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# Electrical Probing of Surface and Bulk Traps in Proton-Irradiated Gate-assisted Lateral PNP Transistors

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*Abstract*

The effects of 46 MeV proton irradiation-induced trap generation and its impact on the electrical characteristics of gate assisted lateral PNP transistors (GLPNP) are investigated for the first time. At proton fluence as high as $10^{12}$ p/cm$^2$ the devices show a negligible current gain degradation, and at $10^{13}$ p/cm$^2$ the devices are still functional. The excellent radiation hardness is attributed to the much thinner gate oxide than in conventional lateral PNPs and its gate assisted operation. By changing the gate bias, and modulating the surface status from accumulation to inversion, the surface traps can be electrically probed from the I-V characteristics. A base current peak is observed after radiation, and is understood using 2D device simulation to be a result of the increase in oxide charge and surface trap density, in conjunction with the different SRH recombination rate limiting mechanism in presence of high density traps. The inverse mode operation is shown to be a useful tool for probing the bulk traps.

## I. INTRODUCTION

The lateral PNP transistor (LPNP), which is widely used in linear IC's, typically exhibits more degradation than the vertical PNP and NPN transistors due to surface conduction [1-2]. The gate-assisted lateral LPNP (GLPNP) transistor avoids the current gain limitation by combining both MOSFET and bipolar operational modes, and thus is widely used in BiCMOS circuits [3]. We present for the first time the effects of proton radiation on GLPNP's in an advanced SiGe Heterojunction Bipolar Transistor (HBT) BiCMOS technology [3]. Radiation-induced surface and bulk traps are electrically probed using a combination of DC measurements and 2D simulation. Figure 1 shows the schematic top view and cross section of a GLPNP, which is essentially a p-MOSFET whose source and drain serve as the emitter and collector of the lateral bipolar transistor. The base is defined by the p+ emitter/collector implant, and is self-aligned to the p+ polysilicon gate. The gate oxide thickness is 7.8nm, the base width is 1.0µm, and the source/drain junction depth is 0.25µm. In this experiment, samples were packaged in 68 pin LCCs and exposed to 46 MeV protons with terminals floating at fluences of $10^{12}$ and $10^{13}$ p/cm$^2$ at the Indiana University Cyclotron. Latest experiments with biased terminals show similar results.

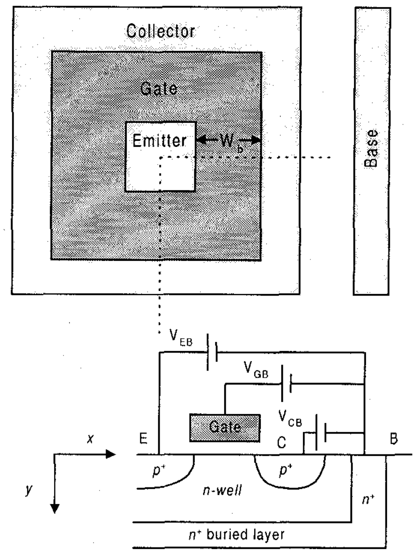


**Figure 1** Schematic top view and cross section of the GLPNP in the SiGe BiCMOS technology.

## II. CURRENT GAIN DEGRADATION

Figures 2 through 4 show the typical pre- and post-radiation Gummel characteristics at three $V_{GB}$s, representing surface strong inversion, depletion, and strong accumulation, respectively. In the normal $V_{GB}$=0 (gate tied to base) mode, the current gain degradation is negligible for $10^{12}$p/cm$^2$ fluence, with a total equivalent gamma dose of 184 krad(Si), as seen in Figure 5. This is far superior to the conventional LPNP, which exhibits 40 –90 % current gain degradation, depending on the emitter doping, after a 200 krad($SiO_2$) gamma radiation [1]. Even at proton fluence as high as $10^{13}$p/cm$^2$(1.84 Mrad(Si) total equivalent gamma dose), the current gain at $V_{EB}$=0.7V is still above 10 with gate-assisted operation, which enables the device to function as an active load in many circuit applications. The excellent radiation hardness of the GLPNP is also due to the use of a much thinner gate oxide (the same $t_{ox}$ as in CMOS), rather than the field oxide sitting above the base of the conventional LPNP. The threshold voltage shift is thus significantly reduced

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because of much larger $C_{ox}$ ($\Delta V_{th}= Q_{ox}/C_{ox}$) and much smaller $Q_{ox}$ due to the reduced oxide volume. With increasing radiation fluence, the fixed oxide charge density increases, thus increasing the threshold voltage to turn on the *p*-MOSFET, and producing an $I_C$ decrease. The radiation-induced G/R centers increase the recombination rate and hence $I_B$, as can be seen from Figures 2 through 4.

