3.3-kV 7th-Generation "X Series" IGBT Chip Technology

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ABSTRACT

The railways, including high-speed rails, use IGBT modules for drive motors. It is essential for IGBT modules to reduce power loss, as they directly contribute to CO_2 reduction. To meet this demand, Fuji Electric has developed a 3.3-kV SiC hybrid module that combines the latest generation "X Series" IGBTs and SiC-SBDs. Using a finer surface structure and a thinner drift layer, the X Series IGBT chip has reduced the collector-emitter saturation voltage by 1.0 V, compared with a previous generation. In addition, by combining it with a SiC-SBD, the hybrid module has achieved significant performance improvements with a turn-on loss reduction of 51% and reverse recovery loss reduction of 98%.

1. Introduction

Against the backdrop of global warming, various initiatives to reduce CO_2 emissions are underway. Approximately 20% of Japan's total CO_2 emissions come from transportation-related activities, and progress is being made in the electrification of transportation. In particular, high-speed rail emits far less CO_2 than airplanes, and for this reason, the number of new railways has increased in recent years, both in Japan and around the world.

Insulated gate bipolar transistor (IGBT) modules are used to drive motors for railway transportation. To reduce power consumption and reduce CO_2 emissions, power-loss reduction in IGBT modules is essential. In addition, to reduce the power consumed by high-speed rail itself, it is essential to reduce the weight of the rolling stock and onboard equipment, leading to demand for IGBT modules that can contribute to reductions in size and weight of the system are essential.

Conventional IGBT modules consist of Si-IGBTs and Si-PiN diodes made from silicon (Si). Practical application of silicon carbide (SiC), a next-generation power semiconductor material, has begun. The use of SiC can significantly reduce losses compared with silicon.[(1),(2)] As devices that use SiC, the introduction of Schottky barrier diodes (SBDs), which have a simpler device structure and manufacturing process, has advanced ahead of metal-oxide-semiconductor field-effect transistors (MOSFETs) and IGBTs.

Fuji Electric has developed a 3.3-kV-rated SiC hybrid high power module (HPM) that combines the latest generation "X Series" IGBT and the SiC-SBD to achieve significant loss reduction.[(3)] This paper describes the 3.3-kV X Series IGBT chip (X-IGBT) technology.

2. Features of 3.3-kV "X Series" IGBT Chips

2.1 Loss reduction technology

(1) Reduction of conduction loss

Figure 1 shows the cross section structures of an IGBT. IGBTs, in which electrons are injected from the MOS channel on the surface and holes are injected from the p^+ collector layer on the back in response, allow carriers (electrons and holes), which are particles responsible for the current, to accumulate in the n^- drift layer with low impurity concentration, resulting in low conductivity modulation to reduce conduction loss. Compared with the conventional "U Series" IGBT chips (U-IGBTs), the newly developed X-IGBT has a finer surface structure that enhances injection enhancement effect to increase the carrier density in the n^- drift layer, reducing the resistance of the n^- drift layer.

Furthermore, the use of advanced thin wafer tech-

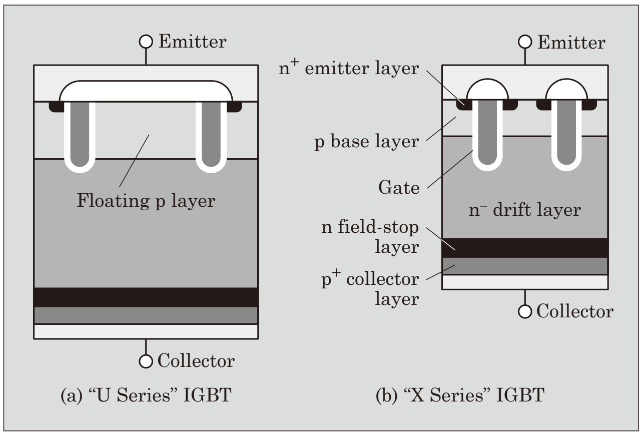

Fig.1 Cross section structures of IGBTs

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nology has made the n⁻ drift layer thinner, thereby physically reducing the length of the conduction pathways of the current flowing between the collector and emitter electrodes, leading to a reduction in the resistance of the n⁻ drift layer.

Figure 2 shows the waveform of collector current I_C and collector-emitter voltage V_{CE}. By reducing the resistance of the n⁻ drift layer as described above, the X-IGBT has the lower V_{CE} than the conventional U-IGBT by 1.0 V at its rated current.

Figure 3 shows the relationship between the turn-off loss E_{off} and the collector-emitter saturation voltage $V_{CE(sat)}$. In general, there is an trade-off relationship between E_{off} and $V_{CE(sat)}$, where increasing a p⁺ collector layer concentration to reduce the $V_{CE(sat)}$ will increase the E_{off}. At the same E_{off}, the $V_{CE(sat)}$ has been lowered for X-IGBT than the conventional one by 1.0 V.

