An Investigation of Proton Energy Effects in SiGe HBT Technology

Shiming Zhang, John D. Cressler, Seshu Subbanna, Rob Groves, Guofu Niu, Tamara Isaacs-Smith, John R. Williams, Hassaram Bakhru, Paul W. Marshall, Hak S. Kim, and Robert A. Reed

***Abstract*-- We present the first investigation of low energy (1.75 MeV) proton irradiation in SiGe HBTs and discuss proton energy effects in SiGe HBT technology. The results show that after 1.75 MeV 1×10^{14} p/cm^2, a semi-insulating substrate is obtained and the peak quality factor of the monolithic inductors is improved by about 18% at 1.6 GHz. Although large current gain degradation for the SiGe HBTs was observed in the RF bias region after 1×10^{14} p/cm^2, the degradation in peak f_T is only about 11%. Proton energy studies from 1.75 MeV-200 MeV in SiGe HBTs suggest that the conventional damage factor can be used to estimate energy-dependent proton-induced radiation damage in this technology.**

I. Introduction

The maturity, high integration level, excellent yield, high speed, and low-cost aspects of SiGe HBT BiCMOS technology make it well-suited for Si-based system-on-a-chip digital, analog, RF, and microwave applications [1]. However, for RF passives and adequate RF isolation for transmission lines, for instance, there is a major concern about the use of the silicon substrate due to the high substrate losses associated with the much lower substrate resistivity compared to GaAs [2]. Recently, high energy (10-30 MeV) proton bombardment prior to packaging [3] was used to create semi-insulating regions on Si IC wafers, increasing the silicon substrate resistivity from 1-10 Ωcm to 10^5-10^6 Ωcm. In general, this technique is compatible with conventional fabrication technology because the bombardment is performed after wafer processing [4].

This work was supported by DTRA under the Radiation Tolerant Microelectronics Program, NASA-GSFC under the Electronics Radiation Characterization (ERC) Program, and the Auburn University CSPAE.

Shiming Zhang was with the Alabama Microelectronics Science and Technology Center, Electrical and Computer Engineering Department, Auburn University, Auburn, AL 36849-5201, USA. He is now with Cypress Semiconductor Corporation, Lexington, KY 40507, USA.

John D. Cressler is with the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0250, USA.

Guofu Niu is with the Alabama Microelectronics Science and Technology Center, Electrical and Computer Engineering Department, Auburn University, Auburn, AL 36849-5201, USA.

Seshu Subbanna and Rob Groves are with IBM Microelectronics, Hopewell Junction, NY 12533, USA.

Tamara Isaacs-Smith and John R. Williams are with the Physics Department, Auburn University, Auburn, AL 36849, USA.

Hassaram Bakhru is with the Physics Department, State University of New York, Albany, NY 12222, USA.

Paul W. Marshall is a consultant to NASA-GSFC.

Hak S. Kim is with Jackson and Tull Chartered Engineers, Washington, DC 20018, USA.

Robert Reed is with NASA-GSFC, Code 562, Greenbelt, MD 20771, USA.

However, high energy protons have one obvious disadvantage: they have a large penetration depth. The projected mean range (R_p) is about 700 µm for 10 MeV protons in Si, while R_p is only about 47 µm for 2 MeV protons. As shown in [5], low energy (1-3 MeV) proton irradiation can also increase the silicon resistivity considerably. Therefore, in this work, the use of low energy proton irradiation to increase the substrate resistivity in SiGe technology was investigated as a means to improve RF isolation and the performance of the passive elements.

In addition to the potential leverage of using low energy protons to improve the substrate properties of SiGe technology, the general energy dependence of proton damage in SiGe HBTs is of obvious interest in the context of space applications, and was also investigated. In general, transistor characteristics are expected to degrade more rapidly under low energy proton irradiation than for high energy proton irradiation [6]-[12], given that they deposit more energy in the active device regions near the wafer surface. Although many energy dependent studies in GaAs devices [6]-[8] and in Si devices [9]-[12] have been published, no energy dependent data exists for SiGe HBTs. Since SiGe technology is a potential candidate for space missions, it is thus necessary to address energy dependent effects.

We present the first low energy (1.75 MeV) proton study of SiGe HBT technology. We then employ the concept of a damage factor (including both displacement damage and ionization damage) to analyze the energy dependence of the observed degradation in SiGe HBT technology using 1.75 MeV (this work), 62.5 MeV [13], 195.8 MeV protons [14], and 1MeV neutrons [15]. Finally, the normalized damage factors for these SiGe HBTs are compared with the energy dependence of the normalized calculated non-ionizing energy loss (NIEL) for Si [12].

