Proton Tolerance of SiGe Precision Voltage References for Extreme Temperature Range Electronics

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***Abstract*—A comprehensive investigation of the effects of proton irradiation on the performance of SiGe BiCMOS precision voltage references intended for extreme environment operational conditions is presented. The voltage reference circuits were designed in two distinct SiGe BiCMOS technology platforms (first generation (50 GHz) and third generation (200 GHz)) in order to investigate the effect of technology scaling. The circuits were irradiated at both room temperature and at 77 K. Measurement results from the experiments indicate that the proton-induced changes in the SiGe bandgap references are minor, even down to cryogenic temperatures, clearly good news for the potential application of SiGe mixed-signal circuits in emerging extreme environments.**

***Index Terms*—BiCMOS analog integrated circuits, heterojuction bipolar transistors, proton radiation effects.**

I. INTRODUCTION

PRECISE voltage references find application in virtually all electronic circuits and systems, including analog-to-digital and digital-to-analog converters, and thus are key components for many space exploration applications (e.g., robotic missions to the lunar surface). In such cases, having electronic circuits that operate robustly under extreme environment conditions (e.g., under radiation exposure and over wide temperature ranges) can greatly improve robotic system performance and reliability by eliminating the need for shielded "warm boxes" and their consequent highly-centralized architectures (the current practice, for instance, on the Moon and Mars). For applications on the Moon, for instance, the ambient temperature under which electronic circuits are desired to function can range from +120°C (in the sunshine) to −230°C (in shadowed polar craters). At such extremely low temperatures, among all available IC technologies, SiGe heterojunction bipolar transistor (SiGe HBT) technology has emerged as a viable candidate [1]. It is well known that Si bipolar transistors do not operate well at cryogenic temperatures [1] and the reliability of CMOS devices generally worsens with cooling, especially below 77 K [2]. From a radiation perspective, previous studies have confirmed the overall robustness of SiGe technologies to total ionizing dose [3], [4]

In this paper we present, for the first time, SiGe bandgap voltage references (BGRs) designed specifically for such emerging extreme environment applications. The degradation of precision reference circuits due to proton irradiation has been previously investigated in [5]–[8]. In [5]–[7], however, only Si BJT voltage references were investigated, and to date no studies on the effects of radiation on their wide-temperature-range behavior have been performed. The BGR circuits presented here employ both CMOS and SiGe HBT transistors, with the HBTs used in the core of the reference circuits. To investigate the effect of technology scaling on the performance of the circuits, the SiGe references studied in this paper were designed in two SiGe technologies: first- and third-generation SiGe technologies. One type of the SiGe circuits exploits an exponential curvature-compensation technique [9].

For radiation experiments, all of the samples were characterized before being irradiated with 63 MeV protons. Three different radiation experiments were performed. In the first experiment, voltage references from the two SiGe technologies were irradiated at room temperature, while being operated under bias. For the second experiment, the references from the two SiGe technologies were irradiated cold while under bias, and for the third experiment, one reference from the third-generation SiGe technology was irradiated at room temperature with all pins grounded. We present, for the first time, results on the effects of proton irradiation on these precision SiGe references down to temperatures as low as −263°C.

II. PROCESS TECHNOLOGY

The bandgap voltage references used for this study were implemented in both commercially-available first- and third-generation SiGe BiCMOS technologies. The first-generation SiGe technology (IBM SiGe 5AM) is a four-level metal process and features SiGe HBTs with an emitter width of 0.5 μm and a unity gain cut-off frequency and maximum frequency of oscillation of 45 GHz and 60 GHz, respectively, nMOS and pMOS transistors with a nominal L_{eff} of 0.35 μm, as well as polysilicon and diffused resistors, and various capacitors. The response of first-generation SiGe HBTs to proton irradiation has been reported previously [10].

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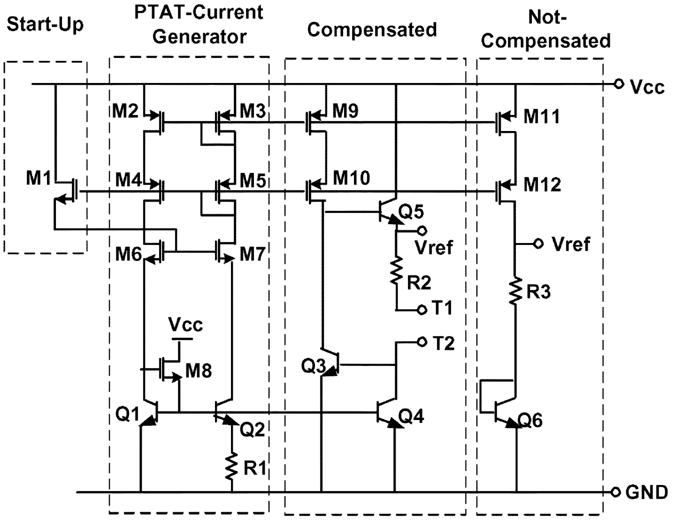

Fig. 1. Schematic of the 8HP SiGe bandgap references.

