High Power IGBT Module for Three-level Inverter

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ABSTRACT

In recent years, power conversion equipment used in the field of new energy and the field of traction advance high efficiency by a multi-level inverter system. Fuji Electric has developed a new high-power IGBT (insulated gate bipolar transistor) module having high isolation voltages which could apply to three-level inverter as one of multi-level inverter systems. Newly developed high-power IGBT modules have rating of 600 to 3,600 A/1,700 V. They have three packages and product lineup for 1-in-1 and 2-in-1 modules.

1. Introduction

With advances in high voltage and high power device technology, the application range of IGBT (Insulated Gate Bipolar Transistor) modules has expanded to industrial-use high-voltage high-power inverters.

In recent years, emerging countries have been experiencing rapid economic growth, but their development of an electricity infrastructure is still lagging, and severe power shortages have occurred for years. Also, because of delays in the development of a transportation infrastructure, the use of automobiles and the like that run on fossil fuels has increased, the emission of greenhouse gases (such as CO_2) have risen year after year, and there is a concern that these trends will accelerate global warming.

Wind-power and solar-power are promising clean energy sources that do not emit greenhouse gases at the time of power generation, and facilities for the generation of wind and solar power are being installed throughout the world. In addition, high-speed railways that link major cities and the electric railways and streetcars that connect to the suburbs are capable of transporting large amounts of people and cargo. Furthermore, these energy sources are attracting attention because they do not emit greenhouse gases, and their development is progressing.

Fuji Electric has developed and deployed a high

Table 1 Product lineup

	Product type	Package type	Package size (mm)	Rated voltage (V)	Rated current (A)	Base material	Isolation substrate	Isolation voltage V_{iso} (kV)
1 in 1	1MBI1200U4C-170	M151	130×140×38	1,700	1,200	Cu	Silicon nitride (Si_3N_4)	4.0
	1MBI1600U4C-170				1,600			
	1MBI2400U4D-170	M152	190×140×38		2,400			
	1MBI3600U4D-170				3,600			
	1MBI1200U4C-170	M151	130×140×38	1,700	1,200	Aluminum silicon carbide (AlSiC)	Aluminum nitride (AlN)	6.0
	1MBI1600U4C-170				1,600			
	1MBI2400U4D-170	M152	190×140×38		2,400			
	1MBI3600U4D-170				3,600			
2 in 1	2MBI600U4 G-170	M256	130×140×38	1,700	600	Cu	Silicon nitride (Si_3N_4)	4.0
	2MBI800U4 G-170				800			
	2MBI1200U4 G-170				1,200			
	2MBI600U4 G-170	M256	130×140×38	1,700	600	Aluminum silicon carbide (AlSiC)	Aluminum nitride (AlN)	6.0
	2MBI800U4 G-170				800			
	2MBI1200U4 G-170				1,200			

: New product

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power IGBT module for use in the fields of high-power industrial applications and clean energy.

In recent power conversion systems for wind-power, solar-power and traction use, the use of a multi-level inverter system to increase the efficiency (reduce the conversion loss) of the equipment is considered.

A high-power 1,700 V IGBT module having a high isolation capability and targeting application to 3-level inverters (see explanation on page 108), a type of multi-level inverter system, and having a power cycle tolerance that also accommodates application to the traction field has been newly developed. This paper presents an overview and description of the technical development of this high power IGBT module.

2. Product Lineup

The product lineup of newly developed high power IGBT modules is shown in Table 1. The product lineup consists of seven models having a rated voltage of 1,700 V and rated currents ranging from 1,200 to 3,600 A for the 1-in-1 module and 600 to 1,200 A for the 2-in-1 module.

Fig. 1 shows the appearance of the packages.

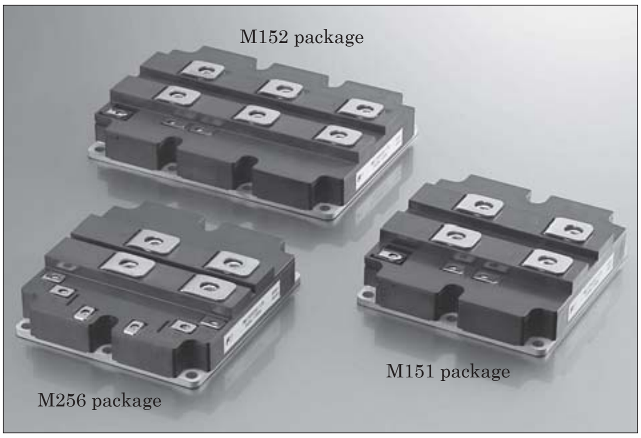

Fig.1 External appearance of high-power IGBT module package

Table 2 Absolute maximum ratings and characteristics (model: 1MBI1200U4C-170X)

