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Investigation of effects of lateral boundary conditions on current filament movements in Trench-Gate IGBTs

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ABSTRACT

When designing the reliability of high voltage power devices, it is very useful to confirm the behavior of current filaments in various structures and situations by Technology CAD simulation. Current filaments are caused by the electrical instability inherent in the device when a large voltage is applied to the device or a large current flows through the device, which is the current concentration phenomenon into only a few cells and moves around mainly in the plane of the cell region of the device. The ease of movement of the current filament is determined by the design of the device structure and has a great impact on device reliability. This design is difficult to examine by actual measurement, so simulations are often used. Since device simulations with a large three-dimensional (3D) structure take a huge amount of calculation time, it is common to cut out a part of the chip as small as possible and set boundary conditions on each cut surface to build a simulation setup that fits the purpose of the simulation. In 2D current filament simulations, it is known that when the reflective boundary condition (ideal Neumann) are imposed on the sidewalls, the boundary condition can significantly affect the results. In this work, to the best of my knowledge, I clearly show for the first time the relationship between the current filament movements and lateral boundary conditions in a large-scale three-dimensional trench-gate IGBT structure under conditions especially in which the current filament is highly mobile. In this case, the convergence is very poor and the calculation is difficult, so I also describe how to calculate it well by mathematical settings.

1. Introduction

In developing high-power devices, it is extremely difficult to achieve both high-performance electrical characteristics and high reliability. The main reason is that improving electrical properties in the direction of high electric field and high current density reveals electrical instability of the device. Electrical instability of the device appears at the time of the negative resistance characteristic when the normal operation mode of the device transitions to another mode. Negative resistance properties are often studied as the negative differential conductivity (NDC) that appears in large currents or high voltage regions [1,2]. During the transition, it has been observed that a local current concentration phenomenon called the current filament formation occurs in the device, and they actively move in the cell region [3–6]. How many current filaments are generated per unit area and how long they move around in the device mainly depend on the current–voltage state of the device at the time when the current filaments were generated, the external circuit conditions and ambient temperature. In either case, the current density is much higher than the normal operating current, and Joule heat causes the device lattice temperature to rise locally in a short time. The movement of the current filament is mainly due to the non-uniform distribution of the impact ionization rate and the carrier density in the lateral direction. The main factor of the former is the local decrease in the impact ionization rate due to the local increase in the lattice temperature. Of course, the structural non-uniformity of the actual device also affects the formation and movement of the current filament, however if it is too large, the current filament cannot move from its vicinity. The causes of the current filament becoming difficult to move are as follows: feedback between a local increase in lattice temperature and an local increase in leakage current on the front surface side, an increase in impact ionization on the back surface side, and a local increase in hole carrier injection on the back surface side [7]. Since the typical movement of the current filament appears especially in the fine vibration of the voltage waveform, it is necessary to make a good match between the measured voltage waveform and the simulated voltage waveform.

The various phenomena related to current filaments have been studied by actual measurements and Technology CAD (TCAD)

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simulations [8–11]. For simplicity, device simulations are often performed with a structure that limits one direction of current filament movements, that is, a 2D cross section in which the chip is cut vertically. Even in the 3D case, it is common to cut out a part of the chip as a simulation structure and set boundary conditions on each cut out surface. Which structure we use for the simulation depends on our purpose and available time. In any case, for current filament simulations, the lateral boundary conditions are especially important as the filaments move laterally. The boundary condition of the side wall of the device is the reflective boundary condition by default, which is fine in the absence of lateral flow. However, when the current filament moves and hits the side wall, the value of the physical quantity in the vicinity of the side wall becomes larger than the original value. That is, since the current filament carries the lattice temperature and the carrier density, those values in the vicinity of the side wall become larger than the original values under the reflective boundary condition, and the current filament becomes difficult to move in the vicinity of the side wall.

