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Radiation Effects on Current Gain in BC-107 Transistor

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Abstract

Bipolar Junction Transistors are known to exhibit changes in their electrical characteristics when exposed to low level gamma radiation. The study examines the forward current gain factor in silicon npn BJT's due to radiation from a weak cesium-137 source. Barium K X-ray photons 32.6 keV and 662 keV gamma photons from Cesium-137 weak source bombard the p-n junction of the transistor. 32.6 keV X-ray photons interaction causes additional electron in the junction and 662 keV gamma photons interact through Compton scattering and cause secondary electrons in the p-n junction with energy of 0.2 MeV to 1.0 MeV. These secondary electrons displace the Si atoms near the p-n junction of the transistor and cause damages by forming trapping centres in the junction region altering the electrical properties of the transistor. In this work, we have investigated the current gain in BC-107 transistor operating in Common Emitter mode through its input and output characteristics to assess variation in its performance both before and after radiation exposure. Collector current shows decrement due to trapping centers formed in the collector region. The current gain of the transistor decrease with radiation exposure. Anomaly in the current gain of BC-107 transistor is accounted for the photo electrons added in the forward bias region of the emitter base junction due to radiation exposure. An uncertainty of less than 2% in the measurement of current gain and transconductance is been reported.

1 Introduction

Bipolar Junction Transistors (BJTs) are essential in a number of applications where radiation tolerance is critical for electronic devices in nuclear reactors and space technology [1, 2]. Most of these electronic devices are still dependent on transistors that operate in low, medium and high frequency bands. Due to high frequency performance, dependability, and capacity to function in harsh conditions, these devices needs thorough investigations at all conditions for a reliable current gain output. However, many researchers have reported degradation in junction potential and electrical characteristics of such semiconductor devices, including transistors both unipolar and bipolar, FETs', MOSFETs' etc. [2, 3]. Of the electrical parameters of transistors, it is reported the forward current gain (β) to be severely affected by exposure to ionising radiation, such as the gamma rays and neutron irradation. Low energy gamma rays interact with Si atoms in the p-n

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junction and may produce photoelectrons or Frenkel defects in the crystal. High-energy gamma photons interact with outer electrons of Si atoms through Compton scattering and cause lattice defects in the crystal. This produces anomaly in the transistor behavior viz. current gain, junction capacitance, frequency response etc. Hence, gamma radiation creates bulk damage by generating secondary electrons, which then cause the atoms to shift and create defect centres in the semiconductor crystals. These centres decrease the lifetime of minority carriers, leading to a reduction in forward current gain [4]. These interaction processes can also change the carrier mobility in both NPN and PNP transistors, depending on gamma ray energy, which grossly can affect the devices' performance. Previous studies have shown that BJTs' irradiated with gamma rays or heavy ions exhibit reduced current gain and increased leakage currents [5]. The effects of ionizing radiation on current gain degradation in vertical bipolar junction transistors been studied comprehensively in [6-13]. The extent of degradation depends on the total dose and energy of the radiation. In practical applications, understanding these effects is essential for optimising BJT design and ensuring reliable operation in radiation-prone environment. This study focuses on the radiation effects in Silicon atoms of BC-107 n-p-n transistors, a widely used type of BJT. The procedure and method adopted in this work is discussed in section II. The forward current gain factor and the transconductance of the transistor is determined and tabulated in section III. We have also reported the uncertainty in these measured parameters in the present study. In this study, suggestions for improvised current gain measurement and shielding material to avoid defects in the crystal lattice due to irradiation of either particle or energy is briefed in section IV as scope for further research.

2 Methods and Material

A weak radioactive point source Cs-137 of activity 79kBq procured from the Board for Radioisotope and Technology (BRIT) Mumbai, India. Transistor (BC-107) metal capped, lead sheets for shielding and metal container were purchased from a local vendor. Before exposing the transistor to external radiation, the transistor's characteristics in CE configuration are carefully studied. The forward current gain (β) from its output characteristics is calculated using equation 1. The procedure is repeated for 5 trials for consistency and reproducibility in the current gain. The transistor is now disconnected from the circuit carefully and is placed in a metal container for radiation exposure. The set up to irradiate the transistor is as shown in fig. 1. The lead sheet, were cut to match the diameter of the metal container and nearly covers its base and another as lid. The transistor is sandwiched between the Cs-137 source kept on a lead sheet, and another lead sheet covering the transistor in a nearly 2π geometrical configuration.

