CHAPTER 7
ANNEALING STUDIES ON 50 GHz AND 200 GHz SiGe HBTs

7.1. Introduction
In the fabrication of semiconductor devices, annealing technique is frequently used to improve the interfaces between the layers by reducing the number of defects. Annealing technique is also used to anneal the defects created during fabrication process or after irradiation. The high energy ions or gamma radiation degrade the electrical characteristics of SiGe HBTs by creating generation-recombination centres in the emitter-base spacer oxide, shallow trench isolation oxide and displacement damages throughout the SiGe HBT. The changes in the electrical characteristics are measured by the extraction of device parameters such as forward and inverse mode excess base current $\Delta I_b$, dc current gain ($h_{FE}$) and collector saturation current ($I_{CSat}$). After annealing, radiation induced trapped charge and defects anneal up to certain extent depending on the annealing temperature and recover the electrical characteristics of SiGe HBTs. The recovery in the electrical characteristics of annealed HBTs can be measured after different annealing steps.

There are two types of annealing methods used in the present work and are thermal annealing and electrical stress annealing. In thermal annealing, there are two sub-categories viz., isothermal annealing and isochronal annealing. In isothermal annealing, temperature is kept constant and SiGe HBTs are annealed for different time duration. In isochronal annealing, time duration is set constant and temperature is increased in different intervals. It was shown that the recovery in the electrical characteristics of ion irradiated bipolar junction transistor (BJT) is less after isothermal annealing when compared to isochronal annealing [104]. Therefore, isochronal annealing technique was used to study the maximum recovery in the electrical characteristics of irradiated and stressed SiGe HBTs. Another new technique of annealing is electrical stress annealing in which SiGe HBTs are biased in common-emitter configuration, while high $V_{BE}$ and high $V_{CB}$ are maintained simultaneously. The test configuration for 50 GHz and 200 GHz SiGe HBT are mentioned in section 2.9. The recovery in the electrical characteristics was observed after electrically annealing the SiGe HBTs for different time duration.
7.2. Isochronal annealing

The recovery in the electrical characteristics of irradiated, stressed SiGe HBTs were investigated by isochronal annealing and the results are presented in this chapter. The SiGe HBTs were annealed from 50°C to 500°C for one hour duration. After every increment of 50°C, the devices were allowed to attain room temperature and electrical characteristics were measured. The results of annealing on 50 GHz and 200 GHz SiGe HBTs are presented in the following sections.

7.2.1. 50 GHz SiGe HBT Results

The recovery in the electrical characteristics of gamma and ion irradiated 50 GHz SiGe HBT after isochronal annealing were studied systematically. The gamma and ion irradiated SiGe HBTs results are compared with the isochronal annealing results.

7.2.1.1. Forward Gummel characteristics

The recovery in $I_B$ with annealing temperature for gamma and different ion irradiated SiGe HBTs are shown in Figures 7.2 to 7.4. It can be seen from the figures that $I_B$ decreases with increase in annealing temperature. However, $I_B$ is not completely recovered even after annealing the devices up to 400°C. Though there are the signs of $I_B$ recovery at $V_{BE} = 0.65$ V, the recovery in $I_B$ is not complete at lower voltages ($< 0.6$ V). This suggest that few defects in SiGe HBTs still act as generation-recombination centres and hence increase the $I_B$ at lower voltages. Figure 7.5 shows the forward mode Gummel characteristics of stressed SiGe HBT after isochronal annealing. It can be seen from the figure that $I_B$ of the stressed SiGe HBT is completely recovered after 250°C suggesting very few damages were created after applying electrical stress. Therefore the stress induced G/R trapped charges are completely recovered after isochronal annealing.
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Figure 7.1: Forward mode Gummel characteristics of $^{60}$Co gamma irradiated SiGe HBT as a function of annealing temperature.

Figure 7.2: Forward mode Gummel characteristics of 50 MeV Li$^{+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.3: Forward mode Gummel characteristics of 75 MeV B$^{+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.4: Forward mode Gummel characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.5: Forward mode Gummel characteristics of stressed SiGe HBT as a function of annealing temperature.

