Proton Radiation Response of SiGe HBT Analog and RF Circuits and Passives

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***Abstract*--We present the first experimental results of the effects of 63MeV proton irradiation on SiGe HBT analog and RF circuits and passive elements. A SiGe HBT bandgap reference circuit, commonly used to generate stable on-chip voltages in analog IC's, a SiGe HBT voltage controlled oscillator, an key building block for RF transceivers, and an LC bandpass filter routinely used in RF circuit design, were each irradiated to proton fluences as high as $5\text{x}10^{13}$ p/cm^2. The degradation associated with these extreme proton fluences was found to be minimal, suggesting that SiGe HBT technology is robust for these types of circuit applications.**

I. INTRODUCTION

Silicon-germanium heterojunction bipolar transistor (SiGe HBT) technology utilizes bandgap engineering techniques using thin strained layers of SiGe on conventional Si wafers to attain comparable performance to III-V technologies such as GaAs and InP, while maintaining strict compatibility with conventional Si IC fabrication. SiGe HBT technology thus combines III-V like device performance with the high integration levels, high yield, and hence low-cost associated with Si ICs. The recent merger of SiGe HBT technology with state-of-the-art Si CMOS to form SiGe HBT BiCMOS technology presents exciting possibilities for low-cost Si-based system-on-a-chip solutions for a wide variety of digital, analog, and RF applications in the 1-40 GHz range [1]. Our recent work has established that first generation SiGe HBTs are robust with respect to gamma, proton, and neutron irradiation without any additional radiation hardening (SEE sensitivity is still under investigation), and thus SiGe technology may offer great promise for emerging low-cost space applications [2]-[6]. To date, however, no results have been presented on total dose and displacement effects in actual SiGe HBT circuits. In this work we present the first experimental results of the effects of proton irradiation on critical SiGe HBT analog and RF circuits and passive elements implemented in IBM's first-generation UHV/CVD SiGe HBT process technology, which is currently in commercial production and available through MOSIS.

II. SIGE HBT TECHNOLOGY

This SiGe technology is 100% Si processing compatible, uses deep and shallow trench isolation, and a UHV/CVD deposited SiGe base which is thermodynamically stable, and hence is high yielding and manufacturable. The Ge profile is graded and the peak Ge content is 10%.

Table I. SUMMARY OF THE SIGE HBT PARAMETERS

Drawn Emitter Width (μm)	0.50
Actual Emitter Width (μm)	0.42
peak β	115
V_A (V)	60
peak f_T (GHz)	50
peak f_{max} (GHz)	70
BV_{CEO} (V)	3.3

The SiGe technology investigated in this work is known as SiGe 5HP, and is a full BiCMOS technology in commercial production at IBM. The technology integrates a 0.42μm, 3.3V BV_{CEO}, 70 GHz f_{max} SiGe HBT with 3.3V V_{DD}, 0.25μm L_{eff} CMOS technology, together with a full suite of RF passives (polysilicon and implanted resistors, inductors, metal-insulator-metal capacitors) as well as a gated lateral pnp, and a second, higher breakdown (5.3V) SiGe HBT [7]. This SiGe technology has not been intentionally radiation-hardened in any way. A schematic cross-section of the SiGe HBT is shown in Fig. 1 and typical transistor parameters are summarized in Table 1.

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III. EXPERIMENT

Because the major goal of this work was to assess the impact of radiation exposure on actual SiGe HBT circuits, we have chosen two very important, yet very different types of circuits, one heavily used in analog ICs (the bandgap reference circuit), and one heavily used in RF ICs (a voltage controlled oscillator). Each circuit represents a key building block for realistic SiGe ICs that might be flown in space. Each of these SiGe HBT circuits was designed using fully-calibrated SPICE models, layed-out, and then fabricated on the same wafer to facilitate unambiguous comparisons. In addition, because any realistic RF IC must also necessarily include passive elements such as monolithic inductors and capacitors, we have also investigated the effects of protons on an RF LC bandpass filter. SEU is obviously extremely important for space-based ICs, and initial results [8] suggest some SEU softness in this SiGe technology, but for brevity, SiGe SEU effects will be addressed in a separate paper.