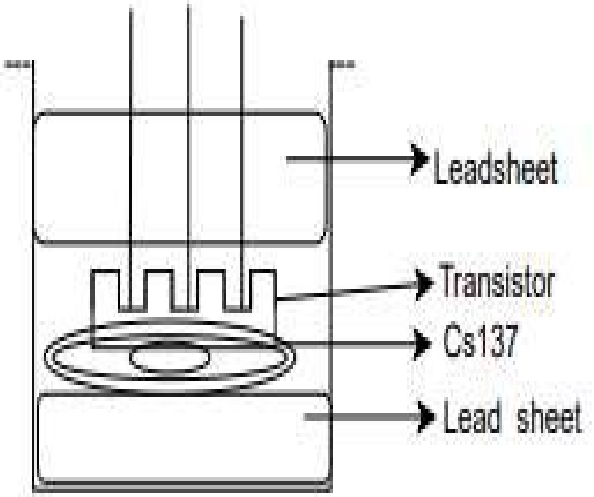

Figure 1: Block diagram of source and transistor holder.

Cesium-137 radioisotope, through the process of (Internal conversion) IC, undergoes with a 5.3% direct transition to the ground state of ^{137}Ba by β^- decay of energy 1.18 MeV. Around 94.7% of the Cs-137 atoms decays to an excited meta stable state of ^{137}mBa and later to the ground state of barium 137 by emitting a 662 keV gamma photons. In addition to gamma photons and β^- particles, barium K X-ray photons of weighted average energy 32.6 keV are also emitted. The 32.6 keV barium K X-ray photons and 662 keV gamma photons were assumed to bombard the p-n junction of the transistor. The sample is been irradiated at room temperature, with all pins unbiased for about 94 hours. The dose rate of the incident radiation from Cs-137 weak source in the forward hemisphere of the nearly 2π - geometrical configuration is 2896.14 rad calculated using equation 3. The output characteristics of radiation exposed transistor was studied and from which, the forward current gain of the transistor after exposing to radiation is been calculated using equation 1. The forward current gain of the irradiated transistor is studied for 5 trials for reproducibility and consistency. The transistor is exposed to the radiation for the said duration only. The forward current gain of the transistor in the former and latter cases is been compared and tabulated as detailed in section III. The current gain of the transistor in CE mode is calculated using the relation given as,

$$\beta = \left.\frac{\Delta I_C}{\Delta I_B}\right|_{V_{CE}} \tag{1}$$

The dose (D) and dose rate (D*) of the incident radiation on the transistor is calculated using equation 2 and 3 as according to G. F. Knoll [14]:

$$Dose(D) = Doserate(D^*) \times Time(T) \tag{2}$$

$$D^* = \tau_\delta \frac{\alpha}{d^2} \tag{3}$$

α is the activity of the source (79 kBq), d is the distance to the source (˜ 1mm). τ_δ is defined as the exposure rate constant for the specific radionuclide of interest. The subscript δ implies that the assumptionhas been made that all X-rays and gamma rays emitted by the source above an energy δ contribute to the dose, whereas those below this energy are not sufficiently penetrating to be of practical interest. The value of exposure rate for a particular radionuclide can be calculated from its gamma ray and the energy dependent absorption properties of air. Exposure rate constant for Cs-137 is 3.3 (R.cm^2)/(hr.mCi) [13] .

The dose rate D* using above mentioned parameters is 61.62 rad/hr. Since the sample was irradiated for 94 hours, the total dose D, from equation (2) is found out to be 5792.28 rad isotropically, considering the exposure in forward hemisphere, the dose D is 2896.14 rad.

Transconductance of BC -107 is calculated using [15] as,

$$gm = \frac{eI_C}{kT} \tag{4}$$

e- charge of the electron in C, I_C - collector current in mA, k- Boltzmann constant and T- Room temperature in K.