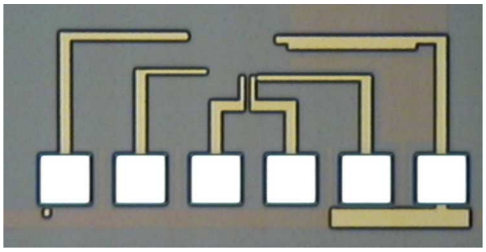

Fig. 2. Die micrograph of the 8HP SiGe bandgap references.

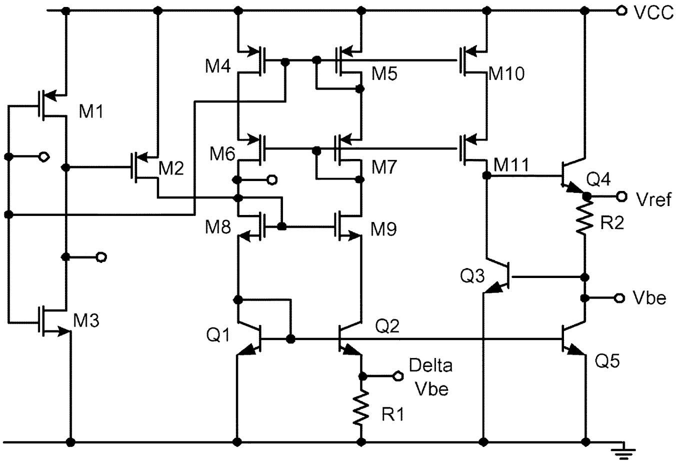

Fig. 3. Schematic of the 5AM SiGe bandgap reference.

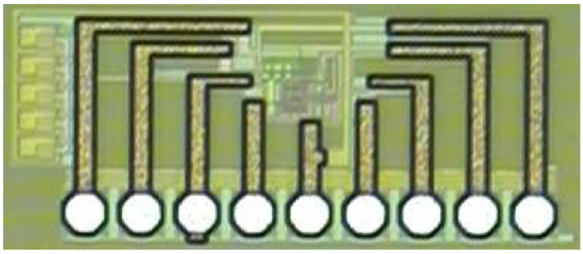

Fig. 4. Die micrograph of the 5AM SiGe bandgap reference.

IBM's third-generation SiGe technology (IBM SiGe 8HP) employs a reduced thermal cycle, "raised extrinsic base" structure utilizing conventional deep and shallow trench isolation, an in-situ doped polysilicon emitter, and an unconditionally stable, 25% peak Ge, C-doped, graded UHV/CVD epitaxial SiGe base [11]. The device structure has been scaled laterally to 0.12 μm emitter stripe width in order to minimize base resistance and improve the frequency response and broadband noise characteristics. Proton tolerance and the cryogenic performance of the SiGe HBTs in this technology have been previously reported in [4] and [12], respectively.

III. CIRCUIT DESCRIPTION

The schematic of the voltage references implemented in 8HP technology is shown in Fig. 1. The circuit consists of two bandgap voltage references: an exponential curvature-compensated BGR [9] which exploits the temperature characteristics of the current gain of the SiGe HBT for curvature compensation, and a first-order (uncompensated) version [13]. The geometry of all of the SiGe HBTs, except for the Q_2, is 0.12 × 5.0 μm^2. The area of transistor Q_2 consists of sixteen parallel copies of Q_1. Transistor M_1 is the startup circuit and transistors $M_2 - M_8$ and $Q_1 - Q_2$, along with the resistor R_1, generate the bias current for the various stages, which is proportional to the absolute temperature (PTAT). The third stage is designed to produce a curvature-compensated output voltage. Pads T_1 and T_2 are designed for external trimming (if required). The forth stage is simply a first-order bandgap reference, in which the negative temperature dependence of the base-emitter voltage of transistor Q_6 is canceled with the positive voltage generated by passing the PTAT current through the resistor R_3. Both circuits were designed for a power supply voltage of 2.5 V. The circuit, including the pads, occupies 0.87 × 0.43 mm^2. The micrograph of the SiGe reference is shown in Fig. 2. Since the 8HP process is a seven metal layer technology, the circuit is not easily seen below the top layers.

