Development of a Next-generation IGBT Module using a New Insulating Substrate

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1. Introduction

In response to the recent demand for energy-efficient electronic appliances, insulated gate bipolar transistor (IGBT) modules are being utilized in a wider scope of applications, ranging from conventional industrial applications to home-use electronic appliance applications and the like. There is strong demand for low-capacity IGBT modules, which are used mainly for these home-use electric appliances, to be low cost, lightweight and have a compact size.

In response to this demand, Fuji Electric has developed and has begun producing its “Small Pack” series of IGBT modules. This series utilizes a heat-dissipating base-free structure (which does not contain a heat-dissipating metal base) in order to realize low-cost and lightweight IGBT modules.

This paper introduces a heat-dissipating base-free structure that utilizes a new insulating substrate to achieve an additional 30 % decrease in thermal resistance.

2. Design Concept [(1), (2)]

Heat-dissipating base-free structures, which typically have larger thermal resistance than heat-dissipating metal-base-equipped structures, have been difficult to use in industrial applications and other such applications where the usage conditions are severe. Heat-dissipating base-free structures are presently used only in low power applications and, unless a new technological approach is employed, their application to medium and large capacity applications is seen as unlikely.

Figure 1 shows a cross-sectional view of typical IGBTs. In the heat-dissipating metal-base-equipped structure of Fig. 1(a), the DCB substrate (substrate with ceramic insulation) is soldered to a heat-dissipating metal base, and a cooling fin is attached to the base. In the heat-dissipating base-free structure of Fig. 1(b), a cooling fin is attached directly to the DCB substrate.

In order to transfer the heat efficiently to a cooling fin, a thin thermal compound must be used to fill any gaps between the fin and module. In actuality, it is important that a screw be tightened in order to maintain the pressure between the fin and module surfaces, and in order to prevent damage to the module while the screw is tightened, the module must maintain its mechanical strength. In the conventional heat-dissipating base-free structure, the alumina ceramic portion of the DCB substrate is made thicker in order to maintain the mechanical strength. As a result, however, the thermal resistance becomes larger than in the case of a heat-dissipating metal-base-equipped structure, and this is a factor which limits applications for heat-dissipating base-free structures.

Figure 2 shows Fuji Electric’s “6 in 1” IGBT module. In terms of the power per unit area of an IGBT module, the heat-dissipating metal-base-equipped structure of Fig. 2(a) has a capacity of 4.7 W (max)/

Fig.1 Cross section of an IGBT module

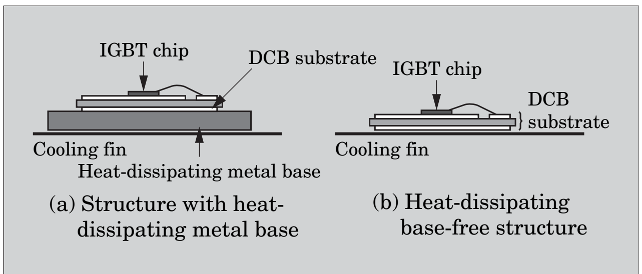
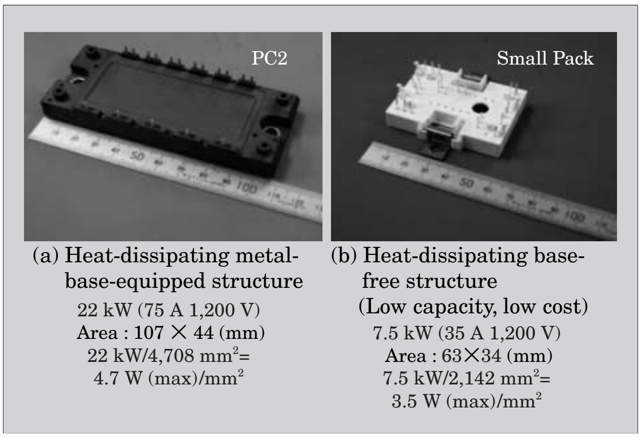


Fig.2 Fuji’s 6-pack module



mm^2, while the heat-dissipating base-free structure of Fig. 2(b) has a capacity of 3.5 W (max)/mm^2.