II. Experiment

Initial low energy proton radiation experiments were conducted at The State University of New York (SUNY) at Albany. A Dynamitron Accelerator was used to implant 8-inch SiGe wafers using 1.75 MeV protons with a dose up to 1×10^{14} p/cm^2 (the accuracy of the dose is better than ± 5%). The dc and ac performance of the SiGe HBTs and the performance of the monolithic inductors and substrate resistivity were measured before and after irradiation at room temperature (T = 300 K).

Additional 1.75 MeV proton irradiations were then performed at Auburn University using a 6SDH-2 Pelletron Accelerator at fluences ranging from 1×10^{13} p/cm^2 to 1.5×10^{14} p/cm^2. Two different technologies were used in these experiments: IBM's first generation SiGe technology (5HP), which has 50 GHz f_T, 0.5 μm SiGe HBTs [16], as well as IBM's third generation SiGe technology (7HP), which has 90 GHz f_T, 0.2 μm SiGe HBTs [17]. In the latter proton experiment, the samples (about 1cm × 1cm die for each sample) were mounted on diced conductive Si substrates. Two 5HP SiGe HBT die and two 7HP SiGe HBT die were irradiated, and each die had multiple transistors. These samples were measured at room temperature (T = 300 K) before and after irradiation using an HP 4155 Semiconductor Parameter Analyzer.

III. Low Energy Proton Results

Fig. 1 shows the forward Gummel characteristics of a typical 7HP SiGe HBT for pre-irradiation and after two low energy (1.75 MeV) proton fluences. The base current degrades monotonically with increasing proton fluence, thereby causing a drop in the current gain. This is the conventional radiation-induced degradation mechanism observed in these transistors. However, after 1×10^{14} p/cm^2 fluence, the current gain at J_C=1 mA/μm^2 for 7HP SiGe HBTs degrades from 250 to 70, meaning even in the RF bias region ($J_C\geq0.1$ mA/μm^2) the degradation is large. In contrast, for the 5HP SiGe HBTs reported in [18] (46 MeV proton irradiation), the current gain in the RF bias region shows little degradation and the change in the cutoff frequency is very small after 5×10^{13} p/cm^2. Given that the degradation for the 7HP SiGe HBTs is known to be worse than that of the 5HP HBTs at 63 MeV [19], and lower energy and higher fluence are expected to enhance this difference, we naively expected some degradation in the cutoff frequency for these 7HP SiGe HBTs, as shown in Fig. 2. The peak cutoff frequency degrades from 88 GHz to 78 GHz after 1×10^{14} p/cm^2 fluence, an 11% degradation. As illustrated in Fig. 3, after 1×10^{14} p/cm^2 irradiation, the total depletion capacitance increases from 0.79 fF to 0.96 fF, and the transit time degrades from 1.89 ps to 2.20 psec, primarily due to a current gain-induced increase in the emitter transit time. For the base resistance, we did expect some increase after irradiation, but not large for these 7HP SiGe HBTs, since the doping level in the base is very high (only a small increase of resistivity for 1.0 Ωcm p-type layer is observed even after 1×10^{15} p/cm^2 for 15 MeV proton bombardment in [4]). Although the current gain degradation in the RF bias region for these 7HP SiGe HBTs is substantial after 1×10^{14} p/cm^2, the ac performance is still respectable for many RF applications.

Fig. 4 shows the substrate resistivity as a function of proton fluence for both the 5HP and the 7HP p-type substrates. For the 5HP technology, the substrate resistivity for pre-irradiation is about 15 Ωcm, while after 1×10^{13} p/cm^2 irradiation, the substrate resistivity increases to about 46 Ωcm. After 5×10^{13} p/cm^2 and 1×10^{14} p/cm^2 irradiation, the substrate become highly resistive, making the resistivity determination difficult. After 1×10^{14} p/cm^2 irradiation, the estimated resistivity for 5HP and 7HP substrates is about 5×10^5 Ωcm. Physically, the increase of the resistivity after proton irradiation is primarily due to carrier removal by proton-induced charge trapping [20]-[22] and the Coulomb scattering of the carrier by the charged traps [21].

Title:
version 7.1 10 Mar 1995 u-ps 7gum (eps bare replace
Creator:
U-PS by R.F. Voss
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Fig.1. Forward Gummel characteristics of 7HP SiGe HBTs for pre-irradiation and two proton fluences at 1.75 MeV.

Title:
version 7.1 10 Mar 1995 u-ps ft (eps bare replace
Creator:
U-PS by R.F. Voss
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Fig. 2. The cutoff frequency as a function of collector current density for 7HP SiGe HBTs for pre-irradiation and 1×10^{14} p/cm^2 at 1.75 MeV.

Title:
version 7.1 10 Mar 1995 u-ps capd (eps bare replace
Creator:
U-PS by R.F. Voss
Preview:
This EPS picture was not saved
with a preview included in it.
Comment:
This EPS picture will print to a
PostScript printer, but not to
other types of printers.

Fig. 3. Reciprocal cutoff frequency as a function of reciprocal collector current for 7HP SiGe HBT for pre-irradiation and 1×10^{14} p/cm^2 at 1.75 MeV.

