Superlattices and Microstructures 122 (2018) 194–202

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices

Experimental studies of collector-emitter voltage bias influence on the total ionization dose effects in *NPN* Si BJTs

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ARTICLE INFO

Keywords:
Bipolar junction transistor
Total ionization dose effects
Collector-emitter voltage bias conditions
Excess base current
Ideality factor
Power dissipation

ABSTRACT

The voltage V_{CE}, bias influence studies on total ionizing dose (TID) in bipolar junction transistors (BJTs) were investigated. The BJTs were set at forward active mode of base-emitter voltage (V_{BE}) swept from 0 to 1.0 V at different biased conditions of V_{CE}, ranging from 1 V to 2 V at an interval of 0.25 V during ^{60}Co γ irradiation. The damage mechanism of TID in BJTs at different V_{CE} bias conditions were analysed by forward Gummel characteristics, forward current gain (β_f), normalized excess base current ($\Delta I_B/I_{Bpre}$), normalized excess collector current ($\Delta I_C/I_{Cpre}$), normalized current gain ($\beta_{fpost}/\beta_{fpre}$), ideality factor ($n$) and power dissipation (P_d). The results show that the increments of base current (I_B) and collector current (I_C) are slightly different in various V_{CE} bias conditions which also effects slight changes in their current gain ($\Delta\beta_f$) degradation. The current gain degradation (β_f) at high bias V_{CE} degraded more slightly than low bias V_{CE}. The $\Delta I_B/I_{Bpre}$, $\Delta I_C/I_{Cpre}$ and $\beta_{fpost}/\beta_{fpre}$ estimated shows similar trend of different V_{CE} bias conditions resulting into varying distribution of performance degradation of the BJT. The ideality factors (n) for excess base current (ΔI_B) were ~2 for V_{BE} from 0.35 V to 0.6 V at different V_{CE} bias conditions. Thus, ideality factor (n) slightly increases as the V_{CE} bias rises and decreases with the increased accumulated total dose level after the n peak value was obtained at TID equals to 130 krad (Si) for irradiated BJTs. Finally, the power dissipated (P_d) by BJTs were compared as $V_{CE} = 2\,V > 1.75 > 1.5\,V > 1.25 > 1\,V$ and were noted to be more effective at $V_{BE} > 0.6\,V$ which also concur with temperature rise T_R. The T_R in BJTs resulted into self-heating effects.

1. Introduction

The speed advantage, linearity, excellent matching, high driving capability, appropriate gains current, voltage and power of bipolar transistors make them widely applied in many electronics systems [1,2]. However, the work reliability of the BJTs will be threatened when they worked in harsh environment, such as space, nuclear reactor, etc. According to studies, the total ionizing dose (TID) effects of ^{60}Co gamma γ, irradiations on BJTs would create electron-hole pairs within the BJTs such as Si and dielectric layers such as SiO_2. The electrons diffuse away by electric field after a short time, while the holes would recombine and captured by intrinsic defects in the SiO_2 and Si-SiO_2 interface regions for a longer time. Thus, the captured trapped charges created are positive oxide trapped charges (N_{ot}) (at the SiO_2 layer) and interface trapped charges (N_{it}) (at the Si-SiO_2 interface). The induced defects in BJTs by irradiation degrade the electrical characteristics of BJTs from its normal state [3,4] and even failure in performance. However, the irradiated BJTs' working condition such as voltage bias is a contributory factor to performance degradation.

Bipolar transistors are mostly operated in active mode of two junctions (forward-biased B-E junction and reverse-biased B-C

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https://doi.org/10.1016/j.spmi.2018.08.008
Received 29 May 2018; Received in revised form 2 August 2018; Accepted 5 August 2018
Available online 06 August 2018

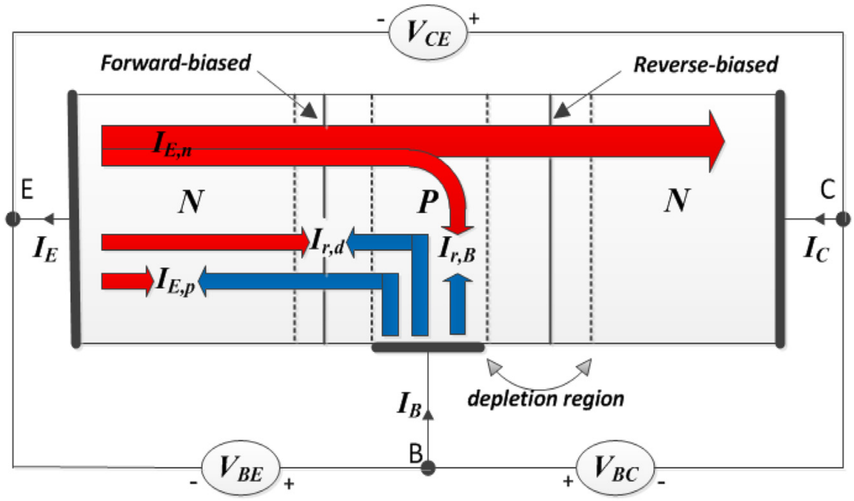

Fig. 1. Operation of NPN Si BJT in the active mode.

