PROTON IRRADIATION FOR IMPROVED GTO THYRISTORS

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Introduction

The beneficial use of fast ion irradiation for local lifetime control in power devices has been reported occasionally ever since the first reports appeared over 15 years ago (1, 2). The technique has been demonstrated on almost all types of fast switching and high voltage devices (3-6). Despite of this, it has not yet been fully established in production. We apply proton irradiation to tailor the lifetime in large area 2.5 kV and 4.5 kV standard GTO thyristors. Various combination of doses and energies are used and the results show much improved characteristics.

I. Background

We generally talk about device optimisation in terms of the overall performance fulfilling demands set simultaneously on a number of key device parameters like on-state voltage, V_T, gate trigger current, I_{GT}, turn-off losses, E_{off}, and the storage time, t_S, (or the maximum gate current I_{GQM}). Trade-off curves, e.g. E_{off} versus V_T, have to be used since the demands on minimising the above parameters are in conflict with each other. It is of interest to determine in what way proton irradiation changes the basic trade-offs established by using electron irradiation.

Referring to the two transistor equivalent of the thyristor, the different parameters are determined by the properties of the distinct parts of the structure. I_{GT} and t_S are mainly determined by the properties controlling the α_{npn} current gain. These are doping, thickness and lifetime in the cathode emitter and p-base. In general the doping and thickness of these two layers in GTO thyristors are already as high as technologically possible due to the SOA requirements. Considering that the maximum turn-off current is inversely proportional to the p-base resistivity and that the lifetime is inversely proportional to the doping, it is easy to realise that the margins for reduction of the lifetime in the upper part of the modern GTO structures are not large. This is also the reason why proton irradiation from the cathode side often leads to a dramatic increase in the on-state voltage, V_T, and in I_{GT} (7).

The E_{off}, on the other hand is determined by the properties influencing the α_{pnp}. Both E_{off} and V_T depend on the charge carrier distribution in the n-base of the device. The charge carrier distribution is controlled by the anode emitter efficiency and the carrier lifetime in the wide n-base. The degree of improvement is strongly dependent on the actual device and is related to the design, technology and blocking voltage of the device. It can be expected that the improvement potential is greater for higher voltages as the thickness of the n-base increases. According to previous work (8), larger benefits could also be expected using more than one proton energy.

II. Experiment

A. Devices

Standard GTO devices, 2.5 kV and 4.5 kV, were taken from regular production lots. The 2.5 kV devices are rated for 2 kA turn-off current and the 4.5 kV devices for 3 kA turn-off current. Devices have a non-punch-through (NPT) design with a shorted anode. The diameter of devices is 68 mm for 2.5 kV and 85 mm for 4.5 kV respectively. Main difference between 2.5 kV and 4.5 kV devices is the thickness and doping of the n-base required to block the specified voltage. Thickness is 550 µm for 2.5 kV devices and 830 µm for 4.5 kV devices respectively. For both devices a broad database from standard electron irradiated devices is available for comparison.

B. Proton irradiation

Proton irradiations were performed from the anode side with energies ranging from 1.58 to 6.20 MeV, corresponding to depths in the devices of 25 to 300 µm, according to TRIM simulations (9), taking into account the effect of metalisation. Doses varied in the 10^{10} to 10^{11} cm^{-2} range and the flux did not exceed 1 nA/cm^2s. After irradiation the devices were subjected to a stabilising thermal anneal for 4 hours at 200 °C. The irradiation facilities, which include a 6 MV tandem accelerator with a specially designed target station for automatic sample feeding, are described in (10).

