Radiation hardness studies of a 130 nm Silicon Germanium BiCMOS technology with a dedicated ASIC

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Abstract

We present the radiation hardness studies on the bipolar devices of the 130 nm 8WL Silicon Germanium (SiGe) BiCMOS technology from IBM. This technology has been proposed as one of the candidates for the Front-End (FE) readout chip of the upgraded Inner Detector (ID) and the Liquid Argon Calorimeter (LAr) of the ATLAS Upgrade experiment. After neutron irradiations, devices remain at acceptable performances at the maximum radiation levels expected in the Si tracker and LAr calorimeter.

I. INTRODUCTION

Large Hadron Collider (LHC) upgrade, the Super-LHC, will imply a luminosity increase in the experiment of an order of magnitude [1]. This means a significant increase in the radiation levels inside the ATLAS detector [2]. Based on the working "strawman" layout for the silicon strip detector of the upgraded ATLAS detector, the current studies predict 30 Mrad(Si) of total ionizing dose (TID) and 9.8 x 10^{14} cm^{-2} 1 MeV neutron equivalent fluence in the "short-strips" region, and 8.4 Mrad(Si) - 3.5 x 10^{14} cm^{-2} in the "long-strips" region, while the radiation levels for the liquid Argon calorimeter (LAr) are expected to be in the order of 300 Krad(Si) total ionizing dose (TID) and a total 1 MeV neutron equivalent fluence of 9.6 x 10^{12} cm^{-2}. All these numbers include the 2x safety factor.

The increased luminosity and enhanced degradation created by the new radiation environment will force to replace completely the current Inner Detector and the readout electronics for the Liquid Argon Calorimeter (LAr). One of the technological options for these applications is the use of SiGe BiCMOS technologies. Those technologies provide high amplification factors at low shaping times as well as very low noise vs. power ratio. Nevertheless, their radiation hardness must be validated up to the high radiation levels expected in the ATLAS Upgrade experiment. After previous studies of several SiGe technologies from different foundries, and given the preliminary radiation studies [3], [4], the main option chosen from the SiGe group for this application is the 130 nm 8WL BiCMOS technology from IBM. This technology provides an easy portability with the 8RF IBM 130 nm CMOS technology, which is the baseline technology for the digital part of the upgraded FE readout chip of the Si Tracker. We present in this work the performance of bipolar devices from the SiGe BiCMOS 8WL technology after neutron radiation exposure, as part of the radiation hardness assurance test program of this technology. Other experiments scheduled in the test program are gamma irradiations, proton irradiations and Enhanced Low Dose Rate Sensitivity (ELDRS) studies. All of them are in progress and will be reported soon. Two prototype FE readout Test Chips (TC) have also been designed and fabricated for both the Si Tracker and the LAr calorimeter and their pre-irrad results are also reported in this conference [3], [5], [6].

II. IBM 8WL SIGE BICMOS TECHNOLOGY

Fig. 1 shows a schematic cross-section of the bipolar transistors of the high-performance 130 nm 8WL SiGe BiCMOS technology (100 / 200 GHz peak f_T / f_{max}). Detailed information about the features of the 8WL technology is reported in [7]. On the purpose of studying the radiation resistance of the IBM 8WL technology, a dedicated TC with different test structures has been designed and fabricated in this process. It is the so-called SiGBiT ASIC.

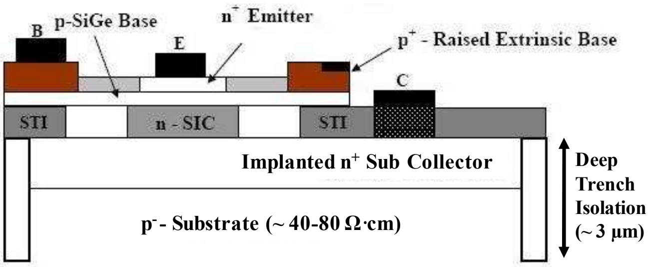

Figure 1: Schematic cross-section of the 8WL SiGe BiCMOS technology

The Silicon-Germanium Bipolar Test chip (SiGBiT) consists of several test structures from the 8WL process. It includes 40 design-kit bipolar transistors of different types, geometries and emitter sizes (18 differential pairs and 4 single transistors), and several resistors of different geometries. All these devices are summarized in Table 1. The SiGBiT ASIC also includes a CMOS test structure ported from the 130 nm 8RF CMOS technology structure designed by the CERN microelectronics group. Figure 2 shows a picture of the chip layout.

