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Evaluation of the radiation tolerance of several generations of SiGe heterojunction bipolar transistors under radiation exposure

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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.

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1. Introduction

Bipolar circuits using bandgap-engineered silicon–germanium (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 heterojunction bipolar transistors (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 application-specific integrated circuit (ASIC) for the silicon strip detectors planned for the large hadron collider (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

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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 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.

2. 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 six sets (one for each fluence step) of transistors each containing one $0.5 \times 1\,\mu$m^2, two $0.5 \times 2.5\,\mu$m^2, five $0.5 \times 10\,\mu$m^2, one $0.5 \times 20\,\mu$m^2 and one $4 \times 5\,\mu$m^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, 0.5×2.5 and $0.5 \times 20\,\mu$m^2. Two of each size were also tested for the 7HP: 0.2×1.2, 0.2×2.5, 0.2×5 and $0.2 \times 10\,\mu$m^2. For the 8HP, two sets were tested—one shorted and one biased. Each set contained two $0.12 \times 1\,\mu$m^2, two $0.12 \times 2\,\mu$m^2, two $0.12 \times 4\,\mu$m^2 and two $0.12 \times 8\,\mu$m^2 transistors.

3. Irradiations

Proton and gamma irradiations were performed. The proton irradiations were performed at CERN in October 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} and 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 $-23\,^\circ$C. It is assumed that no appreciable annealing occurred while the transistors were at $-23\,^\circ$C. Several annealing steps were performed after irradiation until full annealing was achieved (11 days at room temperature (20 °C), plus 1 day at 60 °C, plus 7 days at 100 °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.

4. Results on transistor performance

4.1. 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, $\beta(I_C/I_B)$, vs. collector current for a $0.5 \times 10\,\mu$m^2 transistor at several fluences. The general performance of the SiGe HBTs is marginally still acceptable at 4×10^{15} p/cm^2. The data at each fluence are shown after full annealing. For further details, see Ref. [10].

4.2. Gamma irradiation results

Figs. 3–5 display the DC current gain, β, as a function of collector current, I_c, for each dose of a minimally sized structure. Fig. 3 shows data from a $0.5 \times 1\,\mu$m^2 5AM device. Fig. 4 presents data from a $0.2 \times 2.5\,\mu$m^2 7HP

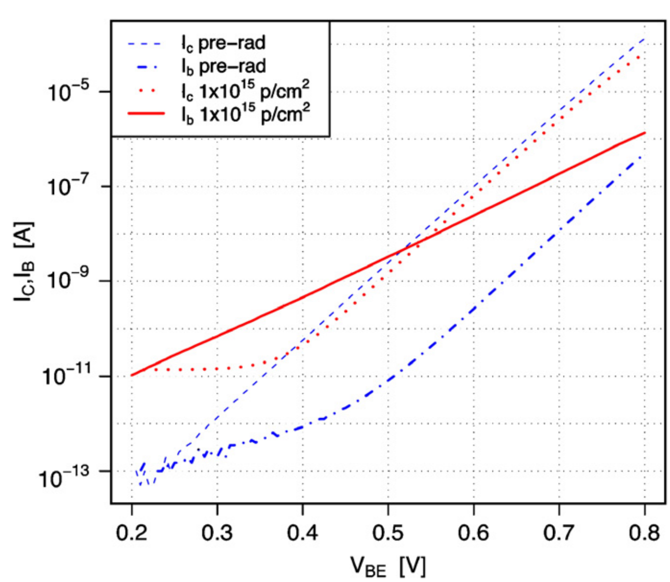

Fig. 1. The Forward Gummel plot is shown for a $0.5 \times 2.5\,\mu$m^2 SiGe HBT at 1×10^{15} p/cm^2. After irradiation and annealing, the base current increases substantially while the collector current remains the same causing the gain of the device to decrease.