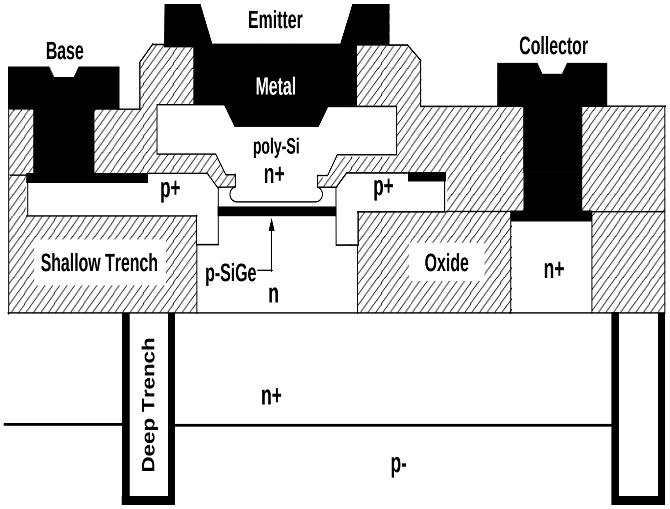

Fig. 1. Schematic cross-section of the UHV/CVD SiGe HBT.

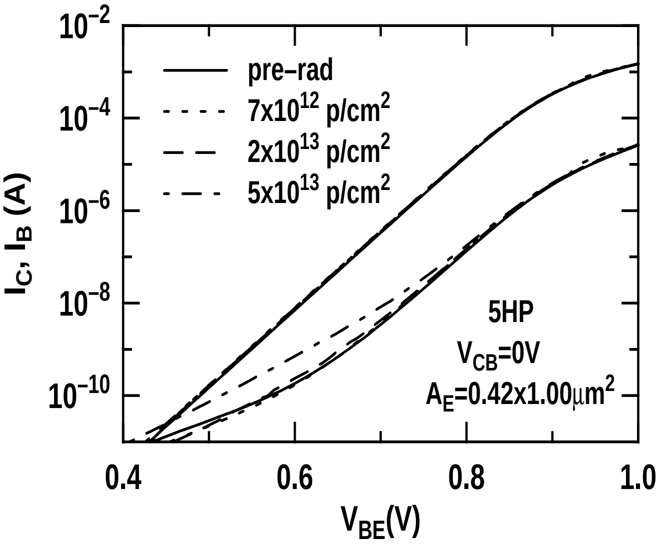

Fig. 2. SiGe HBT Gummel characteristics as a function of proton fluence.

The circuits were diced and mounted in 68 pin LCC packages. Because it only requires dc measurements, the BGR circuit was wirebonded and measured *in-situ* as fluence accumulated. During radiation exposure all BGR circuit terminals were held at ground. The VCO and LC filter, however, required on-wafer S-parameter measurements post-radiation, and thus were irradiated with circuit terminals floating. Our previous studies indicate that this has minimal effect on the transistor-level radiation response [6] (in addition, see discussion in Section IV below). Three separate samples were used for each circuit type to ensure reproducibility of the measured results.

Samples were exposed to 62.5MeV protons at the Crocker Nuclear Laboratory cyclotron located at the University of California at Davis. The dosimetry measurements used a 5-foil secondary emission monitor calibrated against a Faraday cup. Ta scattering foils located several meters upstream of the target establish a beam spatial uniformity of 15% over a 2 cm radius circular area. Beam currents from about 5 pA to 50 nA allow testing with proton fluxes from 10^6 to 10^{11} protons/cm^2 /sec. The dosimetry system has been previously described [9]-[10] and is accurate to about 10%. At a proton fluence of $1\text{x}10^{12}$ p/cm^2, the measured equivalent gamma dose was approximately 136 krad(Si). The SiGe HBT circuits were irradiated to accumulated proton fluences ranging from $1.0\text{x}10^{12}$ p/cm^2 to $5.0\text{x}10^{13}$ p/cm^2.

IV. TRANSISTOR-LEVEL RESPONSE

Measurements of the dc and ac properties of individual SiGe HBTs were made to quantify the transistor-level radiation tolerance. Figures 2 and 3 show the impact of proton exposure on typical HBT current-voltage characteristics and frequency response, both of which can potentially affect circuit behavior. As has been reported previously [4,6], the proton-induced device degradation is minor in the bias range of interest to actual circuits (typically $I_C > 100\ \mu A$).

