

New Concept IGBT-PIM Using Advanced Technologies

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1. Introduction

With the dramatic development of power electronics in recent years, IGBT (insulated gate bipolar transistor) modules have become the mainstream semiconductor devices used in industrial power conversion applications, and are being applied in a wide range of fields including manufacturing, transportation, home electronics and the like. With each successive generation, IGBT modules have incorporated novel technology to realize energy savings, higher efficiency, smaller size, lower cost and higher reliability. Also, in order to realize higher integration to comply with requests for smaller size and higher performance inverters, IGBT modules have developed into PIMs (power integrated modules), in which an inverter circuit, an input rectifier circuit and a dynamic braking circuit for regeneration are all housed within a single package. Fuji Electric has previously brought to market a 3rd generation N series PIM in 1995, a 4th generation S series Econo-PIM in 1999, and a 5th generation U series in 2002. Requests for smaller size and lower cost machines have been especially strong in recent years, and in response to such requests Fuji Electric has newly developed IGBT-PIMs that incorporate the latest chip package technology. This paper introduces Fuji Electric's latest IGBT-PIM technologies and product lineup.

2. Challenges in Achieving Smaller Size and Higher Integration

Shrinking the die size is an extremely effective technique for realizing the smaller size and lower cost required by the market in recent years. However, shrinking the die size causes an increase in thermal resistance $R_{th(j-c)}$ and also a simultaneous rise in chip temperature as expressed by Equation (1) (where ΔT_{j-c} is the width of the temperature rise), and therefore lower power dissipation and higher heat dissipation of the chip are requirements.

$$\Delta T_{j-c} = \text{power dissipation} \times R_{th(j-c)} \dots\dots\dots (1)$$

In order to reduce power dissipation, not only must the on-state voltage be reduced, but higher speed switching must also be adopted to reduce switching

loss. However, noise radiation will increase as a result. The level of noise radiation is limited by the European standard EN61800-3 and the like. Overcoming this tradeoff between lower power dissipation and noise radiation has presented a new challenge in recent years. As a solution, in 2005 Fuji Electric fully incorporated the latest chip technologies to develop the U4 series of chips in which the noise and power dissipation characteristics were optimized. Also, due to the smaller size and higher density mounting of these chips, it is necessary to develop a package having higher heat dissipation capability, and it is also necessary to increase the mounting efficiency by adopting a high heat dissipating DCB (direct copper bonding) substrate (insulating ceramic substrate), to eliminate thermal coupling, and to use an optimized internal layout, etc. Additionally, RoHS*1 compliance is also a recent requirement of the marketplace. Accordingly, products must be developed so as to satisfy all of these challenges.

3. Characteristics of New Concept IGBT-PIMs

Product development based on the following concepts was carried out to realize not only energy savings, higher efficiency and higher reliability, but also smaller size, higher integration, and lower cost.

- (1) Coexistence of low noise and low power dissipation
 - Improved tradeoff between noise and power dissipation through applying IGBT chips that utilize the latest technology and FWD (free wheeling diode) chips
 - Lower noise realized through improved internal layout of package
 - (2) Realization of small package size and low cost
 - Use of a high heat dissipating new DCB substrate
 - Optimal chip layout to eliminate thermal coupling
 - Optimal internal layout to increase chip mounting efficiency
- Adopting the above concepts, the die size was re-

*1: RoHS is restriction of the use of certain hazardous substances in electrical and electronic equipment.

duced by approximately 30 % compared to the conventional die size, and higher integration was realized.

