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IGBT structure with electrically separated floating-p region improving turn-on dVak/dt controllability

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***Abstract*—IGBT cell structure for improving the turn-on dIc/dt controllability is presented. The difference from the conventional structure is that the floating-p region of the new structure is electrically disconnected from the trench-side-wall region. TCAD simulation suggests that the new device structure achieves better turn-on characteristics and almost the same static and turn-off characteristics compared to the conventional structure. It turned out that the high potential of the trench-side-wall region of the new structure, at the moment just before the collector current start to flow, is the cause of the improved turn-on dIc/dt controllability.**

Keywords— Insulated gate bipolar transistors, Floating P, Turn on, Controllability, Noise, Transient analysis

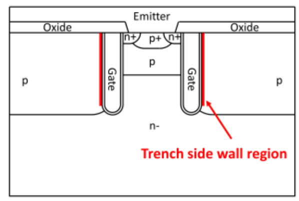
I. Introduction

It is well known that the IGBT with floating-p region has a poor controllability over the turn-on dIc/dt (Collector current increase rate). High dIc/dt of IGBT causes high reverse recovery dVak/dt (Anode-Cathode voltage increase rate) of FWD at the opposite arm which leads to EMI noise and voltage oscillation during switching [1]. Previous research has suggested that the rapid increase of the gate voltage during the turn-on period is caused by the displacement current flowing from the floating-p region of which potential show rapid increase induced by the start of the collector current flow [1-3]. In ISPSD 2017, it was suggested that the initial potential of the floating-p region has significant influence on the turn-on dIc/dt controllability [4]. When the potential of the floating-p region is high, the turn-on dIc/dt controllability is better. In this study, a novel IGBT cell structure for improving the turn-on dIc/dt controllability is presented.

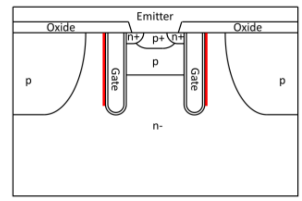
II. Device structure

Figure 1 shows IGBT device structures used for TCAD simulation analysis. Compared to the conventional structure A (Fig. 1(a)), the floating-p region of the structure B is separately placed from the trench gate (Fig. 1(b)). Compared to the structure B, n+ region is placed on the surface of separation region of the structure C (Fig. 1(c)). The portion "trench-side-wall region" is indicated and defined in the three figures, and is frequently referred, hereafter, in the present paper.

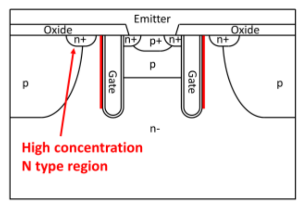
In the next section, TCAD simulation results for these structures are shown.



(a) Structure A



(b) Structure B



(c) Structure C

Fig. 1. Cross section of IGBT device structures

III. SIMULATION RESULT

Figure 2 shows the simulated distributions of doping concentration, electric potential and hole density of the structure A during the off state. The potential of the floating-p region is not zero but have a certain value. The turn-on dIc/dt controllability improves as the potential value is higher.

Figure 3 shows the simulated distributions of doping concentration, electric potential and hole density of the structure B during the off state. The calculated electric potential of the floating-p region of the structure B is not much higher than that of the structure A. It turned out that hole inversion layer created at the surface of separation region connects the floating-p region and trench-side-wall region. It can be noticed that once the hole inversion layer created, the potential of the floating-p region is fixed at the potential of inversion layer and cannot increase further more.

It is expected that if the creation of hole inversion layer is suppressed, the potential of the floating-p region can take a much higher value. Figure 4 shows simulated distributions of doping concentration, electric potential and hole density of the structure C during the off state. By placing n+ region on the separation region, the creation of the hole inversion layer is successfully suppressed. Instead, hole current flows from the floating-p region to the trench-side-wall region through a path of an electric potential minimum point between the floating-p region and the trench-side-wall region.

