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Impact of 3-D Simulation on the Analysis of Unclamped Inductive Switching

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Abstract

The detailed failure mechanism of UIS(Unclamped Inductive Switching) was analyzed, for the first time, by large scale 3D TCAD simulations. We also propose, for the first time, that there are two kinds of current filaments. These are avalanche (impact ionization) induced current filament and heat (high temperature) induced current filament. First, avalanche induced current filament developed and moved around. It finally caused huge temperature increase in the P-base inside the filament. This triggered a destructive heat induced current filament, which stayed in the same location and caused device failure. It was found that these phenomena were accurately treated only by large scale 3D simulation of at least 160um x 160um device area.

1. Introduction

Unclamped Inductive Switching(UIS) is one of the important topics of modern IGBTs. It was experimentally observed[1-3] that the current filaments are formed and they move around inside the IGBT chip during UIS. The filament dynamics have been discussed, thus far, by using 2D TCAD simulations[4-6]. It was suggested that the filament leads device destruction. However, because of the limitation of these modeling capabilities, detailed failure mechanism has not been discussed yet.

In this paper, we show the detailed failure mechanism of UIS by large scale 3D TCAD simulations. We report, for the first time, that there are two kinds of current filaments. These are avalanche (impact ionization) induced current filament and heat (high temperature) induced current filament. First, avalanche induced current filaments were formed and sustained by localized large impact ionizations under the trench gates. They moved around inside the chip and finally caused huge temperature increase in the P-base inside the filament because of large electron injection from the N$^+$ emitter(latch-up). This triggered a destructive heat induced current filament, which stayed in the same location, because the P-base had already become intrinsic semiconductor, keeping current flowing and continuing local temperature rising. This finally caused thermal runaway and device failure.

2. Simulation setup

Large scale 3D TCAD simulations of completely uniform multi-cell IGBT(Fig. 1) have been performed, taking into account self-heating. The 3D 8-cell IGBT structure is created by repeatedly copying a half-cell IGBT structure for lateral and depth directions. The footprint of the simulated structure is 160um x 160um. The IGBT is 1.2kV rated and the N-Base thickness is 120um. The turn-off current, applied voltage and the ambient temperature are set at 400A/cm^2, 800V and 400K, respectively. The load inductance, L, has been varied to change the sustaining period.

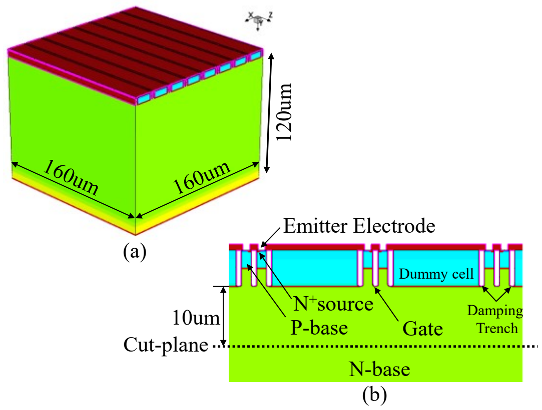

Fig. 1 Simulation structure. The cut-plane will be used in Fig. 3.

3. Results and Discussion

It is shown in Fig. 2 that the IGBT fails to turn-off 400A of current when L=7uH, whereas it succeeds when L=6uH. In the case of L=7uH, the electron current starts to be injected directly into the P-base from the N$^+$ emitter at t=1.2us because of the avalanche induced current filament. This causes local rapid temperature increase, as described later. On the other hand, large current filaments do not grow in the case of L=6uH. Thus, the device safely turns off.

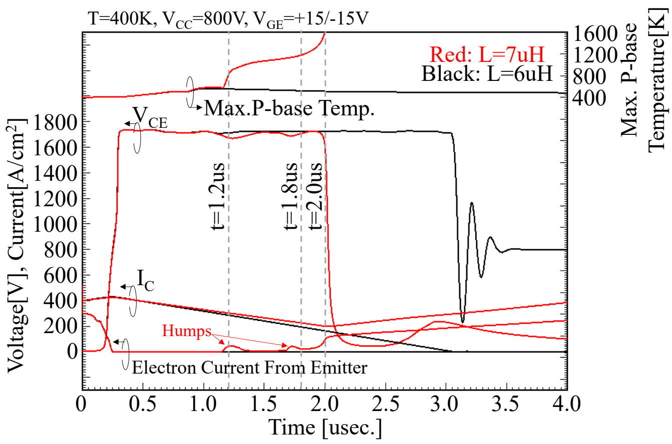

Fig. 2 Calculated UIS waveforms.