In first-generation SiGe technology, only the curvature-compensated reference was implemented. The schematic is shown in Fig. 3. Each of the bipolar transistors shown in this figure, except for Q_2, consists of four parallel copies of the $0.5 \times 2.5\ \mu\text{m}^2$ SiGe HBT. The area of transistor Q_2 is eight times larger than that of the other transistors. No pads were used for external trimming, while several pads have been inserted to monitor the nodes of individual transistors internal to the circuit. The circuit was designed for a power supply voltage of 3.3 V. With the pads, the circuit occupies an area of 1.3 × 0.4 mm^2 (Fig. 4). In all cases, careful layout techniques were employed to reduce transistor mismatch effects.

IV. EXPERIMENT

The major goal of this work was to carefully assess the impact of radiation exposure on precision voltage references operating down to very low temperatures. Such extreme conditions occur in many potential space exploration missions. Each circuit intended for test was mounted in a 28 pin ceramic DIP package, wire-bonded, and characterized before being sent for proton irradiation. The samples were irradiated with 63.3 MeV protons

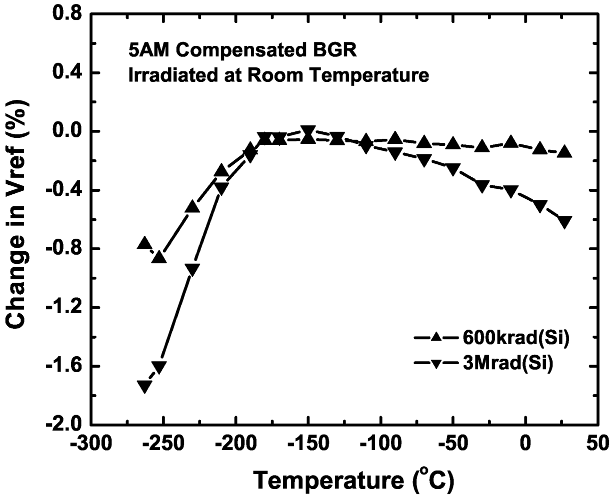

Fig. 5. Change in the output voltage of 5AM BGR irradiated at room temperature as a function of temperature.

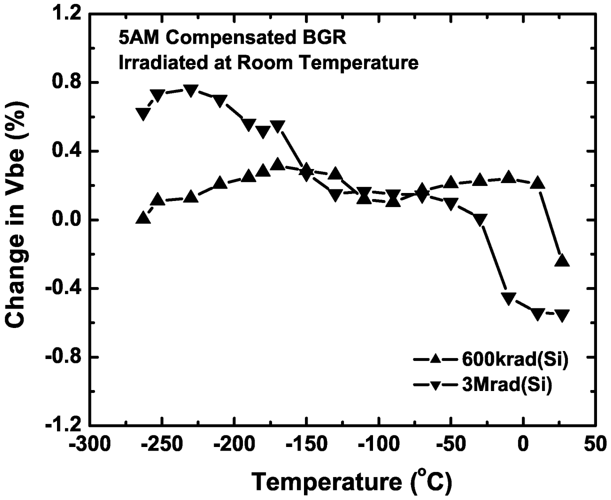

Fig. 6. Change in the base-emitter voltage of Q_3 inside 5AM BGR irradiated at room temperature as a function of temperature.

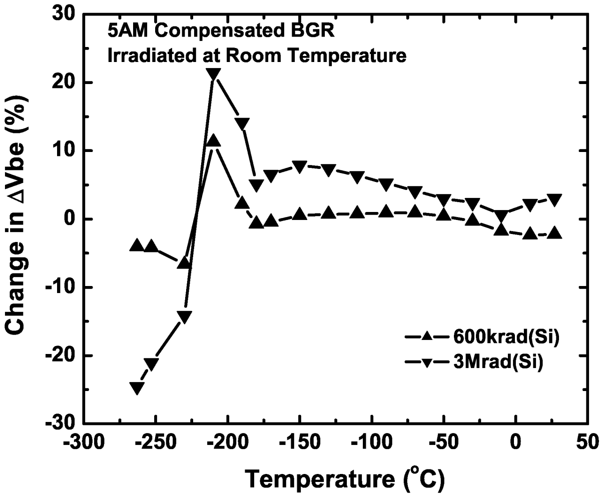

Fig. 7. Change in the difference of Q_1 and Q_2 base-emitter voltages of 5AM BGR irradiated at room temperature as a function of temperature.