The simplest modeling of the current filament response in TCAD is a 2D structure in which a large number of cells are arranged horizontally and the left and right boundary conditions are set as periodic boundary conditions [7–9]. This model is useful for checking the mobility of current filaments, observing bounces at termination structures and separation regions, and confirming interactions with structural defect models. However, since the filament can move only in the lateral direction in this case, it is necessary to pay attention to the collision between the filaments when a plurality of current filaments are formed. That is, in the original three-dimensional current filament, since there is a direction of escape, even if they collide, they immediately avoid each other. In trench gate IGBTs, it is known that the three-dimensional layout, especially on the surface side, has an essential effect on electrical characteristics. When more accurate modeling is required, the simulation needs to be performed in 3D. Another problem with modeling in 2D is due to the nature of the current filament to move in areas of lower lattice temperature. When the current filament moves a long distance, the filament warms the inside of the structure from the colder part, however on the second lap it warms the part that should not actually be warmed. In other words, the filament moves in the direction of another lower temperature in the original 3D, but in 2D there is no escape, so it is often the case that the previously warmed part is reheated. Of course, even in 3D, if the structure is too small, the same situation will occur.

2. Targets and simulation approch

In this study, overcurrent turn-off phenomena are simulated by Synopsys TCAD with the thermodynamic model. As shown in Fig. 1, the simulated structure consists of 8 cells in the X direction and 16 cells in the Z direction, with 4 cut out surfaces on the lateral sides. The size of the structure is determined as the size that one current filament can be formed in the structure and can move freely to some extent within the range of the phenomenon determined by the circuit conditions and device characteristics. Since the number of mesh points is in the millions, the direct matrix solver cannot be used from the viewpoint of calculation time, so I use the iterative matrix solver. In that case, the convergence of the calculation becomes very sensitive to the meshes, so it is necessary to carefully consider the phenomenon and set the meshes. As a strategy for the mesh settings, Normally Offset meshes are generated near the trench interface and normal tetrahedral meshes are generated for the other areas, and the meshes are so fine that the result is almost the same even if the densities of the meshes are changed to some extent. The meshes set this time are such that the calculation time and the calculation result are almost the same even if the meshes are changed to brick meshes (hybrid meshes) instead of tetrahedral meshes [12].

Reflective or periodic boundary conditions are imposed on these lateral surfaces in three ways (a), (b) and (c). From now on, the reflective boundary condition will be referred to as RBC, and the periodic boundary condition will be referred to as PBC. Mortar periodic boundary condition (MPBC) is used as PBC.Especially in 3D device simulations with the iterative matrix solver, if the MPBC is imposed, the convergence becomes even worse, so it is necessary to more carefully set the mesh strategy and use a specialized linear solver for MPBC (Schur Solver implemented in SDevice) [13]. Furthermore, in order to improve the calculation speed, it is necessary to use the numerical calculation options and physical models suitable for the trench gate IGBT structure, change the preprocessing settings of the matrix solver, and apply parallel calculations.

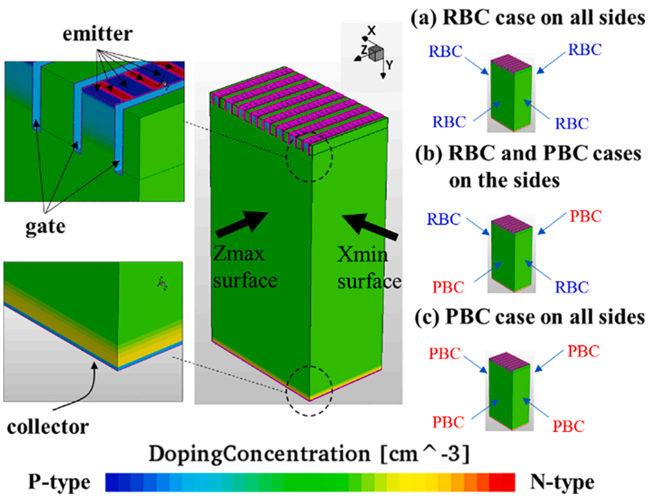

Fig. 1. Schematic view of the simulated structure (Trench-Gate IGBT 8 × 16 cells). (a), (b), and (c) represent three types of boundary condition settings for the cut out vertical plane. RBC represents the reflective boundary condition and PBC represents the periodic boundary condition.