Table 1: SiGBiT npn HBTs and resistor inventory.

NPN SiGe Bipolar transistors (120 nm emitter width)

Count	Pair	Single	Type	Emitter	Stripes
4	X		HP	20	2
2	X		HB	20	2
3	X		HP	8	1
3	X		HB	8	1
6	X		HP	1	1
4		X	HP	4	2

Resistors

Count	Pair	Single	Type	L (µm)	W (µm)	Value (kΩ)
3		X	PP	35	6	2
2	X		PR	30	3	2.3
2	X		RR	30	3	17

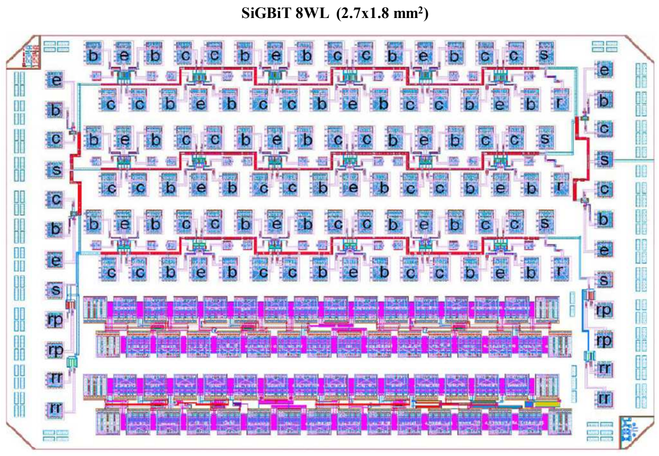

Figure 2: Layout of the SiGBiT test chip. Bipolar parts are located on the upper part and the sides of the chip. 8RF-ported CMOS test structure is located at the bottom of the chip.

Our study will be focused on the bipolar devices configured as differential pairs. Their emitter sizes are 4.8 µm^2 for the 20x2 high-performance (HP) and high-breakdown (HB) devices, 0.96 µm^2 for the 8x1 HP and HB devices, and 0.12 µm^2 for the 1x1 HP devices. There are 2 kΩ polysilicon resistors placed in series between the base of the transistors and the base pads, in order to avoid high frequency oscillations of the devices during measurements. The value of these resistors did not change with radiation. There are also direct contacts to the base of the transistors, although we did not use them in our measurements.

III. EXPERIMENT AND MEASUREMENTS

In order to evaluate the displacement damage created on the devices due to radiation, we performed neutron irradiations on several test chips. Neutron irradiations were performed in the TRIGA nuclear research reactor facilities, in Jozef Stefan Institute (JSI), Ljubljana, Slovenia. Five fluences were reached: 2x10^{13}, 2x10^{14}, 6x10^{14}, 1x10^{15} and 5x10^{15} cm^{-2} (1 MeV n$_{eq}$). In order to minimize the activation of the samples during irradiation, we glued the test chips on bare Si boards with no additional material. Devices were irradiated with all terminals floating. Previous studies performed on other SiGe bipolar transistors showed that devices do not change their radiation behaviour with respect to different bias configurations during neutron irradiations [8]. All irradiations were performed with a cadmium (Cd) shielding surrounding the samples to reduce the effect of thermal neutrons [9]. All results shown here correspond to devices that have gone through 15 days of room temperature annealing after irradiation. Nevertheless, room temperature annealing showed no significant effect on the performance of the devices under test.

