Influence of Quasi-3D Filament Geometry on the Latch-Up Threshold of High-Voltage Trench-IGBTs

C. Toechterle[1)], F. Pfirsch[2)], C. Sandow[2)] and G. Wachutka[1)]
[1)] Institute for Physics of Electrotechnology, Technical University of Munich,
Arcisstraße 21, D-80333 Munich, Germany
[2)] Infineon Technologies AG, *Am Campeon 1-12, D-85579 Neubiberg, Germany*
Email: toechterle@tep.ei.tum.de

***Abstract*—Current filaments are inherently three-dimensional phenomena regardless of the chip topography, which can be stripe- or checkerboard-shaped. Therefore, we consider an alternative mapping of the real-chip IGBT cell topography to a quasi-3D simulation geometry in order to attain a computationally affordable approximation of 3D-filamentation effects that limit the SOA. The new approach extends that of previous work ([1], [2]) by using large, monolithically integrated cell arrays as simulation domain in cylindrical cell geometry (Figs. 1, 2), resulting in cylindrical filaments. In this way we obtain a quasi-3D and, hence, more realistic approximation of the filamentary current flow and the resulting critical phenomena in real-world IGBT-chips, which provides the basis for the quantitative numerical analysis of the latch-up threshold.**

I. Introduction

Current inhomogeneities during over-current turn-off essentially limit the safe-operating area (SOA) of high-voltage (3.3kV) trench-IGBTs, because they may lead to device latch-up. Two-dimensional simulations of the turn-off process beyond the SOA based on 2D cross-sections of structures as simulation domain do not satisfactorily reproduce the data measured on three-dimensional chips. This is due to the fact that the 3D-nature of the filaments is not taken into account, leading to a considerable over-estimation of the threshold current density for latch-up limiting the SOA. With a view to getting a better approximation of filamentary current flow in the real 3D chips, we introduce a cylindrical simulation geometry on the basis of previously reported work ([1], [2], [3]).

II. Simulation Approach

A. Simulation Structures in Cylindrical Geometry

The generation of simulation structures in cylindrical geometry is, analogously to the generation of those in stripe symmetry, based on a specific mapping of the geometric dimensions of the real chip-cells (Fig. 1): the ratio of contact areas and non-contact areas inside a single IGBT cell is held constant. In stripe geometry this condition is fulfilled automatically, when the monolithically integrated simulation structure is generated by consecutive mirroring of a single IGBT simulation structure. In cylindrical symmetry, however, the generation of large simulation structures that consist of multiple IGBT cells, where each of which obeys the constant ratio introduced above makes it necessary to define the dimensions of each cell individually by an iterative process.
For ease of comparison, the overall total active area of the simulation structure is held constant. Consequently, these structures differ from each other by their number of individual cells as well as by their lateral extension only. Both features, on the one hand, facilitate a more pronounced redistribution of the current densities and, on the other hand, provide a structure that is large enough to fully comprise a single current filament, regardless of the symmetry type of the simulation domain. In addition, homogeneous Neumann boundary conditions are applied along the edges of the structures in both geometries.
The theoretical reproduction of the data measured within the SOA is achieved by calibration with reference to static and transient characteristics of a model structure without special measures against latch-up, respectively.

B. Transient Turn-Off Simulations

In order to determine the SOA of the device under investigation, transient turn-off simulations with an inductive load were conducted in analogy to investigations using stripe symmetry ([1], [2]). In cylindrical symmetry, the cells surrounding the innermost cell are used for generating a nearly homogeneous current density at the beginning of the turn-off process only. They play the role of hole extraction regions from the device after the closing of the MOS-channels (see Fig. 3). In simulations in cylindrical symmetry considering multiple, physically connected IGBTs in a cell array, the innermost cell is asumed to be surrounded by neighbouring cells which, as approximation of the situation in the real chip, are represented by ring-shaped cells emulating the impact of the ambient on the central cell under investigation.
This approach proves to be applicable to filamentary current flow during the turn-off process in real IGBT chips by determining that cell where a current filament gets 'trapped' due to slight asymmetries e.g. of the gate connection or of the actual temperature. This cell may be any arbitrary cell in the bulk of the chip. The center of the cell at which the current filament is eventually located defines the point where the axis of revolution of the cylindrical coordinate system is placed.

