T. Suwa, "2D-TCAD Simulation Study of Capture Layer and Repellent Layer of Current Filament in Trench-Gate IGBTs", 2021 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), Dallas, TX, USA, 2021, pp. 32-35. Doi:10.1109/SISPAD54002.2021.9592570

2D-TCAD Simulation Study of Capture Layer and Repellent Layer of Current Filament in Trench-Gate IGBTs

Takeshi Suwa
Toshiba Electronic Devices & Storage Corporation, Kawasaki, Japan
Email:takeshi.suwa@glb.toshiba.co.jp

Abstract— For reliability designs of high voltage power devices, it is very important to understand and control local heat generation caused by current filaments. The current filament is a phenomenon that currents are concentrated in some cells and is caused by the instability inherent in the devices. It moves around in the active region of the device and locally raises the Si lattice temperature of the passage mainly due to Joule heat. It slows down at terminal boundaries or defective cells and is likely to create a hotspot and damage the device. Therefore, keeping the current filament away from such weak places and confining it in a structure specialized for heat dissipation effects are useful for the reliability design of the device. By changing a part of the field stop layer of the IGBT to a capture layer or a repellent layer to control the movement of the current filament, the current filament can be confined in the capture layer or kept away from the repellent layer. The purpose of this paper is to investigate the mechanism of current filament capture and repellent so that they can be used as one of the effective means of device reliability design.

Keywords—IGBT, current filament, self-heating, avalanche model, highly injected carrier, UIS test, reliability design

I. INTRODUCTION

Power devices such as IGBTs include electronic instability due to the negative differential conductivity (NDC) that appears in large currents or high voltage regions [1][2]. If the amount of carriers injected into an area of the device is greater than the amount drained, the carriers will accumulate in that area for some time. Locally accumulated carriers have a large electrical effect on the distribution of potential energy and band energy in that region. As a result, the current-voltage response of the device transitions to a significantly different response states, and NDC is observed during that transition. It has been observed that during the transition of the conduction state, local current concentration phenomena called current filaments occur in the IGBT, and they actively move in the cell region [3][4][5][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.

Since one current filament can carry the normal current of tens or hundreds of cells, the current density of the current filament is very high and a lot of Joule heat is generated locally. The current filament is formed by horizontally and locally gathering both electrons flowing toward the back surface and holes flowing toward the front surface from the collector electrode on the back surface. The electrons on the surface side include a component generated by impact ionization at the bottom of the trench and a component leaking from the emitter electrode on the surface [7]. As a result of the increase in the silicon lattice temperature, carrier scattering due to phonons becomes stronger in the region where the current filament exists. Therefore, the acceleration of carriers in the electric field is reduced, and impact ionization is less likely to occur. The heavily impact-ionized region under the trench then moves towards the adjacent unheated cell, and the distribution of carriers forming the current filament is skewed. The hole injection area of P+ Collector region on the back side moves accordingly, and the current filament moves between cells. That is, if the upper or lower movement is blocked, the current filament movement is restricted [8].

Normally, the current filament travels through the cooler parts of the cell region, sometimes bouncing off at the boundary with the termination region, and sometimes getting caught in defective cells. The current filament warms the cell region locally, but when the current is cut off, the current filament also disappears. The phenomena has been investigated by both actual measurements and Technology CAD (TCAD) simulations [9][10][11]. There is no problem while the current filament is moving smoothly, but once it gets caught somewhere and cannot move, the lattice temperature may rise locally and the device may be destroyed. In other words, if the device specifications are such that the generation of current filaments is unavoidable, it is necessary to design the current filaments to prevent them from being pinned locally or to keep them away from weak structural regions. On the other hand, the current filament may be used for screening for unexpected structural defects, however in that case, it is necessary to prevent the current filament from breaking the device in a part other than the defect to be detected. To achieve that, we need to understand how current filaments respond to specific structures and conditions. TCAD simulations are useful for that purpose because current filament responses occur very quickly and locally.

The simplest modeling of the current filament response in TCAD is a two-dimensional 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][8]. In an actual device, the current filament moves three-dimensionally and is strongly influenced by the boundary region, however a two-dimensional multi-cell structure is sufficient for investigating the relationship between the movement of the current filament and the cell structure. Of course, when considering the phenomenon of multiple current filaments interacting, or the phenomenon of one current filament disappearing and another current filament being generated elsewhere, a two-dimensional multi-cell structure is not sufficient.