Forward Gummel plots (FGP) of the transistors were measured before and after irradiation. Measurements were performed in a CASCADE manual probe test bench with a HP4155B semiconductor parameter analyzer. FGPs were obtained in common-emitter configuration, which means sweeping V_{BE} from 0 to 1 V (applying a sweep in V_E from 0 to -1 V and keeping $V_B = V_S = V_C = 0$ V). In order to evaluate the degradation created on the samples by neutron irradiations, several figures-of-merit were extracted from the FGPs: the common-emitter current gain of the transistors after irradiations, $\beta_f = I_{Cf}/I_{Bf}$, the change in their reciprocal gain, $\Delta(1/\beta) = 1/\beta_F - 1/\beta_0$, and their normalized current gain, $\beta_N = \beta_f/\beta_0$. All these parameters were extracted at $V_{BE} = 0.75$ V, an arbitrary selection corresponding to or close to the injection levels that these transistors are expected to work in the real circuits.

IV. RESULTS

The main effect of non-ionizing radiation on the characteristics of a SiGe bipolar transistor is an increase of the base current (I_B), which produces a reduction in the common emitter current gain ($\beta_f = I_{Cf} / I_{Bf}$). This effect becomes more important at lower injection levels, as can be seen as in Fig. 3 for IBM 8WL 1x1 transistors.

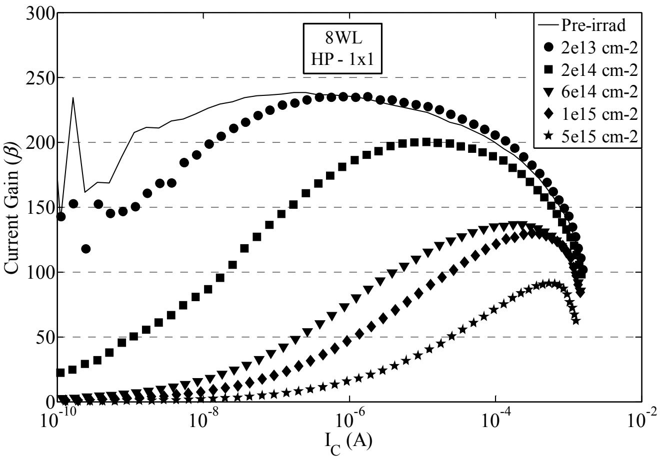

Figure 3: Final current gain (β_f) versus collector current (I_C) for transistors *HP - 1x1* after different neutron fluences

A. Neutron irradiations

Fig. 4 shows the value of the common-emitter current gain (β_f) for the different transistor types versus the neutron fluence. This parameter illustrates the absolute gain degradation of the devices. As it can be observed from the figure, transistors remain with values of β_f above 50 at the target values of neutron fluence (~1x10^{13} cm^{-2} for LAr and ~1x10^{15} cm^{-2} for Si Tracker). These final values of β_f are within the circuit operation specifications. In spite of this, a very severe degradation of the devices at the highest fluence reached in the experiment (5x10^{15} cm^{-2}) can also be observed. This fluence value is far beyond the maximum fluence expected in the "short-strips" region of the Si Tracker.

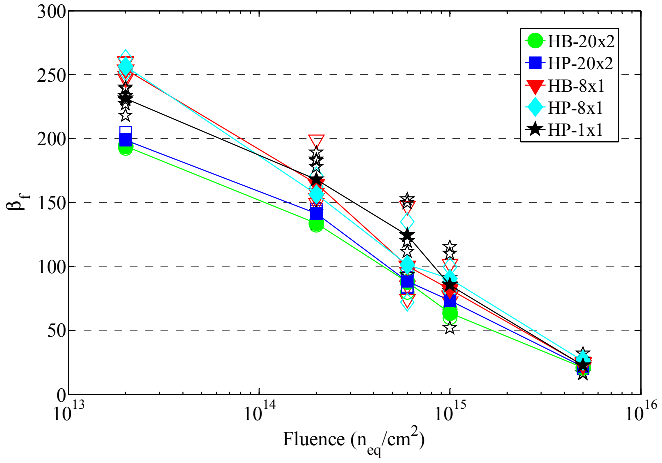

Figure 4: Final current gain (β_f) versus neutron fluence for all transistor types. Filled points correspond to mean values.

The values of the reciprocal gain ($\Delta(1/\beta)$) versus neutron fluence are shown in Fig. 5. The figure demonstrates a very clear linear dependence of the radiation damage created on the transistors with the non-ionizing particle fluence, as expected from the literature [10]. The linear fits of the mean values for each type of transistor are also shown in the figure.