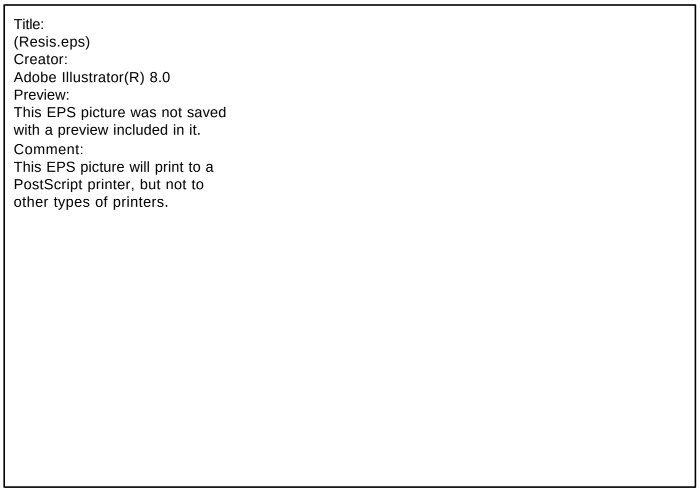

Fig. 4. Substrate resistivity as a function of proton fluence for 5HP and 7HP p-type substrates at 1.75 MeV.

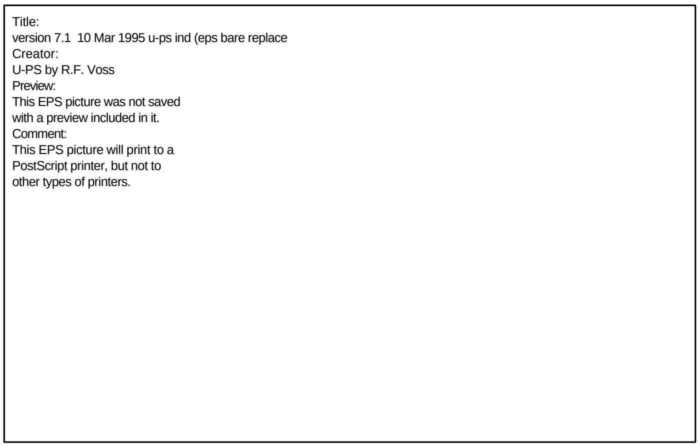

Fig. 5. Quality factor and inductance of the monolithic inductor on 7HP technology as a function of frequency for pre-irradiation and 1×10^{14} p/cm^2 at 1.75 MeV.

Fig. 5 shows the inductor performance for pre-irradiation and after 1×10^{14} p/cm^2 irradiation. After 1×10^{14} p/cm^2, the quality factor (Q) increases from 8.9 to 10.5 at a typical RF frequency of 1.6 GHz, an 18% improvement. Clearly, low energy proton irradiation can be used to create semi-insulating substrates, and thus improve the inductor Q, the performance of other RF passives, and RF isolation in SiGe technology, although at some cost in transistor performance.

IV. Energy Dependence of Proton-Induced Damage

In order to examine the energy dependence of proton-induced damage in SiGe HBTs, a damage factor needs to be first defined. According to [9], displacement damage reduces the current gain by shortening the minority carrier lifetime. Historically, it was found that over a large range of displacement damage, the reciprocal gain in a bipolar transistor increases linearly with incident particle fluence, and thus it is possible to define the Messenger-Spratt equation [23]:

$$\frac{1}{\beta(\phi)} = \frac{1}{\beta_0} + K\phi \qquad (1)$$

where β_0 is the initial current gain, K is the displacement damage factor, and ϕ is the incident particle fluence. In reality, the reciprocal gain versus proton fluence plot for bipolar transistors only behaves linearly over a certain proton fluence range since both displacement damage and ionization damage exist for proton irradiation. Therefore, both proton and gamma radiation experiments are in principle needed to quantify the displacement damage factor. For the purposes of the present study, it is logical to wonder whether this conventional (and quite old) displacement damage factor definition holds for modern SiGe HBTs, which have far thinner active device regions than older generation Si BJTs, whose current gain were typically dominated by the carrier lifetime in the base.

Conventionally, the following procedure is used to extract the displacement damage factor [10]: (1) plots of reciprocal gain versus total ionizing dose as a function of collector current are made after gamma irradiation; (2) these plots are then approximated by straight lines over the dose range corresponding to the proton irradiation experiments; and finally, (3) the slopes of these plots are then subtracted from the slopes of reciprocal gain versus proton fluence curves for the proton irradiation experiments in order to obtain the corresponding displacement damage factor.

