Design and optimization of linearly graded-doping junction termination extension for 3.3-kV-class IGBTs

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Abstract: A linearly graded-doping junction termination extension (LG-JTE) for 3.3-kV-class insulated gate bipolar transistors (IGBTs) was proposed and experimentally investigated. Unlike conventional multi-implantation utilizing more than one photolithography step, a single mask with injection window widths varied linearly away from the main junction to the edge was implemented in this proposed structure. Based on the simulation results, IGBTs with LG-JTE structures were successfully fabricated on the domestic process platform. The fabricated devices exhibited a 3.7 kV forward-blocking voltage, which is close to the theoretical value of an ideal parallel plane case. This is the first success in fabrication 3.3-kV-class IGBT in a domestic application.

Key words: high voltage IGBT; junction termination extension; IGBT
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1. Introduction

With the advantages of field-effect transistors and bipolar transistors, IGBTs have become the major power switching device in power electronic applications such as traction, due to the improvement of system efficiency[1,2]. Although the forward-voltage drop of equivalent thyristor structures, such as gate turn-off thyristors (GTOs) and silicon controlled rectifiers (SCRs), are lower than that of the high voltage IGBTs, the development of new generations of high voltage IGBTs with higher blocking capability is ongoing, since the reduction of gate control circuitry together with the ease of use of IGBTs are very important. IGBTs have replaced power bipolar junction transistors (BJTs) in high voltage applications and threaten to displace GTOs in the future. The maximum forward-blocking voltage is determined not only by the high voltage IGBT cells but also by the junction termination structures used in the design. Whereas standard floating field limiting rings technique coupled with field plates are commonly used at 600–1200 V, junction termination extension (JTE) is preferred to be used at voltages above 3.3 kV. Conventional JTE structures are implemented by multi-implantation and utilize more than one photolithography steps[3–6].

In this work, junction termination structures of linearly graded-doping JTE (LG-JTE), which utilize a single mask and only one implantation step, incorporated into 3.3-kV-class IGBTs are designed and fabricated. Both poly field plates and metal field plates are also used and optimized. Two-dimensional numerical simulation results for the designed LG-JTE structures and implantation dosage optimization together with high voltage IGBT cells optimization are presented and discussed. Finally, forward-blocking voltage capabilities of 3.7 kV have been measured on the fabricated IGBTs with designed edge terminations.

2. Design and fabrication

The schematic cross section of the proposed LG-JTE is shown in Fig. 1. The graded doping profile is realized by masked implantation of boron followed with drive-in before the oxidation of field oxide.

The maximum forward blocking voltage is determined by various geometrical and technological parameters. Parameters of linearly LG-JTE, shown and explained in Table 1, are demonstrated in Fig. 1. The mask dimensions are designed according to the method demonstrated in Ref. [7]. The lengths of the slits are calculated by

$$x_i + y_i = S, \quad (1)$$

$$x_i = (i - 1)d, \quad (2)$$

where $S = nd$ and $i = 1, 2, \ldots, n$.

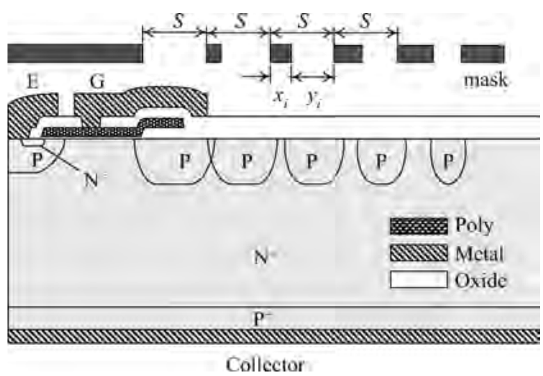

Fig. 1. Schematic cross section of the linearly graded doping JTE (LG-JTE).

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Table 1. Device parameters of LG-JTE used in the simulation and fabrication.