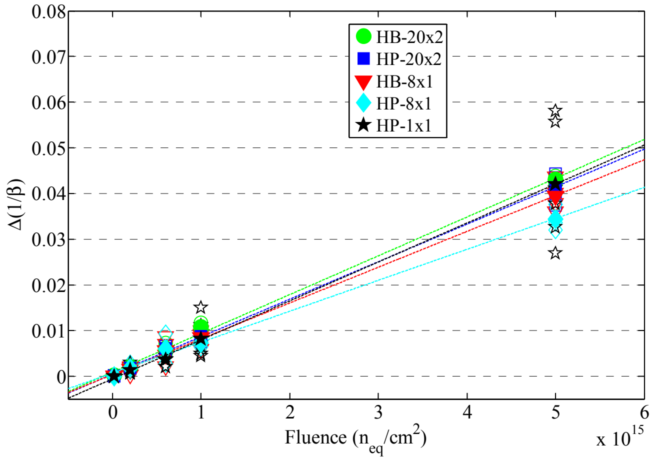

Figure 5: Variation of reciprocal current gain ($\Delta(1/\beta)$) versus neutron fluence for all transistor types. Filled points correspond to mean values. Linear fits of the mean values are also represented.

Fig. 6 shows the value of the normalized current gain (β_N) for the different devices under study. This figure of merit is useful for the comparison of the behaviour under radiation of the different transistor types, as it cancels the dependence of the damage with the value of the initial gain (β_0), which varies substantially from one transistor type to the other. The figure illustrates that degradation is very similar for all transistor types and geometries studied in this experiment.

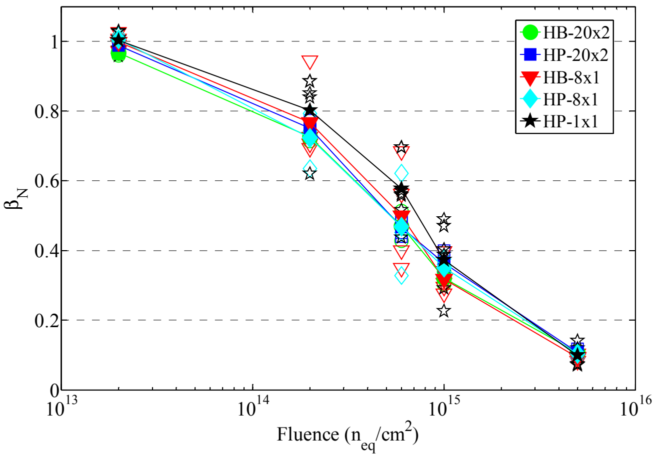

Figure 6: Normalized current gain (β_N) versus neutron fluence for all transistor types. Filled points correspond to mean values.

B. Transistor damage variability

Preliminary radiation studies performed on bipolar devices from IBM 8WL technology revealed high variability on the performance of irradiated transistors, especially after neutron irradiations [3]. Variability of results could lead to an undesirable excessive mismatching in the final circuit. At that time, we attributed this effect to possible problems in the test structure which was not designed by the authors, but obtained from the foundry as "spare" pieces. We decided to repeat the experiment with design-kit transistors and fabricated within process specifications as it is done in the present study.

For the study of the variability of results in this experiment, we calculated the value of the standard deviation (σ) of the base current after irradiation, and then normalized this value to the mean value of the mean base current, that is $\sigma_N = \sigma(I_{Bf})/I_{Bf}$. This value is shown in Fig. 7 for the different fluences and transistor types.

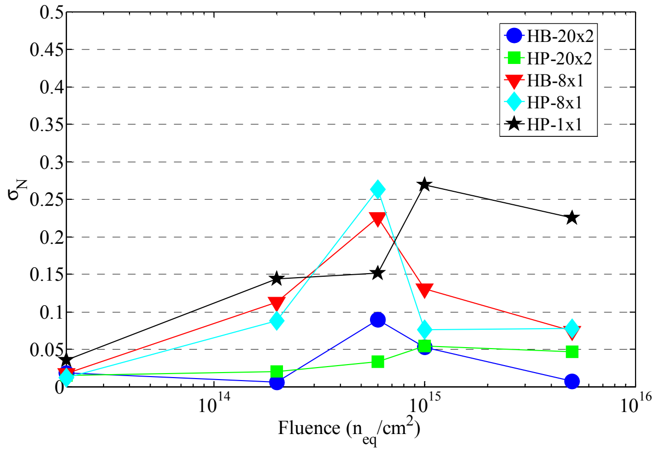

Figure 7: Normalized standard deviation (σ_N) of the final base current (I_{Bf}) versus neutron fluence for all transistor types.