Although in the present work the corresponding gamma irradiation experiments for the SiGe HBTs were not performed, we note that in our case the corrected damage factor versus collector current density data remains parallel with the data of the uncorrected damage factor versus collector current density [10]. Because the uncorrected damage factor data for these 5HP SiGe HBTs for three different proton energy levels remain approximately parallel with the displacement damage factor data for 1 MeV neutron irradiation (pure displacement damage), it is reasonable to use the uncorrected damage factor in these devices to estimate the proton-induced radiation damage. Under this assumption, a fixed percentage of the inferred damage factor will be the displacement damage factor for each corresponding proton energy.

Fig. 6 and Fig. 7 show the forward Gummel characteristics for typical 5HP SiGe HBTs for proton irradiation at two different energies: 1.75 MeV and 195.8 MeV. As expected, the degradation for the 195.8 MeV proton irradiation is very small compared to that at 1.75 MeV, since the damage mechanisms for low and high energy proton irradiations are quite different [12].

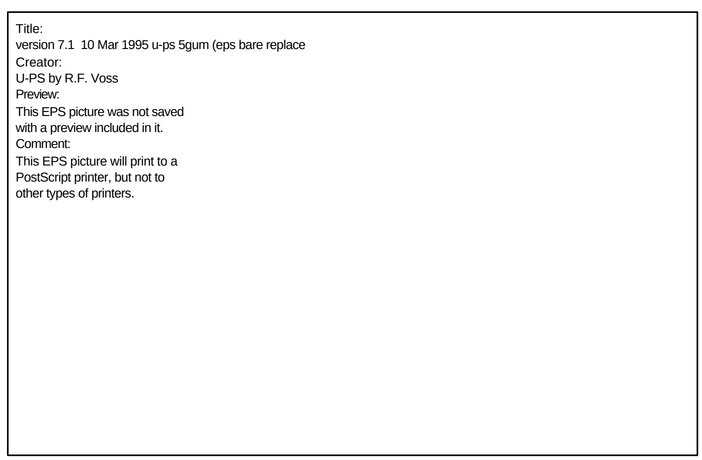

Fig. 6. Forward Gummel characteristics of 5HP SiGe HBTs for pre-irradiation and three proton fluences at a proton energy of 1.75 MeV.

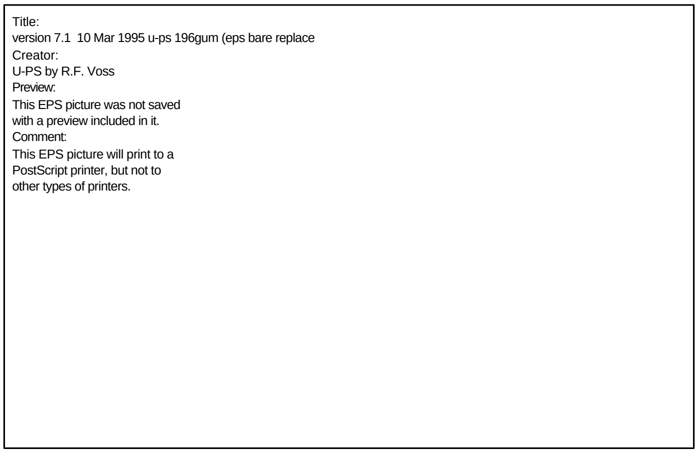

Fig. 7. Forward Gummel characteristics of 5HP SiGe HBTs for pre-irradiation and four proton fluences at a proton energy of 195.8 MeV.

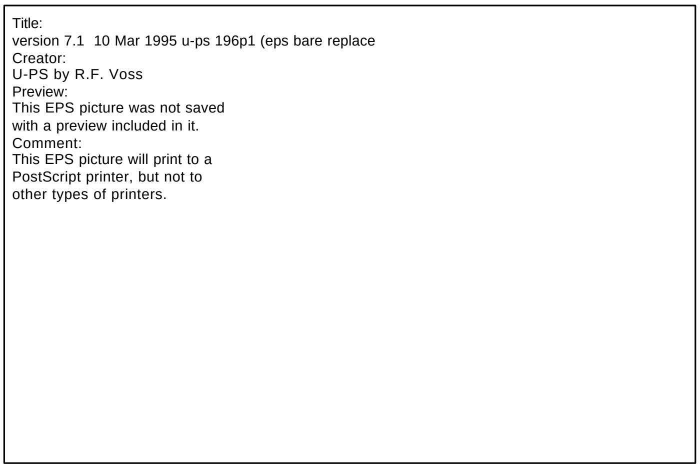

Fig. 8. Reciprocal current gain as a function of proton fluence for 5HP SiGe HBTs at two bias conditions at a proton energy of 195.8 MeV.

