Thyristors with Low Circuit Commutated Turn-off Time for HVDC and FACTS

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ABSTRACT

Electron and proton irradiation for carrier lifetime control was combined to reduce the circuit commutated recovery time t_q. Using the latest generation of large area 7.2 kV / 6 kA Phase Control Thyristors for HVDC and other demanding applications, we show the impact of t_q reduction on the technology curve between the ON-state voltage drop V_T and recovery charge Q_{rr}, as well as the limits of this reduction. A procedure for the best t_q – V_T relation for the range of V_T below 2 V suitable for HVDC is proposed.

1. INTRODUCTION

The circuit commutated recovery time of thyristors t_q is a period during turn-off process, when the state of device is unknown. The device is neither in forward conduction nor capable of a safe blocking. The spatial distribution of charged carrier concentration is strongly non-homogeneous in both vertical and lateral direction and the device is vulnerable to destruction by fast growing anode to cathode voltage. For this reason, the device is usually protected against external voltages either by internal protection structures or by external recovery protection circuitry [1].

From application viewpoint, t_q is the period of time without possibility of power control by HVDC valve. As a result, it is an important parameter in valve design when it comes to a smooth power control without commutation failures, which can cause a temporary cessation of power transfer and overloading of the valves. Even though a well-designed Thyristor Control Unit avoids such failures, the shorter t_q means a smoother and cheaper power control. Last but not least, for the application of thyristors, which require a higher operation frequencies, a shorter t_q is the necessary condition. All this motivated us to study the technological possibilities and limitations to achieve low t_q at large area thyristors produced at 150 mm silicon wafers.

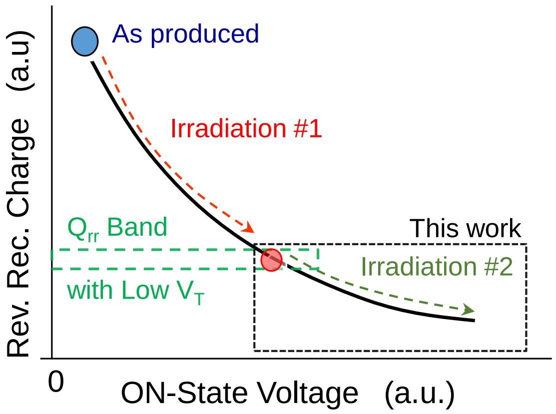

Fig.1: Trade-off between recovery charge Q_{rr} and ON-state voltage V_T, the lower part of which is studied in this work.

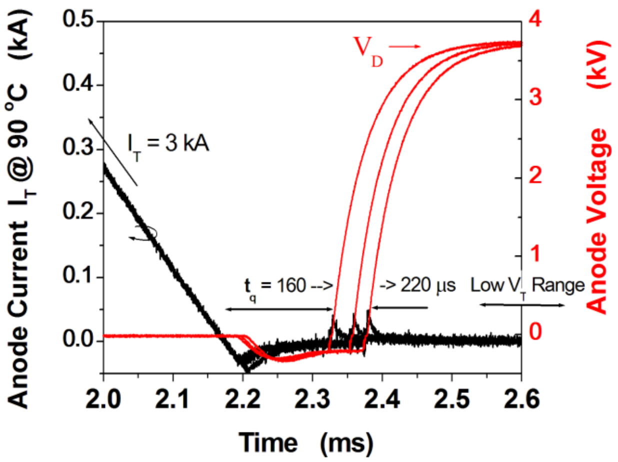

Fig.2: Three exemplary waveforms from t_q test starting from the ON-state current of 3 kA with di/dt = -1.5 A/us and V_R = 200 V followed by dV/dt = 50 V/us to V_D = 3.7 kV.

2. EXPERIMENTAL

We have used our standard production devices of the latest generation [2, 3], which are normally brought into a narrow Q_{rr} band either by electron or proton irradiation as required for a reliable serial connection in a HVDC valve. The Q_{rr} band features a low V_T to minimize the dominant valve losses, which take place in the ON-state.

We have further irradiated these devices using the electron and combined proton-electron irradiation shown in Fig.3 in order to move them towards the lower magnitudes of Q_{rr} and t_q according to the Fig.1 and Fig.2.

