Proton Radiation Effects in Vertical SiGe HBTs Fabricated on CMOS-Compatible SOI

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***Abstract*—Proton radiation effects in vertical SiGe HBTs fabricated on CMOS-compatible silicon-on-insulator (SOI) are investigated for the first time. Proton irradiation at 63 MeV is found to introduce base leakage current at low base-emitter voltage, delay the onset of Kirk effect at high injection, and increase the frequency response of SiGe HBTs on SOI. The latter two effects are in contrast to those found in conventional bulk SiGe HBTs. Proton irradiation also generates positive fixed oxide and interface charge in the buried oxide, which alters both M-1 and BV_{CEO} in the SiGe HBT by modulating the electric field in the collector region.**

***Index Terms*—HBT, radiation, SiGe, SOI.**

I. Introduction

Silicon-on-insulator (SOI) CMOS technology has matured over the past 15 years to become mainstream [1]. The thin oxide-isolated silicon layer allows a reduction in device parasitics, a built-in higher operating voltage capability, a reduction in signal crosstalk, improved soft error immunity, and an elimination of latchup [2]. From a space electronics perspective, SiGe technology offers an advantageous built-in total dose tolerance [3], but has proven susceptible to single event upset [4]. Clearly, placing SiGe HBTs on SOI, particularly thin film CMOS-compatible SOI, is an attractive option in the context of SEU and SiGe. Achieving the best of SiGe and SOI has proven exceptionally difficult in practice, however. Bipolar transistors need thick sub-collectors to maintain low parasitic collector resistance, and this is incompatible with thin-film SOI CMOS technologies. Recently, however, novel vertical SiGe HBTs suitable for integration on CMOS-compatible SOI were demonstrated on 120 nm SOI [5]. Fig. 1 shows the SEM cross section of the vertical SiGe HBT on CMOS-compatible SOI. We present here, for the first time, an investigation of the impact of 63 MeV protons on SiGe HBTs fabricated on CMOS-compatible SOI.

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II. Vertical SiGe HBTs on SOI

The SiGe HBTs used in this work feature a 120 nm silicon layer with an average collector doping concentration of 1.5×10^{17}/cm^3 on top of a 140 nm buried oxide layer [5]. The substrate is used as an active terminal in this device. The collector region of the SiGe HBT on SOI is effectively bent by 90 ° such that the carrier transport in the collector is horizontal for part of its current flow path. Under forward active bias, the carriers flow horizontally from the depleted collector region to the collector reachthrough, as indicated in Fig. 1. The pre-radiation Gummel characteristics of the SiGe HBTs on SOI with an emitter area of $0.16 \times 0.8\ \mu$m^2 are shown in Fig. 2, with the substrate voltage increasing from 0 to 20 V. Observe that the collector and base currents are influenced by the substrate bias at V_{BE} greater than about 0.9 V The collector current increases while the base current decreases, for a fixed V_{BE}, when the substrate bias voltage increases from 0 to 20 V. This behavior indicates that quasisaturation, due to the inherently high collector resistance ($\boldsymbol{R_c}$) in this structure, is partially suppressed when the substrate bias increases. To obtain deeper insight into this substrate bias-induced $\boldsymbol{R_c}$ modulation, calibrated two-dimensional MEDICI simulations were used [6]. The simulated electron current flow under two different substrate bias voltages of 0 and 20 V are shown in Fig. 3. With the increase of substrate voltage, a very thin n$^+$ electron accumulation layer forms at the collector-buried oxide interface. This accumulation layer serves as a bias-induced "sub-collector," and the collector current conduction path is modified from the uniform distribution across the Si collector layer, to the lower-impedance very thin "sub-collector" as the substrate voltage increases from 0 to 20 V. As such, $\boldsymbol{R_c}$-induced quasisaturation effects decrease with the increase of substrate bias voltage. The substrate bias affects not only the quasisaturation of the transistor, but also the CB junction multiplication factor (M-1), and hence the device breakdown voltages, as will be shown.