In our previous investigations, the SiGe HBTs were always irradiated either with all terminals grounded or with all terminals floating. No significant difference was found between these two bias conditions. In real circuit applications, however, the SiGe HBTs necessarily experience a wide variety of operating bias conditions which differ from grounded or floating bias, and thus rigorous hardness assurance requires a deeper look at the bias condition sensitivity. Many different bias configurations are relevant for bipolar circuits. In non-saturating, high-speed logic families such as CML or ECL, for instance, the transistor operates only under forward-active bias. For most analog circuits, the transistor is also biased in forward-active mode. For certain RF power applications, the transistor can experience saturation mode bias. Finally, in certain BiCMOS logic families, or even during switching transients in non-saturating logic families, the emitter base (EB) junction of the transistor can become reverse-biased.

To quantify the impact of terminal bias condition during irradiation on the measured radiation tolerance, representative transistors were held at different bias conditions during radiation exposure, and then compared after specific accumulated fluences. When the desired fluence was reached, the bias was set to ground on all terminals, and the samples were removed from the beam and immediately measured. The appropriate bias was returned to the DUT and then it was reinserted into the proton beam until the next desired fluence was reached. This process was repeated in a controlled manner throughout the experiment. Figure 4 compares the normalized current gain degradation as a function of fluence for three relevant bias configurations: 1) all terminals grounded, 2) forward-active mode, and 3) reverse-biased emitter-base (EB) junction. As can be seen, there are no large differences between the three bias conditions, and the all-terminals-grounded condition represents a close to worst case scenario (and is comparable to the all terminals floating condition).

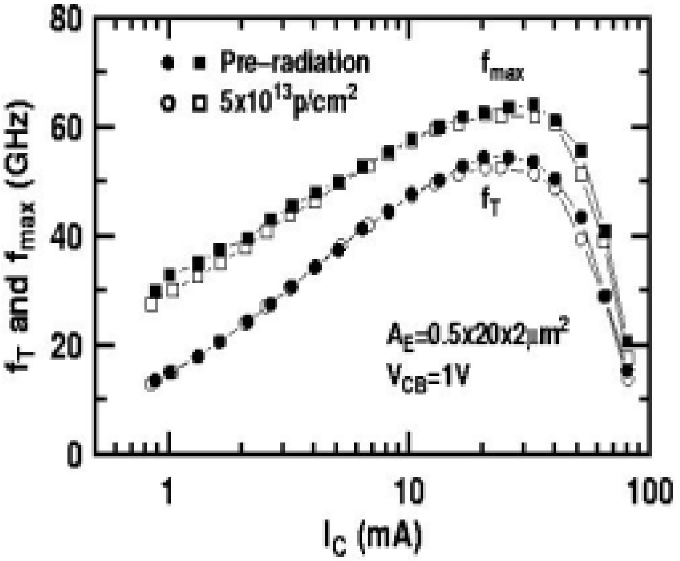

Fig. 3. SiGe HBT frequency response as a function of proton fluence.

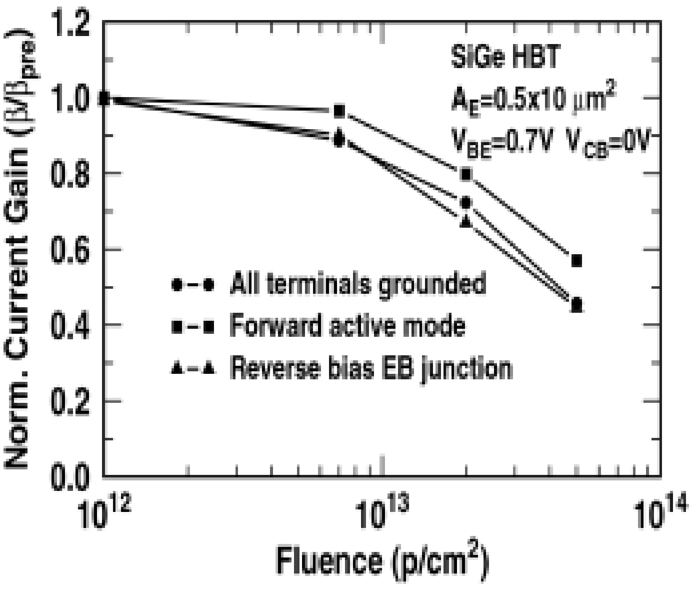

Fig. 4. Gain degradation as a function of proton fluence for various bias conditions during radiation exposure.

