Evaluation of the Radiation Tolerance of Several Generations of SiGe Heterojunction Bipolar Transistors Under Radiation Exposure

J. Metcalfe, D. E. Dorfan, A. A. Grillo, A. Jones, F. Martinez-McKinney, P. Mekhedjian, M. Mendoza, H. F. – W. Sadrozinski, G. Saffier-Ewing, A. Seiden, E. Spencer, M. Wilder
University of California Santa Cruz

R. Hackenburg, J. Kierstead, S. Rescia
Brookhaven National Laboratory

J. D. Cressler, G. Prakash, A. Sutton
Georgia Institute of Technology

***Abstract*-For the potential use in future high luminosity applications in High Energy Physics (HEP) (e.g. the Large Hadron Collider (LHC) upgrade), we evaluated the radiation tolerance of several candidate technologies for the front-end of the readout Application-Specific Integrated Circuit (ASIC) for silicon strip detectors. The devices investigated were first, second and third-generation Silicon-Germanium (SiGe) Heterojunction Bipolar Transistors (HBTs).**

The DC current gain as a function of collector current was measured before and after irradiation with 24 GeV protons up to fluences of 10^{16} p/cm^2 and with a ^{60}Co gamma source up to 100 MRad. The analog section of an amplifier for silicon strip detectors typically has a special front transistor, chosen carefully to minimize noise and usually requiring a larger current than the other transistors, and a large number of additional transistors used in shaping sections and for signal-level discrimination. We discuss the behavior of the three generations of transistors under proton and gamma exposure, with a particular focus on issues of noise, power and radiation limitations.

***Index Terms*— Bipolar transistors, Gain measurement, Germanium, Integrated circuits, Radiation effects**

I. INTRODUCTION

Bipolar circuits using bandgap-engineered SiGe technology [1] have potential advantages when compared with Complementary Metal Oxide Semiconductor (CMOS) for fast shaping times and large capacitive loads. As a front device for large detector loads and fast shaping times, SiGe HBTs have excellent noise/power ratios, minimal base resistance, and high output impedance. For fast shaping times, SiGe HBTs have very efficient bandwidth/power ratios. Thus, they are good candidates for the technology choice of the front-end of readout ASICs for the silicon strip detectors planned for the LHC upgrades, if their radiation hardness up to a fluence level of 10^{15} p/cm^2 can be proven [2], [3].

In a future high luminosity collider, e.g. the LHC upgrade, the instantaneous flux of particles dictates the detector geometry as a function of radius. In the inner detector layers, pixel detectors will be needed, and their small capacitances allow the use of deep sub-micron CMOS as an efficient readout technology.

Starting at a radius of about 20 cm, short strips can be employed, with a detector length of about 3 cm and capacitances of the order of 5 pF. This is the region where the accumulated fluence over the detector lifetime (5 years) is about 10^{15} p/cm^2. At a radius of about 60 cm, the expected fluence is about a few times 10^{14} p/cm^2, and longer strips of about 10 cm with capacitance of 15 pF can be used. In the two outer regions where bipolar SiGe might be used in the front-end readout ASICs, power savings and fast shaping to identify the beam time crossing are important requirements [4].

We present the measurements of the DC current gain as a function of collector current for a variety of SiGe HBTs manufactured in the IBM 5AM, 7HP and 8HP processes, taken before and after irradiation at proton fluences up to 10^{16} p/cm^2 and photon doses up to 100 MRad. Previous studies by others on the radiation tolerance of 5HP SiGe HBTs have been performed, but only up to proton fluences of 5×10^{13} p/cm^2, not sufficient for qualification for the use at the sLHC [5]. Studies on the radiation tolerance of other SiGe technologies exposed to gamma and neutron irradiation have also been conducted by others in the past [6], [7].

The data allows the design and layout of prototype front-end ASICs and their optimization with respect to noise performance as a function of strip length and with respect to power consumption.