The $M-1$, as a function of V_{CB} and substrate bias, was measured using the techniques described in [7], and the results are shown in Fig. 4. Two depletion widths in SOI are affected by collector bias: the depletion width in the collector side of collector-base junction, and the depletion width at the buried oxide region. At 0 V substrate bias, the collector becomes fully depleted when the collector voltage increases to a value such that the two depletion widths reach the SOI thickness. Any further increase in V_{CB} won't affect the vertical electric field in the intrinsic collector region, and the additional collector voltage will be absorbed by the increase of lateral field. We call this process collector voltage "pinning." As can been seen from Fig. 4, at

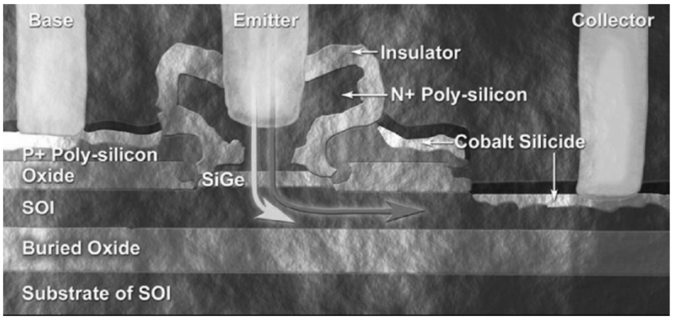

Fig. 1. Cross-sectional SEM micrograph of a SiGe HBT fabricated on CMOS-compatible 120 nm SOI.

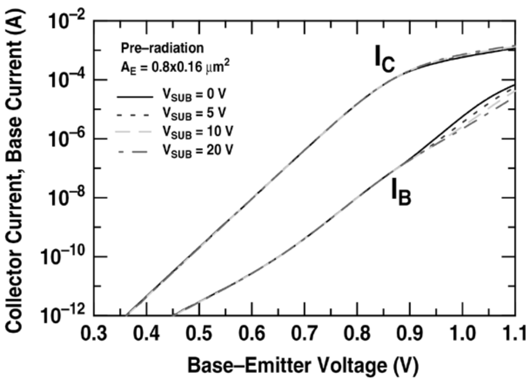

Fig. 2. Forward-mode Gummel characteristics of a SOI SiGe HBT under four substrate bias conditions: 0, 5, 10, and 20 V.

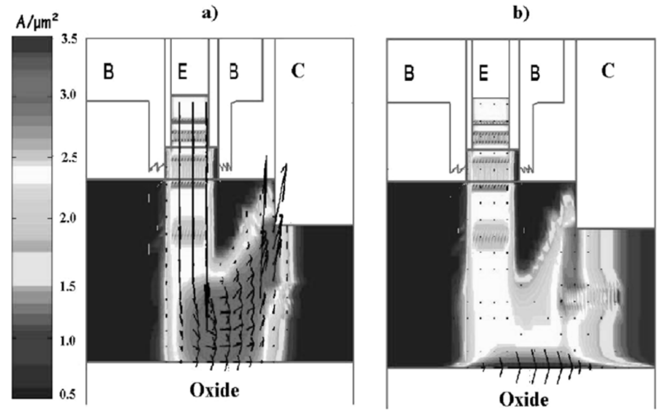

Fig. 3. MEDICI simulation results showing electron flow contours at two different substrate bias conditions: (a) 0 V; (b) 20 V.

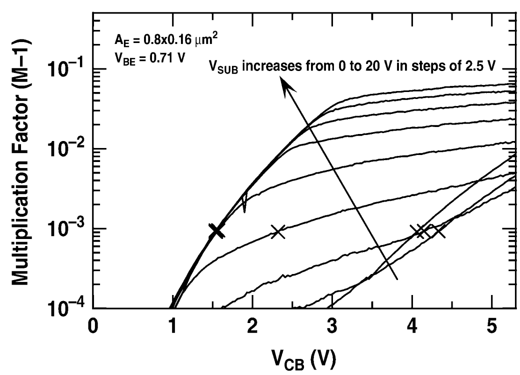

Fig. 4. M-1 as a function of collector-base voltage and substrate bias. The cross marks are the bias points where base current reversal occurs.

