7th-Generation “X Series” RC-IGBT Module for Industrial Applications

YAMANO, Akio* TAKAHASHI, Misaki* ICHIKAWA, Hiroaki*

ABSTRACT

In recent years, IGBT modules have been increasingly required to be smaller in size while exhibiting lower loss and higher reliability. To meet the requirements, Fuji Electric has developed an industrial-use reverse conducting IGBT (RC-IGBT) module by using an RC-IGBT that integrates an IGBT and a free wheeling diode (FWD) on a single chip. Furthermore, the module greatly reduces loss and thermal resistance and enhances reliability through optimization based on our 7th-generation “X Series” technology. These technology innovations have achieved enhancements such as expansion of rated current, increased power density and miniaturization, all of which were impossible through the combination of conventional IGBT and FWD.

1. Introduction

In recent years, there have been increasing expectations for power electronics technology that utilizes energy efficiently and contribute to energy savings in order to prevent global warming and realize safe, secure and sustainable society. Above all, the demand for power semiconductors is expanding as a key device of power conversion system used in wide-ranging fields including the industrial, consumer, automotive and renewable energy fields.

Fuji Electric has commercialized insulated gate bipolar transistor (IGBT) modules, which are power semiconductors, in 1988. Ever since then, Fuji Electric has contributed to miniaturization, cost reduction and performance improvement for power conversion system through many IGBT module technology innovations such as miniaturizing the size, reducing the loss and improving the reliability. However, any further miniaturization of IGBT modules increases power density, which may lead to lower reliability due to an increase in operating temperatures of IGBTs and free-wheeling diodes (FWDs). Accordingly, to miniaturize IGBT modules while maintaining high reliability, the chips and packages technology innovation is essential to miniaturize IGBT modules and maintain the high reliability.

Fuji Electric has carried out chip and package technology innovation, and commercialized the 7th-generation “X Series” IGBT module(1),(2). In addition, we have developed a reverse-conducting IGBT (RC-IGBT), which integrates an IGBT and a FWD into one chip, and then the 7th-generation “X Series” RC-IGBT module for industrial applications(3),(4). By applying the chip technology of the 7th-generation X Series and optimizing the chip structures, we have successfully reduced the number of chips and the total chip area in spite of the power loss equivalent to the combination of the X Series IGBT and X Series FWD. Furthermore, by combining the package technology of the 7th-generation X Series with the RC-IGBT, we have reduced the thermal resistance and improved the reliability. Through the technology innovations, we have achieved further high power density and miniaturization of IGBT modules, which were impossible through conventional combination of IGBT and FWD.

2. Features

2.1 Features of the “X Series” RC-IGBT for industrial applications

In the conventional IGBT, a current flows only from the collector to the emitter when a voltage is applied to the gate.

An inductor, which is used as a load of inverters widely used as power conversion system, generates induced electromotive force in the direction to prevent any current change by the self-induction effect. As a result, even if the IGBT is turned off, the current tend to flow in the same direction, therefore it is necessary to connect the FWD in antiparallel to the IGBT in order to flow the current in reverse direction. Meanwhile, the “X Series” RC-IGBTs achieve the same purpose with one device by using an RC-IGBT technology (see Fig. 1).

Figure 2 shows a cross-section view of the X Series RC-IGBT. The X Series RC-IGBTs employ the 7th-generation X Series IGBTs chip technology that use a trench gate as the surface structure and a field stop (FS) layer as the backside structure. As with the X Series IGBTs, the X Series RC-IGBTs employ even fine pattern design rules as compared with the 6th-genera-

---

* Electronic Devices Business Group, Fuji Electric Co., Ltd.

