Improvement of Clamped Inductive Turn-Off Ruggedness of Trench IGBT at Overcurrent Condition with Optimized Split Gate Structure

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Abstract

In this paper, the clamped inductive turn-off ruggedness of a novel Trench Insulated Gate Bipolar Transistor (TIGBT) at overcurrent condition is studied by numerical simulation. This proposed structure is optimized by using split gate structure to improve the turn-off reliability. Simulation result shows that the maximum turn-off critical current of the proposed TIGBT increases for about 42.8% compared with the conventional TIGBT structure. The main reason is that the electric field of the proposed structure is redistributed by RESURF effect at the trench bottomed area, resulting to attenuate the current filament at local area. In addition, the hole which concentrated at the trench bottom area is less because the bottom part of split gate polysilicon is shorted with the emitter. Therefore, the local dynamic avalanche effect which triggered by the excessive carriers concentration and high peak electric filed accumulation is weakened. The turn-off ruggedness of the proposed structure is enhanced effectively and the electrical parameters are not compromised but even better compared with conventional structure.

Keywords: Trench Insulated Gate Bipolar Transistor (TIGBT), dynamic avalanche, split gate, turn-off ruggedness.

1. INTRODUCTION

The Trench Insulated Gate Bipolar Transistor (TIGBT) is widely used in power electronic area due to a great trade-off performance between the on-state saturation voltage and switching losses. Typically, the TIGBT is used as the power switch application under the clamped inductive condition. It is inevitable to work at the harsh circumstances with high current and voltage simultaneously and the safe turn-off ability is important for the long-time working requirement. During the overcurrent turn-off process, the peak electric field is accumulated at the local small area and the current filament is formed easily after the electron current form the MOS channel disappeared and then the dynamic avalanche phenomenon is triggered at the trench area [1]. This dynamic avalanche behavior is related to the excessive holes which cumulated at the trench bottom area, leading to the large local peak electric filed. In order to suppress this behavior, some optimizing strategies are investigated, such as using the large gate resistance, changing the cell pitch size or using negative gate drive voltage at the turn-off process [2-4]. However, these methods will sacrifice other electric parameters to a certain extent or increase the fabrication cost due to an additional gate drive design.

In this paper, an optimized TIGBT with split gate structure to enhance the turn-off reliability is proposed by numerical simulation. As we known, the split gate structure is originally from the low voltage power MOSFET design skill to reduce the gate-drain charge [5]. Moreover, it also brings an improved RESURF effect on the breakdown ability by local electric filed optimization [6]. We use these structure advantages to enhance the turn-off reliability under clamped inductive condition. In order to analysis the performance of the proposed structure, the turn-off behavior is compared with the conventional TIGBT structure by investigating the inner electric field distribution and carrier movement.

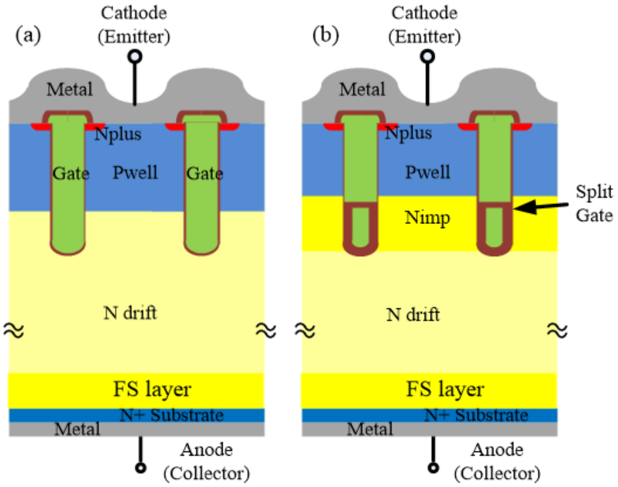

Fig. 1. Cross-sectional view (not to scale) of (a) the conventional structure and (b) the proposed structure.

