Analysis in Commutation of a New High Voltage Thyristor Structure for High Temperature

Gaëtan Toulon, Abelhakim Bourennane, and Karine Isoird

***Abstract*—In this paper, a high voltage thyristor structure using Schottky contacts on the anode side is analysed through 2D physical simulations in terms of switching performance. The replacement of the P emitter of a conventional symmetrical thyristor by a judicious association of P diffusions and Schottky contacts at the anode side contributes to the reduction of the leakage current in the forward direction and hence improves the forward blocking voltage at high temperature while maintaining its reverse blocking capability. It is shown by comparing this structure with a conventional thyristor, that the presence of Schottky contact does not degrade the turn-on process. It is also shown that the presence of Schottky contact reduces the device turn-off time, improving the maximum operating frequency of the device.**

***Index Terms*—Pulsed power, High voltage thyristor, TCAD simulations, high temperature, Schottky contacts**

I. INTRODUCTION

IN high voltage and high current applications, such as HVDC transmission [1] or pulsed power application [2], a thyristor is commonly used as a power switch because of its high power switching capabilities. However, the thyristor architecture composed of four layers of different doping forming an N-P-N and a P-N-P bipolar transistor limit its maximum operating temperature to 125°C. Under high operating temperature, the leakage current increases amplified by the transistor gains, leading to the parasitic turn-on of the thyristor. Moreover, the temperature induced high leakage current can degrade the functioning of the application in some cases, such as pulsed power circuits, as that shown in figure 1 [3], where a capacitor is charging while the thyristor is maintained in the off-state and is discharging through an R-L circuit when the thyristor is turned-on. However, at high temperature when the thyristor leakage current becomes high, part of the current for the capacitor charging is deviated by the thyristor and flows through the R-L circuit, which results in a longer time required for charging the capacitor.

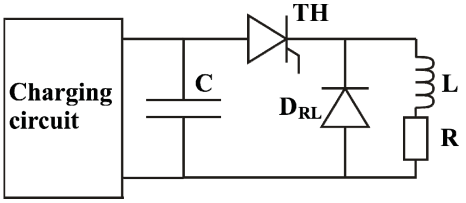

Fig. 1. Example of a pulsed power circuit highlighting the thyristor role.

Current gain reduction can be achieved by different techniques, such as:

- Local electron or proton irradiation at the main junctions in order to reduce the carrier lifetimes [4]
- N-type buffer layer between the N-base and P emitter
- Anode short-circuits [5]

The two last methods lead to a degradation of the reverse blocking capability, which means that additional components, such as a diode connected in series with the thyristor, must be added. Moreover, the reduction of the carrier lifetime leads to the degradation of the on-state voltage because of the higher carrier recombination.

Silicon carbide, thanks to its physical proprieties, could be considered for high temperature power applications. However, some technological issues still need to be solved, such as the reduction of basal plane dislocation density during thick epitaxial layers growth, which leads to a degradation of the carrier lifetime and then the increase of the on-state voltage drop, or the development of novel termination techniques for bi-directional blocking capability [6].

The thyristor leakage current at high temperature can also come from surface currents at the chip periphery [7]. Adequate edge termination and passivation techniques are then necessary [8] in order to minimize theses currents which can represent a significant part of the total leakage current in the thyristor device.

We proposed a thyristor structure based on the utilization of Schottky contacts associated to P diffusions at the backside of a symmetrical silicon thyristor for symmetric blocking voltage as shown in figure 2 [9]. The Schottky contact on the thyristor anode side leads to a reduction of the emitter injection efficiency of the J_2 junction, similar to conventional anode shorts, while preserving the reverse blocking capability of the device. We showed, by means of TCAD simulation, that the

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thyristor with Schottky contacts could, with only a slight degradation of the on-state voltage drop, highly improve the forward breakover voltage at high temperature thanks to the reduction of the leakage current, while preserving the reverse blocking capability of the thyristor structure.

