Analysis of the Latch-up Process and Current Filamentation in High-Voltage Trench-IGBT Cell Arrays

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***Abstract*—We present a theoretical analysis of the formation of current filaments leading to the latch-up state that can occur during the turn-off process in a cell array of high-voltage (3.3 kV) trench insulated-gate bipolar transistors (trench IGBTs). Our investigations, based on self-consistent physical device simulations, aim at understanding the behavior of multiple cells, i.e. parallel cells as well as integrated structures, during overcurrent turn-off by studying the behavior of a representative single cell under identical conditions. With these insights we are able to analyse the latch-up mechanism itself as well as its consequences for the robustness of the device against latch-up. Furthermore, we gain an understanding of the formation of current filaments inside IGBT cells and their relation to device latch-up.**

I. Introduction

The robustness of semiconductor power devices is limited by multiple physical effects, some of which occuring during the turn-off process of the device. To enhance the devices' ruggedness, an improved understanding of the physical effects limiting their performance is sought. A considerable effort has been spent on the investigation of physical processes in high-voltage IGBTs as is shown in [1]-[3].

This work aims at extending these results to arrays of IGBT cells in order to investigate effects that occur between different cells contained in the same array and their consequences for the robustness of the entire device itself. This paper is structured as follows: After a short description of the simulation approach the numerical results are presented for arrays of cells which are discretely connected in parallel as well as for cells that are physically connected, i.e. integrated structures. A discussion of these results along with a comparison of these two alternative approaches concludes the paper.

II. Simulation approach and physical models

The analysis of the transient behavior of parallel IGBT cells was performed using the mixed-mode simulation approach and was implemented in the Sentaurus Device simulator framework. The device simulations were carried out in two dimensions and then mapped to quasi-3D structures using cylindrical symmetry on the one hand (cylindrical structure) and a linear extension into the third spatial dimension on the other hand (stripe structure). Reflective boundary conditions were assumed along the vertical boundary parts of the simulation domain. In order to simulate high current densities and the effects of current crowding during turn-off, the IGBT cells, which are connected in parallel inside the electrical circuit, were chosen to be highly asymmetric in size. The calibration of the underlying physical models was achieved by comparing measured data from static characteristics as well as from transient turn-off measurements with an inductive load. Concerning the choice of the physical models employed, special attention was, on the one hand, paid to models describing carrier mobility inside the device [4]-[7] as well as along oxide-silicon interfaces [8] and, on the other hand, to models describing impact ionization [9]-[10]. The coupled thermodynamic model used to describe the spatial distribution of lattice temperature is based on [11].

The simulations presented in this work are self-consistent (i.e. electrothermally coupled) numerical calculations of the overcurrent turn-off in 3.3kV trench IGBT cells, with different structure variants. In addition, isothermal calculations of the same structures were conducted to get more insight into the temperature dependence of the processes involved in the failure mechanisms.

For analyzing the latch-up process and the formation of current filaments, conditions that favour the occurrence of such phenomena were chosen: these are high temperature, high load current, high DC link voltage, and additional gate resistors to produce a slightly non-concurrent turn-off of cells connected in parallel. Additionally, the latch-up robustness of the IGBT cells was intentionally reduced compared to productive chips.

III. Results and discussion

A. Turn-off of a single cell

The first step in the analysis of the latch-up process of an entire cell array is understanding the behaviour of a single cell during overcurrent turn-off. Simulating turn-off of a single cell under overcurrent conditions demonstrated a high level of robustness against destruction. Even for currents one order of magnitude above the specified ratings the cell did not fail, suggesting that latch-up does not occur [1]. However, a closer inspection of the composition of the total current over time

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at the emitter contact reveals traces of the on-set of latch-up. This is a characteristic increase of electron current at the emitter contact reflected in a current peak that gets more pronounced for higher current densities as is shown in Fig. 1. This peak originates from the injection of electrons caused by the fact that the pn-junction between source and body becomes forward biased in consequence of the high amount of holes moving underneath the source during turn-off. One should note that the peak occurs when the MOS-channel is already closed, because the gate voltage is already below its threshold voltage. This peak appears in isothermal as well as in electrothermal calculations. In the latter case, however, the peak is significantly more pronounced for identical current densities, as shown in Fig. 2. This can be traced back to the fact that the additional local increase in temperature at the source-body pn-junction caused by the high current densities causes an increased injection of electrons from the source. This result suggests that in thermodynamic calculations latch-up already occurs at lower current densities than in isothermal calculations. The height of this current peak in the case of a single cell was found to be limited only by the total current present in the circuit for both types of calculations.

