| LET (MeV cm$^2$/mg) | 1.422 |

### *3.2. Current – Voltage Characteristics*

Current voltage measurements for 2N 6052 transistor is carried. Figure 2 shows the variation of collector current as a function of base-emitter voltage (forward Gummel plots) before and after exposure to various fluence of 60 MeV boron. From the plots it can be seen that for unirradiated device the surface leakage currents are practically low for e.g. its valve is about 9x10$^{-10}$ ampere and switch on voltage is 0.1 volts, after irradiation for a fluence of 1x10$^{10}$ ions cm$^2$ the leakage current has been increased to 1.3x10$^{-8}$ ampere and switch on voltage 0.2 volts, as radiation fluence increases there will be an increase in surface leakage current with a shift in turn on voltage towards higher voltage valves.

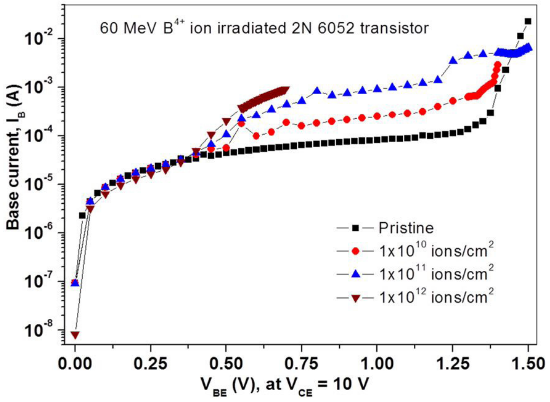

Fig. 3 Variation of base current $I_B$ for different $V_{BE}$ at constant $V_{CE}$ for 60 MeV boron ion irradiated 2N 6052.

In the forward active voltage region of the device ($V_{BE}$ = 0.7 volt) the collector current is found to be 1.22 ampere for unirradiated device and it decreases as ion fluence increases when transistor is irradiated with 60Mev boron ion. The surface leakage current corresponding to 60 MeV boron ion irradiated transistor but no considerable variation in collector current at $V_{BE}$ = 0.7 Volts, this may be because the range of the 60 MeV boron has larger producing defects in the bulk of the same, hence the bulk collector current degradation increased with increase in fluence for 60 MeV irradiated sample.

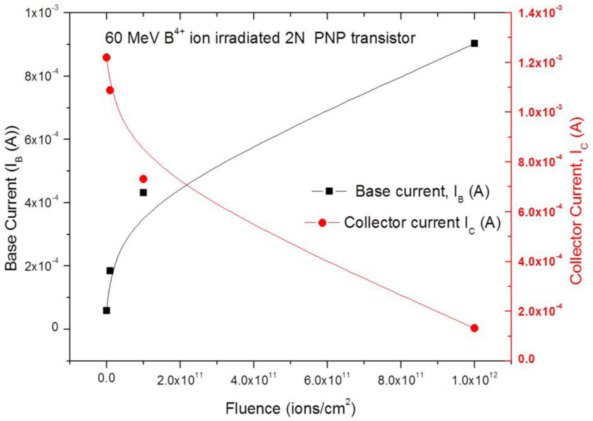

Fig.4 Variation of base current and collector current for different boron ion fluences. The values extracted from Gummel plots at $V_{BE}$=0.7V (constant $V_{CE}$=10V)

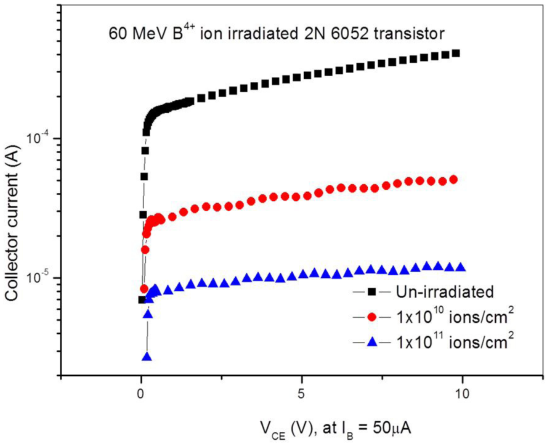

Fig. 5.Collector current charateristics of 60 Mev Boran ion irradiated trasister for different fluences at constant $I_B = 50\ \mu A$