II. DEVICES

The devices were a variety of SiGe HBTs manufactured by IBM [8]. Three generations of devices were tested including the 5AM, 7HP and 8HP. Several sizes of a modified (gain-enhanced) 5AM HBT were tested under proton irradiation. There were 6 sets (one for each fluence step) of transistors each containing one 0.5×1 μm^2, two 0.5×2.5 μm^2, five 0.5×10 μm^2, one 0.5×20 μm^2, and one 4×5 μm^2. A variety of sizes of 5AM, 7HP and 8HP devices were tested under gamma irradiation. For the 5AM, two of each of the following sizes were tested: 0.5×1 μm^2, 0.5×2.5 μm^2, and 0.5×20 μm^2. Two of each size were also tested for the 7HP: 0.2×1.2 μm^2, 0.2×2.5 μm^2, 0.2×5 μm^2, and 0.2×10 μm^2. For the 8HP, two sets were tested—one shorted and one biased. Each set contained two 0.12×1 μm^2, two 0.12×2 μm^2, two 0.12×4 μm^2, and two 0.12×8 μm^2 transistors.

III. IRRADIATIONS

Proton and gamma irradiations were performed. The proton irradiations were performed at CERN in October of 2004 with 24

GeV protons as part of the common RD50 project [9]. The following fluence steps were taken: 4.15×10^{13}, 1.15×10^{14}, 3.50×10^{14}, 1.34×10^{15}, 3.58×10^{15}, 1.05×10^{16} p/cm^2. The devices were irradiated with all terminals shorted. Studies indicate this is a worst-case scenario compared to irradiation under operating bias conditions [5]. The irradiations were performed at room temperature at constant flux (with the highest fluence taking 5 days). The samples were stored at –23 ^{o}C. It is assumed that no appreciable annealing occurred while the transistors were at -23 ^{o}C. Several annealing steps were performed after irradiation until full annealing was achieved (11 days at room temperature (20 ^{o}C) plus one day at 60 ^{o}C plus seven days at 100 ^{o}C at which point there was no appreciable change in the device performance).

The gamma irradiations were performed in May 2006 at Brookhaven National Laboratories using a ^{60}Co source. A single set of devices were irradiated at dose steps of 0.5, 1, 5, 10, 50 and 100 MRads and measured at each step. The devices were irradiated at room temperature with a total exposure of approximately 2 weeks and stored in a freezer between irradiations to prevent unnecessary annealing.

IV. RESULTS ON TRANSISTOR PERFORMANCE

A. Proton Irradiation Results

The Forward Gummel plot (Fig. 1) for the fluence of 1×10^{15} p/cm^2 shows the degradation in the base current after irradiation and annealing. This is the typical response for a SiGe HBT exposed to proton irradiation. Fig. 2 shows the plot of the DC current gain, β (□□□□), versus collector current for a 0.5×10 μm^2 transistor at several fluences. The general performance of the SiGe HBTs is marginally still acceptable at 4×10^{15}. The data at each fluence is shown after full annealing. For further details see [10].

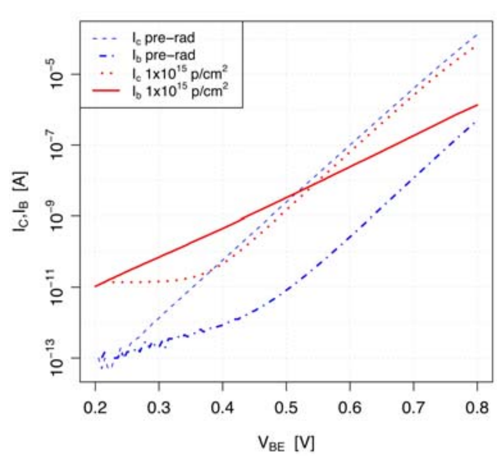

Fig. 1. The Forward Gummel plot is shown for a 0.5x2.5 μm^2 SiGe HBT at 1×10^{15} p/cm^2. After irradiation and annealing, the base current increases substantially while the collector current remains the same causing the gain of the device to decrease.

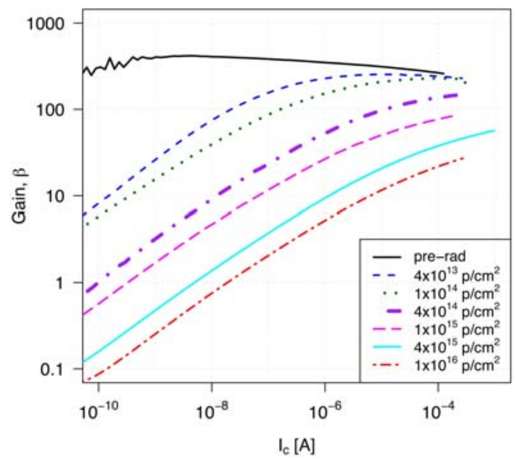

Fig. 2: Current gain (β) vs. collector current I_c for a 0.5x10 μm^2 device for several proton fluences, including full annealing. The gain of the transistor degrades with increasing fluence. Performance is still acceptable at 4×10^{15} p/cm^2.

