Effects of back-side He irradiation on MOS-GTO performances

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***Abstract*— A new version of a 1200V-20A MOS-GTO with 0.4 cm^2 die area is presented. The improvements of the switching performances have been achieved thanks to a new He irradiation technique performed from the back side of the device in order to avoid the degradation of the surface gate oxide. The high energy He irradiation allowed us to kill the lifetime in proximity of the N^-/N^+ interface in such a way to significantly improve the device switching performances as suggested by the simulations. The irradiation did not affect the on-state characteristics. Instead, a reduction by a factor ~4 in the storage time and more than 30% decrease in the turn-off energy losses have been measured on irradiated samples with respect to not irradiated ones.**

I. INTRODUCTION

Insulated Gate Bipolar Transistor (IGBT) devices are widely used in power conversion, but their performances are limited in high voltage applications, because the conductivity modulation of the N^-base present in their vertical structure is sustained only by the collector junction. As a consequence, for devices with blocking voltages larger than 3 kV, the required wide base causes the ON state voltage drop to become relatively high. To overcome this limitation, in the last years, many thyristor-like structures have been proposed [1-3]. Among them, the MOS-GTO (Metal Oxide Semiconductor Gate Turn-Off thyristor) seems to be very promising especially in high voltage applications, thanks to a very low voltage drop and good switching performances. The MOS-GTO is the monolithic functional integration of an emitter switched GTO [4] and ensures better performances than those of IGBT, even in its clustered version [5], thanks to the fact that the conductivity modulation of the N base region of the MOS-GTO is sustained by both anode and cathode junctions. In addition, this new device is not affected by the presence of parasitic thyristors which was the main limitation of other MOS controlled thyristors [2, 3] because of their negative impact on the safe operations of those devices. As for the other bipolar devices, the switching performances of a MOS-GTO are affected by the carriers lifetime in the N base and a trade off between on-state and switching performances can be achieved thanks to the implementation of lifetime killing techniques [6, 7].

The objective of this paper is to present the results of a study executed on 1200V-20A MOS-GTO samples irradiated with He in order to improve their switching performances. It is shown that irradiation can be executed from the back side of the die in order to avoid any degradation of the gate oxide and of the active region of the structure. Simulation and experimental results show much better performance of the irradiated devices in terms of storage time, switching losses and voltage drops, compared to not irradiated ones.

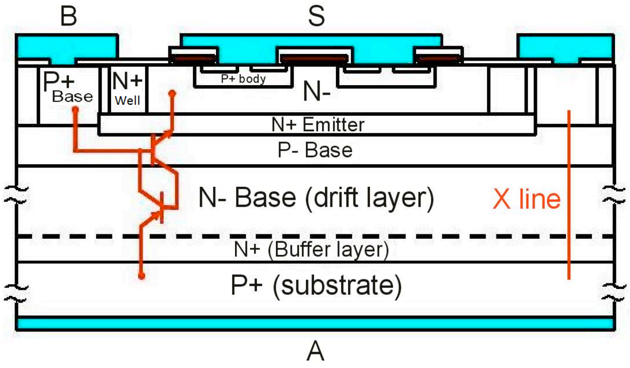


Figure 1. Elementary cell of the MOS-GTO.

II. MOS-GTO STRUCTURE

Fig. 1 shows the monolithic structure of the MOS-GTO elementary cell. It is obtained by integrating low-voltage diffused MOS (DMOS) cells inside the emitter region of the high voltage thyristor. Each DMOS cell is surrounded by N^+ wells that have the function of inhibiting the action of the lateral PNP parasitic transistor. The presence of an N^+ buffer layer makes this device a PT (punchthrough) version, however it is possible to fabricate non-PT devices without the buffer layer. In spite of MOS-GTO apparent complexity the perspective cost of the device is expected to be comparable with that of similar ratings IGBTs [1]. In fact the fabrication process of the MOS-GTO requires only slight modifications

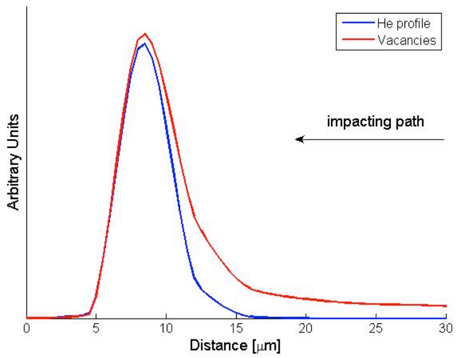


Figure 2. Typical He distribution and vacancies profile in a silicon target

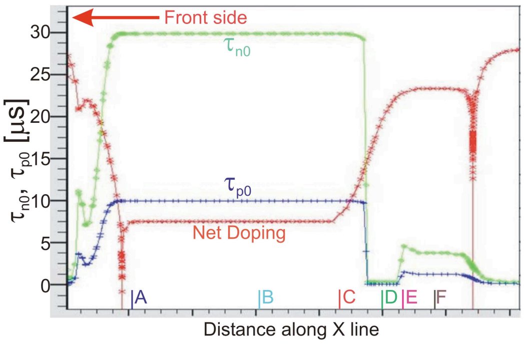


Figure 3. Lifetime and doping profile inside the elementary cell along the X line marked in Fig. 1.

of the flowchart used to fabricate the commercially available emitter-switched bipolar transistor (ESBT) [8].