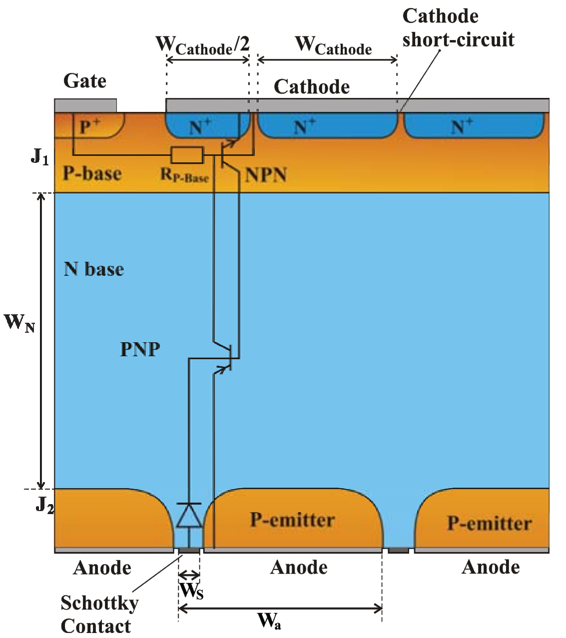


Fig. 2. Overview of the thyristor structure with Schottky contacts on the anode side

In this paper, after a description of the structure operating modes, we will analyse the thyristor structure with Schottky contacts during switching on a pulsed power circuit. The electrothermal simulations results will be compared with those of the conventional thyristor structure during the turn-on and turn-off transients.

II. STRUCTURE PRESENTATION

A. Thyristor with Schottky contact principle

The leakage current in a thyristor can be expressed by the following equation:

$$I_{AK} = \frac{I_{C0}}{1-\alpha_{PNP}-\alpha_{NPN}} \qquad (1)$$

where I_{C0} is the leakage current of a PN junction in reverse conducting mode and α_{PNP} et α_{NPN} the gain of the bipolar transistors composing the thyristor shown in figure 2. The thyristor leakage current reduction can be achieved by minimizing the different elements of equation 1. The α_{NPN} gain can be lowered during forward blocking mode by cathode shorts, as used in commercial thyristors. It is possible to reduce the α_{PNP} gain using the different techniques presented in introduction section. However, with some of these techniques the thyristor loses its reverse blocking capability. We proposed in [9] a solution based on an association of Schottky contact and P diffusions as used in the JBS (Junction Barrier Schottky) diodes [10] at the thyristor anode side, replacing the P emitter in the conventional thyristor. The structure has been compared to a conventional thyristor structure and a thyristor with anode shorts, similar to the structure presented in figure 2. These structures have been studied by means of TCAD simulations for a high voltage (V_{DRM} = V_{RRM} = 4,5 kV), high temperature pulsed power application in terms of forward and reverse breakover voltage, leakage current and on-state voltage drop. Some results are summarized here after.

B. On-state and off-state simulation results

Figure 3, comparing the anode current in the forward blocking mode for different thyristor structures, shows that the use of anode shorts or Schottky contacts can greatly reduce the leakage current at high temperatures. This reduced leakage current leads to an improved forward breakover voltage.

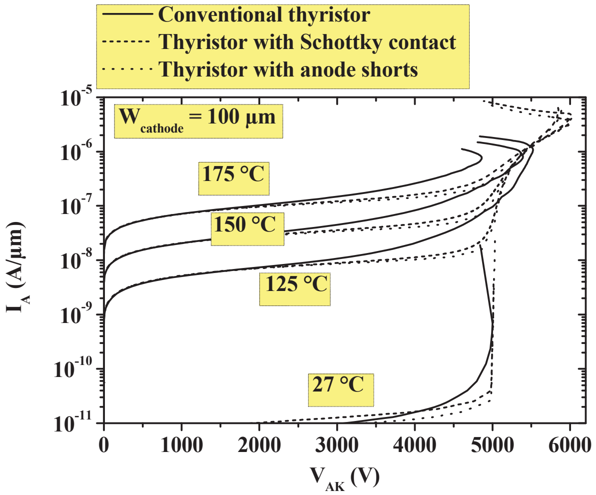


Fig. 3. Forward blocking characteristics of the three structures for different temperatures.

The on-state voltage drop of the three structures is presented on figure 4 for a current density of 200 A.cm^{-2}.

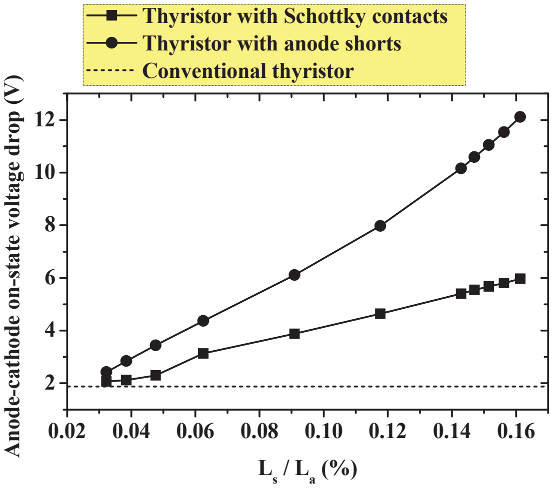


Fig. 4. On-state voltage drop as a function of the Schottky contact ratio on the anode width for the three structures.