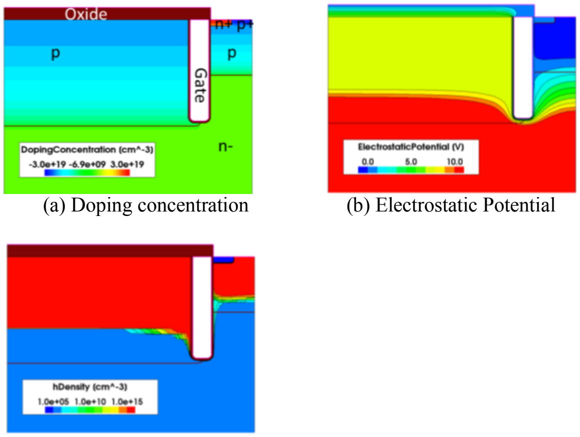
Figure 5 shows the turn-on waveforms of structure A, B and C for three different gate resistances, Rg. The waveforms of the structure A (solid line) and B (dotted line) show no significant difference. And both gate voltages rapidly increase as the collector current start to flow. On the other hand, the increase of the gate voltage is relatively small in the waveform of the structure C (red line). Figure 6 shows dIc/dt as a function of gate resistance Rg. The dIc/dt controllability by gate resistance of the structure C is better than that of the other structures. Figure 7 shows the turn-on loss Eon as a function of reverse recovery dVak/dt of FWD. The turn-on characteristics of the structure C is better than that of the other structures.

Figure 8 shows the turn-off loss, Eoff, as a function of Collector-Emitter saturation voltage Vce(sat). The turn-off characteristics of the structure C is almost the same as that of the other structures.

Table 1 lists the breakdown voltages. Although the breakdown voltage of the structure C is slightly lower than that of the other structures, the difference is small.

As described above, the structure C has significantly improved turn-on characteristics without any substantial deterioration of other characteristics.

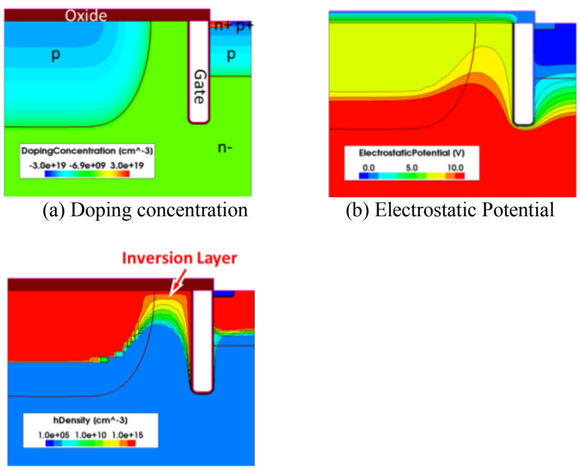
In the next section, the reason why the structure C is effective to improve the turn-on dIc/dt controllability is analyzed.



(a) Doping concentration (b) Electrostatic Potential

(c) Hole Density

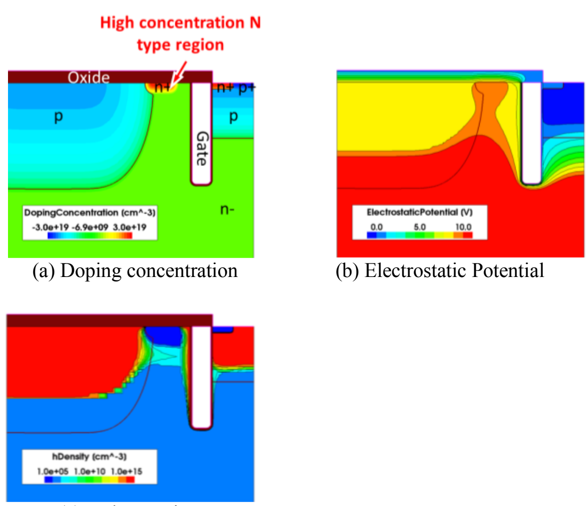
Fig. 2. Simulated off state of the structure A



(a) Doping concentration (b) Electrostatic Potential

(c) Hole Density

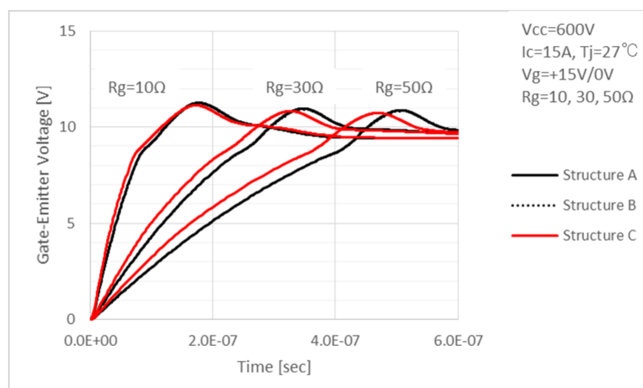
Fig. 3. Simulated off state of the structure B



