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Investigation of Electrical Properties in Silicon BJTs With Varying Base Widths Under Heavy Ion Irradiation

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Abstract

Objective: This study explores the radiation-induced degradation of two indigenous silicon <111> npn power transistors, 2N3055 and 2N6688, under heavy ion irradiation to evaluate their performance in radiation-rich environments. **Methods:** The transistors were exposed to ions ranging from 50 MeV Li^{3+} to 120 MeV Ni^{+}, with atomic numbers (Z) between 3 and 28 and a fluence of 1×10^{11} ions/cm^2. The effects of ion mass, nuclear stopping power, and implantation regions on displacement damage and current gain (β) degradation were systematically analysed. Displacement damage increased non-linearly with Z, from 1,296.8 displacements/ion for Li to 37,889.17 displacements/ion for Ni. **Findings:** Heavy ions with higher stopping powers caused significant lattice disruptions, particularly in critical regions such as the emitter. Electrical measurements revealed substantial reductions in forward saturation current (I_{Sat}), with a pronounced impact from lighter ions (Li, B) compared to heavier ones (Si, Ni). Normalized reciprocal current gain ($1/\beta$) increased sharply with Z, with the 2N3055 showing sixfold degradation, while the 2N6688 exhibited up to 300% lower degradation, demonstrating superior radiation tolerance due to its structural advantages. Lighter ions implanted deeper in the collector region caused minimal damage, whereas heavier ions affected the emitter and base, leading to severe degradation**.** **Novelty:** The findings of this work underscore the significant influence of high-Z ions on BJT performance and offer critical insights for designing radiation-hardened electronics for space and nuclear applications. This study also provides a foundation for developing theoretical models and indigenous device designs to enhance the radiation resilience of BJTs.
PACS Codes - **61.80.-x** – Physical radiation effects, radiation damage, **61.82-Fk** – Radiation effects on semiconductors, **85.30.De** – Semiconductor-device

characterization, design, and modeling, **85.30.-z** – Semiconductor devices, **61.82.-d** – Radiation effects on specific materials.

Keywords: Bipolar Junction Transistors (BJTs); Ion Irradiation Effects; Radiation-Induced Damage; Current Gain Degradation; Heavy-Ion Radiation; Nuclear Stopping Power; Semiconductor Device Reliability; Radiation-Hardened Electronics; Space and Nuclear Applications

1 Introduction

High-energy particle accelerators, space missions, nuclear reactors, and many other applications in radiation-rich environments depend on semiconductor devices. Because of their high efficiency and current gain, silicon-based bipolar junction transistors (BJTs) are essential components for power control and amplification [1,2]. However, by causing displacement damage and ionization effects, high-energy particles like heavy ions can seriously degrade BJTs, changing electrical properties including gain, leakage current, and breakdown voltage [3,4]. Understanding the specific impact of ion species, energies, and structural changes in BJTs under heavy ion irradiation is still difficult, despite research using non-ionizing energy loss (NIEL) models providing insight into the damage mechanisms [5,6].

Current Research and Gaps: Current studies demonstrate how ion energy, mass, and device design elements like resistivity and base width affect BJT performance deterioration. It has been demonstrated that structural variations in BJTs, such as emitter thickness and base doping concentrations, have a major impact on radiation tolerance [2,7,8]. For example, low-energy ions mostly harm the emitter-base junction, whereas higher-energy ions tend to enter deeper layers and destroy important areas like the base or collector. There is a noticeable lack of experimental data on domestic BJTs, nevertheless, as these research frequently concentrate concentrates on theoretical models or imported commercial BJTs [9–11]. Furthermore, a comprehensive assessment of structural characteristics like base width and their relationship to radiation resistance is still lacking, despite some attempts to evaluate damage profiles across various ion species [12].

Limitations of Current Methods: Despite improvements in testing and modeling radiation-induced damage in BJTs, several restrictions still exist. The function of particular structural characteristics, such as base width, in reducing radiation damage is not adequately covered in many much research. Little research has been done to compare BJTs with different designs under the same irradiation circumstances. The majority of experimental data focuses focus on expensive, imported devices, which limits the findings' practical relevance to transistors made locally [5,13,14].