It is observed in the case of L=7uH that rather broad avalanche induced current filaments appear from the beginning of the sustaining period. Then, at t=1.2us, the broad current filaments eventually turn into a single narrow avalanche induced current filament as shown in Fig. 3(a). The latch-up occurs inside the current filament, because the hole current density becomes very high and the lattice temperature exceeds 700K in the P-base of the filament. The latch-up can be observed in the first hump of the emitter electron current, which is indicated by an arrow in the Fig. 2. Then, the avalanche induced current filament is divided into the two current filaments of the avalanche induced current filament and the heat induced current filament. This phenomenon is described, later, in detail. The avalanche induced filament moves to the other lower temperature region, as indicated in Fig. 3(b). This is because the avalanche breakdown voltage in the original filament position increases due to the higher lattice temperature. The avalanche induced current filament further moves to another corner of the device and grows larger there, as shown in Fig. 3(c). It causes another latch-up at t=1.8us, which is shown by the second hump of the emitter electron current in Fig. 2.

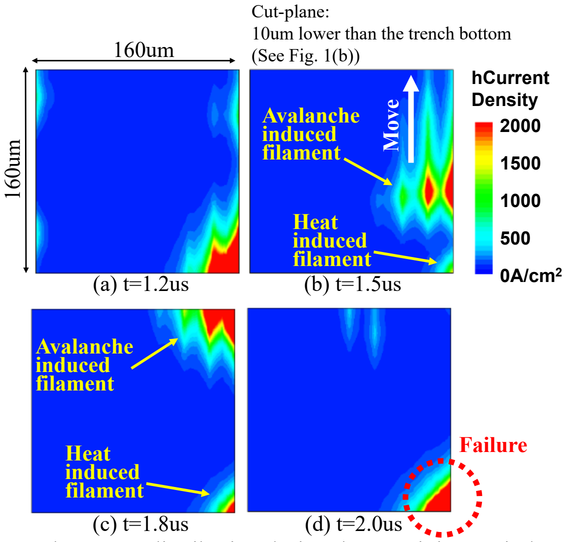

Fig. 3 Hole current distribution during the sustaining period.

When the temperature of the P-base becomes very high inside the avalanche induced current filament, a heat induced current filament is activated inside the avalanche induced filament. Once the heat induced filament is created, it continues to stay and grow in the same position, although the avalanche induced filament moves to the other lower temperature point, as stated before. The electron current injection directly into the P-base keeps continuing inside the heat induced current filament after 1.2us because the P-base becomes already intrinsic and the temperature still keeps increasing. The heat induced filament eventually causes UIS failure at t=2.0us as shown in Fig. 3(d). The device no more sustains the breakdown voltage because the lattice temperature exceeds 1600K at t=2.0us as shown in Fig. 2.

It should be noted that when the size of the simulated device is smaller than 80um x 80um, the observed current filament does not grow sufficiently. The simulated UIS failure energy of the smaller devices, shown in Fig. 4, become very large, which does not agree with the observed value in the datasheet[7]. This is because the huge local temperature increase does not occur by the immature current filaments. The device temperature increases almost uniformly in the entire device. The calculated breakdown voltage, V_{CE}, keeps increasing, as seen in black line of Fig. 5. This does not agree with the experimental results, either.

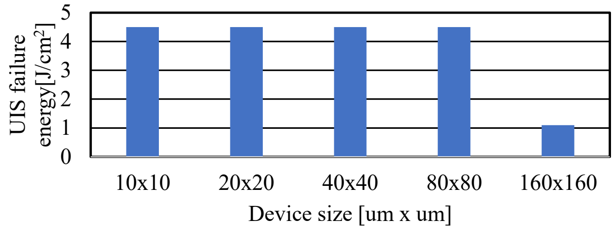

Fig. 4 UIS failure energy vs. size of simulated device.

It is shown in Fig. 5 that in the 3D simulation of 160um x 160um large sized device, the calculated voltage waveform, V_{CE}, becomes almost flat throughout the UIS, which agree with previously reported experimental results[1]. It was found that sufficiently large size of the simulated device is required to execute accurate UIS simulation.

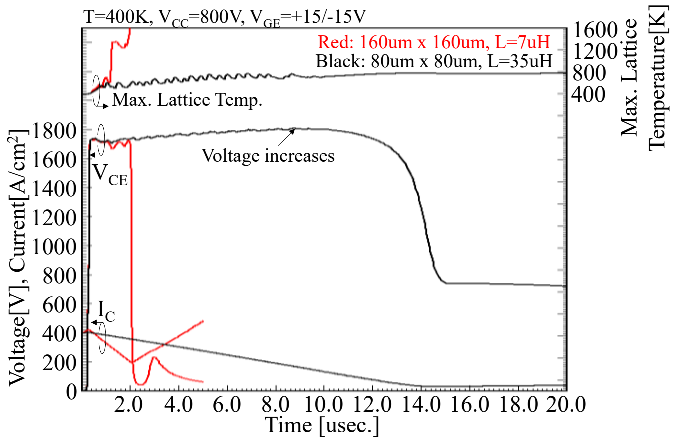

Fig. 5 UIS failure waveforms for 80um x 80um and 160um x 160um device sizes.

4. Conclusion

The detailed failure mechanism of UIS was analyzed by large scale 3D TCAD simulations, for the first time. We found that the UIS failure is caused by local temperature increase due to the heat induced current filament.

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