(2) Improved controllability of di/dt and dv/dt at turn-on

As shown in Fig. 1, a structure with a floating p-layer on the surface has been conventionally adopted to reduce the on-state voltage by suppressing the carrier emission and enhancing the injection enhancement effect. However, the presence of a floating p-layer increased the di/dt and dv/dt at turn-on, the suppression of which required higher gate resistance, resulting in an increase in turn-on loss E_{on}. The presence of a floating p-layer deteriorates the controllability of di/dt and dv/dt. As shown schematically in Fig. 4, it was revealed through cause analysis that holes accumulate in the floating p-layer, the potential of the floating p-layer increases rapidly, and the rate of increase in the potential (dv/dt) causes a displacement current to flow through the gate electrode, which leads to faster charging of the gate electrode regardless of the resistance value of the gate resistance R_G.[4]

As a result of the refinement of the surface structure, the X-IGBT achieves a low on-state voltage without using a floating p-layer, and the elimination of the floating p-layer improved the controllability of di/dt and dv/dt by R_G at turn-on. Figure 5 shows the di/dt R_G dependence at turn-on. When the R_G increases, the di/dt of the conventional product slightly decreases, whereas that of the X-IGBT largely decreases. For example, when di/dt is set to 0.15 kA/μs, the R_G needs to be 60 Ω or greater for the U-IGBT, but only approximately 40 Ω for the X-IGBT, allowing the E_{on} to reduce.

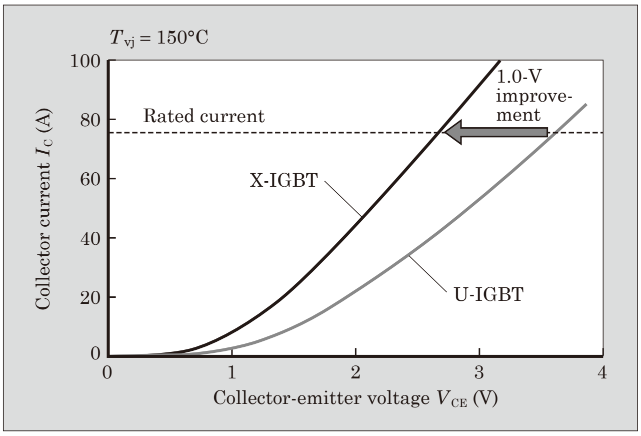

Fig.2 Collector current to collector-emitter voltage waveforms

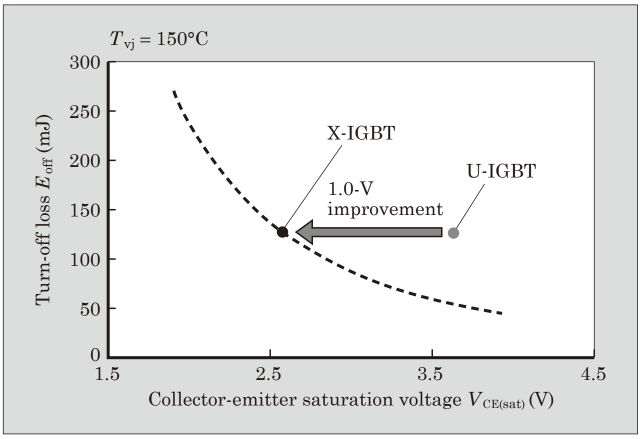

Fig.3 Relationship between the turn-off loss and the collector-emitter saturation voltage