Given these circumstances, we investigated and then developed a DCB substrate having low thermal resistance and high strength in order to increase the usable power per unit area of an IGBT module while realizing lighter weight, smaller size and lower cost.

3. Design of a New Alumina Insulating Substrate

3.1 A comparison of characteristics according to IGBT module structure

Table 1 lists the characteristics of the conventional heat-dissipating base-free structure and of the heat-dissipating metal-base-equipped structure. The heat-dissipating base-free structure uses a 0.635 mm-thick alumina ceramic layer in order to maintain mechanical strength of the IGBT module. On the other hand, the heat-dissipating metal-base-equipped structure has sufficient mechanical strength and the thickness of its alumina ceramic layer can be reduced to 0.32 mm.

Due to this difference, the thermal resistance of the heat-dissipating base-free structure is 1.6 times that of the heat-dissipating metal-base-equipped structure.

3.2 Factors that inhibit thermal conduction and measures for improvement

Figure 3 shows cross sections of IGBT modules having a heat-dissipating base-free structure. Heat generated at the junction in an IGBT chip passes through the DCB substrate and is transferred to a heat-dissipating fin. Because the thermal conductivity of the alumina ceramic of the insulated portion of the DCB substrate is 20 W/(m·K) and the thermal conductivity the copper used for the electronic circuitry is 390 W/(m·K), the alumina ceramic layer of the DCB substrate acts as a thermal resistance layer through which heat generated from the IGBT chip has difficulty in passing through.

In order to make it easier for heat to pass through this layer, it is efficient to make the thermal resistance layer smaller and to decrease the heat flow (heat density) per unit area. Specifically, the following two countermeasures are proposed.

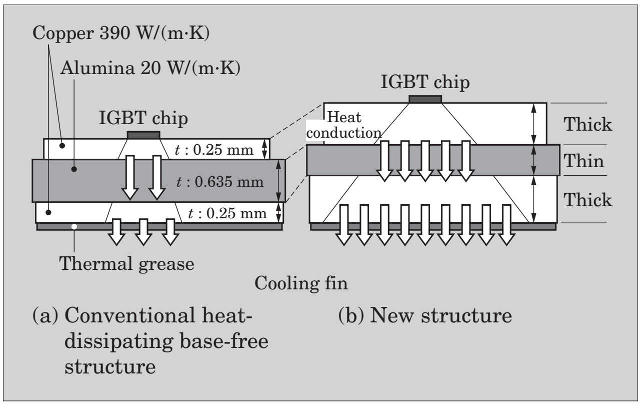
(1) Decrease the thickness of the alumina ceramic layer
(2) Increase the thickness of copper foil in order to disperse the heat and decrease the heat flow per unit area of the alumina ceramic layer

Accordingly, reducing the thermal resistance of the DCB substrate is an efficient way to lower the temperature of the IGBT chip. Moreover, by increasing the thickness of the copper foil, an improvement in the mechanical strength of the DCB substrate itself can be expected.

Table 1 Comparison between the metal-base free structure and the structure having a metal base

		Conventional heat-dissipating base-free structure	Heat-dissipating metal-base-equipped structure
DCB substrate characteristics	Alumina thickness	0.635 mm	0.32 mm
	Bending strength	108 N	53 N
Thickness of metal base		–	3.0 mm
Thermal resistance $R_{th(j\text{-}c)}$		100	62

