7th-Generation “X Series” IGBT Module

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ABSTRACT

In recent years, the IGBT module market has been seeing increasing demand for compact modules with low loss and high reliability. In order to meet these demands, we have developed the 7th-Generation “X Series” IGBT Module. By significantly reducing the loss of IGBT and FWD chips and developing a package characterized by its high heat dissipation, high heat resistance and high reliability, we have reduced the module’s footprint by approximately 36% and power loss by approximately 10% and achieved long-term reliability. Furthermore, by enhancing its withstanding and characteristics during high-temperature operation, we increased the maximum temperature for continuous operation to 175 °C, from the conventional temperature of 150 °C. These enhancements have enabled the module to significantly increase output current, and this further increase the power density and miniaturizes the size of power converters.

1. Introduction

In recent years, there has been increasing demand to improve energy efficiency and reduce CO_2 emissions as measures for preventing the depletion of fossil fuels and mitigating global warming. As a result, the use of power conversion equipment that utilize power semiconductors has been spreading to a wide variety of fields, and the market for these devices has been expanding rapidly. Insulated-gate bipolar transistor (IGBT) modules are commonly being used as power semiconductor devices in a wide range of fields such as the industrial, consumer, automotive and renewable energy sectors. Since the introduction of IGBT modules to the market, there have been many technological innovations that have facilitated significant advances in miniaturization and reduced power dissipation(1). These developments have contributed to the miniaturization (reduced cost) and increased efficiency of power conversion equipment. However, the miniaturization of IGBT modules has caused a rise in chip junction temperature T_j due to increased power density, as well as degradation in reliability. Therefore, further miniaturization of IGBT modules in the future will require not only improvements in the characteristics of IGBT and free wheeling diode (FWD) chips, but also improvements in exothermicity and reliability through packaging technology innovation.

Fuji Electric has newly developed a 7th-generation “X Series” IGBT module that adopts 7th-generation chip technology and packaging technology in order to achieve further miniaturization, reduced power dissipation and increased reliability for IGBT modules. The X Series IGBT module not only achieves miniaturization, but also makes continuous operation at T_j=175 °C possible by improving chip characteristics and the long-term reliability of packaging. As a result, operation at even greater output currents is now possible when compared with the previous 6th-generation “V Series” IGBT modules, which supported continuous operation up to 150 °C.

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2. 7th-Generation Chip Technology

By significantly reducing the loss for the IGBT and FWD, the X Series IGBT module simultaneously achieves reduced power dissipation and chip size miniaturization. Furthermore, the module secures sufficient capability in the various areas that tend to be problematic at high temperature operation, thus enabling it to support continuous operation at T_j=175 °C.

2.1 7th-generation IGBT chip technology

Figure 1 shows the cross sectional structure of the IGBT. The basic structure of the 7th-generation IGBT is the same as the 6th-generation IGBT, having a trench-gate structure for the front surface structure. It also adopts a thin wafer IGBT that uses a field stop (FS) layer for the back side. Compared with the 6th-generation IGBT, the reduction in the thickness of the drift layer has enabled it to achieve a reduced on-state voltage (collector-emitter voltage). Moreover, by refining the design and optimizing the trench-gate structure of the front surface, it is able to suppress the hole pull-out from the p-channel at the time of conduction, while also increasing the injection enhanced (IE) effect by raising the carrier concentration on the front surface side, as well as significantly improving the trade-off relation between the on-voltage and turn-off loss. Generally, a thinner drift layer would create concern regarding voltage oscillation and degradation in with-

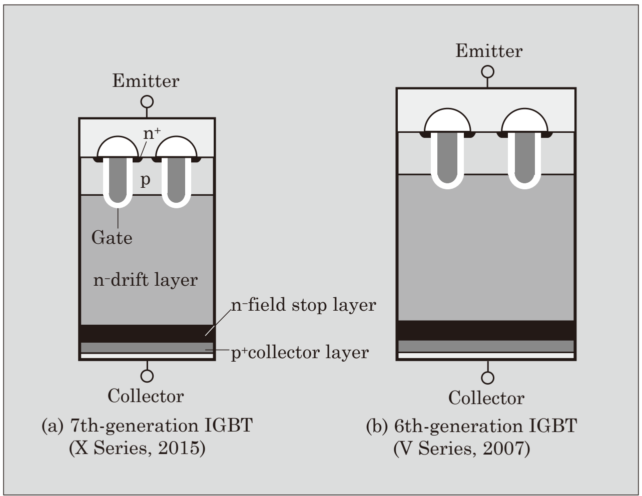

Fig.1 IGBT cross sectional structure

stand voltage at the time of turn-off, but by optimizing the FS layer, we have been able to suppress voltage oscillation and secure a sufficient withstand voltage.

