Radiation damage of SiGe HBT Technologies at different bias configurations

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Abstract

SiGe BiCMOS technologies are being proposed for the Front-end readout of the detectors in the middle region of the ATLAS-Upgrade. The radiation hardness of the SiGe bipolar transistors is being assessed for this application through irradiations with different particles. Biasing conditions during irradiation of bipolar transistors or circuits have an influence on the damage and there is a risk of erroneous results. We have performed several irradiation experiments of SiGe devices from IHP in different bias conditions. We have observed a systematic trend in gamma irradiations, showing a smaller damage in transistors irradiated biased compared to shorted or floating terminals.

I. INTRODUCTION

The LHC at CERN is expected to start taking data during next year. In the meantime, a new project has started to try and extract more physics benefits after its expected life span of 10 years. The plan is to upgrade the accelerator in order to increase its luminosity in around one order of magnitude, it is called the Super-LHC. It has been shown that this will force the modification of the different experiments installed in the accelerator. In particular, the total inner detector of the ATLAS detector will have to be upgraded. Some of the microelectronics technologies proposed for the front-end readout of the detectors in the middle region of the upgraded inner detector are the SiGe BiCMOS technologies. These technologies should provide better performances in terms of power consumption, signal to noise, and processing speed, but they have to be evaluated in terms of radiation hardness.

In order to perform this evaluation, the devices should be submitted to different irradiation experiments, and then measure their performance after irradiation. These experiments are usually performed in complex irradiation facilities with difficult access to the irradiation area. This complicates the irradiation setup, in particular, biasing the devices during irradiation in order to mimic the real conditions is very difficult, and often impossible. This work studies the results of radiation damage in the SiGe HBT transistors when submitted to irradiations in various bias configurations, in order to verify the validity of irradiation experiments carried out at bias conditions different from the real case.

We have performed irradiations of SiGe HBT transistors with Co60 gamma particles in three different bias configurations: biased in forward active region (in similar conditions as they will be working in the real experiment); with all their terminals short-circuited; and with all their terminals floating. Differences in radiation damage have been observed for SiGe transistors submitted to gamma irradiations in biased configuration with respect to shorted and floating configurations. Biased transistors suffer less current gain degradations than shorted transistors, and these suffer less degradations than floating transistors.

The variation of radiation damage in time after irradiation (annealing) has also been studied in order to discard differences in radiation degradation coming only from different degree of annealing of the damage due to their different biases during irradiation. Transistors have been measured right after irradiation, and then left for some time in the same bias conditions and at room-temperature, then re-measured. Less annealing has been observed for gamma irradiations in the biased transistors indicating that some of the damage differences observed actually come from different annealing levels, nevertheless some differences in damage remain after the full annealing process.

II. MOTIVATION

In our radiation hardness studies of bipolar technologies previous to the present work, in the framework of the radiation hardness tests of the front-end electronics of the ATLAS-SCT detector [1], we had performed several experiments irradiating bipolar transistors with gamma rays in different bias configurations. Our results from those experiments (unpublished) always indicated that ionizing radiation effects in devices with floating terminals were more intense than those on devices whose terminals are wire bonded and biased, regardless of dose rate, temperature, or device type (NPN, PNP). An example of this can be seen in Figure 1, which shows the excess base current density, defined as the base current density increase after irradiation ($\Delta J_B = J_B - J_{B0}$) at $V_{BE} = 0.7$ V, of transistors from the MAXIM's CB2 bipolar technology (well described in [2]), gamma-irradiated at a wide range of total doses from 100 krad(Si) to 10 Mrad(Si). In that figure, filled points represent single-transistor results, and empty symbols correspond to the calculated averages for all transistors irradiated at the same total dose and bias configuration. As it can be seen, there is a clear increase in radiation damage on devices irradiated with terminals floating compared to those irradiated in biased configurations for the whole range of doses.

