High-power IGBT Modules

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1. Introduction

To help curb global warming, clean energy, rather than fossil fuels, has been used increasingly in recent years. Markets for new types of energy (wind-power generation, solar-power generation) capable of supplying electric power without emitting green house gases (CO_2) are growing rapidly, and the inverter systems used in these fields are trending toward higher power capacities.

The main power device in industrial-use high-power inverter systems is the GTO (gate turn-off) thyristor, which easily handles high voltages and currents. However, as a result of outstanding advances in technologies for increasing the voltage and power capacities of IGBT (insulated gate bipolar transistor) modules, GTO thryistors in high-voltage and high-power applications are being replaced by IGBT modules which have an insulated structure that facilitates assembly, handling and maintenance inspections. Fuji Electric has expanded its IGBT product lineup by developing high-power IGBT modules for industrial, high-power applications.

Targeting applications in the growing field of new energy, Fuji Electric has newly developed 1,200 V and 1,700 V high-power IGBT modules equipped with U4 chips, an improved version of the U-series chips, and that feature enhanced thermal characteristics and significantly improved environmental durability. This paper presents an overview and discusses the technical development of the modules.

2. Product Lineup

Table 1 shows Fuji Electric's product lineup of newly developed high-power IGBT modules. A 1-in-1 package has a current capacity of 1,200 to 3,600 A and a 2-in-1 package has a current capacity of 600 to 1,200 A, and the module voltages are 1,200 V or 1,700 V for a total of 14 models. Figure 1 shows an external view of the packages.

Table 1 Fuji Electric's product lineup of high-power IGBT modules

	Package type	Package size (mm)	CTI*	Insulating substrate	Base	Rated voltage (V)	Rated current (A)	Model number
1 in 1	M151	130 × 140 × 38	600 or more	Silicon nitride (Si_3N_4)	Copper (Cu)	1,200	1,200	1MBI1200U4C-120
							1,600	1MBI1600U4C-120
						1,700	1,200	1MBI1200U4C-170
							1,600	1MBI1600U4C-170
	M152	190 × 140 × 38				1,200	2,400	1MBI2400U4D-120
							3,600	1MBI3600U4D-120
						1,700	2,400	1MBI2400U4D-170
							3,600	1MBI3600U4D-170
2 in 1	M256	130 × 140 × 38	600 or more	Silicon nitride (Si_3N_4)	Copper (Cu)	1,200	600	2MBI600U4G-120
							800	2MBI800U4G-120
							1,200	2MBI1200U4G-120
						1,700	600	2MBI600U4G-170
							800	2MBI800U4G-170
							1,200	2MBI1200U4G-170

*CTI : Comparative Tracking Index

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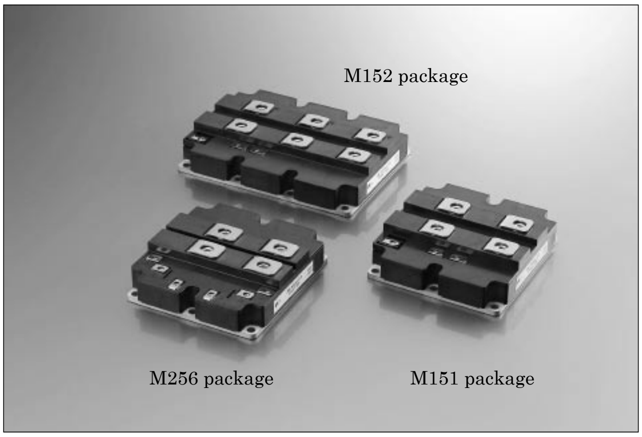
3. Electrical Characteristics

Electrical characteristics of the 2MBI800U4G-170 (2-in-1, 800 A/1,700 V), a representative model, are described below. The maximum rated values and characteristics are listed in Table 2.

Fig.1 External view of Fuji Electric's high-power IGBT modules



3.1 *V-I* characteristics

By reducing the injection efficiency of the pnp transistor, increasing the transport efficiency without using lifetime control, and providing a positive temperature coefficient, the collector-emitter saturation voltage characteristic of the IGBT chip has been improved to achieve higher performance. Also, in the FWD (free wheeling diode) chip, carrier lifetime control was optimized so the forward voltage has a positive temperature coefficient as in the IGBT.