3. Results and discussion

The results of the overcurrent turn-off simulation under the three boundary conditions are shown in Fig. 2. As can be seen from the figure, the waveforms of the collector-emitter voltage Vce, the gate-emitter voltage Vge and Tmax start to be jagged when the collector current Ic starts to decrease from a constant state. Tmax represents the maximum lattice temperature value of the Si region at each time. The jaggedness of these waveforms is caused by the generation and the movement of a high current density current filament. The timing of current filament generation is mainly determined by the trigger value of the snapback

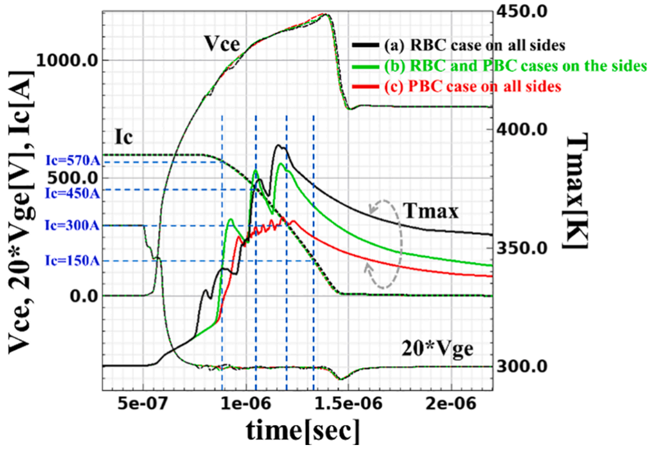

Fig. 2. Waveforms of overcurrent turn-off simulation calculated under the three boundary conditions in Fig. 1. Tmax represents the maximum lattice temperature of the Si region at each time.

characteristic, which is determined by the voltage value, the current value, and the lattice temperature. The main cause of the current filament movements is that the lattice temperature becomes locally non-uniform due to Joule heat, and the filament moves to lower temperature parts where impact ionization is likely to occur. This is because the lower the lattice temperature, the less phonon scattering, and the carriers are further accelerated even at the same electric field value. As can be seen from the jaggedness in the figure, the heat generation inside the device differs greatly depending on how the boundary conditions are imposed.

Fig. 3 shows the current density and the lattice temperature distributions under the boundary condition (a) at each current value. From the figure, it can be seen that when the current value is large, the carriers are still accumulated on the back surface side, and the current density is high and the heat generation is large on the front surface side of the device. You can also see the current filament moving around inside the device. In Fig. 4, the 2D distributions cut out horizontally on the cut plane are shown. In the 2D current density distributions, some arrows show the trajectory of the current filament movements. The current filament initially crosses the center of the device and hits the Xmin plane. The current filament that hits the horizontal boundary spreads like a crush and separates into two filaments. After that, it moves along the boundaries and disappears as Ic decreases. In the case of the simulation with a 2D structure, there is no place to escape, so the filament bounces off the side boundary line, but in a 3D case it travels along the boundary surface. The reason why the filament moves along the boundaries and the filament occurs at the boundary surface is that under the reflective boundary condition (RBC), the values of the physical quantities near the boundary surface become large when there are physical quantity flows in the horizontal direction. This is because in the case of RBC, in order to obtain a solution so that the derivative of the physical quantity in the horizontal direction becomes zero, it becomes simulated results as if the flow of the virtual physical quantity comes from the opposite side and collides. For this reason, the current filament becomes difficult to move due to the large hole injection from the back surface and the large leakage current from the front surface. The increase in the leakage current is due to temperature rise and potential barrier drop in the base region. After all, the current filament is difficult to move due to the influence of RBC. The difficulty of movements is also reflected in the large jaggedness of the waveform shown in Fig. 2. However, the fact that the Tmax waveform becomes larger than it actually is due to the influence of the boundary conditions makes it difficult to trace the heat generation characteristics of the cell region by simulation, which adversely affects the device evaluation. In particular, the large jagged waveform of Vce can be seen in the measured data when the current filament moves in the cell region and hits the end of the terminal part, but this time it is only the influence of the boundary condition of the simulation. RBC is not suitable as a simulation to confirm the behavior of the current filament in the cell region.