Suggested Contribution: This work aims to fill these gaps by methodically examining how heavy ion irradiation affects two native silicon <111> npn BJTs with different base widths, 2N3055 and 2N6688. The study assesses the effects of ion-induced displacement damage on electrical parameters such as leakage current, current gain (β), and forward saturation current (ΔIsat). In addition to using actual observations and SRIM (Stopping and Range of Ions in Matter) simulations, we examine how implantation locations, ion mass, and nuclear stopping power affect device performance. To get insight into the design of radiation-hardened circuits, compare the radiation tolerance of BJTs with narrow and broad base widths. Establish a basis for creating theoretical models used to forecast BJT performance in the presence of radiation.

To illustrate the developments and constraints in the subject,Table 1 provides a comparative overview of earlier research. This puts the work's innovative contributions in perspective.

Table 1. An overview of previous research that compares and contrasts novel contributions

Reference	Ion Species/Energy	Device Type	Parameters Studies	Limitations
Wu et al. (2024)	Si ions, 50-120 MeV	SiC MOSFETs	Displacement damage, gain degradation	Limited to SiC devices; no comparison with silicon BJTs
Tonigan et al. (2018)	Protons, 250 MeV	PNP BJTs	Gain degradation	Focused on imported BJTs; lacked structural variation analysis
Niskanen et al. (2023)	Proton irradiation	SiC BJTs	Reliability under radiation	No data on base width effects
Vinayakprasanna et al. (2023)	Different particles radiation	Bipolar transistors	Reliability under radiation	General particle focus; lacks high-Z heavy ion-specific analysis
Tamana Baba et al. (2024)	General review	SiC MOSFETs	Radiation-induced degradation	Focused on SiC materials; lacks details for silicon BJTs
Zhang et al. (2023)	Heavy ions, TCAD simulation	SiGe Heterojunction BJTs	Single Event Effects	Simulation-focused, limited real-world validation
Ren et al. (2024)	Radiation effects overview	Microelectronic devices	Damage effects and protection techniques	General overview; lacks specific experimental validations
This Work	Heavy ions, 50-120 MeV	2N3055, 2N6688	Gain, leakage current, ΔIsat	Focuses on indigenous BJTs with detailed structural comparisons

This work fills research gaps and offers useful design insights for radiation-hardened electronics used in nuclear and space applications by concentrating on domestic BJTs. Optimized designs are made possible by the comparative study of the 2N3055 and 2N6688 transistors, which clarifies the function of base width and doping concentration in reducing radiation-induced damage.

2 Methodology

The effects of radiation on the electrical properties of commercial n-p-n BJTs, namely the 2N3055 and 2N6688 versions produced by BEL in Bangalore, India, were investigated. To ensure repeatability, four devices of each type—all from the same production batch—were subjected to every ion. All measurements were then repeated.

Table 2. Specifications of 2N 3055 and 2N 6688

Device Code	2N 3055	2N 6688	Region
Structure	<111 > P/N/N+	< 111 > N-/N/N+	Collector
Doping Substrate	Sb/525 μm / 0.01 – 0.02 Ω – cm	Sb/525 μm / 0.01 – 0.02 Ω - cm	
Dopants/Thickness μm / Electrical Resistivity Ω-cm	B* (epilayer1) 14.96 μm / 5.930 Ω-cm	P** (epilayer1) 32.370μm / 2.820-Ω cm	Base
	P** (epilayer2) 22.28 μm / 14.790 Ω-cm	p** (epilayer2) 34.970μm / 26.63 Ω-cm	Emitter
Application	Power Switching	Power switching / Amplification	

*B-boron and **P-phosphorus

(i) 50 MeV Li^{3+}, (ii) 60 MeV B^{+}, (iii) 108 MeV O^{+}, (iv) 110 MeV Si^{+}, and (v) 120 MeV Ni^{+} ions were used to irradiate these transistors. Every irradiation experiment was carried out in New Delhi at the Inter University Accelerator Center (IUAC). Keithley 2400 Source Meter Units (SMUs) with computer interfaces were used to measure the electrical characteristics of both irradiated and unirradiated BJTs. The output I_C-V_{CE} characteristic curves were utilized to extract the collector saturation current I_{Csat} at the fluence chosen, and the forward current gain was measured as a function of ion fluence[15].

2.1 SRIM Calculations

The SRIM (Stopping and Range of Ions in Matter) tool is critical in analyzing degradation effects on BJTs under ion irradiation, as it calculates parameters such as ion range R, electronic energy loss Se, nuclear energy loss Sn, and displacements per ion. SRIM simulations reveal that nuclear energy loss Sn is substantially greater, often four to five orders of magnitude higher than Se, making nuclear interactions the dominant factor in BJT degradation, particularly in the sensitive emitter and collector regions[(9,16)].