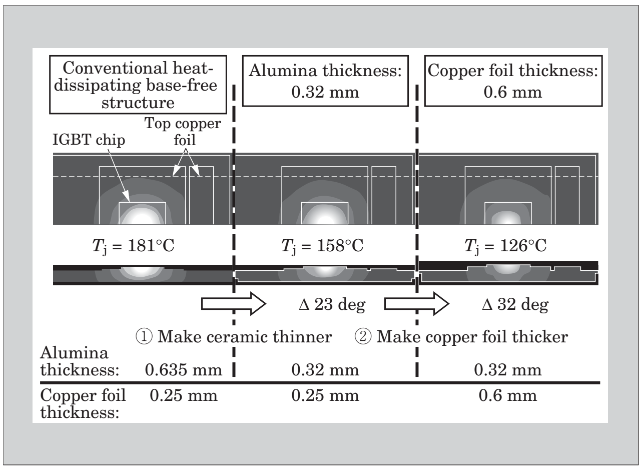
Fig.3 Cross-section of DCB structures and thermal characteristics



3.3 FEM analysis results

Next, as a first step to verify the effectiveness of the above, we performed a steady-state thermal analysis using the finite element method (FEM). The analysis was performed under the conditions of a DC 80 A current applied to a 3-dimensional half-scale model of a 9.25 mm-square IGBT chip, a 33 × 30 (mm) DCB ceramic substrate, and a 25 × 17 (mm) copper foil on top of the DCB surface. In the steady-state analysis, we varied the thickness of the alumina ceramic layer and the thickness of the copper foil to analyze their effect on IGBT chip temperature. The

Fig.4 Thermal simulation results for each structure (DC 80 A steady state condition)



results are shown in Fig. 4.

From the results of this analysis, it can be seen that by reducing the thickness of the aluminum ceramic layer from 0.635 mm to 0.32 mm, the IGBT chip temperature decreases by 23°C. Moreover, while maintaining the thickness of the alumina ceramic layer at 0.32 mm and increasing the thickness of the copper foil from 0.25 mm to 0.6 mm, it can be seen that the chip temperature decreases by an additional 32°C.

Next, we performed a steady-state heat analysis in which the IGBT chip temperature was fixed at 126°C, and we analyzed the relationship between copper foil thickness and heat conduction. Those results are shown in Fig. 5.

Compared to the DCB substrate copper foil thickness of 0.25 mm, a copper foil thickness of 0.6 mm exhibited greater conduction of heat. From this result, it can be understood that increasing the thickness of the copper foil decreases the density of heat flow through the alumina ceramic layer.

Additionally, we performed a steady-state heat analysis to investigate the correlation between copper foil thickness and chip temperature for the two alumina ceramic layer thicknesses of 0.32 mm and 0.635 mm. Those results are shown in Fig. 6.

It can be seen that decreasing the alumina ceramic layer thickness and increasing the copper foil thickness are effective measures for lowering the IGBT chip temperature. Moreover, in a steady-state heat analysis under the same conditions, the IGBT chip temperature was 125°C in the case of a heat-dissipating metal-base-equipped structure. To realize an IGBT chip temperature of 125°C with a heat-dissipating base-free structure, the same thermal resistance was obtained by selecting an alumina ceramic layer thickness of 0.32 mm and a copper foil thickness of 0.6 mm.

Fig.5 Relationship between copper foil thickness and heat conduction area

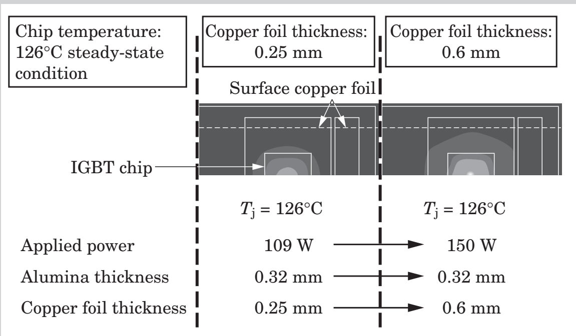
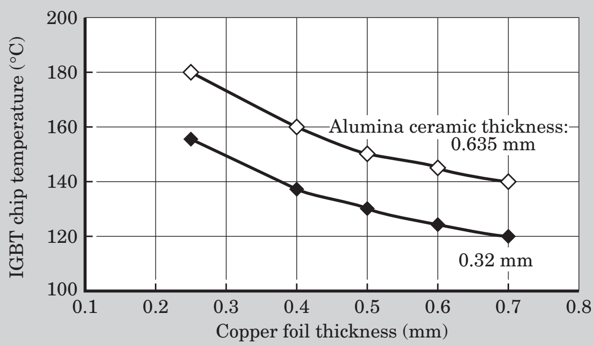