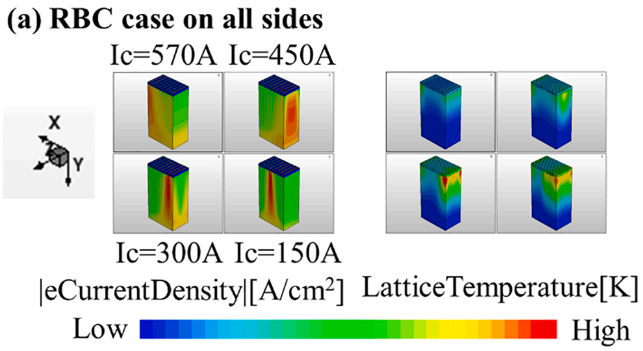

Fig. 3. Distributions of electron current density and lattice temperature at each collector current value in the case of (a) in Fig. 1.

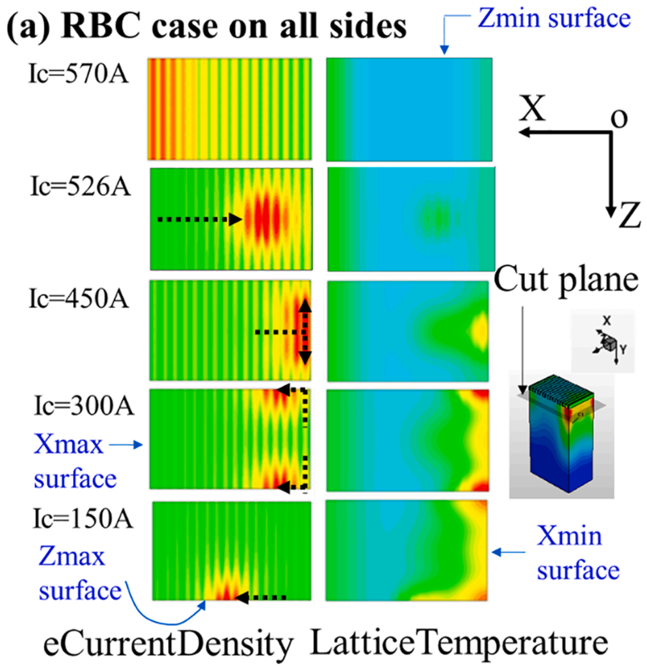

Fig. 4. Distributions on the horizontal plane cut out by “Cut plane” in the figure. The arrows in the figure indicate the trajectory of filament movement.

Figs. 5 and 6 show the same distributions as in Fig. 4 under the boundary conditions of (b) and (c). In Fig. 5 (in case (b)), a current filament is formed on the side wall and crosses the cell region to reach the opposite side wall. The current filament then moves again along the side wall and the cell region in the opposite side wall direction. In Fig. 6 (in case (c)), the timing of a current filament formation is the latest and the filament does not move along the boundary. The former can be seen from the fact that the timing of the steep rise of the Tmax waveform is the slowest. Due to the periodic boundary condition, the filament that reach Xmin plane emerges from Xmax plane. After that, it is scattered by the high heat part formed at the position where it was first generated, and it moves toward Zmax and disappears as Ic decreases. Which direction the current filament avoids is likely to be determined by simulation noise such as mesh asymmetry, however in most cases it does not affect the purpose of the simulation. From Fig. 5, it can be seen that the