Ion range and stopping power variations also show how different ions affect BJT regions differently, such as Ni ions embedding in the emitter and lighter ions like B and O reaching deeper into the collector. SRIM's ability to model these nuanced interactions is particularly valuable for assessing the resilience of semiconductor devices under heavy-ion conditions, as demonstrated in recent studies.

The PySRIM extension of SRIM further enhances this research by automating calculations and integrating comprehensive data analysis tools, which facilitates evaluations of displacement-per-atom (DPA) values and cumulative dose impacts on BJT performance[(9)]. Research applying PySRIM has shown its effectiveness in simulating and predicting degradation under varied ion fluences and energies, illustrating the tool's practical importance in semiconductor studies and radiation resistance research[(5)].

SRIM simulations were used to analyze degradation effects on BJTs with varying base widths due to irradiation, as detailed in Table 1. Calculations included the ion range R, electronic energy loss Se, nuclear energy loss Sn, and average displacements per ion. Results indicate that Sn is four to five orders of magnitude greater than Se, emphasizing the role of nuclear energy loss in device degradation over electronic excitations. For each ion, average displacements increase with atomic number Z as R decreases, showing that ions of different energies implant at different device regions. Ni ions, for instance, embed are embedded in the emitter, Si ions reach the base, and B and O ions penetrate to the collector regions, while Li ions embed in the substrate of the collector.

Figure 2 illustrates current degradation from ion irradiation, revealing that damage in the emitter region directly reduces output current gain. Additionally, Figure 3 shows that total dose influences degradation, as gain reduction is largely unaffected by ion type. This effect may relate to the npn device structure, where the n-type emitter recombines with the incoming ions' positive charges, causing gain degradation.

Table 3. Impacts of differences in ion species, mass, energy, energy loss methods, range, damage caused by each ion, and implantation of each ion in the corresponding devices on the BJT devices

Ion	Z	Energy (MeV)	Se	Sn × 10^4	Range, R (μm)	Average displace-ments /ion	Region of ion gets implanted in each transistor	
			(MeV cm^2/mg)				2N 3055	2N 6688
Li	3	50	0.408	2.293	310.24	1296.8	Collector	Collector
	4	60	1.422	7.89	116.34	2220.2	Collector	Collector
O	8	108	2.948	16.21	106.6	4549.7	Collector	Collector
Si	14	110	10.21	76.98	39.62	9925.7	Base	Base
Ni	28	120	31.39	501	22.93	37889.17	Emitter	Emitter

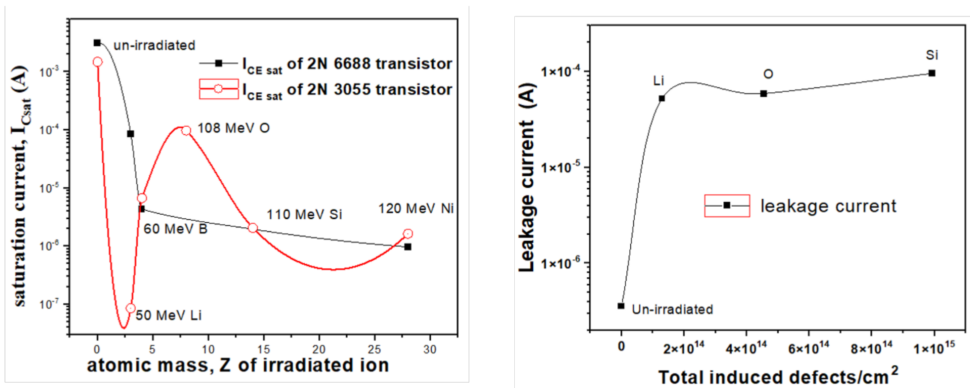
The table illustrates how non-ionizing energy loss, primarily due to nuclear scattering, generates displacement damage in the emitter, base, and collector regions, subsequently reducing the current gain of the device. The degree of current gain reduction increases with the average displacements per ion (as shown in column 7 of Table 3). Figure 2 parts (**a**) and (**b**) indicate that transistors with a narrow base width exhibit greater vulnerability and higher degradation levels compared to those with a wider base width, such as the 2N 6688 transistor model. The decrease in saturation current alongside an increase in leakage current may also contribute significantly to the observed decline in current gain.