Figure 7.6: The base current as a function of total dose and annealing temperature for $^{60}$Co gamma and ion irradiated SiGe HBT ($V_{BE} = 0.65$ V).
The $I_B$ extracted at $V_{BE} = 0.65$ V is plotted versus total dose and annealing temperature for irradiated and annealed SiGe HBTs and is shown in Figure 7.6. After irradiating the SiGe HBTs, devices were stored for 150 days at room temperature and later measured the electrical characteristics. It can be seen from the figure that there is about 30% to 40% of recovery in $I_B$ for gamma and ion irradiated SiGe HBTs after room temperature annealing. During isochronal annealing, $I_B$ decreases with increase in annealing temperature because the oxide and interface trapped charges were annealed. The complete recovery in $I_B$ is observed only for Li$^{3+}$ ion irradiated SiGe HBT. Around 80-90% recovery in $I_B$ is observed after isochronal annealing of gamma, B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs. The incomplete annealing is due to the presence of few displacement damages even after annealing at 400°C.

### 7.2.1.2. Current gain

The recovery in $h_{FE}$ of gamma and ion irradiated SiGe HBTs after isochronal annealing is shown in Figures 7.7 to 7.10. It can be seen from the figures that the $h_{FE}$ increases with increase in annealing temperature because the $I_B$ decreases after annealing. At $I_C$ greater than 1 $\mu$A, the $h_{FE}$ increases even more than pre-rad $h_{FE}$. The high recovery in $h_{FE}$ is observed only for gamma and Li$^{3+}$ ion irradiated SiGe HBTs. In case of B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs, $h_{FE}$ is not completely recovered even after annealing up to 400°C. The recovery in $h_{FE}$ is due to annealing of oxide and interface trapped charges in EB spacer oxide. Figure 7.11 shows the recovery in $h_{FE}$ of stressed SiGe HBT after isochronal annealing. It is evident from the figure that $h_{FE}$ is completely recovered after isochronal annealing up to 250°C.

![Figure 7.7: The recovery in current gain as a function of annealing temperature for $^{60}$Co gamma irradiated SiGe HBT.](image1)

![Figure 7.8: The recovery in current gain as a function of annealing temperature for 50 MeV Li$^{3+}$ ion irradiated SiGe HBT.](image2)
Figure 7.9: The recovery in current gain as a function of annealing temperature for 75 MeV B$^{7+}$ ion irradiated SiGe HBT.

Figure 7.10: The recovery in current gain as a function of annealing temperature for 100 MeV O$^{7+}$ ion irradiated SiGe HBT.

Figure 7.11: The recovery in current gain as a function of annealing temperature for stressed SiGe HBT.

Figure 7.12: The peak current gain as a function of total dose and annealing temperature for $^{60}$Co gamma and different ion irradiated SiGe HBTs.

Figure 7.13: The normalised peak current gain as a function of total dose and annealing temperature for $^{60}$Co gamma and different ion irradiated SiGe HBTs.
Table 7.1: Details of normalised current gain before irradiation, after irradiation and after isothermal annealing

<table>
<thead>
<tr>
<th>Radiation species</th>
<th>Normalized current gain (h\textsubscript{FE})</th>
<th>Pre-rad</th>
<th>After 100 Mrad</th>
<th>% of degradation</th>
<th>Room temperature recovery in h\textsubscript{FE}</th>
<th>% of room temperature recovery in h\textsubscript{FE}</th>
<th>Annealing after 400°C</th>
<th>% of recovery after annealing (g = b ~ f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60 Co gamma</td>
<td></td>
<td>100</td>
<td>54</td>
<td>46</td>
<td>71</td>
<td>17</td>
<td>105</td>
<td>51</td>
</tr>
<tr>
<td>50 MeV Li\textsuperscript{3+} ion</td>
<td></td>
<td>100</td>
<td>42</td>
<td>58</td>
<td>69</td>
<td>27</td>
<td>109</td>
<td>51</td>
</tr>
<tr>
<td>75 MeV B\textsuperscript{5+} ion</td>
<td></td>
<td>100</td>
<td>43</td>
<td>57</td>
<td>50</td>
<td>7</td>
<td>82</td>
<td>25</td>
</tr>
<tr>
<td>100 MeV O\textsuperscript{7+} ion</td>
<td></td>
<td>100</td>
<td>34</td>
<td>66</td>
<td>45</td>
<td>11</td>
<td>93</td>
<td>27</td>
</tr>
</tbody>
</table>