III. OPTIMIZATION OF THE MOS-GTO PERFORMANCES BY HE IRRADIATION

A preliminary study has been performed by means of the 2D SILVACO ATLAS software [9] in order to study the effects of He irradiation on the performances of a 1200V-20A MOS-GTO. As well known, this lifetime killing technique can be used to modify the carrier lifetime in a very localized region whose depth can be chosen by using a proper energy of the impacting particles [10]. Typical He profile and primary vacancies distribution in the silicon target, obtained by SRIM [11] simulations, are reported in Fig. 2.

The doping profile of the simulated device, reported in Fig. 3, was obtained by ATHENA [9] process simulator applied to the fabricated device. The profile refers to the X line marked on the cell of Fig. 1, starting from the P^{+}Base region. In Fig. 3, the lifetime profiles of holes and electrons for one of the simulated cases are reported too. The width of the modified lifetime region has been chosen of about 6 μm according to SRIM simulations and experimental results reported in [10]. A reduction of two orders of magnitude in the lifetime profile of majority and minority carriers was imposed according to the results shown in [12] for common dose values used in lifetime killing techniques. Six different positions of the He peak concentration, indicated from A to F in Fig. 3, were considered in the simulations.

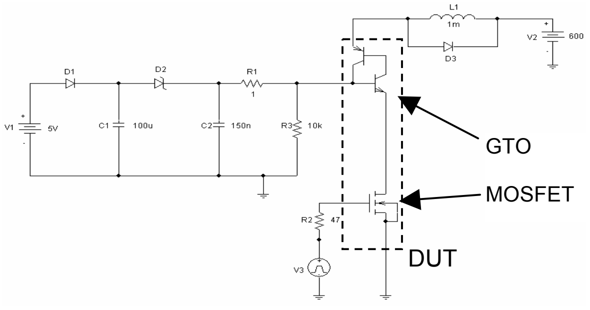
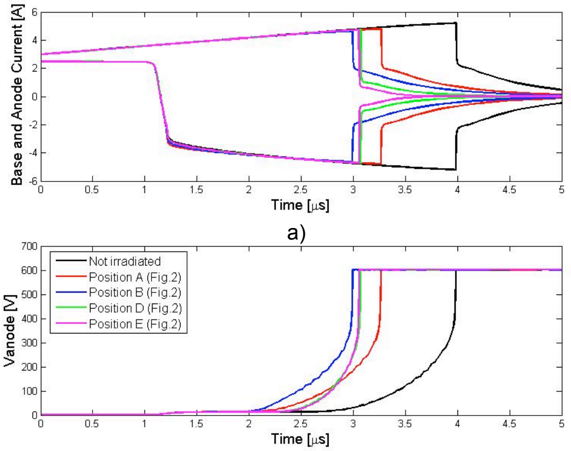


Figure 4. Circuit used for the switching study. The DUT (Device Under Test) is the dashed rectangle and includes a GTO section and a MOSFET section.



a)

b)

Figure 5. Simulated (a) anode and base currents and (b) anode voltage waveforms, for not irradiated device and for A, B, D and E positions of the He peak concentration.

The schematic of the circuit used for the switching simulation is reported in Fig. 4. The driving circuit includes a standard MOSFET driver and a passive network: V_1, D_1, D_2, C_1, C_2, R_1 and R_2. This network is able to supply a forward base current to trigger the GTO at the turn-on and to keep the voltage across the MOSFET below the breakdown limit during the extraction of the base current at the turn-off [1].

The anode and base currents (a) and the anode voltage (b) waveforms are reported in Fig. 5 for positions A, B, D and E of He peak concentration. For comparison, the waveforms of a not irradiated device is reported too. The test conditions are: V_2=600V, $I_{B,ON}$=2A, I_A=6A @ turn-off.

When the He peak concentration is located in the N base, moving the peak from the surface toward the buffer layer (positions A and B) causes a significant reduction of storage time and voltage rise time. When the peak is located across the N/N^{+} transition (positions D and E), current tailing and voltage rise time are significantly reduced, whereas the storage time has a weak increase compared to results obtained for the position B.

