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Performance Degradation and Defect Analysis of 2N3055 BJT Under High-Energy Lithium-Ion Irradiation

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ABSTRACT
This study examines the impact of 50 MeV lithium ion irradiation on 2N3055 BEL transistors under room temperature conditions. The devices were subjected to ion fluences ranging from 5×10^9 to 1×10^{13} ions/cm^2. SRIM simulations estimated a range (R) of 310.24 µm, with electronic (S_e) and nuclear (S_n) energy losses calculated at 0.408 MeV cm^2 ^2/mg and 2.293×10^{-4} MeV cm^2/mg, respectively. Deep Level Transient Spectroscopy (DLTS) identified defect types such as A-centers (EC–0.17 eV, trap concentration 1.29×10^{14} cm^{-3} and (Bi-Oi) complexes (EC–0.27 eV, trap concentration 4.59×10^{15} cm^{-3}, with capture cross-sections of 2.18×10^{-19} cm^2 and 5.00×10^{-18} cm^2, respectively. Electrical characterization revealed a reduction in forward current gain ($\beta=I_C/I_B$) with increasing fluence, from pristine levels to a notable decline at 1×10^{13} ions/cm^2. Carrier lifetime and effective lifetime diminished to 4.24×10^{-3} s and 4.74×10^{-6} s, respectively. Additionally, Gummel plots and excess base and collector current analyses confirmed performance degradation due to trap-assisted recombination. These findings elucidate the effects of ion-induced defects on transistor operation, contributing to the understanding of silicon device behavior in radiation-prone environments.

Keywords: Lithium ion irradiation, BEL Transistor, SRIM Simulation, DLTS, Gummel Plots

1. 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[1], [2], [3], [4]. Among these, the 2N3055 transistor, a widely used bipolar junction transistor, has garnered significant attention due to its robustness and versatility in power applications[5], [5], [6], [7]. However, its performance under ionizing radiation remains a critical factor for reliability and functionality[8].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 2N3055 transistor, a widely used power transistor, has been relatively underexplored in this context. Prior studies primarily focus on radiation effects in advanced CMOS technologies [9], [10] and other emerging semiconductor devices, leaving a paucity of data on the reliability and performance degradation of conventional power transistors like the 2N3055. Existing literature has addressed the impact of gamma radiation and neutron flux on bipolar transistors[11], but limited work has been conducted on ion irradiation, especially with high-energy ions such as 50 MeV lithium[7]. The mechanisms of defect formation, their spatial distribution, and their specific influence on critical electrical parameters, including gain, carrier lifetime, and doping concentration, are not comprehensively documented. Additionally, most studies emphasize general trends rather than providing quantitative insights into trap densities, activation energies, and capture cross-sections, which are crucial for modeling and predicting device behavior under irradiation[3], [10], [12], [13], [14].This gap necessitates a detailed investigation of ion-induced defects and their correlation with the electrical performance of 2N3055 transistors. A deeper understanding of these interactions is essential for enhancing the design and radiation hardness of silicon-based devices, ensuring their reliability in environments subjected to high-energy radiation[5].Ion irradiation introduces a variety of defects in semiconductor materials, including vacancy-interstitial pairs, dislocation loops, and complex defect centers. These defects degrade the electrical properties of devices by altering carrier dynamics, doping concentrations, and charge trapping phenomena[6]. High-energy ions, such as 50 MeV lithium ions, interact with the silicon lattice through electronic and nuclear energy loss mechanisms, creating both shallow and deep-level defects that influence device performance[6], [9], [15].This study aims to investigate the effects of 50 MeV lithium ion irradiation on 2N3055 transistors. The experimental setup includes irradiation at varying fluence levels, ranging from 5×10^9 to 1×10^{13} ions/cm^2, to evaluate changes in electrical and structural properties. Key analytical techniques, such as Deep Level Transient Spectroscopy (DLTS) and Gummel plot analysis, were employed to characterize defects, quantify their activation energies, and assess their impact on forward current gain, carrier lifetime, and overall device reliability[16], [17].The findings of this study provide valuable insights into the degradation mechanisms of silicon-based transistors under ionizing radiation, paving the way for improved design and application of semiconductor devices in extreme environments.