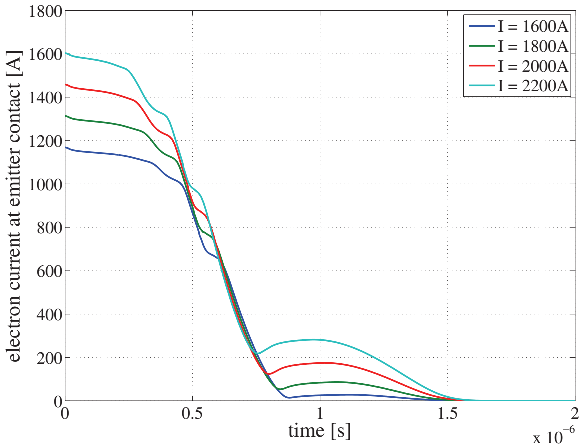

Fig. 1. Electron current at the emitter-contact as a function of time. The current peaks appear at a time, at which the gate voltage is already below threshold, i.e. at about 0.7 μs (for $I = 2200A$) to 0.8 μs (for $I = 1600A$), and gets more pronounced with higher current I, i.e. with higher current densities. The data presented in this plot originate from isothermal calculations.

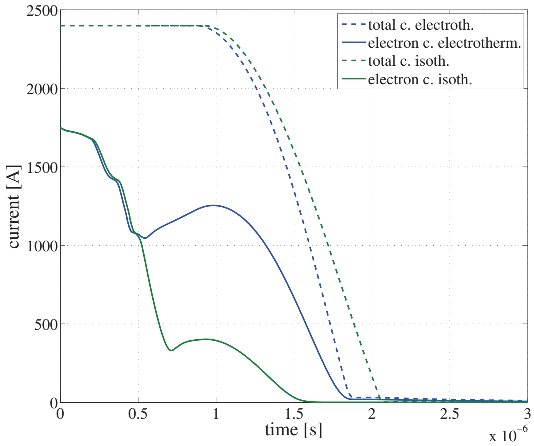

Fig. 2. Comparison of the electron current at the emitter contact during turn-off of a single cell for an isothermal and an electrothermal calculation as a function of time. The difference in size of the peaks is clearly visible, as the peak in the electrothermal calculations is about three times as high as the respective peak in isothermal calculations. These graphs represent identical conditions for the total current ($I = 2400A$) in the circuit.

B. Turn-off of multiple cells in a parallel circuit

We extended our investigations to multiple cell arrays connected in a parallel (external) circuit. The first step consisted in considering a scenario of two identical IGBT structures in parallel, where the total device area is kept constant, but is asymmetrically distributed in order to stimulate current crowding in the cells. However, this setup is a rather inaccurate approximation to the real structure, since the cells are isolated from each other in this case, so that a spatially distributed crosstalk between them cannot occur. The respective collector currents through each of the cells is displayed in Fig. 3. It clearly shows the abrupt takeover of the entire current by the smaller-sized cell at the latch-up current I_L, eventually leading to breakdown in consequence of the latch-up process. At this point the difference between isothermal and electrothermal calculations has to be pointed out. We found that latch-up occurred at current densities as much as 30 % lower in the electrothermal calculations.

Next the IGBT array was extended to six cells in parallel. The simulations for this scenario show the same qualitative behaviour as in the case of two parallel cells, i.e. the smallest-sized structure takes over the entire current and subsequently latches. This occurs at a current which is only slightly smaller than the one for the two-cell structure, leading to the conclusion that the latch-up current has only a weak dependence on the number of parallel cells in the circuit.

It is worth mentioning that in these simulation scenarios the peak in the electron current at the emitter contact also appears in this case, but the maximum peak height shows an upper limit of about 18 % of the load current I, for both the two cell and the six cell scenario. At a slightly higher value of the load current latch-up occurs.

C. Turn-off of an integrated structure

To incorporate processes of spatially distributed electrical and thermal interaction between neighbouring cells during the turn-off process, integrated structures, i.e. structures with adjacent cells, were considered in various sizes in order to get a detailed insight into the latch-up mechanism inside an IGBT array as well as into the overcurrent turn-off capabilities of these arrays.

This approach can be considered as being more realistic to the real structure than the approach presented in the previous section since it allows crosstalk, both electrical and thermal, respectively, between cells. For investigations using integrated cells, the simulation approach stays basically the same. Again, two asymmetric structures are connected in parallel, but with