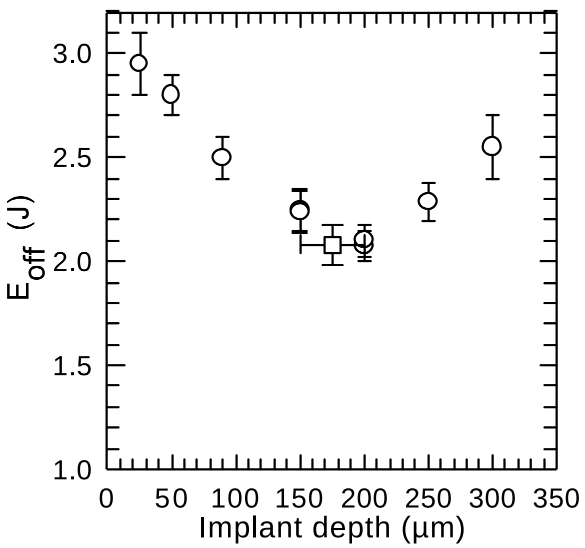
C. Electrical Measurements

Electrical parameters of the devices are measured typically at 2 kA and 2.5 kA and with di_{GQ}/dt= 30 and 40 A/µs for 2.5 kV and 4.5 kV devices, respectively, at room temperature (RT) and 125 °C. The maximum voltage V_{DM} is equal to full rated voltage, V_D is equal to 1/2 V_{DM} and C_S equal to 4 µF. Gate trigger current is measured by applying a constant gate current and a sine halfwave anode-cathode voltage with an amplitude of 12 V and 18 V for 2.5 kV and 4.5 kV devices, respectively. Test conditions for standard electron irradiated devices and proton irradiated devices are identical. To enable comparison with non-irradiated devices turn-off is measured at lower current as well.

III. Results

The influence of proton irradiation on the turn-off energy of the 2.5 kV devices is shown in Fig. 1 as a function of the irradiation depth using single proton energy. The plotted data are for different doses resulting in the constant on-state voltage of 2.2 V at rated current of 2 kA. The maximum reduction of the turn-off energy is obtained for the implantation depth between 180 µm and 200 µm.

Fig. 1 Turn-off energy of 2.5 kV GTO thyristors for different single energy proton irradiations (O) and for double energy irradiation (150 µm and 200 µm) (❑). Comparison is done at V_T=2.2 V and 125°C.



The experimental devices come from different lots and the absolute values of parameters, especially I_{GT} and t_S, vary between the lots. Some of the fine features are revealed only when the parameter values are normalised with respect to the original values of the as processed devices. This is done in Fig. 2 for the same 2.5 kV devices. It can be seen that the gate trigger current is reduced for shallow implantation depths compared to the as processed value and exceeds this value only for implantation depths greater than 150 µm. The storage time is basically unaffected by proton irradiation for irradiation depths below 150 µm. The reduction of the I_{GT} for low implantation energies, shown here for the first time, is most probably due to the increase of the resistivity associated with the proton irradiation (11). This increases the lateral voltage drop under the p^+ emitters and the on-set of the hole injection occurs at a lower value of the cathode electron current.

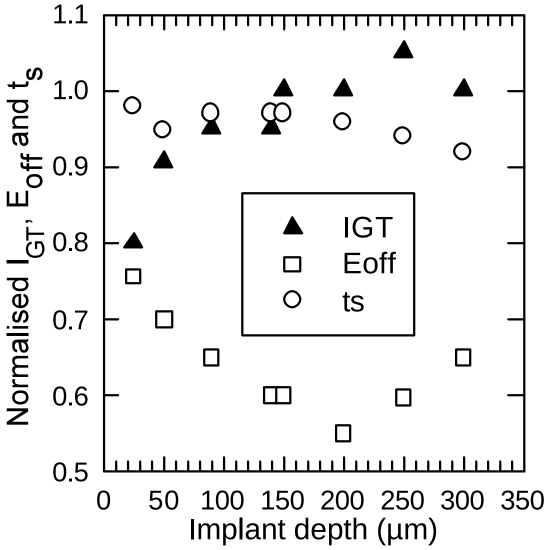


Fig. 2 I_{GT} (25°C), E_{off} (125°C) and t_S (125°C) values of 2.5 kV devices normalised with respect to the values for as processed devices. The corresponding normalised values for electron irradiated devices are 1.36, 0.65 and 0.88 for I_{GT}, E_{off} and t_S, respectively. The absolute I_{GT}, E_{off} and t_S values for electron irradiated devices are 1900 mA, 2550 mJ and 17 µs.

