CHAPTER 2

SiGe HBT DEVICE STRUCTURE AND EXPERIMENTAL DETAILS

2.1. Introduction

The NPN SiGe heterojunction bipolar transistor (SiGe HBT) device structure consists of n-Si/p-SiGe emitter-base heterojunction and a p-SiGe/n-Si base-collector heterojunction. The bandgap diagram of the SiGe HBT is compared with NPN Si BJT and is shown in figure 2.1. The doping profile of the first generation 50 GHz SiGe HBT is shown in figure 2.2. The SiGe HBTs have wide applications in fields of space, high energy physics experiments, military and communication systems. A set of devices studied in the present work were taken from the same batch with identical characteristics. The devices were characterized before irradiation and after $^{60}$Co gamma and different high energy ion irradiation. The DC I-V characteristics of the pre and post irradiated SiGe HBTs were performed using computer interfaced Keithley 2636A and 2612A dual source meters. The different DC I-V characteristics like forward mode Gummel characteristics, inverse mode Gummel characteristics, excess base current, current gain, neutral base recombination, avalanche multiplication of carriers and output characteristics were measured before and after irradiation. The SiGe HBTs were subjected to mixed mode electrical stress using Keithley 2636A dual source meter. The DC I-V characteristics were measured before and after electrical stress. Further, the irradiated and electrically stressed devices were annealed to study the recovery in the electrical characteristics. The details of the experimental methodology and the related aspects are presented in this chapter.

![Figure 2.1: The comparison of energy band diagram of Si BJT and graded base SiGe HBT, both biased in forward active mode at low injection.](image)
2.1.1. 50 GHz SiGe HBTs

The IBM 5HP SiGe BiCMOS ICs integrates a 0.5 μm, 3.3 V BVCEO, 50 GHz peak $f_T$ SiGe HBTs, together with 0.35 μm $L_{\text{eff}}$, 3.3 V Si CMOS devices. The metallurgical base width is about 90 nm, the metallurgical emitter junction depth is about 35 nm and the peak Ge content is about 8%. The emitter polysilicon layer is doped with arsenic atoms up to $1 \times 10^{21} \text{ cm}^{-3}$. Multiple self aligned phosphorus implants were used to locally tailor the collector doping profile and the peak base doping is about $4 \times 10^{18} \text{ cm}^{-3}$. The polysilicon extrinsic base contacts with self-aligned extrinsic base implants were fabricated to lower the total sheet resistance. The Ge profile is trapezoidal in shape, with substantial grading across the neutral base region [92]. The vertical doping profile is designed to achieve a peak cut-off frequency of 50 GHz. A variety of 3 to 6 levels back-end-of-the-line (BEOL) metallization schemes were borrowed from the existing CMOS processes. The schematic cross section of a first generation SiGe HBT is shown in figure 2.3 [4].
2.1.2. 200 GHz SiGe HBTs

The IBM 8HP SiGe BiCMOS ICs integrates a 0.12 μm, 1.7 V BV$_{CEO}$, 200 GHz peak $f_T$ SiGe HBTs, together with 0.12 μm $L_{eff}$, 1.2 V standard Si CMOS devices. The high $f_T$ and $f_{MAX}$ of SiGe HBTs were obtained by reducing the vertical and lateral dimensions compared to the earlier generations of SiGe HBTs [57]. This improvement in peak $f_T$ over previous technology nodes was realized through fundamental changes in the physical structure of the device. Therefore 200 GHz SiGe HBTs employ raised extrinsic base structure. The SiGe base region features an unconditionally stable, 25% peak Ge and a C-doped SiGe profile deposited using the UHV/CVD epitaxial growth technique. The boron dose in the as-grown SiGe base layer is $5 \times 10^{13}$ cm$^{-2}$. In addition to an in-situ doped polysilicon emitter, the conventional deep trench (DT) and shallow trench isolations (STI) were maintained from the previous technology nodes [72]. The epitaxial layer thickness, collector and base doping concentrations were similar to that described in [93] to achieve a target performance of 200 GHz. A low pinched base sheet resistance is targeted along with the high $f_T$ to maintain good manufacturing control of $f_T$ as well as high $f_{MAX}$. The emitter in this new structure is defined by a disposable mandrel. A raised extrinsic base is formed self aligned to this mandrel. The mandrel is then etched away and an in-situ phosphorus doped polysilicon emitter is formed by deposition and annealing. Base resistance ($R_{BB}$) is reduced by minimizing the resistance of the extrinsic base polysilicon and narrowing the emitter and the emitter to extrinsic base spacer dimensions [58]. The schematic device cross section of the SiGe HBT used for the present study is shown in figure 2.4.

