TEMPERATURE SIMULATION OF COMMERCIAL 2N6688 BJT FOR SPACE AND RADIATION RICH ENVIRONMENTS.

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Abstract: This study investigates the radiation response of silicon-based <111> NPN bipolar junction transistors (BJTs) (2N6688) under irradiation with 110 MeV Si^{8+} heavy ions for applications in space and radiation-rich environments. The devices, produced by Bharath Electronics Limited (BEL), were irradiated at the Tandem accelerator facility at the Inter University Accelerator Centre, New Delhi. Fluences ranged from 5×10^9 to 1×10^{13} ions/cm², with the beam current maintained at 1 pnA to minimize thermal effects during irradiation. Simulations using SRIM and TRIM showed a projected ion range of 39.62 µm, with energy deposition predominantly due to electronic energy loss (LET = 10.2177 MeV/(mg/cm²)). Experimental results revealed a significant increase in base current (I_B) with radiation fluence, as characterized at different temperatures (27°C, 50°C, and 100°C). At a fluence of 1×10^{12} ions/cm², I_B increased from 48.66 µA (unirradiated) to 1165.66 µA at 27°C, from 147 µA to 1755 µA at 50°C, and from 317.66 µA to 1885.33 µA at 100°C. These trends indicate a monotonic increase in I_B with fluence and temperature, suggesting a combination of total ionizing dose (TID) effects and displacement damage (NIEL) as key contributors to device degradation. The findings highlight the sensitivity of BJTs to radiation, emphasizing the importance of understanding radiation-induced degradation mechanisms for the design of robust devices in high-radiation environments

Introduction

The advancement of electronic devices for use in radiation-prone environments, such as space exploration, nuclear reactors, and high-energy physics experiments, necessitates a thorough understanding of radiation-induced effects on semiconductor components. Among these, the 2N3055 transistor, a widely used bipolar junction transistor, has garnered significant attention due to its robustness and versatility in power applications. However, its performance under ionizing radiation remains a critical factor for reliability and functionality[1–3].

While significant progress has been made in understanding the effects of radiation on semiconductor devices, several gaps remain in the literature regarding the behavior of bipolar junction transistors under high-energy ion irradiation. The 2N6688 transistor, a widely used power transistor, has been relatively underexplored in this context. Prior studies primarily focus on radiation effects in advanced CMOS technologies and other emerging semiconductor devices, leaving a paucity of data on the reliability and performance degradation of conventional power transistors like the 2N6688[1,4,5].

The silicon-based <111> NPN power transistor (2N6688), manufactured by Bharath Electronics Limited (BEL), is a widely used component known for its high power gain and

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amplification. However, its performance in radiation-intense environments remains a topic of considerable interest. Ionizing radiation can induce defects in the silicon lattice, alter the device's electrical properties, and lead to degradation over time. Two primary effects are commonly analyzed in this context: Total Ionizing Dose (TID) and Non-Ionizing Energy Loss (NIEL). These effects influence carrier mobility, base leakage currents, and overall device behavior, particularly at elevated temperatures and fluences[5–8].

This study investigates the radiation response of 2N6688 BJTs irradiated with 110 MeV Si^{8+} heavy ions at varying fluences. The experimental work utilizes advanced facilities, including the Tandem accelerator at the Inter University Accelerator Centre (IUAC) in New Delhi, to simulate space-like radiation conditions. Simulations using SRIM and TRIM software were employed to model energy deposition mechanisms, providing insights into electronic and nuclear energy losses.

The paper focuses on characterizing the changes in base current (I_B) as a function of radiation fluence and temperature. Statistical analysis of pre- and post-irradiation data highlights the significant effects of ionizing radiation, with a particular emphasis on its temperature dependence. These findings contribute to a deeper understanding of the challenges and design considerations for deploying BJTs in environments subject to high radiation exposure.

Experimental Methods

The device analyzed is a silicon <111> NPN power transistor (2N6688) produced by Bharath Electronics Limited (BEL), India. The device's power gain and amplification are both high. The thickness of insulating silicon dioxide (SiO2) is approximately 5 micrometres. The electroder (epilayer 2) is P 34.79 µm / 26.63 Ω-cm, the base is B (epilayer 1) 32.37 µm / 2.82 Ω-cm, and the substrate (collector) is Sb 525 µm / 0.02 Ω-cm. The 15 UD, 16 MV Tandem accelerator facility [13], which is accessible at the Inter University Accelerator Centre (IUAC), New Delhi, India, is used to irradiate the transistor with a 110 MeV Si8+ ion beam. In an MS beam line with a typical pressure of 13 × 10-9 torr the irradiation is carried out. By mounting the semi-processed decapped transistors on a vertical metal ladder, the transistor may be directly exposed to the beam, preventing energy loss in the protective metal cap. From 5 × 109 to 1 × 1013 ions/cm2, the fluence is changed. The beam current is kept at 1 pnA [1 pnA (particle nanoampere) = 6.25 × 108 particles/cm2/s] to prevent the heating impact. This is tested using a Faraday cup at a considerable distance prior to the actual target assembly[4,9].