Even in the simulation using the two-dimensional multi-cell structure, the static electrical characteristics of the device, the dynamic electrical characteristics of the device, and the thermal resistance value need to be close to the actual measurement to some extent. If you do not pay attention to the calculation settings, calculation environment and mesh structure, the simulation time may become unbearably long. It is necessary to appropriately set the range and mesh of the structure to be simulated according to the purpose and required calculation accuracy, and carefully select the model and parameters to be used and the setting of numerical

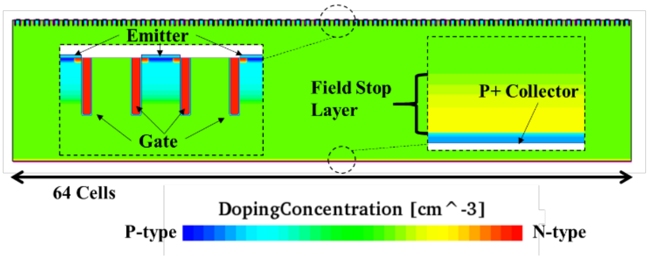

Fig. 1: Schematic view of the simulated structure (IGBT 64cells). The two figures surrounded by dotted lines are enlarged views of the front and back side surface.

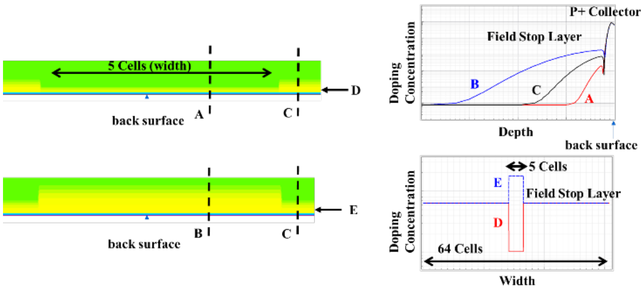

Fig. 2: Impurity distributions in the current filament capture layer (top) and the repellent layer (bottom). The symbols A to E represent the impurity distribution of each one-dimensional cross section in the left figures.

calculation in consideration of high electric field and high lattice temperature conditions.

II. TARGETS AND SIMULATION APPROCH

In this study, unclamped inductive switching (UIS) test [7] [10] was simulated by Synopsys TCAD with thermodynamic model and periodic boundary condition for lateral sides. In order to investigate the movement of the current filament independently for a long time, the UIS test simulations were calculated under the circuit condition of a low total current value and a large inductance value. Simulated IGBT structure has 64 cells arranged side by side as shown in Fig. 1. In a normal IGBT structure, the field stop layer near the back surface has a uniform distribution in the horizontal direction, preventing the depletion layer from contacting the back surface. When it is desired to capture or repel the filament in a certain place, it can be realized by changing the vertical distribution of the field stop layer in the place as shown in Fig. 2. The capture layer has less impurity distribution in the vertical direction than the normal field stop layer, and the repellent layer has more impurities. Each width of the capture layer and the repellent layer was set to the width of 5 cells. UIS test simulations were performed on five structures, each having a different field stop layer as shown in Fig. 3. The only difference between (b) and (d) in Fig. 3 is the position where the capture layer is formed. The difference between (c) and (e) is the same.

III. RESULTS AND DISCUSSION

The simulation results of each structure are shown in Fig.4. The symbols (a) to (e) in the figure correspond to the simulation results of the structure having the field stop layer in Fig. 3. In the structures (b) and (d), the same filament capture layer is arranged in different places, however the UIS test simulation results are almost the same, and it can be seen

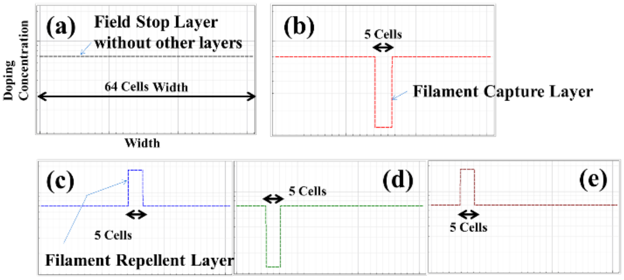

Fig. 3: Impurity distributions of each field stop layer of the five structures to be simulated.