Parameter	Symbol	A	B
Length of poly plate (μm)	L_p	10	10
Length of metal plate (μm)	L_m	25	25
Length of segment (μm)	S	34.5	40
Decrement (μm)	d	1.5	2
Total number of slits	n	23	20
Total length (μm)	L	793.5	800

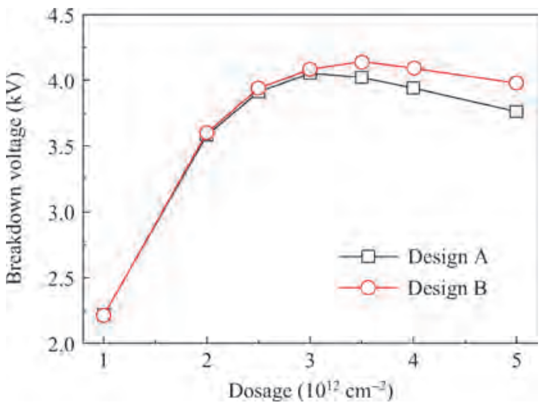

Fig. 2. Breakdown voltages of edge terminations A and B with different junction termination edge implantation dosages of boron.

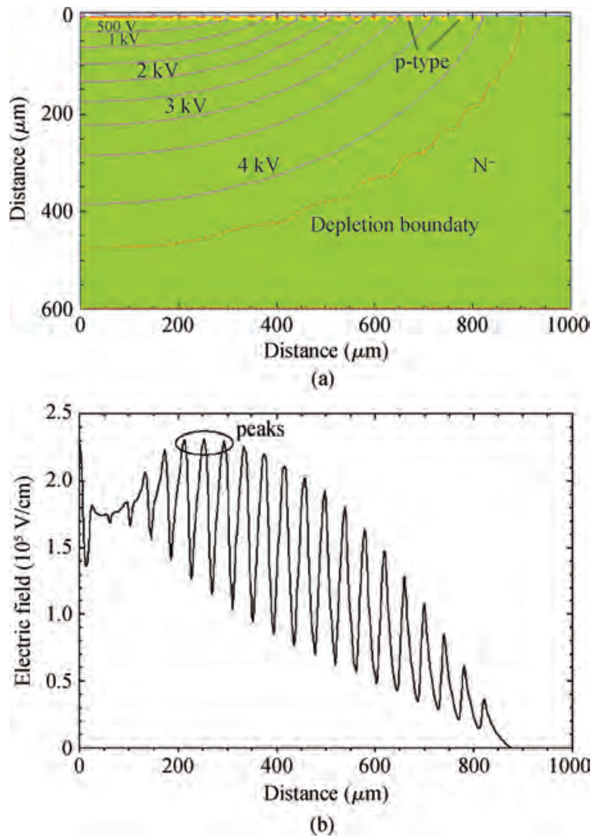

Fig. 3. (a) Potential distribution in the body and (b) surface electric field distribution along the breakdown point of the optimized JTE structure with dosage of 3 $\times$ 10^{12} cm^{-2}. The blocking voltage is 4082 V.

Two types of LG-JTE, designs A and B, shown in Table 1, are well designed according to both process capabilities (e.g. photolithography resolution) and simulation results. The forward-blocking voltages of both A and B are functions of the dosage of junction termination edge implantation. To obtain the optimum dosage, two-dimensional numerical simulations were performed using Tsuprem4 and Medici[8, 9]. The resistivity of drift region used in the process simulations is 195 Ω·cm and the carrier lifetime used in the device simulations is 10 μs. The simulation results of the relation of forward-blocking voltages and dosage are shown in Fig. 2. According to the curves dosage of 3–3.8 $\times$ 10^{12} cm^{-2} is selected.

The potential distribution in the body and depletion boundary of the edge termination is shown in Fig. 3(a). The vertical maximum depletion width is between 450 and 500 μm. The thickness of wafer is selected based on it. The equipotential line demonstrates that the implantation windows are well optimized. This can also be confirmed by the surface electric field distribution along the surface crossing the breakdown point, shown in Fig. 3(b). For the optimized case, the breakdown voltage of IGBTs with LG-JTE structure is over 4.2 kV, which is close to 95% of the parallel-plane case.