B. Gamma Irradiation Results

Figures 3-5 display the DC current gain, β, as a function of collector current, I_C, for each dose of a minimally sized structure. Figure 3 shows data from a 0.5x1 μm^2 5AM device. Figure 4 presents data from a 0.2x2.5 μm^2 7HP device. Figure 5 displays the results from a 0.12x2 μm^2 8HP device. The degradation for the 5AM and 8HP devices show a similar pattern while the 7HP devices degrade more rapidly—even at high currents the initial gain cannot be recovered. The difference is accountable due to the manufacture of the Emitter-Base (EB) spacer oxide region. "Ionizing radiation has been shown to damage the EB spacer region in these SiGe HBTs, and produce a perimeter-dependent space-charge generation/recombination (G/R) base-current leakage component that progressively degrades the base current (and current gain) as the fluence increases. …the 7HP device degrades much more rapidly than the 5HP device. This result is consistent with significantly higher EB electric field under the EB spacer region in the 7HP device, which has both more abrupt doping profiles…as well as a decreased EB spacer thickness compared to the 5HP device…" [11]

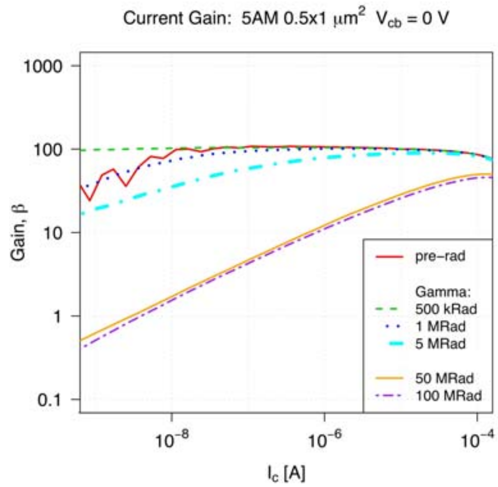

Fig. 3: Current gain (β) vs. collector current I_c for a 5AM 0.5x1 μm^2 device for several gamma doses. The gain of the transistor degrades similarly to the 8HP HBT.

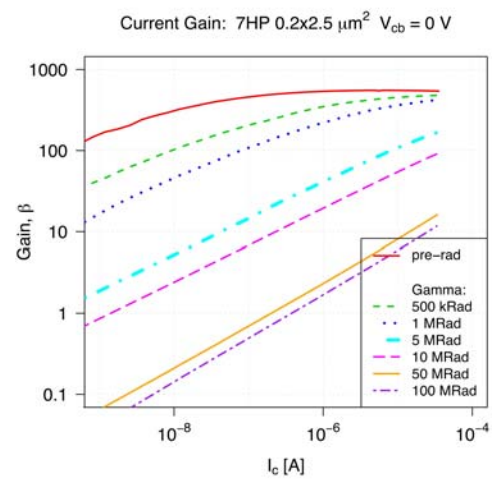

Fig. 4: Current gain (β) vs. collector current I_c for a 7HP 0.2x2.5 μm^2 device for several gamma doses. The gain of the transistor degrades more rapidly than the 5AM or the 8HP HBT.

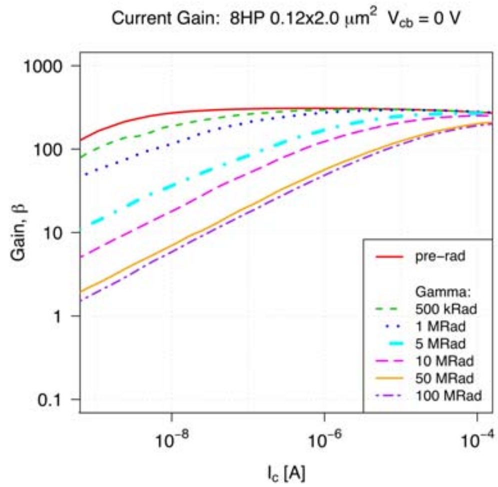

Fig. 5: Current gain (β) vs. collector current I_c for an 8HP 0.12x2 μm^2 device for several gamma doses. The gain of the transistor degrades similarly to the 5AM HBT. The 8HP generation shows the most resistance to radiation damage.