- (3) Realization of 1,200 V/150 A PIM in conventional EP3-size package

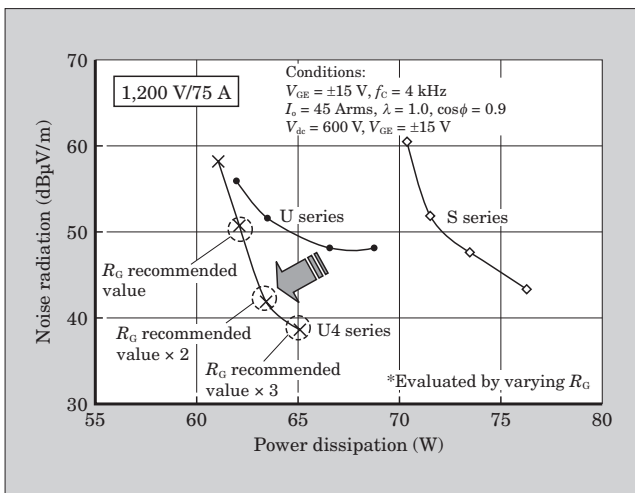
4. Latest Chip Technology

The 1,200 V/1,700 V U series of IGBTs developed in 2002 are the latest models of Fuji Electric's IGBT chips that utilize a trench gate structure and a field stop (FS) structure⁽¹⁾. Further improving the characteristics of this technology, Fuji Electric has also developed an easy-to-use 1,200 V/1,700 V U4 series of IGBT modules (U4-IGBT). Specifically, optimization of the trench gate structure enabled the turn-on speed controllability to be improved compared to a conventional trench IGBT, and the decrease in Miller capacitance (C_{res}) enabled an approximate 30 % reduction in turn-on loss. The noise radiation during switching depends not only on the reverse recovery characteristics of the FWD, but also on the IGBT turn-on characteristics which determine the reverse recovery characteristics of the FWD. Therefore, to reduce noise radiation, both the FWD and the IGBT characteristics must be optimized.

It has been reported that oscillation from a resonant closed loop circuit between the IGBT module and snubber capacitance constitutes a radiation source and is the mechanism by which noise radiation is generated, and that di/dt and dv/dt during switching trigger the resonance. In particular, the resonance condition is determined by di/dt and dv/dt when the IGBT is turned on, and the reverse recovery characteristics of the FWD are similarly determined by the turn-on characteristics.

The U4-IGBT enhances the above-described chip characteristics to realize improved di/dt and dv/dt controllability at turn-on and reduced turn-on loss, and improved tradeoff between noise radiation and power dissipation as shown in Fig. 1.

Fig.1 Tradeoff between noise radiation and power dissipation



5. Latest Package Technology

5.1 Optimal internal pattern layout

- (1) Eliminating thermal coupling

In an IGBT-PIM containing multiple power chips within the same package, since all elemental devices emit heat during actual inverter operation, heat becomes concentrated within the package interior due to thermal coupling among neighboring chips. In order to realize the smaller product sizes required in the marketplace, the concentration of heat due to thermal coupling must be eliminated. Therefore, when developing the new package, we used three-dimensional FEM (finite element method) thermal analysis to investigate and optimize the internal chip layout. Figure 2 compares the temperature distributions in conventional and new packages, for the same package size. In the conventional package, power chips are concentrated in the vicinity of the package center, and therefore the chip temperature at the center of the package is higher due to the effect of thermal coupling. On the other hand, in order to eliminate thermal coupling among power chips, the chip layout and chip spacing were optimized in the new package. As the result, the temperature distribution became nearly uniform, and the effect of decreasing T_j by a maximum of 10°C was verified.

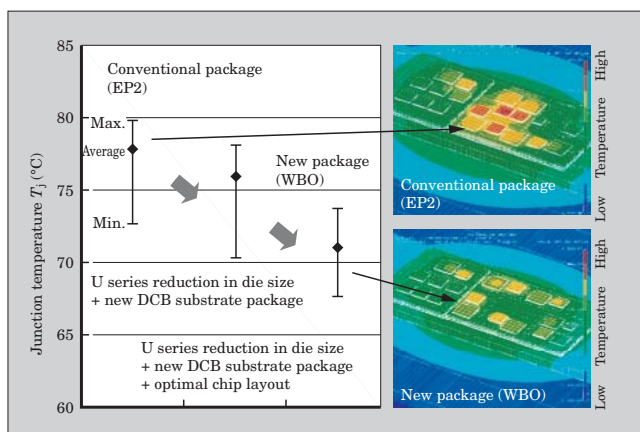
- (2) Improving the chip mounting efficiency

With a thermally distributed chip layout and optimal DCB pattern layout, the new package increases the chip installation area ratio from 16.7 % to 26.1 % and increases the chip mounting efficiency by 56 %.