![Figure 2.4: The schematic cross section of 200 GHz SiGe HBT.](image)
2.2. Sample preparation
The 50 GHz and 200 GHz SiGe HBTs were selected by dicing the 200 mm SiGe BiCMOS IC's and the emitter, base and collector terminals are wire bonded in 28 pin dual inline package (DIP). In case of 50 GHz SiGe HBT, the two sets of two different emitter area ($A_E$) geometries $0.5 \times 1 \, \mu m^2$ and $0.5 \times 2.5 \, \mu m^2$ were selected for irradiation studies. Similarly in case of 200 GHz SiGe HBTs, two sets of three different emitter area geometries $0.12 \times 2 \, \mu m^2$, $0.12 \times 4 \, \mu m^2$ and $0.12 \times 8 \, \mu m^2$ were selected for irradiation studies. For brevity the irradiation results of the devices with $A_E$ of $0.5 \times 2.5 \, \mu m^2$ and $0.12 \times 4 \, \mu m^2$ will be discussed and other geometry devices showed similar degradation. The photograph of 28 pin DIP packages containing 50 GHz and 200 GHz SiGe HBTs are shown in figure 2.5.

![Figure 2.5: The photograph of 28 pin DIP packages containing 50 GHz (L10) and 200 GHz (C3) SiGe HBTs.](image)

2.3. Characterization of SiGe HBT
The computer interfaced Keithley dual channel source meters 2636A and 2612A were used to characterize the pre and post irradiated SiGe HBTs by DC I-V method. The Keithley meters have two voltage sources and two current sources. The source voltage and source current can be varied from 200 mV to 200 V and from 100 pA to 10 A respectively. The voltage and current measuring sensitivity of these meters is 5 $\mu$V and 20 fA respectively. A custom made measurement box was fabricated for the off-line measurement of DC I-V characteristics. The measurement box is made up of steel to provide electromagnetic shielding to the sample and to avoid fluctuations while measuring the currents as low as pA [94]. The photograph of the computer interfaced Keithley source meter 2636A with measurement box is shown in figure 2.6.
The in-situ I-V measurements of SiGe HBTs were performed during gamma and ion irradiation. The important DC I-V characteristics such as (i) forward mode Gummel characteristics, (ii) inverse mode Gummel characteristics, (iii) excess base current, (iv) current gain, (v) neutral base recombination, (vi) avalanche multiplication of carriers and (vii) output characteristics were measured before and after irradiation. The detailed description of these measurements and the respective circuit diagrams are given in the following sub-sections.

2.3.1. Forward mode Gummel characteristics

The basic bipolar device characterization involves the knowledge on certain device parameters. The most of bipolar device/circuit simulators require inputs on operational parameters of the device. For bipolar devices, the majority of the parameters can be estimated from DC I-V characteristic curves. The fundamental I-V curve is called a “Gummel Plot” which is a shortened version of the Gummel-Poon
device model. The Gummel characteristic is a plot of collector current ($I_C$) and base current ($I_B$) plotted on a logarithmically scaled vertical axis versus emitter-base voltage ($V_{BE}$) on the linearly scaled horizontal axis. The plot was first used by H. K. Gummel and H. C. Poon to measure the integrated base charge of a device [95]. The forward mode Gummel characteristic is measured by biasing the SiGe HBT in common emitter configuration. The data for a Gummel plot is obtained by sweeping the base-emitter voltage ($V_{BE}$) from 0 to 1.2 V in step size of 0.01 V and by measuring the base current ($I_B$) and the collector current ($I_C$) at constant collector-emitter voltage of 1 V ($V_{CE} = 1$ V). These curves can then be analyzed graphically or numerically to extract different parameters. The current gain of the pre and post irradiated SiGe HBTs was measured using this method. The different parameters like excess base current ($\Delta I_B$), excess collector current ($\Delta I_C$) and surface recombination velocity of the carriers were extracted from the Gummel characteristics [96-98]. Figure 2.7 shows the test configuration of input and output characteristics of SiGe HBTs using Keithley 2636A and 2612A dual source meters.