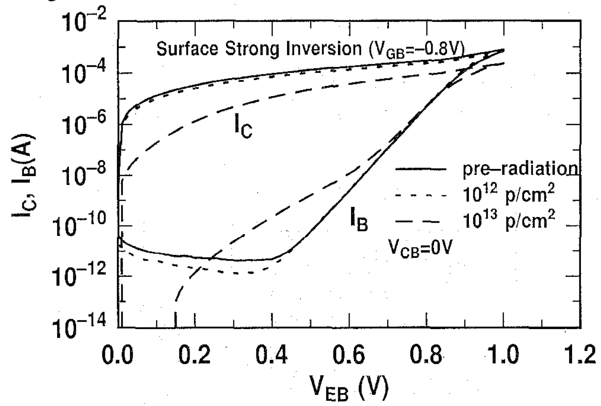


**Figure 2** Gummel characteristics when the surface is at strong inversion ($V_{GB}$=-0.8V).

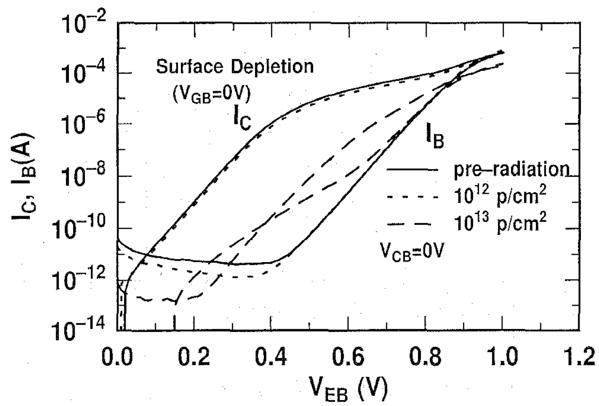


**Figure 3** Gummel characteristics when the surface is at depletion ($V_{GB}$=0V).

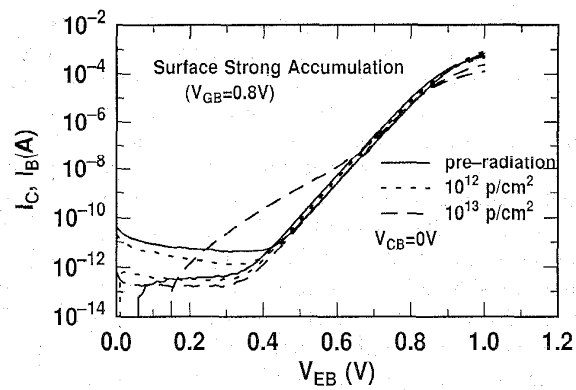


**Figure 4** Gummel characteristics when the surface is at accumulation ($V_{GB}$=0.8V).

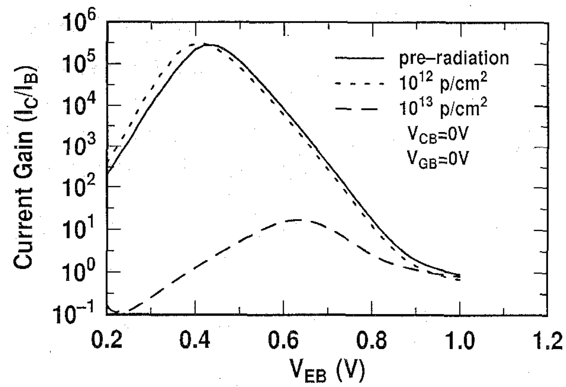


**Figure 5** Current gain versus emitter-base bias with gate tied to base ($V_{GB}$=0V).

## III. GATE-ASSISTED SURFACE TRAP PROBING

By varying the gate bias $V_{GB}$, the surface status can be modulated from accumulation to inversion, consequently producing a change in the recombination rate profile in the surface layer where the radiation-induced trap density is the highest. Therefore, the base current change with gate bias is expected to provide useful information on the nature of the surface traps. The collector current response with $V_{GB}$, on the other hand, provides information on the fixed oxide charge density. Figure 6 shows the $I_C$ and $I_B$ versus $V_{GB}$ at $V_{EB}$=0.3 and 0.6V.