This table (Table 3) summarizes the effects on bipolar junction transistors (BJTs) when subjected to different ion species with varying atomic numbers (Z), masses, and energies. The table details the specific energy loss mechanisms for each ion – namely, the electronic stopping power (S_e) and nuclear stopping power (S_n), given in (10^4) MeV·cm^2/mg, as well as the range (R) in micrometers and the average number of displacements per ion within the BJT materials. The region of each ion's implantation within each BJT model (2N 3055 and 2N 6688) is also highlighted.

For lower-energy, lighter ions such as lithium (Li, Z=3, 50 MeV) and boron (B, Z=4, 60 MeV) penetrate deeply into the collector region of both transistors due to their extended range and moderate displacement per ion. Conversely, heavier ions like nickel (Ni, Z=28, 120 MeV) exhibit a high nuclear energy loss (S_n = 501 times 10^4), resulting in significant displacement damage within the emitter region. These high-energy, high-mass ions generally have shorter ranges but cause a much greater number of displacements per ion, with Ni creating nearly 38,889 displacements per ion in the emitter, leading to notable degradation in device performance.

Additionally, silicon ions (Si, Z=14, 110 MeV) primarily affect the base region, while oxygen ions (O, Z=8, 108 MeV) target the collector. These variations demonstrate how the base width and specific region targeted by each ion correlate with the observed degradation effects, including current gain reduction, increased leakage, and saturation current changes, as detailed in the earlier discussions.

3 Results and Discussions



(a) (b)

Fig 1. (a) Variation of I_{CEsat} for 2N 6688 and 2N 3055 transistors at a fluenceof 1×10^{11} ions/cm^2 as a function of mass number of irradiating ion (b) 2N 3055 transistor's leakage current is equal to the reverse breakdown voltage divided by the total induced defects, which is equal to the fluence of 1×10^{11} ions/cm^2 for each irradiation ion (Total induced defects = fluence $\times$ defects created in silicon per ion)

The graph illustrates the saturation current (I_{Csat}) variation in 2N 3055 and 2N 6688 transistors after irradiation with ions of different atomic masses (Z). The black and red curves show the (I_{Csat}) values for the 2N 6688 and 2N 3055 transistors, respectively. The y-axis is plotted on a logarithmic scale, representing the saturation current in amperes, while the x-axis shows the atomic mass of the irradiated ions.

Key observations from the graph are, that as the atomic mass of the ion increases, both transistors exhibit a significant drop in I_{Csat}, indicating that heavier ions induce greater degradation in saturation current. The 2N 3055 transistor (dotted red line) experiences a more pronounced drop in I_{Csat} compared to the 2N 6688, particularly at lower atomic masses. This suggests that the 2N 3055 transistor, with its narrower base width, is more susceptible to ion-induced damage. The lower atomic mass ions (50 MeV Li and 60 MeV B) cause a steeper initial drop in I_{Csat} for the 2N 3055 than for the 2N 6688. For the medium atomic mass ions (108 MeV O and 110 MeV Si), the difference between the two transistors' responses becomes less pronounced, but both continue to show reduced saturation current. The heaviest ion, 120 MeV Ni, shows the lowest I_{Csat} for both transistors, highlighting its significant impact on the emitter region.

This graph emphasizes the vulnerability of transistors with narrower base widths to displacement damage, as seen in the 2N 3055 model. It also illustrates the cumulative effect of nuclear energy loss, where ions with higher atomic mass produce greater displacement per ion, directly impacting the device's electrical characteristics. This behaviour behavior is consistent with findings that nuclear scattering and resultant lattice displacement are primary contributors to BJT degradation in radiation-rich environments.

This graph also depicts the relationship between leakage current and the total induced defects per cm^2 for a transistor exposed to different ions. The x-axis shows the total induced defects per square centimetrecentimeter, while the y-axis represents the leakage current, both on logarithmic scales.

As the total number of induced defects per cm^2 increases, the leakage current also rises, suggesting a direct correlation between defect density and leakage current. The un-irradiated transistor has the lowest leakage current, and exposure to ions results in progressively higher leakage currents.