![Figure 2.7: The circuit diagram to measure forward mode characteristics of NPN SiGe HBTs using three SMU measurement set-up.](image)

### 2.3.2. Inverse mode Gummel characteristics

The inverse mode Gummel characteristic is measured by biasing the SiGe HBT in common base configuration. The data for a Gummel plot is obtained by sweeping the $V_{BC}$ from 0 to 1.2 V in steps of 0.01 V and by measuring $I_B$ and $I_E$ at constant emitter-base voltage ($V_{BE} = 0$ V). The inverse Gummel characteristics is a combined plot of emitter current ($I_E$) and base current ($I_B$) in logarithmic scale versus collector-base voltage ($V_{BC}$) in linear scale. The radiation damage in shallow trench isolation (STI) oxide is studied by measuring inverse mode Gummel characteristics. The inverse mode excess base current is extracted from the inverse mode Gummel characteristics to measure the increase in $I_B$. The three SMU test configuration to measure inverse mode Gummel characteristics is shown in figure 2.8.
2.3.3. Neutral base recombination

Neutral base recombination (NBR) is measured in common base configuration. In case of 50 GHz SiGe HBTs, the data for NBR is obtained by sweeping the collector base voltage \( V_{\text{CB}} \) from 0 to 3 V in steps of 0.005 V by measuring \( I_B \) at constant \( V_{\text{BE}} = -0.7 \) V. In case of 200 GHz SiGe HBTs, the data for NBR is obtained by sweeping the collector base voltage \( V_{\text{CB}} \) from 0 to 1 V in steps of 0.005 V by measuring \( I_B \) at constant emitter-base voltage \( V_{\text{BE}} = -0.7 \) V. The NBR is calculated by dividing \( I_B \) by \( (I_B)_{V_{\text{CB}} = 0} \) and plotting this ratio against \( V_{\text{CB}} \). The test configuration for measuring NBR is given in figure 2.8.

2.3.4. Avalanche multiplication of carriers

Avalanche multiplication (M-1) of carriers in collector base junction is measured by biasing the SiGe HBT in common-base configuration. In case of 200 GHz SiGe HBTs, the data for M-1 is measured by sweeping \( V_{\text{CB}} \) from 0 to 2 V in steps of 0.01 V while measuring \( I_C \) and \( I_B \) at constant emitter current \( I_E = -1 \) μA. Similarly for 50 GHz SiGe HBTs, the data for M-1 is measured by sweeping \( V_{\text{CB}} \) from 0 to 5 V in steps of 0.01 V while measuring \( I_C \) and \( I_B \) at constant emitter current \( I_E = -1 \) μA. The M-1 is calculated using the following formula [99]:

\[
M = \left( \frac{I_C}{1\mu A - I_B} \right)_{V_{\text{CB}} = 0} - 1 \quad \rightarrow 2.1
\]

The test configuration for measuring M-1 is shown in figure 2.8.
2.3.5. Output characteristics

I_C-V_{CE} characteristic curve of SiGe HBT is a plot of collector current (I_C) versus collector-emitter voltage (V_{CE}) at constant base current (I_B). The output characteristic is measured by biasing the SiGe HBT in common-emitter configuration. In case of 200 GHz SiGe HBTs, the data for output characteristics is obtained by sweeping the collector-emitter voltage (V_{CE}) from 0 to 2.2 V in steps of 0.1 V for different I_B ranging from 1 µA to 6 µA in five steps. In case of 50 GHz SiGe HBTs, the output characteristics is obtained by sweeping the collector-emitter voltage (V_{CE}) from 0 to 3.5 V in steps of 0.1 V for different I_B ranging from 1 µA to 10 µA in five steps. The I_C corresponding to different I_B is plotted in vertical Y-axis versus V_{CE} in horizontal x-axis. From these characteristics the variation of collector saturation current at various doses for different ionizing radiation were studied. The circuit diagram for measuring the output characteristics is shown in figure 2.7.