at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup, and Ta scattering foils located several meters upstream of the target establish a beam spatial uniformity of 15% over a 2.0 cm radius circular area. The dosimetry system has been previously described [14], and is accurate to about 10%. Three different experiments were performed as follows:

A. *Experiment I*

The circuits from both SiGe technologies, while being kept under operational bias, were irradiated at room temperature. Two different equivalent total doses were used: 600 krad(Si) (a proton fluence of 4.3×10^{12} p/cm^2) and 3 Mrad(Si) (a proton fluence of 2.1×10^{13} p/cm^2).

B. *Experiment II*

The circuits from both SiGe technologies, while under bias, were inserted into a liquid nitrogen bath and were irradiated at 77 K. The output voltages of the 8HP references were measured at 77 K, during irradiation, at four total dose levels of 300 krad(Si), 600 krad(Si), 1 Mrad(Si) and 3 Mrad(Si). The measured equivalent total dose for the 5AM reference was 3 Mrad(Si) (a proton fluence of 2.1×10^{13} p/cm^2).

C. *Experiment III*

The curvature-compensated circuit from the third-generation SiGe technology was irradiated at room temperature, with all terminals grounded (previously shown to have negligible impact on the radiation response of individual SiGe HBTs [15]). The measured equivalent total dose was 600 krad(Si) (a proton fluence of 4.3×10^{12} p/cm^2).

V. RESULTS AND DISCUSSION

The output voltage of the circuits was measured before and after irradiation, at different temperatures ranging from 27°C down to −263°C. Electrical measurements were performed using an Agilent 4155 Semiconductor Parameter Analyzer. In the following sections, the measurement results of each experiment are discussed.

A. *Experiment I*

Measurement results from Experiment I are shown in Figs. 5–11. As mentioned above, in this experiment the samples were irradiated at room temperature while they were under bias. Fig. 5 shows the percentage change in the output voltage of the 5AM BGR as a function of temperature for total dose values of 600 krad(Si) and 3 Mrad(Si). Previous studies on the effects of radiation on precision voltage references usually report this percentage change as a function of total dose/proton fluence, but only at room temperature. Here, we have shown these changes down to extremely low temperatures. The percentage change was calculated according to

$$\Delta\mathrm{Vref(T)(\%)} = \frac{\mathrm{Vref}_{\mathrm{post-rad}}(\mathrm{T}) - \mathrm{Vref}_{\mathrm{pre-rad}}(\mathrm{T})}{\mathrm{Vref}_{\mathrm{pre-rad}}(\mathrm{T})} \times 100. \quad (1)$$

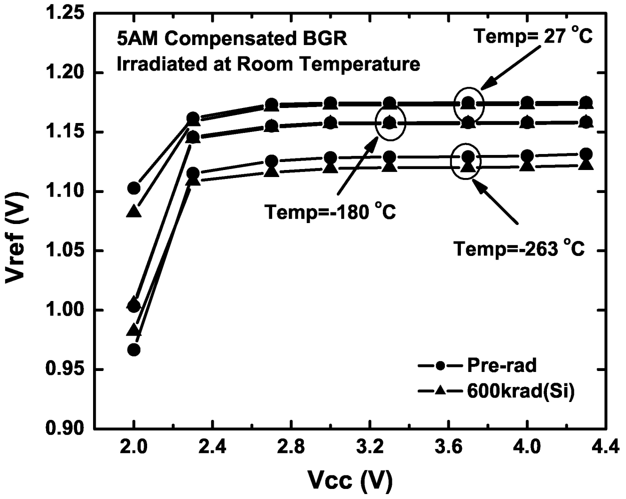

Fig. 8. Output voltage of the 5AM BGR irradiated at room temperature and total dose of 600 krad(Si) as a function of power supply at 27°C, −180°C and −263°C.