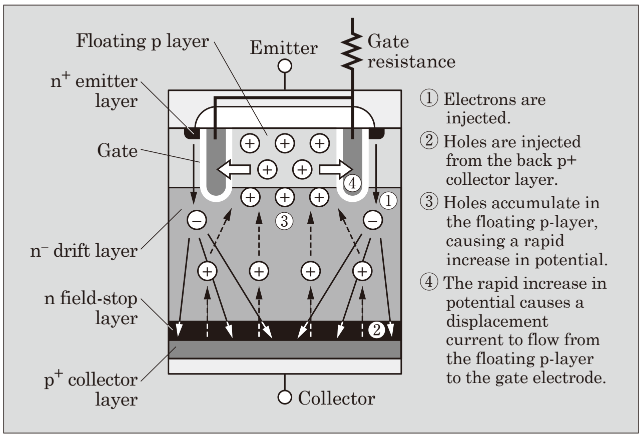

Fig.4. Floating p-layer and displacement current schematic diagram

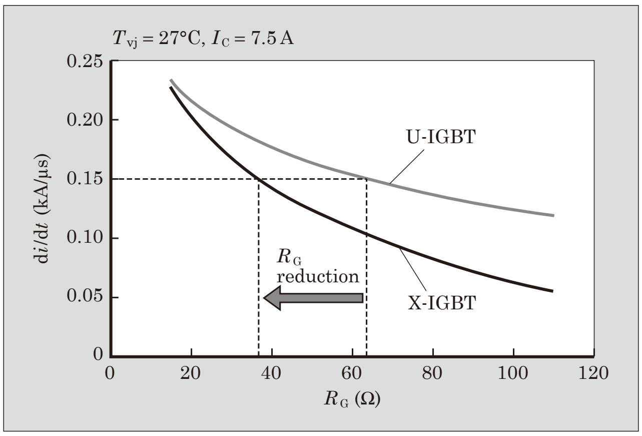

Fig.5 di/dt R_G dependence at turn-on

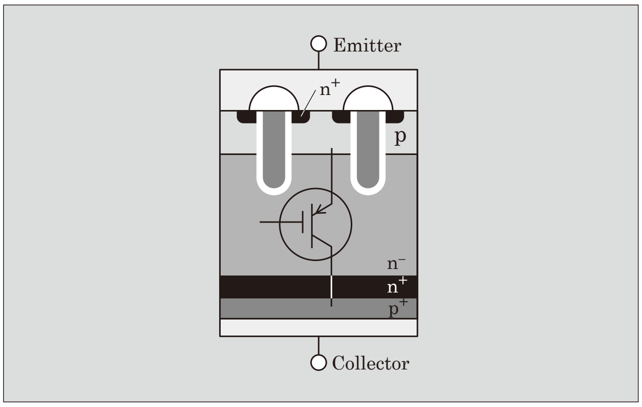

Fig.6 Parasitic PNP bipolar transistors in the IGBT

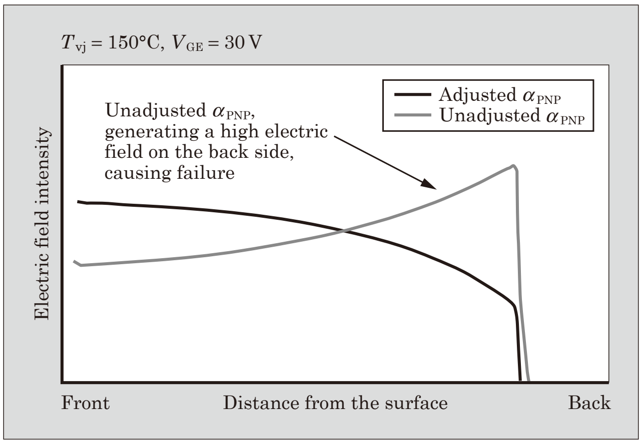

Fig.7 Electric field distribution during the short-circuit of the 3.3-kV IGBT

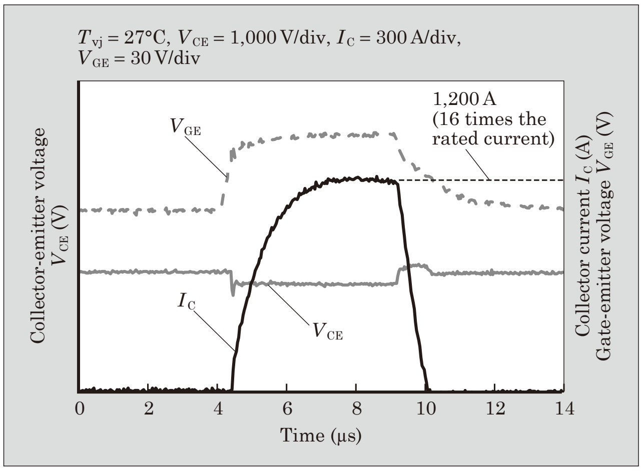

Fig.8 Waveforms during short-circuit operation

2.2 Technology for improving short-circuit ruggedness

IGBTs must have a short-circuit ruggedness to remain intact for a certain amount of time under short-circuit conditions. However, high blocking voltage IGBTs have less positive fixed charge in the n⁻ drift layer, which makes it easier for the positive fixed charge to be canceled out by the large number of electrons injected during the short circuit. As a result, the peak of the electric field shifts to the back side and causes avalanche breakdown, leading to IGBT breakdown (back side avalanche breakdown).[5]

To avoid this back side avalanche breakdown, it is effective to optimize the injection of holes from the back side. Optimizing hole injection from the back side is possible by controlling the gain of the parasitic PNP bipolar transistor in the IGBT shown in Fig. 6.

$$\alpha_{PNP} = \alpha \times \beta \times \gamma \quad \cdots\cdots (1)$$

α_{PNP}: Base ground current gain
α: Collector efficiency
β: Base transmission efficiency
γ: Emitter injection efficiency

Where α_{PNP} is the base ground current gain, α is the collector efficiency, β is the base transmission efficiency, and γ is the emitter injection efficiency.