zero substrate voltage $M-1$ is negligibly small at this collector pinning voltage. When the collector voltage increases to about 3 V, the M-1 at the lateral (extrinsic) collector begins to increase. With the increase of the substrate voltage, electrons accumulate near the buried oxide interface. This accumulation layer allows the vertical potential drop to follow the collector voltage drop and breaks the collector voltage pinning, and the $M-1$ at the lateral collector is suppressed at the same time. Under positive substrate bias and low $V_{\rm CB}$, which corresponds to the accumulated sub-collector condition, $M-1$ in the intrinsic collector dominates and increases exponentially with $V_{\rm CB}$.With a further increase of $V_{\rm CB}$ the collector becomes fully depleted and M-1 is less dependent on $V_{\rm CB}$ due to collector voltage pinning. Note, however, that the collector pinning voltage increases with substrate bias. Hence, with the increase of the substrate bias, the M-1 increases in the "flat" portion of M-1 data. The cross points in Fig. 4 represent the $\rm BV_{CEO}$ of the transistor at different substrate bias values. $\rm BV_{CSO}$ is to first-order determined by the product of the M-1 and the current gain, β. Since β is only weak function of substrate bias, $\rm BV_{CSO}$ occurs at a fixed level of M-1, which is a sensitive function of substrate bias.

III. Experiment

63.3 MeV proton irradiation of the SiGe HBTs was performed at the Crocker Nuclear Laboratory at the University of California at Davis, to fluences as high as 5×10^{13} p/cm^2 [equivalent to 6.8 Mrad(Si)]. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) located several meters up-stream of the target establish a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 20 nA to 100 nA allow testing with proton fluxes from 1.0×10^9 to 1.0×10^{12} proton/cm^{2}sec. The dosimetry system has been previously described [8], [9], and is accurate to about 10%.

The SiGe HBT dc and ac test structures were irradiated with the E,B,C terminals grounded at four different proton fluences of $1.0\times10^{12}, 7.0\times10^{12}, 2.0\times10^{13}$, and 5.0×10^{13} p/cm^2, respectively. The HBTs used in this work have the same emitter width (0.16 μm) but two different emitter lengths (0.8 and 1.6 μm). In-situ dc measurements were immediately performed on an Agilent 4155C Semiconductor Parameter Analyzer after each proton fluence. Wirebonding of ac test structures is not compatible with robust broadband measurements, and hence on-wafer probing of S-parameters was used to characterize the high-frequency performance. The transistor S-parameters were measured using an Agilent 8510C Vector Network Analyzer (VNA) both pre- and post-proton irradiation, and the corresponding f_T and $f_{\max}$ values were extracted. The substrate was biased at 0, 5, and 20 V during proton exposure.

IV. Radiation Effects

Fig. 5 shows the forward-mode Gummel characteristics of the SOI SiGe HBT at different proton fluences. The base cur-

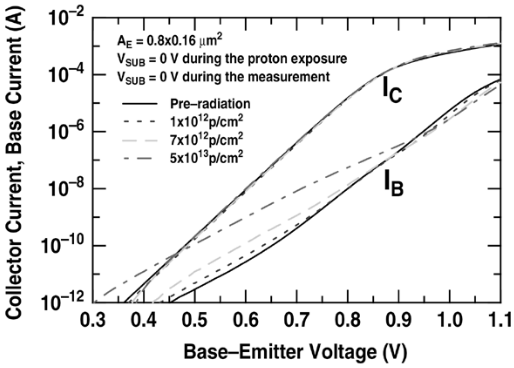

Fig. 5. Forward-mode Gummel characteristics of a SOI SiGe HBT at different proton fluences.

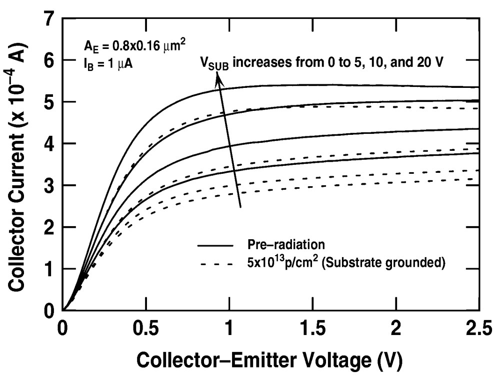

Fig. 6. Pre- and post-proton irradiation common-emitter output characteristics of a SOI SiGe HBT.

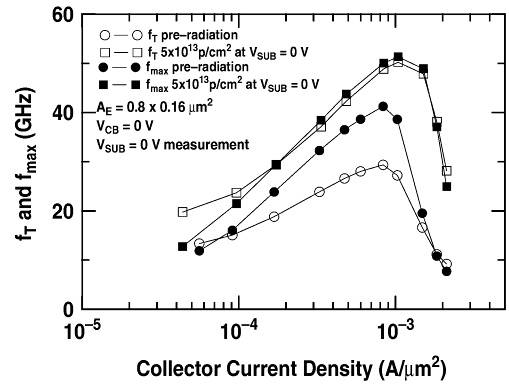

Fig. 7. Pre- and post-proton irradiation f_T and $f_{\max}$ versus collector current density for a SOI SiGe HBT.