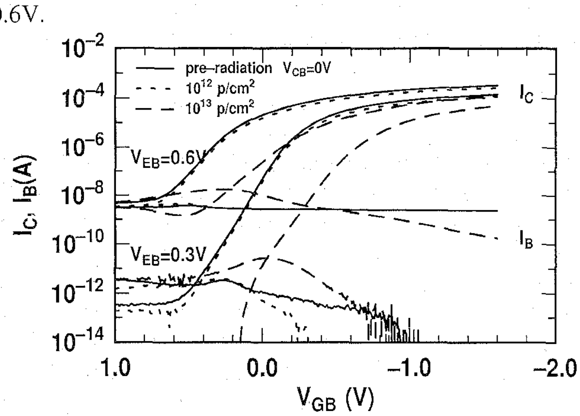


**Figure 6** Collector and base currents vs gate-to-base bias at $V_{EB}$=0.3 and 0.6V.

Note that a peak in the $I_B$ curve is observed after radiation. As $V_{GB}$ becomes more negative, $I_B$ first increases, then reaches a peak around the threshold voltage as indicated by a rise of the collector current, and finally starts to decrease. The peak is more obvious at higher radiation fluences, and serves as a signature of the surface traps. This observed $I_B$ peak **cannot** be explained using the conventional GLPNP theory [4], which predicts a monotonic $I_B$ decrease as $V_{GB}$ becomes more negative because electrons are pushed away from the surface where the recombination determines $I_B$. To understand the physics underlying the observed $I_B$ peak, we performed extensive 2D simulations using MEDICI, by placing positive charges in the oxide, and introducing a thin surface layer of traps [5]. The simulations show that the radiation-induced threshold voltage increase, as evidenced by the shift of $I_C$ in Figure 6, and the carrier lifetime decrease at the surface are responsible for the $I_B$ peak. Different combinations of the trap density and spatial distribution of traps were used, and only those with higher surface trap densities can reproduce the observed $I_B$ peak. Figure 7 shows the evolution of the simulated electron (solid) and hole (dash) densities versus depth with $V_{GB}$ change at $V_{EB}$=0.45V.

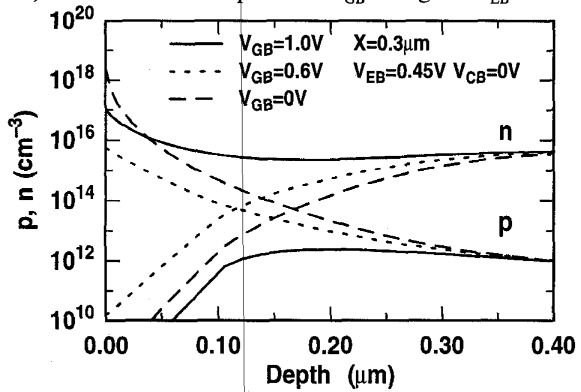


**Figure 7** Simulated electron and hole densities vs depth at different gate-to-base biases (x=0.3$\mu$m).

At $V_{GB}$=1.0V, the hole density is less than the electron density at the surface, and thus the recombination rate R is limited by the hole density. As $V_{GB}$ becomes more negative, the hole density at the surface increases (Figure 7), and thus $I_B$ increases because the lifetime at the surface is lower than in bulk due to radiation-generated traps. The rate of the increase depends on the relative magnitude of the surface recombination rate integral and the bulk recombination integral. The $10^{13}$p/cm$^2$ irradiated device has the highest trap density, and thus exhibits the most significant $I_B$ increase. At $V_{GB}$=0.6V, the electron and hole densities are becoming comparable, giving a peak in the recombination rate according to the SRH statistics, as shown in Figure 8. As $V_{GB}$ goes more negative, however, the surface is inverted, and the electron density is much lower than the hole density (Figure 7), and thus the surface recombination rate is limited by electrons. The surface electron density decreases as $V_{GB}$ becomes more negative, thus $I_B$ decreases. The contour plots