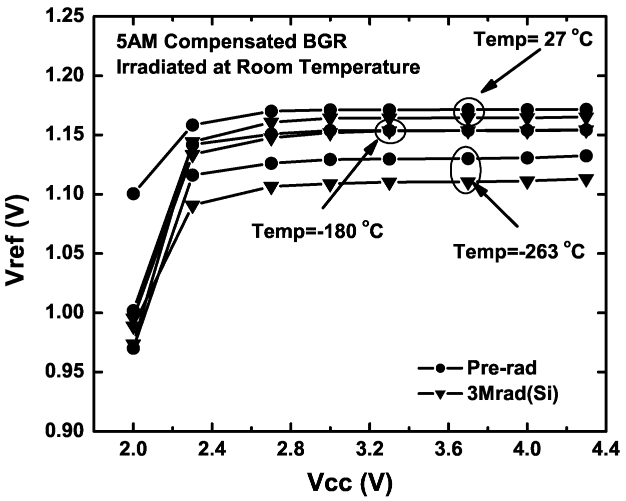

Fig. 9. Output voltage of the 5AM BGR irradiated at room temperature and total dose of 3 Mrad(Si) as a function of power supply at 27°C, −180°C and −263°C.

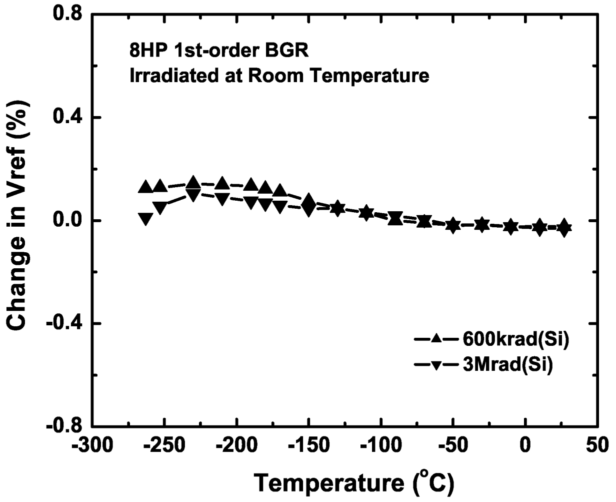

Fig. 10. Change in the output voltage of 1st-order 8HP BGR irradiated at room temperature as a function of temperature.

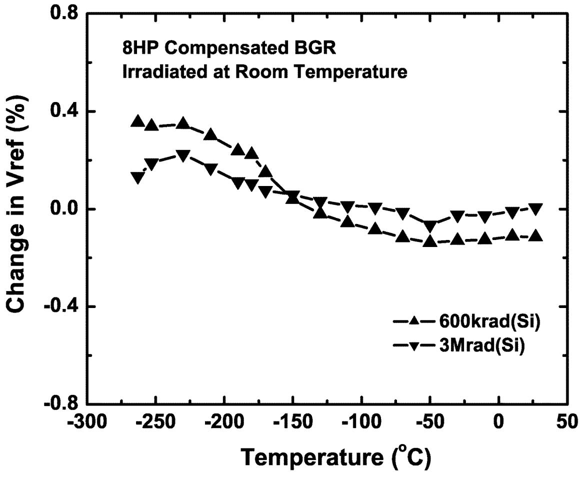

Fig. 11. Change in the output voltage of curvature-compensated 8HP BGR irradiated at room temperature as a function of temperature.

As can be seen, for the case of 3 Mrad(Si) total dose, the percentage change in the output voltage of 5AM BGR is larger than for the case of 600 krad(Si), and the percentage change becomes larger at very low temperatures. To assess what part of circuit plays the role in causing the value of the output voltage to change after the reference was irradiated, the base-emitter voltage of transistor Q_3 and the base-emitter voltage difference of transistors Q_1 and Q_2 were measured both before and after irradiation and their percentage changes have been plotted in Figs. 6 and 7, respectively. One can see that the percentage change in the base-emitter voltage difference is much larger than the percentage change in the base-emitter voltage, indicating that the PTAT current generator likely plays the main role in causing the output voltage to change following irradiation. For this PTAT current generator section to operate properly, the current in the two branches should remain equal. Any mismatches between the large and small area transistors in these two branches can degrade the overall performance of the circuit and measurement results confirms this assumption. Figs. 8 and 9 show the measured output voltage of the 5AM BGR as a function of power supply at three different temperatures for total doses of 600 krad(Si) and 3 Mrad(Si), respectively. It can be seen that the line regulation remains well-behaved across the extreme temperature range both before and after irradiation, clearly good news.

Figs. 10 and 11 show the percentage change in the output voltages of the 8HP first-order and curvature-compensated BGRs, respectively, for total dose values of 600 krad(Si) and 3 Mrad(Si). From these data, it can be seen that the circuits function well down to temperatures as low as −263°C. It can be observed that the proton-induced changes in the BGR are minor, even at cryogenic temperatures. Comparing the effects of proton radiation on the circuits for the two SiGe technologies, we can see that 5AM references are generally more susceptible to radiation damage than 8HP references, consistent with the overall TID robustness of the individual transistors [4].