One can deduce from these results, that there is a risk of largely overestimating the damage that bipolar transistors will receive in the real experiment when performing experiments in unrealistic bias conditions. Therefore, one could decide to reject some technologies or designs (ICs) as candidates for the experiment under wrong assumptions. In the light of these

results, we decided to perform a systematic study on the effects of the bias configuration during irradiation (*bias effects*) on the radiation degradation of bipolar transistors for high energy physics applications.
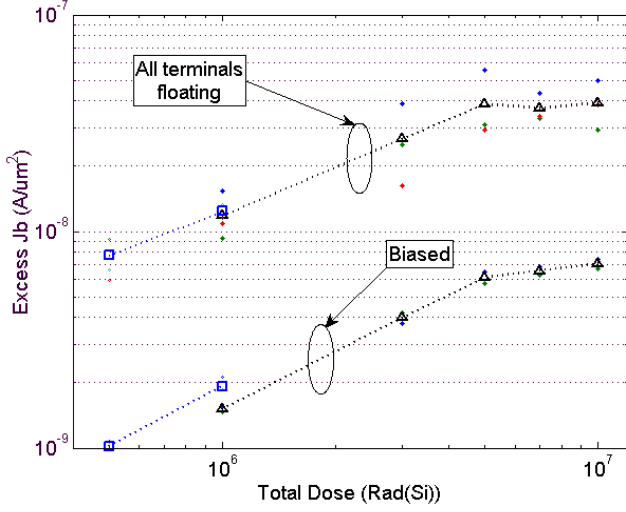

Figure 1 : Excess base current density at $V_{BE} = 0.7$ V of bipolar transistors gamma-irradiated at different total doses in biased or floating terminals configurations.

III. EXPERIMENTAL DETAILS

In order to perform a systematic study of the bias effects under ionizing radiation, we irradiated several bipolar devices, in three different bias configurations:

(a) All terminals floating.

(b) All terminals shorted together.

(c) Transistor biased in forward active region with $V_{BE} \approx 0.7$ V and $V_{CB} = 0$ V.

The transistors used for the study are included in test chips fabricated on a SiGe:C HBT technology from Innovation for High Performance Microelectronics (IHP) [3]. The technology, called SGB25VD, presents the following key characteristics: $f_T = 75$ GHz, $BV_{CE0} = 2.4$ V, $\beta = 190$. An schematic cross-section of the NPN transistor of this technology can be seen in Figure 2. This is one of the technologies being studied as candidates for its use in the front-end electronics of the ATLAS Upgrade for the Super-LHC at CERN [4].

All transistors were irradiated with gamma particles in the same conditions other than the bias configuration. The total dose reached was 5 Mrad(Si), at a dose rate of 342 rad(Si)/s. The irradiations were carried out in the *Nayade* facility at CIEMAT (Madrid, Spain), a water well Co60 irradiator. The dosimetry was performed by means of a Fricke system [5]. All irradiations were performed using a PbAl shielding box to avoid dose enhancement effects due to secondary photons and to reach charged particle equilibrium at the samples, according to irradiation standards [6]. The devices remained close to room temperature during irradiation. The temperature of the samples during irradiation was obtained via PT100 sensors.
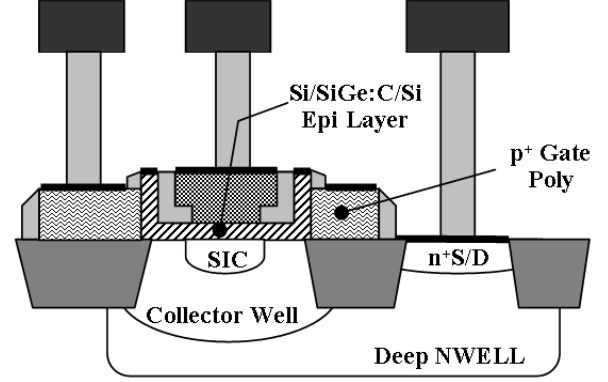

Figure 2 : Cross sections of the NPN SiGe:C heterojunction bipolar transistors (HBT) used. The devices stem from IHP's BiCMOS technology SGB25VD.