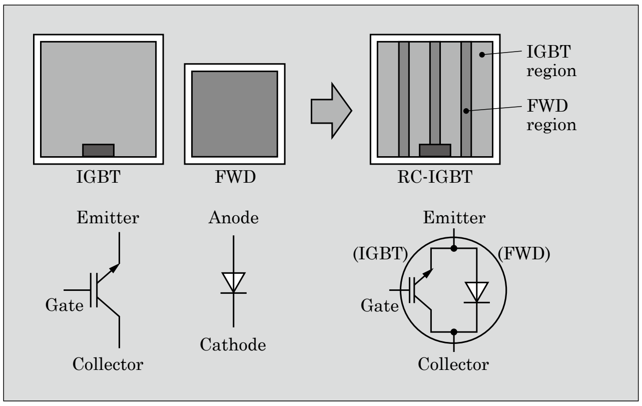


Fig.1 Schematic view and equivalent circuit of “X Series” RC-IGBT

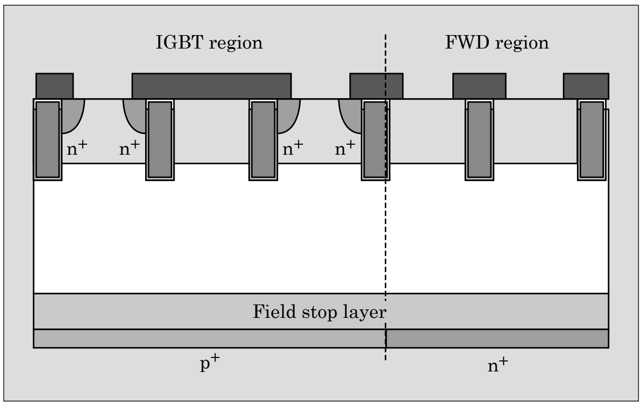


Fig.2 Cross-section view of “X Series” RC-IGBT

tion “V Series” IGBTs and optimized the surface structure. In this way, they have achieved a significant reduction of the collector-emitter saturation voltage $V_{\mathrm{CE(sat)}}$ that contributes to conduction loss. The latest thin wafer processing technology has also been applied to improve the trade-off relationship between the saturation voltage and turn-off switching loss. The X Series RC-IGBTs integrate FWD regions and have p-n junctions on the collector side. Accordingly, we have added the processes of patterning and impurity layer formation on the backside to form the p-type layer on the collector side of the IGBT and the n-type layer on the cathode side of the FWD on the backside of the same chip. In addition, the trade-off relationship has been improved by lifetime control.

2.2 Electrical characteristics

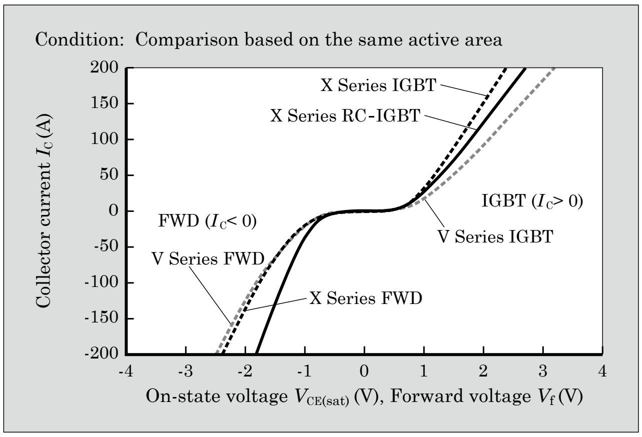


Fig.3 Output characteristic of “X Series” RC-IGBT

Figure 3 shows the output characteristic of the 1,200-V X Series RC-IGBTs. The X Series RC-IGBTs are capable of outputting a current in both the forward direction (IGBT) and reverse direction (FWD) with one chip. A saturation voltage lower than that of the V Series IGBTs has been realized by applying the chip technology of the 7th-generation X Series. With RC-IGBTs, electrons are injected into the cathode layer of the FWD region. This suppresses hole injection from the collector layer of the IGBT and thus hinders conductivity modulation. For that reason, snapback phenomenon has been reported to occur(5),(6) in the low saturation voltage region. Meanwhile, with the X Series RC-IGBTs, snapback phenomenon has been solved by optimizing the each structures of the chip.

Turn-off waveforms of the X Series RC-IGBTs are shown in Fig. 4, turn-on waveforms in Fig. 5 and reverse recovery waveforms in Fig. 6. Figure 4 indicates that the surge voltage of the X Series RC-IGBTs is equivalent to that of combinations of the V Series