When the junction temperature increases, a chip having a positive temperature coefficient acts to equalize the junction temperature among chips connected in parallel and performs self-balancing to balance the current, and is therefore suitable for use with configurations in which many chips are connected in parallel for high-power IGBT modules. Figure 2 shows the collector-emitter saturation voltage vs. collector current characteristics and Fig. 3 shows the forward voltage vs. forward current characteristics.

Table 2 Absolute maximum ratings and characteristics (Model: 2MBI800U4G-170)

(a) Maximum ratings ($T_j = T_c$ = 25 ˚C, unless otherwise indicated)

Item	Symbol	Condition		Rating	Unit
Collector-emitter voltage	V_{CES}	V_{GE} = 0 V		1,700	V
Gate-emitter voltage	V_{GES}	–		± 20	V
Collector current	$I_{C(DC)}$	Continuous	T_c = 80 °C	800	A
	$I_{C(pulse)}$	1 ms	T_c = 80 °C	1,600	A
Max. collector dissipation	P_C	1 device		4,800	W
Max. junction temperature	T_{jmax}	–		150	˚C
Storage temperature	T_{stg}	–		–40 to +125	˚C
Isolation voltage	V_{iso}	AC : 1 minute		3,400	V

(b) Electrical characteristics ($T_j = T_c$ = 25°C, unless otherwise indicated)

Item	Symbol	Condition		Min.	Typical	Max.	Unit
Collector-emitter leakage current	I_{CES}	V_{GE} = 0 V, T_j = 125 °C, V_{CE} = 1,700 V		–	–	1.0	mA
Gate-emitter leakage current	I_{GES}	V_{GE} = ± 20 V		–	–	2.4	µA
Gate-emitter threshold voltage	$V_{GE(th)}$	V_{CE} = 20 V, I_C = 0.8 A		5.5	6.5	7.5	V
Collector-emitter saturation voltage (chip)	$V_{CE(sat)}$	V_{GE} = +15 V, I_C = 800 A	T_j = 25 °C	–	2.25	2.40	V
			T_j = 125 °C	–	2.65	–	
Input capacitance	C_{ies}	V_{GE} = 0 V, V_{CE} = 10 V, f = 1 MHz		–	75	–	nF
Turn-on time	t_{on}	V_{CC} = 900 V, I_C = 800 A V_{GE} = ± 15 V T_j = 125 °C		–	3.10	–	µs
	t_r			–	1.25	–	
Turn-off time	t_{off}			–	1.45	–	
	t_f			–	0.25	–	
Forward voltage (chip)	V_f	V_{GE} = 0 V, I_f = 800 A	T_j = 25 °C	–	1.80	2.15	V
			T_j = 125 °C	–	2.00	–	
Reverse recovery time	t_{rr}	V_{CC} = 900 V, I_F = 800 A, T_j = 125 °C		–	0.45	–	µs

(c) Thermal characteristics

Item	Symbol	Condition	Min.	Typical	Max.	Unit
Thermal resistance (1 device)	$R_{th(j-C)}$	IGBT	–	–	0.026	K/W
		FWD	–	–	0.045	

3.2 Switching characteristics

Optimization of the balance between input capacitance (C_{ies}) and reverse transfer capacitance (C_{res}) in a U4-series IGBT chip provides the chip with such characteristics as significantly lower turn-on loss, reduced *di*/*dt* during low current, improved controllability of turn-on *di*/*dt* by gate resistance, and reduced surge voltage during reverse recovery. Figure 4 shows turn-on, turn-off and reverse recovery waveforms for a module at the rated current (800 A) under the conditions of $V_{CC} = 900$ V, $R_{g(on)} = 4.7\ \Omega$, $R_{g(off)} = 1.2\ \Omega$ and $T_j = 125$ °C. The switching loss was 257 mJ during turn-on, 254 mJ during turn-off, and 228 mJ during reverse recovery. Figure 5 shows the current dependency of the switching loss and Fig. 6 shows the gate resistance dependency of the switching loss.