3 Results and Discussion

The radiation effect on the forward current gain (β) of the transistor (BC -107) in CE configuration is been studied. Firstly, the transistor is connected in the CE configuration and the input characteristics is been studied using high precision dc sources and current measuring meters. Emitter base junction is forward biased and the collector- base junction is reversed biased. The base current for different base- emitter voltage at constant collector - emitter voltage is noted. The experiment is repeated for 5 trials and the variation in readings been monitored. Similarly, the collector current is measured for different collector – emitter voltage at 5 different constant base currents have been studied. The output characteristics of the transistor before radiation exposure is characterised. The procedure is repeated 5 times and the variation in the respective values of currents are monitored. Now, the transistor after exposing to the incident radiation is brought back into the circuit and the input and output characteristics is studied under identical conditions for same number of trials. The input characteristic curves both before and after irradiation is shown in fig. 2.

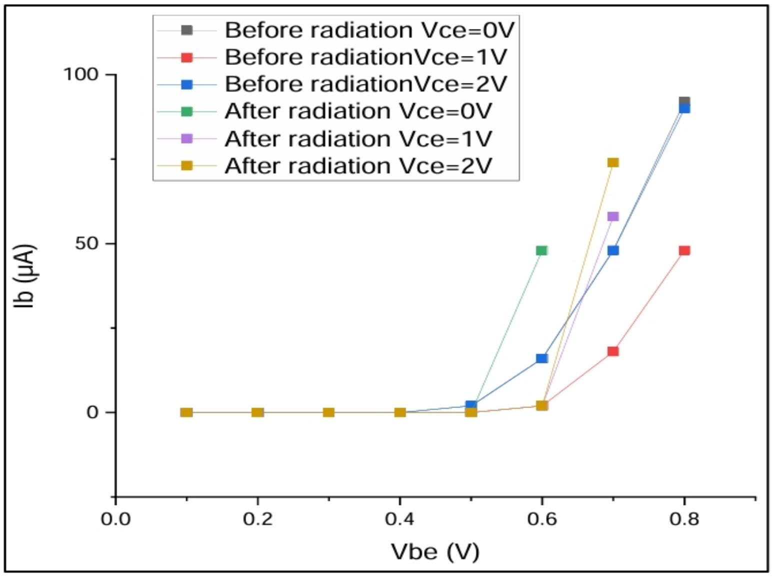

Figure 2: Input characteristics (Before and After Radiation exposure).

Before irradiation, the input characteristics follows the typical exponential behaviour of a p-n junction, where I_B increases with V_{BE}. After irradiation, a noticeable shift in the input characteristic curve was observed. There seems to be a clear shift of knee voltage by 0.1V in the forward biased emitter – base junction after radiation exposure. This could possibly be due to the photoelectric absorption and emission of Auger electrons due to the interaction of 32.6 keV K X-ray photons with Si atoms of the transistor material. This leads to the formation of radiation-induced defects, which act as recombination centres, thereby reducing carrier injection efficiency and increasing base current requirements. The input current and the emitter base voltage of the five trials is as shown in table 1.

Table 1: Input characteristics of BC -107 in CE mode.

	Before irradiation I_B (μA)			After irradiation I_B (μA)		
VBE (V)	VCE 0V	VCE 1V	VCE 2V	VCE 0V	VCE 1V	VCE 2V
0.1	0	0	0	0	0	0
0.2	0	0	0	0	0	0
0.3	0	0	0	0	0	0
0.4	0	0	0	0	0	0
0.5	2	0	2	0	0	0
0.6	16	2	16	48	2	2
0.7	48	18	48	-	58	74
0.8	92	48	90	-	-	-

The output characteristics were measured by recording the collector current (I_C) as a function of collector-emitter voltage (V_{CE}) for fixed base currents (I_B = 20, 40, and 60 μA). Before irradiation, the transistor exhibited the expected linear increase in I_C with V_{CE} in the active region, followed by saturation at higher V_{CE} values. Hence the forward current gain (β) agrees with the theoretical prediction. However, after irradiation we observe a reduction in β indicating radiation-induced damage to the silicon lattice, which increases recombination centres and reduces charge carrier mobility in the collector region. This suggests increased base current leakage and degradation of carrier transport due to radiation-induced displacement damage and interface states. Further, the collector base region as the doping concentration a tenth of base region, there seems to be a dearth of charge carriers (electrons) as the 662 keV gamma photons interact with the outer electrons of Si atoms via Compton scattering creating trapping centers for the electrons and hence leading to recombination effects. This reduces the collector current and cause a decrement in the calculation for the forward current gain in radiation induced transistor (BC -107). From the measured collector current (I_C) for different values of collector - emitter voltages, at constant base current, the output characteristics is studied for both before and after radiation exposure shown in fig. 3. The measured values of collector current (I_C) against different collector emitter voltages (V_{CE}) are tabulated in table 2.