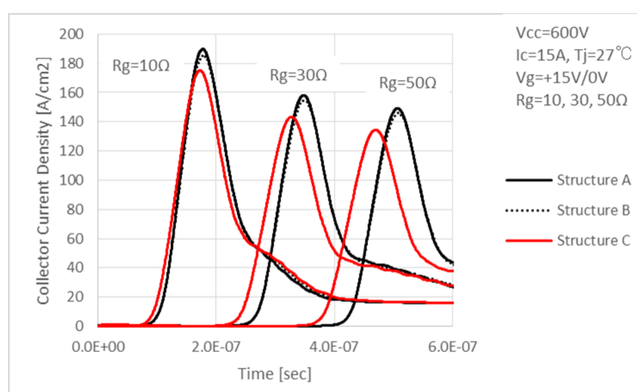
(a) Doping concentration (b) Electrostatic Potential

(c) Hole Density

Fig. 4. Simulated off state of the structure C



(a) Gate-Emitter Voltage



(b) Collector Current Density

Fig. 5. Turn-on waveform with varied gate resistance Rg

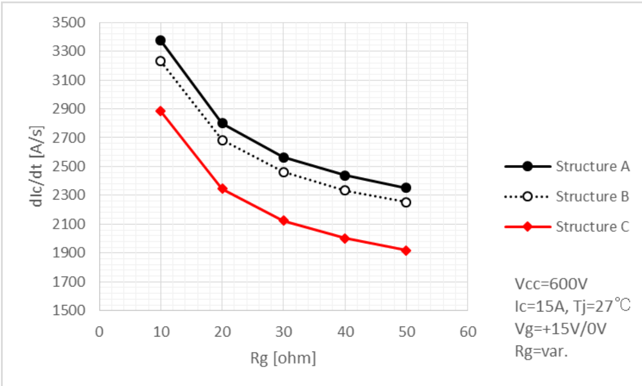


Fig. 6. dIc/dt as a function of gate resistance Rg

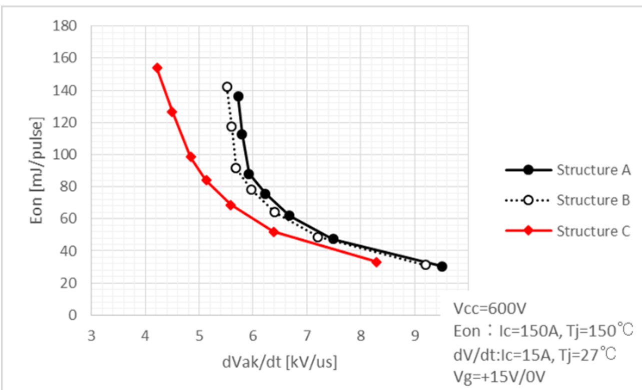


Fig. 7. Turn-on loss Eon as a function of Reverse recovery dVak/dt

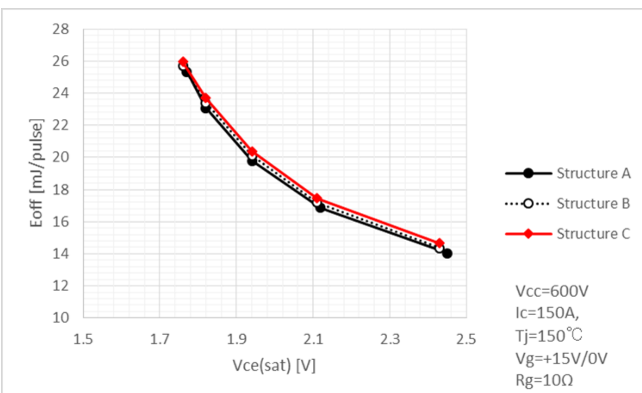


Fig. 8. Turn-off loss Eoff as a function of Vce(sat)

Table 1. Breakdown voltage

	Breakdown Voltage [V]
Strucutre A	1460
Structure B	1428
Structure C	1412

IV. DISCUSSION

When the floating-p region is separately placed from the trench gate, as is the cases of the structure B and C, the potential of the trench-side-wall region, facing the trench gate, is important. Figure 9 shows the turn-on waveform of the potential of the trench-side-wall region, the gate-emitter voltage and the collector current density.