Before irradiation the devices were measured first on wafer. Then, the wafers were cut and the selected test chips were wire bonded to the biasing boards, except for the ones that were to be irradiated in floating configuration which remained with their terminals pads floating during the whole experiment (obviously, except for the short testing cycles). Devices were then, re-measured to make sure that their characteristics had not changed or that they had not died during the bonding process. After irradiation, all devices were kept at low temperature (< 0 ºC) in order to avoid annealing until they were measured. Then they were left for annealing at room temperature with their terminals shorted together and grounded, except for the devices irradiated in floating configuration which were left also floating for the whole annealing process. Several measurements were later performed at consecutive time periods, systematically observing a beneficial annealing of the damage. Beneficial annealing proceeds for around two weeks until it reaches a saturation. The final stable value after saturation of the annealing was taken as the final result of the irradiation.

The measurements were performed with a Keithley 4200 Semiconductor Characterization System and the use of a manual probe station and microprobes. The environmental temperature of the laboratory was measured during the tests process. This temperature remains in the range of 25 ± 2 ºC. Nevertheless, a commonly used correction for small temperature differences has been used for the base current by applying a factor to the post irradiation value which is equal to the ratio between the pre- and post- irradiation value of the collector current (which is known not to be affected by gamma radiation) [7]. Forward Gummel plots of the transistors were obtained, and the following figures-of-merit for the radiation damage were extracted from them: *Final Current Gain* (β_F): defined as the post-irradiation common emitter current gain of the transistors at $V_{BE} = 0.7$ V; *Normalized Current Gain* (β_N): defined as the ratio between post- and pre-irradiation common emitter current gain (β_F/β_0) at $V_{BE} = 0.7$ V; and *Excess Base Current Density* (ΔJ_B): defined as the difference between post- and pre-irradiation base current density at $V_{BE} = 0.7$ V.

IV. RESULTS

The radiation damage suffered by transistors submitted to gamma irradiations in different bias configurations is shown in Figure 3 in terms of the Excess Base Current Density (ΔJ_B) after annealing. As it can be seen, less damage is obtained for transistors irradiated in biased configuration than for the transistors with their terminals shorted or floating. Also, floating transistors suffer the most damage among all cases. Overall, the damage differences observed are small at the dose reached of 5 Mrads(Si), but higher differences can be expected at radiation doses where the devices are closer to the edge of their usability. This has been observed in previous results as the ones presented in Section II, and other irradiations that we have performed. Quantitative differences with other cases are related to technological diversity which make some devices relatively more immune to ionization damage (quality of spacer oxide, size, etc).
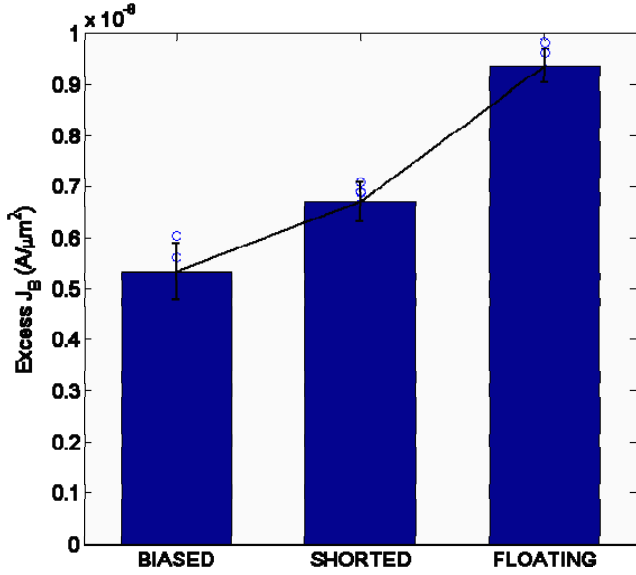

Figure 3 : Excess Base Current Density (ΔJ_B) of transistors irradiated in different bias configurations.