TABLE II. **Summary of SiGe HBT Circuit Results**

SiGe HBT Circuit	Parameters	Pre-Radiation	After $5x10^{13}p/cm^2$	Units
Bandgap Reference	V_{cc}	3.0	3.0	V
	I_{cc}	0.773	0.767	mA
	V_{out} at 300K	1.37416	1.37209	V
	Stability over -55 to 85°C	81.2	81.7	ppm/°C
Voltage Controlled Oscillator	Frequency	5.0	5.0	GHz
	V_{cc}	3.3	3.3	V
	I_{cc}	22.5	22.5	mA
	Output Power	-5.0	-5.5	dBm
	Phase Noise	-112.5	-111.8	dBc/Hz
	Tuning Range	4,595-5,452	4,623-5,470	MHz
LC Bandpass Filter	Frequency	1.9	1.9	GHz
	Filter Q (@3dB bw)	7.6	7.6	-
	Insertion Loss	16.8	16.8	dB
	L	2.5	2.5	nH
	Inductor Q	7.4	7.4	-
	C	6.0	6.0	pF
	Capacitor Q	58	58	-

V. BANDGAP REFERENCE CIRCUIT

The bandgap reference (BGR) circuit has been widely used as a voltage reference source in A/D and D/A converters, voltage regulators, and other precision analog circuits due to its good long-term stability and its ability to operate at low supply voltages [11]. This SiGe BGR employed conventional circuit architecture, and did not include any special temperature compensation circuitry (Figure 5). In Si BJT BGR's, radiation-induced degradation in output voltage and temperature sensitivity are of concern [12]. In addition, due to the bandgap-engineered nature of the SiGe HBT, unique effects associated with the Ge grading in the neutral base region of the transistor can potentially cause problems in BGR operation and necessitates investigation [13]. Because

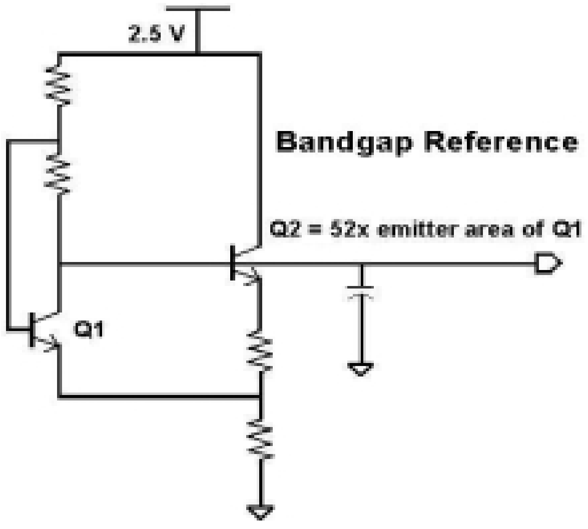

Fig. 5. Circuit schematic of the SiGe HBT bandgap reference circuit.

transistors Q1 and Q2 operate at constant collector current bias, any radiation-induced changes, which influence the matching properties between large and small area devices, can degrade BGR temperature stability (in this case Q2 = 52 parallel copies of Q1, which has an emitter area of 0.5x1.0 μm^2). As can be seen in the data (Table 2 and Figures 6, 7), the impact of even an extreme proton fluence of $5x10^{13}$ p/cm^2 has minimal effect on both the output voltage and temperature sensitivity. This result is significantly better than for conventional Si BJT BGRs [12], and is indicative of the overall robustness of this SiGe technology for analog circuit applications. As we have discussed previously [4], the robustness of the present SiGe technology to ionizing radiation is mostly due to the structural nature of the epi-base design, not the presence of the Ge in the base.