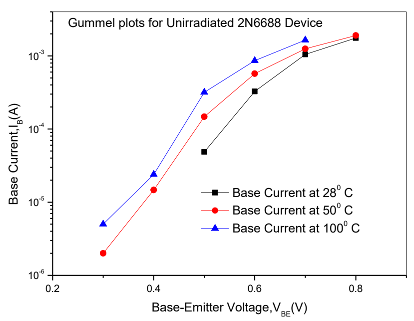
SRIM Data

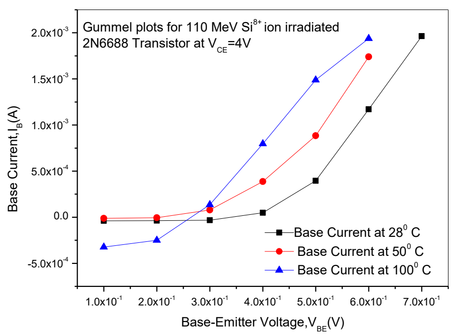
Table 1 SRIM simulated results for 110 MeV Si ion irradiation on silicon target.

Parameter	**Value**
R (µm)	39.62
S_e (MeV cm^2/mg)	10.21

S_n (MeV cm^2/mg)	7.698×10^{-03}			
NIEL up to R (MeV cm^2/g)	42.67			
Fluence (ions/cm^2)	**5×10^{9}**	**1×10^{11}**	**1×10^{12}**	**1×10^{13}**
TID (rad)	0.8174	16.348	163.482	1634.82
D_d (rad)	3143.4	68268	6.8268×10^{5}	6.8268×10^{6}

Table 1 depicts that the nuclear energy loss of 110 MeV Si^{8+} ion is much smaller than the electronic energy loss (3 orders of magnitude, Table. 1) in a Si-target material due to smaller elastic scattering cross-section. Therefore the maximum energy deposited to the material is expected mainly due to the electronic energy loss during its passage through the Si-material. The device suffers non-uniform irradiation effects as the projected ion range (39.46 µm) is lower than the device thickness (~ 600 µm) and it is expected to implant at base-collector region. The damage caused due to the linear energy transfer [LET = $S_e + S_n$ ~ 10.2177 MeV/(mg/cm^2)] in the Si target is obtained using TRIM calculations. LET dependent TID and NIEL dependent D_d are tabulated in table 1[4,10–13].





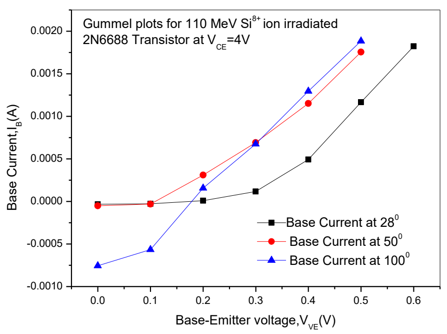


Figure. 1 show the pre-irradiation, 1×10^{11} and 1×10^{12} ions/cm^2 LDR irradiated base currents for NPN BJTs over the specified temperature range (27^0, 50^{0}C 100^{0}C).

The experimental results demonstrate a significant increase in I_B with increasing fluence and temperature. For example, at a fluence of 1×10^{12} ions/cm², the base current increased from

48.66 μA (unirradiated) to 1165.66 μA at 27°C, from 147 μA to 1755 μA at 50°C, and from 317.66 μA to 1885.33 μA at 100°C. This monotonic increase in I_B reflects the cumulative impact of radiation-induced defects in the silicon lattice, which enhance carrier recombination and reduce the base dopant concentration[3,5,7,12,14]. Figure 1 illustrates the variation of I_B as a function of temperature for both unirradiated and irradiated BJTs. The results indicate that the devices exhibit similar trends, with I_B increasing consistently across the temperature range for all fluence levels.

Impact of Total Ionizing Dose and Displacement Damage

The observed increase in I_B can be attributed to both Total Ionizing Dose (TID) and Non-Ionizing Energy Loss (NIEL) effects. TID effects dominate due to the high electronic energy loss (LET = 10.2177 MeV/(mg/cm²)) compared to nuclear energy loss (Sn = 7.698×10^{-3} MeV cm²/mg). TID leads to the generation of oxide-trapped charges and interface states, which exacerbate leakage currents. On the other hand, NIEL-induced displacement damage results in defect clusters in the silicon substrate, further amplifying recombination activity.