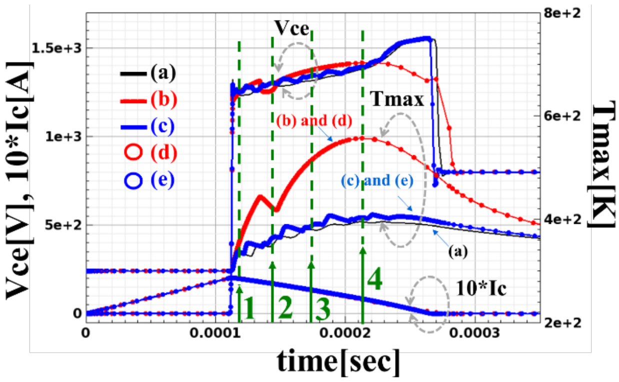

Fig. 4: UIS test simulation results. (a) to (e) correspond to the simulation results of the structure having the field stop layer in Fig. 3. The results of (b) and (d) are almost the same and overlap, and so are the results of (c) and (e).

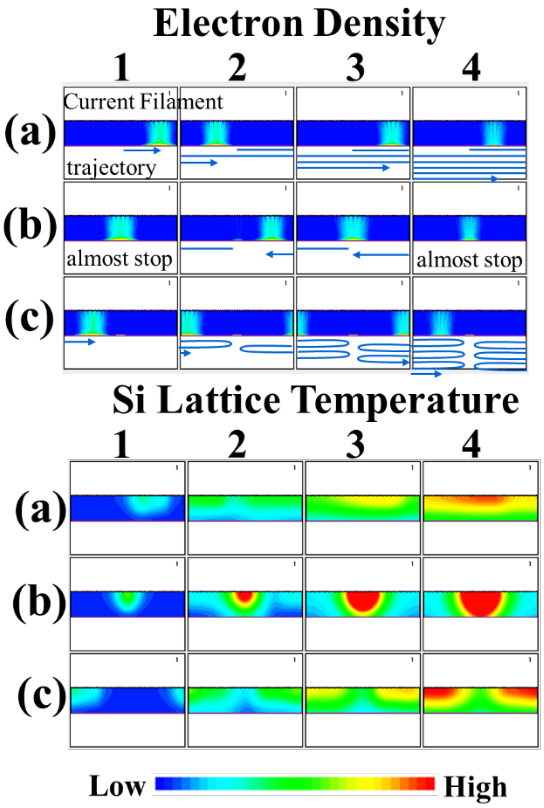

Fig. 5: Distributions of simulation results of structures (a), (b) and (c). The numbers 1 to 4 represent the distributions at the time indicated by each number in Fig. 4. Arrows indicate the movement of the current filament.

that there is no position dependence of the capture layer in this simulation. The same tendency applies to structures (c) and (e) with a repellent layer. Regarding the capture layers of (b) and (d), it can be seen that the collector-emitter voltage Vce waveform and the Tmax waveform, which is the maximum temperature of the silicon lattice temperature at each time, are less jagged than the results of the normal structure (a). The jaggedness of these waveforms occurs as the current filament moves between cells. Regarding the repellent layers of (c) and (e), Vce and Tmax waveforms are more jagged than the results of the normal structure (a). This is due to the fact that in this simulation, the current filament moves in a narrow area other than the repellent layer, which causes a little more heat generation in that area. Fig. 5 shows the physical quantity distributions of each structure. As can be seen from the distributions and the trajectory shown below each distribution, the current filament moves evenly between the cells in the normal structure (a). The trajectory of the current filament movements can be found by observing the time transition of the distribution maps of the lattice temperature. The current filament occurs in the center of the structure and then moves to the right. This is expected to be mainly due to the slight asymmetry of the mesh structure. In the structure having the capture layer (b), the current filament moves a little, however the current filament is attracted around the capture layer region, and the heat generation on the surface side of the region is increased intensively. On the contrary, in the structure having the repellent layer (c), it can be seen that the current filament avoids the repellent layer region and moves around the other region. Since each structure with a capture layer and a repellent layer is affected by the periodic boundary conditions, it can be seen that not only the density difference and width setting of each layer but also the spacing between each layer is an important factor.

Although not shown in the figure, the movement of the current filament of the structure (d) showed the same movement as the structure (b) except for the location. In other words, the current filament was generated at the location of the capture layer, then moved a little from there, and then returned to the capture layer. Of course, the place with the highest heat generation was near the trench on the surface side of the capture layer where the current filament stayed for a long time.

