Research on junction termination of 6500V IGBT

Mingchao Gao, Rui Jin, Yaohua Wang, Lili, Jiang Liu, Cui Li, Wanru Sun, Ruifen Nie, Junmin Wu
State Key Laboratory of Advanced Power Transmission Technology Global Energy Interconnection Research Institute Co., Ltd. Beijing, China

gaomingchao@geiri.sgcc.com.cn

Abstract. In this paper, a novel junction termination design for 6500V IGBT is proposed. A floating P+ rings termination where the P+ rings are highly doped is less than 2500um. The termination is immune to interface charges at the Si/SiO2 interface and other layers at the top as well as in the moulding compound. The simulation results show that the breakdown voltages are all above 7000V when the interface charges change from -3E11cm-2 to 5E11cm-2. This device was fabricated and the test results show that the breakdown voltage is more than 7000V, which is agreement with the simulation results.

1. Introduction
Insulated Gate Bipolar Transistor (IGBT) is a kind of power device which has the MOS input and the bipolar output, so it has the advantages of both bipolar and unipolar components. It is widely used in the smart grid, locomotive traction, electric vehicle, variable-frequency speed control system, etc. owing to its excellent performance [1-5]. IGBT chip is composed of cell and junction termination. The junction termination is used to efficiently spread the potential at the edge of the chip and prevent premature breakdown. With the increase of the breakdown voltage, the junction termination size of IGBT increases and the area of the active region decreases accordingly when the chip area is fixed, so the flow capacity decreases. This is also the reason why the rated current of high voltage IGBT is not high. Therefore, in the design of high voltage IGBT, it is necessary to minimize the junction termination size and improve the efficiency of the junction termination.

2. Device structure and simulation
The junction termination structure of 6500V IGBT is shown in Fig.1. It is composed of floating P+ rings. The P+ rings were highly doped (>1E18cm3) and they are spaced with increasing gaps from left to right. The P+ rings opening were fixed. The whole junction termination is 2500um.
2.1. Interface charge (Qit) simulation

Interface charges (including positive charges and negative charges) are introduced in the process of chip manufacturing and packaging. The positive charges mainly refer to Na⁺ ions, K⁺ ions, H⁺ ions and so on residual in the chip processing process. Negative charges usually come from OH⁻ ions if there is moisture in the moulding compound or at the surface of the die before encapsulation. The junction termination structure needs to be immune to interface charge at the Si/SiO₂ interface and other layers at the top as well as in the moulding compound.

Fig. 2 shows the breakdown voltage simulations with different interface charge levels. Since P⁺ rings were highly doped, interface charges cannot deplete the P⁺ rings much. Proposed termination design can support high breakdown with a wide charge levels from negative 3E11cm⁻² to positive 5E11cm⁻², which means the device having a better stability.

Figure 1. The junction termination structure of 6500V IGBT.

Figure 2. Breakdown voltage at different interface charge levels.

Figure 3. Internal characteristics of 6500V at different interface charge levels.
Fig. 3 shows the impact ionization and equipotential lines of 6.5kV at different interface charge levels. From Fig.3 we can see that high positive charge crowds the potential towards active area, High negative charge crowds the potential towards the channel stopper region.

2.2. Oxide electric field simulation
High electric field in the oxide can be a concern in high voltage devices. In this design, Oxide electric field is below 3E5V/cm at 7000V with the max interface charge of 5E11cm⁻² and this is below the critical electric field of the oxide (typically about 5E6V/cm), which can be seen from Fig.4.

![Electric field of oxide layer of 7000V at different interface charge levels.](image)

2.3. P+ ring doping variation simulation
In the manufacturing process, the maximum deviation of injection dose can reach 10%, and the termination structure needs to meet the breakdown voltage requirements within the deviation range. In the simulation, we enlarge the P+ ring injection dose deviation to 20%. Fig. 5 shows when the P+ ring injection dose is increased or decreased by 20%, the breakdown voltage almost has no differences. The breakdown voltage is more than 7000V at different interface charge levels when the doping varied.

![Breakdown voltage of varied P+ ring doping at different interface charge levels.](image)

2.4. Rectangular and circular simulation
All previous simulations were on rectangular co-ordinate system and here we investigate both rectangular and circular co-ordinate systems. Circular design will represent the die corners. Simulations were run with four different widths of grounded P+ region next to the active area, L in Fig.6 represents the width of grounded P+ region, it is set as 50um, 150um, 350um and 550um. The extended P+ may represent gate busbar region between the active area and the termination area. Wide
P+ structure in the circular co-ordinate system will be equivalent to a corner design with a very large curvature.

Fig.6. The junction termination with different widths of grounded P+ region.