Non-punch-through (NPT) IGBTs with active area of 4 $\times$ 4 mm^2 were fabricated and characterized. The resistivity of the monocrystalline silicon wafers used in this fabrication, which are doped by neutron transmutation, is 195–199 Ω·cm. The process flow is well designed and optimized. The laser mark is followed by the JTE implantation of Boron and the dosage is (3–3.8) $\times$ 10^{12} cm^{-2}. After the active etching, low dosage of phosphorus implantation of the order 1 $\times$ 10^{12} cm^{-2} was selectively carried out by the splitting plan before 100 nm gate oxides were grown. A high dosage of boron implantation followed with the ohmic contact etching, for better ohmic contact of the P-base and aluminum. The front side processing is completed with cathode metallization and passivation. The wafers were ground to the thickness of 550–600 μm followed by back boron implantation and annealing in the backside process. The layout of the LG-JTE and the photo of fabricated devices are shown in Fig. 4.

3. Results and discussion

In this work, the 3.3-kV-class IGBT devices with junction termination structures A and B were fabricated with the same process run. The measured results of the fabricated devices are shown in Fig. 5. On the one hand, the breakdown voltages of IGBTs with A and those of IGBTs with B are over 3700 V. A difference of 100 V (smaller than 3%) between IGBTs with edge termination of design A and B indicated that the designed LG-JTE has good robustness to dimensions in this range. From Figs. 5(a) and 5(b), it also can be seen that the breakdown voltage of IGBTs with A and B is little sensitive to LG-JTE implantation dosage and high-temperature drive-in time, which indicated that the proposed structure has a good process tolerance.

Fabricated IGBTs are tested by transistor curve tracer. Figure 6 shows the forward-blocking capabilities of typical IGBTs fabricated with the use of different termination of LG-JTE structures.

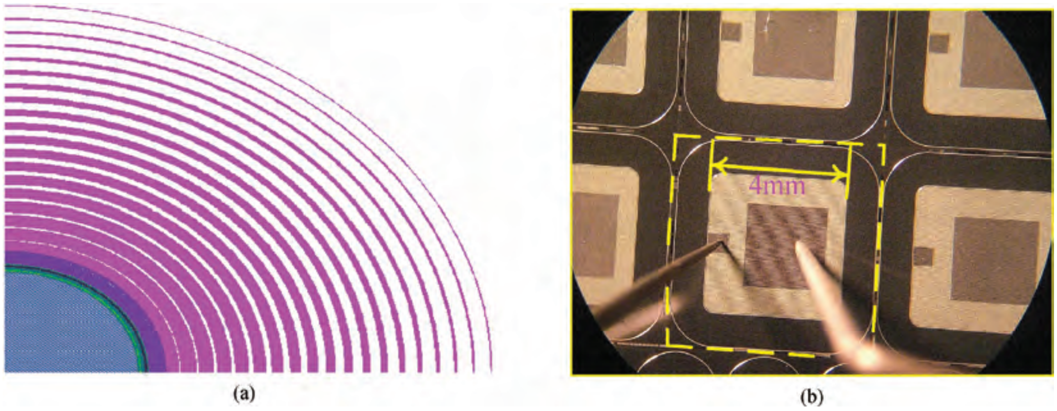

Fig. 4. (a) Layout of LG-JTE and (b) photo of fabricated wafer with IGBTs, which shows that the implantation slits decreases from the main junction (the innermost circles) to termination edge.