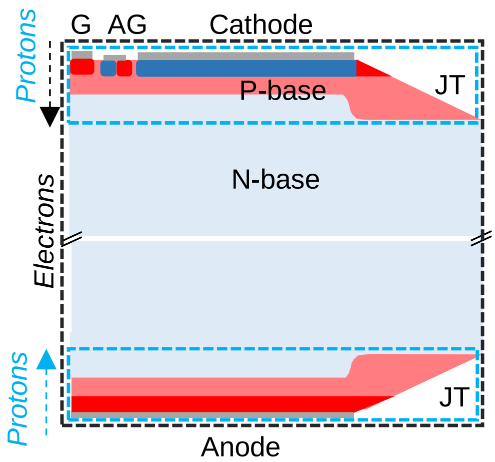

Fig.3: Device under test. The proton irradiation is symmetrical in energy and dose for both sides.

The combined proton-electron irradiation was divided into two cases. One with dominant dose of electrons (Electrons >> Protons) and one with the dominant dose of protons (Protons >> Electrons). We have hereby received devices

- with a very uniform spatial distribution of excess carrier lifetime (Electrons),
- with less uniform lifetime distribution having a shorter lifetime close to the anode and blocking junction (Electrons >> Protons) and
- with very non-uniform lifetime distribution with a much shorter lifetime close to the anode and blocking junctions compared to the N-base (Protons >> Electrons).

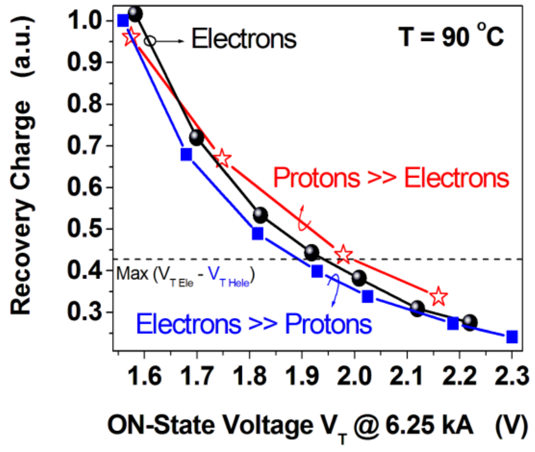

Fig.4a): Trade-off curve Q_{rr} – V_T for various irradiation treatments. The highest Q_{rr} is that of the Q_{rr} band of the standard HVDC thyristor of 7.2 kV class with very low V_T.

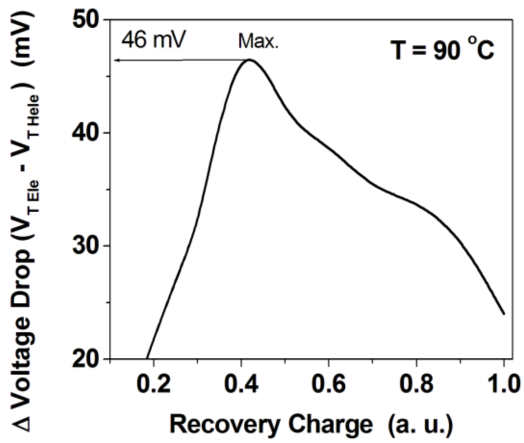

Fig.4b): Difference in V_T for equal Q_{rr} between curves "Electrons" and "Electrons >> Protons" from Fig.4a. Maximal difference is also shown in Fig.4a (dashed).

The impact of these three treatments on the V_T, t_q and Q_{rr} is shown below. The circuit commutated recovery time t_q was measured up to V_D = 3.8 kV with dV/dt = 50 V/us. This represents the conditions of slow and partial depletion of the N-base region. Slow in terms of dV/dt and partial in terms of the width of the space charge region in the forward direction.

The recovery time t_q was also measured up to the maximal forward blocking voltage V_D = 7.2 kV with dV/dt = 1 kV/us to cover the conditions of fast and full depletion of the N-base.