Fig.7 shows that width of the P+ region doesn’t make much difference in the breakdown voltage when rectangular coordinate system is used for simulations. This is as expected as the potential spreading is already optimum for 50um width and further increase does not bring benefits in breakdown voltage. However, in the circular simulations, wider P+ (larger curvature of the corner) grounded P+ region helps to increase the breakdown voltage of this area to the same level as seen in the rectangular design. This result indicates that the device corners need to be designed with larger radius to prevent premature breakdown.

(a)                                                                                       (b)

Figure 7. Breakdown voltage simulation with different widths of grounded P+ region in rectangular and circular co-ordinate systems. (a)Qit=5E10cm⁻² (b) Qit=5E11cm⁻².

3. Device results and discussion

The 6500V IGBT chip was fabricated, which has a SPT structure with the trench gate and N enhancement layer in the active area [6-9]. From the Fig.8 we can see that the breakdown voltage is more than 7000V which is similar with the simulation result (see Fig.8). Some cases below 7000V are inferred to be caused by abnormal process.

Figure 8. Test results of breakdown voltage
4. Conclusion
A novel junction termination with a highly doped floating P+ rings for 6500V IGBT is proposed. The termination is less than 2500um. The termination is immune to interface charges and P+ ring doping variation. The suggested gate busbar size and the corner radius are given by simulation. The simulation results show that the breakdown voltages are all above 7000V when the interface charges change from -3E11cm⁻² to 5E11cm⁻². This device was fabricated and the test results show that the breakdown voltage is more than 7000V, which is agreement with the simulation results.

Acknowledgements
This work was financially supported by the State Grid Co., Ltd. Science and Technology Project: Research on Modeling and Simulation of 6500V IGBT Chip (No. 52060018009M).

References
[1] A. A. Gannshin, V. I. Meleshin, S. A. Sachkov and D. V. Zhiklenkov, "Railway auxiliary power converter operating with 3 kV DC supply line on the basis of 6.5 kV IGBT modules," 2014 16th International Power Electronics and Motion Control Conference and Exposition, Antalya, 2014, pp. 654-660, doi: 10.1109/EPEPEMC.2014.6980570.
[2] S. Rezwan, S. Hossain, S. Tasnim and M. M. Rahman, "H2D4-Type Single Phase Transformer-Less Inverter with Reactive Power Control for Grid-tied PV System," 2018 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE), Kajang, 2018, pp. 112-118, doi: 10.1109/ICSGCE.2018.8556641.
[3] A. Jokin, A. Eneko, Z. Ignacio, L. Igor, S. Katsuaki and M. Neil, "Output power increase of a 3-level converter using state-of-the-art 4.5kV IGBT modules," 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Karlsruhe, 2016, pp. 1-9, doi: 10.1109/EPE.2016.7695620.
[4] D. Zhang, J. He and S. Madhusoodhanan, "Three-level two-stage decoupled active NPC converter with Si IGBT and SiC MOSFET," 2017 IEEE Energy Conversion Congress and Exposition (ECCE), Cincinnati, OH, 2017, pp. 5671-5678, doi: 10.1109/ECCE.2017.8096943.
[5] J. Yang, Z. He, J. Ke and M. Xie, "A New Hybrid Multilevel DC–AC Converter With Reduced Energy Storage Requirement and Power Losses for HVDC Applications," in IEEE Transactions on Power Electronics, vol. 34, no. 3, pp. 2082-2096, March 2019, doi: 10.1109/TPEL.2018.2839117.
[6] J. Zhang et al., "Numerical Analysis of Impact of Shield Gate on Trench IGBT and CSTBT," 2019 IEEE International Conference on Electron Devices and Solid-State Circuits (EDSSC), Xi'an, China, 2019, pp. 1-3, doi: 10.1109/EDSSC.2019.8754191.
[7] M. T. Rahman et al., "A novel carrier accumulating structure for 1200 V IGBTs without negative capacitance and decreasing breakdown-voltage", Proc. IEEE 30th Int. Symp. Power Semicond. Devices ICs (ISPSD), pp. 491-494, May 2018.
[8] M. Antoniou et al., "Deep p-Ring Trench Termination: An Innovative and Cost-Effective Way to Reduce Silicon Area," in IEEE Electron Device Letters, vol. 40, no. 2, pp. 177-180, Feb. 2019, doi: 10.1109/LED.2018.2890702.
[9] S. Honda, T. Harada, A. Nishii, Z. Chen and K. Shimizu, "High voltage device edge termination for wide temperature range plus humidity with surface charge control (SCC) technology," 2016 28th International Symposium on Power Semiconductor Devices and ICs (ISPSD), Prague, 2016, pp. 291-294, doi: 10.1109/ISPSD.2016.7520835.