Fig.2 Output characteristics

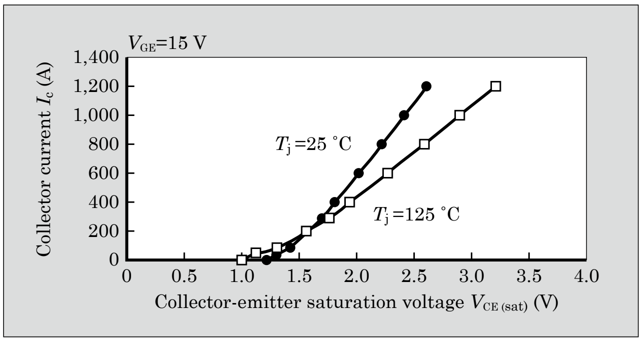
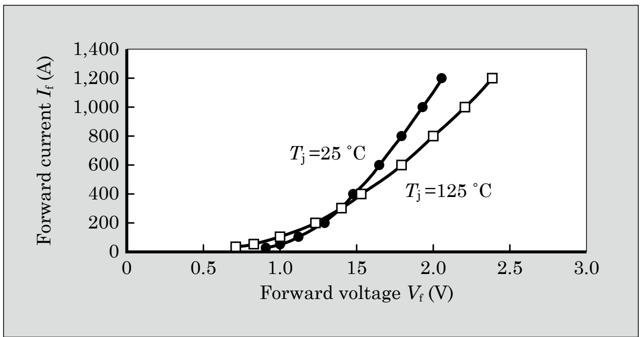


Fig.3 Forward *I*-*V* characteristics



4. Package Technologies

4.1 Reduction in thermal resistance

The majority of industrial-use high-power inverter systems achieve greater power by connecting many modules in a serial and parallel configuration. Customer needs for system downsizing result in higher densities. Reducing the size of cooling fins that radiate heat generated by the module results in decreased heat dissipation efficiency and leads to higher junction temperatures in the semiconductor chip. Higher junction temperatures raise concern about the reliability of a module, and therefore junction temperatures must be reduced. The following three methods can be used for this purpose.

Fig.5 Switching loss dependency on I_c, I_f

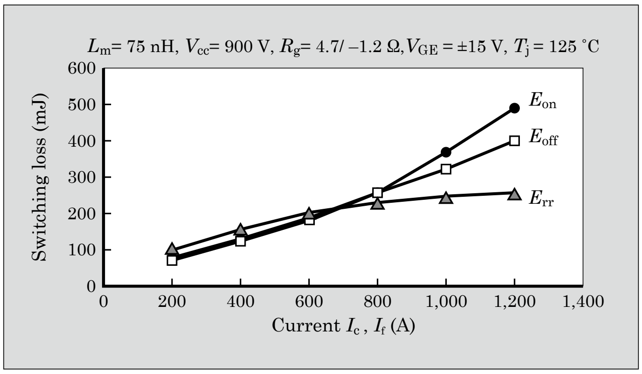


Fig.6 Switching loss dependency on R_g

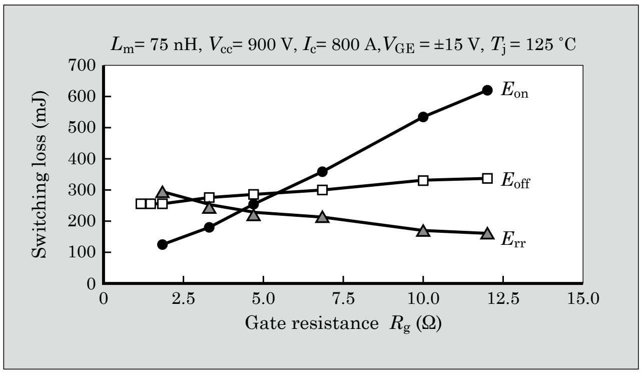
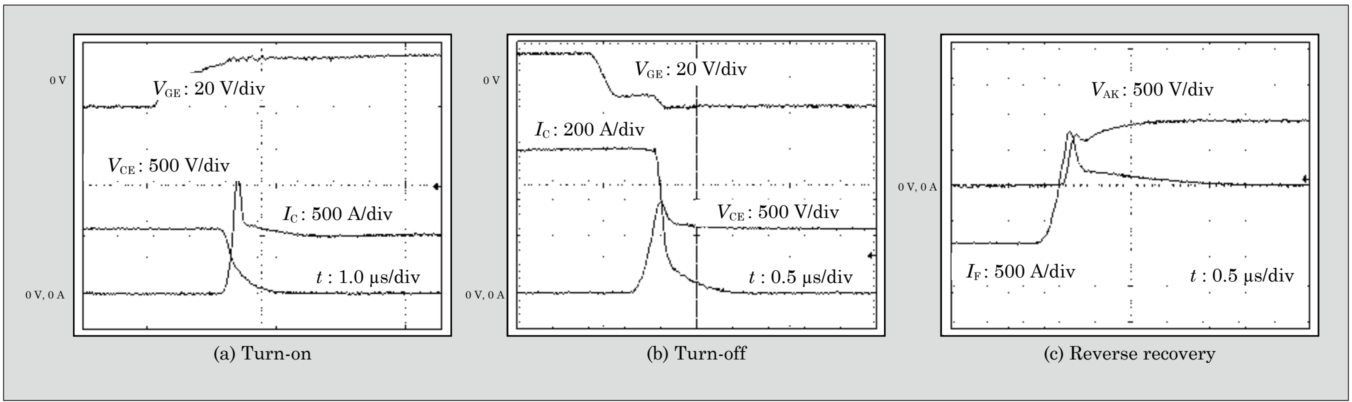