2. DEVICE STRUCTURE AND SIMULATION SETUP

Fig. 1 shows the structure of the conventional TIGBT and the proposed TIGBT. Both of structures are designed with the 120μm wafer thickness, low concentration Ndrift region and high implant dose FS layer to achieve 1.2kV targeted breakdown voltage. The cell pitch and trench depth are 4μm and 5 μm, respectively. Furthermore, two structures are designed with the same doping profile and structure size parameter except the trench gate area. As can be seen from the Fig. 1(b), the gate polysilicon is split into top and bottom parts. The bottom gate polysilicon is enclosed by thick oxide layer and connect with the emitter through the cell periphery contact. In order to balance the electric field of the trench bottom area, the N enhanced layer with higher doping concentration, namely Nimp, is used at the local split gate area. And it also increases the conduction modulation effect as the hole blocking layer. The simulations are performed by Synopsis Sentaurus Technology Computer Aided Design (TCAD) software. Basic semiconductor models are included to analyze the device's physical behavior in simulation. The generation and recombination models include the Shockley-Read-Hall (SRH) recombination, auger recombination and avalanche generation by Van Overstraeten model. The mobility models include the high-field saturation, carrier-carrier scattering and mobility degradation by normal electric field (Enormal) model. In order to save the simulation time, we select the single cell pitch 4μm and the 1 mm^2 die area factor in the simulation.

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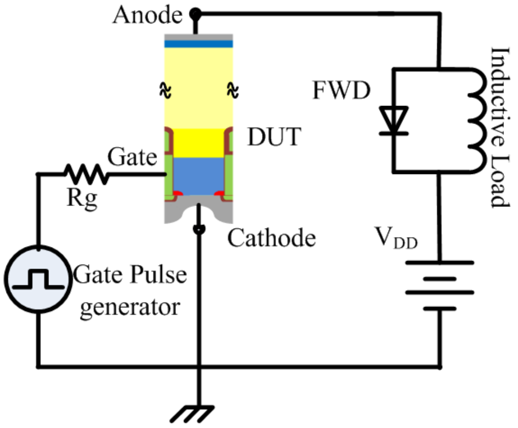

Fig. 2. Circuit used in mixed-mode transient TCAD simulations for investigating the turn-off behavior of TIGBT at clamped inductive condition.

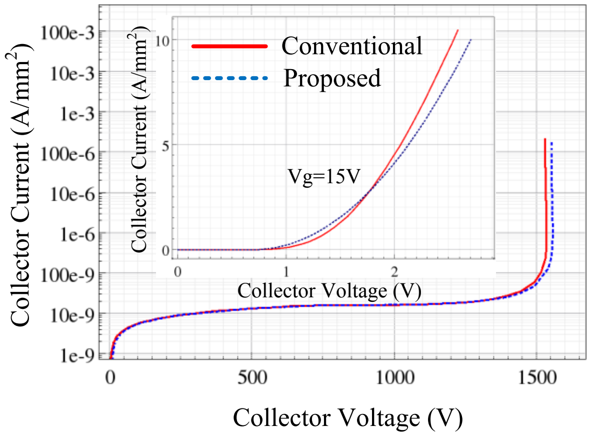

Fig. 3. Simulation results of the breakdown voltage and I-V characteristic. The curve of I-V characteristic is set at V_g=15V.

Fig. 2 shows the simulated circuit setup of the device with clamped inductance by freewheeling diode (FWD). During the turn-off process, the bias voltage was fixed at the rated voltage 1.2kV and several times current over the rated current was set to flow in the device. Here the gate pulse generator is used to control the on-off state and the current value which flowed through the device and the inductance. Once the current reached to the critical current, the device can't turn off normally. We capture the critical conditions to compare the different performance of two structure devices. Through this procedure, the device turn-off ruggedness at the clamped inductance and overcurrent condition is evaluated.

3. RESULTS AND DISCUSSIONS

Before analyzing the clamped inductive turn-off ability of the proposed structure, the basic electric parameter is compared with the conventional TIGBT. Fig. 3 shows the curve of the breakdown voltage and I-V characteristic for each structure. It can be seen that the breakdown voltage are all over 1.5kV and the proposed structure is much higher due to the local RESURF effect. From The I-V characteristic comparison of the conventional structure and the proposed structure, it can be captured that the saturation voltage at Vge=15V with current density 200A/cm^2 are 1.63V and 1.60V, respectively. Therefore, the basic electric parameters of the proposed structure are better through this gate structure adjustment.

Then, the turn-off ability of two structures is compared by using the circuit setup based on the Fig. 2. As we mentioned before, the bias voltage is fixed at 1.2kV and the gate pulse width is set to increase gradually until the device out of control. Once the current reaches to the critical value, it can be seen in Fig. 4 that the collector current cannot down to zero although the gate voltage already disappeared. Here we capture the maximum critical current of two structures. From the results, the maximum peak current density for the conventional TIGBT and the proposed TIGBT are 72.5A/mm^2 and 103.6A/mm^2, respectively. It indicates that the maximum critical current which the device can turn off safely for the proposed structure increases for about 42.8% compared with the conventional structure. That is to say, the proposed structure achieves great turn-off reliability and better basic electric parameters compared with the conventional structure.