VI. VOLTAGE CONTROLLED OSCILLATOR

The voltage controlled oscillator (VCO) is a fundamental building block for transceivers in communications systems. A VCO uses a control voltage for limited frequency tuning and provides the local oscillator (LO) signal for up- and down-conversion of the RF carrier to intermediate frequencies (IF) within the transceiver. VCO's are particularly sensitive to phase noise, which physically represents the up-conversion of low-frequency (1/f) noise to RF frequencies through the inherent transistor non-linearities. In the frequency domain, phase noise manifests itself as parasitic side-bands on the RF carrier, and thus represents a fundamental limit on the spectral purity and signal-to-noise ratio of a communications link. Of interest in this context is the impact of radiation exposure on the VCO phase noise.

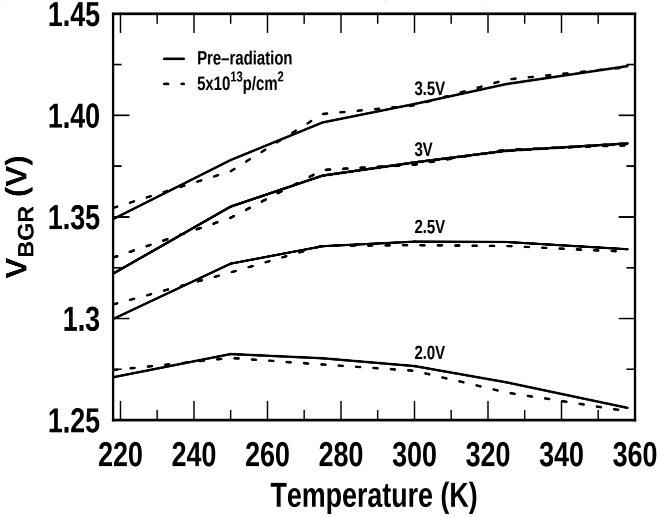

Fig. 6. Pre versus post-rad output voltage as a function of temperature at multiple power supply voltages for the SiGe HBT bandgap reference circuit.

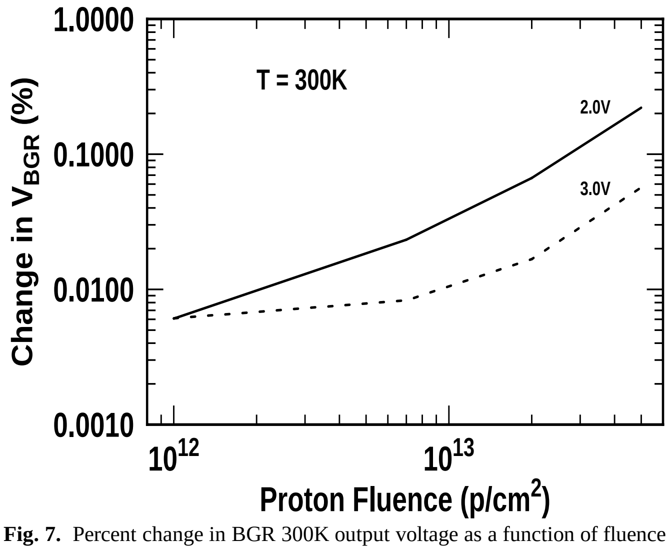

Fig. 7. Percent change in BGR 300K output voltage as a function of fluence and supply voltage.

This SiGe VCO employs a conventional circuit architecture, and is designed to operate at 5.0 GHz (Figure 8) [12]. As can be seen in Table 2, and Figures 9,10, the impact of extreme proton fluences on this SiGe VCO are minimal. After $5x10^{13}$ p/cm^2, the phase noise at 1MHz offset from the 5.0 GHz signal slightly increases (worsens) from an excellent value of -112.5 dBc/Hz to a still excellent value of -111.8 dBc/Hz. This negligible proton-induced degradation is nonetheless experimentally repeatable. To understand the result we measured the low-frequency noise properties of the component SiGe HBT. As can be seen in Figure 11, there is in fact a small but observable change in the 1/f noise at realistic circuit bias levels. The fact that this minor 1/f noise change couples only weakly to the observed circuit level phase noise suggests that the radiation exposure does not strongly affect the inherent transistor linearity at these frequencies.