Figure 2 shows the output characteristics of the 7th-generation IGBT. Comparing its rated current density with the 6th-generation IGBT, it has a lower on-state voltage of approximately 0.5 V at T_j=150 °C. Furthermore, even when operating at 175 °C, it has an on-voltage of approximately 0.45 V lower than that of the 6th-generation IGBT at 150 °C.

In general, it is well known that a trade-off relation between IGBT on-state voltage and turn-off loss exists. Figure 3 shows the trade-off characteristics of the 7th-generation IGBT on-state voltage and the turn-off loss. As mentioned earlier, the 7th-generation IGBT significantly reduces on-voltage, and it also greatly reduces tail current during turn-off by thinning its drift layer. It thereby decreases turn-off loss by 10%. As a result, compared with the 6th-generation IGBT, it achieves a significant improvement in the trade-off characteristics of turn-off loss and on-state voltage.

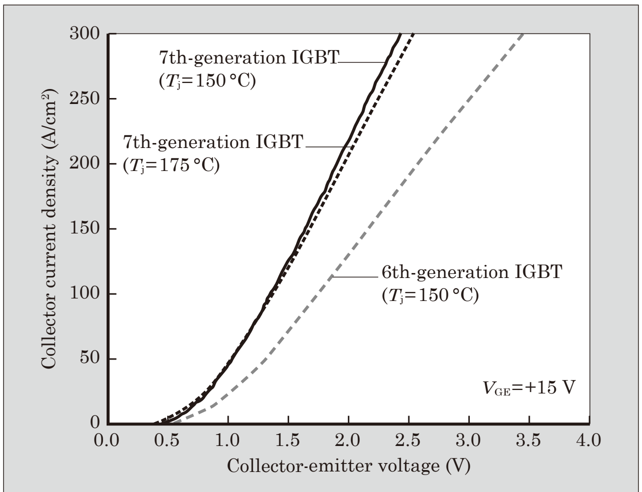

Fig.2 7th-generation IGBT output characteristics

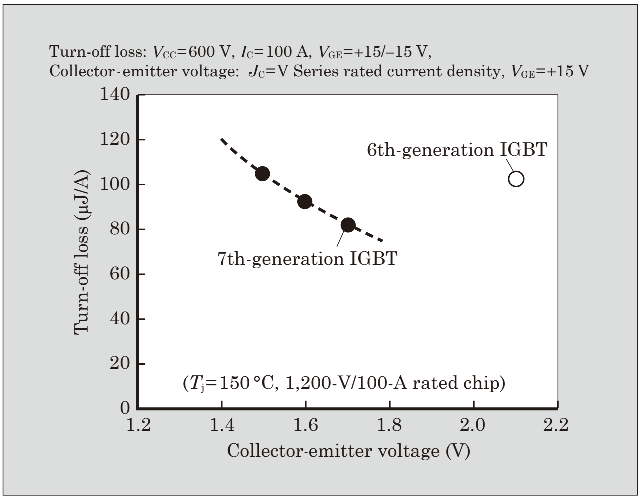

Fig.3 7th-generation IGBT trade-off characteristics

2.2 7th-generation FWD chip technology

By reducing the thickness of the drift layer, the 7th-generation FWD reduces forward voltage, and as shown in Fig. 4, it achieves smooth reverse recovery waveforms compared with the 6th-generation FWD through optimization of local lifetime control. In addition, it significantly reduces reverse recovery loss by reducing reverse recovery peak current and tail current. Figure 5 shows the trade-off characteristics of reverse recovery loss and forward voltage. When compared with the 6th-generation FWD at the same forward voltage, it achieves a reverse recovery loss reduction by approximately 30%.