978-1-5090-0818-6/16/$31.00

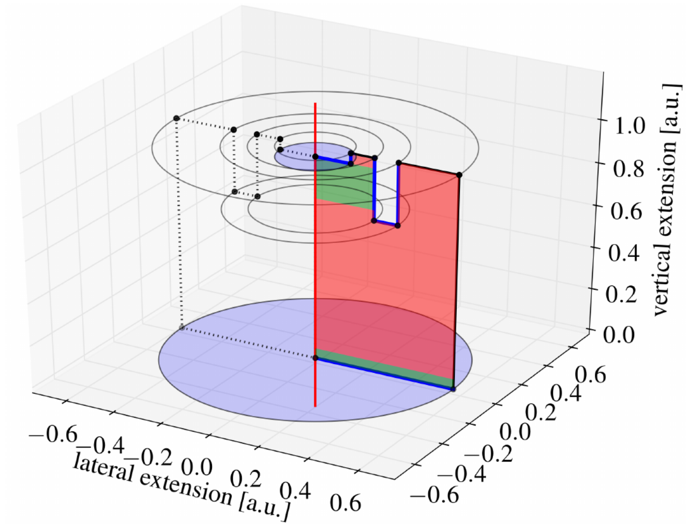

Fig. 1. Sketch of cylindrical trench-IGBT structure used for single cell simulation. Regions with n (p) doping are depicted in red (green), whereas the contact regions (emitter, collector and gate) are coloured in blue.

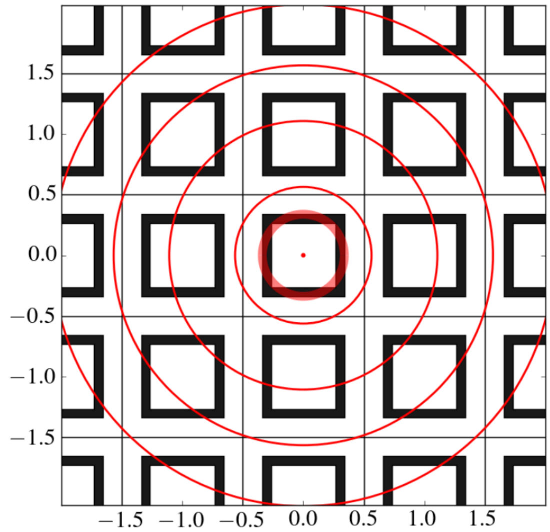

Fig. 2. Comparison of the chip layout of a real trench-IGBT cell-field (top-view) and the measures of the corresponding cylindrical simulation structure (solid red circles: borders of 4 innermost cells, ring-shaped light-red region: trench structure).

III. Results and Discussion

A. Comparison between Geometries

Qualitatively, the mechanisms causing the IGBT to latch in cylindrical symmetry are identical to those identified in stripe symmetry ([1]). Also the temporal evolution during device turn-off does not show any qualitative differences: the closing of the MOS-channels is followed by building up an electric field and subsequent onset of dynamical avalanche triggered by sharply localized field peaks at the trench bottoms in consequence of the strong curvature of the gate-contact. Furthermore, a laterally inhomogeneous but periodic current density pattern occurs, which originates from the basic cell design itself and which extends from the trench bottoms to the electron-hole plasma region in vertical direction.

A significant qualitative difference cannot be observed up to the instance when symmetry-breaking takes place: in stripe structures one or several current filaments arise, depending on the lateral extension of the simulation structure, whereas in cylindrical structures one central current filament arises, exhibiting a conical shape. In any case the filamentation process is such that no interaction between coexisting filaments takes place.

As can be deduced from an additional analysis of static I-V-characteristics and especially the regions exhibiting negative differential conductivity, the tendency for filamentation is different for both geometries. This feature leads to significantly different latch-up current densities as well.

B. Central Current Filament with Conical Shape

The basically two-dimensional shape of the filament is trapezoidal-like in each of the two symmetries. The length of the short side is mainly determined by the distance between two adjacent trenches in stripe geometry and by the diameter of the circle described by the innermost trench-circle in cylindrical symmetry. These measures do not significantly differ from each other. At the lower side of the filament, i.e. at the border between space-charge region and electron-hole plasma, stripe-shaped filaments have an extension of about 100μm, whereas the central current filament has an extension of up to 400μm in cylindrical symmetry at the instant when latch-up sets on. Thus conical current filaments have, in conjunction with high vertical electric fields (which cause the carriers to move with saturation velocity), a large potential to extract holes from the electron-hole plasma. Due to a spatially inhomogeneous distribution of electrons and holes inside a filament, a strong and far ranging electric field in lateral direction exists, which focusses the flow of holes on their way to the emitter side and de-focusses the flow of electrons on their way to the collector side. As a result we obtain the trapezoidal shape of a filament in two dimensions. As can be seen in Fig. 5, the lateral electric field inside