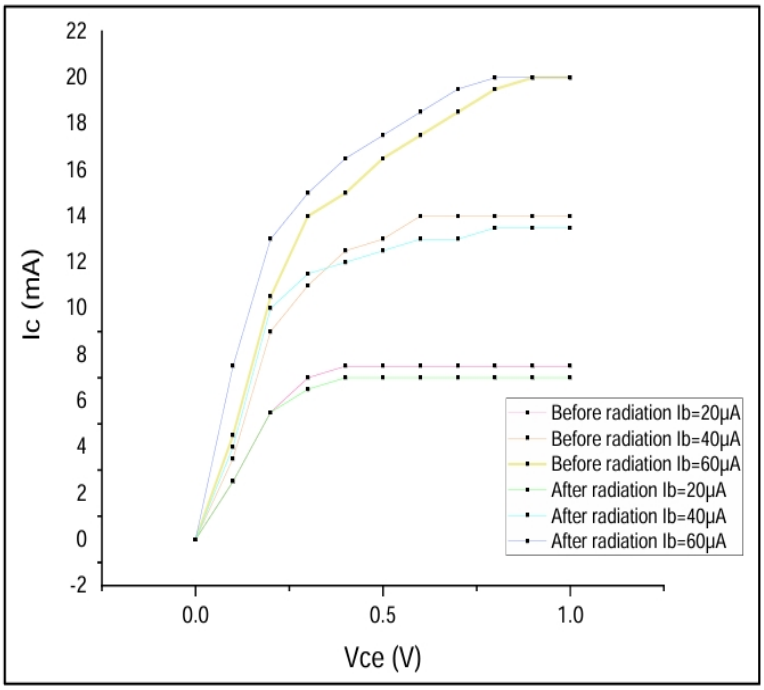

Figure 3: Output characteristics (Before and After Radiation Exposure)

From the output characteristics of the transistor, the transfer characteristics (BC-107) for both before and after radiation is plotted and shown in fig. 4. The transfer characteristics of the BC-107 transistor were analysed by measuring the collector current (I_C) as a function of base current (I_B) for fixed collector- emitter voltage ($V_{CE} = 0.5$ V). It is found that, before irradiation, the transfer curve followed the expected exponential relationship, where small increases in V_{BE} resulted in significant increases in I_C. However, when the transistor is exposed to radiation, a decrease in the collector current at the same collector-emitter voltage is observed to decrease and hence causes a decrease in the forward current gain. The transfer parameters are tabulated and is shown in table 3.

Table 2. Output characteristics of BC -107 in CE mode.

	Before irradiation I_C (mA)			After irradiation I_C (mA)		
VCEV	IB20µA	IB40µA	IB60µA	IB20µA	IB40µA	IB60µA
0.1	2.5	3.5	4.5	2.5	4	7.5
0.2	5.5	9	10.5	5.5	10	13
0.3	7	11	14	6.5	11.5	15
0.4	7.5	12.5	15	6.5	12	16.5
0.5	7.5	13	16.5	7	12.5	17.5
0.6	7.5	14	17.5	7	13	18.5
0.7	7.5	14	18.5	7	13	19.5
0.8	7.5	14	19.5	7	13.5	20
0.9	7.5	14	20	7	13.5	20
1.0	7.5	14	20	7	13.5	20

Table 3: Transfer Characteristics of BC-107

I_B (μ A)	Before irradiation	After irradiation for various trials I_C in mA				
	I_C (mA)	I	II	III	IV	V
20	7.5	7.5	7	7	7	6.5
40	13	13	13	12.5	13.5	13.5
60	16.5	18	18	17.5	17.5	17.5
80	-	21	21	21	21	21
100	-	24	24	23.5	23.5	23.5