The on-state voltage drop for the thyristors with Schottky contacts and anode shorts is presented as a function of the ratio of the Schottky contact width (L_s on figure 2) to the anode cell width (L_a on figure 2). For large P emitter values, the on-state voltage drop of the thyristor with Schottky contacts and the anode short thyristor tends to that of the conventional thyristor value. Moreover, the L_s/L_a ratio has only little effect on the forward breakover voltage and leakage current. Consequently, the Schottky contact area has been defined small compared to that of the P emitter one in order to keep the on-state voltage drop low.

III. SWITCHING SIMULATIONS

A. *Simulation circuit*

All the switching simulations will be based on the circuit represented in figure 5. This circuit presents a standard ignition system for helicopter turbine. The C_1 capacitor accumulates the energy thanks to the charging circuit. The L inductor limits the current di/dt during the turn-on. The spark plug discharge is modelled by the R_1, R_2, C_2 and D_Z.

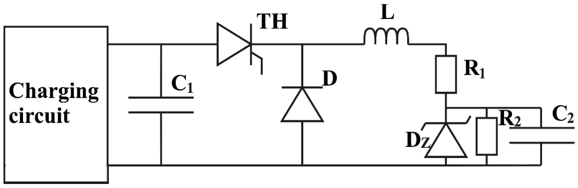
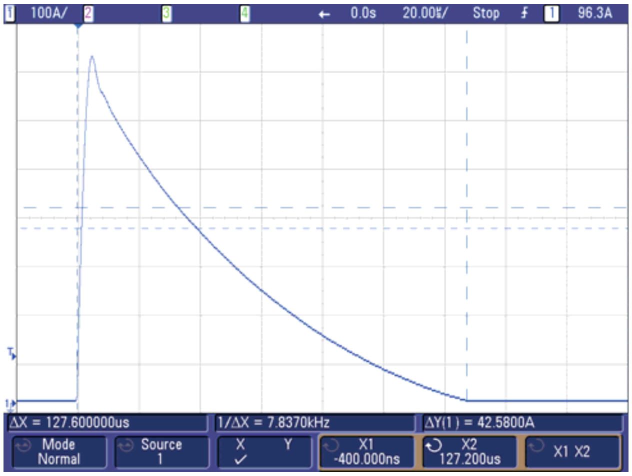


Fig. 5. Simulated circuit of the ignition system

The values of the elements modelling electrically the spark plug have been chosen in accordance to the experimental results of the shape of the curve of the current during the ignition. In this case, the capacitor has been charged to a voltage of 4000V. The current reaches its maximum of 1500A within 5µs. After 5µs, the capacitor has transferred its energy to the inductor, and the current begins to decrease. During this phase, the thyristor has stopped to conduct, and the freewheeling diode begins to conduct.



ΔX = 127.600000us
1/ΔX = 7.8370kHz
ΔY(1) = 42.5800A

Fig. 6. Experimental current waveform evolution in the spark plug (20µs per division horizontally, 100A per division vertically)

The switching circuit has been simulated by means of mixed-mode simulations under Sentaurus. This means that all the circuit elements are defined by their Spice equivalent model, except the thyristor which is considered by its physical models. Two different thyristor structures are being studied: the thyristor with Schottky contacts presented in figure 2, and a symmetrical conventional one. Both structures exhibit the same physical and geometrical parameters, except the anode side configuration.

Figure 7 that present the simulated current waveform through the spark-plug shows good agreement with experimental results.

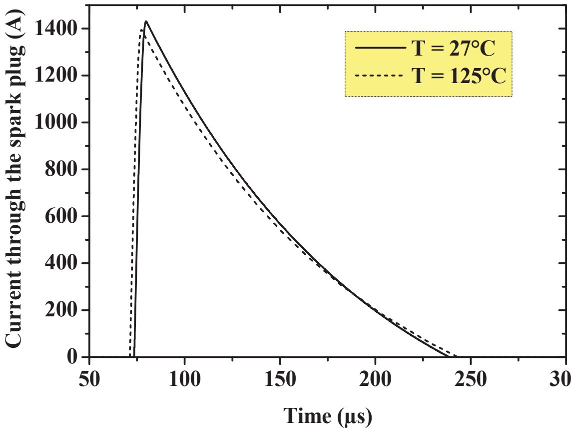


Fig. 7. Simulated current waveforms in the spark plug

Temperature has an influence on the current waveform as seen in figure 7. At higher temperatures, the leakage current in the thyristor increases, which leads to a higher sensitivity to thyristor latch-up and the maximum switching current presents a lower value.

