IGBT Avalanche Current Filamentaion Ratio: Precise Simulations on Mesh and Structure Effect

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***Abstract*—Current filamentaion effect with dynamic avalanche during turn-off transient in IGBT has been discussed for years. In the prior papers, the possibility of device failure has been reported based on TCAD simulation and simulation results have shown that variety of filamentation phenomena exist for conditions assumed in each simulation. It is discussed in this paper, for the first time, that the relationship of filamentation current concentration strength to device design parameters and categorizes filamentation phenomena, introducing current filamentation ratio (CFR). In the paper, guidelines for appropriate mesh pattern selection are also described to ensure the validity of simulation results.**

Keywords—IGBT; dynamic avalanche; current filamentation; mesh;

I. INTRODUCTION

The current filamentation effects during turn-off of Insulated Gate Bipolar Transistor (IGBT) has been have been discussed for years. Specially, avalanche induced current filamentation has become critical as the possible turn-off failure mechanism under high current density operation of IGBTs. The filamentation mechanism has been explained based on classical negative differential resistance and so called micro-plasmas effect [1, 2, 3, 4 etc.]. Multi cell simulations unveil moving current filamentations according to temperature dependence of impact ionization rate and gate resistance inhomogeneity [5, 6, 7, 8]. Large scale multi cell simulations show formation of periodical filaments across chip area [7, 9, 10]. The phenomena have strong device structure dependence on cell pattern, P-emitter and N-base structure of the device [11, 12]. Decrease of critical latch up current density under filamentation was discussed in papers [7] and it is reported that isothermal simulation shows similar results to electro-thermally coupled simulation and the paper also show the guideline of number of cells for simulations.

The avalanche induced current filamentation will be critical to device SOA design for future high current density IGBTs. This paper categorizes the device design parameters of vertical structure, cell structure and doping inhomogeneity among cells for current filamentation control. Based on the TCAD simulation, SOA design guideline is described based on multi-cell simulation results. We introduced current filamentation ratio (CFR) as an index of SOA derating.

II. APPROACH TO INVESTIGATE STRUCTURE DEPENDENCY OF CURRENT FILAMENTATION

A. Selection of appropriate mesh pattern

In some of previously reported simulations, current filamentation appears even under perfectly homogeneous device structure which might show difficulty to distinguish device physics and instability due to numerical discretization (mesh patterms). To eliminate the numerical discretization effect, mesh patterns for simulations must be carefully selected so that homogeneous current distribution is confirmed for homogeneous device structures. Fig. 1 compares the influence of mesh patterns to simulation results for homogeneous device structure. The avalanche current simulations were performed for two types of triangular mesh patterns and a rectangular mesh pattern.

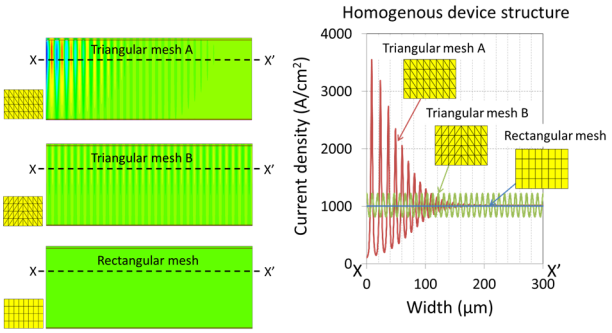

Fig. 1 Avalanche current simulation result for two types of triangular mesh patterns and a rectangular mesh pattern for laterally homogeneous device structure. Only rectangular mesh reproduces the homogeneity of the current distribution.

Although the device structure is homogeneous along horizontal direction, the avalanche current simulation results with both types of triangular mesh A and B show current imbalance. While the result with the rectangular mesh reproduces the homogeneity of the current distribution. Since the homogeneous structure mathematically leads homogeneous current density, the rectangular mesh was selected as the appropriate discretization method for avalanche induced current filamentation simulation.