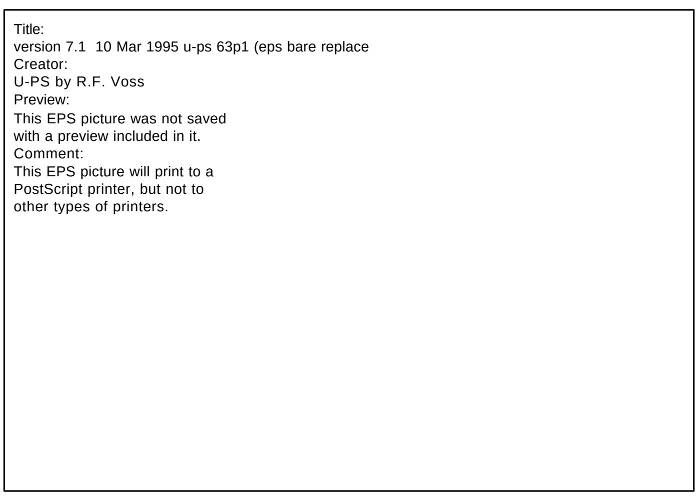

Fig. 9. Reciprocal current gain as a function of proton fluence for 5HP SiGe HBTs at two bias conditions at a proton energy of 62.5 MeV.

Fig. 8 shows the reciprocal current gain as a function of proton fluence for these 5HP SiGe HBTs at two bias conditions at a proton energy of 195.8 MeV. The slopes of the two linear-fits in Fig. 8 are the damage factors for these two bias conditions. The same approach can be used to extract the damage factor for the 62.5 MeV proton data, as shown in Fig. 9. It can be seen that for these 5HP SiGe HBTs at two proton energies, the reciprocal current gain linearly increases with proton fluence in the range of 7×10^{12} p/cm^2 to 5×10^{13} p/cm^2, as expected. Thus, the same fluence range was used to extract the damage factor for 1.75 MeV proton data.

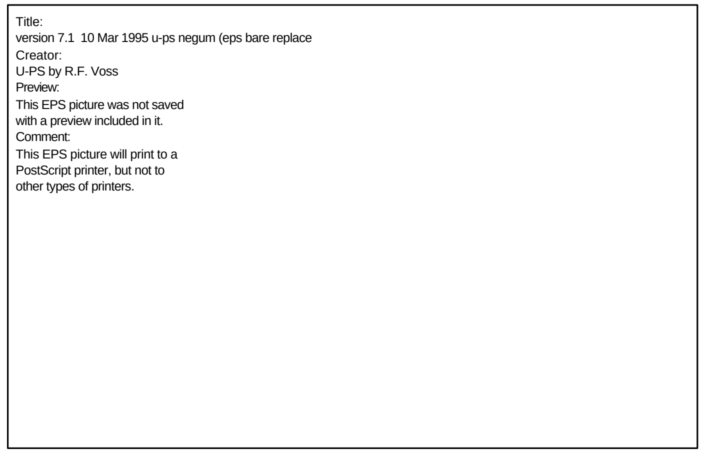

Fig. 10. Forward Gummel characteristics of 5HP SiGe HBTs for pre-irradiation and three neutron fluences at a neutron energy of 1 MeV.

For neutron radiation (Fig. 10), displacement damage dominates at high neutron fluences for these 5HP SiGe HBTs [15], and thus the range from 1×10^{14} n/cm^2 to 1×10^{15} n/cm^2 was used to extract the displacement damage factor.

Fig. 11 and Fig. 12 shows the calculated damage factor (displacement damage factor for neutrons) as a function of collector current density for the 5HP SiGe HBTs and the 7HP SiGe HBTs (62.5 MeV). All four curves in Fig. 11 are nearly parallel, suggesting that the damage factor defined here can be used to estimate the proton-induced radiation damage in these SiGe HBTs, and a fixed percentage of the damage factor can be inferred as the displacement damage factor for each proton energy. Comparing Fig. 12 with Fig. 11, at the same proton energy (62.5MeV), the damage factor for the 7HP SiGe HBTs is much higher than that of the 5HP SiGe HBTs, as expected, which further indicates that the damage factor defined here is reasonable.

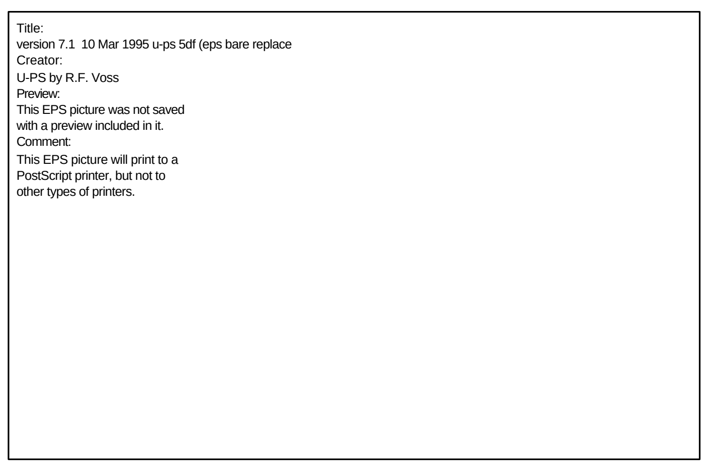

Fig. 11. Damage factor as a function of collector current density for 5HP SiGe HBTs at three proton energy levels and one neutron energy level.