Fig.6 Relationship between copper foil thickness and chip junction temperature



4. Results of Testing and Verification with Actual Machines

In order to verify the above analysis results, we measured the transient thermal resistance and steady-state thermal resistance of a DCB test piece and measured the mechanical characteristics of a DCB substrate.

4.1 Transient thermal resistance

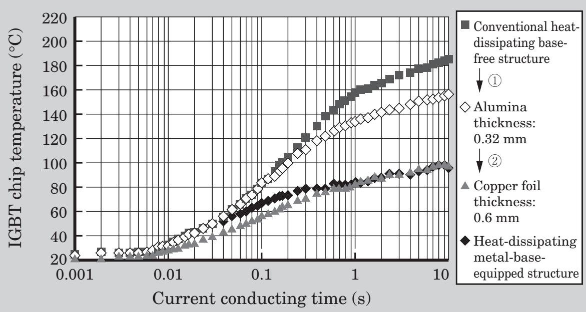
We input a DC 80 A current to the IGBT chip and investigated the relationship between current conduction time and IGBT chip temperature for three different types of DCB substrates (using the same conditions as the FEM simulation of Fig. 4).

Figure 7 shows the relationship between the current conduction time and chip temperature.

First of all, one second after the start of current conduction, it can be seen that the conventional heat-dissipating base-free structure (alumina ceramic thickness of 0.635 mm, copper foil thickness of 0.2 mm) had an IGBT chip temperature which was 85°C higher than that of the heat-dissipating metal-base-equipped structure (DCB: alumina ceramic layer thickness of 0.32 mm, copper foil thickness of 0.2 mm, and base thickness of 3 mm).

Secondly, while maintaining the heat-dissipating base-free structure but reducing the thickness of the alumina ceramic layer in the DCB substrate from 0.635 mm to 0.32 mm, it can be seen that the IGBT chip temperature decreases by approximately 20°C. (See ① of Fig. 7.)

Fig.7 Time dependent temperature rise of three different types of substrates



Thirdly, by reducing the thickness of the alumina ceramic layer in the DCB substrate to 0.32 mm and increasing the copper foil thickness to 0.6 mm, it can be seen that the IGBT chip temperature decreases by 66°C compared to the case where the copper foil thickness is 0.25 mm (see ② of Fig. 7).

Fourthly, by reducing the thickness of the alumina ceramic layer to 0.32 mm and increasing the copper foil thickness to 0.6 mm, it can be seen that the IGBT chip temperature decreases by 86°C compared to the conventional heat-dissipating base-free structure.

This value is nearly the same as the IGBT chip temperature of the heat-dissipating metal-base-equipped structure. Accordingly, the above results verify that decreasing the thickness of the alumina ceramic layer in the DCB substrate and increasing the copper foil thickness are extremely effective measures for improving the transient thermal resistance characteristic.

4.2 Steady-state thermal resistance

We measured the steady-state thermal resistance under the same conditions as used in the measurement of transient thermal resistance. Figure 8 shows thermo-photographs of the IGBT chip in a steady-state condition. With a new heat-dissipating base-free structure using an alumina ceramic layer thickness of 0.32 mm and a copper foil thickness of 0.6 mm, the IGBT chip temperature decreased by 62°C compared to the conventional heat-dissipating base-free structure, and this IGBT chip temperature is approximately the same as that of the heat-dissipating metal-base-equipped structure. From these experimental results, it was verified that the use of a thinner alumina layer in the DCB substrate and a thicker copper foil are effective measures for improving the steady-state thermal resistance.