2. Experimental

The device analyzed is a silicon <111> NPN power transistor (2N3055) 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 micrometers. The electrode (epilayer 2) is P 22.28 µm / 14.790 Ω-cm, the base is B^* (epilayer 1) 14.96 µm / 5.930 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 50 MeV Li^{3+} ion beam. In an MS beam line and GPSC with a typical pressure of 13×10^{-9} and 8×10^{-9} torr the irradiation is carried out. By mounting the semi-processed recapped transistors on a vertical metal ladder, the transistor may be directly exposed to the beam, preventing energy loss in the protective metal cap. From 1×10^{11} to 1×10^{13} ions/cm^2, the fluence is changed. The beam current is kept at 1 pnA [1 pnA (particle nanoampere) = 6.25×10^8 particles/cm^2/s] to prevent the heating impact. This is tested using a Faraday cup at a considerable distance prior to the actual target assembly.

3. Results and Discussions

The effects of 50 MeV lithium ion irradiation on the electrical and defect characteristics of 2N3055 BEL transistors analysis are encompassed through defect formation, carrier dynamics, and electrical performance degradation across varying fluences (5×10^9 to 1×10^{13} ions/cm^2)[5].

3.1 Energy Loss and Defect Formation

Simulations using the SRIM software revealed an electronic energy loss Se, S_n and R are as shown in table 1. These energy losses contributed to the formation of deep-level defects, including A-centers (EC - 0.17 eV) and (Bi-Oi) complexes (EC–0.27 - 0.27 eV), identified using DLTS. The trap concentrations for these defects were quantified as 1.29×10^{14} cm^{-3} and 4.59×10^{15} cm^{-3}, respectively, with corresponding capture cross-sections of 2.18×10^{-19} cm^2 and 5.00×10^{-18} cm^2[18].

Table 1 Details of Ion-Irradiation and beam characteristics.

Device code	Ion and Energy (MeV)	S_e	S_n	Range (µm)	Temperature (K)	Fluence (ions/cm^2)	Current (pnA)	
		(MeVcm^2/mg)						
2N 3055	Li^{3+} & 50	0.408	2.29E – 4	310. 24	300	5E9	0.3	-
						1E11	0.3	-
						1E12	-	3.0
						1E13	-	3.0

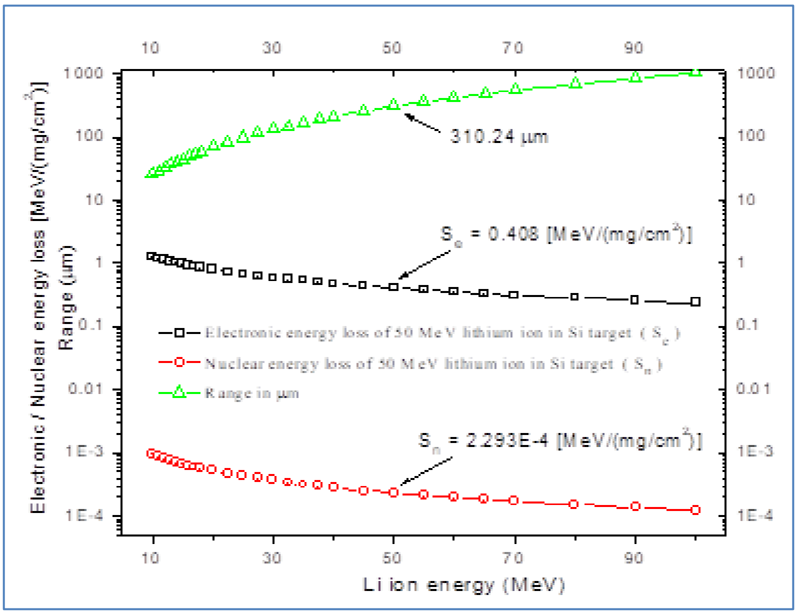

Figure 1 Linear energy transfer and range calculations as a function of energy for lithium ion.

3.2 Electrical Performance Degradation Forward Current Gain ($\beta = I_C/I_B$).

The forward current gain exhibited a significant decline with increasing ion fluence. For pristine devices, the gain was consistent with baseline values; however, at 1×10^{13} ions/cm^2, the gain reduced by over 50%, highlighting the detrimental effects of radiation-induced defects on carrier recombination[6].