On the other hand, reverse recovery surge voltage and voltage oscillation during reverse recovery can become problematic since a thinner drift layer generally makes it easier for the depletion region to reach the surface of the reverse side during reverse recovery(2). The 7th-generation FWD has optimized the reverse surface structure to suppress stretching of the depletion region during reverse recovery operation, and by preventing the depletion layer from reaching the reverse surface side, it is able to reduce reverse recovery voltage oscillation and reverse recovery surge voltage

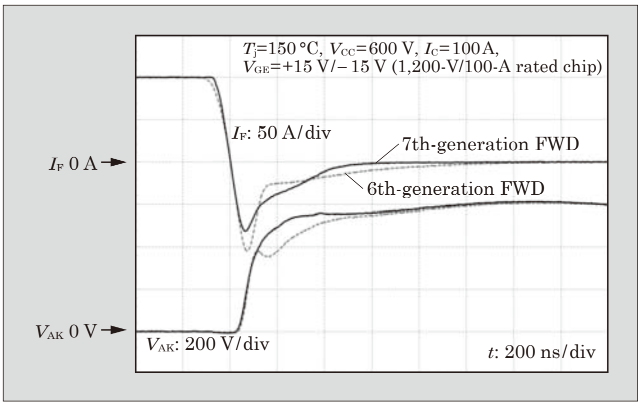

Fig.4 7th-generation FWD reverse recovery waveforms

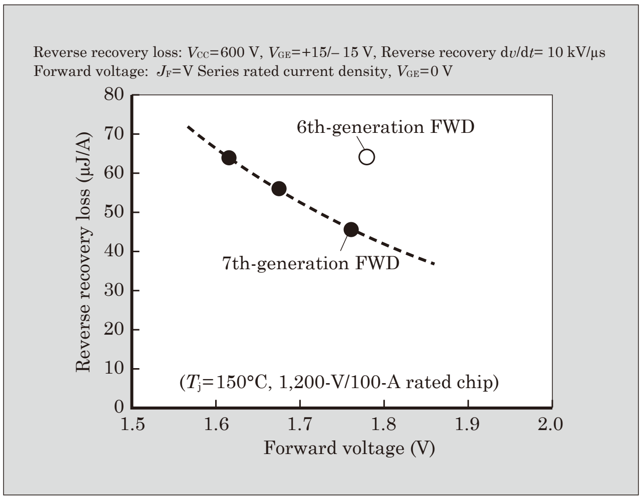

Fig.5 Reverse recovery loss and forward voltage trade-off characteristics

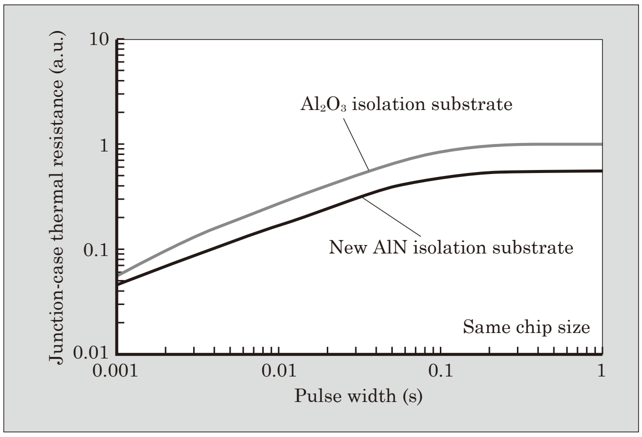

Fig.6 Junction-case thermal resistance

to not more than those of the 6th-generation FWD.

3. 7th-Generation Packaging Technology

In order to miniaturize IGBT modules, it is necessary to miniaturize the IGBT and FWD. However, miniaturization of the chip results in increased power density, and this causes degraded reliability due to a rise in chip temperature. To solve the issue, the X Series IGBT module makes use of a development in high heat-dissipating packaging technology to further suppress the rise in chip temperature, as well as high-reliability and high heat-resistant packaging technology to achieve continuous operation at 175 °C.