2.4. Mixed mode electrical stress

The DC I-V characteristics of the SiGe HBTs degrade when SiGe HBT is subjected to mixed mode electrical stress. In mixed mode electrical stress condition, the SiGe HBT is biased in common-base configuration where the collector-base junction is maintained at high voltage (V_{CB}) and emitter is biased at high negative emitter current (I_E) [83]. During the mixed mode stress condition, the I_E is dependent on the device emitter area. Therefore the bias conditions for mixed mode stress vary for different emitter area geometry of the SiGe HBT. For 50 GHz SiGe HBTs, the mixed mode stress conditions are as follows;

- A_E = 0.5 x 1.0 µm², the V_{CB} = 3.0 V and I_E = -8.0 mA
- A_E = 0.5 x 2.5 µm², the V_{CB} = 3.0 V and I_E = -38.0 mA

Similarly for 200 GHz SiGe HBT the mixed mode stress conditions are as follows;

- A_E = 0.12 x 2.0 µm², the V_{CB} = 3.0 V and I_E = -12.0 mA
- A_E = 0.12 x 4.0 µm², the V_{CB} = 3.0 V and I_E = -20.0 mA
- A_E = 0.12 x 8.0 µm², the V_{CB} = 3.0 V and I_E = -30.0 mA
2.5. Irradiation facilities

The 50 GHz and 200 GHz SiGe HBTs were exposed to $^{60}$Co gamma radiation using Gamma chamber 5000 at Pondicherry University, Puducherry. The ion irradiation was carried out in 15 UD Pelletron Accelerator available at Inter University Accelerator Centre (IUAC), New Delhi. A brief description of these irradiation facilities are given in the following sub-sections.

2.5.1. Gamma chamber

The gamma chamber 5000 available at Pondicherry University, Puducherry was used to irradiate NPN transistors and MOSFETs. The radiation source in the gamma chamber is $^{60}$Co, the most commonly used source for semiconductor irradiation. It is an isotope formed by thermal neutron capture in a nuclear reactor from $^{59}$Co.

$$^{59}\text{Co} + n = ^{60}\text{Co} + \gamma$$

$$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + 2\gamma$$

The $^{60}$Co is a beta emitter and the emission of two gamma rays from $^{60}$Ni having energies 1.33 and 1.17 MeV combined with a half-life of 5.3 years. Usually a $^{60}$Co source is kept in the form of metal slug, pellet or rod. It is doubly encapsulated with stainless steel in the form of a pencil. A fine source assembly contains multiple pencils in a case or plaque with planar, circular or other geometric configuration. Figures 2.9 and 2.10 show photograph of gamma chamber 5000 and its cross sectional view respectively. Gamma chamber 5000 is a compact and self-contained irradiation unit offering an irradiation volume of 5000 cc. Adequate shielding is provided so that the radiation leakage outside the unit is well below the maximum permissible dose levels. The main unit consists of a source cage, biological shield for the source and a central shaft incorporating sample chamber. The source cage holds the radiation source in an annular cylinder. The coaxial hole in the centre of the cage provides space for irradiation chamber. The cage is designed to hold 18/24 pencils containing cobalt-60 in the form of pellets or aluminium clad slugs. The lead shield surrounding the source cage serves the dual purpose of a transport container and the biological shield. The central shaft is a stainless steel clad solid lead cylinder at the centre of which the sample chamber is located. The purpose of lead filled central shaft is to provide shielding during the upward and downward movement of the sample.
chamber. The sample chamber is raised or lowered by a wire rope using a system of pulleys and a rotating drum. The drum is rotated by an electric motor and self-locking reduction gear unit. Extreme upper and lower positions of the sample chamber are determined by micro switches, which are fixed in appropriate positions so as to locate the sample chamber exactly in the centre of the cage when it is in extreme down position.

The 50 GHz and 200 GHz SiGe HBTs were exposed to $^{60}\text{Co}$ gamma photons from gamma chamber 5000 under laboratory conditions. Gamma chamber was calibrated with standard $^{60}\text{Co}$ source. The dose rate was found to be 167 rad/s at the middle of the sample holder. Care was taken to see that all devices were receiving the same doses by keeping the devices at the middle of the sample chamber. The sample holder is capable of rotating the samples at a rate of 60 rpm during irradiation to provide
uniform dose rate on all the mounted samples. All the terminals of the SiGe HBTs were floating during gamma irradiation. The different total doses given to SiGe packages were 600 krad, 1 Mrad, 3 Mrad, 6 Mrad, 10 Mrad, 30 Mrad, 60 Mrad and 100 Mrad.