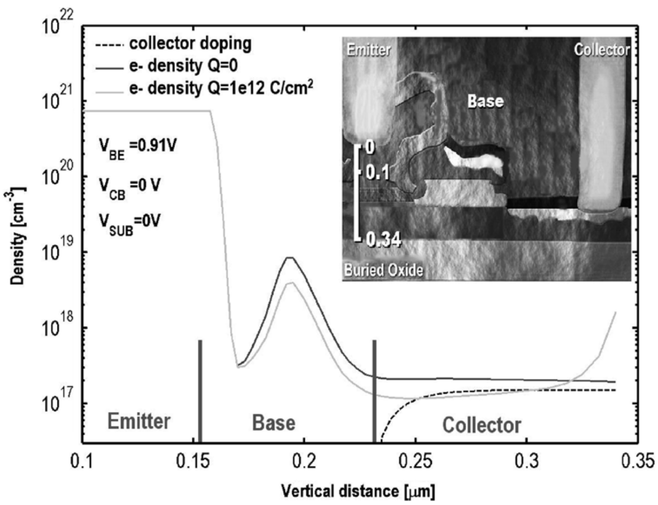

Fig. 8. Electron density distribution with and without positive collector-buried oxide interface charge under high injection conditions.

rent at low $V_{\rm BE}$ increases monotonously with proton fluence, a classical signature of radiation-induced damage in the emitter-base spacer region. Proton irradiation is known to create generation-recombination (G/R) trap centers near the emitter-base spacer oxide and shallow-trench isolation edges [10], and this leads to the observed increase of base current leakage in these SiGe HBTs. It is interesting to note that at high $V_{\rm BE}$ (>0.9 V) the base current decreases as the proton fluence increases, while the collector current increases with proton fluence. There could be two possible mechanisms responsible for this: a) a decrease of quasisaturation effects through the decrease of the collector resistance, or b) the delay of the onset of Kirk effect (base push-out) [11]. The common-emitter output characteristics for the SOI SiGe HBT are shown in Fig. 6, both before and after proton irradiation. The collector resistance can be estimated from the inverse of the slope at low collector-emitter voltage (in the saturation region). It can be seen from Fig. 6 that the collector resistance decreases as substrate bias increases, consistent with the substrate effects described in Section II. The post-radiation collector resistance, however, increases for the same substrate voltage compared with the pre-radiation data. This rules out mechanism a) for the observed base and collector current variation at high $V_{\rm BE}$ in the Gummel characteristics. As discussed below, we believe that proton irradiation introduces positive charge in the buried oxide and at the collector-buried oxide interface which acts to retard (reduce) Kirk effect by altering the local electron density and electric field in the collector-base junction. This was confirmed by examining the simulated electron density distribution under high-injection conditions, as shown in Fig. 8. It can be seen from Fig. 8 that the electron density on the collector side of collector-base junction depletion region decreases significantly when the interface charge increases from 0 to 1.0×10^{12} C/cm^2. This decrease of electron density would effectively serve to postpone the onset base pushout (Kirk effect).

The measured f_T and $f_{\max}$ versus bias current are shown in Fig. 7 for a SOI SiGe HBT both pre- and post-proton irradiation. Interestingly, both the post-radiation peak f_T and $f_{\max}$ increase significantly compared to their pre-radiation values. The scattering-parameters (S-parameters) for the open and short de-embedding structure are essentially identical for pre- and post-radiation samples, and the raw data (without de-embedding) show similar f_T and $f_{\max}$ percentage increases, as shown in Fig. 7. This indicates that the increase of f_T and $f_{\max}$ is not due to any measurement related artifact. From Fig. 8, we know that after proton irradiation the onset of Kirk effect is delayed, increasing f_T at high collector current density. Fig. 9 shows the simulated peak f_T increase at various interface charge density, indicating that a positive interface charge density of about 1.5×10^{12} C/cm^2 correlates to the observed post-radiation experimental