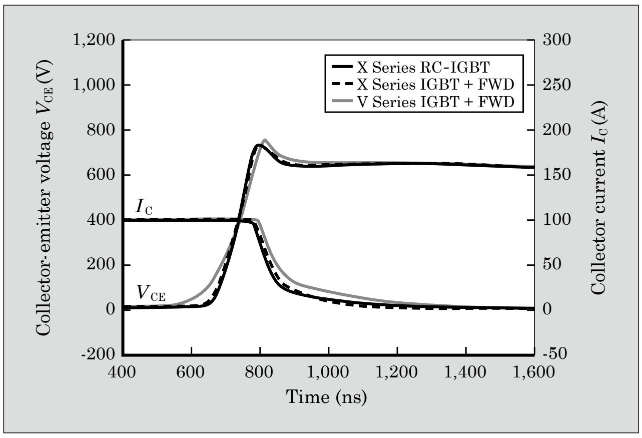


Fig.4 Turn-off waveforms of “X Series” RC-IGBT

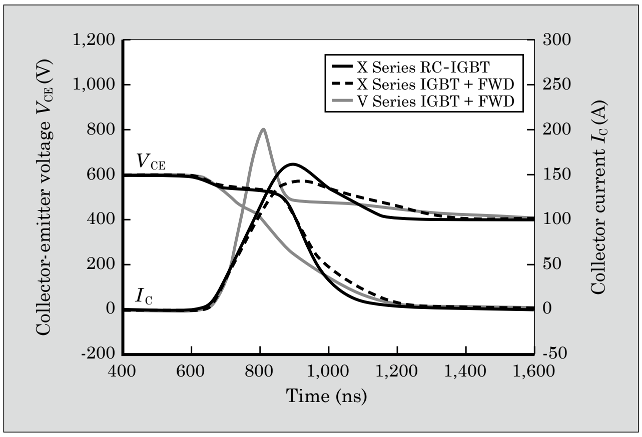


Fig.5 Turn-on waveforms of “X Series” RC-IGBT

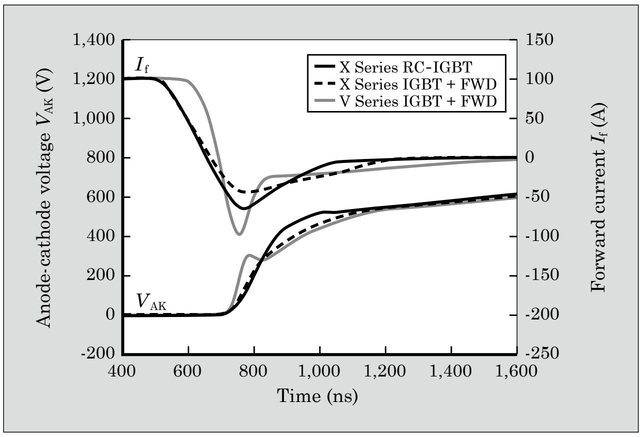


Fig.6 Reverse recovery waveforms of “X Series” RC-IGBT

IGBT and FWD and of the X Series IGBT and FWD. The tail current during turn-off switching is smaller than that of the combination of the V Series IGBT and FWD and the turn-off loss E_{off} is lower by 23% with no abnormal waveforms observed. The X Series RC-IGBTs use a thinner wafer than that of the combination of the V Series IGBT and FWD in order to improve the characteristics. Use of a thinner wafer concerns oscillation at turn-off and breakdown voltage degradation. However, with the X Series RC-IGBTs, the wafer resistivity and the each structures have been optimized to successfully suppress oscillation and breakdown voltage degradation. As shown in Fig. 5 and Fig. 6, the current waveforms for the combination of the V Series IGBT and V Series FWD have steep slopes, but the X Series RC-IGBT realizes soft recovery waveforms by optimizing lifetime control. Lowering the reverse recovery current peak I_{rrm} and the tail current has reduced the reverse recovery loss E_{rr} by 20%. No abnormal waveforms are observed in either the turn-on or the reverse recovery waveforms.

Figure 7 shows the trade-off characteristic of the IGBT as a comparison based on the same active area. Each point for the X Series RC-IGBT in the figure is a result of carrying out trade-off adjustment by changing lifetime control. Based on the same switching loss, the X Series RC-IGBT has improved the saturation voltage by 0.5 V as compared with the V Series IGBT. In addition, IGBT characteristics equivalent to those of the X Series IGBTs can be expected.