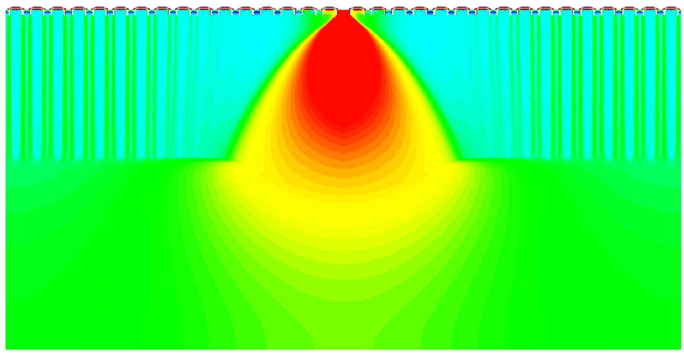

Fig. 3. 2D plot of the electric current density 1.2μs after the begin of turn-off of a 32-cell cylindrical simulation structure. For clarity, the simulation structure is mirrored along the central vertical axis. Latch-up of the innermost cell is clearly visible (color scale: blue: 10A/cm^2, red: 5kA/cm^2). The initial current density amounts to 100A/cm^2.

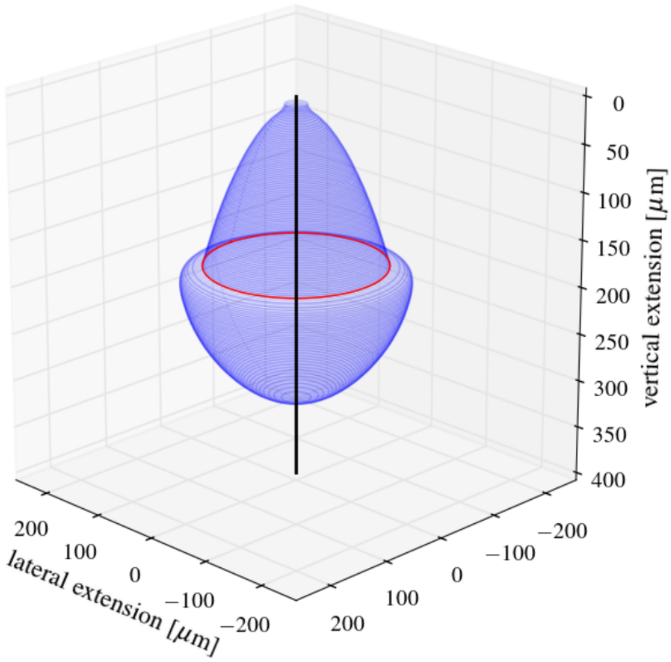

Fig. 4. Shape of cylindrical current filament around the axis of revolution (solid black line) obtained from isothermal simulations at 1.2μs, just as in Fig. 3. The vertical extension of the simulation structure amounts to 400μm. The lateral extension of the filament at the border between space-charge region and electron-hole plasma is depicted in red. The filament itself is defined as the region where the electric current density is above-average in this plot. See also Figs. 3, 5.

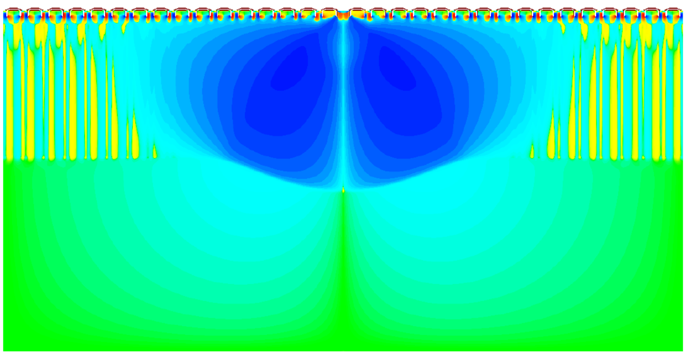

Fig. 5. 2D plot of the lateral component of the electric field at 1.2μs. Colour scheme: dark (light) blue: strong (weak) component pointing towards structure centre, dark red (yellow): strong (weak) component pointing away from structure center, green: zero x-component. Note the wide range of the electric field in lateral direction which extends to nearly 250μm from the center. The color scheme in this plot was chosen to be logarithmic.

the plasma region, just below the location of the filament, is non-zero, as is the vertical component. Due to the coordinate mapping used in the respective simulation approach, this may lead to fundamentally different current distributions at the emitter side and, consequently, to largely deviating predictions of the SOA limits of the device.