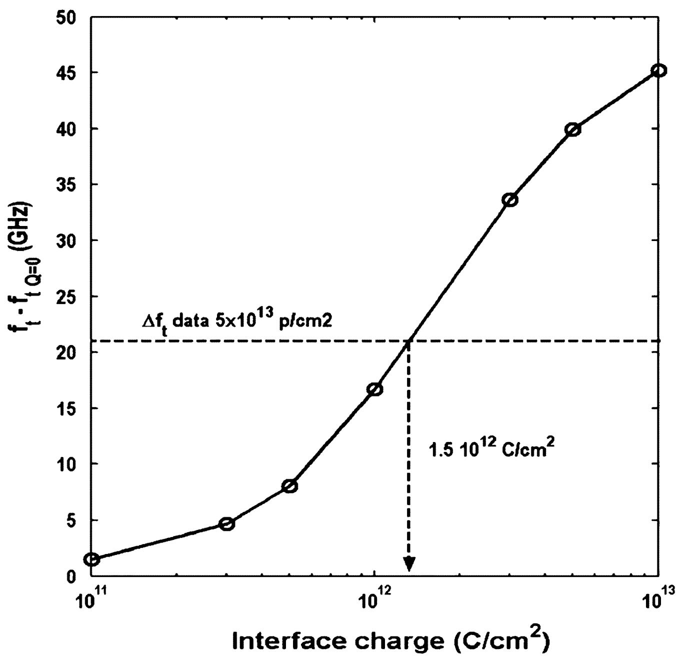

Fig. 9. Increase of peak f_T at various interface charge density simulated by MEDICI.

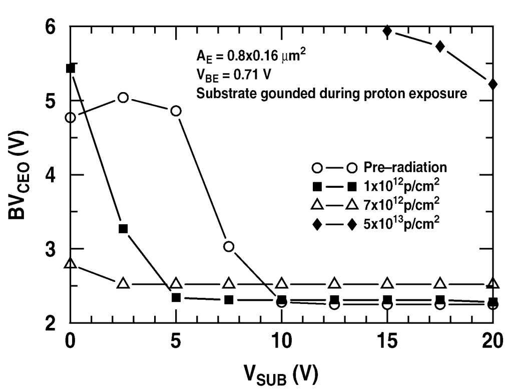

Fig. 10. Variation of $\mathrm{BV}_{\mathrm{CEO}}$ with substrate voltage and proton fluence for a SOI SiGe HBT.

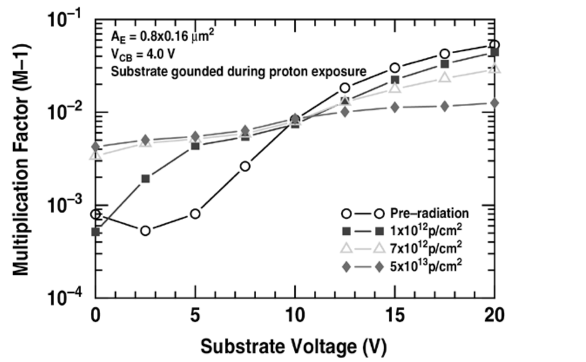

Fig. 11. M-1 as a function of substrate voltage for a SOI SiGe HBT at different proton fluences.

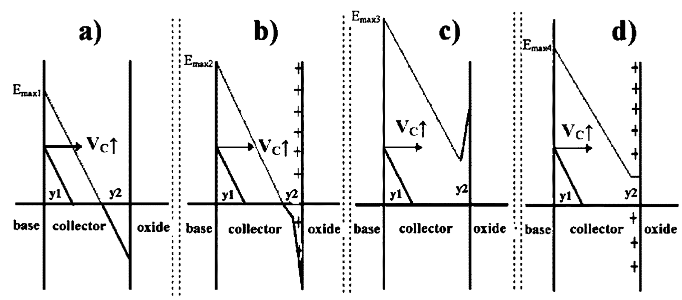

Fig. 12. Electric field distribution in the intrinsic transistor: (a) pre-radiation, V_{SUB} low; (b) post-radiation, V_{SUB} low; (c) pre-radiation, V_{SUB} high; (d) post-radiation, V_{SUB}high.

f_T increase. Previous radiation work on SOI CMOS [12] suggests that at a proton fluence of 5×10^{13} p/cm^2, the net interface charge introduced by 63 MeV proton irradiation is about 1.7×10^{12} C/cm^2, which is in good agreement with the value inferred in the present work. The value of the forward transit time τ_F, which is comprised of the base, emitter, and collector transit times, was extracted from a plot of $1/2f_T$ versus $1/I_c$ [13]. The extracted forward transit time was found to decrease from 4.64 ps for pre-radiation to 2.61 ps after proton irradiation, presumably due to a combination of a radiation charge-induced altered current flow path and the retarded Kirk effect.