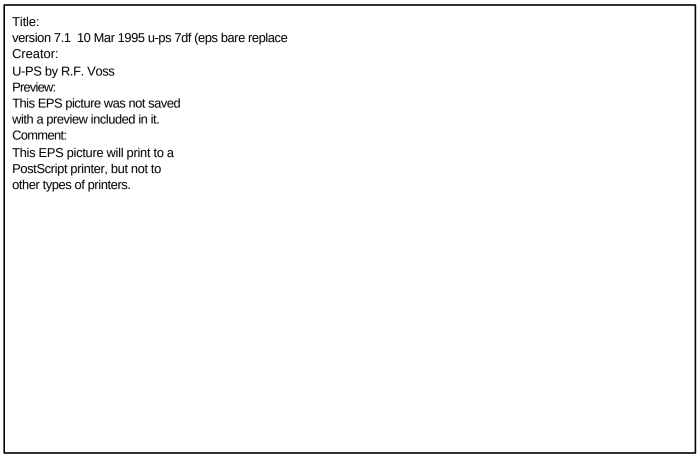

Fig. 12. Damage factor as a function of collector current density for 7HP SiGe HBTs at a proton energy of 62.5 MeV.

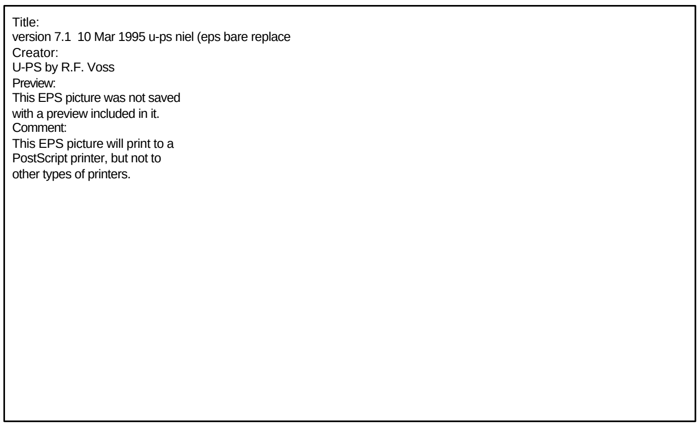

Fig. 13. Damage factor ratios for SiGe HBTs and calculated NIEL ratios in Si (both using 1MeV neutron as a reference) as a function of proton energy.

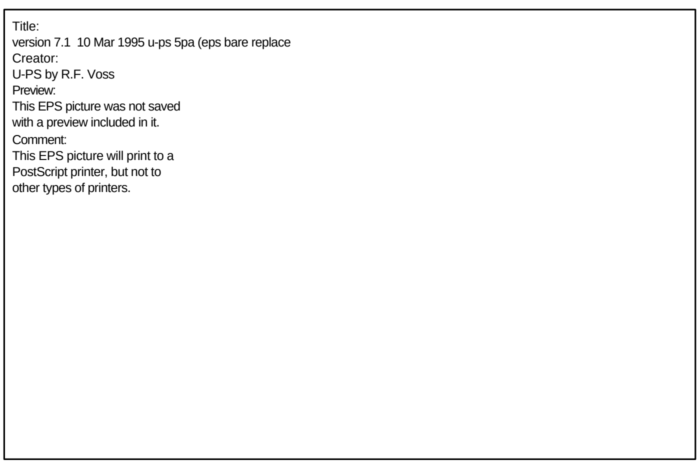

Fig. 14. Excess base current as a function of electrical emitter perimeter to area ratio for 5HP SiGe HBTs after 1×10^{13} p/cm^2 irradiation at a proton energy of 1.75 MeV.

From Fig. 11, we can also see that the ratios of proton damage factors to 1 MeV neutron displacement damage factors nearly remain constant over a large collector current density range. Thus, a unique correlation exists between the proton damage factors and the 1 MeV neutron displacement damage factors, as shown in Fig. 13. Since the damage factor for proton irradiation includes both displacement damage and ionization damage, it is not surprising that the damage factor ratios are higher than the calculated NIEL ratios. It is interesting to note that at very high (195.8 MeV) proton energy, the damage factor ratio is about 1.2-1.8 times the calculated NIEL ratio, while at low (1.75 MeV) proton energy, the damage factor ratio is about 1.6-2.4 times the calculated NIEL ratios. At moderate (62.5 MeV) proton energy, the damage factor ratio is about 3-7 times the calculated NIEL ratios. It was shown in [19] that ionization damage dominates in these 5HP SiGe HBTs for 62.5 MeV proton irradiation, which is consistent with the results shown in Fig. 13. A perimeter-to-area study at 1.75 MeV for these 5HP SiGe HBT after 1×10^{13} p/cm^2 (Fig. 14) also suggests that ionization damage is important for these 5HP SiGe HBTs. It is expected that the displacement damage factor ratios for these 5 HP SiGe HBTs should follow the trend of the calculated NIEL ratios in Si. Therefore, ionization damage in these 5HP SiGe HBTs is also energy dependent, and is an important damage mechanism for these 5HP SiGe HBTs at proton energy up to 200 MeV.