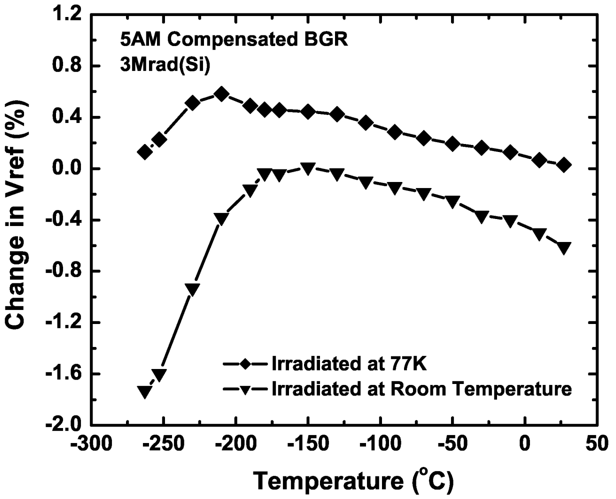

Fig. 12. Change in the output voltage of 5AM BGR irradiated at 77 K as a function of temperature.

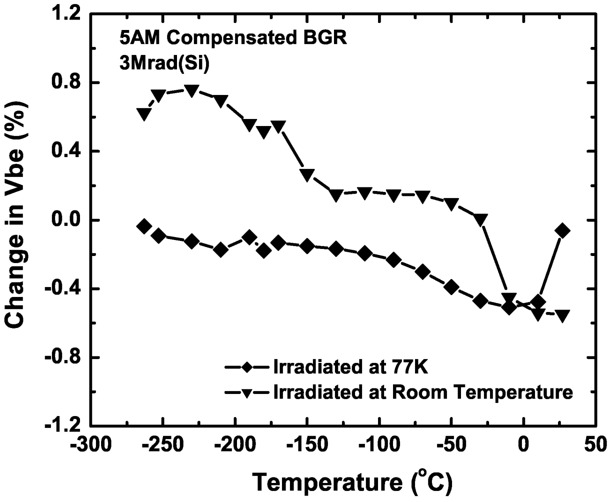

Fig. 13. Change in the base-emitter voltage of Q_3 inside 5AM BGR irradiated at 77 K as a function of temperature.

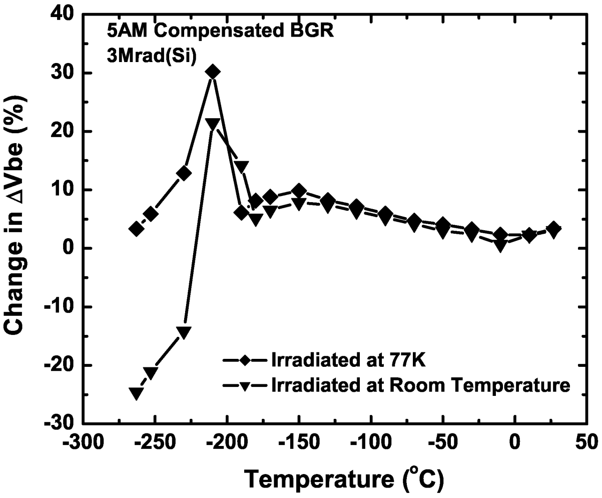

Fig. 14. Change in the difference of Q_1 and Q_2 base-emitter voltages of 5AM BGR irradiated at 77 K as a function of temperature.

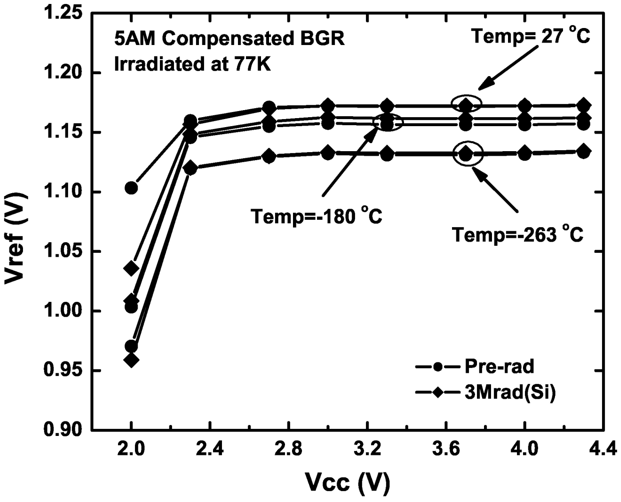

Fig. 15. Output voltage of the 5AM BGR as a function of power supply at 27°C, -180°C and -263°C-irradiated at 77 K.