According to Equation (1), the α_{PNP} is adjustable by β, which is determined by the neutral region of the n field-stop layer, and γ, which is determined by the p^+ collector layer. By optimizing layers such as the n field-stop layer and the collector layer, it is possible to control the injection of holes from the back side and bring α_{PNP} to an appropriate value. This adjustment can inhibit back side avalanche breakdown during the short-circuit period.

Figure 7 shows the electric field distribution of a 3.3-kV IGBT during the short-circuit. It suggests that adjusting the α_{PNP} to an appropriate value can suppress the increase of the electric field on the back side.

However, the n field-stop layer or collector layer that has been adjusted from the conventional one so that only the α_{PNP} is an appropriate value increases the leakage current at high temperatures, increasing the risk of failure during high-temperature operation. To overcome this issue, we use the newly developed n field-stop layer and collector layer for the X-IGBT. By optimizing the concentration distribution, this series has achieved an appropriate value of α_{PNP} while suppressing the leakage current. This optimizes hole injection during the short-circuit period to suppress the leakage current at high temperature operation while suppressing back side avalanche breakdown. Figure 8 shows waveforms during short-circuit operation. We have confirmed that the X-IGBT can turn-off a current 16 times the rated current without failure.

3. Application Example (Loss Reduction through Combination with SiC-SBDs)

In the newly developed 3.3 kV-rated SiC hybrid HPM, replacing a conventional Si-PiN diode to a newly developed SiC-SBD as the free wheeling diodes to be combined with an IGBT can not only reduce the reverse recovery loss E_{rr} of the diode, but also reduce the E_{on} of the IGBT.

The Si-PiN diode accumulates minority carriers inside the device when conducting, so that it needs to

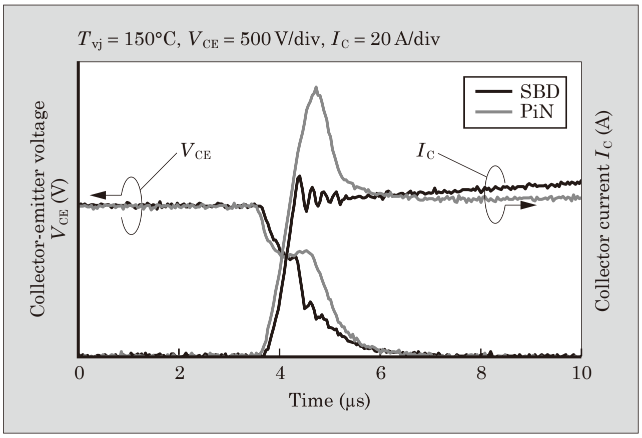

Fig.9 Turn-on waveforms

Table 1 Switching loss comparison

Item	Conventional HPM Si-PiN/Si-IGBT	New HPM SiC-SBD/ Si-IGBT	improve-ment rate
Turn-on loss (mJ)	2,933	1,425	51%
Turn-off loss (mJ)	1,957	1,900	3%
Reverse recovery loss (mJ)	1,548	30	98%

sweep out the carriers at turn-off time. This operation, appearing as the reverse recovery peak current I_{rp} in the reverse recovery waveform of the free wheeling diode, results in the superimposition on the collector peak current I_{cp} in the turn-on waveform of the IGBT, causing a corresponding loss. On the other hand, SiC-SBDs do not accumulate carriers inside the device, and therefore, I_{cp} and I_{rp} do not occur in principle, and no corresponding loss occurs. Figure 9 shows the turn-on waveforms of an IGBT combined with a Si-PiN diode and a SiC SBD. The combination with a Si-PiN diode produces a large I_{cp}, while the combination with a SiC-SBD produces no I_{cp}.

Table 1 shows a comparison of switching losses between the new product and conventional products.

Using a SiC-SBD reduced E_{on} and E_{rr} by 51% and 98%, respectively, achieving significant characteristic improvements.

4. Postscript

In this paper, we described the chip technology for the 3.3-kV latest generation “X Series” IGBT. This technology has improved losses by optimizing the surface and back structures. The 3.3-kV SiC hybrid high power module equipped with 3.3-kV X Series IGBTs described in this paper have been commercially used for high-speed rail. These modules have contributed to the reduction of power consumption of the high-speed rails as well as to reductions in the size and weight of equipment.[(6)] Moving forward, we will continue to improve the characteristics of IGBTs and contribute to the creation of a responsible and sustainable society by reducing CO_2.

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