The overall effects of the variation of the position of the He peak concentration is summarized in Fig. 6, where the

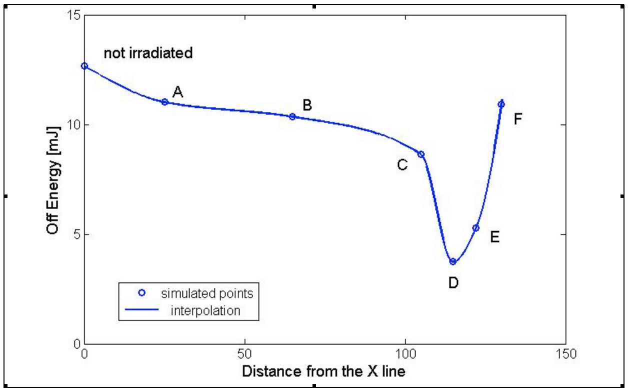


Figure 6. Turn-off energy losses as a function of the position of the He peak concentration.

simulated turn-off energy losses are reported as a function of the peak position. The minimum corresponds to the case when the lifetime is reduced at the N/N$^+$ interface (position D). In this case, a reduction of about 75% of the turn off energy is observed with respect to the not irradiated device.

Further simulations, not reported here for brevity, have shown that He irradiation has almost no effects on the on-state characteristics and on the turn-on switching performances of the device.

IV. EXPERIMENTAL RESULTS

The samples used in the experiment are rated at 1200V-20 A with a die area of ~ 0.4 cm^2. He irradiation was executed at high energy, ~ 40MeV, at the Cyclotron facility at the Laboratory Nazionali del Sud, Catania, Italy. On the basis of SRIM simulations, the energy of the beam was chosen in order to obtain an expected localization of the He peak concentration at the transition between N-drift and N$^+$ buffer layers (position D of Fig. 3).

The irradiation was executed from the back side of the wafer in order to avoid damages at the gate oxide and inside the active region of the device. The wafer were irradiated at the end of all technological process, metallization included, before cut and packaging.

The duration of the irradiation was changed in order to achieve tree different doses (namely, $2.5 \cdot 10^9$, $5 \cdot 10^9$ and $1 \cdot 10^{10}$ atoms/cm^2) on the samples placed at the centre of the beam. Moreover, the radial variation of the ion flux was used to obtain other intermediate doses. A thermal annealing was performed after the irradiation in order to stabilize the defects induced.

The first interesting result of the experimental characterization is the confirmation that the on-state characteristics of the MOS-GTO are practically independent of the He irradiation dose, as shown in Fig. 7 which reports the I-V characteristics measured at I_B=100mA and V_{GS}=10V on not irradiated (black curve) and $1 \cdot 10^{10}$ atoms/cm^2 He irradiated (red curve) devices.

The turn-on waveforms are reported in Fig. 8 for not irradiated device (black curve), and devices irradiated with $0.75 \cdot 10^9$ Atoms/cm^2 (blue curve) and $3.1 \cdot 10^{10}$ atoms/cm^2 (red curve). The test conditions are: V_2=1000V, $I_{B,ON}$=100mA, I_A=12A @ turn-on. Also in this case only weak variations of the current rise time are observed.

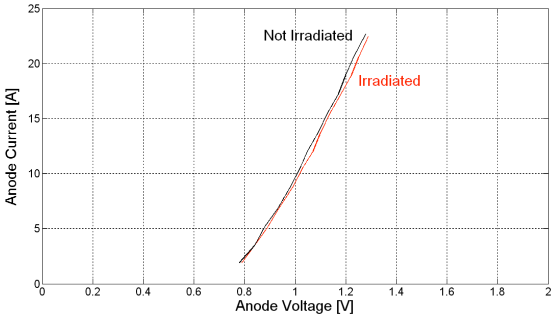


Figure 7. Experimental IV characteristics of not irradiated (black) and $1 \cdot 10^{10}$ atoms/cm^2 He irradiated (red) devices

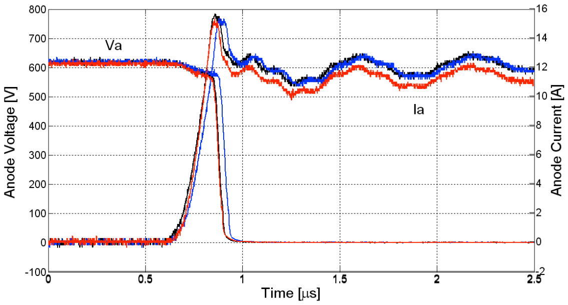


Figure 8. Anode current and voltage waveforms during turn-on of not irradiated (black), $0.75 \cdot 10^9$ (blue) and $3.1 \cdot 10^{10}$ (red) Atoms/cm^2 He irradiated devices.