C. Quantitative Aspects

The initial current density at which device latch-up occurs significantly depends on the hole current density that

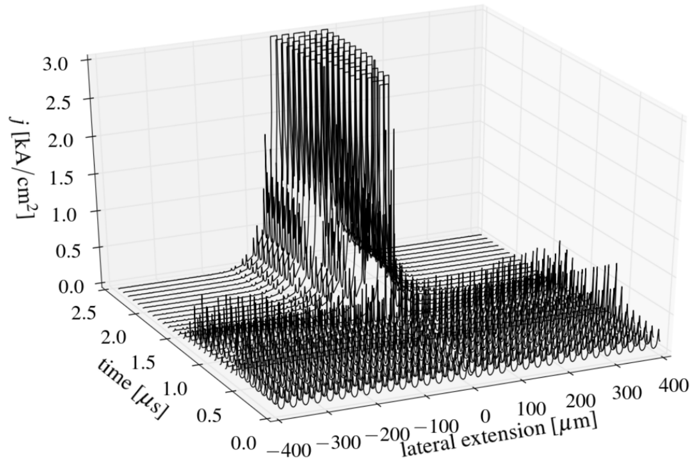

Fig. 6. Current density along a lateral cut-line beneath the trenches asfunction of time for an isothermal simulation of a 32-cell integrated structure. Note that there is just one single current filament at each point in time, which does not move. The initial current density in this plot is 100A/cm^2.

is extracted from the electron-hole plasma during the turn-off process by a single current filament ([1] and Figs. 3, 6). The novel approach considered here focuses on a single, non-moving filament that evolves in the center of a cylindrical structure under isothermal conditions. The cylindrical symmetry allows current filaments to assume a conical shape (Fig. 4), as opposed to stripe symmetry, where the filaments are forced to take an (unphysical) stripe-shaped form: hence, we obtain a better approximation of the real situation as long as only one central filament has to be considered. This approach is valid as long as there are no coexisting interacting filaments and thermal cross-talk, and it relies on previous observations that moving filaments do not play a crucial role for the latch-up threshold as does the number of coexisting filaments during the turn-off process ([1]). In addition, thermal effects play a minor role in determining the limits of the SOA, as can be concluded from Fig. 8. The focusing of holes towards a single cell, however, is much more pronounced in cylindrical symmetry than in stripe symmetry. Therefore, a larger hole current density flows to the central cell, which comes closer to the situation in real IGBT chips.

D. Device Latch-Up

The formation of a central current filament (Figs. 3, 6) may subsequently lead to device failure, if a sufficiently large current density at the emitter side (Fig. 7) is attained due to electron injection from the emitter side and the formation of a plasma channel, (i.e. the turn-on of the parasitic thyristor). The threshold current density for this process is roughly 20% larger in cylindrical geometry (1.2kA/cm^2 compared to 1.0kA/cm^2). This is a consequence of the fact that the geometry of the source-body pn-junction depends on the simulation symmetry. The excessive amount of holes that moves beneath the source during over-current turn-off causes a voltage drop at this pn-junction. In the case of stripe symmetry the pn-junction exhibits a rectangular shape and the condition for forward

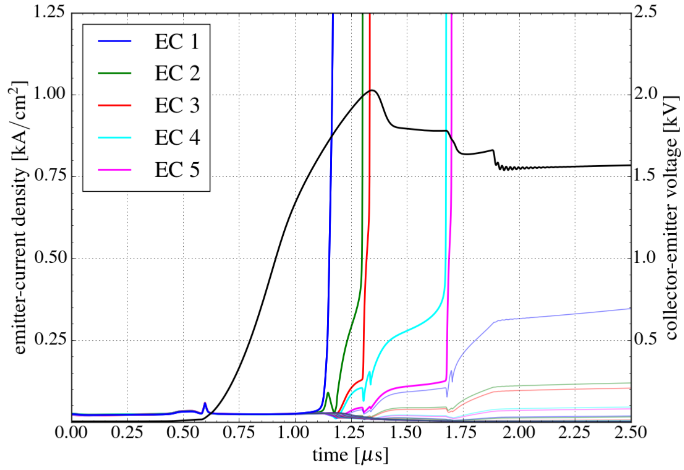

Fig. 7. Current density (left y-axis) as well as collector-emitter voltage (black dashed line, right y-axis) at each emitter contact (EC) of a 32-cell integrated structure as a function of time. The innermost cell takes nearly the entire current shortly before device latch-up occurs. The emitter contacts are numbered in ascending order, beginning at the innermost cell. Note the homogeneous distribution of current densities at the emitter contacts until shortly before device latch-up.