The Li-irradiated sample shows an initial increase in leakage current at lower defect densities, but the current levels off quickly, indicating moderate sensitivity to induced defects. The O-irradiated transistor displays a higher leakage current than Li at a similar defect density, showing that oxygen ions induce a stronger degradation effect. The highest leakage current is observed with silicon irradiation, indicating that it produces more significant damage to the transistor's junction, resulting in substantial leakage current even at higher defect densities. As defect density increases, the leakage current begins to plateau, suggesting that beyond a certain defect threshold, further increases in induced defects result in diminishing returns in leakage current growth. This data underscores the importance of managing defect density to maintain leakage current levels, particularly in radiation-rich environments. Heavier ions like Si cause more extensive damage, which could necessitate design considerations for transistors intended for high-radiation applications to minimize leakage current and ensure device longevity.

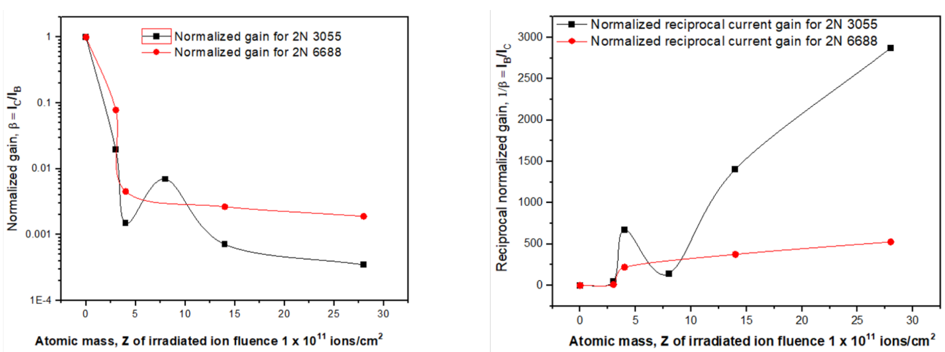
Commercial silicon npn power transistors, 2N 3055 and 2N 6688, demonstrate sensitivity to ionizing radiation. Exposure to 50 MeV Li ions causes significant degradation in their electrical characteristics, notably a reduction in the forward current gain (β). The transistor with a larger base width (2N 6688) exhibits greater resilience compared to the smaller base width transistor (2N 3055), highlighting the critical role of base width in radiation tolerance.

The multi-phonon recombination processes that deteriorate the forward current gain are responsible for the rise in base current. Defect identification is based on their fingerprints, including activation energy, annealing temperature, and capture cross-section, in comparison with those reported in the literature. For the smaller base width transistor (2N 3055), only one deep-level defect, identified as an A-centre (oxygen-vacancy complex), is observed post-irradiation. In contrast, the larger base width transistor (2N 6688) reveals two defect levels, corresponding to divacancy and boron-oxygen (B-O) complexes[2].

Irradiation with lithium ions also increases the forward resistance in the collector-emitter region, reducing conductivity. The observed increase in built-in voltage and decrease in doping density suggest suggests the formation of new defects within the emitter-base region. These findings underscore the impact of ionizing radiation on device performance and the importance of material and structural design considerations for improved radiation hardness in power transistors.

Additionally, it has been noted that when fluence increases, I_{Csat} decreasedecreases. The creation of vacancies, interstitials, and displacements brought on by Si ions is the primary cause of the decline in I_{Csat}. These MeV ion-induced defects cause the shift of I_{Csat} and V_{CEsat} by decreasing the minority carrier lifetime and increasing series resistance[15]. The atomic displacement damage due to 110 MeV silicon ion in the semiconductor causes an increase in the collector-emitter saturation voltage V_{CEsat}. The rate of this increase with fluence is roughly the same as that with which gain decreases. Transistors with high breakdown voltages have high resistivity (low doping) in the collector region. At very high bulk damage levels, the resistivity may be changed noticeably, causing changes in V_{CEsat}. Low V_{CEsat} values are necessary for the effective operation of power transistors, particularly switching power transistors. As a result, silicon ion radiation significantly impairs transistor performance in current devices. In the oxide passivation layer, namely the portion of the oxide that covers the emitter-base junction area, ionization is the other primary driver of gain deterioration.