B. Simulation Approach

The Avalanche induced current filamentation phenomena are considered to occur during high current turn-off transient. For this investigation, however, static simulation approach is chosen. It is because that index for current crowding into cells, which will be introduced in the next section, must be clearly defined to investigate risk for device failure for structures and for current density. Furthermore, static approach has advantages in simulation time and simplicity of simulation procedure.

For the static simulations, a current source is connected to collector electrode so as to simulate the effect of induced current by inductances in switching circuit, since the induced current during turn-off is the origin of dynamic avalanche inside the device.

Isothermal condition is automatically chosen for the static simulation and the previously reported paper[7] shows that isothermal simulations show sufficient agreement with electro-thermal simulation in current crowding induced by dynamic avalanche.

Device structure used in simulations is a PNP structure with N-buffer layer, which is identical to IGBT P-base, N-base with N-buffer and P-emitter structure.

III. Influence of Lateral Interaction between Cells in IGBT Chip during Current Filamentation

A. Classical model of negative differential resistance

Current filamentation induced by dynamic avalanche has been classically explained as the effect of the negative differential resistance (NDR), which is modeled as follows. Avalanche injection near both ends of N-base (i-layer) forming plasma in center portion of N-base by the injected holes and electrons [1, 2]. Higher conduction current causes more plasma expansion by injected carriers and high charge density near both ends of N-base. This effect leads decrease of voltage across the device.

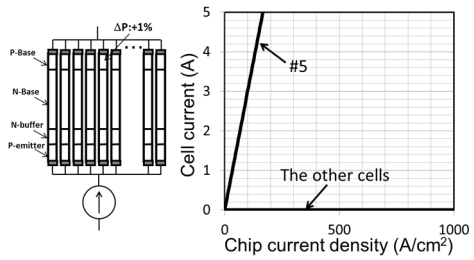

Fig. 2 Circuit level paralleled device simulation for avalanche induced current filamentation. 18 devices with P-base, N-base, N-buffer and P-emitter are paralleled by circuit. Total current concentrates into a single cell.

Circuit level paralleled device simulation shown in Fig .2 supports the classical theory. In the simulation single cell devices with P-base, N-base, N-buffer, P-emitter are connected in parallel and one device has small inhomogeneity to trigger the imbalance. Total current is concentrated into a single chip with NDR effect.

B. Existence of lateral interaction between cells inside chip

Current filamentaion simulation was performed with 2-dimensional structure with 18 cells with P-base, N-base, N-buffer and P-emitter (Fig. 3). The fifth cell has 1% deeper P-base to trigger imbalance. Comparing with circuit-device coupled simulation with 18 paralleled devices shown in Fig. 2, Current never concentrate into single cell and because of lateral interaction between cells, half of cells maintain the conduction. Current filamentation typically occur with three phases. Low current region (<50A/cm^2) with drift current charge comparable to doping charge in N-base, the currents are balanced among cells even the structure has NDR characteristics. The lateral interaction contributes to current balance.

First filamentation occurs when the drift current charge exceeds the certain level current density (>50A/cm^2). However, half of cells (9 cells) maintain conduction and the current concentration ratio to average current is only 2 in this case. The filamentation phenomena with IGBT structure are completely different with PiN diode case.

At second filamentation phenomena under higher current density (>200A/cm^2), imbalance enhanced among conduction cells (4 cells up, 4cells down among 9 cells) due to electric field pile-up in collector side of current concentrated cells [4]. Then, the current concentration ratio increases up to 3.8. While number of conduction cell doesn't change through 1st and 2nd filamentation.

Re-balancing of the current occurs for very high current density of over 600A/cm^2. The electric field pile-up at collector side occurs for all of the cells and current concentration rate decreased to 2.