![Figure 2.10: The schematic cross section of Gamma chamber 5000](image)

### 2.5.2. 15UD Pelletron accelerator

The 15 UD 16 MV Pelletron Accelerator at Inter University Accelerator Centre (IUAC), New Delhi belongs to a class of particle accelerators known as tandem Van de Graff accelerator. It is capable of accelerating almost all the ion beams (hydrogen to uranium) of energies from a few MeV to hundreds of MeV. In this machine, negative ions are produced and pre-accelerated to ~400 keV in ion source and injected into strong electrical field inside an accelerator tank filled with SF₆ insulating gas. At the centre of the tank is a terminal shell, which is maintained at a high voltage (~15 MV). The whole machine is mounted vertically and the schematic cross section of the machine is shown in figure 2.11.
The negative ions on traversing through the accelerating tubes from the column top of the tank to the positive terminal get accelerated. On reaching the terminal they pass through a stripper, which removes some electrons from the negative ions, thus transforming the negative ions into positive ions. These positive ions are then repelled away from the positively charged terminal and are accelerated to ground potential to the bottom of the tank. In this manner same terminal potential is used twice to accelerate the ions. On exiting from the tank, the ions are bent into horizontal plane by analyzing magnet. The switching magnet diverts the high energy ion beams into a particular beam line out of various beam lines in the different experimental areas of the beam hall. The entire machine is computer controlled and is operated from the control room [100].

Figure 2.11: The cross sectional view of 15UD Pelletron accelerator at IUAC, New Delhi.
Material Science Beam Line

The multi-port switching magnet can redirect the ion beam to any one of the seven beam lines. The material science (MS) beam line is at 15º to right with respect to the zero degree beam line. The MS beam line has a stainless steel high vacuum irradiation chamber with a diameter 68 cm. The photograph of the MS beam line and irradiation chamber is shown in the figure 2.12.

![Figure 2.12: Photograph of high vacuum irradiation chamber in material science beam line hall at IUAC, New Delhi.](image)

The vacuum in the irradiation chamber is created with the help of turbo molecular pump. The vacuum in the irradiation chamber should be in the order of 10^-7 mbar to provide the ion beam to the beam line. The SiGe packages are mounted on the target ladder which is provided with feed-through for external connections. The wire connections are made from the SiGe package to the feed-through before inserting the ladder into the irradiation chamber. A stepper motor in combination with suitable mechanical assembly is used to control the vertical motion of the ladder. The vertical motion of the ladder can be remotely controlled from the data acquisition room using an electronic control system. The ion beam is visually monitored by glow on quartz and the packages are positioned below the quartz crystal vertically. A CCD camera with a light bulb arrangement is provided to view inside the chamber during the experiments. Initially the beam position is marked on the CCTV when the ion beam glows after falling on the quartz crystal. The SiGe package is brought to the marked
position by moving the ladder up and down. The beam is scanned in X and Y directions in the area of $10 \times 10$ mm$^2$ with the help of an electromagnetic scanner. The scanning ensures the uniformity of irradiation over the whole area of the sample.

Figure 2.13: (a) A view of in-situ experimental set-up at material science beam line. (b) Electrical connectors connected to in-situ ladder. (c) In-situ ladder showing electrical connections from bread-board to feed-through; (inset: bread-board on A-face having 18 to 20 connections). (d) SiGe packages on B-face inside the irradiation chamber; to the left of B-face is A-face containing an in-situ SiGe package which is facing the ion beam.
The 50 GHz SiGe HBTs and 200 GHz SiGe HBTs were irradiated with 50 MeV lithium ion \([\text{Li}^{3+}]\), 75 MeV boron ion \([\text{B}^{5+}]\) and 100 MeV oxygen ion \([\text{O}^{7+}]\) in the total dose ranging from 600 krad to 100 Mrad. The beam current during ion irradiation were 0.833, 0.500 and 0.285 p-nA (particle-nano ampere) for Li\(^{3+}\), B\(^{5+}\) and O\(^{7+}\) ions respectively. Before irradiation, the devices are characterized by placing the ladder in the irradiation chamber and these measurements are called ‘pre-rad’ measurements. The I-V measurements were taken after different radiation total doses viz., 600 krad, 1 Mrad, 3 Mrad, 6 Mrad, 10 Mrad, 30 Mrad, 60 Mrad and 100 Mrad. The in-situ experimental set-up used to measure the electrical characteristics during ion irradiation is shown in figure 2.13. The irradiation time was calculated for different total doses for different ion species. The table 2.1 shows the comparison of irradiation time taken to reach a particular total dose for \(^{60}\text{Co}\) gamma and different high energy ions.