junction) as shown in Fig. 1. The electrons in emitter region are injected into base region with forward bias voltage V_{BE} supplied for E-B junction. Most of the injected electrons that reached the edge of B-C junction before being recombined will be swept in the collector region due to reverse bias V_{BC}. Collector-emitter voltage ($V_{CE} = V_{BE} + V_{BC}$) as a summation of base-emitter voltage (V_{BE}) and base-collector voltage (V_{BC}) plays a vital role in the BJTs amplification process. Obviously, changes in the bias condition of V_{CE} will shift the quiescent operation point of the BJT. As the V_{CE} increases (i.e. greater reverse bias across the B-C junction), the collector–base depletion region increases in size with a decrease in the base effective width of BJT. An increase in the output V_{CE} means an increase in V_{BC} which will eventually resulted into a decrease in base current (I_B) with an increase in collector current (I_C). According to [5] as shown in Fig. 1, the back injection of holes from base to emitter ($I_{E,p}$) are the main components of the base current (I_B) that dominates in an unirradiated BJT, while for TID irradiated BJT, both $I_{r,d}$ and $I_{r,B}$ increase with $I_{r,d}$ normally dominating. Meanwhile, the I_C of an irradiated BJT remains virtually unchanged except at very low bias levels in comparison with I_B increments. As concluded by Refs. [6,7], the V_{CE} bias condition of irradiated BJT would result into a small decreasing I_C and a large increasing I_B which leads to current gain degradation (β_f) is still open for further investigation. However, seldom studies provided the bias V_{CE} impacts on TID effects of BJT. Therefore, it is essential to investigate the response characteristics of BJT supplied with different V_{CE} to TID effects.

In this work, the forward Gummel characteristics of the tested samples before and after different total dose levels were measured and compared under different bias V_{CE} (1 V, 1.25 V, 1.5 V, 1.75 V, 2 V) conditions. The changing trends for BJT's base current (I_B), the collector current (I_C), the *DC* current gain (β_f), the ideality factor (n) and power dissipation (P_d) changed with different irradiation gamma total dose and device bias conditions were compared. The degradation mechanisms of BJT's performance were analysed according to the experimental results.

2. Experiment details

The tested samples used in this experiment were *NPN* Si BJTs (BCW72). The SOT-23 plastic package encapsulated BJT was designed as a general purpose amplifier and switch, commonly used in electronic systems for aeronautics and space. The BJTs were also designed for low-frequency operation with a peak transition frequency of about 100 MHz and their maximum static current gain value is between 250 and 300 depending on the device. Five samples were placed on a FR4 substrate and biased as a common-emitter amplifier during the entire experiments. The BJT's base terminal as shown in Fig. 1 was biased through a voltage source ($Rb = 0\Omega$.) as the collector terminal voltage varies.

The tests on the samples were conducted with ^{60}Co γ source at Northwest Institute of Nuclear Technology, Xian in China. The test samples were put into a 3 cm thick *Pb/Al* shielding box in order to keep changed particle equilibrium (CPE) condition according to MIL-STD 883 Method 1019.6. The dose rate measured at the samples' irradiation positions was about 50.1 rad (Si)/s with PTWU-DIDOS dosimeter. The PTWUDIDOS dosimeter is of a high quality and universally used in radiation field.

The samples at the ^{60}Co gamma irradiation room were connected with a 30 m long flat cable to the *DC* voltage supply source via a multi-channel switch at the control room as shown in Fig. 2. The BJTs were electrically biased and monitored in *situ*. The forward Gummel characteristics of samples were measured with a semiconductor parameter analyzer (HP4156) before and after ^{60}Co radiation at different dose levels (i.e. from 46 krad (Si) to 600 krad (Si)). The base-emitter junction bias V_{BE} of the samples was swept from 0 to 1.0 V and the V_{CE} was ranged from 1 V to 2 V with an interval of 0.25 V during Gummel characteristics measurement. All experiments and parameter measurements were performed at room temperature.