B. *Thyristors turn-on process*

The two thyristor structures have been studied and compared in terms of switching performance. First, the number of cathode shorts and N^+ emitter diffusions has to be defined. Figure 8 shows the current density distribution according to a horizontal cut line for different designs of the conventional thyristor when the cathode current reaches 1500A.

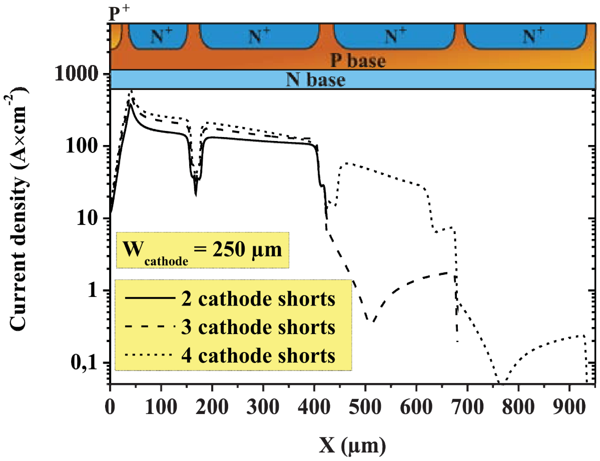


Fig. 8. Current distribution in the thyristor structure for different cathode shorts and N+ diffusion numbers

For every case, the N^+ cathode diffusion width has been chosen equal to 250 µm. This value presents a good trade-off between the gate current necessary to turn-on the device and the maximum breakover voltage. Since the P-base resistance R_{Base} (figure 2) is proportional to the N^+ cathode width, the current flowing through this resistor required to forward bias the P-N junction between P-base and N^+ will be high if the R_{Base} is small.

The results of figure 8 show that beyond two diffusion N^+ regions, the current distribution is not uniform, and a higher current magnitude is present at the end of first diffusion near the gate contact where the conduction happens first, as seen in figure 9. These results are consistent with the fact that plasma spreading speed is limited of about 100µm/µs [11] and the thyristor must turn-on within about 5µs. Consequently, with the used technological parameters, two N^+ diffusion regions should be chosen for the application.

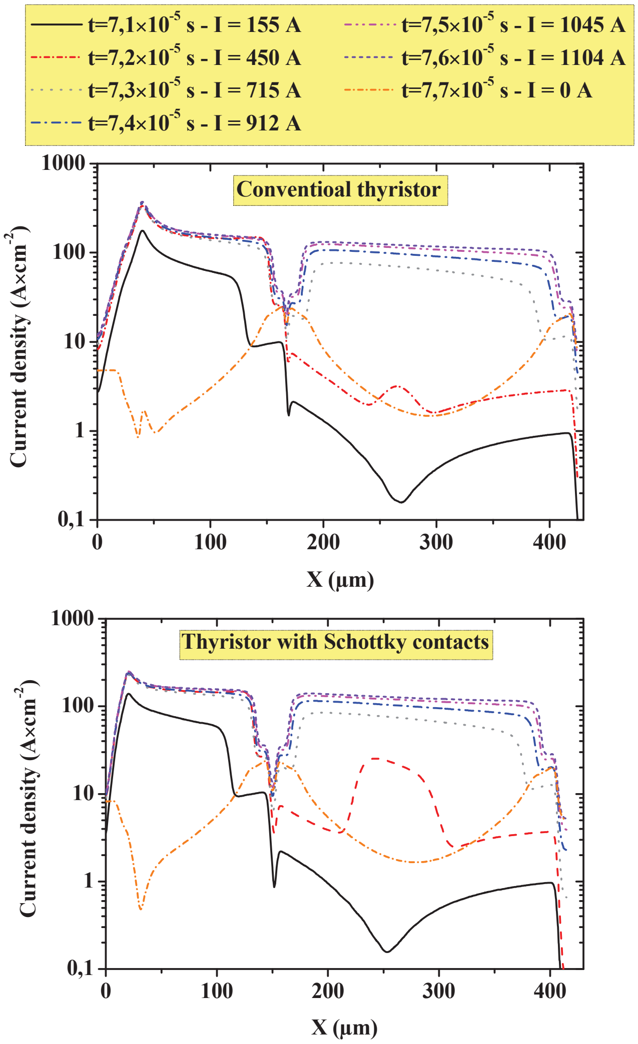


Fig. 9. Horizontal current distribution in the two thyristor structures during the turn-on process for different instants

