High-Voltage Thyristors with Enhanced Dynamic Robustness

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Abstract

Two cathode design concepts of phase control thyristor (PCT) are compared for 6.5 kV class in the housing with 47mm pole piece (5STP 08F6500). For the same technology curve V_T-Q_{rr}, the achievement of different combination of dynamic parameters like commutation turn-off time t_q, dV/dt and di/dt capability are discussed. This work expands the know-how on the cathode emitter engineering previously presented for 1.8, 2.8 and 8.5 kV voltage classes.

Keywords: PCT, high-voltage thyristors, dynamic parameters, dynamic robustness

INTRODUCTION

As the device with the lowest ON-state losses from all available switching concepts, thyristors maintain their application importance by providing cost efficiency in energy saving technologies of high societal impact. More specifically, high-power hockey puck types, discussed in this paper, are expected to show the compound annual growth rate (CAGR) about 3 % till 2030. Continuous improvement and cost reduction of silicon technology provide new opportunities for further improvement, especially in the high-voltage classes like that of 6.5 kV class demonstrated below.

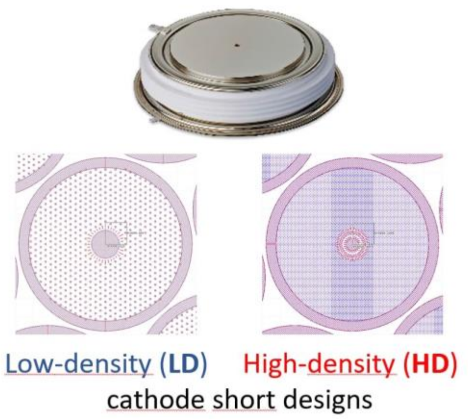

Fig. 1 Device under test: 5STP 08F6500 rated to V_{DRM} = 6.5 kV, I_{TAVmax} = 850 A. Two cathode designs: low-density (LD) and high-density (HD) cathode short pattern.

The aim of this paper is to show that one can further improve device ratings using improved technology means, like for example the better resolution of photolithography for masking the fine cathode shorting pattern. The dimension of the shorts can be significantly reduced while their density can be increased at the same time. The resulting device performance can change beyond the usual know-how and relevant electrical parameters can be improved. Last, but not least, some processing steps could be omitted, and production cost reduced.

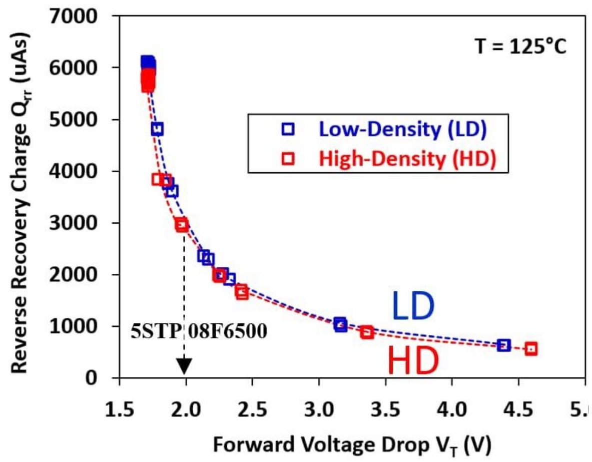

Fig. 2 Technology curve V_T-Q_{rr} for LD and HD designs. Individual doses of electron irradiation are equal for both designs. V_T-Q_{rr} point for existing product 5STP 08F6500 is highlighted.

EXPERIMENTAL RESULTS AND DISCUSSION

Phase Control Thyristors of 6.5 kV class for housings with the pole piece diameter of 47 mm were produced using classical low-density (LD) and high-density (HD) cathode shorting pattern. The distance between shorts for the HD design was reduced 3 to 4 times (Fig. 1). The doses of electron irradiation were chosen to carry out the points at the technology curve Q_{rr}-V_T which expand the range of possible variants over that of the standard product 5STP 08F6500 with the aim to cover all possible power electronics applications (Fig. 2). In spite of higher consumption of cathode area by cathode shorts of the HD design, the technology curves Q_{rr}-V_T are identical. The effect of denser shorts of the HD design manifests itself only in a slightly lower Q_{rr} for the same irradiation dose – see the distance between the individual points on Fig. 2. Contrary to the low-voltage PCTs, the HD design of the 6.5 kV class cannot be used to control the Q_{rr} without the usage of electron irradiation (EI) similarly to the 8.5 kV class presented in [1]. As will be shown below, some relevant dynamic parameters can still be improved.

Fig. 3 shows the dependence of the circuit-commutated turn-off time t_q on the dose of EI. The t_q was measured at T_{jmax} = 125 °C from the ON-state current of 2 kA with di/dt = –1.5 A/µs, and V_R = 200 V according to the industrial standard up to 0.67×V_{DRM} = 4.4 kV with dV_D/dt = 20 V/µs. While the LD design requires a reasonable dose of EI to satisfy the datasheet specification, the HD design provides sufficiently low t_q already on as-processed wafers.

The t_q of the HD devices is reduced to less than 50 % and this trend holds up to relatively high V_T. Moreover, the sensitivity of t_q on the EI is much lower with the HD design. The efficiency of the HD design is also manifested by much better trade-off curve between the turn-off time t_q and ON-state voltage V_T as presented in Fig. 4. We do not need to sacrifice the low magnitudes of V_T to achieve good dynamic parameters.

Also, the critical rate of rise of the forward blocking voltage (dV/dt capability) is improved using the HD devices. It is illustrated on Fig. 5 for the dV/dt test up to the full blocking voltage V_D = 6500 V, where dV/dt is shown nearly doubled for the HD design in the full range of EI doses. This is in a good agreement with the testing of t_q above, where dV/dt test is part of the t_q test. The dV/dt capability of industrial thyristors is usually specified for 0.67×V_{DRM} = 4.4 kV likewise the t_q. For this condition, both designs reached the limit of our tester. Consequently, we have chosen harder test conditions up to full V_D to show the strength of the HD design.

The penalty for the improved t_q and dV/dt can be found in the reduced critical rate of rise of the ON-state current di/dt (di/dt capability) measured at frequency of 1 Hz as shown in Fig. 6. The LD design passed the 4× nominal magnitude of standard product representing the limit of our tester (4 kA/µs). On the other hand, the HD design has been found to reach di/dt = 2.5 kA/µs, which is 2.5× the requested datasheet value. This means that the di/dt margin has been reduced at HD design. This result follows the general relation between the thyristors with easier triggering and higher di/dt capability and the ones with protracted triggering and higher dV/dt capability and

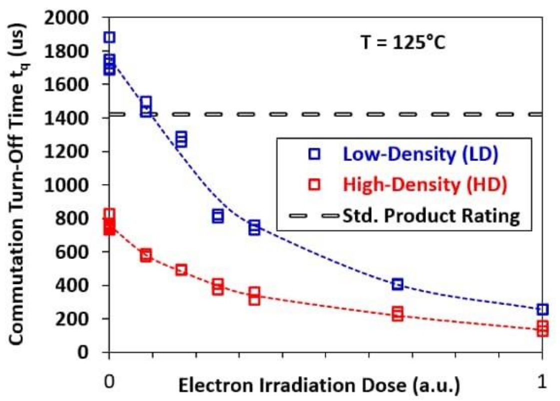

Fig. 3 Commutation turn-off time t_q vs. electron irradiation dose. Measured at T = 125 °C. The horizontal dashed line shows the datasheet limit.

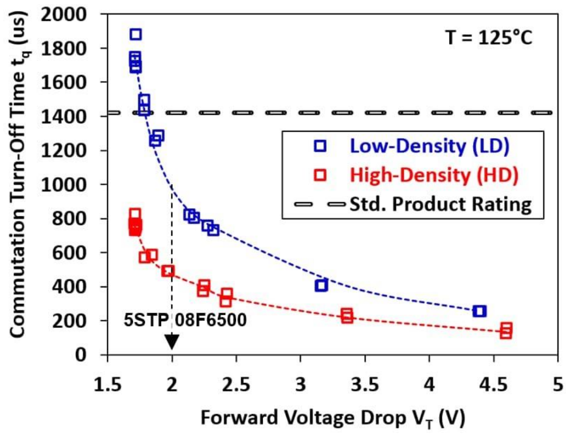

Fig. 4 Commutation turn-off time t_q vs. ON-state voltage V_T. V_T was measured at I_T = 1 kA and T = 125 °C. The horizontal dashed line shows the datasheet limit.