Table 2 SRIM simulation results for 50 MeV Li^{3+} ion irradiation on silicon target

Parameter			**Value**	
Range, R (µm)			310.24	
S_e (MeV cm^2/mg)			0.408	
S_n (MeV cm^2/mg)			2.293×10^{-4}	
Displacement energy of Si (eV)			15	
Binding energy of Si (eV)			2	
Surface binding energy of Si (eV)			4.7	
Average Displacements/ion			1296.8	
Average Replacements/ion			99.2	
Average Vacancies/ion			1197.6	
NIEL up to R (MeV cm^2/g)			0.7113	
Fluence (ions/cm^2)	**5×10^9**	**1×10^{11}**	**1×10^{12}**	**1×10^{13}**
TID (rad)	3.27×10^4	6.53×10^5	6.53×10^6	6.53×10^7
D_d (rad)	56.90	1.14×10^3	1.14×10^4	1.14×10^5

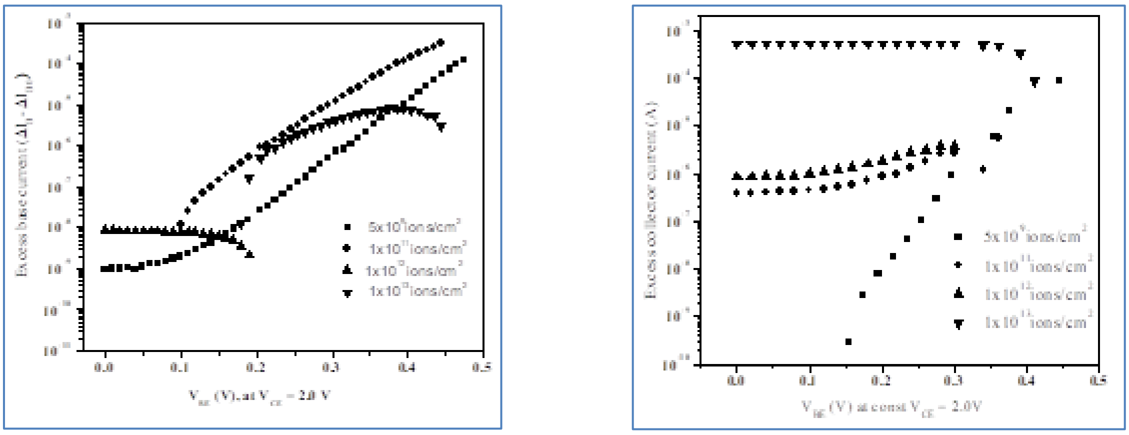

Figure 2 Excess base and excess collector currents (ΔI_B - ΔI_{B0} and ΔI_C - ΔI_{C0} Vs V_{BE}) of 50 MeV Li^{3+} ion irradiated transistor 2N 3055 irradiated at room temperature (The results recorded at V_{CE} = 2.0 V constant).

2.2 Carrier Lifetime and Doping Concentration

Carrier lifetimes were found to decrease sharply with higher fluences, with values dropping to 4.24×10^{-3} s at 1×10^{13} ions/cm². This reduction correlates with increased trap density and recombination activity. Doping concentrations also declined, as observed from the reduction in effective carrier density from 2.52×10^{18} m^{-3} to 3.95×10^{17} m^{-3}, further confirming defect-induced carrier removal[7].

Gummel Plot Analysis

The Gummel plots (I_B and I_C vs. V_{BE}) (Fig 3) showed a clear shift in the device characteristics with increasing fluence. Excess base and collector currents were observed due to defect-assisted recombination, significantly impacting the transistor's output characteristics (Fig 4). The excess base current (ΔI_B) increased by an order of magnitude at higher fluences, confirming enhanced defect interaction with carriers. DLTS spectra (Fig 5) and the obtained data shown in Table 3 revealed the presence of radiation-induced deep-level traps. At a fluence of 1×10^{13} ions/cm², the A-center (EC–0.17 eV) dominated the spectra, with a total trap concentration of 1.29×10^{14} cm^{-3}. Arrhenius plots shown in Fig 6 confirmed the activation energies and capture cross-sections, providing a detailed understanding of the defect kinetics[6],[8]. The output collector characteristics (I_C vs. V_{CE}) (Fig 4) indicated a pronounced reduction in current levels with increasing fluences. For a constant base current of 50 μA, the collector current dropped by nearly 40% at 1×10^{13} ions/cm, demonstrating the degradation in charge transport efficiency due to defect-induced scattering. The results confirm that high-energy lithium-ion irradiation significantly impacts the electrical and structural integrity of 2N3055 transistors. The observed degradation in gain, carrier lifetime, and output characteristics underscores the dominant role of radiation-induced defects in altering device behavior[19,20]. These findings provide a critical framework for improving the radiation hardness of silicon-based power transistors through defective engineering and optimized device design. `