(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	1,200	A
	$I_{c\ (Pulse)}$	1 ms	T_c=80 °C	2,400	A
Collector power dissipation	P_c	–		6,250	W
Max. junction temperature	$T_{j\ max.}$	–		150	°C
Storage temperature	T_{stg}	–		−40～+125	°C
Isolation voltage	V_{iso}	AC: 1 min		6,0	kV

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

Item	Symbol	Condition		Minimum	Typical	Maximum	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=1.2 A		5.5	6.5	7.5	V
Saturation voltage (chip)	$V_{CE\ (sat)}$	V_{GE}=+15 V I_c=1,200 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		–	112	–	nF
Turn-on time	t_{on}	V_{cc}=900 V, I_c=1,200 A V_{GE}=±15 V T_j=125 °C		–	1.80	–	μs
	t_r			–	0.85	–	
Turn-off time	t_{off}			–	1.30	–	
	t_r			–	0.35	–	
Forward on voltage (chip)	V_F	V_{GE}=0 V I_F=1,200 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=1,200 A, T_j=125 °C		–	0.35	–	μs

(c) Thermal characteristics

Item	Symbol	Condition	Minimum	Typical	Maximum	Unit
Thermal resistance	$R_{th\ (j\text{-}c)}$	IGBT	–	–	0.020	K/W
		FWD	–	–	0.033	

3. Electrical Characteristics

The electrical characteristics are described below for the 1-in-1 1,200 A/1,700 V module, as an example. The maximum ratings and characteristics are listed in Table 2.

3.1 V-I characteristics

Fig. 2 shows the output characteristics and Fig. 3 shows the forward V–I characteristics of the module.

In the IGBT and FWD (free wheeling diode) chips, the saturation voltage and forward voltage both have a positive temperature coefficient. When the junction temperature increases in a chip having a positive temperature coefficient, the chip operates to equalize the junction temperature among chips connected in parallel, and auto-regulates current imbalances. These chips are well suited for a high power IGBT module employing many parallel chip connections.

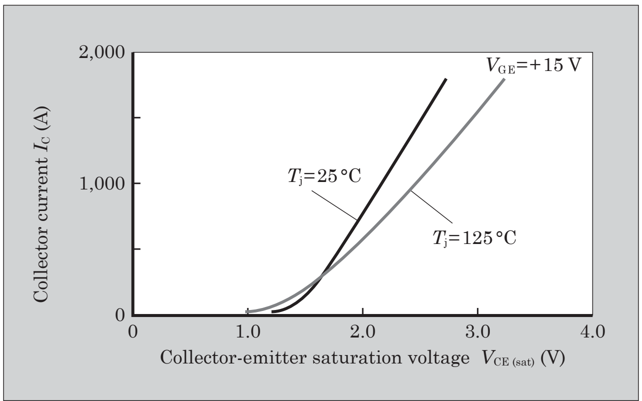

Fig.2 Saturation voltage – collector current characteristics

3.2 Diode reverse recovery characteristics

High power IGBT modules are often used in applications where the stray inductance is large, and the possibility exists that the surge voltage generated at turn-off or during reverse recovery of the FWD may exceed the voltage tolerance of the module. The gate resistance can be increased to limit the surge voltage, however. On the other hand, as a result of the increase in the switching energy (turn-on and turn-off loss), there are expected to be some cases in which, depending upon the operating conditions of the equipment, a high power IGBT cannot be used.

An active clamping circuit inserted between the gate and collector is able to limit the surge voltage generated at turn-off without increasing the off-gate resistance of the gate drive circuit. The surge voltage generated during reverse recovery operation of the FWD, however, is determined by the turn-on di/dt of