Fig. 3 exhibits the variation of $I_B$ with base voltage $V_{BE}$. It is observed that the base current $I_B$ increases with increasing ion fluence. It is well known that the degradation of gain can occur due to both increased recombination in emitter base region induced mainly by total ionizing dose (TID) and increased recombination in the neutral base (Induced mainly by displacement damage). Increased recombination in the base emitter region does not lead to

decrease in the collector current because the number of carriers injected in the base depends on the doping of base and the applied voltage only Xingji et. al., (2010). On the other hand, increased recombination in the neutral base leads to an increase in base current which in turn results in decrease of collector current. Recombination centers are generated in the base region of the transistor and could lead to an increase in base current by decreasing the minority carrier life time Codegoni et.al., (2004), Gnanaprakash et.al., (2004), Soujanya Vipula et.al., (2003).

Enhanced $I_B$ is related to an increase in the surface recombination velocity, as the density of electron and holes is comparable, due to base neutralization. It has in addition been observed that the collector current increases, resulting from a higher emitter injection efficiency. This is again related to the reduction of the base doping concentration after exposure. In BJTs the excess base current depends on number of interface traps (recombination centers) near mid gap. The excess base current due to changes in surface potential depends on the total radiation-induced oxide charge and the base condition. A decrease in the minority carrier life time will be reflected in the gain degradation of forward currant gain of the transistor. Thus displacement damage appears to play a major role than total ionizing dose (TID) induced damage in influencing the gain degradation upon boron ion irradiation. The recombination may be due to the destruction of lattice periodicity in the bulk of the semiconductor and may give rise to additional energy levels in the band gap. Radiation-induced defects may have such energy levels with them that these defects can have a major impact on the electrical characteristics of the transistor Chaoming Liu et.al., (2012).

Fig .4. Exhibits the variation of base current $I_B$ and collector current $I_C$ of the transistor as a function of Boron ions (base-emitter voltage $V_{BE} = 0.7$ V). It is observed that the base current increases with 60 MeV boron ion as the fluence increases. However, the collector current is high with low fluences, decreases as the ion fluence increases for 60 MeV boron ions the collector current decreases with increase in ion fluence.

Fig.5. shows the output collector current as a function of collector-emitter voltage for various boron ion fluences. The output collector current decreases linearly with ion fluence. The gain decreases as the ion fluence increases for 60 MeV $B^{+4}$ ion. The Boron ion induced displacement damage dose ($D_d$) increases the recombination in the base region, which leads to the decrease in collector saturation current. Fig.5. Shows the collector current falls rapidly because of the rapid decrease of the charge carrier gradient at the collector-base junction.

### *3.3. Capacitance – Voltage Characteristics*

Fig. 6. Exhibit A plot of $(1/C^2)$ versus emitter-base junction voltage of the transistor, upon 60 Mev boron ion irradiated trasistor. The plot shows that there is a considerable degradation in the C-V characteristics of the transistors after irradiation; this would indicate that there is a partial loss of charge carriers in the base- emitter junction of the transistor upon irradiation. This loss could be attributed to the increased recombination in the base-emitter junction of the irradiated transistor and indicates that there is a partial loss of charge carriers. It can also be noted that for the unirradiated and irradiated samples, the curves are linear in the measured voltage range indicating the uniformity of shallow doping concentration. The doping concentration for unirradiated device is 1.177 × $10^{19}$/cm$^3$ and after irradiation with fluence 1 × $10^{12}$ ions/cm$^2$ it has been increased to 1.313 × $10^{19}$/cm$^3$. However, it