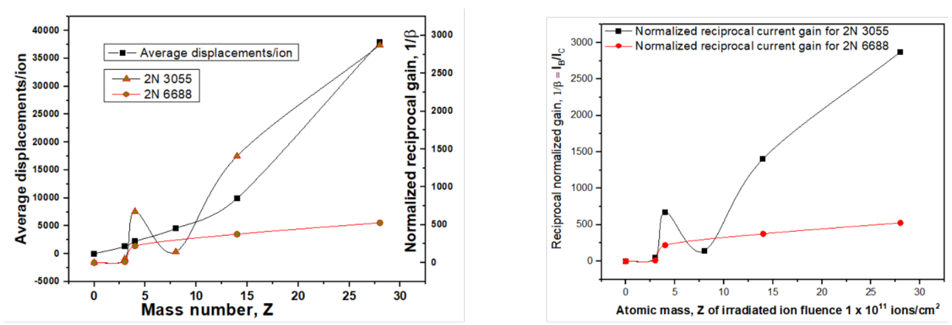
A base reverse bias leakage current (BRBLC) characteristic of the transistor device is obtained with the collector shorted to the ground. It is used to characterize leakage currents in the transistor due to irradiation[7].



(a) (b)

Fig 2. Normalized current gain β versus atomic mass of irradiated ions for 2N 3055 and 2N 6688 transistors for irradiation fluence of 1×10^{11} ions/cm^2

Figure 2 (**a**) gives the displacement of atoms in the BJT material due to ion irradiation is a key factor in the device's performance. The data in the graph show that as the atomic mass (Z) of the irradiated ions increases, the number of average displacements per ion also increases. This can be attributed to the greater energy deposition by heavier ions, which causes more damage to the crystal lattice of the transistor. The comparison between the 2N3055 and 2N6688 transistors shows that the 2N3055 is more vulnerable to displacement damage under similar irradiation conditions. This suggests that 2N3055 may not be ideal for applications where radiation tolerance is a priority, such as in diagnostic X-ray imaging or other environments with high ionizing radiation [17]. Figure 2 (**b**) explores how the current gain (β) of the transistors changes under irradiation. A higher value of $1/\beta$ indicates a loss of current gain (lower β), which typically signifies reduced amplification capacity in the transistor. The graph shows that, as the mass of the irradiated ions increases, both transistors experience a rise in $1/\beta$ (decline in current gain), but the 2N3055 transistor suffers a more significant degradation than the 2N6688. This is a critical factor in understanding the reliability of BJTs when used as radiation sensors. The 2N6688 exhibits less degradation in its performance, which makes it more suitable for environments with high radiation exposure [7]. The data directly ties into the article's objective of investigating how BJTs behave when exposed to diagnostic X-rays. BJTs, though not designed for such conditions, can still be used to sense ionizing radiation. However, as seen from the graphs, the performance degradation varies significantly based on the transistor type and the nature of the irradiating ions. The article emphasizes understanding these effects to improve the use of BJTs as radiation sensors. Based on the graph's findings, when selecting BJTs for use in radiation-prone environments, transistors like the 2N6688, which show less degradation in their current gain and are less affected by ion displacements, might be more suitable than the 2N3055. The ability to understand and predict how BJTs will react under various radiation conditions is important for not only using them as sensors but also for advancing their application in new technologies, including those that rely on radiation effects. The data may also inform future advancements in BJT design to make these devices more radiation-tolerant, which would expand their usability in environments with high levels of ionizing radiation [18].



(a) (b)

Fig 3. Normalized current gain β versus atomic mass of irradiated ions for 2N 3055 and 2N 6688 transistors for irradiation fluence of 1×10^{11} ions/cm^2

Figure 3 (**a**) depicts displacement damage increases with the atomic mass (Z) of the irradiated ions. High-Z ions deposit more energy per collision, causing significant lattice damage in the semiconductor material. The 2N3055 transistors experience higher displacement damage compared to 2N6688, possibly due to differences in material properties, design, or doping concentrations. Figure 3 (**b**) depicts Current gain degradation (β) increases non-linearly with Z, implying a direct relationship between lattice damage and device performance degradation. Steeper Degradation in 2N3055 suggests that 2N3055 transistors are more vulnerable to radiation-induced displacement damage compared to 2N6688. The normalized reciprocal current gain, $1/\beta$ serves as an indirect measure of the extent of damage since lower β values correspond to greater device inefficiencies [2,19].

The 2N6688 transistors show better resistance to radiation-induced degradation, potentially due to superior material properties, higher doping levels, or more robust structural design. The sharper rise in $1/\beta$ for 2N3055 indicates it is less suitable for environments with heavy-ion exposure.