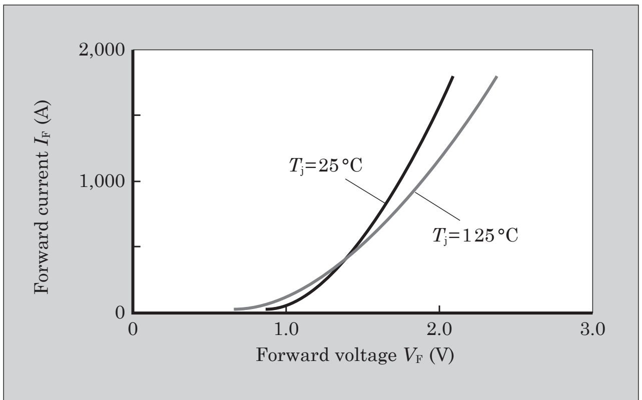

Fig.3 Forward V-I characteristics

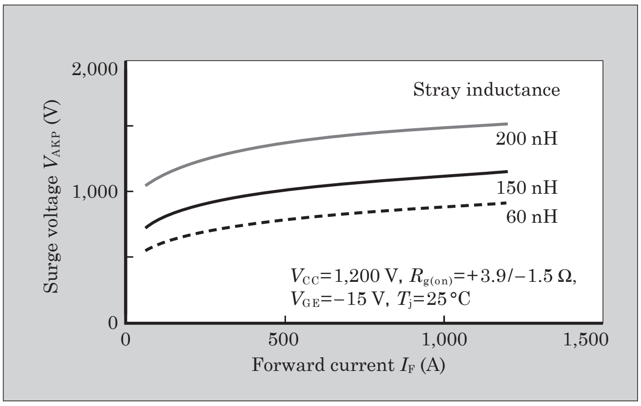

Fig.4 Reverse recovery surge voltage characteristics

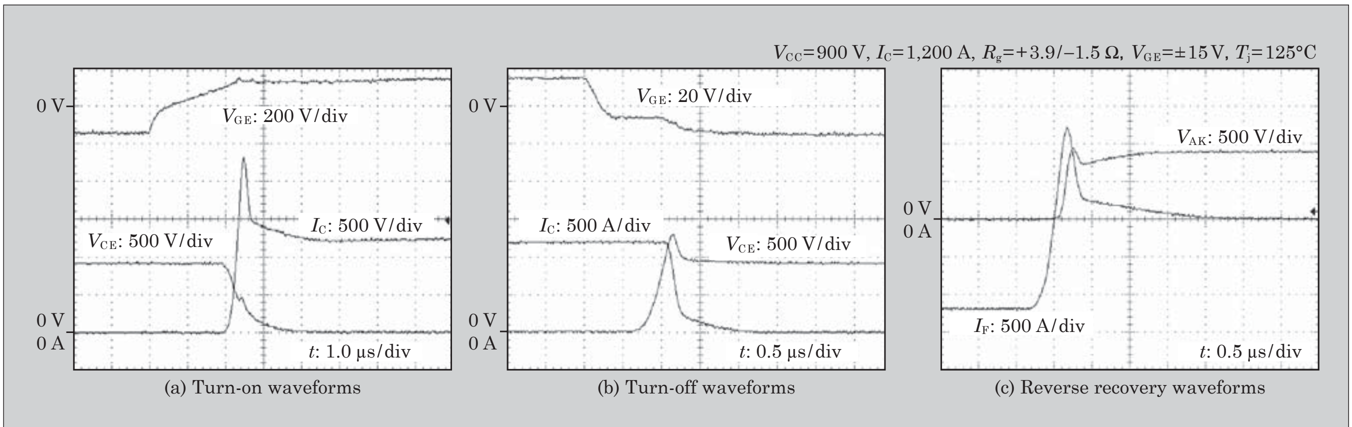

Fig.5 Switching waveform (inductive load)

the IGBT and the stray inductance, and therefore the on-gate resistance must be increased to limit this surge voltage.

The module is equipped with a U4 series IGBT designed with reduced turn-on di/dt to improve the controllability of the turn-on di/dt by gate resistance and requiring significantly lower turn-on energy, and a diode chip with an optimized design to reduce surge voltage during reverse recovery.

Fig. 4 shows the dependence of the surge voltage and stray inductance. It can be seen that the surge voltage is limited, even if the stray inductance is large.

3.3 Switching characteristics

Fig. 5 shows the turn-on, turn-off and reverse recovery waveforms (for an inductive load) of a module at the rated current of 1,200 A and under the conditions of V_{cc}=900 V, R_g=+3.9/−1.5 Ω, and T_j=125 °C. The switching energy is 350 mJ at turn-on, 390 mJ at turn-off and 380 mJ at reverse recovery. Fig. 6 shows the I_c and I_f dependence and Fig. 7 shows the R_g dependence of the switching energy.

4. Package Technologies

4.1 Increasing the isolation voltage V_{iso}

The energy-generating capacity of wind and solar power is highly dependent on the weather. To convey the generated energy to a transmission line requires the use of high-efficiency inverters. New designs for traction use power conversion equipment are also trending toward higher efficiency at an accelerating pace.

2-level inverters, which are generally used for a wide range of applications, have few components, are easy to control and are inexpensive, but have a slightly lower conversion efficiency than 3-level inverters. For this reason, 3-level inverter devices are increasingly being used in newly designed power conversion systems.