B. Experiment II

In this experiment, the effects of proton irradiation on the voltage references implemented in both SiGe technologies were investigated when irradiated cold. The samples were irradiated at 77 K and under operational bias during the experiment. Measurement results are shown in Figs. 12–18. In each figure, result from the radiation performed at room temperature is also shown for comparison. The percentage change in the output voltage of the 5AM BGR is shown in Fig. 12. It can be observed that the change in the output voltage when the reference is irradiated cold is much less than when it is irradiated at room temperature, clearly good news for applications at cryogenic temperatures. This is consistent with what was observed for the individual transistors [16]. Fig. 13 shows that the percentage change in the base-emitter voltage of transistor Q_3 is less than 0.5% when the reference is irradiated at 77 K. The percentage change in the base-emitter voltage difference of transistors Q_1 and Q_2 is shown in Fig. 14. It can be seen that for most temperatures the percentage change remains the same for both samples (irradiated at room temperature and irradiated at 77 K). Interestingly, however, at deep cryogenic temperatures, the percentage change in $\Delta V_{\rm be}$ for the sample irradiated at room temperature is far larger than that of the sample irradiated cold. Fig. 15 shows the output voltage of the 5AM BGR irradiated at 77 K as a function of the power supply at three temperatures. Line regulation remains well-behaved after proton radiation at 77 K.

The percentage change of the output voltages of the 8HP references as a function of total dose at 77 K are plotted in Fig. 16. As can be seen, the percentage change increases as the total dose increases. The change in the output voltage of the first-order and curvature-compensated 8HP BGRs irradiated at 77 K as a function of temperature are shown in Figs. 17 and Figs. 18, respectively. Unlike the case of the 5AM references, the output voltage of the 8HP samples irradiated at 77 K changed more after irradiation compared with the samples irradiated at room temperature. However, the percentage change for both 8HP references is less than 0.4%, clearly acceptable for most applications.

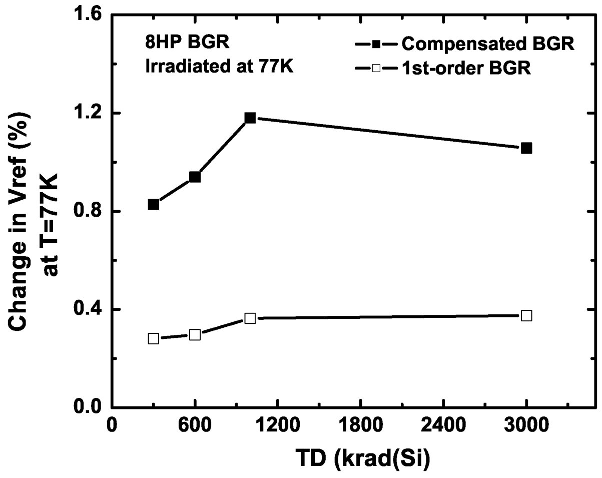

Fig. 16. Output voltage of 8HP references as a function of total dose for 77 K irradiation.

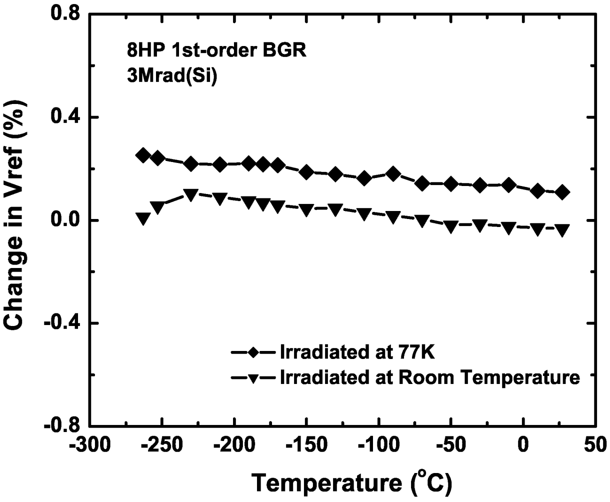

Fig. 17. Change in the output voltage of the first-order 8HP BGR irradiated at 77 K as a function of temperature.

C. Experiment III

In this experiment, the 8HP curvature-compensated reference was irradiated at room temperature with all the pins grounded. Measurement results of this experiment are shown in Fig. 19. Data obtained from experiment I is also shown for comparison. Interestingly, these results indicate the proton damage for this reference is larger for the case when the circuit is under bias during radiation, compared to the case when the circuit is irradiated with all pins grounded.