3.1 New AlN isolation substrate

In order to improve the exothermicity of the chip in the X Series IGBT module, we improved the thermal resistance of the isolation substrate, which occupies the largest portion among thermal resisting components from the chip to the cooling fins. Materials such as Al_2O_3 (alumina) and the highly thermal conductive AlN (aluminum nitride) are often used as materials for isolation substrates. In order to improve thermal resistance, it would be suitable if we could make use of an AlN isolation substrate, but since general AlN isolation substrates utilize a thick ceramic substrate, they are highly rigid, and thus reliability degradation becomes a concern due to higher thermal stress being applied to the solder located below the substrate when the molded case temperature rises. As a countermeasure, it is necessary to reduce the stress generated in the solder. Therefore, we tested methods for decreasing the rigidity of AlN isolation substrates by reducing the thickness of the ceramic substrate, as well as for alleviating the thermal stress that is applied to the solder located below the substrate. Conventionally, developing a thinner AlN isolation substrate has not been practical because there are concerns regarding the degradation of the dielectric strength of the module products and possible cracking in the ceramic substrate during the mounting processes of customers. Therefore, we have developed a new thin type AlN isolation substrate that is characterized by its enhanced strength achieved by optimizing ceramic sintering conditions, distributed thermal stress via an innovative substrate circuit pattern design, and optimized isolation design achieved by revising creepage distance[3].

By thus utilizing this new thin type AlN isolation substrate that achieves high heat dissipation and high reliability, we have ensured long-term reliability for the IGBT module, while also significantly reducing thermal resistance. Figure 6 shows the thermal resistance between the junction and case of an IGBT module that utilizes the new AlN isolation substrate. Thermal resistance has been reduced by approximately 45% on a chip that is the same size as the Al_2O_3 isolation substrates that are currently in widespread use. By using the new AlN isolation substrate for products that are particularly susceptible to increases in power density and rises in chip temperature, it is possible to overcome the temperature rise problems that IGBT module miniaturization has brought about.

3.2 Improvement of ΔT_j power cycle capability

There has been strong demand for long-term reliability in IGBT modules in order to lengthen the service life of power conversion equipment. In particular, capability against repetitive thermal stress (ΔT_j power cycle capability) is a major issue. In order to achieve operation at an even greater output current for the X Series IGBT module, the feasible region for continuous operation has been improved from the previous T_j=150 °C to 175 °C. In general, when T_j rises, the materials around the chip deteriorate quicker, and this, in turn, degrades ΔT_j power cycle capability[4]. ΔT_j power cycle capability is largely influenced by degradation in the product lifespan because wire bonding contact points on the chip and solder below the chip receive the greatest amount of thermal stress. To ensure that the X Series IGBT module has a sufficient ΔT_j power cycle

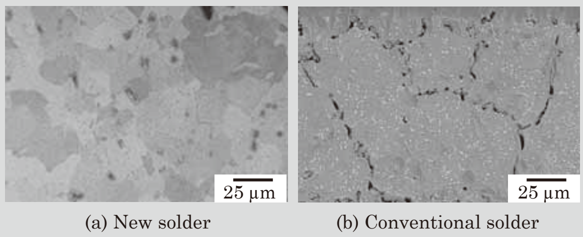

Fig.7 Cross section of solder below chip after a ΔT_j power cycle capability test

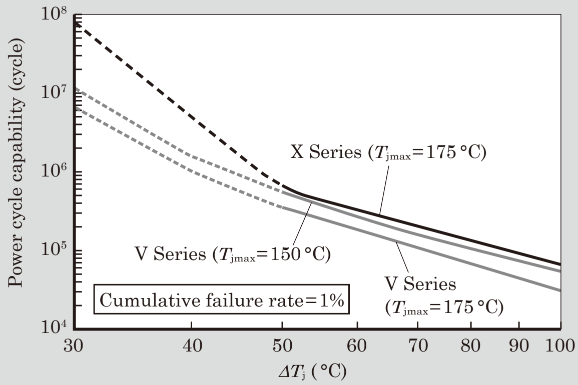

Fig.8 ΔT_j power cycle capability

capability even at T_j=175 °C, we optimized the design of the wire bonding and also applied our newly developed high strength solder.