4.3 Mechanical characteristics of the DCB substrate

Figure 9 shows cross-sectional photographs of DCB substrates. In the figure, (a) shows a DCB substrate that uses the conventional heat-dissipating base-free structure, and (b) shows the newly-developed thick copper foil DCB substrate.

When a copper foil of thickness 0.4 mm or greater is directly bonded to a alumina ceramic layer having a typical purity of 96 %, differences in the coefficients of thermal expansion between the alumina ceramic material and the copper cause cracking to occur in the alumina ceramic layer near the bonded junction. The bending strength of 96 % pure alumina ceramic material is approximately 400 MPa, and as a DCB substrate, this strength is insufficient for bonding to a thick copper foil.

Therefore, by adding zirconia to the alumina ceramic material to increase its mechanical strength and increase its bending strength to 700 MPa, we succeeded in bonding a 0.6 mm-thick copper foil to this alumina ceramic (Table 2). Compared to the conventional heat-dissipating base-free structure, a structure that uses this new DCB substrate achieves an approximate 30 % total improvement in mechanical strength due to the increased thickness of the copper foil, despite the thin alumina ceramic layer.

By making the copper foil thicker and by using a thin zirconia-doped alumina ceramic layer, a new heat-dissipating base-free structure is possible, realizing greater mechanical strength and lower thermal resistance of the module compared to the conventional heat-dissipating base-free structure.

4.4 Evaluation and results of reliability testing

There were concerns that the increase in thickness of the copper foil would lead to an increase in the coefficient of thermal expansion of the copper circuitry, deterioration of the solder at the bottom of the silicon

Fig.8 Thermo-photographs (at steady-state condition)

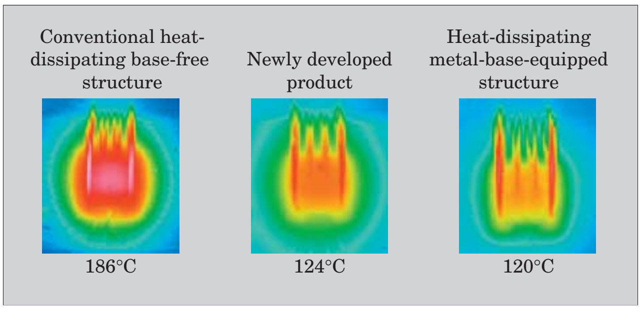
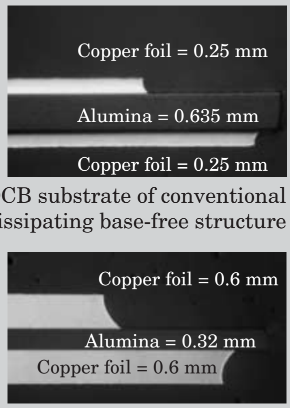


Fig.9 Cross-sectional photographs of DCB substrates



(a) DCB substrate of conventional heat-dissipating base-free structure

(b) Newly developed DCB substrate

Table 2 Fabrication limits for DCB

	Copper foil thickness (mm)				
	0.3	0.4	0.5	0.6	0.7
Alumina	○	×	–	–	–
Zirconia-doped alumina ceramic	○	○	○	○	×

Ceramic thickness: 0.32 mm
○ : Possible × : Not possible

Table 3 Evaluation results of Fuji Electric's new product that uses the new DCR structure

	Conventional heat-dissipating base-free structure	New structure
Thermal resistance $R_{th(j-f)}$	100	71