As it has been mentioned above, the results presented correspond to measurements of devices after annealing has taken place. During the annealing process, the damage produced by radiation is reversed in some amount, in a process called "beneficial annealing". This process continues for a few days (5-10), at room temperature, until it reaches a saturation point after which the damage level of the transistors remains stable. This is the reason why this saturation point is usually taken as the final value of the ionization damage in bipolar transistors. We have monitored the annealing of the devices, taking intermediate measurements for several days along the whole process. Figure 4 shows the post-irradiation current gain (β_F) of the irradiated transistors throughout the whole annealing process until it reaches a saturation, for all the transistors irradiated in the different bias configurations. The saturation in the annealing can be easily seen after about 5 to 10 days at room temperature.
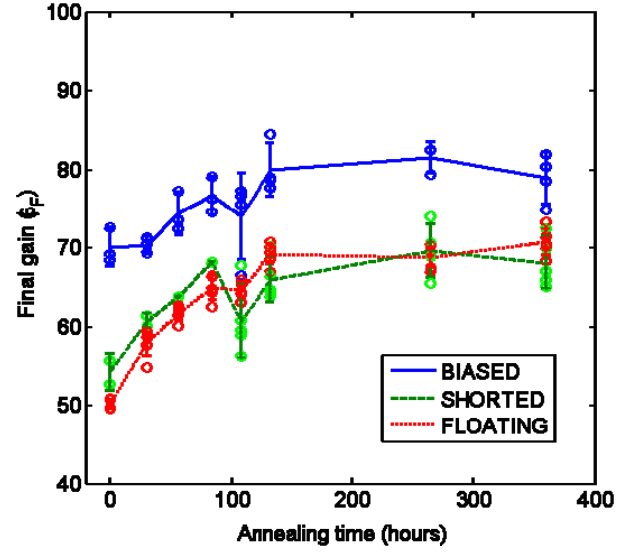

Figure 4 : Final gain (β_F) for all bias configurations during the whole annealing process.

This annealing behavior of the irradiation damage in bipolar transistors, could raise some doubts about the possibility that the differences in radiation damage observed for the different bias configurations could be only related to differences in annealing for the different transistors, and not to actual irradiation bias effects. In order to address this question we have compared the annealing of the devices, along the whole process.

Figure 5 shows the total beneficial annealing occurred for the transistors irradiated at different bias configurations. Annealing is shown in terms of the excess base current density as the difference between the final stable value after the annealing process has taken place, and the initial value obtained in measurements taken right after irradiation. As it can be seen, no significative differences are observed in the annealing of the transistors for the different bias cases. Therefore, it can be concluded that the differences observed in radiation damage of devices irradiated at different bias configurations is an effect related with these bias configurations and not with annealing differences.
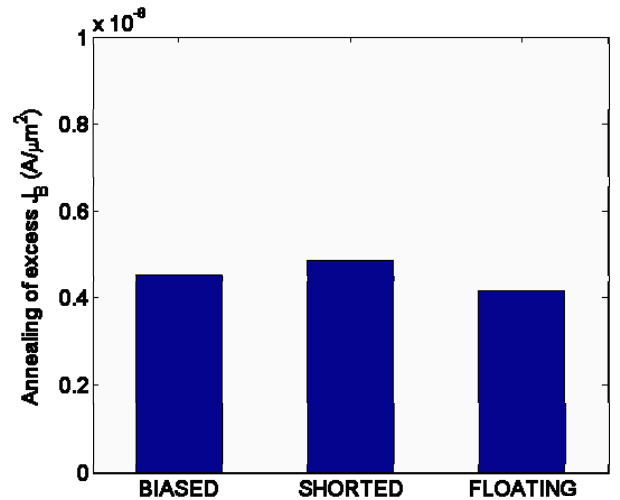

Figure 5 : Annealing of transistors irradiated at different bias configurations in terms of the excess base current density

V. Conclusions

Systematic less damage is observed for bipolar devices irradiated in biased configuration with respect to shorted or floating terminals configurations. Floating devices appear to suffer the highest damages of all the cases. Grounded configuration appears as a "worst-case" configuration in the sense that irradiations performed in these conditions will overestimate the damage in small amounts. Annealing differences are not responsible of the differences observed in the damage for the different configurations.

At the view of these results some practical recommendations can be made when performing irradiation experiments of bipolar technologies for high energy physics applications, where devices are usually biased when they are exposed to radiation in the real life. Special care should be used when trying floating configuration as there is the risk of largely overestimating the damage produced on the transistors. Shorting all the terminals together can be a good practice when biasing the devices can be too difficult or even impossible in the radiations sources used. Quantitative differences seem to be important among technologies, therefore studies of this kind should be performed when considering experiments in bias configurations different from the real-life.

VI. Acknowledgements

VII. References

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