The displacement damage data in Table 2 correlates directly with the trends in Figure 2 **a**, where damage increases non-linearly with Z. Heavy ions like Ni, with higher S_n values and shorter ranges, cause localized damage, as reflected in their steep displacement profiles. Increased displacement damage leads to higher $1/\beta$ values. Ni ions, causing the most severe damage in the emitter region, lead to the most significant degradation in current gain. Light ions (Li, B) result in milder gain degradation, consistent with their lower displacement damage and deeper penetration [7,18,19].

The results highlight the significant effect of heavy ions on the electrical properties of BJTs and support earlier research on ion-induced deterioration. This study, however, distinctively emphasizes the significance of base width in radiation tolerance, providing information on how to optimize the structure of domestic devices. The greater robustness of 2N6688 is demonstrated by a comparative study (Table 4), enhancing design methodologies for applications involving high radiation levels [2].

Table 4. Comparison of BJTs under Radiation Effects: Aspect, Prior Research, Current Research and Contributions

Characteristic	Previous Studies	Current Study	Contributions
Ion Species and Energy	Focused on high-energy ions like protons and carbon ions (50-250 MeV).	Heavy ions (50-120 MeV) with varying atomic masses (Li, B, O, Si, Ni).	Expands scope by exploring heavier ions, showing their impact on different transistor regions.
Device Type	Commercial SiC BJTs and MOS-FETs; imported silicon BJTs.	Indigenous BJTs (2N3055, 2N6688) with different base widths.	Highlights performance of locally manufactured BJTs under radiation.
Parameters Studied	Current gain (β), leakage current, displacement damage.	Current gain (β), leakage current, ICsat, VCEsat.	Broader set of electrical parameters analyzed, revealing critical insights on into radiation effects.
Structural Analysis	Limited or absent focus on base width and doping concentration variations.	Detailed comparison of narrow (2N3055) and wide (2N6688) base width BJTs.	Demonstrates base width's significant role in radiation tolerance.
Comparative Metrics	General comparison between different ion species and energies.	Systematic analysis correlating atomic mass, stopping power, and displacement.	Establishes direct link between ion properties and performance degradation for structural optimization.
Applications	Generalized insights for radiation-hardened electronics.	Focused on space and nuclear environments; potential use as radiation sensors.	Provides practical design recommendations for high-radiation environments using indigenous devices.

4 Conclusions

This study systematically evaluates the radiation-induced degradation of bipolar junction transistors (BJTs), 2N3055 and 2N6688, under ion irradiation with atomic masses (Z) ranging from 3 (Li) to 28 (Ni) and energies from 50 to 120 MeV at a fluence of 1×10^{11} ions/cm2. The following conclusions are drawn based on displacement damage and current gain degradation. The average displacements per ion increased non-linearly with atomic mass (Z), from 1296.8 displacements/ion for Li (Z=3) to 37,889.17 displacements/ion for Ni (Z=28), as shown in Table 3. Heavy ions with higher nuclear stopping powers (Sn) caused significantly more lattice damage, particularly in critical regions such as the emitter for Ni. The normalized reciprocal current gain ($1/\beta$) increased with Z, reflecting a decline in device performance. For example, in Figure 2b, the reciprocal gain for 2N3055 increased from approximately 50 for Li (Z=3) to over 300 for Ni (Z=28), highlighting a sixfold degradation in current gain.

The 2N3055 transistor consistently experienced higher degradation compared to 2N6688, as evident from both displacement and gain loss metrics. The 2N3055 transistor demonstrated lower radiation tolerance, with up to 300% higher displacement damage and $1/\beta$ values compared to 2N6688 under similar conditions. The superior performance of 2N6688 can be attributed to its material and structural properties, which mitigate the effects of lattice damage. Lighter ions (Li, B) with greater penetration ranges are implanted in the collector region, causing minimal damage. Heavier ions (Si, Ni) are implanted in the emitter and base regions, where critical device operations occur, leading to more severe degradation. For instance, Ni ions reduced the emitter region performance, resulting in the highest displacement damage at 37,889.17 displacements/ion. The study highlights the significant impact of high-Z ions, such as Si (Z=14) and Ni (Z=28), on BJTs, causing severe lattice disruptions and pronounced performance degradation. Among the devices tested, 2N6688 outperformed 2N3055, making it a more suitable candidate for applications in high-radiation environments. The findings provide essential design and material insights for improving the radiation hardness of BJTs used in space and nuclear applications.

The degradation of the devices under study is tested for heavy ion radiation response-results may be used for theoretical simulations. Based on these results a BJTs radiation response model may be developed which may be applied for to indigenous devices. This gives major contribution in the field.

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