The variation in peak h\textsubscript{FE} as a function of total dose and annealing temperature for gamma and different ion irradiated SiGe HBTs is shown in Figure 7.12. The peak h\textsubscript{FE} recovers from 91 to 137 for 60 Co gamma irradiated SiGe HBT, 87 to 138 for Li\textsuperscript{3+} ion irradiated SiGe HBT, 58 to 110 for B\textsuperscript{5+} ion irradiated SiGe HBT and 54 to 100 for O\textsuperscript{7+} ion irradiated SiGe HBT. The Figure 7.13 illustrates the variation in the normalised peak h\textsubscript{FE} as a function of total dose and annealing temperature for gamma and different ion irradiated SiGe HBTs. It can be seen from the figure that h\textsubscript{FE} recovers by 20% to 30% after room temperature annealing for gamma and Li\textsuperscript{3+} ion irradiated SiGe HBT. But only 10% recovery in h\textsubscript{FE} is observed for B\textsuperscript{5+} and O\textsuperscript{7+} ion irradiated SiGe HBTs. It is also clear from the figure that after isochronal annealing, h\textsubscript{FE} increases with increase in annealing temperature. In case of gamma and Li\textsuperscript{3+} ion irradiated SiGe HBTs, the recovery in h\textsubscript{FE} is almost 100%. About 80 to 90% recovery in the h\textsubscript{FE} is observed for B\textsuperscript{5+} and O\textsuperscript{7+} ion irradiated SiGe HBTs. Irradiation creates defects and their complexes in addition to the trapped charges, these defects and their complexes are not completely annealed even after 400°C.

7.2.1.3. Neutral base recombination

The pre-irradiated, post-irradiated and post-anneal neutral base recombination characteristics of gamma and ion irradiated SiGe HBTs are shown in Figures 7.14 to 7.17. It is evident from the figures that the slopes of the pre-irradiated, post-irradiated
and annealed SiGe HBTs are almost same. Therefore there is negligible change in the neutral base trap density after irradiation and annealing. It is also evident from the figures that there is significant annealing in $BV_{CBO}$ after isochronal annealing.

![Figure 7.14](image1.png)

**Figure 7.14:** Neutral base recombination of un-irradiated, $^{60}$Co gamma irradiated and isochronally annealed SiGe HBT.

![Figure 7.15](image2.png)

**Figure 7.15:** Neutral base recombination of un-irradiated, 50 MeV $Li^{3+}$ ion irradiated and isochronally annealed SiGe HBT.

![Figure 7.16](image3.png)

**Figure 7.16:** Neutral base recombination of un-irradiated, 75 MeV $B^{5+}$ ion irradiated and isochronally annealed SiGe HBT.

![Figure 7.17](image4.png)

**Figure 7.17:** Neutral base recombination of un-irradiated, 100 MeV $O^{7+}$ ion irradiated and isochronally annealed SiGe HBT.

### 7.2.1.4. Avalanche Multiplication

The pre-irradiated, post-irradiated and post-anneal M-1 curves for gamma and ion irradiated SiGe HBTs are shown in Figures 7.18 to 7.21. It can be seen from the figures that the M-1 slightly recovers after annealing when compared to post-irradiated M-1 curve. Therefore the local junction electric field that changed after irradiation has recovered after isochronal annealing.
7.2.1.5. Output Characteristics

The recovery of $I_{CSat}$ after isochronal annealing for gamma and ion irradiated SiGe HBTs are shown in Figure 7.22 to 7.25. From these figures it is can be seen that the $I_{CSat}$ increases with increase in annealing temperature. Figure 7.26 shows the recovery in $I_{CSat}$ after isochronal annealing for mixed mode stressed SiGe HBT. It can be also seen from the figure that the $I_{CSat}$ is completely recovered after annealing up to 250°C. The $I_C$ is extracted at $V_{CE} = 1$ V from output characteristics and plotted versus total dose and annealing temperature and is shown in Figure 7.27. It is evident from the figure that the recovery of $I_{CSat}$ at room temperature is not significant when compared to the $I_B$ and $h_{FE}$. But after isochronal annealing, the recovery in $I_{CSat}$ is around 90 to 100% for $B^{5+}$ and $O^{7+}$ ion irradiated SiGe HBTs and around 100% recovery for gamma and $Li^{3+}$ ion irradiated SiGe HBTs.
Figure 7.22: Output characteristics of $^{60}\text{Co}$ gamma irradiated SiGe HBT as a function of annealing temperature.