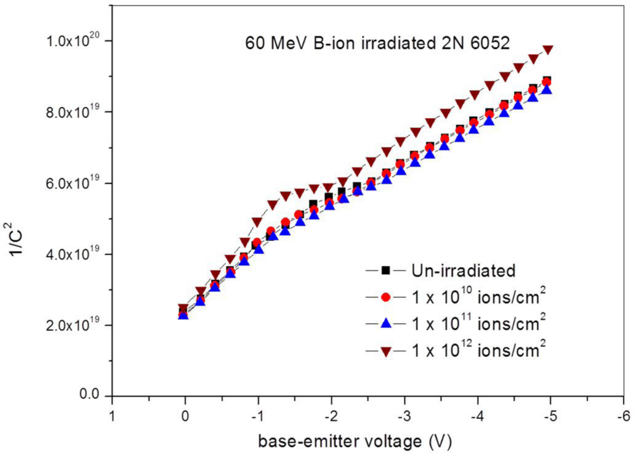

Fig.6.Variation of $1/C^2$verses VBE for different fluence 60 Boron ion irradiated transistor 2N 6052 for different fluhences

shows, the curves deviate from the linearity as the ion fluence during irradiation varies, the shift in the built in potential ($V_{bi}$) is observed for un irradiated device, it is 2.69 V and after irradiation with fluence of $1 \times 10^{12}$ ions/cm$^2$ 2.52 V Madhu et.al., (2007).

The decrease in current and reduction in capacitance due to irradiation is understood on the basis of irradiation-induced disorders and defects like recombination centers, vacancies and interstitials in the emitter-base region. The introduction of compensating defects on irradiation will reduce the conductivity as well as the capacitance. This reduction in capacitance may be mainly due to the change in series resistance Dinesh et.al., (2008).

### 3.4. DLTS Measurements

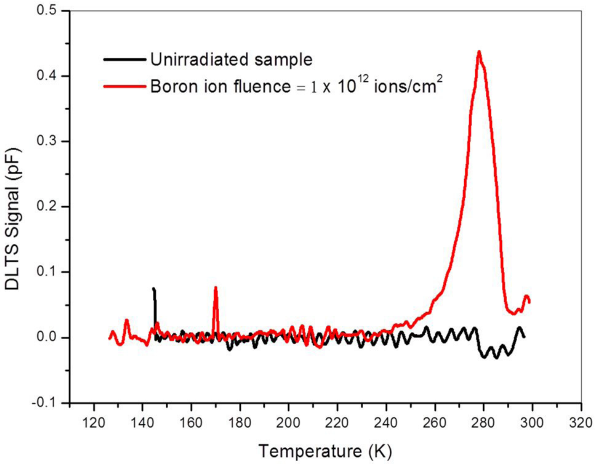

Fig. 7. DLTS spectrum of 60 MeV boron ion irradiated transistor for the fluence $1\times10^{12}$ ions/cm$^2$. Rate window is fixed at 8.3 /s.

The deep level defects generated by irradiation of transistor by 60 MeV Boron ions are characterized using the

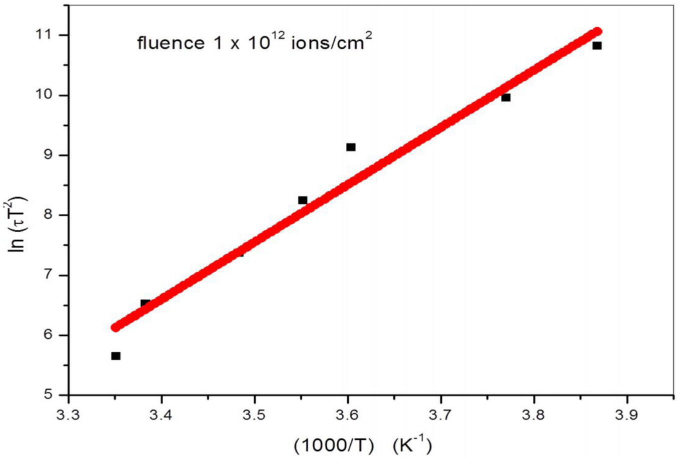

Fig. 8. Arrhenius plot for 60 MeV boron ion irradiated transistor with fluence $1\times10^{12}$ ions/cm$^2$.