The temperature coefficients of the 5AM voltage reference both before and after irradiation from the two experiments, across four different temperature ranges, are summarized in Table. I. These numbers demonstrate that the impact of proton irradiation at 77 K on the output voltages and temperature coefficients of the 5AM BGR circuit are minor, and are clearly encouraging for extreme environment applications of SiGe technology.

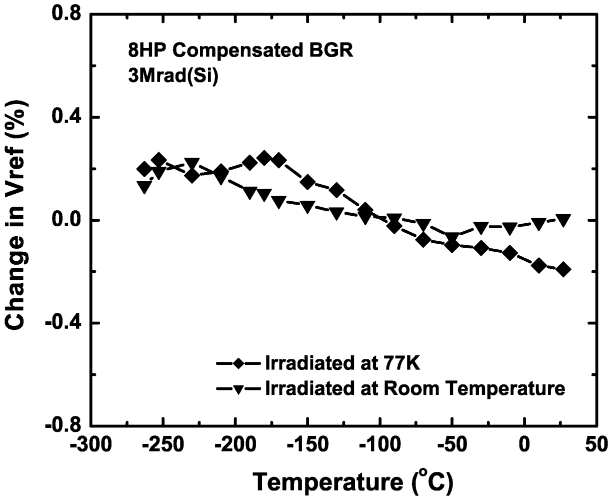

Fig. 18. Change in the output voltage of curvature-compensated 8HP BGR irradiated at 77 K as a function of temperature.

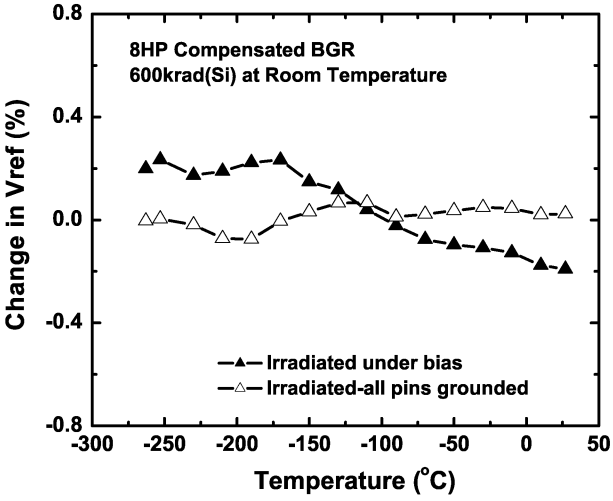

Fig. 19. Change in the output voltage of curvature compensated 8HP BGR irradiated with all pins grounded, as a function of temperature.

VI. SUMMARY

In this paper the proton tolerance of SiGe BiCMOS voltage references intended for extreme temperature range electronics was investigated. The reference circuits were designed in two distinct SiGe technologies (IBM SiGe 5AM and IBM SiGe 8HP). Three separate proton radiation experiments were performed. Measurement results show that the PTAT current generator inside the reference circuits is the most vulnerable component of the circuits to induced proton damage, but in general the circuits work well up to Mrad levels of total dose. The output voltage of the 5AM reference circuits show larger percentage changes than that those of the 8HP references, after irradiation at room temperature. Irradiation at 77 K produces less damage to the 5AM reference circuits than irradiation at room temperature. For the 8HP reference circuits, the damage of radiation at 77 K was slightly larger than the damage of radiation at room temperature, but still relatively minor. Comparing the measurement results at 27°C obtained from this study

TABLE I
Temperature Coefficients of 5AM SiGe Voltage Reference Over Different Temperature Ranges

Temperature Range	Experiment I		Experiment II	
	pre-rad	post-rad (3 Mrad(Si))	pre-rad	post-rad
(-55 to 27)°C	19.52 ppm/°C	27.45 ppm/°C	8.06 ppm/°C	19.22 ppm/°C
(-180 to 27)°C	72.29 ppm/°C	55.11 ppm/°C	64.61 ppm/°C	49.99 ppm/°C
(-243 to 27)°C	96.29 ppm/°C	168.83 ppm/°C	101.66 ppm/°C	88.08 ppm/°C
(-263 to 27)°C	122.37 ppm/°C	167.51 ppm/°C	120.63 ppm/°C	121.52 ppm/°C

with those of previous studies [5]–[7] indicates that the output voltage change due to proton influence is minimal in these SiGe circuits, even down to cryogenic temperatures, demonstrating the utility of SiGe technology for emerging space exploration applications.

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