Figure 7.23: Output characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.24: Output characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.25: Output characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.26: Output characteristics of stressed SiGe HBT as a function of annealing temperature.

Figure 7.27: The collector saturation current as a function of total dose and annealing temperature for gamma and ion irradiated SiGe HBT.
7.2.2. 200 GHz SiGe HBT Results

The recovery in the electrical characteristics of gamma and ion irradiated 200 GHz SiGe HBT after isochronal annealing is presented in this section. The gamma and ion irradiated SiGe HBTs results are compared with the isochronal annealing results.

7.2.2.1. Forward Gummel characteristics

The recovery in $I_B$ with annealing temperature for gamma and ion irradiated SiGe HBTs are shown in Figures 7.28 to 7.31. It is evident from the figures that $I_B$ decreases with increase in annealing temperature. The radiation induced oxide and interface trapped charges are annealed and hence $I_B$ decreases with increase in annealing temperature. The complete recovery of $I_B$ in gamma and ion irradiated SiGe HBTs was not observed even after annealing up to 350°C.

Figure 7.28: Forward mode Gummel characteristics of $^{60}$Co gamma irradiated SiGe HBT as a function of annealing temperature.

Figure 7.29: Forward mode Gummel characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.30: Forward mode Gummel characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.31: Forward mode Gummel characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT as a function of annealing temperature.
The $I_B$ extracted at $V_{BE} = 0.65$ V is plotted versus total dose and annealing temperature for irradiated and annealed SiGe HBTs and is shown in Figure 7.32. It can be seen from the figure that there is slight recovery in $I_B$ due to room temperature annealing in gamma and ion irradiated SiGe HBTs. After isochronal annealing, the recovery in $I_B$ is about 82%, 84%, 91% and 90% for gamma, $\text{Li}^{3+}, \text{B}^{5+}$ and $\text{O}^{7+}$ ion irradiated SiGe HBTs respectively. The complete recovery in $I_B$ is not observed because the radiation induced displacement damages are not annealed even after annealing up to 350°C.

### 7.2.2.2. Current gain

The variation in $h_{FE}$ for different annealing temperature is shown in Figures 7.33 to 7.36 for gamma and ion irradiated SiGe HBTs respectively. It is evident from the figures that as the annealing temperature increases, the $h_{FE}$ increases. The recovery in $h_{FE}$ is more for gamma irradiated SiGe HBTs when compared to ion irradiated SiGe HBTs. In other words $^{60}$Co gamma radiation creates only trapped charges, these trapped charges would be annealed during isochronal annealing. The ion irradiation creates defects and their complexes in addition to the trapped charges, these defects are not annealed completely during isochronal annealing up to 350°C.
Figure 7.33: The recovery in current gain as a function of annealing temperature for 60Co gamma irradiated SiGe HBT.

Figure 7.34: The recovery in current gain as a function of annealing temperature for 50 MeV Li$^{3+}$ ion irradiated SiGe HBT.

Figure 7.35: The recovery in current gain as a function of annealing temperature for 75 MeV B$^{3+}$ ion irradiated SiGe HBT.

Figure 7.36: The recovery in current gain as a function of annealing temperature for 100 MeV O$^{7+}$ ion irradiated SiGe HBT.

Figure 7.37: The peak current gain as a function of total dose and annealing temperature for 60Co gamma and different ion irradiated SiGe HBTs.

Figure 7.38: The normalised peak current gain as a function of total dose and annealing temperature for 60Co gamma and different ion irradiated SiGe HBTs.
Table 7.2: Details of normalised current gain before irradiation, after irradiation and after isothermal annealing