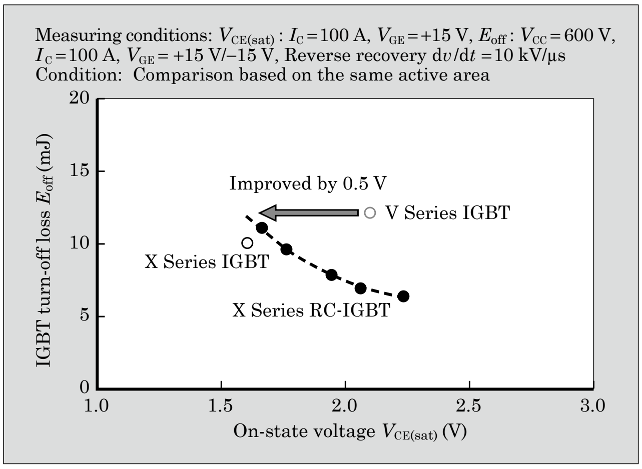


Fig.7 Trade-off characteristic of “X Series” RC-IGBT (IGBT)

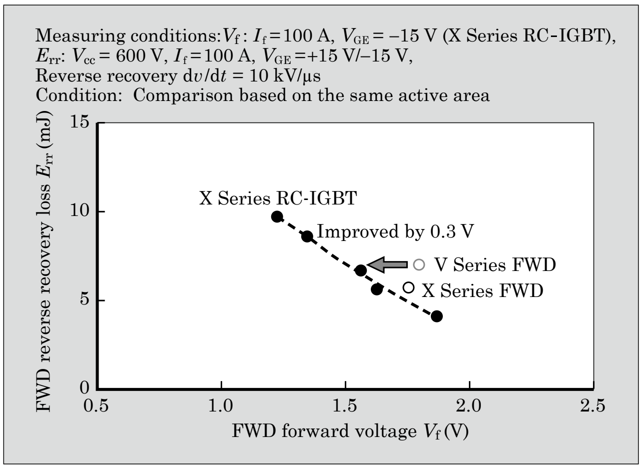


Fig.8 Trade-off characteristic of “X Series” RC-IGBT (FWD)

Figure 8 shows the trade-off characteristic of the FWD as a comparison based on the same active area. Each point for the X Series RC-IGBT in the figure is a result of trade-off adjustment in the same way as Fig. 7. Based on the same switching loss, the X Series RC-IGBT has improved the forward voltage by 0.3 V as compared with the V Series FWD. In addition, FWD characteristics equivalent to those of the X Series FWDs can be expected.

2.3 Thermal characteristics

With the X Series RC-IGBTs, an IGBT and an FWD has been integrated into one chip and the heat generated due to power loss in the IGBT or FWD regions is radiated from the entire chip. Accordingly, reduction of thermal resistance can be expected. To further reduce thermal resistance, a new aluminum nitride (AlN) insulating substrate has been applied as the package technology of the 7th-generation X Series.

General AlN substrates have high thermal conductivity, which decreases thermal resistance and, to deal with their low bending strength, ceramics thicker than alumina (Al_2O_3) insulating substrates, which are widely in use, are used to put them into practical applications. However, thicker substrates affects to the thermal resistance and reliability. To improve these issues, it was necessary to make the thinner AlN insulating substrates. Conventionally, thinning of AlN insulating substrates posed issues such as substrate cracking in the mounting process and reduction of isolation capability, which hindered them from being put to practical use. To address these issues, we have increased the strength by revising the sintering conditions of AlN and optimized the insulation design by revising the creepage distance to realize a new thinner AlN insulating substrate.

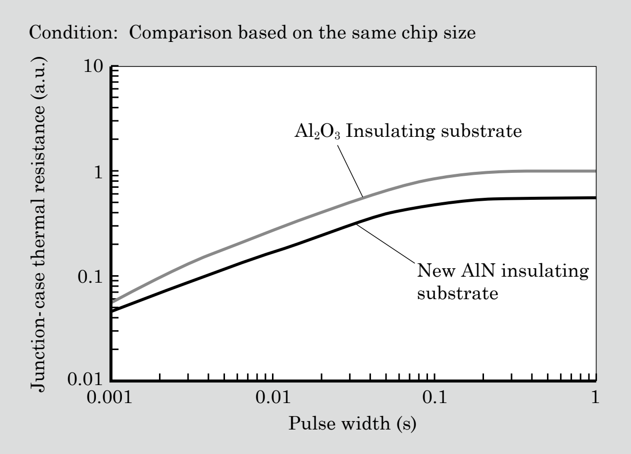


Fig.9 Junction-case thermal resistance

The junction-case thermal resistance is shown in Fig. 9. The new AlN insulating substrate features approximately 45% lower thermal resistance as compared with Al_2O_3 insulating substrates based on the same chip size, which is a significant improvement. This has resolved the issue of a temperature rise caused by miniaturization of IGBT modules. Furthermore, by optimizing wire bonding and applying high-strength new solder and high heat resistance silicone gel, high reliability has been ensured and while guaranteeing continuous operation at 175 °C.