The potential of trench-side-wall region of the structure C increase more rapidly than that of the structure A and B until the rise of collector current. The potential of the trench-side-wall region increases depending on the rate of the gate voltage increase during this period. Because the potential of the trench-side-wall region of the structure A and B is electrically connected to the floating-p region by the inversion layer, the capacitance between the floating p-region and Emitter electrode is relatively large. Thus the increase rate of the potential of trench-side region is relatively small. On the other hand, because the potential of the floating-p region of the structure C is electrically separated from the trench-side-wall region by the n+ region, the capacitance between the trench-side-wall region and the Emitter electrode is relatively small. Thus, the increase rate of the potential of trench-side-wall region is large in the structure C.

The increase rate of the potential of the trench-side-wall region is decided by the hole accumulation rate after the start of the collector current flow. It follows that the potential value of the trench-side-wall region at the very moment just before the collector current start to increase is important. As the potential of trench-side-wall region becomes higher, the hole accumulation and the resulting potential increase rate will be smaller.

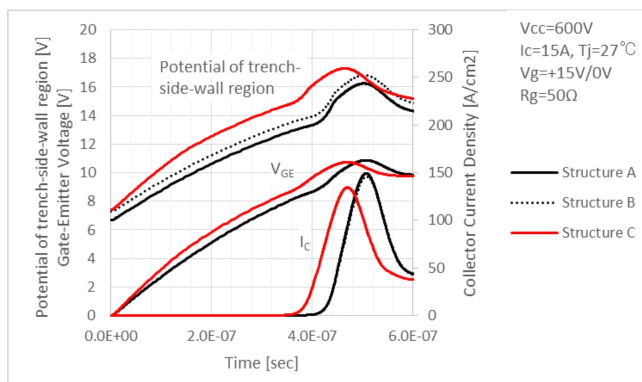


Fig. 9. Turn-on waveform of potential of trench-side-wall region, Gate-Emitter voltage and Collector current density

A TCAD simulation procedure to calculate the turn-on characteristics with arbitrary potential of the floating-p region is described in ISPSD 2017 [4]. In this method, the off state is calculated in which the floating-p region is connected to a fixed voltage source Vfix and the turn-on characteristics are calculated in which a large resistance is connected between the floating-p region and the voltage source Vfix. The simulation suggested that the increase rate of the collector current dIc/dt becomes lower as Vfix increases.

Figure 10 shows the relation between collector current increase rate dIc/dt and the electric potential of the trench-side-wall region at the very moment just before the collector current start to increase for the structure A, B and C when the fixed voltage source value Vfix is changed. All three curves for the structure A, B and C coincide with each other. The electirc potential of trench-side-wall region at the very moment just before the collector current start to increase has the same influence on the increase rate of collector current dIc/dt even for the different device structure A, B and C.

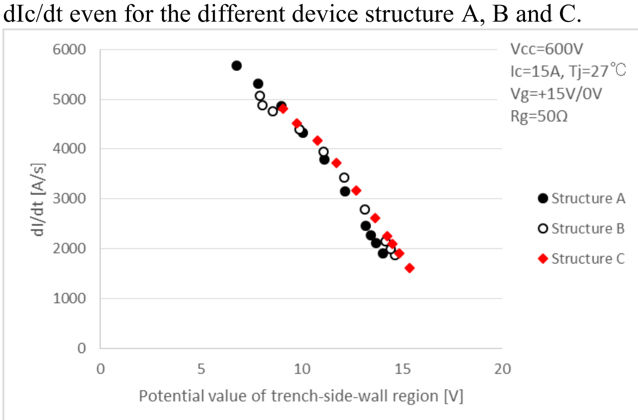


Fig. 10. dIc/dt as a function of the electric potential of the trench-side-wall region at the very moment just before the collector current start to increase

V. CONCLUSIONS

In this study, IGBT cell structure for improving the turn-on dIc/dt controllability is investigated. Simulation suggested that, even if the floating-p region is separately placed from the trench gate, the influence from increasing potential of the floating-p region is not suppressed because the hole inversion layer at the surface of the separation region connects the floating-p region and the trench-side-wall region. Placing n+ region on the separation region as a countermeasure for the hole inversion layer improves the turn-on dIc/dt controllability. Electrically disconnecting the floating-p region from the trench-side-wall region causes the elevation of the potential of trench-side-wall region after the gate voltage starts to increase. It turned out that the potential of trench-side-wall region at the very moment just before the collector current start to increase rules the turn-on dIc/dt controllability.

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