C. Radiation Damage Mechanisms

The inherent structural design of SiGe HBTs lends itself to an enhanced tolerance to radiation damage. The small active volume of the transistor reduces the effects of displacement damage. The emitter-base spacer (the spot most susceptible to ionization damage) is also relatively thin and comprised of an oxide/nitride composite, which increases radiation tolerance. The high base doping beneath the EB spacer also favorably affects the radiation tolerance [12].

There are two principal mechanisms that cause radiation damage—ionization damage and displacement damage (DD). Ionization damage creates oxide trapped charges and interface states in the EB spacer region, consequently increasing the base current and degrading the DC current gain of the device, as shown in the Forward Gummel plot in Fig. 1. The displacement damage shortens hole (minority carrier) lifetime, which is inversely proportional to the base current, thus also degrading the base current and gain [11], [12]. A comparison of the radiation damage caused by protons and photons at approximately equivalent exposure levels reveals comparable damage. Figure 6 shows the damage caused by gammas and protons on 0.5x20 μm^2 devices for several exposure equivalents. Although the initial devices have different starting gains (the device for proton irradiation is a gain-enhanced 5AM device), the resulting damage is very similar. This supports the suggestion that SiGe HBTs are most susceptible to ionization damage. Further studies are currently underway to verify this hypothesis.

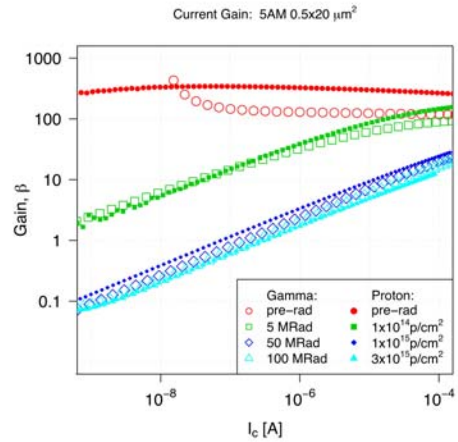

Fig. 6: Current gain (β) vs. collector current I_c for 0.5x20 μm^2 device under gamma and proton irradiations of similar exposure. The degradation in the gain is similar for both radiation sources.

D. Effects of Biasing During Irradiation

The effects of biasing the transistors during irradiation were studied. The devices were biased at 100 μA during irradiation. Figure 7 shows the DC current gain, β, versus collector current, I_C, for 0.12x4.0 μm^2 8HP devices that were biased (solid lines) and shorted (dashed lines) for several doses. The gain for the biased transistor started at a lower gain value (normal fluctuations in the starting gain), but by 5 MRads showed less radiation damage. At higher doses this effect becomes enhanced indicating that device performance at high doses for SiGe HBTs shorted during irradiation will be improved in an environment where the transistor will be in operation. From now on the reported gamma results will refer to biased devices if not specifically noted otherwise.

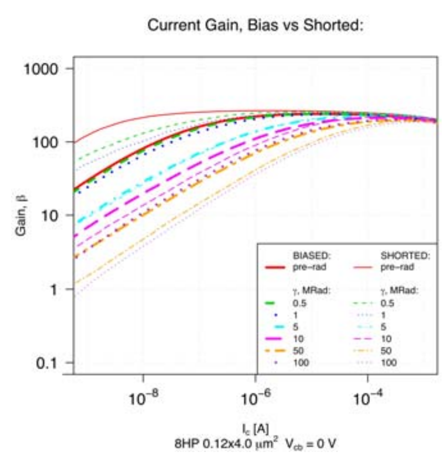

Fig. 7: Current gain (β) vs. collector current I_c for an 8HP 0.12x4 μm^2 device for biased and shorted devices for several doses. Although the shorted HBT starts at a higher non-irradiated gain value, it degrades more rapidly than the biased transistor.