The measured variation of $\mathrm{BV}_{\mathrm{CEO}}$ with substrate voltage and proton fluence is plotted in Fig. 10. $\mathrm{BV}_{\mathrm{CEO}}$ is determined by both β and M-1: β decreases with the increase of proton fluence due to the radiation-induced base current leakage, while M-1 is a very complicated function of both proton fluence and substrate voltage, as discussed above. At low substrate voltage, the increase of M-1 dominates and $\mathrm{BV}_{\mathrm{CSO}}$ decreases compared with pre-radiation value; at higher substrate bias the increase of M-1 has a smaller effect and the decrease of β begins to dominate and $\mathrm{BV}_{\mathrm{CEO}}$ increases. Note that $\mathrm{BV}_{\mathrm{CSO}}$ for samples with a proton fluence of 5.0×10^{13} p/cm^2 is very large, regardless of substrate bias, due to significant β degradation (i.e., a relatively large base current leakage at $V_{\mathrm{BE}} = 0.7$ V). Fig. 11 shows the saturated M-1 as a function of substrate voltage for a SOI SiGe HBT at different proton fluences. It is interesting to note that at low substrate voltage, M-1 increases with proton fluence, but decreases with proton fluence at higher substrate voltage. Based on the depletion approximation, the electric field distribution in the intrinsic transistor is shown qualitatively in Fig. 12 for both pre-and post-radiation SOI SiGe HBTs at different substrate biases. This problem is analogous to a pn diode in series with a MOS capacitor. For Fig. 12(a), the substrate bias is low and both the pn diode and MOS capacitor are reverse-biased $(V_B < V_C, V_S < V_C)$ and there are two distinct depletion regions with widths yl and y2, respectively. With the further increase of the collector voltage, the collector become fully depleted and the maximum electric field at base-collector interface, $E_{\max}$, determines the magnitude of M-1. Further increases of the collector voltage will not influence the vertical field and hence M-1. Proton irradiation introduces positive interface charge at the collector-buried oxide interface, which modulates the electric field in the collector close to the interface, as shown in Fig. 12(b). $E_{\max}$ increases for the post-radiation SiGe HBT compared with its pre-radiation condition, consistent with M-1 data in Fig. 11 at low substrate bias. For high positive substrate voltage, the accumulated electron layer

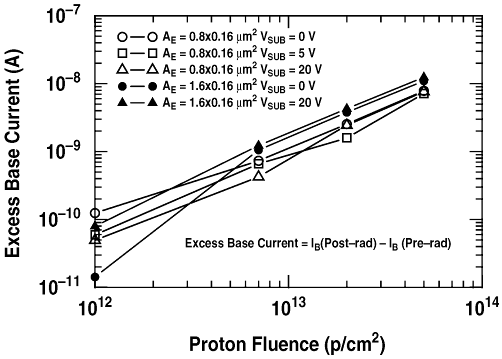

Fig. 13. Variation of excess base current with proton fluence for SOI SiGe HBTs with different geometries and different substrate bias during proton irradiation.

switches the electric field in the y2 region to the opposite direction in Fig. 12(c) as compared with Fig. 12(a) for the low substrate bias. For the post-radiation transistor under high substrate bias, the radiation-induced positive interface charge decreases the electric field in the y2 region and $E_{\max}$ is decreased, hence lowering M-1, as shown in Figs. 12(d) and 11. 2-D MEDICI simulations support this interpretation.

To understand the effects of transistor geometry and the substrate bias condition during proton irradiation on the radiation response, the excess base current at different proton fluences, for SOI SiGe HBTs with different geometries and different irradiation substrate bias conditions, are compared in Fig. 13. The proton-induced base current leakage is similar for the two different transistor geometries and three different substrate bias conditions during proton irradiation. The radiation response of both $\mathrm{BV_{CEO}}$ and M-1 are also very similar across different transistor geometries and substrate bias conditions. Note, however, that this observed lack of geometry dependence is based only on results from HBTs with grounded emitter, base, and collector during proton exposure, and should in principle be different for devices biased under forward-active conditions (with active substrate bias). The coupling of device bias effects (for all the four terminals, emitter, base, collector, and substrate) to the device geometry is currently under additional investigation.