A module used in a 3-level inverter device is required to have an isolation voltage V_{iso} of at least 5.4 kV for a 1.7 kV module. However, the industrial-use high power IGBT modules presently being mass-produced are only able to achieve isolation voltages of up to 4.0 kV for a 1.7 kV module. To achieve isolation voltage of 5.4 kV or higher, the following technologies must be applied.

In order to achieve greater isolation, the materials of the isolation substrate must be changed and the isolation substrate thickness and the design of the creepage distance (distance from the edge of the isolating substrate to the front side Cu pattern) must be optimized, and so on. As shown in Fig. 8, there are two modes of isolation breakdown, penetration and creepage. The penetration mode can be avoided by increasing the thickness of the isolation substrate. However, there is a resulting trade-off in the thermal resistance of the module, and the thickness must be selected to minimize the increase in thermal resistance. Creepage mode breakdown is interfacial breakdown occurring at the boundary between the front side of the isolating substrate and the silicone gel. Optimization of the design of the creepage distance is the most important factor for preventing creepage mode breakdown.

Fig. 9 shows the simulation results of electric field intensity when the isolation substrate thickness and the substrate front side distance are constant. By optimizing the ratio between the front side distance L and the back side distance l, the intensity of the electric field generated at the front side Cu pattern at the boundary between the front side of the isolating substrate and the silicone gel is limited, indicating that the electric field intensity can be distributed to the back side Cu pattern.