The figure shows that dispersion of the results is smaller than the one observed in the previous experiments, in which values of σ_N were above 0.6 in all the cases (these values can be calculated from the results reported in [3]). It can also be observed that variability increases for smaller emitter geometries as it is always expected in mismatching measurements. Some small fluence dependence can be derived from the figure. We believe this effect may be related to low probable nuclear interactions of the neutrons with the nucleus in the lattice of the devices under study, that produce high damage in the active region of the devices with low statistics. Nevertheless, variability is not fully understood, and a deeper study of this effect is ongoing. Results from gamma irradiations in progress, which only produce ionizing damage on the samples, will be a great help to understand this effect. In any case, current gain values remain above 50 at the target fluence even in the worst-case transistor, as can be observed in Fig. 4.

V. CONCLUSIONS

We have performed neutron irradiations on bipolar devices of the 130 nm 8WL Silicon Germanium (SiGe) BiCMOS technology from IBM, in order to study its radiation hardness. Devices remained at sufficiently good performances at the target values of fluence expected in the Si tracker and the LAr calorimeter of the ATLAS Upgrade experiment. We observed some variability on the results that has still to be understood. Nevertheless, transistors remain functional with sufficient performance even in the worst cases.

REFERENCES

[1] F. Gianotti et al. "Physics potential and experimental challenges of the LHC luminosity Upgrade," *The European Physics Journal C- Particles and fields*, vol 39(3), pp. 293-333, 2005.

[2] G. Darbo, et al. "Outline of R&D Activities for ATLAS at an Upgraded LHC," CERN document COM-GEN-2005-002, Jan 2005.

[3] M. Ullán et al. "Evaluation of Silicon-Germanium (SiGe) Bipolar Technologies for Use in an Upgraded ATLAS Detector," *Nuclear Instruments and Methods in Physics Research A*, vol. 604, Issue 3, pp. 668-674, 2009.

[4] S.Díez et al. "IHP SiGe:C BiCMOS technologies as a suitable backup solution for the ATLAS Upgrade Front-End electronics," *IEEE Trans. on Nuclear Science*, vol 56 (4), pp. 2449-2456, 2009.

[5] A. Grillo et al. "A Prototype Front-End Readout Chip for Silicon Microstrip Detectors Using an Advanced SiGe Technology," *Topical Workshop on Electronics for Particle Physics 2009 (TWEPP 09),* Workshop Proceedings, 2009.

[6] M. Newcomer et al. "A SiGe ASIC Prototype for the ATLAS LAr Calorimeter Front-End Upgrade," *Topical Workshop on Electronics for Particle Physics 2009 (TWEPP 09),* Workshop Proceedings, 2009.

[7] J. D. Cressler, A. Sutton, M. Bellini, A. Madan, S. Phillips, A. Appaswamy, T. Cheng. "Radiation Effects in SiGe Devices", *MURI Review*, Vanderbilt University, Nashville, TN, 2008.

[8] M. Ullán, et al. "Radiation damage of SiGe HBT Technologies at different bias configurations," *Topical Workshop on Electronics for Particle Physics 2008 (TWEPP 2008)*, Workshop Proceedings, 2008.

[9] I. Mandic et al. "Bulk damage in DMILL npn bipolar transistors caused by thermal neutrons versus protons and fast neutrons," *IEEE Trans. on Nuclear Science,* vol. 51(4), pp. 1752-1758, 2004.

[10] G. C. Messenger and J. P. Spratt, "The effects of neutron irradiation on germanium and, silicon" *Proc. IRE*, vol. 46, pp. 1038–1044, 1958.