Table 2.1. The irradiation time required to reach a particular total dose for different radiation.

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Radiation/Ion Species</th>
<th>1 Mrad</th>
<th>3 Mrad</th>
<th>6 Mrad</th>
<th>10 Mrad</th>
<th>30 Mrad</th>
<th>60 Mrad</th>
<th>100 Mrad</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(^{60}\text{Co}) gamma</td>
<td>1hr 40min</td>
<td>5hrs</td>
<td>10hrs</td>
<td>16hrs 40min</td>
<td>50hrs</td>
<td>100hrs</td>
<td>166hrs 40min</td>
</tr>
<tr>
<td>2</td>
<td>50 MeV Li(^{3+}) ion</td>
<td>26 s</td>
<td>2 min 18 s</td>
<td>2 min 37 s</td>
<td>3 min 56 s</td>
<td>13 min 9 s</td>
<td>26 min 19 s</td>
<td>43 min 52 s</td>
</tr>
<tr>
<td>3</td>
<td>75 MeV B(^{5+}) ion</td>
<td>16 s</td>
<td>50 s</td>
<td>1 min 40 s</td>
<td>2 min 46 s</td>
<td>8 min 20 s</td>
<td>16 min 40 s</td>
<td>27 min 48 s</td>
</tr>
<tr>
<td>4</td>
<td>100 MeV O(^{7+}) ion</td>
<td>11 s</td>
<td>34 s</td>
<td>1 min 8 s</td>
<td>1 min 53 s</td>
<td>5 min 39 s</td>
<td>11 min 17 s</td>
<td>18 min 4 s</td>
</tr>
</tbody>
</table>

2.6. Military standards and dosimetry

The two test guidelines for testing the radiation hardness of integrated circuits are US test guideline MIL-STD-883, Method 1019.4 and the European test guideline BS 22900 [101]. The US military standards are chosen as standard for irradiation experiments. It is necessary to calibrate radiation source or radiation flux during irradiation to follow test guidelines. A brief note on radiation dosimetry and US military standards are given in the following sub-sections.
2.6.1. Military standards

The test standard that governs the total dose testing of IC's is ‘MIL-STD-883 Method 1019.4 ionizing radiation (total dose) test procedure’ [102]. This test procedure defines the requirements for testing semiconductor integrated circuits for ionizing radiation (total dose) effects using $^{60}$Co gamma radiation source. According to the specifications, the irradiation and electrical characterization must be performed at $24\pm 6^\circ C$. The final total dose is fixed depending on the application for which the test is conducted but the dose rate should be restricted within 50 to 300 rad/s. The customised flow chart for the present irradiation studies is shown in figure 2.14. The test guidelines are defined for testing single event effects due to heavy ions [101], however the test guidelines for studying the total dose effects due to heavy ion irradiation are yet to be developed [103]. Hence ‘MIL-STD-883 Method 1019.4’ is considered as the standard method for studying total dose effects using heavy ions. Slight modifications are made in the military standards at the annealing step. Instead of isothermal annealing, isochronal annealing method is introduced in the annealing stage because after isothermal annealing the heavy ion induced recovery is very slow when compared to isochronal annealing [104]. Therefore it is interesting to study the complete recovery in the electrical characteristics of an ion irradiated SiGe HBT after isochronal annealing.

![Customised test flow chart for MIL-STD 883, method 1019.](image)

Figure 2.14: The customised test flow chart for MIL-STD 883, method 1019.
2.6.2. $^{60}$Co gamma dosimetry
The gamma chamber contains $^{60}$Co radioisotope whose half life is 5.27 years. Therefore its strength reduces by approximately 12% every year. In Gamma chamber 5000, the dose rates and source strength are calculated using a preloaded programme in programmable logic device (PLD). Therefore the dose rate coming from the $^{60}$Co source was found to be 167 rad/s as shown in the PLD display of Gamma chamber 5000.

2.6.3. Faraday cup dosimetry
A Faraday cup (FC) is a well established method of calibration for confirming the ion fluence by direct measurement. A FC is a device that can give an accurate measurement of the number of ions collected by the cup. The accelerated particles are stopped inside the cup and the accumulated electric charge is detected as a corresponding electric current. The FC has a tantalum metal beam absorber that is insulated from the ground container and it completely stops the ion beam. When the ion beam hits the metal (tantalum) surface of FC, the metal gains a small net charge while the ions are neutralized. The metal can be discharged later to measure the small current equivalent to the number of impinging ions. The measured current is amplified and then the current is calibrated using the logarithmic amplifier.