5.2 Technology for reducing noise

An inverter must be designed so that the noise radiation in the frequency range of 30 MHz to 1 GHz is at a level that conforms to certain standards. It has been reported that oscillation from a resonant closed loop circuit between the IGBT module and snubber circuit constitutes a radiation source and is the mechanism

Fig.2 Comparison of temperature distributions according to FEM thermal analysis



by which noise radiation is generated in this frequency region. Maxwell's equation for a distant field is expressed as:

$$E = 1.32 \times 10^{-14} \times f^2 \times S \times I/r \dots\dots\dots (2)$$

(where f is frequency, I is current, S is current loop area, and r is distance),

and a distant field is also dependent on the current closed loop area of the snubber circuit and switching element. Accordingly, in order to reduce the P-N current loop area inside the package, we improved the DCB copper pattern wiring, and tested and studied not only element characteristics, but also the package itself for the purpose of reducing noise. As a result, as shown in Fig. 3, the P-N current loop area was decreased by approximately 50 % compared to a conventional package, and as shown in Fig. 4, the peak value of noise radiation was decreased by approximately 5 dB. Consequently, the turn-on speed can be increased further, and a reduction in switching loss is anticipated.

5.3 Development of new DCB substrate

Figure 5 shows cross sections of IGBT modules (including PIMs). The heat generated by the IGBT chip and FWD chip is conducted through the DCB substrate and copper base plate, and dissipated by the cooling fin. Compared to other materials, the thermal properties of highly strong but less expensive alumina ceramic material are inferior. The thermal conductance of the copper in the DCB substrate is 390 W/m·K, and the alumina ceramic for an insulating layer typically has a thermal conductance of 20 W/m·K, with the ceramic

material acting as a heat insulating barrier. In order to lower the thermal resistance of the DCB substrate, the ceramic material was formed into a thin plate and its thermal conductance improved. On the other hand, based on the results of recent development work, it is understood that reducing the heat flux (heat concentration) per unit area is an effective way to improve the heat dissipation capability. While developing this product, in order to realize lower cost and higher reliability, we considered using alumina ceramic material for the base, as had been done in the past. However, eventually, we adopted the following specific strategy and developed the new DCB substrate⁽²⁾.

- (1) Use a ceramic having high thermal conductivity to ensure long-term reliability and mechanical strength (conductivity: 28 W/m·K)
- (2) Increase the thickness of the DCB substrate copper foil from the existing thickness of 0.25 mm to 0.6 mm in order to disperse heat and reduce the heat flow per unit area
- (3) Achieve higher reliability by increasing the copper foil thickness to remove the constraint on the coefficient of linear expansion that had been imposed by the conventional ceramic material

Figure 6 shows the results of thermal resistance evaluated by the ΔV_{CE} method. We verified that products using the new DCB substrate had lower thermal resistance $R_{th(j-c)}$ by approximately 25 to 30 % than