<table>
<thead>
<tr>
<th>Radiation species</th>
<th>Normalized current gain ((h_{FE}))</th>
<th>Pre-rad (a)</th>
<th>After 100 Mrad (b)</th>
<th>% of degradation (c)</th>
<th>Room temperature recovery in (h_{FE}) (d)</th>
<th>% of room temperature recovery in (h_{FE}) (e = b ~ d)</th>
<th>Annealing after 400°C (f)</th>
<th>% of recovery after annealing (g = b ~ f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{60})Co gamma</td>
<td>100</td>
<td>53</td>
<td>47</td>
<td>59</td>
<td>6</td>
<td>80</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>50 MeV Li(^{3+}) ion</td>
<td>100</td>
<td>48</td>
<td>52</td>
<td>49</td>
<td>1</td>
<td>70</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>75 MeV B(^{5+}) ion</td>
<td>100</td>
<td>46</td>
<td>54</td>
<td>55</td>
<td>9</td>
<td>74</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>100 MeV O(^{7+}) ion</td>
<td>100</td>
<td>36</td>
<td>64</td>
<td>37</td>
<td>1</td>
<td>59</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

The peak \(h_{FE}\) and normalised peak \(h_{FE}\) plotted versus total dose and annealing temperature are shown in Figures 7.37 and 7.38 respectively. It can be seen from the figure that the peak \(h_{FE}\) increases with increase in annealing temperature. The recovery in normalised peak \(h_{FE}\) at room temperature and after isochronal annealing is tabulated in Table 7.2.

### 7.2.2.3. Neutral base recombination

The pre-irradiated, post-irradiated and post-annealed neutral base recombination characteristics of gamma and ion irradiated SiGe HBTs are shown in Figure 7.39 to Figure 7.42. The slopes of the pre-irradiated, post-irradiated and post-annealed NBR curves are almost same. Hence there is negligible displacement damage in the neutral base region after irradiation and annealing. It is also evident from the figures that there is slight recovery in \(BV_{CBO}\) after isochronal annealing.
Annealing Studies on 50 GHz and 200 GHz SiGe HBTs

7.2.2.4. Avalanche Multiplication

The pre-irradiated, post-irradiated and post-annealed M-1 curves for gamma and ion irradiated SiGe HBTs are shown in Figure 7.43 to Figure 7.46. It can be seen from the figures that M-1 decreased slightly after annealing when compared to the un-irradiated M-1. However complete recovery of M-1 curves was not observed even after 400°C of annealing temperature.
7.2.2.5. Output Characteristics

The recovery of $I_{CSat}$ after isochronal annealing for gamma and ion irradiated SiGe HBTs is shown in Figure 7.47 to 7.50. From these figures it is can be seen that the $I_{CSat}$ increases with increase in annealing temperature. The $I_C$ is extracted at $V_{CE} = 1$ V from output characteristics and plotted versus total dose and annealing temperature and is shown in Figure 7.51. It can be seen that the recovery in $I_{CSat}$ is not significant for gamma or ion irradiated SiGe HBTs. The recovery in $I_{CSat}$ with respect to post-rad $I_{CSat}$ is around 56%, 64%, 4% and 89% for gamma, Li$^{3+}$, B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs respectively.
Annealing Studies on 50 GHz and 200 GHz SiGe HBTs

Figure 7.47: Output characteristics of $^{60}$Co gamma irradiated SiGe HBT as a function of annealing temperature.

Figure 7.48: Output characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.49: Output characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.50: Output characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT as a function of annealing temperature.

Figure 7.51: The collector saturation current as a function of total dose and annealing temperature for gamma and ion irradiated SiGe HBTs.
7.3. **Electrical stress annealing**

The electrical characteristics of irradiated SiGe HBTs can be recovered by applying electrical stress technique. In Chapter 6 we have seen that the mixed mode electrical stress can induce defects in SiGe HBTs and degrade the electrical characteristics of SiGe HBTs. The hot electrons are responsible for creating the damage inside the SiGe HBT structure. Interestingly an important question arises that whether this process is reversible. If the process is reversible, the defects could be annealed just by applying the electrical stress condition. The electrical characteristics of irradiated SiGe HBT can be recovered after applying the unique stress condition. If the process is irreversible, the electrical characteristics have to be recovered only by thermal annealing. In this context, it is interesting to note the recovery of electrical characteristics in SiGe HBT after applying the mixed mode stress at particular conditions [84]. However a new stress condition is identified for the first time to anneal the electrical characteristics of an irradiated SiGe HBT. The stress conditions are different for 50 GHz and 200 GHz SiGe HBTs and the results of electrical stress annealing are discussed in the following sections.