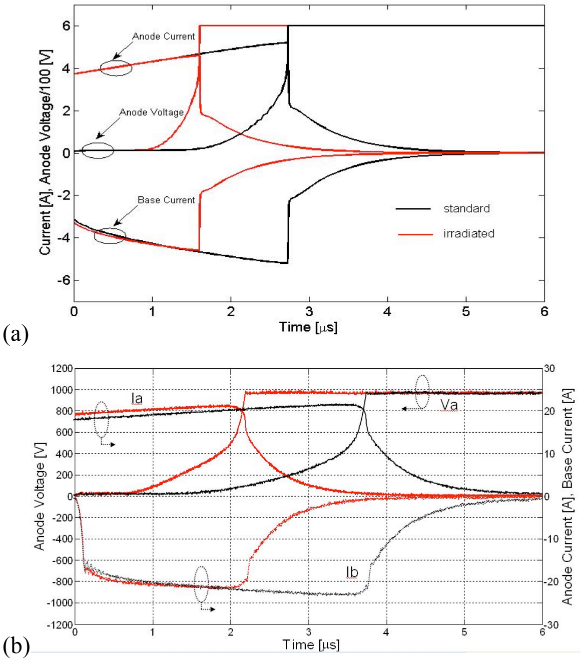


Figure 9. Simulated (a) and experimental (b) anode voltage, anode and base current waveforms of not irradiated (black) and He irradiated (red) devices.

The simulated and experimental turn-off waveforms are reported in Fig. 9 a) and b), respectively. The test conditions are: V_2=1000V, $I_{B,ON}$=100mA, I_A=22A @ turn-off. The waveforms refer to not irradiated (black curves) and $1\cdot10^{10}$ atoms/cm^2 He irradiated (red curves) devices. They demonstrate that, in these conditions, He irradiation is very effective in reducing the storage time and in speeding up the voltage rise, but it produces a lower effect in the tailing current. The speed up of the anode voltage causes a reduction of the turn-off energy of about 30%.

The improvement of MOS-GTO switching performances is quantified in Fig. 10 and Fig. 11, where storage time and turn-off energy, respectively, are reported as a function of the irradiation dose for three values of the anode current. The storage time is reduced by a factor ~4 and the turn-off energy losses are reduced by about 30% for all collector currents.

The experimental results show that the improvement of the switching performances obtained after the irradiation are lower than what we expected from the simulations. We attribute this difference to the fact that the He peak concentration obtained after the irradiation was located in the base region instead of being placed at the N/N$^+$ transition, due to an energy of the ions impacting the target higher than that obtained by SRIM. This behavior is consistent with the measurement of the spreading resistance performed on fresh and irradiated samples, not reported here for brevity. In fact the resistivity profile of the irradiated devices shows a significant reduction in the base region having the peak localized in vicinity of the position B of Fig. 3. This consideration is in agreement with the simulation results of Fig. 4 which shows in that case a 30% reduction of the turn-off energy. Much better performances can be expected with a localization of the He peak concentration at the N/N$^+$ transition.

V. CONCLUSION

The paper demonstrates that it is possible to perform He irradiation from the back side of the wafer thus avoiding any damages at the gate oxide of MOSFET placed on the device surface. Experimental results show that He irradiation can significantly improve the turn-off switching performances of the MOS-GTO without affecting its on-state and turn-on switching characteristics. Simulation results indicate that a proper localization of He peak concentration, obtained by changing the parameters of the irradiation (energy and dose), can be used to optimize the device characteristics and to improve significantly its switching performances. A reduction by more than 70% of the turn off energy losses compared to not irradiated devices can be expected thanks to He irradiations.

ACKNOWLEDGEMENTS

The authors wish to acknowledge Laboratori Nazionali del Sud, INFN, Catania, Italy, for having permitted the experiment. Special thanks goes to the laboratory technicians for the valuable assistance supplied during the irradiations.

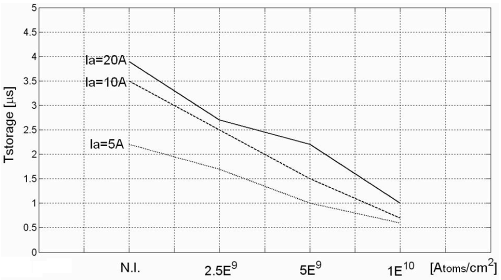


Figure 10. Storage time at different irradiation doses.

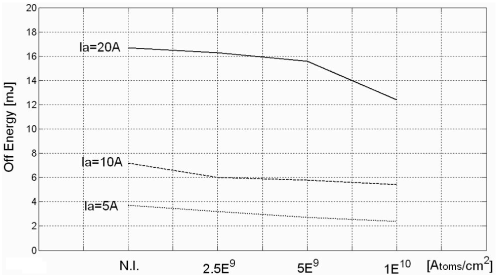


Figure 11. Turn off energy at different irradiation doses.

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