Fig. 6 shows that the physical quantity distributions in shorter time increments. As can be seen from the distributions, an additional lateral electric field is generated in the capture layer region (central part of the structure) because many holes are injected from P+ Collector region on the back surface. It is superimposed on the original lateral electric field that collects the carriers to form the current filament, and plays a role of attracting the carrier and the current filament to the capture region. Conversely, the repellent layer region has less hole injection, so the current filament moves to avoid the repellent layer region. That is, the hole injection changes horizontally depending on the location due to the difference in the impurity distributions on the back surface side, and the carrier density distribution is also biased, and the resulting electric field attracts or keeps the current filament away. This tendency is strongly influenced by the structure of the back surface side, so even if the structure of the front surface side is changed to some extent, the situation of current filament capture and repellent change only a little. However, such an

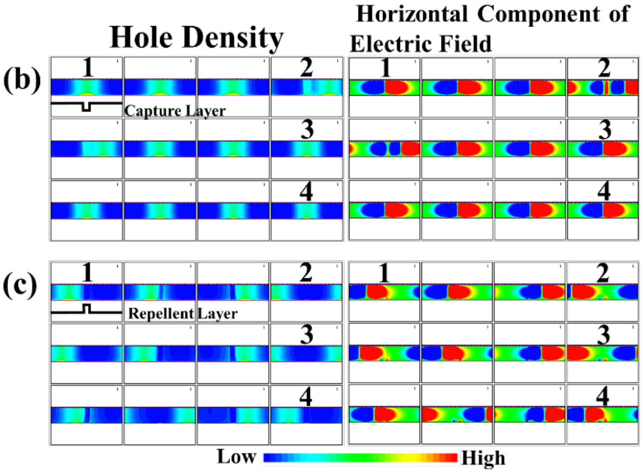

Fig. 6: Distributions of simulation results of structures (b) and (c). The numbers 1 to 4 represent the distributions at the time indicated by each number in Fig. 4. The distributions between those numbers are the distributions at the time between them.

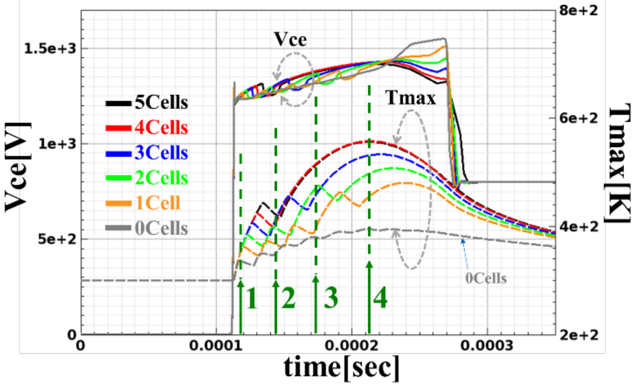

Fig. 7: UIS test simulation results for each structure with different capture layer widths in the structure (d). The results of 0Cells are the same as the result of (a) of Fig. 4. The results of 5 cells are the same as (b) and (d) of Fig. 4.

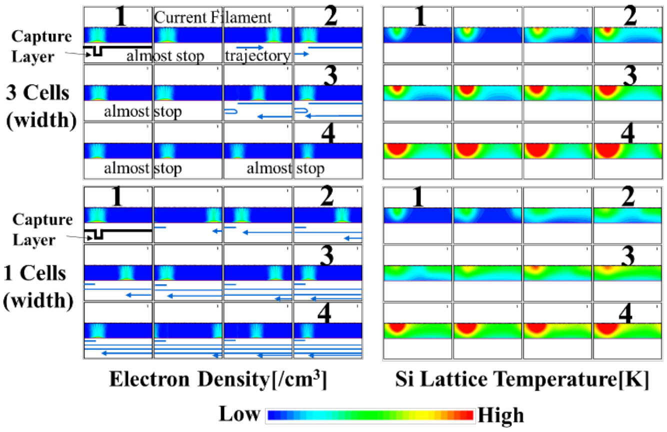

Fig. 8: Distributions of simulation results for structure (d) where the width of the capture layer is 3 cells and 1 cell. The numbers 1 to 4 represent the distributions at the time indicated by each number in Fig. 7. Arrows indicate the movement of the current filament.

operation may not be performed depending on the design of the terminal structure or another structure of the cell region, so we need to carefully and comprehensively design the device.