3. Power Density Increase and Miniaturization

Table 1 shows a comparison with the V Series IGBT module of 1,200 V/100 A, and Fig. 10 shows calculation results of the power loss, junction temperature, T_j and temperature rise from the case to junction, ΔT_{jc} for the respective modules. By applying the chip technology and package technology of the 7th-generation X Series, we have significantly reduced the power loss and thermal resistance as compared with the conventional combination of the V Series IGBT and FWD. We have thus ensured high reliability and guaranteed continuous operation at 175 °C. In addition, use of the X Series RC- IGBT makes it possible to reduce the number of chips and the total chip area, and miniaturization of IGBT modules can be expected.

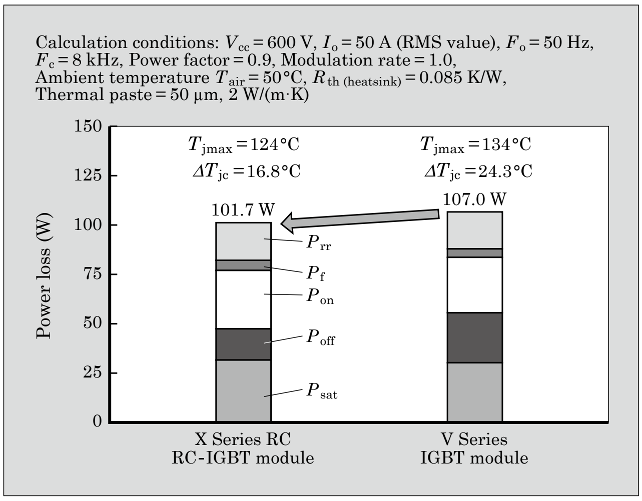


Fig.10 Power loss and junction temperature of 1,200 V/100 A IGBT modules

Based on these merits, applying the RC-IGBT chip technology and the chip technology and package technology of the 7th-generation X Series can expand rated current than that of a conventional combination of IGBT and FWD with the same package.

Table 2 shows Dual XT and PrimePACK2*1 as lineup of products with a rated voltage of 1,200 V and features in Table 3. Conventional Dual XT with a rated voltage of 1,200 V has the upper limit the rated current of 600 A for a combination of the V Series IGBT and FWD. Through the use of the chip technology and package technology of the 7th-generation X Series, the rated current has been increased to 800 A by combining the X Series IGBT and FWD. Furthermore, adopting the X Series RC-IGBT provides a module with a rated current of 1,000 A using the same package. In comparison to PrimePACK2 that uses the V Series IGBT and FWD, Dual XT offers a 40% reduction in the module footprint. In addition, by using the X Series RC-IGBT, thermal resistance $R_{\text{th(jc)}}$ can be reduced by 27%. In this way, it covers the range of PrimePACK2, which uses the conventional V Series IGBT and FWD.

Figure 11 shows the calculation results of output current I_o in inverter operation and the maximum IGBT junction temperature T_{jmax} for the Dual XT products respectively with a combination of the V Series IGBT and FWD, combination of the X Series IGBT and FWD and the X Series RC-IGBT. In addition, using the X Series RC-IGBT can reduce power loss and the junction-case thermal resistance. Furthermore, by ap-

Table 1 Comparison between 1,200-V/100-A IGBT modules

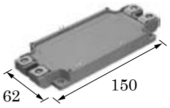
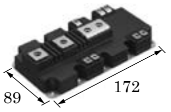
Item	X Series RC-IGBT module	V Series IGBT module
Chip	X Series RC-IGBT	V Series IGBT + FWD
Insulating substrate	New AlN insulating substrate	Al_2O_3 insulating substrate
Continuous operating temperature T_j (°C)	175	150

Table 2 Product lineup of “Dual XT” and PrimePACK2 with a rated voltage of 1,200 V