Fig.10 Characteristics of Fuji Electric's IGBT chips

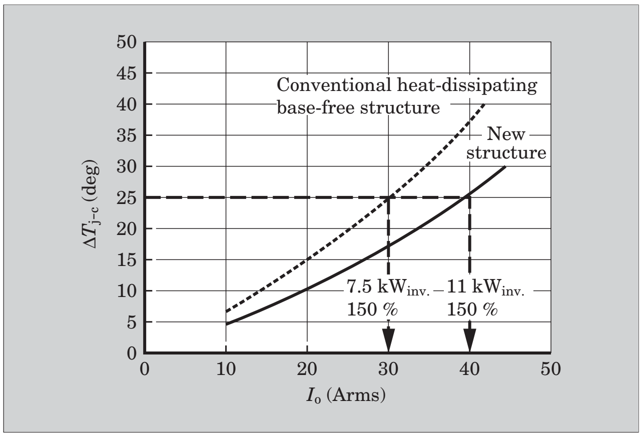
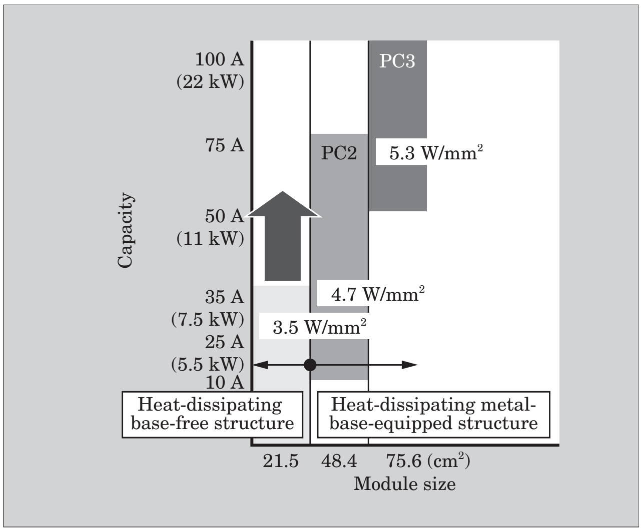


Fig.11 Fuji Electric's 1,200 V IGBT module line-up



chip, cracking of the alumina ceramic layer, and so on. Therefore, we performed heat cycle tests and power cycle tests to investigate the reliability of a heat-dissipating base-free structure that uses this new DCB substrate.

A heat cycle test was performed for 500 cycles under test conditions of −40 to +125°C, and it was verified that there was no degradation of the solder at the bottom of the IGBT chip, no change in thermal resistance due to solder deterioration, and no cracking of the alumina ceramic layer.

A power cycle (intermittent operation) test was also performed under the test condition of ΔT_{j-c} = 75 deg. No changes in thermal resistance or electrical characteristics have been observed through 350 k cycles of the test. The above results demonstrate that an IGBT module using the new DCB substrate achieves the same reliability characteristics as a conventional IGBT module.

5. Product Evaluation Results

Table 3 shows the results of an evaluation of Fuji Electric's Small Pack which uses the new heat-dissipating base-free structure.

The use of the new heat-dissipating base-free structure achieves 30 % lower thermal resistance than the conventional Small Pack. The new heat-dissipating base-free structure also achieves sufficient module mechanical strength and reliability.

Figure 10 shows the characteristics (ΔT_{j-c} and output) of Fuji Electric's latest IGBT chip used in the Small Pack. A Small Pack that employs the conventional heat-dissipating base-free structure can be used in inverter systems of up to 7.5 kW maximum. However, a Small Pack that employs this new DCB substrate can be used in inverter systems of up to 11 kW maximum.

Figure 11 shows Fuji Electric's 1,200 V IGBT module line-up. The application of a new heat-dissipating base-free structure enables the power applied per unit area to be increased from 3.5 W/mm^2 to 5.1 W/mm^2.

6. Conclusion

By adding zirconia to a DCB substrate of alumina ceramic material, decreasing the thickness of the alumina ceramic layer and increasing the thickness of the copper foil, a lightweight, compact and low cost IGBT module that uses a low thermal resistance heat-dissipating base-free structure has been developed.

Fuji Electric efforts in developing this new IGBT module structure have been described above. Fuji Electric intends to continue to expand the range of applications for this technology and to develop IGBT modules that satisfy increasingly severe customer needs and new demand.

References

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(2) Nishimura, Y. et al. New generation metal base free IGBT module structure with low thermal resistance. The 16th International Symposium on Power Semiconductor Devices & ICs (ISPSD'04). Kitakyushu, Japan, May 2004.

(3) US PAT. 5675181, 5869890.