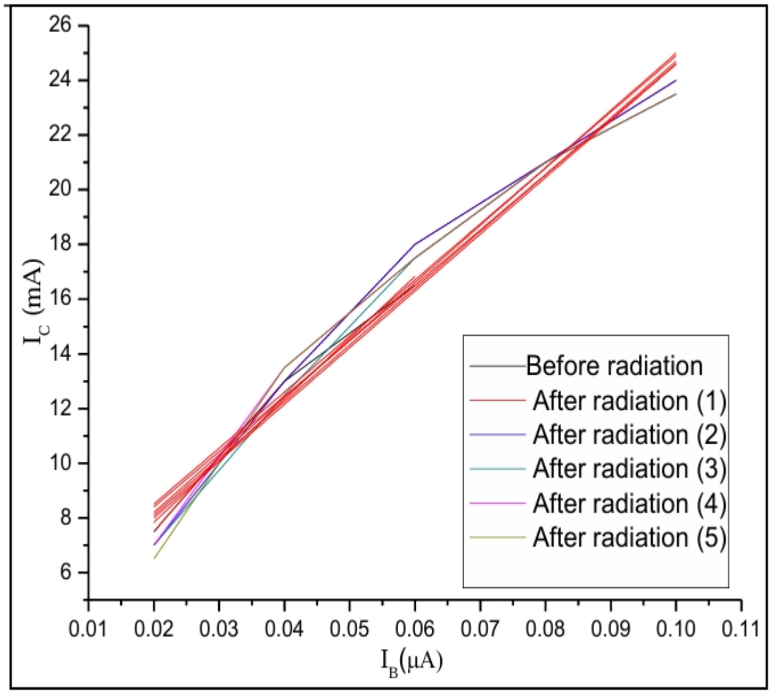

Figure 4: Transfer characteristics (Before & After Radiation Exposure)

Using Origin software, the transfer characteristic curves are fitted using the linear fit tool. The slope values are the measured values for the forward current gain of the transistor. The measured current gain (β) for both before and after radiation is tabulated in table 4. The measured β values are weighted with the error in its measurement and the weighted value of β is reported in table 4. It seems the forward current gain (β) of the transistor under study shows degradation by about 8% upon irradiation. An uncertainty of less than 2% in the measurement of β values in BC -107 transistor in both before and after irradiation is been reported. The uncertainty in the present work is accounted for systematic error and fluctuation in dc currents. Using equation 4, the Transconductance of BC-107 transistor is calculated and tabulated in table 4.

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Table 4: Transistor parameters of (BC- 107) in CE mode.

Parameter	Before irradiation Weighted mean	After irradiation					Weighted mean
		I	II	III	IV	V	
β	225±0.01	205±0.01	210±0.02	208±0.01	203±0.01	208±0.01	207±0.005
gm in S	0.29	0.29	0.27	0.27	0.27	0.25	0.27*

*Arithmetic mean

4 Conclusion

Radiation effect on the current gain of a silicon npn transistor (BC-107) is studied. Ba K X-ray photons and gamma photons from a weak Cs-137 radioisotope were made to be incident on the transistor kept in a closed metal container. The transistor parameters viz. forward current gain and the transconductance have been studied both before radiation exposure and after the radiation exposure. There seems to be an increase in base current due to an excess of recombination centers. However, there is a minor decrease in collector current, which together lead to a drop in current gain (β). This could be due to the increase in base current signifying higher electron-hole recombination in the base region. This ultimately reduces the transistor's current ampliying efficiency. In the present study, Silicon npn bipolar junction transistor (BC-107) at ambient temperature, exhibits degradation in both the parameters of current gain and transconductance when exposed to gamma radiation from a weak Cs-137 source under forward bias conditions. We aslo account for current gain degradation in transistors due to instability in the density states due to imperfection in silicon crystal and electronic noise. The results obtained in the present study indicates a significant increase in base current, due to radiation-induced secondary electron generation and subsequent atomic displacements in silicon crystal lattice. These defect centers may reduce the life time of minority carriers, leading to a reduction in current gain and directly affecting the transistor's performance. This study finds scope in undrstading the behviour of current gain in other type of transistors either npn or pnp and also to study the radiation effects on germanium and other semiconductor material transistors to know their behaviour when exposed to low energy radiation. Using high precision devices, radiation damages in the lattice structure of the material of the transistors for different input frequencies can be studied. Also, the change in p-n junction capacitance with frequency can be studied. This studiy also opens room for the synthesis of materials required for radiation shielding, that can either be coated on the transistor materials and harden them radiation exposure or provide as shielding material from natural radiation.

5 Copyright Notice

6 References

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