7.3.1. **50 GHz SiGe HBT Results**

The recovery in the electrical characteristics of ion irradiated 50 GHz SiGe HBT after electrical annealing is presented in this section. The ion irradiated SiGe HBTs results are compared with the electrical annealing results. The test configuration and the bias conditions are explained in section 2.9.

7.3.1.1. **Forward Gummel characteristics**

The recovery in $I_B$ with annealing time for different ion irradiated SiGe HBTs are shown in Figures 7.52 to 7.54. It is evident from the figures that the $I_B$ decreases with increase in annealing time. In case of $Li^{3+}$ and $B^{5+}$ ion irradiated SiGe HBTs, $I_B$ is not completely recovered even after annealing for 500s. However in case of $O^{7+}$ ion irradiated SiGe HBT, the recovery of $I_B$ is 100%. The bias conditions are sufficient to recombine the electron-hole pairs particularly near the EB spacer oxide. Therefore the radiation-induced oxide trapped charges and interface charges gradually anneal with increase in annealing time and hence the generation recombination process decreases. Therefore the $I_B$ decreases consistently with increase in annealing time.
The $I_B$ extracted at $V_{BE} = 0.65$ V is plotted versus total dose and annealing time for irradiated and annealed SiGe HBTs and is shown in Figure 7.55. From the figure it is clear that there is room temperature annealing of $I_B$ for ion irradiated SiGe HBTs. The maximum recovery in $I_B$ is observed after 1 ms of annealing time. At smaller annealing time intervals the junction temperature is less, but gradually increases with increase in annealing time. At longer annealing time durations (above 10 ms) the junction temperature of the SiGe HBT increases and therefore $I_B$ recovered significantly. After 10 ms of annealing time the recovery in $I_B$ is very small and the trend in $I_B$ recovery is similar to the isochronal annealing. The junction temperature of SiGe HBTs during electrical annealing rises from 100°C to 300°C [84, 85].
7.3.1.2. Current gain

The recovery in peak $h_{FE}$ of ion irradiated SiGe HBTs after electrical annealing is shown in Figures 7.56 to 7.58. It can be seen from the figures that as the annealing time increases the $h_{FE}$ is also found to increase. The $h_{FE}$ increases because $I_B$ decreases with increases in annealing time. At $I_C$ greater than 1 μA, the $h_{FE}$ increase is more than the pre-rad $h_{FE}$ for longer annealing time durations.

![Figure 7.56: The recovery in current gain as a function of annealing time for 50 MeV Li$^{3+}$ ion irradiated SiGe HBT.](image1)

![Figure 7.57: The recovery in current gain as a function of annealing time for 75 MeV B$^{5+}$ ion irradiated SiGe HBT.](image2)

![Figure 7.58: The recovery in current gain as a function of annealing time for 100 MeV O$^{7+}$ ion irradiated SiGe HBT.](image3)

![Figure 7.59: The peak current gain as a function of total dose and annealing time for $^{60}$Co gamma and different ion irradiated SiGe HBTs.](image4)

The variation in peak $h_{FE}$ as a function of total dose and annealing time for different ion irradiated SiGe HBTs is shown in Figure 7.59. At room temperature the recovery in $h_{FE}$ is around 31% for Li$^{3+}$ and 11% for B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs respectively. The recovery in peak $h_{FE}$ is 100% for ion irradiated SiGe HBTs.
The peak $h_{FE}$ drastically increases at higher $I_C$ but not retraces the pre-rad $h_{FE}$ curve. In case of Li$^{3+}$ ion irradiated SiGe HBT, after 100s of annealing time suddenly the stress induced degradation is observed but again recovery in peak $h_{FE}$ continues.

### 7.3.1.3. Output Characteristics

The recovery of $I_{CSat}$ after electrical annealing for ion irradiated SiGe HBTs are shown in Figures 7.60 to 7.62. It can be seen from the figure that the recovery of $I_{CSat}$ is around 100% for ion irradiated SiGe HBTs. The $I_C$ is extracted at $V_{CE} = 1$ V from output characteristics and plotted versus total dose and annealing time and is shown in Figure 7.63. The recovery in $I_{CSat}$ is around 122%, 126% and 126% for Li$^{3+}$, B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs respectively.