Fig.3 Internal layout for lower noise

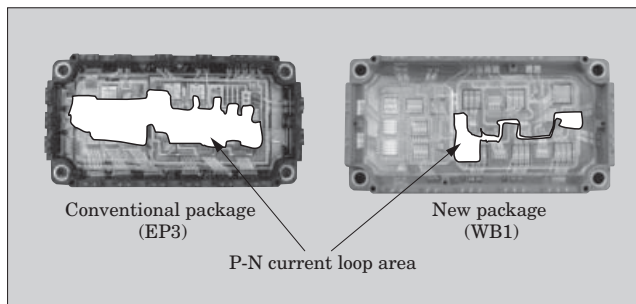


Fig.4 Comparison of noise radiation

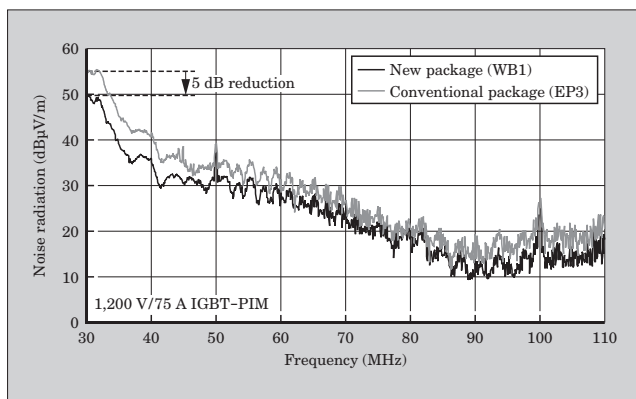


Fig.5 Cross section comparison of IGBT modules

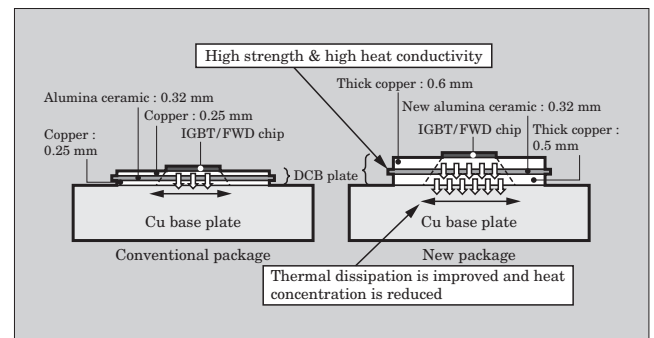


Fig.6 Comparison of transient thermal resistance characteristics

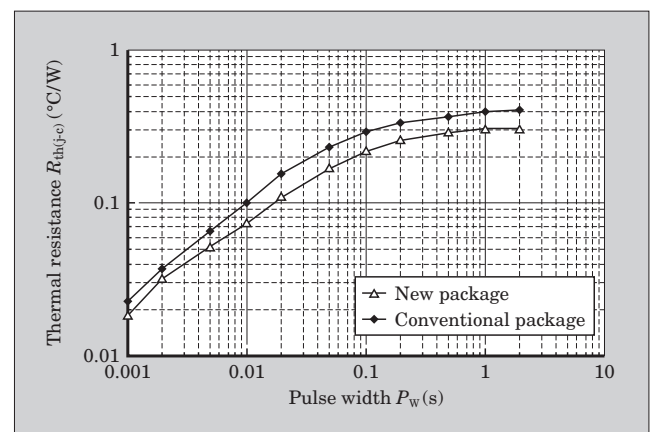


Table 1 Lineup of IGBT-PIM products using next generation package

Break-down voltage	Rated I_c (A)	15	25	35	50	75	100	150	
1,200 V	Existing package U/U4 series	M711 (EP2) 107.5×45 (mm)							
	New package U4 series	M712 (EP3) 122×62 (mm)							
		M719 (WB0) 107.5×45 (mm)			M720 (WB1) 122×62 (mm)				
Break-down voltage	Rated I_c (A)	15	25	35	50	75	100	150	
600 V	Existing package U2 series	M711 (EP2) 107.5×45 (mm)			M712 (EP3) 122×62 (mm)				
	New package U2 series				M719 (WB0) 107.5×45 (mm)				
					M720 (WB1) 122×62 (mm)				

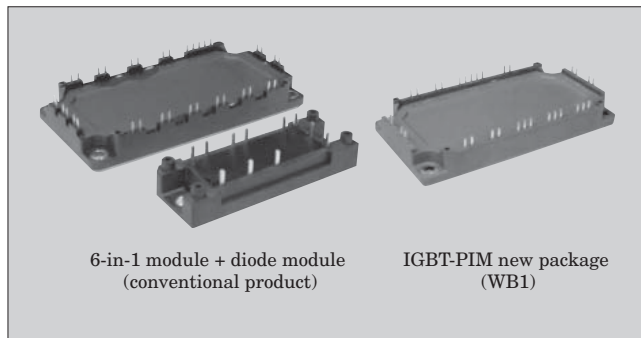
products using the conventional DCB substrate.

This new DCB substrate is selectable as well as AlN and SiN substrates which have high thermal conductance.

6. New Product Lineup

Combining the above-described latest chip technologies with newly developed package technology, Fuji Electric has developed the world's first ultra-small IGBT-PIM, and the 1,200 V series of these devices realizes a current rating that is twice as large as that of conventional device in a package of the same size. Table 1 shows Fuji Electric's lineup of packages for the newly developed IGBT-PIM, and Fig. 7 compares the exterior views of 1,200 V/150 A packages. This lineup

Fig.7 Comparison of external appearances of 1,200 V/150 A conventional and new package products



of new products is expected to enable equipment to be made with smaller size and lower cost. Also, these products were designed in consideration of environmental issues, and this product lineup complies with the RoHS directive, a recent environmental regulation.

7. Conclusion

As IGBT modules have progressed toward lower loss in recent years, the issue of noise radiation has once again become a concern. This paper has introduced new products from Fuji Electric that combine the latest chip and package technologies for the main purposes of reducing noise and size and lowering cost.

Fuji Electric will continue to endeavor to realize elemental devices having higher levels of performance and reliability, to raise the level of its technology in order to resolve new issues and support new marketplace needs, and to contribute to the development of power electronics.

References

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- (2) Nishimura, Y. et al. New generation metal base free IGBT module structure with low thermal resistance. Proc. 16th. ISPSD '04. 2004. p.347-350.