V. SUMMARY

The impact of low energy (1.75 MeV) proton irradiation on the performance of SiGe HBTs, the inductors, and the substrate resistivity were investigated, as well as the energy dependence of proton-induced damaged in SiGe HBTs. After 1×10^{14} p/cm^2 low energy proton irradiation, the substrate resistivity is increased to about 5×10^5 Ωcm, and the peak quality factor of the inductor improved by about 18% at 1.6 GHz. Although large current gain degradation for the 7HP SiGe HBTs was observed in the typical RF bias region after 1×10^{14} p/cm^2 at 1.75 MeV, the degradation of peak f_T was only about 11%, such that the ac performance of the irradiated 7HP SiGe HBTs remains useful for many RF applications. Whether the rather modest improvement in RF passive performance with high-dose proton irradiation is justified given the rather serious transistor degradation remains to be seen. One alternative possibility would be to shield the active devices from proton exposure, although this would not be straightforward (or cost-effective) given particle energy involved (1.75 MeV). It would also be worthwhile to investigate the use of neutrons for improvement of the passives (without shielding), given that ionization damage (the predominant damage mechanism in these devices) could then be removed from the transistors.

The damage factor concept which includes both displacement damage and ionization damage is used to analyze the energy dependence of the proton-induced damage. The proton damage factors normalized by 1 MeV neutron displacement damage factor were compared with the calculated proton NIEL normalized by 1 MeV calculated neutron NIEL. The results show that both displacement damage and ionization damage are energy dependent for these SiGe HBTs.

VI. ACKNOWLEDGMENT

The wafers were fabricated at IBM Microelectronics, Essex Junction, VT. The authors would like to thank S. Clark, L. Cohn, K. LaBel, H. Brandhorst, D. Harame, G. Freeman, A. Joseph and B. Meyerson for their contributions.

References

[1] J. D. Cressler, "SiGe HBT technology: a new contender for Si-based RF and microwave circuit applications," *IEEE Trans. Micro. Th. Tech*., vol. 46, no. 5, pp. 572-589, May 1998.

[2] J. N. Burghartz, M. Soyuer, and K. A. Jenkins, "Microwave inductors and capacitors in standard multilevel interconnect silicon technology," *IEEE Trans. Micro. Th. Tech*., vol. 44, no. 1, pp. 100-104, Jan. 1996.

[3] C. Liao, T.-H. Huang, C.-Y. Lee, D. Tang, S.-M. Lan, T.-N. Yang, and L.-F. Lin, "Method of creating local semi-insulating regions on silicon wafers for device isolation and realization of high-Q inductors," *IEEE Electron Device Lett.*, vol. 19, no. 12, pp. 461-462, Dec. 1998.

[4] L.-S. Lee, C. Liao, C.-Y. Lee, T.-H. Huang, D. Tang, T.-S. Duh, and T.-T. Yang, "Isolation on Si wafer by MeV proton bombardment for RF integrated circuits," *IEEE Trans. Electron Devices*, vol. 48, no. 5, pp. 928-934, May 2001.

[5] E. Ntsoenzok, J. F. Barbot, P. Desgardin, J. Vernois, C. Blanchard, and D. B. Isabelle, "Study of the defects induced in N-type silicon irradiated by 1-3 MeV protons," *IEEE Trans. Nucl. Sci.* vol. 41, no. 6, pp. 1932-1936, Dec. 1994.

[6] R. J. Walters, S. R. Messenger, G. P. Summers, E. A. Burke, S. M. Khanna, D. Estan, L. S. Erhardt, H. Liu, M. Gao, M. Buchanan, A. J. SpringThrope, A. Houdayer, and C. Carlone, "Correlation of proton radiation damage in InGaAs/GaAs quantum well light emitting diodes," *IEEE Trans. Nucl. Sci*, vol. 48, no. 6, pp. 1773-1777, Dec. 2001.

[7] A. L. Barry, A. J. Houdayer, P. F. Hinrichsen, W. G. Letourneau, and J. Vincent, "The energy dependence of lifetime damage constant in GaAs LEDs for 1-500 MeV protons," *IEEE Trans. Nucl. Sci*. vol. 42, pp. 2104-2108, Dec. 1995.

[8] S. R. Messenger, R. J. Walters, E. A. Burke, G. P. Summers, and M. A. Xapsos, "NIEL and damage correlations for high energy protons in GaAs devices," *IEEE Trans. Nucl. Sci.*, vol. 48, no. 6, pp. 2121-2126, Dec. 2001.