Figure 7 shows the results of cross-section observation of the solder below the chip after a ΔT_j power cycle capability test following the same cycle. Although cracks were observed in the conventionally used solder, we verified that cracking was suppressed in the new solder. Figure 8 shows the ΔT_j power cycle capability. The X Series IGBT module achieves approximately twice as much capability as the V Series IGBT module (T_{jmax}=175 °C, ΔT_j=50 °C). Therefore, long-term reliability has been ensured with a ΔT_j power cycle capability equivalent to or better than conventional modules even when operating at T_{jmax}=175 °C.

3.3 High heat-resistant silicone gel

To ensure the long-term reliability of the IGBT module, we were still faced with the issue of deteriorating silicone gel at high-temperature operation. In general, silicone gel hardens in proportion with temperature rise, and this causes a concern regarding cracking in the hardened gel. The cracks fracture the isolation sheath of the gel, and this degrades isolation performance. Therefore, in order to achieve continuous operation at 175 °C, we newly developed a high heat-resistant silicone gel. The high heat-resistant silicone gel makes use of an optimized material composition for suppressing hardening at high temperatures. We performed a high-temperature shelf test (215 °C, 2,000 hours) and verified that there was no cracking in the high heat-resistant silicone gel, although cracking did occur in the conventional silicone gel as a result of the hardening.

Figure 9 shows the relation between the environmental temperature and the lifespan of the silicone gel. The lifespan of the high heat-resistant silicone gel at 175 °C is greatly improved over that of conventional silicone gel, while it also has the same lifespan that the conventional silicone gel has at 150 °C. As a result, isolation performance equivalent to that of the conventional module at 150 °C has been ensured even during continuous operation at 175 °C.

Furthermore, the relation between the environmental temperature and the coefficient of elasticity of the silicone gel is shown in Fig. 10. While the conventional silicone gel is characterized by rapid hardening

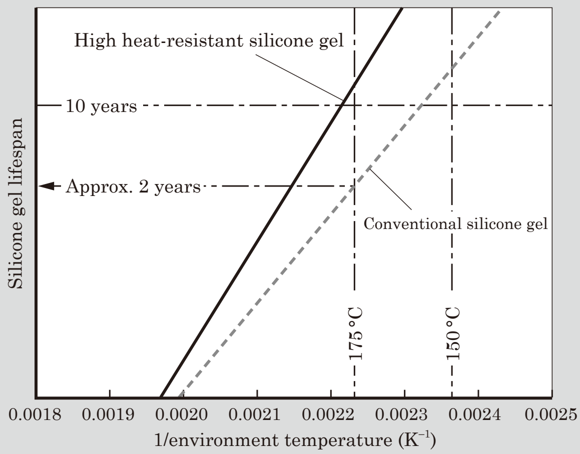

Fig.9 Relation between environment temperature and lifespan of silicone gel

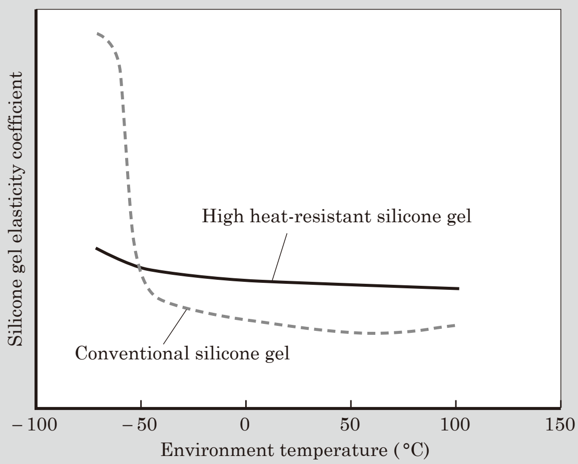

Fig.10 Relation between environment temperature and coefficient of elasticity of silicone gel

at temperatures of −50 °C or below, the high heat-resistant silicone gel suppresses rise in the coefficient of elasticity even at low temperatures, thus enabling it to achieve an improvement in isolation in low temperature environments. By using the high heat-resistant silicone gel, IGBT modules can be used in various installation environments, and they are expected to be utilized in a wide range of applications.