In Figs. 3-5 the basic trade-off curves for 2.5 kV devices proton irradiated to a depth of 200 µm are shown in comparison with the electron irradiated devices from the same production lots. The proton dose varied between $1 \cdot 10^{10}$ cm^{-2} and $6 \cdot 10^{10}$ cm^{-2}. More than 100 wafers from different lots were used.

The basic features of proton irradiation as compared to electron irradiation are clearly demonstrated. Proton irradiation results in lower E_{off} and lower I_{GT} but in higher t_s values compared to the electron irradiation.

Finally, the same basic features of proton irradiation are demonstrated in the case of 4.5 kV GTO thyristors in Figs. 6-8. The basic trade-off curves for 4.5 kV devices are shown using data for single and double energy implantations together with data for as processed and electron irradiated devices.

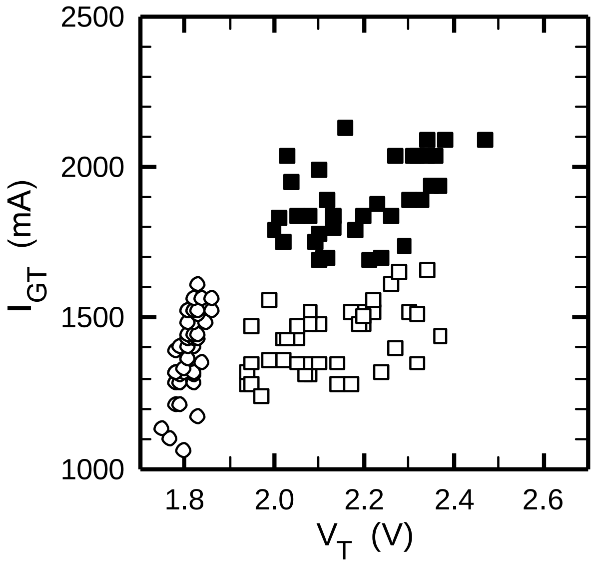


Fig. 3 I_{GT} (25°C) versus V_T (125°C) for proton (❑) and electron (■) irradiated and as processed (O) 2.5 kV GTO thyristors.

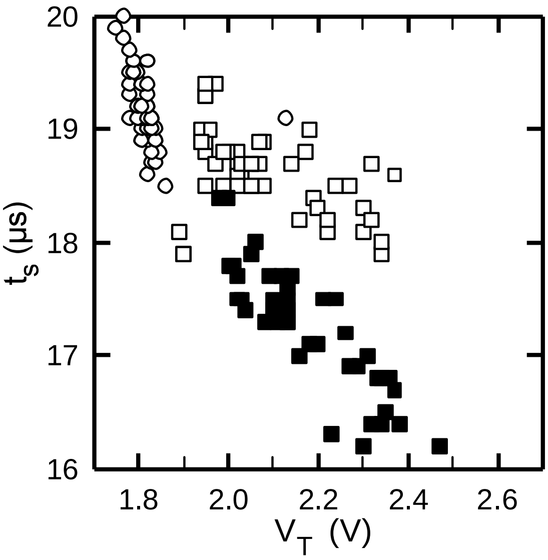


Fig. 5 t_S (125°C) versus V_T (125°C)for proton (❑) and electron (■) irradiated and as processed (O) 2.5 kV GTO thyristors.