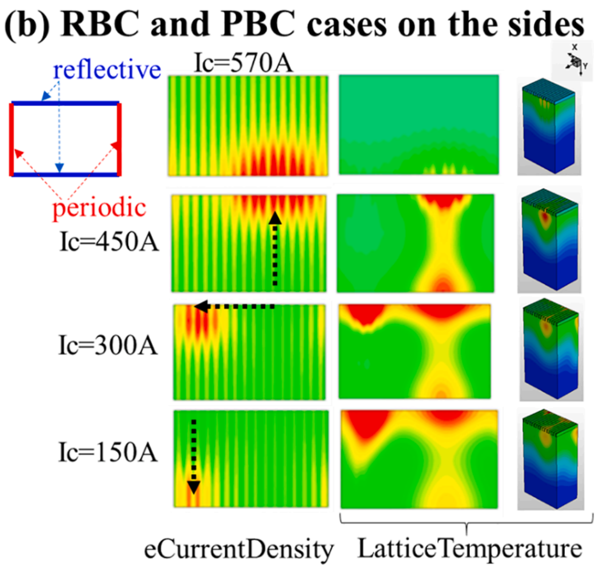

Fig. 5. Distributions similar to Fig. 4 in the case of (b).

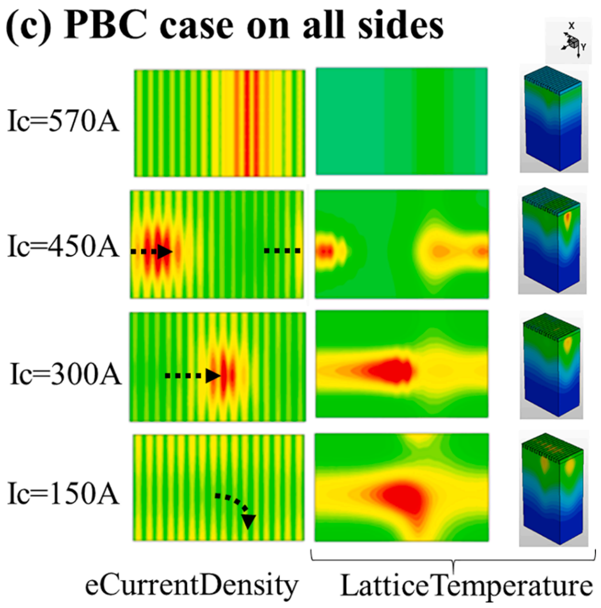

Fig. 6. Distributions similar to Fig. 4 in the case of (c). At 150A in (c), the current filament disappears, but the temperature distribution shows the movement.

movement is as if the features of both (a) and (c) are combined. Regarding the calculation time, (a) is the shortest, (c) is the longest, and (b) is in the middle. However, it cannot be denied that the influence of RBC on the waveform is large. When setting boundary conditions such as (a) and (b) to reduce calculation time and improve convergence, it is necessary to make sure that they meet the purpose of the simulation. In other words, in the cases of (a) and (b), it should be always clarified that the situation where the current filament is very difficult to move near the side wall due to RBC does not affect the simulated results and the simulation purpose. When looking at the effect of the current filament moving through the cell, it is more appropriate to model the phenomenon using PBC.

4. Conclusion

When investigating the behavior of the current filament by 3D simulation, the influence of the boundary condition of the side wall was investigated by TCAD simulation on the overcurrent phenomenon. Although the calculation time is short if the default reflective boundary condition (RBC) is used as the boundary condition of the side wall, it was confirmed that it is desirable to set the periodic boundary condition (PBC) from the viewpoint of the reproducibility of the phenomenon by simulations. Especially when discussing the device phenomenon with the Tmax waveform, or when discussing the generation and movement of the current filament with the distribution graph, it is necessary to pay attention to whether the current filament sticks to the side wall due to the influence of RBC.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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