DLTS technique. The DLTS spectrum is a plot of difference in capacitance (δC) versus temperature. Fig. 7. Exhibits the DLTS spectra of Boron ion irradiated transistor with fluence 1 × $10^{12}$ ions/$cm^2$.

The trap concentration ($N_T$) can be determined by knowing the peak height ($\delta C_{max}$) of the DLTS spectrum. Activation energy ($\Delta E$) and capture cross section ($\sigma$) of the deep levels are calculated by using the equation

$$\tau T^2 = \frac{\exp[(\Delta E)/kT}{\gamma\sigma} \quad (1)$$

In equation (1), $\gamma$ is the material coefficient and all other symbols have usual meaning Kosier et.al., (1993), Kouimttzi (1986). A plot of ln$(\tau T^2)$ versus $1/T$ is known as the Arrhenius plot; the activation energy $\Delta E$ is obtained from the slope of the plot and the capture cross section is obtained by extrapolating the plot on the *Y*-axis. Fig. 8. Exhibits the Arrhenius plots of deep level defects 60 due to MeV Boron ion irradiated transistor with the fluence 1 × $10^{12}$ $cm^{-3}$.

One majority carrier deep level defect type is observed in the DLTS spectra of the 60 MeV boron-ion irradiated transistors for the fluence 1 × $10^{12}$ $cm^{-3}$. The trap concentration, capture cross section and introduction rate of the deep level defect is calculated from the DLTS spectra and presented in table 3. The activation energy due to the defects has been measured to an accuracy of 0.001 eV. The important observation in the present investigation is that the nature of defects induced at a fluence of 1 × $10^{12}$ $cm^{-3}$ is one type. This clearly indicates that a single defect induced mechanism is responsible for the degradation of the current gain Madhu et.al., (2008). The magnitude of trap concentration is 4.62 ×$10^{12}$ $cm^{-3}$. These types of defects are also reported in literature earlier by others. It is reported that A-center (O-V) is a defect that appears in most Si structures after irradiation Kouimttzi (1986). In the present study we have not observed A-center for the fluence 1 × $10^{12}$ ions/$cm^2$, it may be possibly due to concentration of the devices.

Comparison of I-V, C-V and DLTS results indicated that the induced I-cluster defects have major contribution to the decreased collector current, loss of charge carriers and hence degradation of forward current gain of the transistor.

Table 2. Data obtained from DLTS analysis for 60 MeV boron ion irradiated transistor with fluence 1 ×$10^{12}$ ions/cm2.

| Parameter | Value |
|---|---|
| Ion | Boron |
| fluence (ions $cm^{-2}$) | 1x$10^{12}$ |
| Activation Energy (± 0.01 eV) | $E_V$ +0.784 |
| Trap Concentration ($cm^{-3}$) | 4.62X$10^{12}$ |
| Capture Cross section( $cm^2$) | 1.7X$10^{-10}$ |
| Recombination life time (s) | 1.18X$10^{-08}$ |
| Defect type | Interstitial Cluster |

## 4. Conclusions

60 MeV boron ion irradiation effects on commercial BJT device (2N 6052) for various fluences are studied. I-V measurements showed that irradiation decreases $I_C$ and increases $I_B$ with the increase in ion fluence. The atomic displacements and vacancies produced upon irradiation in the bulk of the transistor is estimated using SRIM code. A decrease in the minority carrier lifetime is reflected in the degradation of forward current gain of the transistor. The observed degradation in current gain, $I_{Csat}$, capacitance and variation in doping concentration is due to the boron ion induced defects. It has been observed that the induced defect type is I-cluster through DLTS measurements. The introduction of these cluster defects on irradiation will reduce the conductivity as well as the capacitance. A plot of

($1/C^2$) versus base-emitter voltage shows that the doping concentration of the base-collector junction of the transistor increases upon boron ion irradiation. There is a shift in the built in potential due to irradiation. These studies are useful to understand the interaction mechanism and for better design strategies of these devices

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