V. Summary

We have presented an investigation of the impact of 63 MeV protons on vertical SiGe HBTs fabricated on a CMOS-compatible SOI. Proton irradiation creates G/R trap centers in these SOI SiGe HBTs, leading to base current leakage. The radiation-induced positive charge at the buried oxide interface is generated by proton irradiation, and effectively delays the onset of Kirk effect at high current density, helping to increase the frequency response of SOI SiGe HBTs post radiation. This radiation-induced positive interface charge also changes $\mathrm{BV_{CEO}}$ in the SOI SiGe HBTs by altering both the avalanche factor and current gain.

Acknowledgment

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References

[1] G. G. Shahidi, A. Ajmera, F. Assaderaghi, R. J. Bolam, E. Leobandung, W. Rausch, D. Sankus, D. Schepis, L. F. Wagner, W. Kun, and B. Davari, "Partially-depleted SOI technology for digital logic," in *Proc. IEEE ISSCC Tech. Dig.*, Feb. 1999, pp. 426–427.

[2] D. M. Fleetwood, F. V. Thome, S. S. Tsao, P. V. Dressendorfer, V. J. Dandini, and J. R. Schwank, "High-temperature silicon-on-insulator electronics for space nuclear power systems: Requirements and feasibility," *IEEE Trans. Nucl. Sci.*, vol. 35, no. 3, pp. 1099–1112, Jun. 1988.

[3] J. D. Cresser, R. Krithivasan, G. Zhang, G. Niu, P. W. Marshall, H. S. Kim, R. A. Reed, M. J. Palmer, and A. J. Joseph, "An investigation of the origins of the variable proton tolerance in multiple SiGe HBT BiCMOS technology generations," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 3203–3207, Dec. 1988.

[4] P. W. Marshall, M. A. Carts, A. Campbell, D. McMorrow, S. Buchner, R. Stewart, B. Randall, B. Gilbert, and R. A. Reed, "Singel event effects in circuit-hardened SiGe HBT logic at gigabit per second data rates," *IEEE Trans. Nucl. Sci.*, vol. 47, no. 5, pp. 2669–2674, Oct. 2000.

[5] J. Cai, M. Kumar, M. Steigerwalt, H. Ho, K. Schonenberg, K. Stein, H. Chen, K. Jenkins, Q. Ouyang, P. Oldiges, and T. H. Ning, "Vertical SiGe-base bipolar transistors on CMOS-compatible SOI substrate," in *Proc. IEEE BCTM*, Sep. 2003, pp. 215–218.

[6] *Version 4.1. User's Manual. Synopsis*.

[7] P. F. Lu and T. C. Chen, "Collector-base junction avalanche effects in advanced double-poly self-aligned bipolar transistors," *IEEE Trans. Electron Devices*, vol. 36, no. 9, pp. 1182–1188, Sep. 1989.

[8] K. M. Murray, W. J. Stapor, and C. Castenada, "A proton beam facility for single event research," *Nucl. Instrum. Meth. B*, pp. 1256–1259, 1991.

[9] P. W. Marshall, C. J. Dale, M. A. Carts, and K. A. LaBel, "Particle-induced bit errors in high performance fiber optic data links for satellite data management," *IEEE Trans. Nucl. Sci.*, vol. 41, no. 4, pp. 1958–1965, Aug. 1994.

[10] J. D. Cressler, R. Krithivasan, G. Zhang, G. Niu, P. W. Marshall, H. S. Kim, R. A. Reed, M. J. Palmer, and A. J. Joseph, "An investigation of the origins of the variable proton tolerance in multiple SiGe HBT BiCMOS technology generations," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 6, pp. 3203–3207, Dec. 2002.

[11] C. T. Kirk, "Theory of transistor cutoff frequency falloff at high current densities," *IRE Trans. Electron. Devices*, vol. 3, pp. 164–170, 1964.

[12] Y. Li, "Radiation Effects and Temperature Effects of SOI CMOS Technology," Ph.D. dissertation, Auburn Univ., 2002.

[13] J. D. Cressler and G. Niu, *Silicon-Germanium Heterojunction Bipolar Transistors*. Boston, MA: Artech House, 2003.