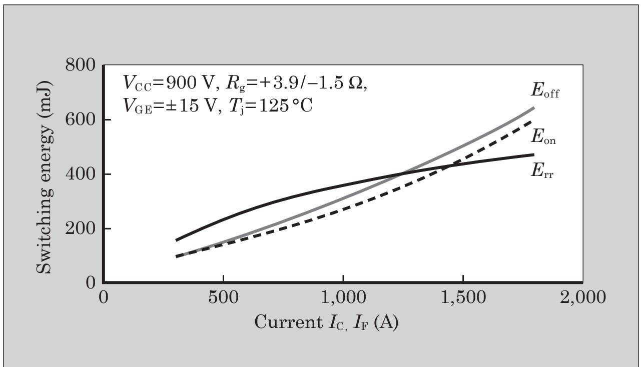

Fig.6 I_c, I_f dependency of switching energy

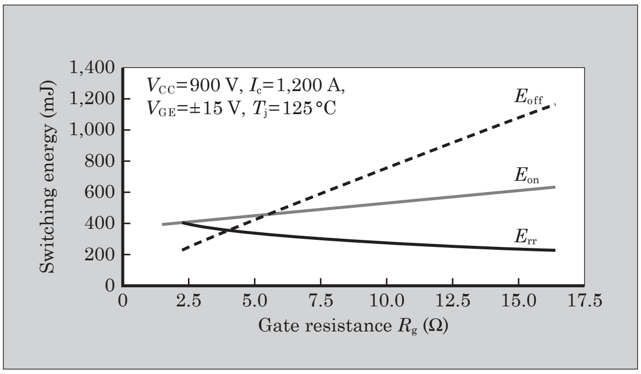

Fig.7 R_g dependency of switching energy

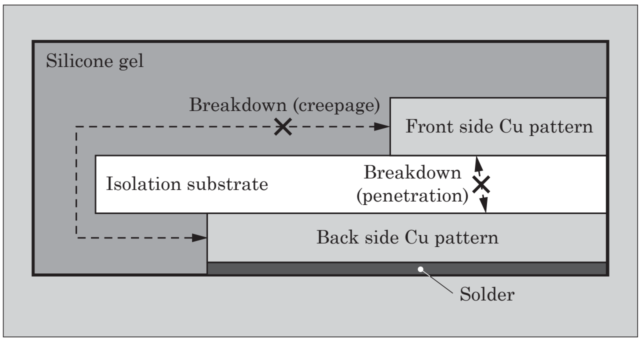

Fig.8 Cross-sectional view of isolation substrate

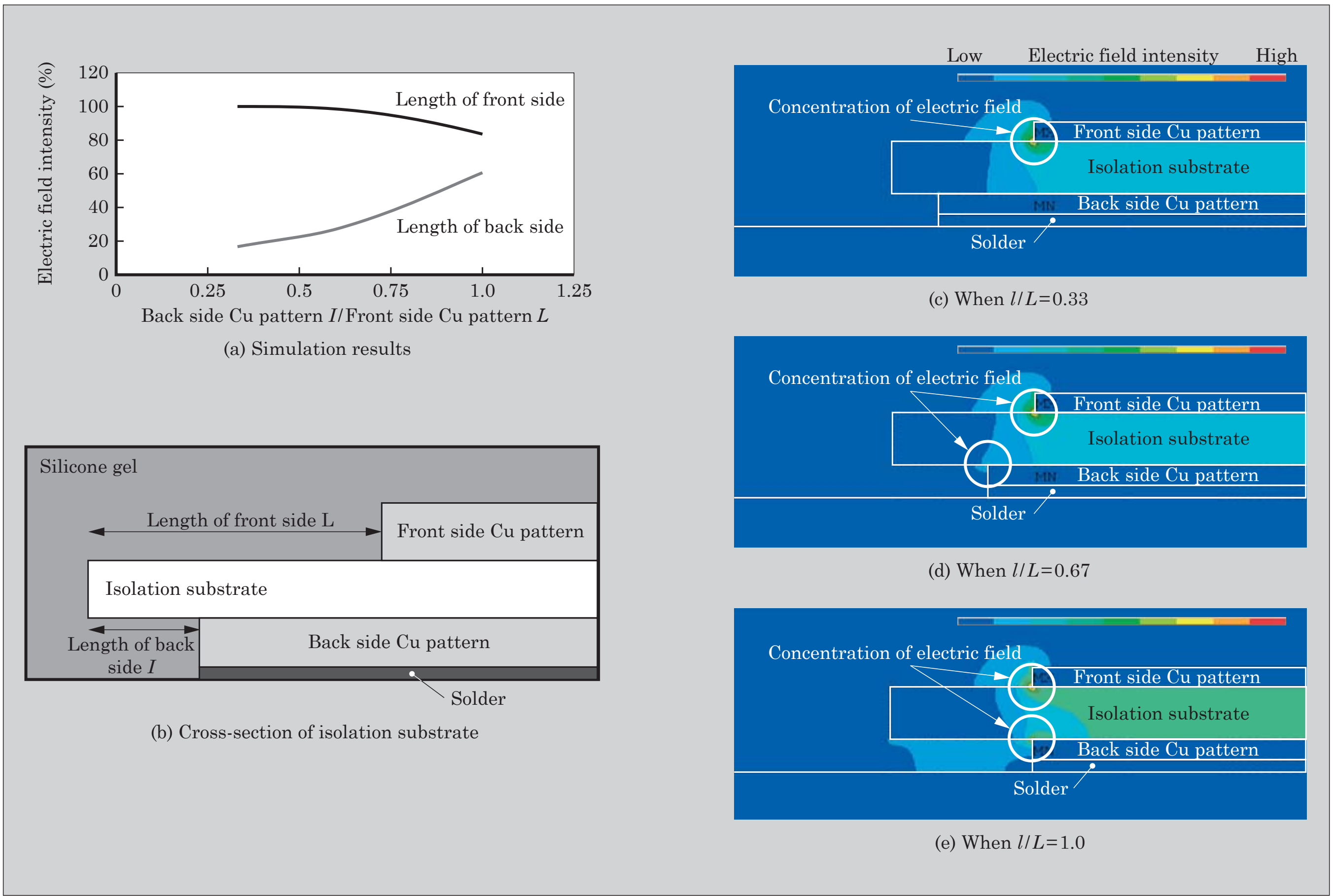

Fig.9 Simulation results of electric field intensity when isolation substrate thickness and substrate surface distance are constant

Furthermore, the process conditions for the silicone gel were optimized to improve adhesion to the isolating substrate and realize isolating voltage (6.0 kV) equivalent to that of a 3.3 kV module.

4.2 Improving the power cycle capability

This module inherits the same high power package technologies[(1)] as used in the currently mass-produced high power IGBT modules. The DCB (direct copper bonding) substrate is divided into separate substrates, the thermal buffering between DCB substrates is alleviated, and the module is provided with a main terminal structure that equalizes the current between the DCB substrates.

Additionally, aluminum silicon carbide (AlSiC) is used for the base plate, and in power cycle tests (ΔT_c=80 °C) that assume traction or other applications for which the high power IGBT module is intended, capability of more than 20,000 cycles was achieved.

5. Postscript

This paper has introduced Fuji Electric's high power IGBT module products that have a high isolation voltage capable of accommodating a 3-level inverter device and that are suitable for applications in the traction field. These modules are certainly capable of satisfying the needs of the new energy field, which is growing at an annual rate of 27%, and the traction field.

In the near future, Fuji Electric will begin to develop high power IGBT modules in conformance with the RoHS directive*1, and in response to further needs, intends to develop new products that will contribute to the advancement of power electronics.

*1: RoHS directive: EU (European Union) directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment