Cathode Emitter versus Carrier Lifetime Engineering of Thyristors for Industrial Applications

J. Vobecký, ABB Switzerland Ltd, Semiconductors, jan.vobecky@ch.abb.com

M. Bellini, ABB Corporate Research Center, Switzerland, marco.bellini@ch.abb.com

K. Stiegler, ABB Switzerland Ltd, Semiconductors, karlheinz.stiegler@ch.abb.com

Abstract

We experimentally demonstrate that the traditional way of reducing the recovery charge Q_{rr} by electron irradiation can be replaced by appropriate density of cathode shorts of an appropriate size. Functionality of this approach is demonstrated for the thyristors of 1.8 and 2.8 kV voltage classes, for which an improvement of technology curve $Q_{rr} – V_T$ was achieved. In addition, the higher density of cathode shorts improves the dV/dt capability and circuit commutated recovery time t_q. The *Irradiation Free Concept* provides thyristors with improved ratings, while it eliminates the fear of annealing the radiation defects from electron irradiation under overload conditions, when thyristors are repeatedly exposed to ON-state currents close to the nominal value of surge ON-state current I_{TSM}.

1. Introduction

A Phase Control Thyristor (PCT) is the device of choice for the applications, where the highest current handling capability per unit area (low ON-state voltage drop), easiness of control and low cost are required, while the missing turn-off capability can be substituted by circuit commutation. This is the reason, why PCTs continuously maintain a significant market share, though they belong to the oldest semiconductor device concepts [1].

Electron irradiation is the state-of-the-art technique for setting the position at the technology curve $Q_{rr} – V_T$ of PCTs [2]. It is practical in volume production, because we can not only set the required reverse recovery charge Q_{rr} after the device is completely processed including metallization, but also because we can repeat the irradiation to further reduce the Q_{rr}, if the required specification was not reached. In this paper, we go beyond these undoubted advantages by designing the PCT, which has a proper Q_{rr} value already after leaving the production line, i.e. without the electron irradiation. The demonstrated technique is suitable for the industrial applications, where PCTs are not operating in parallel and precise tuning of Q_{rr} into a very narrow band is not necessary [4].

2. Thyristor Design

Cathode emitter shorting (shorts) is the design technique widely accepted to reduce the current gain of the internal NPN transistor at low currents under forward blocking [1, 2, 3]. This allows us to achieve an equally high blocking voltage under forward bias (break-over voltage) as under the reverse bias, where the multiplication of leakage current is significantly lower due to the lower current gain of the PNP transistor and no amplification from the NPN one. Analogically, the increased density of shorts reduces the amplification of the displacement current C_{SCR}.dV/dt generated during a steep rise of anode voltage dV/dt hereby increasing the so-called dV/dt capability. C_{SCR} is the capacity of space charge region of the thyristor, which typically amounts to units or tens of nanofarads at low voltage depending on device area.

The above mentioned higher density of cathode shorts lowers the active cathode area used for carrier injection, which can increase the ON-state voltage drop V_T. This trade-off is therefore considered during design optimization. The relevant parameters are short diameter, short separation, relative shorted area (given by the number of shorts), and the shape of shorting array, which is the triangular one in this work. At glance, the doping profiles of the shorts, P-base and cathode are also important items in the design.

The existing level of surface patterning in the silicon technology for bipolar power devices allows us to push the minimal short diameter below the size, which would be considered impractical in the past. Also the cleanliness of starting material and diffusion processes have improved so, that the required levels of leakage current (blocking voltage) can be achieved for any short design and without the electron irradiation at low voltage devices presented below. All these aspects represent a good reason for reviewing the state-of-the-art thyristor design.

Fig.2.1a) shows simulated distribution of the ON-state current density for small and big cathode shorts while the total cathode area consumed by the shorts is equal. The device simulation using Sentaurus Device from Synopsys was used. Fig.2.1b), which is cut out of the Fig.2.1a), indicates that bigger shorts affect the ON-state current density deeper in the bulk and that the smaller shorts result in more homogeneous current distribution. This feature provides a degree of freedom for further optimization of device performance.

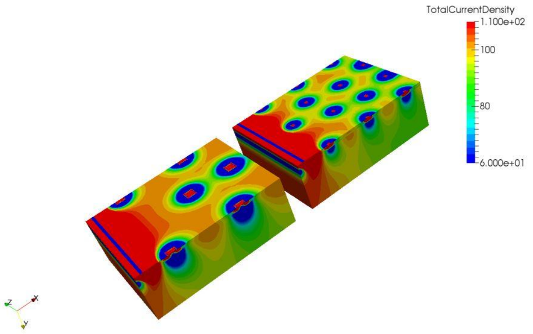


Fig.2.1a): ON-state distribution of current density of *Classical* (left) and *New* (right) devices with equal cathode area covered by shorts (3D device simulation).

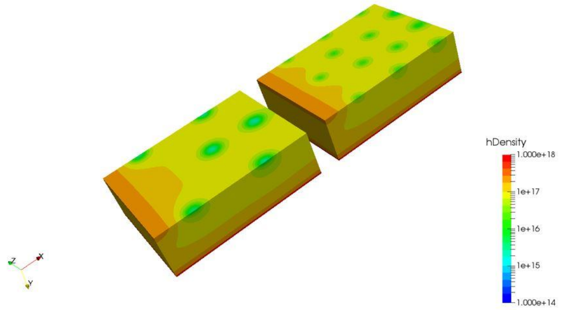


Fig.2.1b): ON-state distribution of current density of devices from Fig.2.1a) with top layer 50 μm below the cathode surface.

The device simulation further confirms, that by increasing the number of shorts we can create the technology curve Q_{rr} – V_T likewise we normally do by increasing the dose of electron irradiation (see Fig.2.2). The simulation, which is based on drift-diffusion approximation of electron-hole transport, includes standard settings for silicon with Shockley-Read-Hall model of generation-recombination, and models of Auger recombination, impact ionization and bandgap narrowing.

We show experimentally below that, in addition to improved technology curve, we can improve the dV/dt capability and circuit commutated recovery time t_q while keeping the rest of parameters unchanged. The smaller short diameter used in this concept also facilitates its placement around the regions with complex shape like the amplifying gate structures, which allows us to keep the gate triggering likewise the dV/dt and di/dt capability at required level.

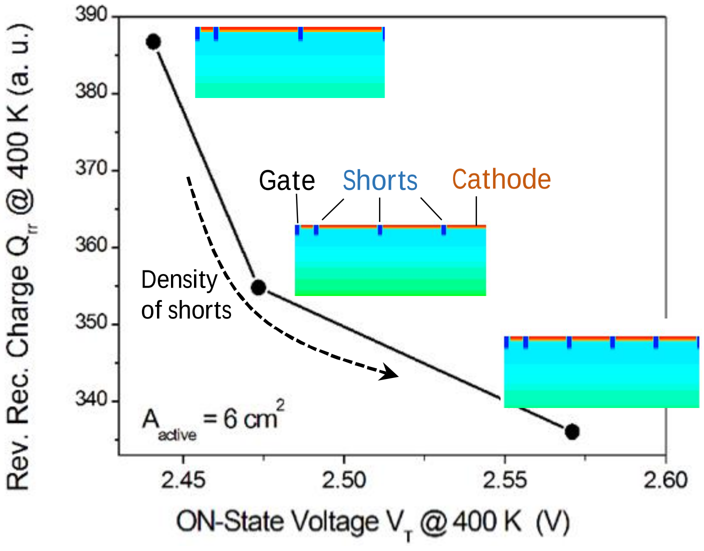


Fig.2.2: Simulated trade-off curve Q_{rr}-V_T by changing the cathode area coverage by shorts of similarly small size as in Fig.2.1b). V_T is simulated at I_T = 4 kA, T = 400 K. Q_{rr} is simulated at I_T = 2 kA, T = 400 K, with snubber parameters R_s = 20 Ω, C_s = 5 µF.

3. Experimental Results and Discussion

Figs.3.1 and 3.2 compare the measured trade-off curves of *Classical* and *New* PCTs with active area of about 6 cm^2 for 1.8 kV and 2.8 kV voltage classes. The relative shorted area in % is shown as a parameter. Figs.3.2 and 3.4 show that the similar curves for larger devices (three times in this case). The advantage of having a smaller short diameter in the *New* device is that it improves the cathode utilization for current conduction in agreement with the Fig.2.1 and gives us a lower V_T for the same shorted area. This feature allows us to place more shorts to reduce Q_{rr} while keeping the V_T equally low.

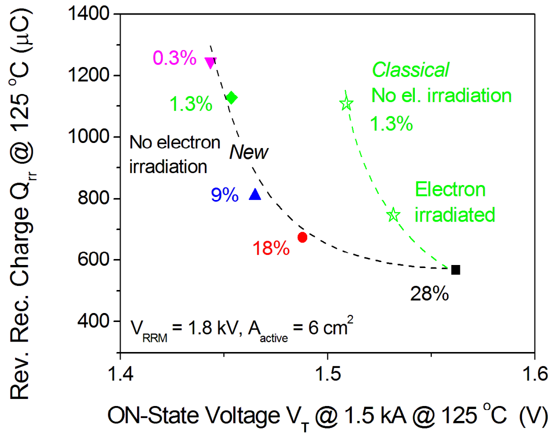


Fig.3.1: Trade-off curve Q_{rr} – V_T of *Classical* and *New* 1.8 kV PCTs. Active area ≈ 6 cm^2.

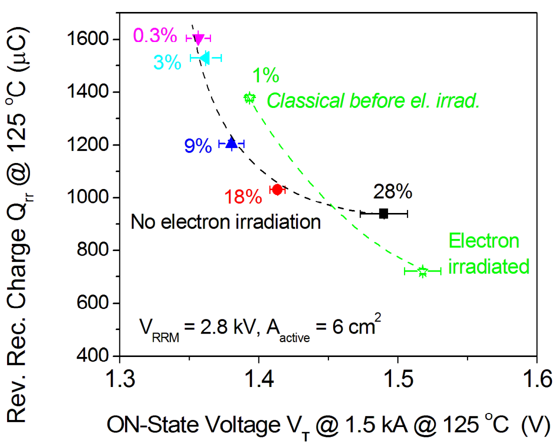
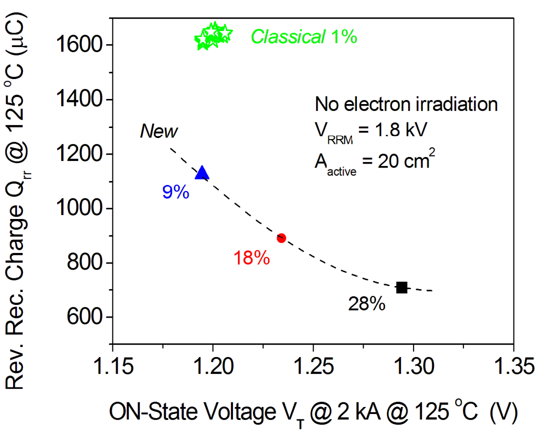


Fig.3.2: Trade-off curve Q_{rr} – V_T of *Classical* and *New* 2.8 kV PCTs. Active area ≈ 6 cm^2.



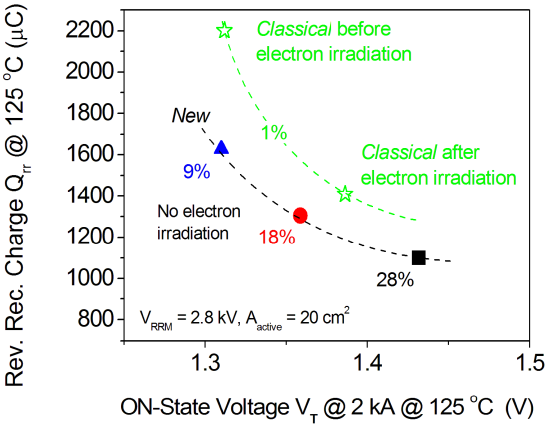


Fig.3.3: Trade-off curve $Q_{rr} - V_T$ of *Classical* and *New* 1.8 kV PCTs. Active area ≈ 20 cm^2.

Fig.3.4: Trade-off curve $Q_{rr} - V_T$ of *Classical* and *New* 2.8 kV PCTs. Active area ≈ 20 cm^2.

The possibility to replace the electron irradiation by the densely placed shorts is obvious from the figures above. On one hand, it is clear that the *Irradiation Free Concept* brings a better technology curve. On the other hand, it is clear that the beneficial effect vanishes at certain percentage of shorted area at which the technology curve of the *Irradiation Free concept* crosses that of the *Classical* one achieved by electron irradiation. This limit depends on voltage class (wafer thickness) and device specification for Q_{rr} and V_T. However, for the two voltage classes and device sizes the mentioned crossing does not appear before the devices run out from their typical $Q_{rr} - V_T$ specifications for industrial PCT.

At glance, the *Irradiation Free Concept* (cathode short engineering) is not functional at high-voltage PCTs processed at thicker wafers. This is illustrated for the 8.5 kV PCT in Fig.3.5, which illustrates the limited control of Q_{rr} by changing the short density between 0.3 and 12 % in comparison with the electron irradiation using the short density of about 1 %. The Q_{rr} values achieved by increasing the shorted area are not much different from the Q_{rr} values of unirradiated ones with low shorted area.

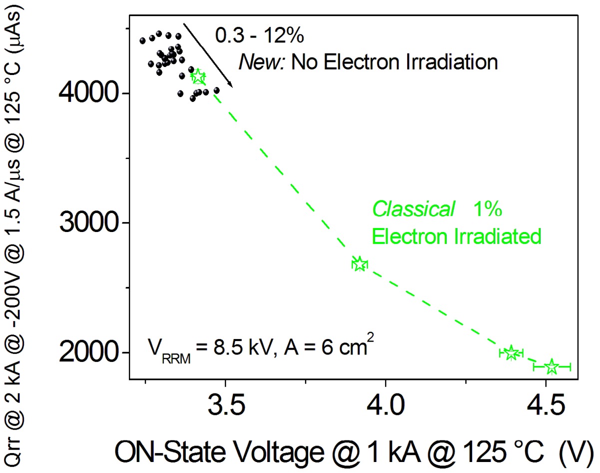


Fig.3.5: Trade-off curve $Q_{rr} - V_T$ of *Classical* and *New* 8.5 kV PCTs. Active area ≈ 6 cm^2.

Fig.3.6 and 3.7 illustrate how can the dV/dt capability benefit from the New concept. The graphs take into account the PCTs with both single gate and amplifying gate structures and they utilize an equal cathode area. The test was performed at harder conditions in comparison with the ones specified at typical data sheets to obtain a better sorting of device capability. This consists in increasing the maximal applied forward voltage V_D from the standard specification test level at 2/3 of the V_{DRM} value to the nominal value of V_{DRM} = 1.8 and 2.8 kV.

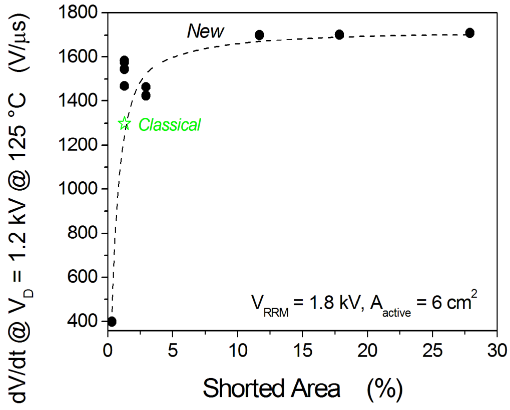


Fig.3.6: dV/dt capability of *Classical* and *New* 1.8 kV PCTs. Active area ≈ 6 cm^2.