<table>
<tr><th rowspan="2">Product name</th><th colspan="7">Rated current (A)</th></tr>
<tr><th>225</th><th>300</th><th>450</th><th>600</th><th>800</th><th>900</th><th>1,000</th></tr>
<tr><td rowspan="2">Dual XT</td><td colspan="4">V Series IGBT + FWD</td><td></td><td></td><td></td></tr>
<tr><td colspan="5">X Series IGBT + FWD</td><td></td><td>X Series RC-IGBT</td></tr>
<tr><td>PrimePACK*</td><td></td><td></td><td></td><td colspan="3">V Series IGBT + FWD</td><td></td></tr>
</table>

*PrimePACK: Trademark or registered trademark of Infineon Technologies AG

Table 3 Features of “Dual XT” and PrimePACK2 with a rated voltage of 1,200 V

Item	Dual XT			PrimePACK*
External appearance				
Module footprint (cm^2)	93	93	93	153
Chip	V Series IGBT + FWD	X Series IGBT + FWD	X Series RC-IGBT	V Series IGBT + FWD
Module rated current (A)	600	800	1,000	900
Insulating substrate	SiN insulating substrate	New AlN insulating substrate	New AlN insulating substrate	Al_2O_3 insulating substrate
Thermal resistance $R_{th(jc)}$ (K/W)	IGBT: 0.04 FWD : 0.06	IGBT: 0.037 FWD : 0.044	IGBT: 0.022 FWD : 0.022	IGBT: 0.03 FWD : 0.054

*PrimePACK: Trademark or registered trademark of Infineon Technologies AG

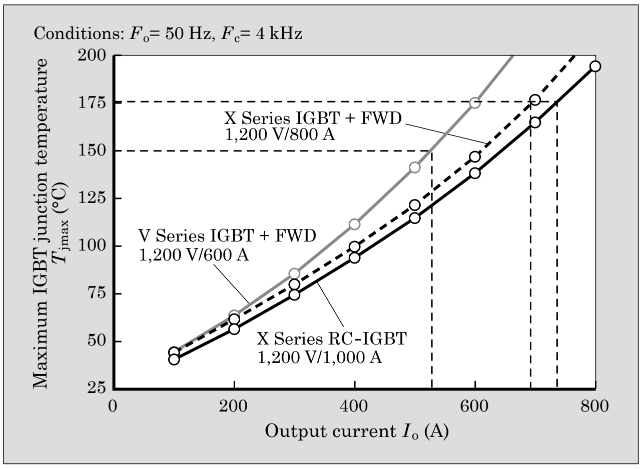


Fig.11 Maximum IGBT junction temperature of “Dual XT”

plying the package technology of the 7th-generation X Series, the guaranteed continuous operating temperature has been increased from the conventional 150 °C to 175 °C. As a result, a higher current density than before has been achieved with the same package and even higher power density and miniaturization of IGBT modules realized. In this way, it is possible to meet the requirements expected of IGBT modules such as miniaturization, loss reduction and higher reliability.

4. Postscript

This paper has described the 7th-generation “X Series” RC-IGBT modules for industrial applications. They have achieved even higher power density and miniaturization by applying an RC-IGBT, which integrates an IGBT and an FWD into one chip. We believe that using this module will lead to further miniaturization and cost reduction of power conversion equipment and widely contribute to society. In the future, we intend to continue working on technology innovation of IGBT modules and contribute to the realization of a safe, secure and sustainable society.

References

(1) Kawabata, J. et al. “The New High Power Density 7th Generation IGBT Module for Compact Power Conversion Systems”, Proceeding of PCIM Europe 2015.

(2) Kawabata, J. et al. 7th-Generation “X Series” IGBT Module. FUJI ELECTRIC REVIEW. 2015, vol.61, no.4, p.237-241.

(3) Takahashi, M. et al. “Extended Power Rating of 1200 V IGBT Module with 7 G RC- IGBT Chip Technologies”, Proceeding of PCIM Europe 2016.

(4) Takahashi, K. et al. “1200 V Class Reverse Conducting IGBT Optimized for Hard Switching Inverter”, Proceeding of PCIM Europe 2014.

(5) Takahashi, H. et al. “1200 V Reverse Conducting IGBT”, Proceeding of ISPSD 2004. p.133-136.

(6) M, Rahimo. et al. “The Bi- mode Insulated Gate Transistor (BIGT) A Potential Technology for Higher power Applications”, Proceeding of ISPSD 2009. p.283-286.

---

*1: PrimePACK: Trademark or registered trademark of Infineon Technologies AG

Fuji Electric

Innovating Energy Technology