The comparison between the thyristor with Schottky contacts and conventional one represented in figure 9 shows similar behavior, except a slightly lower current density because of the higher on-state voltage drop as seen in figure 4. This lower current density has a direct consequence on the temperature increase during the current pulse. Figure 10 shows the maximum temperature and current in both thyristor structures.

The peak current decrease in the thyristor with Schottky as compared to the conventional one makes the device limited in terms of commutated power. However, the difference in currents peak is about ten amps and does not affect the circuit operation.

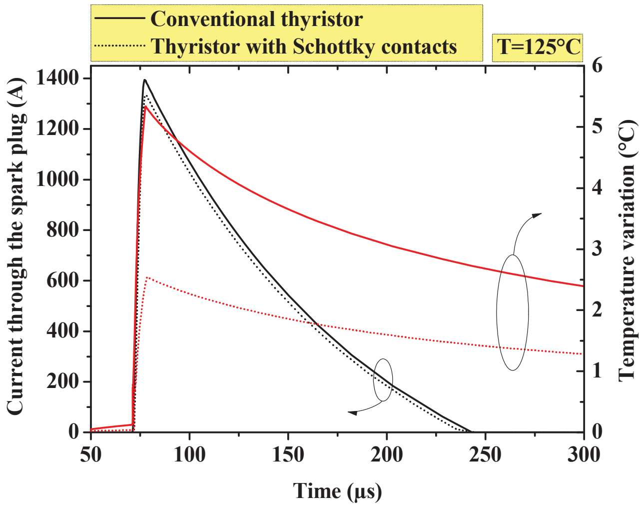


Fig. 10. Current waveform comparison (black curves) and maximum temperature evolution (red curves) in both structures

In applications such as ignition systems as presented in section A, a series of pulses are applied to the spark-plug. Consequently, the heat could accumulate after each pulse and a thermal runaway could occur.

In the simulations of figure 10 and 11, the thermal boundary conditions values have been chosen on accordance to [12] in the case of a natural convection heatsink, which represents the worse case in terms of thermal resistance.

The evolution of maximum temperature in Figure 11 shows that during the first pulses, the heat accumulates in the thyristor, where, in the case of the conventional thyristor, the maximum temperature reaches a value of more than 10°C compared to the ambient one. After the first pulses, the temperature stabilizes in the switch. The average temperature is always lower in the case of the thyristor with Schottky contacts as seen in figures 12 (a) and (b). Moreover, for higher frequencies, more elevated temperatures are expected. The maximum temperatures observed in the present cases are not excessive because of the chosen frequency and thyristor active areas. However, the reduction of the thyristor surface or the increase of the switching frequency could change adversely the switch performances.

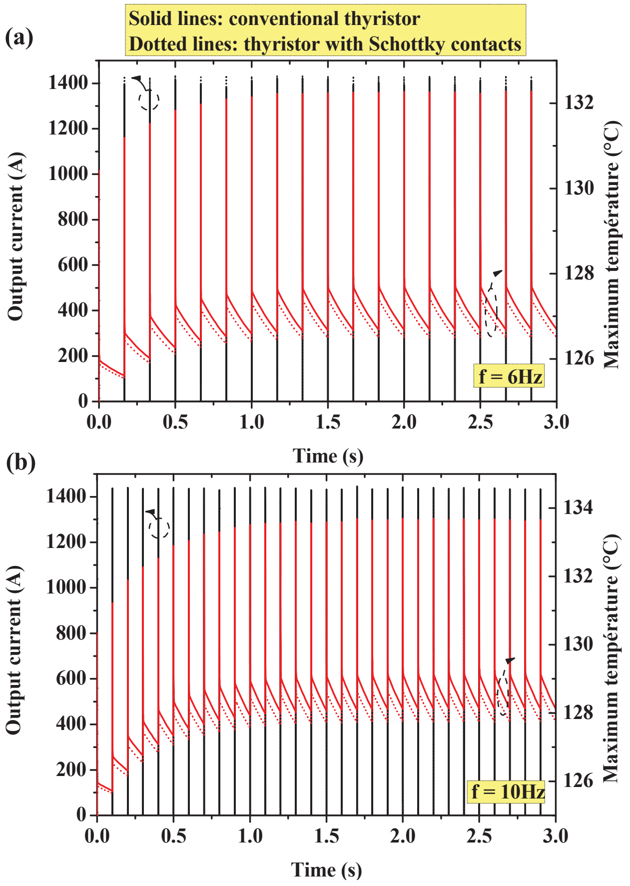


Fig. 11. Evolution of output current (black curves) and maximum temperature (red curves) versus time in both thyristor structures for series of pulses at (a) 6Hz and (b) 10Hz