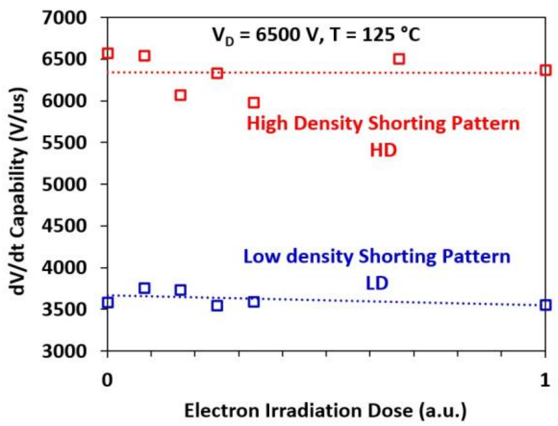

Fig. 5 dV/dt capability measured up to full blocking voltage V_D = 6.5 kV vs. electron irradiation dose at T = 125 °C.

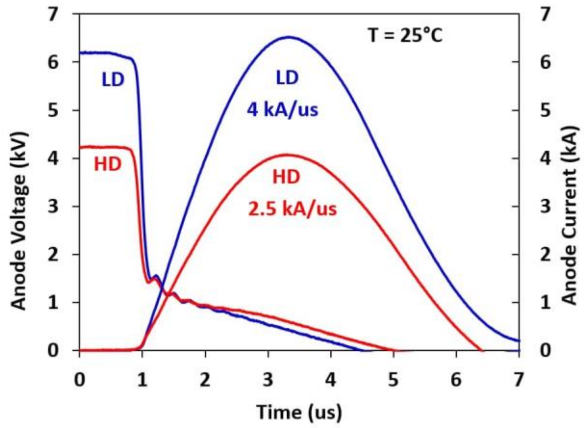

Fig. 6 di/dt capability measured at room temperature and frequency of f = 1 Hz.

lower commutation turn-off time t_q. Further improvement of the di/dt capability of the HD design would require a further optimization of the gatecathode structure.

The difference between the LD and HD designs manifests itself in significantly different static IV curves at low currents. This difference is illustrated for two device designs on devices with the same ON-state voltage V_T at 125 °C in Figs. 7 and 8. The close proximity of cathode shorts bringing the high dV/dt and t_q increases the ON-state voltage V_T at low currents and low operation temperature. Consequently, the crossing point current of the HD design is increased by 35 %.

It has been shown that the electron irradiation changes the crossing point current of P-i-N diodes in a complex way [2, 3]. At very low electron irradiation doses, the crossing point current is lowered compared to the unirradiated diode. From certain dose level, the crossing point current grows to disappear at high doses. The dependence of the crossing point current vs. electron irradiation dose of P-i-N diode is therefore U shaped [3]. We can see similar U shape dependence for the thyristor LD design (Conventional) in Fig. 9. However, for the HD thyristor design, the U shape is missing. The local minimum of the crossing point current is replaced by the region of constant crossing point current which is

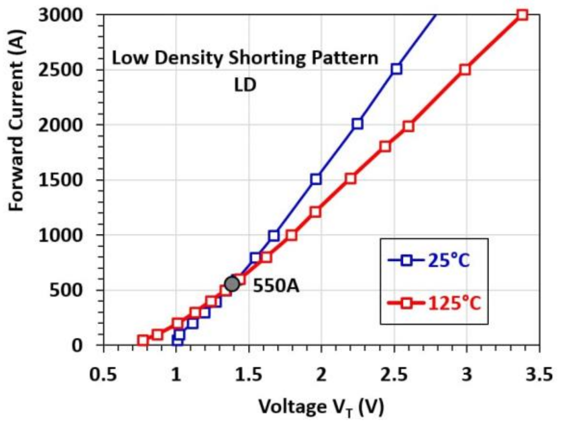

Fig. 7 Forward IV curves of LD design at 25 °C and 125 °C for the device with V_T = 1.8 V, dV/dt = 3.5 kV/µs, t_q = 1500 µs.