Fig.4 Switching waveforms (inductive load)



(a) Turn-on (b) Turn-off (c) Reverse recovery

(a) Reduce the amount of heat generated by the module
(b) Reduce the thermal resistance (between the junction area and case) of the module
(c) Improve the heat dissipation efficiency of the cooling fins

Two of the above methods can be implemented with a module itself: reducing the amount of generated heat and reducing the thermal resistance. The ability to reducing the amount of generated heat largely depends on the chip characteristics, and next-generation chip technology is eagerly awaited. On the other hand, a reduction in thermal resistance can be achieved, regardless of the chip characteristics, by optimizing the module structure.

Figure 7 shows the results of a thermal simulation of a conventional high-power IGBT module that uses a DCB (direct copper bonding) substrate made of aluminum oxide (Al_2O_3). Since the thermal resistance of the DCB substrate accounts for approximately 52% of the thermal resistance of the entire module, we determined that reducing the thermal resistance of the DCB substrate would be the most effective way to reduce the total thermal resistance. Table 3 lists the results of comparison of various DCB substrates, and Fig. 8 shows the results of comparison by thermal simulation of module thermal resistance. In selecting a DCB substrate, we took a comprehensive approach that considered such factors as the thermal resistance reduction effect, ease of assembly, cost and so on, and decided to use silicon nitride (Si_3N_4) for which a significant thermal resistance reduction effect can be expected. We measured the thermal resistance and verified reductions in thermal resistance of 33% at the IGBT area and 31% at the FWD area as compared to the case of the aluminum oxide substrate.

Fig.7 Thermal resistance of each layer (by percentage)

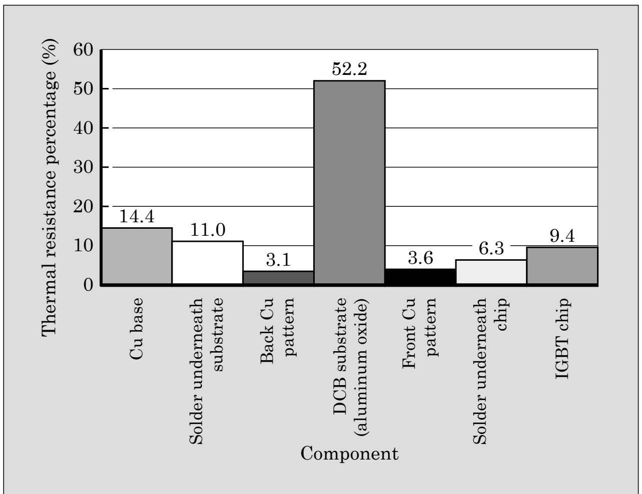


Table 3 Comparison of various DCB substrates

	Aluminum oxide Al_2O_3	Aluminum oxide Al_2O_3	Silicon nitride Si_3N_4	Aluminum nitride AlN
Thickness	0.32 mm	0.32 mm	0.32 mm	0.65 mm
Heat transfer coefficient	× (21 W/(m^{2}K))	△ (24 W/(m^{2}K))	○ (90 W/(m^{2}K))	◎ (170 W/(m^{2}K))
Bending strength	○	△	◎	×
Insulation breakdown voltage	◎	◎	◎	◎
Cost	◎	△	△	×
Easy of assembly	○	○	△	△
Thermal resistance reduction effect	×	△	○	◎