2.7. Dose to fluence calculation
The dose to fluence conversion formula is given below:

$$\text{Dose (rad)} = 1.612 \times 10^{-8} \times S \times \Phi \quad \rightarrow 2.2$$

where, $S$ is the sum of electronic energy loss $\left( \frac{dE}{dx} \right)_{\text{elec}}$ and nuclear energy loss $\left( \frac{dE}{dx} \right)_{\text{nucl}}$ in MeV-cm$^2$/mg, $\Phi$ is the fluence of any ion in ions/cm$^2$, $1.6 \times 10^{-8}$ is the conversion factor. Using this formula the pre-determined total doses were converted in to corresponding ion fluence. The linear energy transfer (LET) and non-ionizing energy loss (NIEL) of different radiation was obtained using SRIM-2011 software. The LET of the ion increases with increase in atomic number of the incident ion. The
ion fluence decreases systematically with increase in LET of ions. The damage created by 1 MeV electron is equivalent to the damage created by $^{60}$Co gamma radiation, hence the LET of 1 MeV electron is considered for fluence calculation in case of gamma radiation [105]. The dose to fluence conversion graph for different LET radiation is given in figure 2.15.

![Dose to fluence conversion graph for different LET radiation.](image)

Figure 2.15: Dose to fluence conversion graph for different LET radiation.

### 2.8. Thermal annealing of irradiated SiGe HBTs

The recovery in the I-V characteristics of irradiated and electrically stressed SiGe HBTs were studied by annealing from 50°C to 500°C for 1 hr duration and is called isochronal annealing. Figure 2.16 shows the high temperature oven (50°C to 350°C) and figure 2.17 shows the furnace (400°C to 500°C) used to study isochronal annealing. The 50 GHz and 200 GHz SiGe HBTs irradiated up to 100 Mrad are subjected to annealing at different temperatures from 50°C to 500°C for 1 hr duration at each temperature and allowed for natural cooling before measuring the I-V characteristics. The results obtained from these studies are discussed in detail in Chapter 7.
2.9. Electrical annealing

The irradiated and mixed mode stressed SiGe HBTs were electrically annealed using a novel mixed mode electrical annealing condition. The irradiated SiGe HBTs were annealed under bias condition using Keithley 2636A dual channel source meter. The bias conditions presented in the thesis are different from the mixed mode electrical
annealing bias conditions reported in [84]. The SiGe HBTs are biased in common-emitter configuration, while $V_{BE}$ and $V_{CB}$ are simultaneously maintained at high voltage. The annealing bias conditions for 50 GHz SiGe HBTs are as follows:

- $A_E = 0.5 \times 1.0 \, \mu m^2$, the $V_{BE} = 1.2 \, V$ and $V_{CE} = 3 \, V$
- $A_E = 0.5 \times 2.5 \, \mu m^2$, the $V_{BE} = 1.2 \, V$ and $V_{CE} = 3.3 \, V$

Similarly for 200 GHz SiGe HBT the mixed mode annealing conditions are as follows:

- $A_E = 0.12 \times 2.0 \, \mu m^2$, the $V_{BE} = 1.2 \, V$ and $V_{CE} = 2.2 \, V$
- $A_E = 0.12 \times 4.0 \, \mu m^2$, the $V_{BE} = 1.2 \, V$ and $V_{CE} = 2.2 \, V$
- $A_E = 0.12 \times 8.0 \, \mu m^2$, the $V_{BE} = 1.2 \, V$ and $V_{CE} = 2.2 \, V$

The different time intervals like 1 ms, 5 ms, 10 ms, 50 ms, 100 ms, 500 ms, 1 s, 5 s, 10 s, 50 s, 100 s, 500 s and 1000 s were set to stop the electrical annealing bias condition and to measure the I-V characteristics. A time gap of 15 to 20 min was given between electrical stress condition and I-V measurements. In this time gap the junction temperature reduces to normal temperature without influencing the electrical characteristics of SiGe HBTs. The results obtained from annealing of 50 GHz and 200 GHz SiGe HBTs are presented Chapter 7.