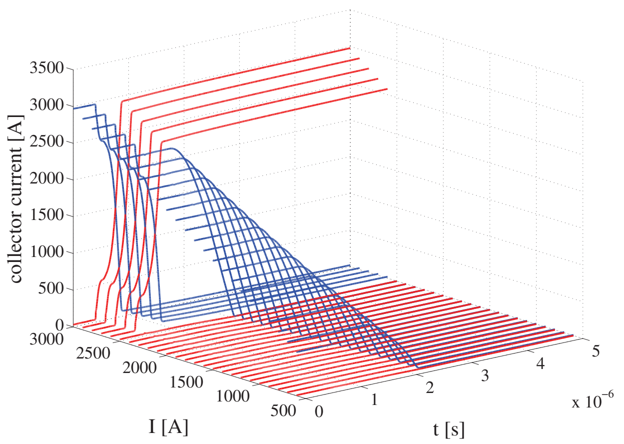

Fig. 3. Collector currents for a two-cell structure in parallel as a function of time and load current I (the current to be turned off). Evidently at approximately $I = 2600A$ the entire current is abruptly taken over by the smaller cell structure, which does not turn off and runs into latch-up. The data presented in this plot originate from isothermal calculations.

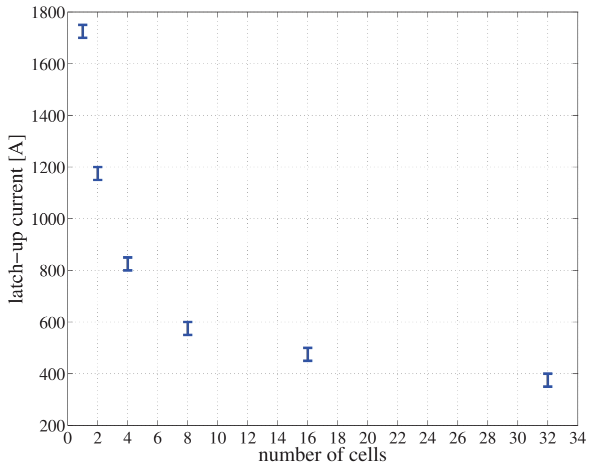

Fig. 4. The latch-up current I_L as a function of the number of cells in the integrated structure considered in the electrothermal simulations. Evidently, for a large structure size it tends to a current value of about $350 - 400A$. For smaller structures the dependence of the latch-up current on the size of the structure is significant. Obviously the variation of the difference in the latch-up current amounts to a factor of about five.

the modification that the smaller-sized structure is now an integrated structure consisting of several IGBT cells.

It was found in the simulations that the current, at which the integrated structure latches, depends on the size of the integrated structure, i.e. on the number of adjacent cells in such a structure. This current tends to become smaller for larger structures, until it seems to reach a final value (see Fig. 4). Several conclusions can be drawn from these results: First, there is a significant crosstalk among the cells that causes latch-up already at smaller currents as compared to the same number of cells in a parallel circuit, where this crosstalk does not exits. Second, this crosstalk extends to several cells and is not restricted to the nearest neighbours, since there is a significant change in the latch-up current for smaller-sized structures. Third, the interaction is not exclusively caused by thermal crosstalk, since isothermal simulations showed qualitatively the same behaviour. The reason for this dependence on the size of the integrated structure is not fully understood yet. It has to be mentioned that the latch-up results obtained with integrated structures are considerably closer to experimental results.

The latch-up of IGBTs in the simulations with integrated structures is preceded by the formation of current filaments, i.e. localized regions inside a device that show a drastically higher current density than neighbouring regions. During the device destruction process these two phenomena always occur concurrently. However, the formation and existence of current filaments does not irreversibly lead to latch-up.

Analyzing the details of the latch-up process, we found the formation of moving current filaments during the turn-off of the integrated structures. Effects that go along with these kind of filaments like avalanche multiplication, field bending and self-stabilizing structure formation (as described, e.g., in [13] and [12]) were observed in IGBT arrays of every size. It showed that moving current filaments appear in electrothermal simulations only and occur at lower current densities than those leading to latch-up. It was also observed that the formation of current filaments does not necessarily lead into the destruction of the device, as was also found in [2]. Our simulations also reveal that filaments can extend and travel over the entire structure and that they are not restricted to a certain region, regardless of the size of the structure. In principle multiple current filaments can simultaneously co-exist at the same time, not just a single, as demonstrated in Fig. 5. The lifetime of non-destructive current filaments is approximately 1 μs, and their vertical length increases with time proportionally to the propagation of the electron-hole plasma within the low-doped n-base of the device. In Fig. 6, the emergence of such a filament is depicted together with a plot of the lattice temperature distribution.

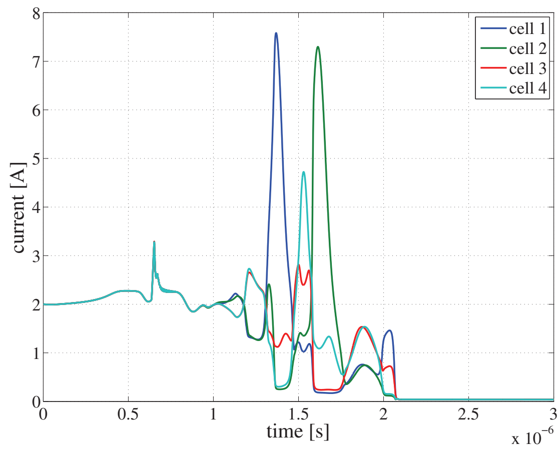

Fig. 5. Absolute value of total current at each emitter contact as a function of time for an integrated structure consisting of four cells. An inhomogeneous current flow as well as the simultaneous occurrence of current filaments are visible.