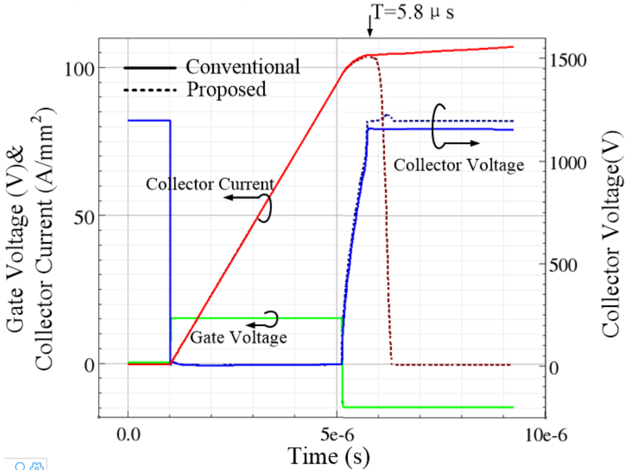

Fig. 4. Turn-off waveform at the same bias condition: (a) the conventional TIGBT (solid line) and (b) the proposed TIGBT (dotted line).

In order to analyze the inner difference of electric field distribution and carrier profile at the turn-off process, we capture the turn-off waveform of the device with the same bias condition. Fig. 4 shows the comparison waveform of two structures with the same gate voltage pulse width. It can be seen that there is a turning point at the time 5.8μs, where the current and voltage reached to the maximum value for each structure. After this time point, the collector current of the proposed structure (dark red dotted line) drops to zero instantly and that means the device turns off safely. However, the collector current of conventional TIGBT (red solid line) still exists and flows continually although the gate voltage already disappeared. It indicates that the conventional TIGBT cannot turn off by gate control at this current density. At this time point, the electric current disappears because the gate voltage is turned off and the huge holes accumulate at the bottom of trench area. If the peak electric field at the local area is too high, the electric-hole pairs will generate by local micro dynamic avalanche effect continually [2].

Then, the inner physical behavior of the device is analyzed at this time point. Fig. 5 shows the 3D electric field profile of two structures at time 5.8μs. It can be seen in Fig. 5(a) that the peak electric field of the conventional structure accumulates at

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the trench bottom corner area. According to the enlarged electric filed profile (right side in Fig. 5), the peak electric field locates near the corner of trench bottom and the maximum peak value is about 5×10^5V/cm. However, for the proposed structure in Fig. 5(b), the electric field distributes along the split gate area with two peak locations, which can be seen in the enlarged electric field profile. This phenomenon is related to the local RESURF effect and the maximum peak electric field is only 4×10^5V/cm. Obviously, the peak electric field of the proposed structure is lower compared with the conventional structure at the same overcurrent and voltage bias condition. Thus, it helps to attenuate the local dynamic avalanche effect which related to the local electric field accumulation and carrier generation.

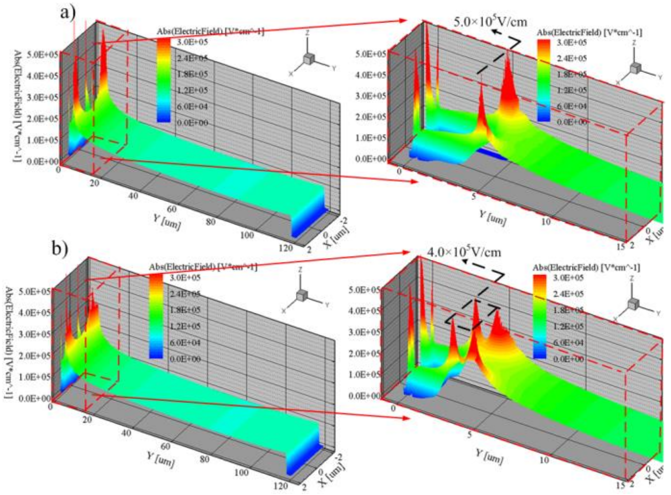

Fig. 5. TCAD simulated 3D electric field profiles during the turn off situation: (a) the conventional TIGBT and (b) the proposed TIGBT.