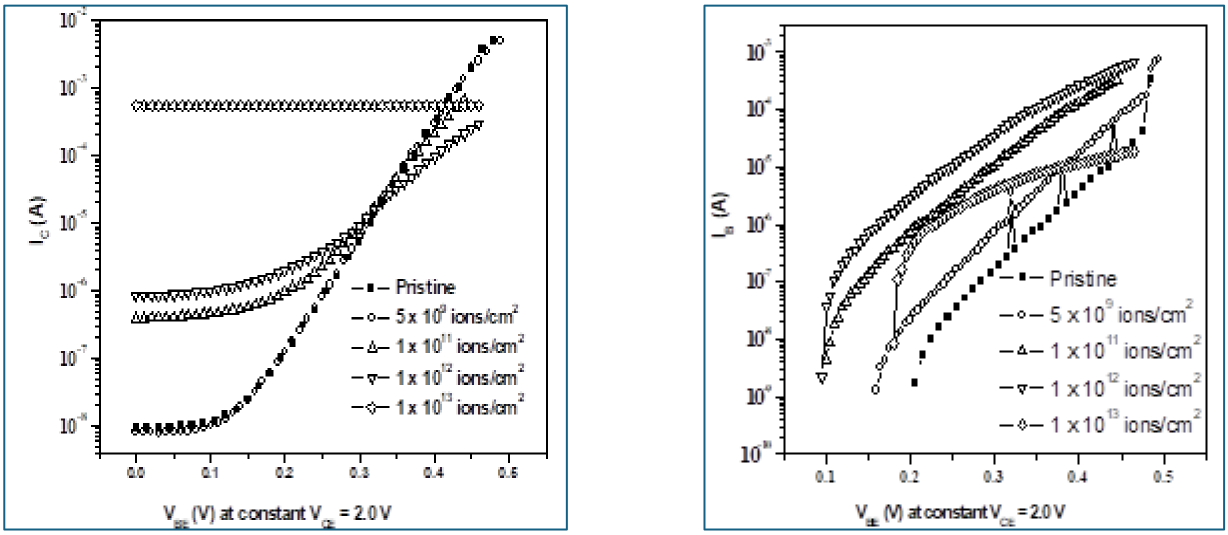

Figure 3 Gummel plots (I_B and I_C Vs V_{BE}) of 50 MeV Li^{3+} ion irradiated transistor 2N 3055 irradiated at room temperature (The results recorded at V_{CE} = 2.0 V constant).

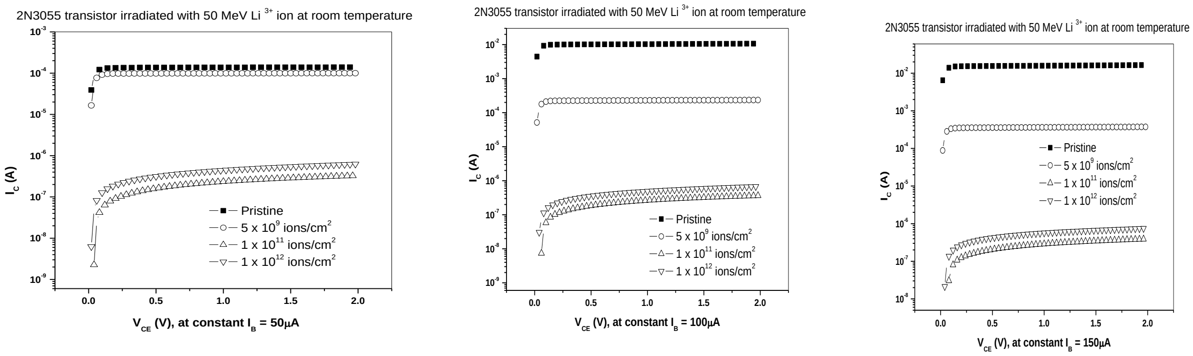

Figure 4 Output collector characteristics of 2N 3055 transistors irradiated with 50 MeV Li^{3+} ion at room temperature (The results recorded at I_B = 50, 100, 150 μA constant).