Fig. 7 shows that the results of the UIS test simulation when the width of the capture layer is reduced in the structure (d). The wider the capture layer, the less jagged the waveform and the more heat generated. This is because the wider the capture layer, the easier it is for the current filament to be captured, and when captured, the local heat generated in the capture region increases. Fig. 8 shows how the physical quantity distributions of the structure in which the width of the capture layer is 3 cells and 1 cell change with time. The numbers 1 to 4 in the figures correspond to each distribution map at the time represented by the numbers 1 to 4 in Fig. 7. It can be seen that the smaller the width of the capture layer, the more the trajectory of the current filament traverses the device.

By making it easier to dissipate heat or making it difficult for parasitic NPNs to turn on in the surface side structure of the capture area, it is possible to create a reliable device that is resistant to destruction as a total design. In other words, effective use of the capture layer and the repellent layer is useful for designing a highly reliable device. However, depending on the structure and usage, it may be necessary to place several capture layers at different widths and depths, and carefully consider where and how to place them.

IV. CONCLUSION

UIS test simulations were performed to clarify how the capture and repellent layers act on the current filament. As a result, it was confirmed that the capture layer traps the current filament and limits the range of movement, and the repellent layer keeps the current filament away from the region. The physical cause of the action of these two layers on the current filaments is that the carriers forming the current filaments are affected by the electric field generated by the different hole injections in these layers and the other cells. The ability to capture or repel current filaments depends on the impurity profile of each layer and the distance between layers placed in the chip. It was also confirmed that the effect of confining the current filament differs depending on the width of the layer. Based on these understandings, it is important to design the reliability of the device.

ACKNOWLEDGEMENT

I am grateful to K. Nakamura for useful discussion. Company names, product names, and service names may be trademarks of their respective companies.

REFERENCES

[1] A. Blicher, “Field-Effect and Bipolar Power Transistaer Physics”, Academic Press, 1981, pp. 186–190.

[2] M. P. Shaw, V. V. Mitin, E. Scholl, H. L. Grubin, “The Physics of Instabilities in Solid State Electron Devices”, Plenum Press, 1992, pp. 1–11.

[3] K. Endo et al., “Direct Photo Emission Motion Observation of Current Filaments in the IGBT under Avalanche Breakdown Condition,” Proc. ISPSD 2016, pp. 367-370.

[4] K. Endo and K. Nakamae, “Temporally- and Spatially-Resolved Observations of Current Filament Dynamics in Insulated Gate Bipolar Transistor Chip During Avalanche Breakdown,” IEEE Transactions on device and materials reliability, Vol. 19, No. 4, Dec. 2019, pp. 723-727.

[5] R. Bhojani, J. Kowalsky, J. Lutz, D. Kendig, R. Baburske, H. J. Schulze and F. J. Niedernostheide, “Observation of Current Filaments in IGBTs with Thermoreflectance Microscopy,” ISPSD 2018, pp. 164-167.

[6] R. Bhojani, M. L. Mysore, Md. R. Raihan, J. Kowalsky, J. Lutz, R. Baburske, H. J. Schulze and F. J. Niedernostheide, “Current filament behavior in IGBTs of different voltage classes investigates by measurements and simulations,” Proc. ISPSD 2020, pp. 466-469

[7] T. Tamaki, Y. Yabuuchi, M. Izumi, N. Yasuhara and K. Nakamura, “Numerical study of destruction phenomena for punch-through IGBTs under unclamped inductive switching,” Microelectronics Reliability, Vol. 64, September 2016, pp. 469-473.

[8] T. Suwa, “Investigation of the relationship between current filament movement and local heat generation in IGBTs by using modified avalanche model of TCAD,” Proc. SISPAD 2020, pp. 141-144.

[9] M. Tanaka and A. Nakagawa, “Simulation studies for short-circuit current crowding of MOSFET-Mode IGBT,” Proc. ISPSD 2014, pp. 119-122.

[10] T. Shoji, M. Ishiko, T. Fukami, T. Ueta and K. Hamada, “Investigations on current filamentation of IGBTs under unclamped Inductive switching conditions,” ISPSD 2005, pp. 227-230.

[11] M. Tanaka and A. Nakagawa, “Growth of short-circuit current filament in MOSFET-Mode IGBTs,” Proc. ISPSD 2016, pp. 319-322