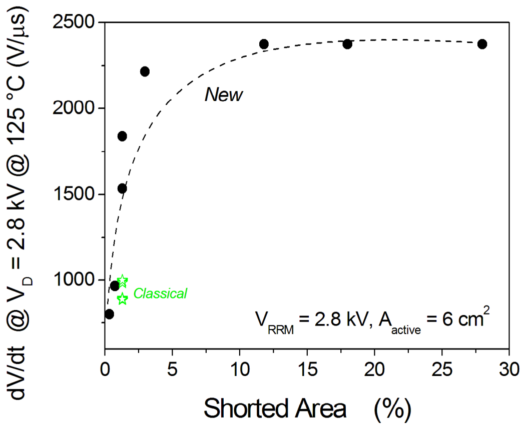


Fig.3.7: dV/dt capability of *Classical* and *New* 2.8kV PCTs. Active area ≈ 6 cm^2.

The increased short density increases the dV/dt capability likewise does the electron irradiation. The measurements show that the dV/dt capability saturates at about the relative shorted area of ≈ 10 %. This value already lowers the reverse recovery charge Q_{rr} to a typical datasheet value obtained by electron irradiation. Moreover, this shorting density brings the benefit of lower V_T compared to the electron irradiation.

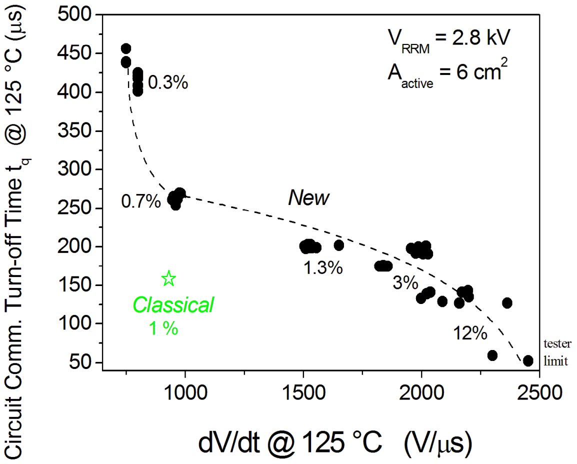


Fig.3.8: dV/dt capability vs. circuit commutated recovery t_q of *Classical* and *New* 2.8 kV PCTs.

Fig.3.8 brings the circuit commutated recovery time t_q into play. Note that the t_q for the *Classical* and *New* devices in Fig.3.8 do not appear at the same curve, because they have different gate structures in this example. For the density of shorts equal or higher than ≈10 %, we hit the limit of our tester for both the dV/dt and t_q. For the density of shorts below

1 %, the dV/dt capability and circuit commutated recovery time t_q get outside a typical datasheet specification. On the other hand, the leakage current under both forward and reverse biases remains equally low regardless of short density. This indicates the unrivalled importance of cathode shorts for the dynamic performance of contemporary PCTs.

4. Conclusions

The increasing shorted area of the *Irradiation Free Concept* has a similar effect as the increasing dose of electron irradiation of the *Irradiation Concept*. The cathode shorts of state-of-the-art PCTs are indispensable for the dynamic performance (circuit commutation time t_q and dV/dt), while they also improve the technology curve. It is proved for phase controlled thyristors of 1.8 and 2.8 kV voltage classes with sizes between 5 and 20 cm^2.

In addition to the reduced cost of processing, it allows one to reduce the safety margin on surge current I_{TSM} rating, because there is no fear of annealing the radiation defects from electron irradiation during repetitive overload conditions at the ON-state.

5. Reference

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