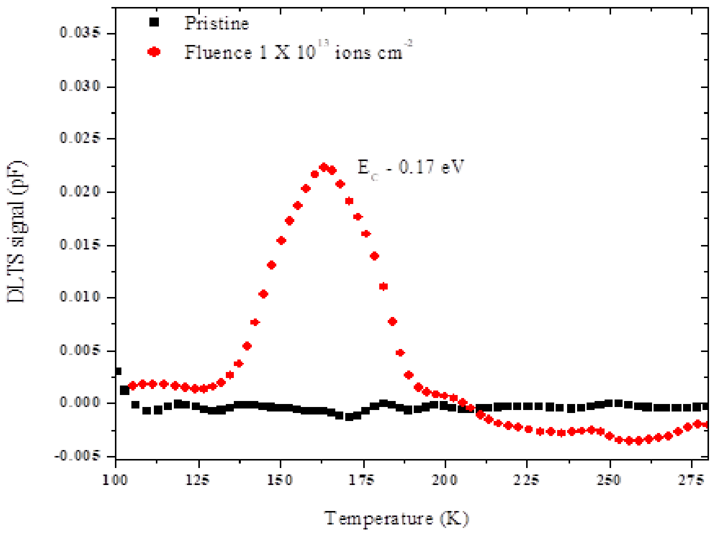

Figure 5 DLTS spectra 50 MeV Li^{3+} ion irradiated 2N 3055 transistor for a fluence of 1×10^{13} ions/cm^2

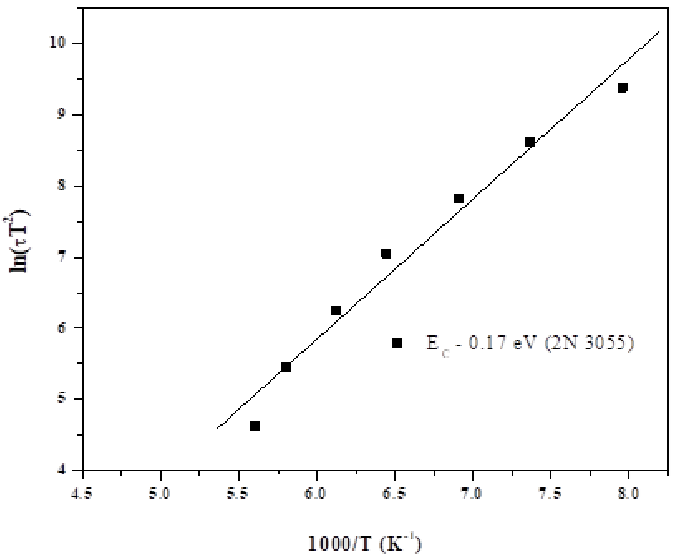

Figure 6 Arrhenius plot for deep level defects for an ion fluence of 1×10^{13} ions/cm^2.

Table 3 Data obtained from DLTS analysis of irradiated transistors.

Device	**Ion fluence (ions cm^{-2})**	**Defect type**	**Activation Energy (eV)**	**Trap concentration (cm^{-3})**	**Total trap concentration (cm^{-3})**	**Capture Cross section (cm^2)**	**Introduction rate η (cm^{-1})**	**Carrier life time (s)**	**Effective life time (s)**
2N 3055	1×10^{13}	A-center	$E_C - 0.17$	1.29E+14	1.29E+14	2.18E-19	12.86	4.24E-03	4.24E-03
		(B_i-O_i) complex	E_C - 0.27	4.59E+15		5.00E-18	459.4	4.74E-06	

Conclusion

This study systematically analyzed the effects of 50 MeV lithium ion irradiation on 2N3055 BEL transistors, focusing on defect formation and its impact on electrical performance. The findings reveal that radiation-induced defects, such as A-centers and (Bi-Oi) complexes, significantly degrade key device parameters, including forward current gain, carrier lifetime, and doping concentration. Quantitative analysis showed a sharp decline in gain and carrier lifetime, with trap concentrations reaching 1.29×10^{14} cm^{-3} for A-centers and 4.59×10^{15} cm^{-3} for (Bi-Oi) complexes at a fluence of 1×10^{13} ions/cm^2. The increase in defect density and recombination activity disrupted charge transport, reducing collector current and doping levels, thereby compromising the transistor's functionality in radiation-rich environments. These results provide valuable insights into the mechanisms of radiation-induced degradation in silicon-based power transistors. They emphasize the need for advanced defect mitigation strategies and material enhancements to improve device robustness. Future work may focus on developing radiation-hardened designs and validating the findings across other power transistor types to extend their applicability in extreme environmental conditions.

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