E. Device Scaled Irradiation Damage

The similarity of the radiation induced degradation in performance of different device sizes is shown in Figures 8 and 9 where $\Delta(1/\beta)$, the difference between $1/\beta$ post-rad and $1/\beta$ pre-rad, is plotted versus fluence and dose respectively, for all devices at a given current density, J_c=10 $\mu A/\mu m^2$ and J_c=16 $\mu A/\mu m^2$ respectively. (Note that in Figures 8 and 9 there are a few missing points. This is a result of device failure most likely due to ESD and uncorrelated with radiation exposure.) As expected, for equal current density, the radiation damage is a unique function of the fluence, independent of the transistor geometry, with the notable exception of the 4×5 μm^2 device in the case of the proton irradiated samples and the biased devices under gamma irradiation. As expected, the values are nearly linear with the log of the fluence and are reasonably consistent. This allows one to predict the performance of similar devices and will guide further test structure investigation, as well as optimization of noise and power.

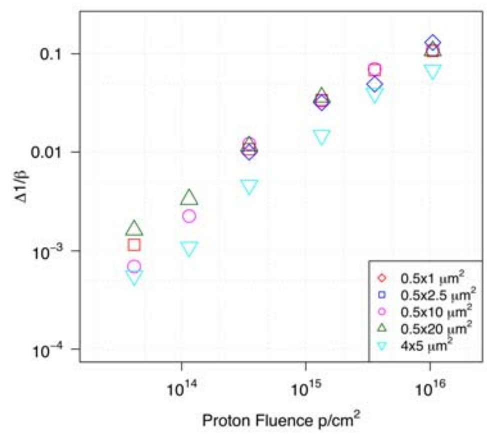

Fig. 8: Difference of $1/\beta$ post-rad and pre-rad vs. fluence for all sizes of gain-enhanced 5AM devices at a fixed collector current density of J_c = 10 $\mu A/\mu m^2$, after annealing. The geometries scale with collector current density. $\Delta 1/\beta$ depends little on the initial gain value revealing a tighter linear fit. We also see that the devices with a higher aspect ratio are more affected by radiation damage especially at lower fluences probably due to the larger perimeter-to-area ratio of the EB spacer.

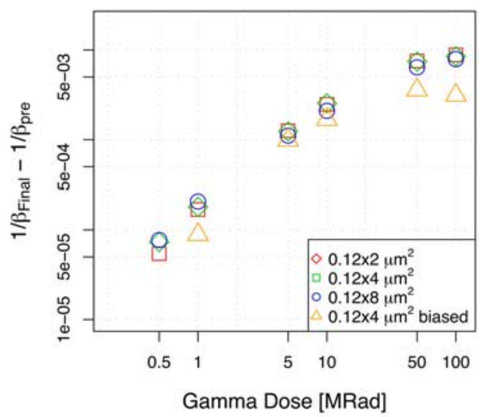

Fig. 9: Difference of 1/β post-rad and pre-rad vs. dose for all sizes of 8HP devices at a fixed collector current density of J_c = 16 μA/μm^2. The geometries scale with collector current density. Δ1/β depends little on the initial gain value revealing a tighter linear fit. The biased HBT shows a divergence from the shorted HBTs.

V. CONSIDERATIONS FOR FRONT-END READOUT ASICS FOR SILICON STRIP DETECTORS

As mentioned above, we will consider for the LHC upgrade two different regions (radii of 20cm and 60cm) where bipolar technology could be potentially used. The regions are characterized by detector capacitances of about 5 pF at fluences near 10^{15} p/cm^2 ("short strips") and capacitances of about 15 pF at fluences near 10^{14} p/cm^2 ("long strips"), respectively. In the so-called binary readout systems for silicon strips, the front-end consists of an analog amplifier-shaper-comparator circuit followed by a digital data storage and data transfer section. While the front-end is a candidate for bipolar technology, the latter two parts are built with CMOS circuitry, thus requiring a BiCMOS technology. We note that all commercially available SiGe technologies embody both SiGe HBTs and standard Si CMOS. The analog section of an amplifier typically has a special front transistor, chosen carefully to minimize noise and usually requiring a larger current than the other transistors, and a large number of additional transistors used in shaping sections and for signal-level discrimination. Our experience with the design of bipolar front-end readout for silicon detectors [13], [14], indicates that DC current gains of about β = 50 are required for efficient circuit designs. In Table I, the currents required to reach a DC current gain of β = 50 are shown for the different gain-enhanced 5AM transistors investigated after proton irradiation to a fluence of 3.5×10^{14} p/cm^2 and 1.3×10^{15} p/cm^2, with and without annealing. Table II shows the collector current required to reach a gain of 50 for the 5AM, 7HP and 8HP transistors exposed to gamma irradiation up to a dose of 100 MRad.