During the turn-off process, the hole in plasma area is pushed to the cathode by the electric field stress. Due to the negative gate voltage, some holes accumulate easily at the trench bottom area and the local electric field is intensified continuously by this influence [7-8]. Fig. 6 shows the 2D hole density profile at the time 5.8μs and the compared distribution of the hole density by lateral cutline beneath the trench bottom 0.05μm. The cutline on the conventional structure and the proposed structure are the A-A' (red solid line) and the B-B' (blue dotted line), respectively. It can be seen in Fig. 6. that the hole density of conventional structure is much higher at the trench bottom area. But for the proposed structure, lots of holes accumulate at the center of the two adjacent split gate areas due to the gate at bottomed area is shorted with emitter contact. That means that holes which concentrated at the bottom are less for the proposed structure.

By analyzing the turn-off behavior of the proposed TIGBT with clamped inductance at overcurrent bias conditions, the physical failure mechanism can be concluded as following reasons. Firstly, it can be known that the peak electric field profile of proposed structure is smaller and smother by RESURF effect at trench bottom area compared with the conventional structure. For the proposed structure, the electric field doesn't concentrate at the trench bottom area but distribute more smoothly. On the contrary, the electric field in the conventional structure is easy to accumulate at the corner of bottom because of the cylindrical structure. Thus, the conventional structure induces higher peak electric field at local area and the dynamic avalanche behavior is much severe inevitability. The electron-hole pairs which generated by the high electric field continue increasing and the latch-up is triggered easily.

Secondly, the hole is not easy to accumulate at the trench bottom area for the proposed structure. During the turn-off process, the excessive holes are pushed by the electric field to the cathode side. The bottom part polysilicon of the split gate connects with the emitter contact (ground) instead of the negative gate voltage which appealed the hole at turn-off condition. As we already known, latch up is the destruction effect in the IGBT [9]. If the fewer holes are concentrated at the trench bottom, the less chance is to trigger the latch up behavior. Otherwise, the electric filed increase with the holes concentrating continuously. This feedback behavior causes the intensifying of local peak electric field and increasing of the local current density, which can cause the device burnout at local area finally.

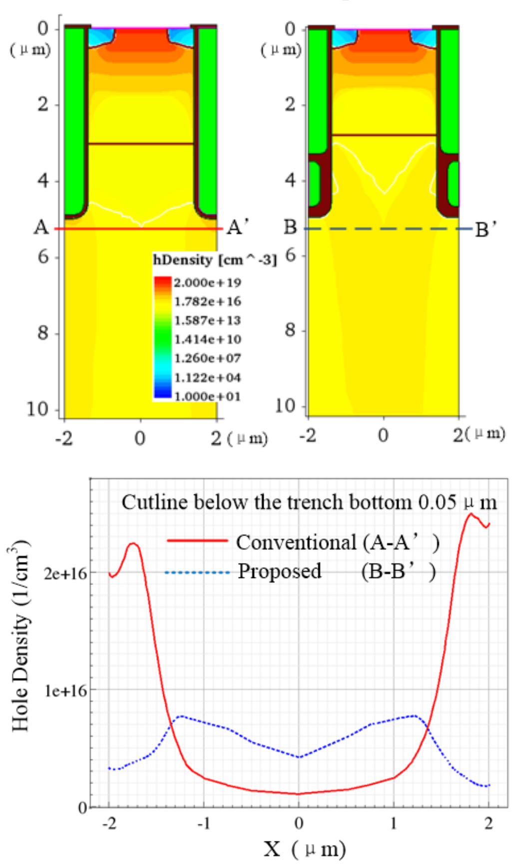

Fig. 6. Simulated 2D hole density distribution at the time 5.8μs and the comparison of hole density by lateral cutline. (a) the conventional TIGBT and (b) the proposed TIGBT.

Conclusions

The clamped inductive turn-off reliability of the optimized TIGBT with split gate structure is compared with the conventional TIGBT by TCAD simulation. From the simulation results, the maximum turn-off critical current of the proposed structure increases for about 42.8% and the basic parameters becomes better simultaneously. The inner electric field distribution and current density profile are analyzed at

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the same overcurrent condition. The electric field distribution of the proposed structure is smaller and smoother at the trench bottom area by RESURF effect. It helps to attenuate the peak electric field stress and the dynamic avalanche behavior. Furthermore, the hole which concentrated at trench bottom is less because the split gate polysilicon is shorted with emitter contact (ground). Therefore, it indicates that this proposed structure shows a great performance in turn-off ruggedness without compromising other parameters. Through these structure advantages, the proposed structure displays a great potential in the clamped inductive application.

Acknowledgments

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