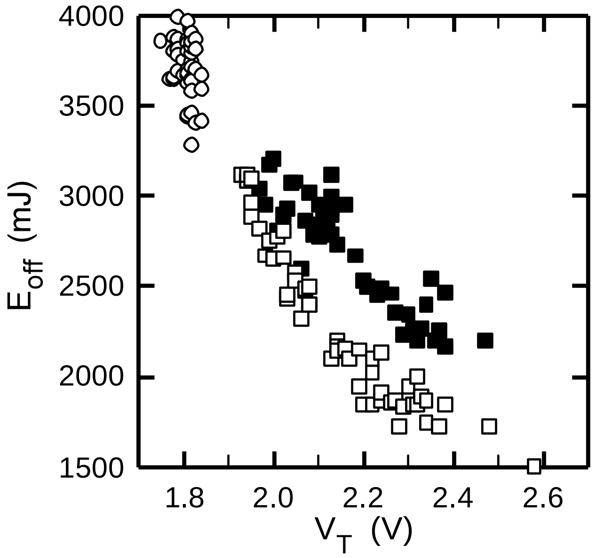


Fig. 4 E_{off} (125°C) versus V_T (125°C) for proton (❑) and electron (■) irradiated and as processed (O) 2.5 kV GTO thyristors.

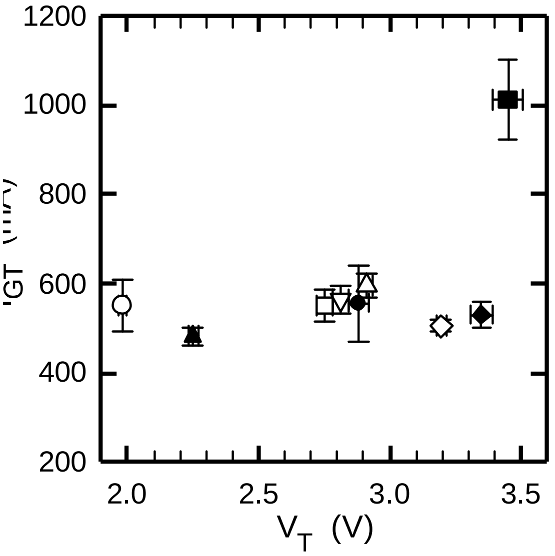


Fig. 6 I_{GT} (25°C) versus V_T (125°C)for proton and electron (■) irradiated and as processed (O) 4.5 kV GTO thyristors

Single energy irradiations have depths of 50 (▲), 150 (●), 200 (❑), 250 (Δ) and 300 (∇) µm and doses of 5, 10, 8, 6 and $4{\cdot}10^{10}$cm^{-2}, respectively. Double energy irradiations have depths of 50/300µm (◆) and 150/250µm (◊) and doses of $1{\cdot}10^{11}/4{\cdot}10^{10}$ cm^{-2} and $4{\cdot}10^{10}/3{\cdot}10^{10}$ cm^{-2}, respectively. Refer to Figs. 6-8.

IV. Discussion

The results for 2.5 kV GTO thyristors show clearly that a single energy irradiation to a depth of between 150 µm and 200 µm yields the best trade-off for all the parameters. No additional improvement was found by using the extra energies or by combining proton and electron irradiations. The data available at this point for 4.5 kV devices are not conclusive.

A very interesting result of this study is that the I_{GT} values of as processed devices can be reduced by shallow proton irradiations. A 20% reduction of the I_{GT}, compared to the as processed values is demonstrated. Measurements down to -40 °C confirm the beneficial influence of the proton irradiation compared to the as processed and electron irradiated devices. The results also show that I_{GT} is almost unaffected by the proton irradiation for implantations deeper than 100 µm and up to 80% of the total n-base width.

A possible draw back of using proton irradiation is that the storage time, t_S, values are higher in the case of the proton irradiation as compared to the electron irradiated devices. The t_S values are larger than for the electron irradiated devices up to the proton implantation depth of 80% of the n-base width (Fig. 2).