C. Thyristors turn-off comparison

The current density in the thyristor, after the device switch-off, is also represented in figure 12.

Just after the current in the spark plug has reached its maximum, it is transferred to the freewheeling diode and there is no more current flowing in the thyristor, then the thyristor voltage falls to 0V. The current density in the structure decays progressively due to the recombination of free carriers in the structure. The carrier concentration according to a vertical cut-line is represented for both structures in figure 12 after the freewheeling diode begins to conduct.

At t=76µs, the current is maximum in the thyristor, and falls abruptly just after. At this moment, the carrier density, identical for both structures, is high close to the anode and cathode electrodes and decrease at the center of the thyristor. When the structure stops to conduct, the free carriers decrease first close to the PN junctions J_1 and J_2 (see figure 2). Afterwards, the carrier density decays in all the structure. From figure 12, we can see that in the case of the thyristor with Schottky contacts, the presence of the Schottky contacts at the anode side leads to a faster reduction of free carriers, mainly at the anode side.

As a consequence, because of the faster recovery of the thyristor with Schottky contact, this structure can work at a higher frequency compared to a conventional one, if the limit is not thermal.

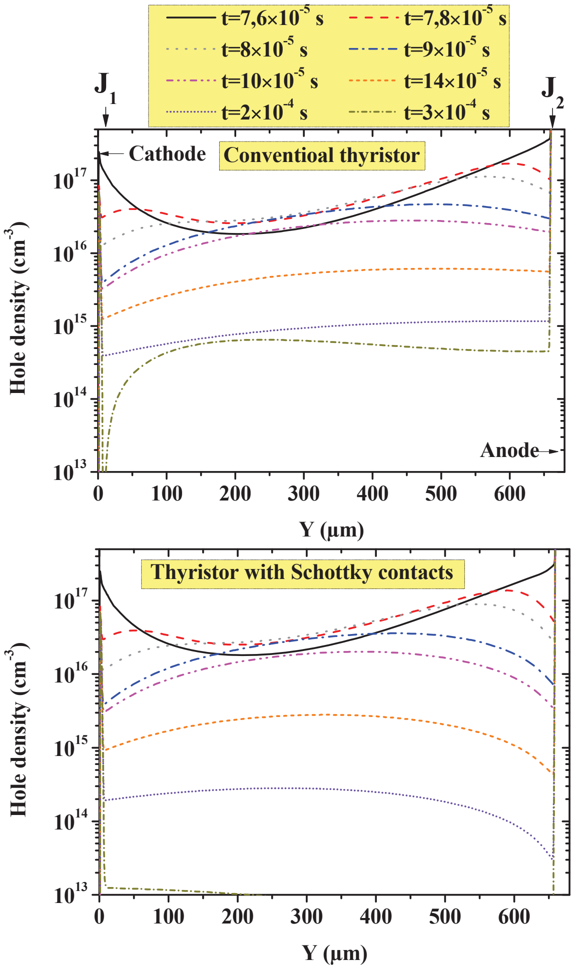


Fig. 12. Carrier distribution within both thyristors structures after deices turn-off at different instants

IV. CONCLUSION

In this paper, we studied the impact of the insertion of a Schottky contact on the backside of symmetric thyristor in commutation. The utilization of Schottky contact at the anode side could reduce the leakage current and improve the breakover voltage with only a slight degradation of the on-state voltage drop. The simulation results showed that the thyristor with Schottky contacts could replace a conventional symmetrical thyristor in pulsed power applications. The presence of Schottky contacts don't have influence during the thyristor turn-on transient because it doesn't add delays during this phase, but can greatly improve the recovery process, which can be long in a conventional thyristor. The faster recovery of the excess carriers in this thyristor improves its maximum operating frequency. Moreover, the thyristor with Schottky contacts presents better thermal management during one and a series of pulses. As a consequence, the proposed thyristor with backside Schottky contacts is well suited for pulsed power application

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