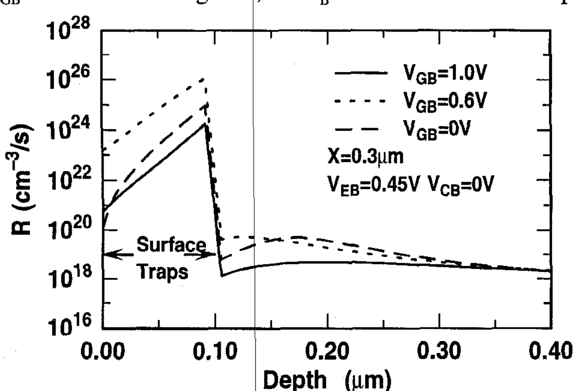


**Figure 8** Simulated recombination rate vs depth at different gate-to-base biases (x=0.3$\mu$m).

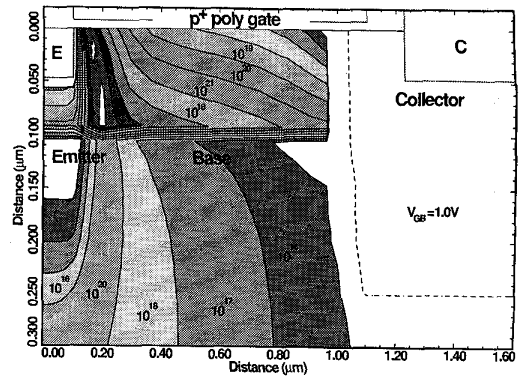


**Figure 9** Simulated 2D recombination rate contour at $V_{GB}$=1.0V (prior to the base current peak). $V_{EB}$=0.45V.

of the recombination rate at these three representative gate biases are shown in Figures 9 through 11, which clearly explain the $I_B$ change with $V_{GB}$ variation. The $V_{GB}$ at which $I_B$ peaks is less negative at higher $V_{EB}$, as can be seen in Figure 6, because the threshold voltage decreases with the increasing forward source to substrate bias of the *p*-MOSFET. For the same reason, the peak becomes less obvious at higher $V_{EB}$.