Table 2 summarizes the statistical values of IB for different fluence levels and temperatures, highlighting the temperature dependence of radiation effects. The exponential dependence of IB on temperature aligns with the Boltzmann factor, as modeled by Equation (1):

$$\Delta I_B = I_{SE} \exp\left(\frac{-qV_{BE}}{nkT}\right)$$

Here, I_{SE} represents the radiation-induced change in low-injection base leakage current, n is the ideality factor, q is the electronic charge, k is Boltzmann's constant, and T is the junction[1,2,9].

Previous studies on BJTs irradiated with heavy ions have indicated that TID effects significantly impact electrical characteristics, with displacement damage playing a secondary role. The results of this study corroborate these findings but also emphasize the cumulative effect of both mechanisms, particularly at higher fluences and elevated temperatures. The increase in I_B with radiation exposure and temperature underscores the need for improved radiation-hardening techniques for BJTs used in high-radiation environments. Strategies such as dopant engineering, silicon-on-insulator (SOI) technology, and advanced passivation layers could mitigate the effects of radiation and enhance device reliability.

It can be observed that both the pre- and post-irradiated PNP BJTs show similar trends, i.e., a monotonic increase in base current with increasing temperature. Similar trend can be observed for the pre- and post-irradiated NPN BJTs. Most of the earlier studies have indicated that the impact of displacement damage is marginal compaed with the total dose effect. However, it has been shown that total – dose irradiation may indirectly affect the silicon substrate by reducing the active p-type base dopant concentration, may lead to an increase in base current as shown in figure 2[15,16].

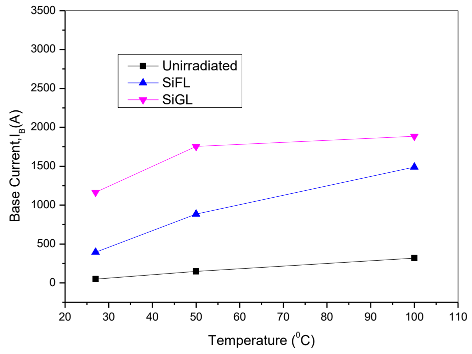


Figure. 2 show the base currents at |VBE| = 0.5 V as a function of temperature for un-irradiated and irradiated NPN BJTs respectively.

Table 2: Variation in base current, I_B of BJT tested for different fluence of 110 MeV Si^{8+} ions at specified temperature range (27^0, 50^0C 100^0C)

Temperature ^{0}C	**Un irradiated**	**I_B(A) 5×10^9**	**1×10^{11}**	**1×10^{12}**
27	**48.66**	**126.666**	**394.66**	**1165.66**
50	**147**	**161**	**884**	**1755**
100	**317.66**	**3200**	**1488.33**	**1885.333**

Conclusions

This study presents a comprehensive investigation into the radiation response of silicon-based <111> NPN bipolar junction transistors (BJTs) (2N6688) under exposure to 110 MeV Si^{8+} heavy ions, with a focus on their suitability for space and other radiation-rich environments. The experimental analysis, supported by simulations using SRIM and TRIM, provided critical insights into the degradation mechanisms induced by varying ion fluences and temperatures. Key findings include – A significant increase in base current (I_B) was observed across all tested fluence levels and temperatures. For instance, at a fluence of 1×10^{12} ions/cm², I_B increased from 48.66 μA (unirradiated) to 1165.66 μA at 27°C, 1755 μA at 50°C, and 1885.33 μA at 100°C. The temperature dependence of I_B demonstrated an exponential trend, consistent with models incorporating the Boltzmann factor, emphasizing the role of junction temperature in radiation-induced degradation. Total Ionizing Dose (TID) effects emerged as the primary mechanism for degradation, driven by electronic energy loss (LET = 10.2177 MeV/(mg/cm²)). These effects resulted in oxide-trapped charges and interface states, which elevated leakage currents. Non-Ionizing Energy Loss (NIEL) contributed through displacement damage, forming defect clusters in the silicon substrate and further amplifying carrier recombination. Both pre- and post-irradiation tests revealed a monotonic increase in I_B with fluence and temperature, indicating a cumulative effect of radiation exposure. The projected ion range (39.62 μm) confirmed implantation near the base-collector region, amplifying degradation at the critical junctions. The study highlights the vulnerability of BJTs to radiation-induced degradation, especially at elevated temperatures and higher fluence levels. These findings underscore the importance of incorporating robust radiation-hardening techniques to enhance the reliability of BJTs in extreme environments. The findings open avenues for further exploration, including: Investigating the long-term stability of irradiated BJTs under operational conditions. Extending the study to other device geometries and materials, such as wide-bandgap semiconductors, to enhance radiation tolerance. Developing predictive models for the behavior of BJTs under combined TID and NIEL effects, considering real-time environmental conditions such as temperature fluctuations and multi-particle radiation.

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