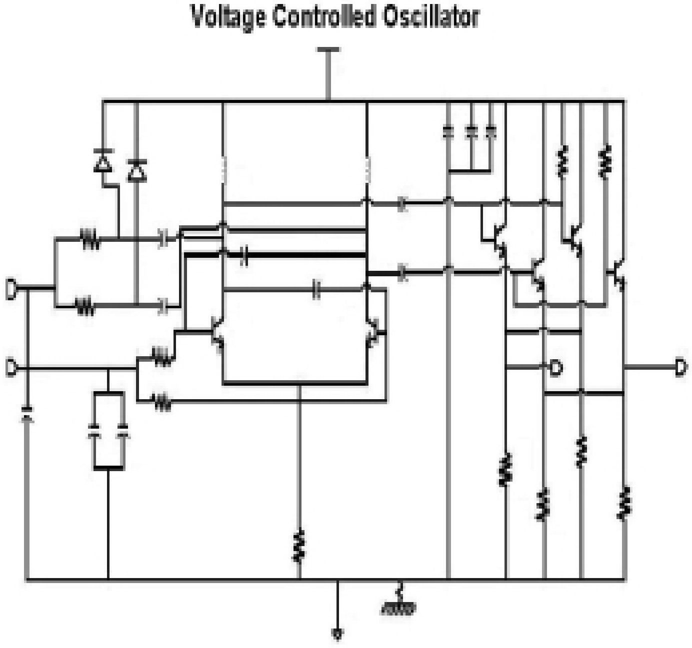

Fig. 8. Circuit schematic of the SiGe HBT VCO circuit.

VII. LC BANDPASS FILTER

High-quality factor (Q) passive elements (e.g., inductors and capacitors) are required in RF communications circuit design, and there has been significant effort in recent years to fabricate these monolithically with the active devices to facilitate single-chip transceiver implementations. The present SiGe technology contains a full suite of RF passives, and to obtain high Q, they are fabricated in the upper level of the multi-level metalization, so that they are far away from the lossy substrate. The inductors are multi-turn spiral inductors, and the capacitors are MIM (metal-insulator-metal) with a 50nm SiO_2 dielectric [16]. To determine the effects of proton irradiation on these RF passives at relevant RF frequencies, S-parameter measurements were made on the L's (Q=7.4 at 1.9 filter implemented from them GHz) and C's (Q=58 at 1.9 GHz), as well as an LC bandpass filter (Figure 12).

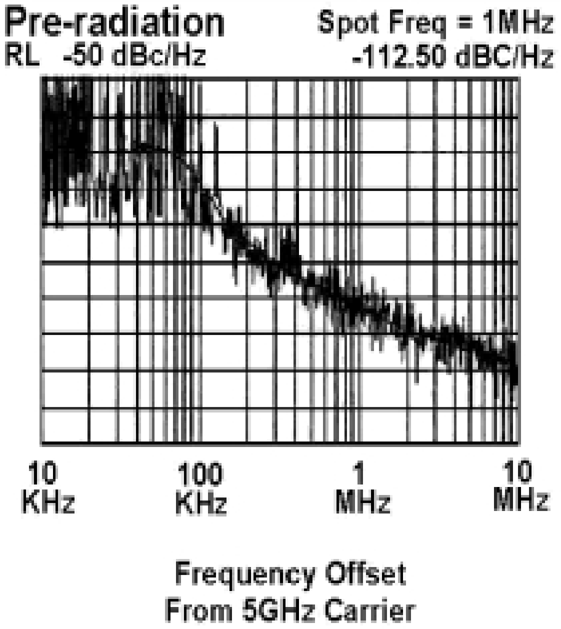

Fig. 9. Pre-radiation phase noise characteristics of the SiGe HBT VCO.

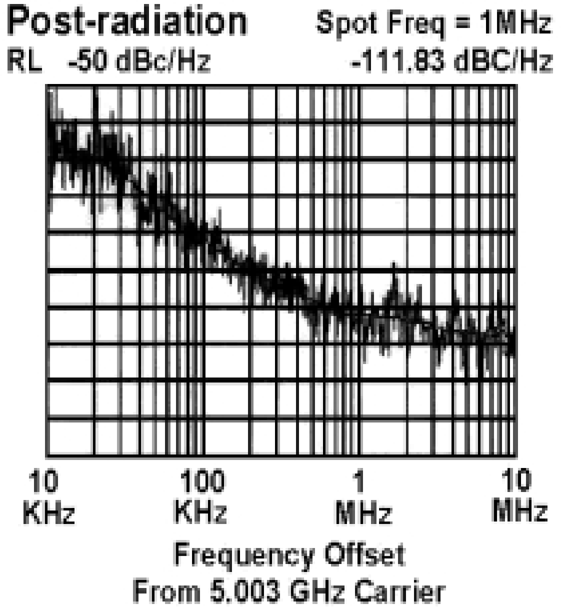

Fig. 10. Post-radiation phase noise characteristics of the SiGe HBT VCO.