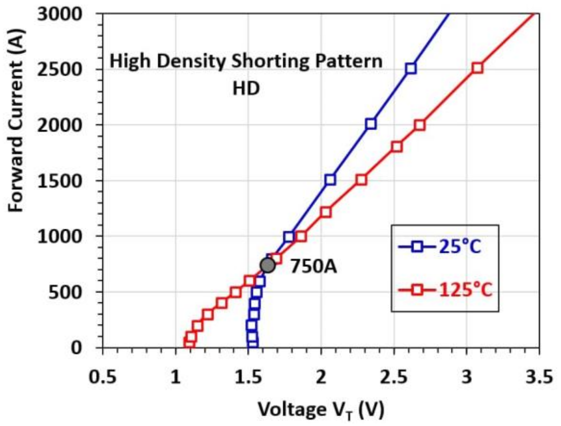

Fig. 8 Forward IV curves of HD design at 25 °C and 125 °C for the device with V_T = 1.8 V, dV/dt = 6.5 kV/µs, t_q = 600 µs.

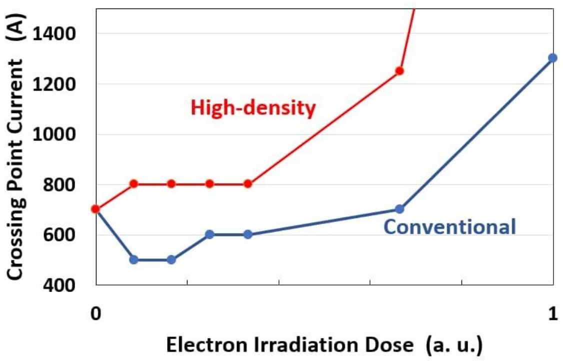

Fig. 9 Crossing point current between forward IV curves vs. electron irradiation dose. Measured at 25 °C and 125 °C for the LD and HD designs.

followed by steep increase at higher doses of electron irradiation. The flat region takes place up to V_T = 2.5 V measured at I_T = 1 kA and T = 125 °C. As we can see in Fig. 5, such HD device shows t_q at about 300 µs. The same magnitude of t_q can be reached with the LD design only by using very high dose of electron irradiation, which results in V_T about 4.0 V measured at the same current and temperature. For this electron irradiation dose, the crossing point current of the HD design is increased only by 25 % over the LD design.

Consequently, by choosing an optimal dose of electron irradiation, one can minimize the drawback of the HD design, which is the higher crossing point current. Eventually, one can omit the electron irradiation of thyristors according to the HD design, if the t_q at about 800 µs is acceptable. The benefit of this choice is the magnitude of the crossing point current around the maximum average ON-state current I_{TAVmax} and reduced production cost [4].

SUMMARY

Two cathode designs of 6.5 kV industrial phase control thyristor with the low (LD) and high density (HD) of cathode shorts were presented with the aim to improve the device ratings and optionally reduce the production cost. The trade-off relations between Q_{rr} and V_T, t_q and V_T, and dV/dt and di/dt were demonstrated for the two distinct designs. While the trade-off curves Q_{rr} and V_T of both the designs are equal, the trade-off between the t_q and V_T shows significant improvement in favor of the HD design. The HD design shows the higher dV/dt capability and worse di/dt capability compared to the classical LD design.

Last, but not least, the increase of the crossing point current with increasing dose of electron irradiation shows much stronger dependence for the HD design. The advantage of the HD design is much lower electron irradiation dose needed for reduction of the commutation turn-off time t_q down to 300 µs and hereby negligibly increased ON-state voltage drop V_T compared to the LD design. Eventually, the electron irradiation of the thyristor with the HD design can be skipped with the benefit of reduced production cost. Hereby the paper provides all information necessary for optimization of device design to satisfy specific conditions of different industrial applications.

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