Regarding the turn-off process itself (see Fig. 5), we found a laterally non-homogeneous, but symmetric current flow through the emitter contact accompanied by a symmetric increase of the lattice temperature during the first third of the turn-off process. At this point the total current density is already locally increased underneath each trench. This symmetry is lost thereafter and the formation of moving current filaments sets on. These filaments have a considerably higher current density compared to the static filaments discussed above, and they lead to a pronounced local increase of lattice temperature which, in turn, can cause thermal runaway of the cell. Non-destructive filaments tend to move around inside the device in the direction of decreasing temperature. During this process, the amount of current conveyed in the filament continuously degrades, until the total current through the integrated structure fades away and the filament extinguishes. In the filaments that were observed in our simulations, the total current density inside the filament was up to two orders of magnitude higher than outside the filament. We also found that thermal destruction mostly occurs at cells located at the edge of the integrated structure and spreads from there to the remaining cells.

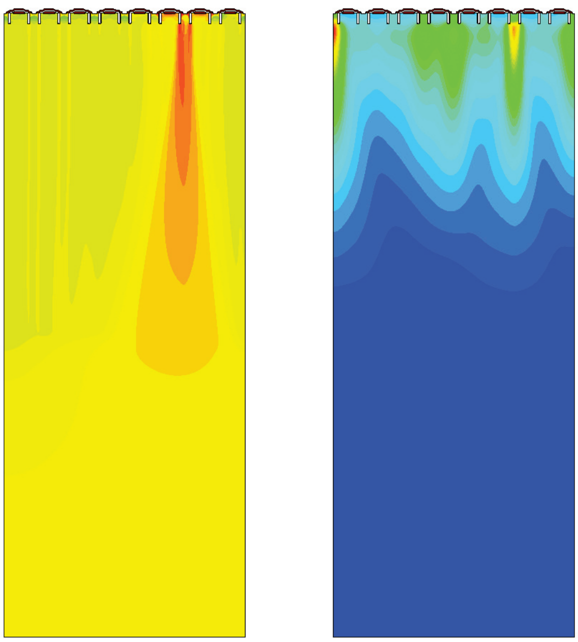

Fig. 6. Two 2D plots of the same integrated 16 cell structure $1.7\mu s$ after the beginning of the turn-off process. The left plot depicts the total current density distribution, whereas the right one depicts the lattice temperature distribution. The movement of the current filament can be deduced from the localized hot spots underneath the trench: the hot-spot on the very left of the structure originates from a filament that emerged at an earlier stage of the turn off-process, whereas the second hot-spot originates from the filament that is depicted on the left-hand side.

IV. Conclusion

The numerical analyses presented in this work demonstrate that in realistic, electrothermally coupled mixed-mode device simulations the latch-up current of high-voltage trench IGBT cell arrays strongly depends on the layout and the size of the

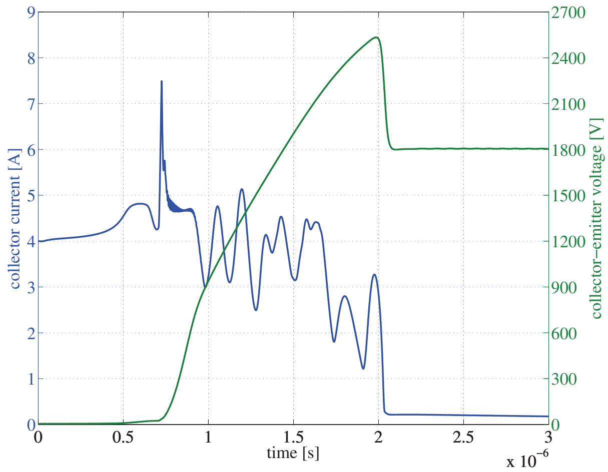

Fig. 7. The collector current and the collector-emitter voltage of the smaller-sized structure during the turn-off process (depicted in Fig. 6) as a function of time.

cell arrays under investigation. Electrical as well as thermal crosstalk between nearest-neighbour cells and beyond has to be taken into account to obtain meaningful, realistic results, which are in agreement with measurement. The simulation approach assuming an array of IGBT cells as discretely connected parallel circuit, where electrical and thermal crosstalk can not occur, gives quantitatively incorrect results.

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