4. IGBT Module Miniaturization

Significant improvement in loss characteristics via the application of 7th-generation IGBT and FWD, as well as large-scale improvement in exothermicity and reliability through the adoption of innovative packaging technology have made it possible for the X Series IGBT module to achieve further miniaturization and greater power density than conventional modules. As an example, for the V Series IGBT module in a EP2 package with a rated capacity of 1,200 V, the maximum current rating was 50 A, whereas the X Series IGBT module is able to achieve a new rating of 75 A. In addition, it is possible to reduce the footprint by approximately 36% when migrating from the conventional V Series IGBT module EP3 package with a rating of 75 A.

The X Series IGBT module not only has a more compact size and greater power density, but it also dissipates less power at the same time. Figure 11 shows the calculated results of power loss and IGBT junction temperature during normal operation in an X Series IGBT module EP2 package with a rated current capacity of 75 A. Compared with a V Series IGBT module EP3 package with a rated product capacity of 75 A, it successfully reduces power loss by approximately 10%, while also reducing the IGBT junction temperature by approximately 10 °C (f_C=8 kHz).

As described above, the improvements in ΔT_j power

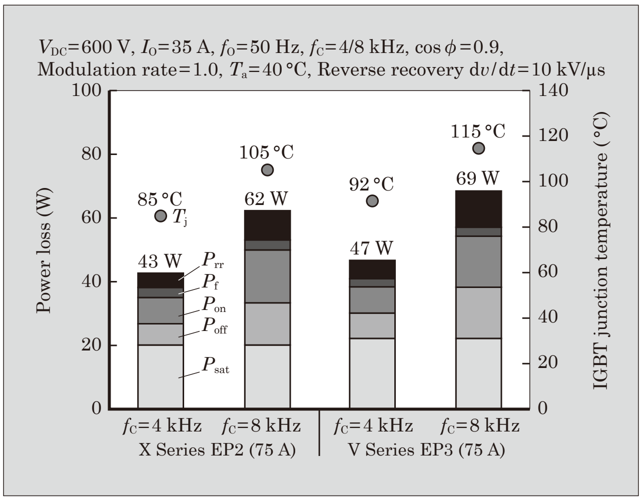

Fig.11 Power loss and IGBT junction temperature during normal operation

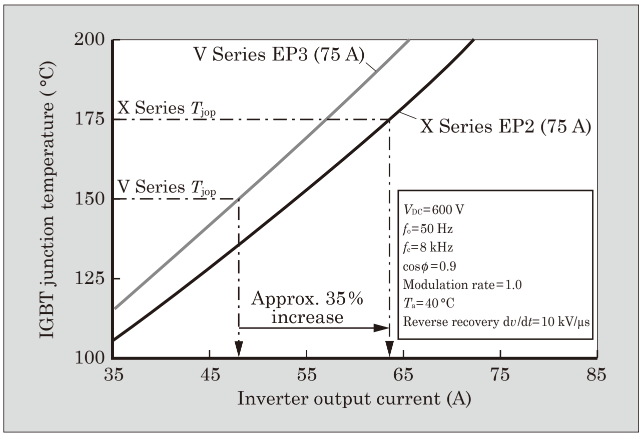

Fig.12 Inverter output current and IGBT junction temperature

cycle capability and silicone gel heat resistance have made continuous operation at 175 °C possible for the X Series IGBT module. As a result, it has become possible to further improve power density in power conversion equipment, and as shown in Fig. 12, it is also possible to increase output current by approximately 35% compared with V Series IGBT module EP3 packages with a rated current capacity of 75 A.

5. Postscript

The 7th-generation “X Series” IGBT module is capable of simultaneously achieving miniaturization, reduced power dissipation and higher reliability by significantly reducing loss for IGBT and FWD, and by taking advantage of the development of high-reliability and high heat-dissipating packaging technology. Since migrating from conventional products to the 7th-generation IGBT module makes it possible to miniaturize the size of power conversion equipment and reduce costs, it is expected that power conversion equipment will become more widely utilized and efficient in the future, thus enabling them to contribute greatly to solving the world’s energy issues.

References

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