[9] G. P. Summers, E. A. Burke, C. J. Dale, E. A. Wolicki, P. W. Marshall, and M. A. Gehlhausen, "Correlation of particle-induced displacement damage in silicon," *IEEE Trans. Nucl. Sci.*, vol. 34, no. 6, pp. 1134-1139, Dec. 1987.

[10] G. P. Summers, E. A. Wolicki, M. A. Xapsos, P. Marshall, C. J. Dale, M. A. Gehlhausen, and R. D. Blice, "Energy dependence of proton displacement damage factors for bipolar transistors," *IEEE Trans. Nucl. Sci.*, vol. 33, no. 6, pp. 1282-1286, Dec. 1986.

[11] C. J. Dale, P. W. Marshall, E. A. Burke, G. P. Summers, and E. A. Wolicki, "High energy electron induced displacement damage in silicon," *IEEE Trans. Nucl. Sci.*, vol. 35, no. 6, pp. 1208-1214, Dec. 1988.

[12] E. A. Burke, "Energy dependence of proton-induced displacement damage in silicon," *IEEE Trans. Nucl. Sci.*, vol. 33, no. 6, pp. 1276-1281, Dec. 1986.

[13] S. Zhang, J. D. Cressler, G. Niu, C. J. Marshall, P. W. Marshall, H. S. Kim, R. A. Reed, M. J. Palmer, A. J. Joseph, and D. L. Harame, " The Effects of Operating Bias Conditions on the Proton Tolerance of SiGe HBTs," *Solid-State Electronics*, in press.

[14] G. Niu, G. Banerjee, J. D. Cressler, J. Rold<n, S. D. Clark, and D. C. Ahlgren, "Electrical probing of surface and bulk traps in proton-irradiated gate-assisted lateral PNP transistors," *IEEE Trans. Nucl. Sci*., vol. 45, pp. 2361-2366, Dec. 1998.

[15] J. Rold<n, W. E. Ansley, J. D. Cressler, S. D. Clark, and D. Nguyen-Ngoc, "Neutron radiation tolerance of advanced UHV/CVD SiGe HBT BiCMOS technology," *IEEE Trans. Nucl. Sci.*, vol. 44, no. 6, pp. 1965-1973, Dec. 1997.

[16] D. Ahlgren, M. Gilbert, D. Greenberg, S.-J. Jeng, J. Malinowski, D. Nguyen-Ngoc, K. Schonenberg, K. Stein, D. Sunderland, R. Groves, K. Walter, G. Hueckel, D. Colavito, G. Freeman, D. Harame, and B. Meyerson, "Manufacturability demontration of an integrated SiGe HBT technology for the analog and wireless marketplace," in *Tech. Dig. Int. Electron Device Meeting*, 1996, pp. 859-862.

[17] G. Freeman, D. Ahlgren, D. R. Greenberg, R. Groves, F. Huang, G. Hugo, B. Jagannathan, S. J. Jeng, J. Johnson, K. Schonenberg, K. Stein, R. Volant, S. Subbanna, "A 0.18 um 90 GHz f_T SiGe HBT BiCMOS, ASIC-compatible, copper interconnect technology for RF and microwave applications," in *Tech. Dig. Int. Electron Device Meeting*, 1999, pp. 569-572.

[18] S. Zhang, G. Niu, J. D. Cressler, S. D. Clark, and D. C. Ahlgren, "The effects of proton irradiation on the RF performance of SiGe HBTs," *IEEE Trans. Nucl. Sci*., vol. 46, pp. 1716-1721, Dec. 1999.

[19] J. D. Cressler, M. C. Hamilton, G. S. Mullinax, Y. Li, G. Niu, C. J. Marshall, P. W. Marshall, H. S. Kim, M. J. Palmer, A. J. Joseph, and G. Freeman, "The effects of proton irradiation on the lateral and vertical scaling of UHV/CVD SiGe HBT BiCMOS technology," *IEEE Transactions on Nuclear Science*, vol. 47, pp. 2515-2520, Dec. 2000.

[20] R. L. Pease, E. W. Enlow, and G. L. Dinger, "Comparison of proton and neutron carrier removal rate," *IEEE Trans. Nucl. Sci.*, vol. 34, no. 6, pp. 1140-1146, Dec. 1987.

[21] G. C. Messenger and S. A. Ash, *The Effects of Radiation on Electronic Systems*, 2nd ed. New York, NY: Van Nostrand, 1992.

[22] A. S. Grove, *Physics and Technology of Semiconductor Devices*, New York: Willey, 1967.

[23] G. C. Messenger and J. Spratt, "The effects of neutron irradiation of germanium and silicon," *Proc. IRE.*, vol. 46, pp. 1036-1044, 1958.