As can be seen from Table 2 and Figure 13, to within the measurement accuracy and site-to-site repeatability, the L's and C's and LC filter are unchanged by even extreme proton fluences. We did consistently observe a shift in the LC filter second resonance (Figure 13), which we believe to be due to a moderate change in the coupling coefficient, but this should not affect the operation of the filter in actual circuit design.

VIII. SUMMARY

The effects of 63 MeV proton irradiation on SiGe HBT analog and RF circuits and passive elements have been investigated. A SiGe HBT bandgap reference circuit, a SiGe HBT voltage controlled oscillator, and an LC bandpass filter, were irradiated to proton fluences as high as $5x10^{13}$ p/cm^2. The degradation associated with these extreme proton fluences was found to be minimal, suggesting that SiGe HBT technology is robust for these types of circuit applications.

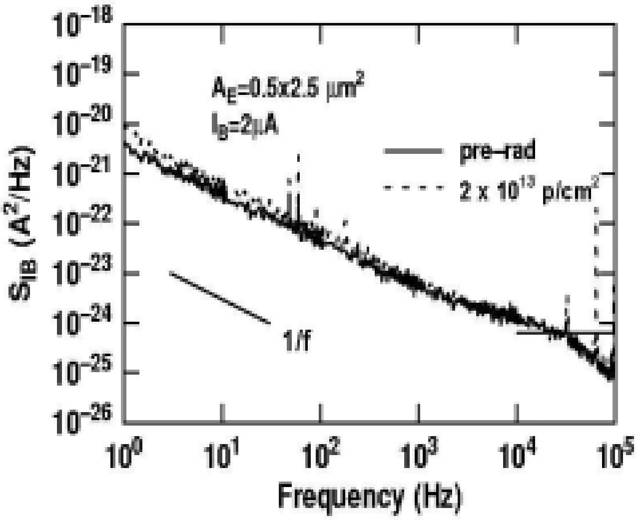

Fig.11. Low frequency noise characteristics of the SiGe HBTs

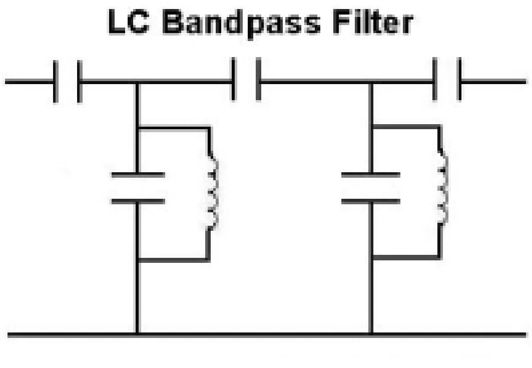

Fig. 12. Circuit schematic of the LC bandpass filter.

IX. ACKNOWLEDGMENTS

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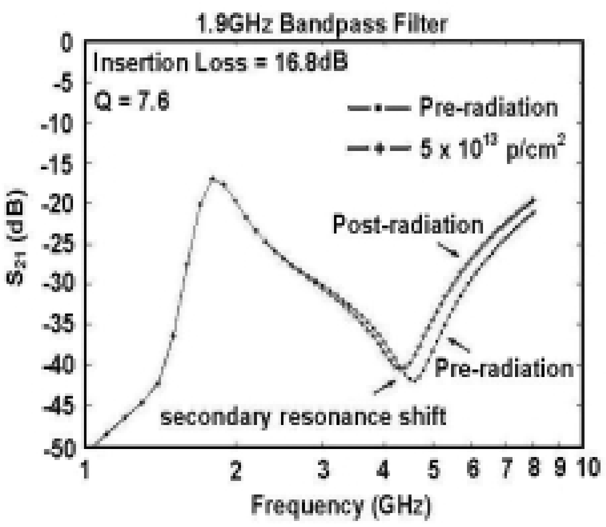

Fig. 13. Pre versus post-radiation frequency response of the LC filter.

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