2. EXPERIMENTAL RESULTS

Fig.4a compares the technology curves of the three irradiation techniques described above. The dominant dose of protons results in the worst technology curve, because the growing dose of protons with ion range located in the N-base close to the junctions brings a higher increase of V_T relative to the overall reduction of Q_{rr}. A low dose of protons with the dominant dose of electrons represents a sweat spot for the fast large-area thyristors. When the proton dose becomes negligible relative to that of the electrons, the “Electrons >> Protons” and “Electrons” curves merge - see Fig.4a with V_T > 2.1 V.

Figs.5a) and b) show a linearly decreasing t_q with decreasing Q_{rr} in the low t_q range for both partial and full depletion of the N-base. For the full depletion (Fig.5b), there is no significant difference between the irradiation techniques. For the partial depletion (Fig.5a), the advantage of using proton irradiation is clearly visible.
Because of the linear dependence $t_q = f(Q_{rr})$ shown above, the graphs of t_q vs. V_T shown in the Fig.6a) and b) should follow the technology curve from the Fig.4a. This is indeed the case of full N-base depletion shown on Fig.6b). The very high dose of protons does not bring any benefit. For the slow and partial depletion on Fig.6a), the electron irradiation represents the worst case.

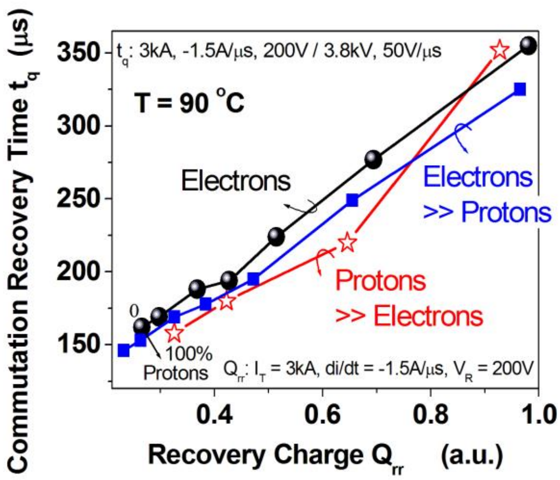

Fig.5a): Q_{rr} vs. V_T for slow and partial depletion of the N-base.

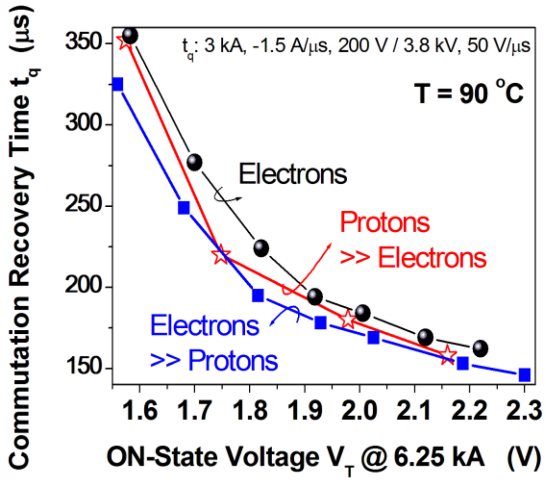

Fig.6a): t_q vs. V_T for slow and partial depletion of the N-base.

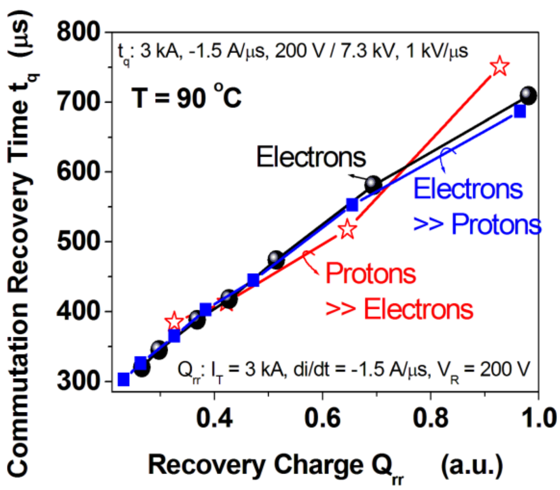

Fig.5b): Q_{rr} vs. V_T for fast and full depletion of the N-base.