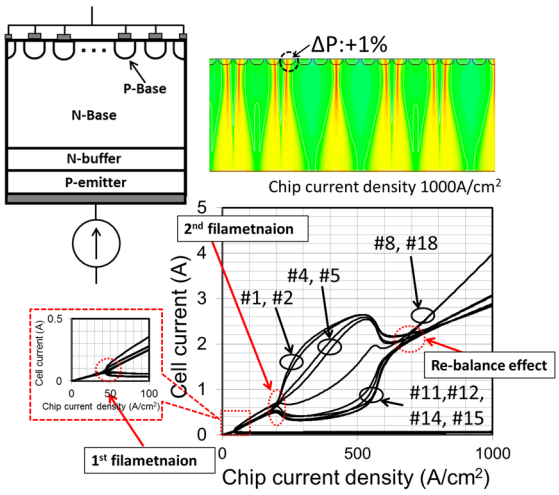

Fig. 3 Current filamentaion with 2-dimensional structure with 18 cells with P-base, N-base, N-buffer and P-emitter. Cell #5 has 1% deeper P-base to trigger imbalance. Because of lateral interaction, half of cells maintain the conduction.

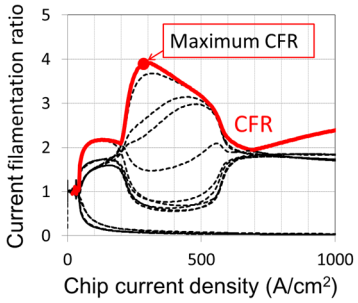

Fig. 4 Current filamentation ratio definition. CFR is defined as the ratio of most concentrated cell current to average of cell current.

IV. AVALANCHE INDUCED CURRENT FIRAMENTATION RATIO SIMULATION FOR IGBT

In this section, simulation results for more than 40 device structures will be shown regarding to SOA redundancy. To simplify the discussion, we introduce current filamentation ratio (CFR) defined as ratio of the most concentrated cell current to average cell current. Figure 4 shows CFR curve example as a function of chip current density, corresponding to the result shown in Fig. 3. Fig. 5 summarized maximum CFR for various structures.

A. Guidelines for the simulations

Prior to device structure dependence analysis, we confirm the condition of simulations. The number of cell for the simulations is 18 based on the discussion in prior paper [7] and as shown in Fig. 5-A, we confirmed that the maximum CFR are identical for different number of cells of 9 cells in 150µm width device, 18 cells in 300µm, 36 cells in 450µm. For triggering current imbalance, 1% deeper P-base is introduced. The position of the deeper cell doesn't affect to the maximum CFR. Based on the simulation above, we use 18-cell structure with 1% deeper P-base located at #5 position from the left side of the device.

B. Injection efficiency (P-emitter and N-buffer impurity)

Low injection efficiency back side structure (low P-emitter dose and/or high N-buffer dose) leads high CFR, i.e. high derating ratio is required for chip current against latch-up (Fig. 5-B). This result supports the transient simulation result reported in [11].

C. N-base doping concentration

CFR decreases with N-base doping concentration over $1x10^{14}/cm^3$. This result also supports the result reported in [11], thanks to the non-punch-through structure. Lower concentration region, however, CFR increases with the concentration and it seems to have a peak at $1x10^{14}/cm^3$ as shown in Fig. 5-C.

D. Cell structure

From the simulation results in Fig. 5-D, cell design with high electric field peak induce high maximum CFR, which support transient simulation result reported in [12].

E. Doping inhomogeneity among cells

Stronger inhomogeneity of P-base causes higher maximum CFR as shown in Fig. 5-E, so that cell uniformity and electric field relaxation design near the edge of cell pattern are required for higher latch-up current.

V. CONCLUSIONS

Multi-cell TCAD simulations for avalanche assisted current filamentation have performed under static condition. Rectangular mesh pattern is used for accurate simulation. Emitter-side cell homogeneity, electric field uniformity near P-base and injection efficiency of collector side structure has dependency to current filamentation. Thanks to lateral interaction inside chip, the current filamentation ratio can be controllable less than 5 by device design, i.e. SOA derating against latch-up during the current filamentation is factor of 5.