◎ : Excellent ○ : Good △ : Fair × : Poor

4.2 Improved environmental characteristics of molded package

When a molded package is placed under a strong electric field, dust and moisture adhering to the surface of the molded package carbonize and form carbonized tracks, which may lead to decreased insulation and sometimes to insulation breakdown. In some cases there is a risk of fire. Wind-power and solar-power generators are often installed at sites having high grit, dust and salinity content, and high humidity. For high-power IGBT modules to be usable in such an environment, the development of a molded package that is resistant to the formation of carbonized tracks is essential. The following two methods exist for realizing molded packages that are resistant to the formation of carbonized tracks.

(a) Lengthen the creepage surface (carbonized track) of the molded package
(b) Use mold resin that resists forming carbonized tracks

To lengthen the creepage surface of the molded

Fig.8 Comparison by thermal simulation of module thermal resistance

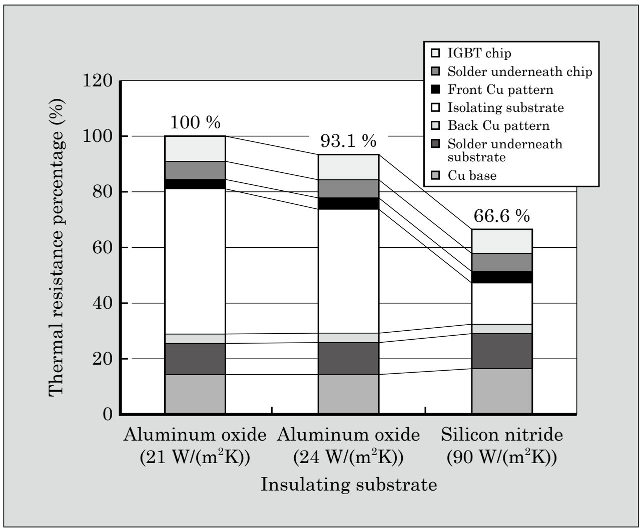


Table 4 Comparative tracking index

	PLC *	CTI : Comparative tracking index
High level	0	600 ≤ CTI
↑	1	400 ≤ CTI < 600
	2	250 ≤ CTI < 400
	3	175 ≤ CTI < 250
↓	4	100 ≤ CTI < 175
Low level	5	CTI < 100

* PLC : Performance Level Category

package, the surface of the molded package must have uneven shape, and in order to prevent an increase in external dimensions that would forfeit compatibility with competitors' package sizes, Fuji Electric selects and uses a mold resin having a CTI (comparative tracking index) of one rank higher. Table 4 shows the tracking index ranges. The highest level is assigned to the tracking index range of 600 ≤ CTI.

5. Power Cycle Capability

Inheriting the same high-power package technology as the conventional high-power IGBT module, this newly developed high-power IGBT module uses high-rigidity Sn-Ag solder for soldering underneath the chip, partitions the DCB substrate into several segments to suppress thermal interference among the DCB substrates, and has a main terminal structure that equalizes current among the DCB substrates. Additionally, by optimizing the thickness of the solder underneath the DCB substrate and by improving the method of production, the ΔT_j power cycle was confirmed to be equivalent to that of a conventional module having a smaller number of chips connected in a parallel configuration. Furthermore, in a ΔT_c power cycle test where the package temperature changes significantly for a characteristic high-power IGBT module application, 10,000 cycles were verified at the condition of $\Delta T_c = 70$ °C

6. Postscript

This paper has introduced Fuji Electric's improved high-power IGBT module products, which are equipped with a U4-series chip and that feature enhanced thermal characteristics and improved environmental durability. These modules constitute a product group capable of meticulous supporting not only the diversifying needs of the high-power field, but also the needs of the rapidly growing field of new energy.

To support these increasing needs, Fuji Electric intends to continue to advance power semiconductor and package technologies, and to develop new products that contribute to the progress of power electronics.