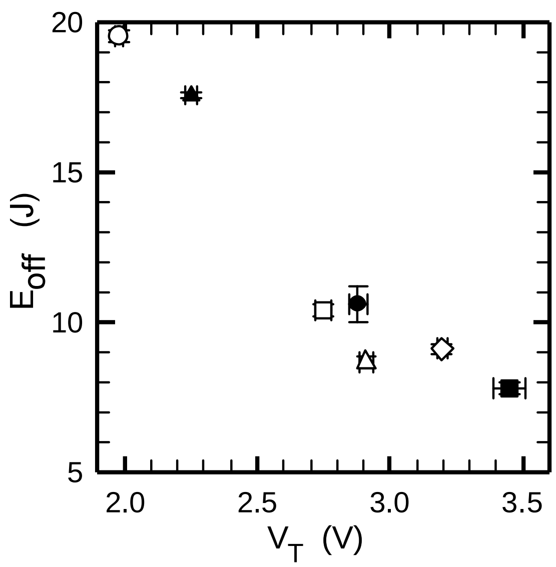
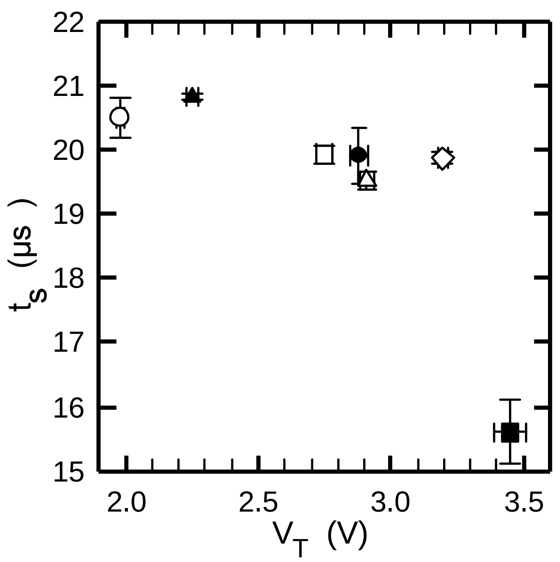


Fig. 7 E_{off} (125°C) versus V_T (125°C) for proton and electron (■) irradiated and as processed (O) 4.5 kV devices.

Fig. 8 t_S (125°C) versus V_T (125°C) for proton and



electron (■) irradiated and as processed (O) 4.5 kV devices.

The potential for improvements is expected to be greater with increased design voltage since the relative importance of the p-n-p transistor for the overall device performance increases. The comparison of the results for 2.5 kV and 4.5 kV devices supports this prediction. The difference in parameter values between electron and proton irradiated devices is greater for 4.5 kV devices. I_{GT} is 30% and 50% lower (Figs. 3 and 6) and E_{off} is 25% and more than 30% lower (Figs. 4 and 7) compared to the electron irradiated 2.5 and 4.5 kV devices, respectively. t_S values are about 10% and 30% higher (Figs. 5 and 8) compared to the electron irradiated 2.5 and 4.5 kV devices, respectively.

An important advantage of the proton irradiation is the possibility of controlling separately the I_{GT} and E_{off}. For other lifetime control techniques, for instance electron irradiation and impurity diffusion, these two parameters are coupled together by a trade-off relation.

Relative insensitivity of both the I_{GT} and t_S to the proton irradiation is related to the fact that irradiations are performed from the anode side. This way we can influence the α_{pnp} without influencing the α_{npn}.

V. Conclusions

GTO devices used in this investigation are already optimised with respect to the trade-offs between physical properties and also with respect to the economy of manufacturing. Nevertheless, it is possible, as is shown here, to improve important parameters without necessarily impairing others by replacing electron irradiation with proton irradiation for lifetime control. Specifically it is shown that proton irradiation allows for individual optimisation of I_{GT} and E_{off}, increasing the degree of freedom for the GTO design. These two parameters can thus be trimmed independently in accordance with customers demand after processing and before encapsulation.

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