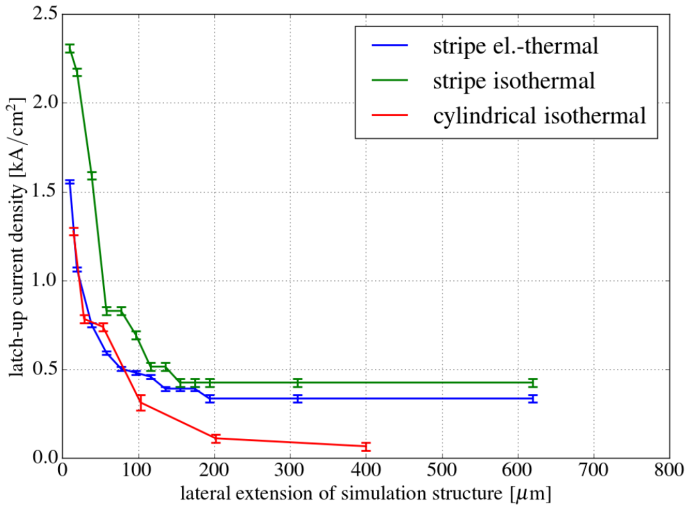

Fig. 8. The latch-up current density of the model structure as a function of the lateral extension of the integrated structure for both isothermal (green) and electro-thermally coupled simulations (blue) in stripe symmetry as well as for isothermal simulations in cylindrical symmetry (red). The limiting latch-up current density for the cylindrical structure amounts to approximately one-fifth of the corresponding value for the stripe structure.

biasing is reached for a certain hole current density at the emitter contact. In cylindrical symmetry, on the other hand, the pn-junction is ring-shaped, and the same hole current density causes a lower voltage drop since the focusing of holes is less pronounced. Consequently, a higher hole current density is needed in order to forward-bias the junction. This hole current density is substantially determined by the extension of the filament along the border between the space-charge region and the electron-hole plasma (Figs. 3, 4) due to its capability to extract holes from the plasma and focus them on their way to the emitter side. The lateral range of hole collection of the central current filament amounts to approximately 10 simulation cells, which corresponds to approximately 400μm, as it is visible from the shape of the time-dependent contact current densities: in the course of developing a high current density, the innermost cell collects holes from all adjacent concentrical cells up to where the lateral component of the electrical field (cf. Fig. 5) is not strong enough anymore to move the holes towards the center. This leads to a drop in the local current densities of the un-latched cells at the respective emitter contacts which is noticeable up to cell number 10 from the axis of revolution (note the drop in current densities at the emitter contacts in Fig. 7 between 1.10μs and 1.20μs). In addition, each time a non-central cell runs into latch-up the next-neighbour cell shows a drop in the local current density as well, which derives from the same mechanism as described above. Thus, in cylindrical symmetry, device failure due to latch-up occurs at considerably lower initial current densities, i.e. much closer to the measured data, by at least a factor of five (Fig. 8).

In order to fully take these physical effects into account, large simulation structures, i.e. structures with a large lateral extension, are needed. In turn, if the lateral extension is too small, i.e. if the structure used for the analysis is too small, these physical effects are not reproduced satisfactorily and quantitatively sensible predictions of the SOA are not possible. The innermost cell always latches first, with the consequence that the IGBT structure would be destroyed if heating was taken into account (Fig. 6). Destruction may then spread to the adjacent cells as well.

The time span between the beginning of turn-off and the formation of a plasma channel strongly depends on how close the initial current density before turn-off lies above the latch-up current density: the more the critical current density is exceeded, the faster latch-up occurs. In any case, latch-up does not occur before the gate-emitter voltages have fallen below the threshold voltage of the MOS-channels.

IV. Conclusion

A new approach for the numerical analysis of real-chip 3D-current filaments by means of a quasi-3D approximation in cylindrical symmetry has been presented. The results that were obtained in this work promise a quantitatively more realistic prediction of the SOA of 3.3kV trench-IGBTs with regard to device latch-up during an over-current turn-off situation. A significant dependence of the latch-up current density on the quasi-3D geometry of the current filament has been identified by comparison with results of previous work using stripe-shaped, monolithically integrated simulation structures.

References

[1] C. Toechterle, F. Pfirsch, C. Sandow and G.Wachutka: Evolution of current filaments limiting the safe-operating area of high-voltage trench-IGBTs, *Proc. 26th ISPSD*, pp. 135-138, (2014).

[2] C. Toechterle, F. Pfirsch, C. Sandow and G. Wachutka, Analysis of the Latch-up Process and Current Filamentation in High-Voltage Trench-IGBT Cell Arrays, *Proc. 18th SISPAD*, pp. 296-299, (2013).

[3] A. Mueller, F. Pfirsch and D. Silber, Trench IGBT behaviour near to latch-up conditions, *Proc. 17th ISPSD*, pp. 255-258, (2005).