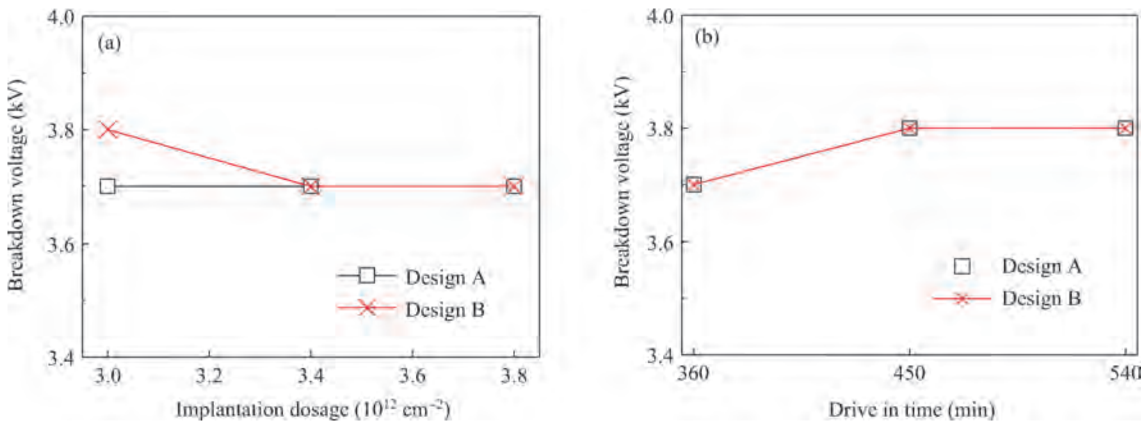

Fig. 5. Breakdown voltage versus (a) implantation of LG-JTE and (b) drive in time.

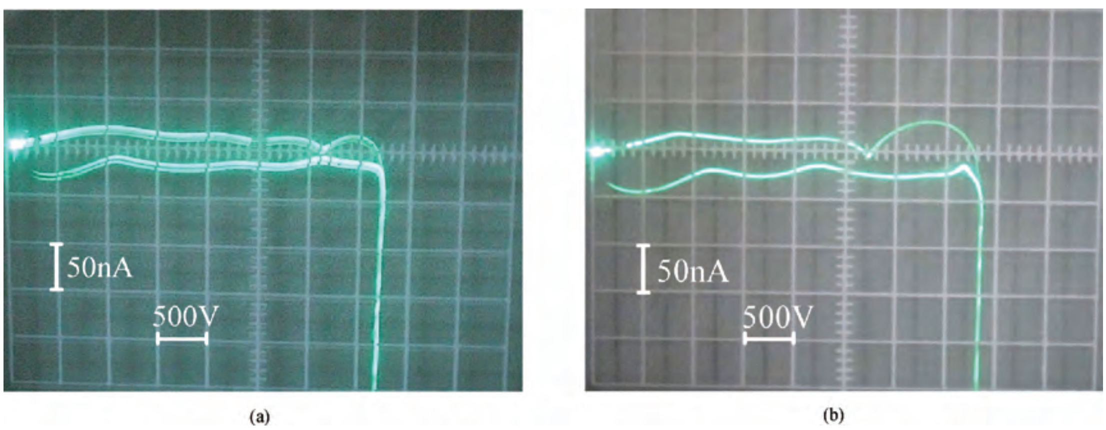

Fig. 6. Forward blocking capability of designed IGBTs with junction termination structure of LG-JTE. (a) The IGBT fabricated with A can block 3.7 kV and (b) that fabricated with B can block 3.8 kV. Implantation dosage of both is 3×10^{12} cm^{-2}.

4. Conclusion

Junction termination structures of linearly graded-doping JTE (LG-JTE) for high-voltage power IGBTs have been designed and optimized. A single mask is used to implement the graded doping by varying the injection window widths linearly away from the main junction to the edge. IGBTs with active area of 4×4 mm^2 have been designed and fabricated using the designed edge termination. The fabricated devices exhibited a forward-blocking voltage of 3.7 kV, which is close to the theoretical value of an ideal parallel plane case. Test results demonstrated that the breakdown voltage is not sensitive to dimension and implantation dosage and thus proving the effectiveness and robustness of the designed edge termination. It is a breakthrough in domestic research on high-voltage IGBTs (over 3.3-kV-class) fabrication.

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