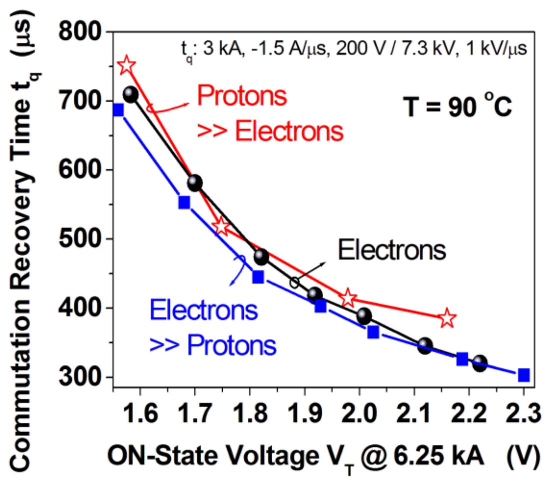

Fig.6b): t_q vs. V_T for fast and full depletion of the N-base.

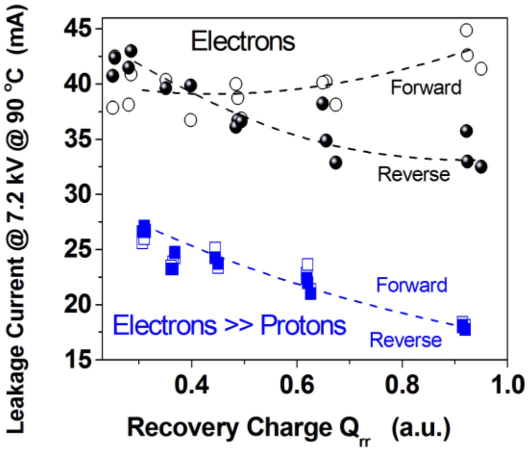

Fig.7: Forward and reverse leakage current vs. Q_{rr} for irradiation concepts "Electrons" and "Electrons >> Protons". Open circles and boxes = forward direction. Full = reverse direction.

The characteristics above have shown either the best performance of the irradiation concept "Electrons >> Protons" or a similar performance of the "Electrons" and "Electrons >> Protons". Since the differences in performance are not that distinct, if the very low t_q values are targeted, the easier and cheaper electron irradiation is the method of choice. The situation can change, if other relevant electrical parameters come into play.

Fig.7 compares the forward and reverse leakage currents of devices from the Figs.3 – 6 as received from half sine wave test at the frequency of 6.25 Hz. The direct comparison with Fig.5 implies that the reduction of t_q is connected to the lower Q_{rr} achieved using a higher irradiation dose and subsequently increased leakage current. The value added by the proton irradiation of the "Electrons >> Protons" concept is obvious - the leakage current is reduced by about 50 % and the forward and reverse leakage currents are always equal in agreement with the results from the ref. [2]. The increasing leakage current with reduced Q_{rr} in the Fig.7 is then given by the increasing dose of electron irradiation, which affects the whole device volume.

Interestingly, the forward leakage current of the electron irradiated devices stays unchanged and becomes equal to that of the reverse bias for the highest electron irradiation doses – see $Q_{rr} < 0.5$. This can be explained by a further reduction of the amplification factor of the internal NPN transistor, which plays the dominant role in the amplification of leakage current generated at the reverse biased junction between the P-base and N-base.

A further advantage of the proton irradiation on top of the reduced leakage current is the surge current capability, especially the one with the reapplied forward voltage presented in more details in the ref. [2].

3. Conclusion

Combined proton-electron irradiation with the dominant dose of electron irradiation is shown to provide the best technology curve Q_{rr} – V_T in the region of low t_q. The same irradiation concept gives the lowest t_q for applied forward voltages ≤50% of the maximal non-repetitive peak off-state voltage V_{DSM} = 7.2 kV. For the applied forward voltages up to the full V_{DSM}, there is no difference compared to the sole electron irradiation. A benefit of the proton irradiation can be found, if other parameters like leakage current are also accounted for.

The minimal magnitude of t_q with still reasonably low V_T was achieved at about 170 us for V_D = 3.8 kV and about 350 us for V_D = 7.3 kV, both at T = 90 °C.

Acknowledgments

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4. Literature

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