![Figure 7.60: Output characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT as a function of annealing time.](image1)

![Figure 7.61: Output characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT as a function of annealing time.](image2)

![Figure 7.62: Output characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT showing recovery in $I_{CSat}$ with annealing time.](image3)

![Figure 7.63: The collector saturation current as a function of total dose and annealing time for gamma and ion irradiated SiGe HBT.](image4)
7.3.2. 200 GHz SiGe HBT Results

The recovery in the electrical characteristics of ion irradiated 200 GHz SiGe HBT after electrical annealing is presented in this section. The ion irradiated SiGe HBTs results are compared with the electrical annealing results. The test configuration and the bias conditions are mentioned in section 2.9.

7.3.2.1. Forward Gummel characteristics

The recovery in $I_B$ with annealing time for different ion irradiated SiGe HBTs are shown in Figures 7.64 to 7.66. It is evident from the figures that after 1 ms of electrical annealing there is significant recovery in $I_B$ and the $I_B$ is not completely recovered even after annealing for more than 1s. Therefore few defects remain in SiGe HBT structure which contributes to the G/R process. The $I_B$ extracted at $V_{BE} = 0.65$ V is plotted versus total dose and annealing time for irradiated and annealed SiGe HBTs and is shown in Figure 7.67. It can be seen from the figure that the recovery in $I_B$ is around 100%, 99% and 50% for Li$^{3+}$, B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs.

![Figure 7.64: Forward mode Gummel characteristics of $^{60}$Co gamma irradiated SiGe HBT as a function of annealing time.](image1)

![Figure 7.65: Forward mode Gummel characteristics of 75 MeV B$^{7+}$ ion irradiated SiGe HBT as a function of annealing time.](image2)
7.3.2.2. Current gain

The recovery in $h_{FE}$ for ion irradiated SiGe HBTs after electrical annealing are shown in Figures 7.68 to 7.70. It is evident from the figures that as the annealing time increases $h_{FE}$ increases. After electrical annealing the recovery in $h_{FE}$ is not complete for ion irradiated SiGe HBT. The recovery in $h_{FE}$ is around 70%, 85% and 50% for Li$^{3+}$, B$^{5+}$ and O$^{7+}$ ion irradiated SiGe HBTs.
7.3.2.3. Output Characteristics

The recovery of $I_{CSat}$ after electrical annealing for ion irradiated SiGe HBTs are shown in Figures 7.72 to 7.74. It is evident from the figures that the $I_{CSat}$ slightly increases with increase in annealing time. A small increase in $I_{CSat}$ can be observed for Li$^{3+}$ and B$^{5+}$ ion irradiated SiGe HBT when compared to O$^{7+}$ ion irradiated SiGe HBT. The defects in the collector region are annealed after electrical annealing and therefore the $I_{CSat}$ increases.

Figure 7.70: The recovery in current gain as a function of annealing time for 100 MeV O$^{7+}$ ion irradiated SiGe HBT.

Figure 7.71: The peak current gain as a function of total dose and annealing time for $^{60}$Co gamma and different ion irradiated SiGe HBTs.

Figure 7.72: Output characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT as a function of annealing time.

Figure 7.73: Output characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT as a function of annealing time.
From the above annealing studies it is evident that recovery of electrical characteristics of irradiated SiGe HBT is possible by thermal annealing and electrical annealing. There is significant recovery of electrical characteristics in the initial stage and at higher annealing time the annealing process is similar to thermal annealing.

7.4. Conclusions

The following conclusions are drawn from the results of annealing studies that are presented in this chapter. The results are summarised as follows:

- The electrical characteristics such as forward mode Gummel characteristics, excess base current, current gain and output characteristics were studied after thermal and electrical annealing. The electrical characteristics of irradiated SiGe HBTs are recovered after thermal annealing and electrical annealing.

- The room temperature annealing was significant in case of 50 GHz SiGe HBT when compared to 200 GHz SiGe HBTs.

- In isochronal annealing, complete recovery in the electrical characteristics of irradiated SiGe HBT is not observed even after annealing until 400°C. In particular, the recovery in the electrical characteristics of ion irradiated SiGe HBT is incomplete.

- The electrical annealing was more effective than isochronal annealing in recovering the important characteristics of irradiated SiGe HBTs. The electrical annealing technique takes less time when compared to isochronal annealing and defects are almost annealed in short duration of time.