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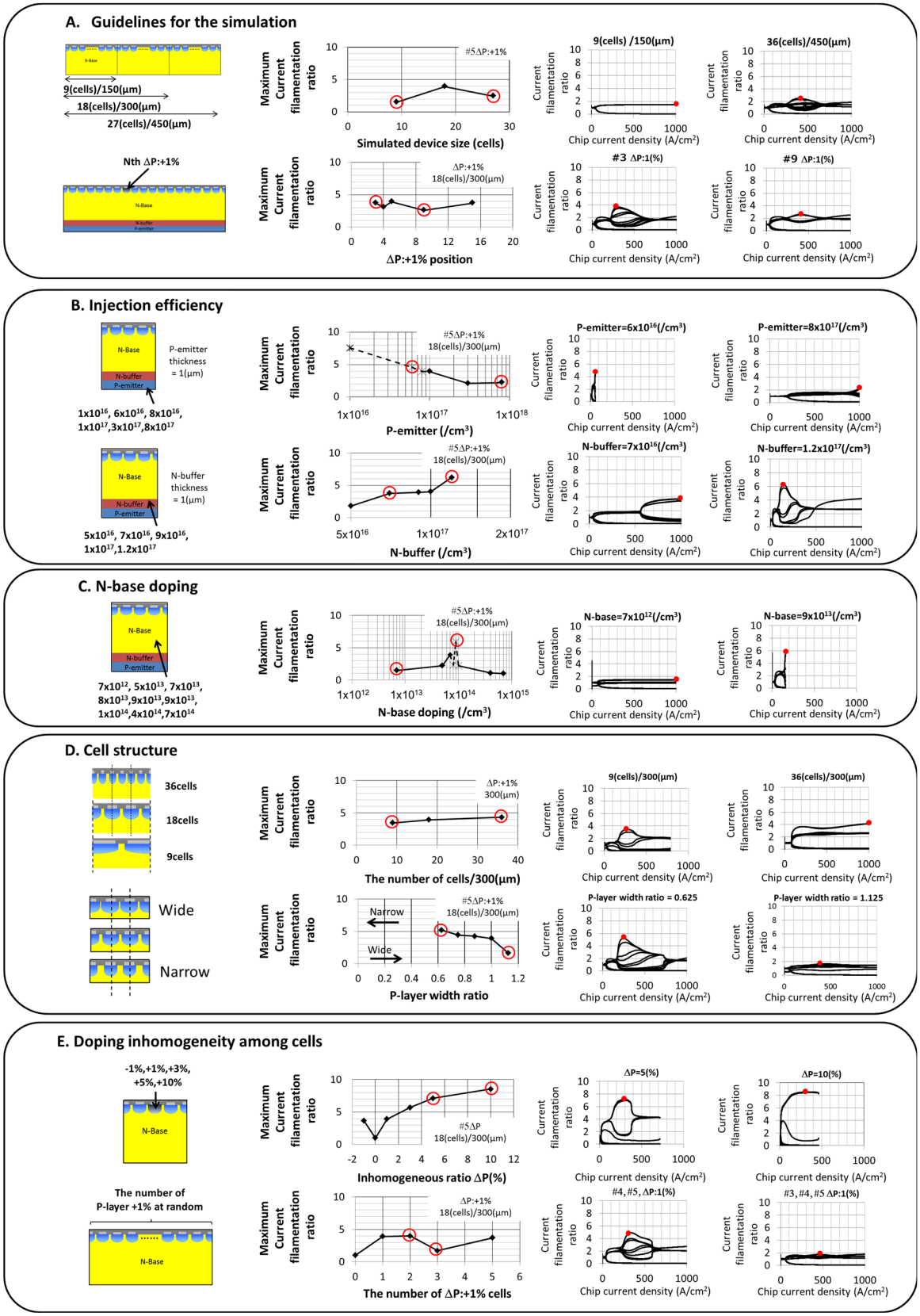

Fig. 5 Maximum current filamentation ratio (CFR) for various device structures. High CFR requires latch-up derating for IGBT cell design.