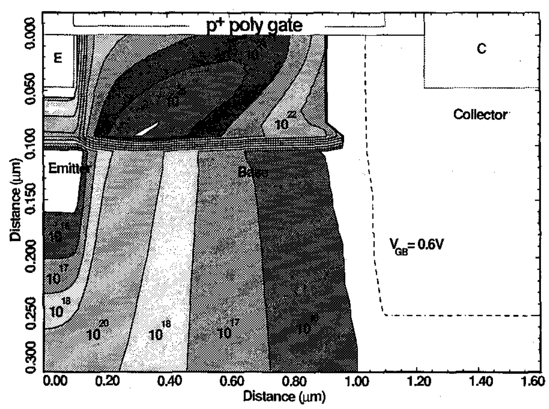


**Figure 10** Simulated 2D recombination rate contour at $V_{GB}$=0.6V (at the base current peak).$V_{EB}$=0.45V.

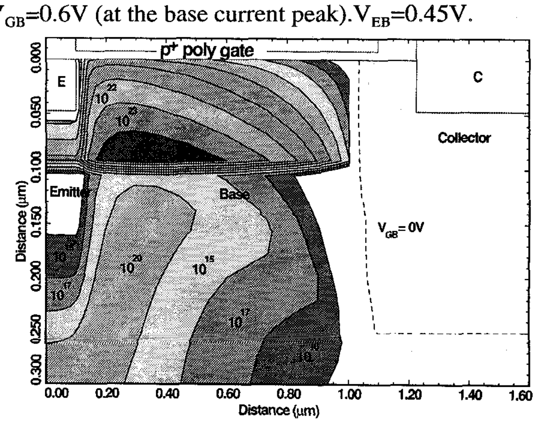


**Figure 11** Simulated 2D recombination rate contour at $V_{GB}$=0V (after the base current peak).$V_{EB}$=0.45V.

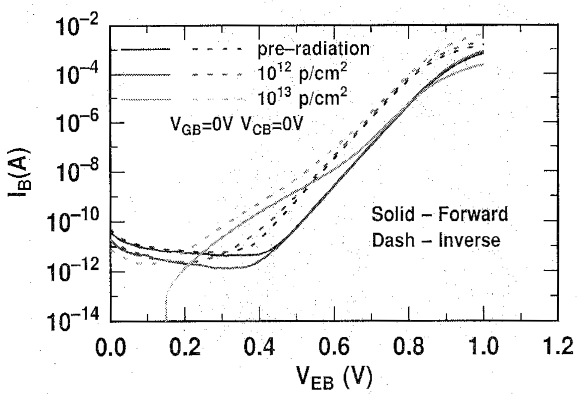


**Figure 12** Comparison of forward and inverse operation base currents.

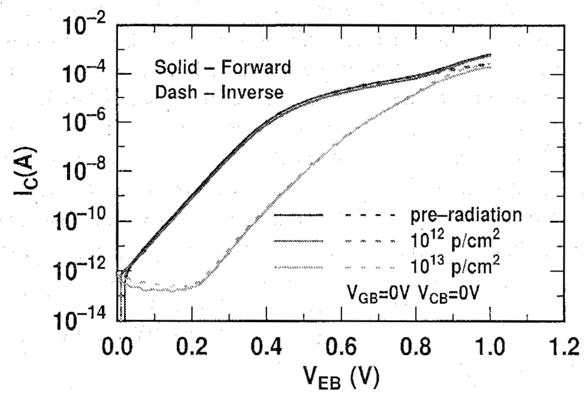


**Figure 13** Comparison of forward and inverse operation collector currents.

## IV. PROBING OF BULK TRAPS USING INVERSE OPERATION

Another characteristic of the GLPNP is that minority carrier injection occurs not only through the side-wall (laterally) but also at the bottom of the emitter (vertically). Due to the enclosed layout topology (Figure 1), the vertical injection component in the inverse operation mode (emitter and collector switched) is much higher than in the forward operation mode. Consequently, the base current under inverse operation is higher than in the forward mode, as shown in Figure 12 for $V_{GB}$=0V. In general the difference is smaller at lower $V_{EB}$ and higher radiation fluence because the lateral injection is dominant. The collector current under inverse operation, however, is almost the same as in the forward mode, because most of the vertically injected holes recombine with electrons before reaching the collector, due to the 2D current flow path, as seen in Figure 13. Consequently, the vertical injection is independent of the gate bias, and when the vertical injection-induced base current dominates over the lateral injection induced-base current, the base terminal current becomes independent of gate bias, as seen in the $V_{EB}$=0.6V curves in Figure 14. The $I_B$ increase with radiation fluence in such a case is solely due to the vertical injection, which is independent of the oxide charges and surface traps. Therefore, operation of GLPNP under such a bias configuration provides an excellent way to de-couple the determination of the radiation-induced bulk traps from the surface traps and oxide charges. For $10^{13}$ p/cm$^2$ fluence, $I_B$ at $V_{EB}$=0.6V increases by a factor of 2, indicating a 2x decrease in the bulk lifetime. The $I_B$ peak, however, is still observable at $V_{EB}$=0.3V, but with a smaller magnitude than in the forward operation mode, because of higher vertical injection component.

Figure 15 shows the transfer characteristics of the GLPNP in the pure *p*-MOSFET mode at $V_{DS}$= -1.5 and −0.05V. The $10^{13}$p/cm$^2$ irradiated device shows a degradation of subthreshold slope due to the interface states, in addition to an expected threshold voltage increase. The post-irradiation inverse operation $I_{DS}$ is the same as in the forward mode, because of its lateral conduction path.

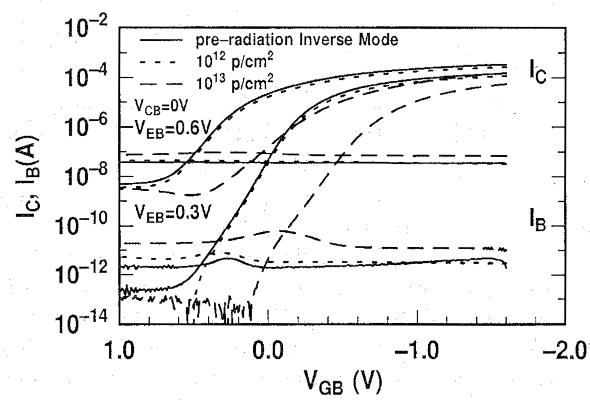


**Figure 14** Collector and base currents vs gate-to-base bias under inverse operation.

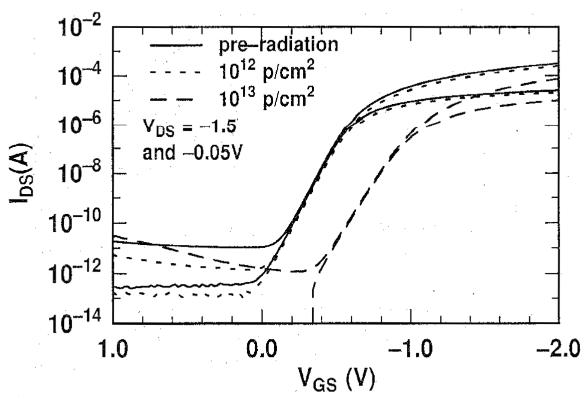


**Figure 15** Drain current versus gate-to-source bias in pure FET operation mode.

## V. CONCLUSION

In summary, the proton radiation-induced degradation of GLPNP transistors is investigated using DC measurements and numerical simulations. The GLPNP exhibits superior radiation hardness compared to conventional LPNP' s because of a much thinner oxide, and its gate-assisted operation. The gate bias is shown to be a useful tool for probing the nature of surface traps, and the inverse mode operation is shown to be a useful tool for probing the bulk traps. A radiation-induced peak in the base current versus gate bias curve, which cannot be explained by the conventional theory, is shown to be a result of the increase in fixed oxide charge and surface trap densities, in combination with the different SRH recombination rate limiting mechanisms in the presence of high density surface traps.

## ACKNOWLEDGMENTS

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