High-Voltage, High-Current IGBT Modules

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1. Introduction

The demand for IGBTs (Insulated-Gate Bipolar Transistors), widely used in inverter circuits for the power conversion of general purpose inverters, uninterrupted power supplies, and numerically controlled machines, is rapidly increasing because of their low loss characteristics and suitability for designing low loss gate driver circuits. Power device capacity has progressively increased and loss was decreased by year by year. Using these improved power devices, large capacity power converters with higher performance, higher efficiency, smaller size and lighter weight have been realized.

In the electrical railway which is one of the major applications of the large capacity power converter, GTOs (Gate Turn-Off thyristors) have been used in an inverter circuit which controls the electric train's induction motor since 1980.

Recentrly, a new type of vehicle which uses IGBT modules has been developed for Teito Rapid Transit Authority. Some of these new vehicles have already been placed in operation.

The IGBT module is superior to the GTO module in high speed switching characteristics, isolation configuration, and is expected to contribute to the reduction of size, noise, and to improved maintainability, therefore the IGBT module will be rapidly adopted by the moving vehicle industry.

This paper summarizes a 2,000V/400A IGBT developed by Fuji Electric for the high-voltage and high-current converter of electric vehicles.

2. Overview of the Product

2.1 Outline

A three-level inverter system outlined below is used in the circuits of the vehicles currently in operation.

(1) Low voltage semiconductor elements can be used since the applied voltage is limited to half the power supply voltage.
(2) Fine voltage control is facilitated by optimizing the modulation method.
(3) Reduction of higher harmonics is facilitated.

To construct this three-level inverter, clamping diodes must be used to connect the IGBT modules to the middle DC potential. For this reason, a 2,000V/400A IGBT and a 2,000V/600A clamping high speed recovery diode (1FI600A-200) have also been developed.

Table 1 Absolute maximum ratings (T_j=25° C)

Item		Symbol	Max. rating	Unit
Voltage between collector and emitter		V_{CES}	2,000	V
Voltage between gate and emitter		V_{GES}	±20	V
Collector current	DC	I_C	400	A
	Pulse (1 ms)	$I_{C\,pulse}$	800	A
Maximum power dissipation		P_C	2,500	W
Junction temperature		T_j	+150	°C
Storage temperature		T_{stg}	−40 to +125	°C
Isolation voltage		V_{is}	AC5,400 (1 min)	V

Table 2 Electrical characteristics (T_j=25° C)

Item		Symbol	Condition	Min.	Typ.	Max.	Unit
Cut-off current between collector and emitter		I_{CES}	V_{CE}=2,000V V_{GE}=0V			10	mA
Leakage current between gate and emitter		I_{GES}	V_{CE}=0V V_{GE}=±20V			1	µA
Threshold voltage between gate and emitter		$V_{GE(th)}$	V_{CE}=20V I_C=400mA	3.0		6.0	V
Saturation voltage between collector and emitter		$V_{CE(sat)}$	I_C=400A V_{GE}=15V		3.5	4.5	V
Diode forward voltage		V_F	I_F=400A V_{GE}=0V		2.2	2.7	V
Switching characteristics		t_{on}	V_{CE}=750V		1.2		µs
		t_r	I_C=400A		0.6		µs
		t_{off}	V_{GE}=±15V		1.5		µs
		t_f	R_G=1.1Ω		0.8		µs
		t_{rr}	I_F=400A di/dt=900A/µs		0.6		µs
Thermal resistance	IGBT	$R_{th(j\text{-}c)}$				0.05	°C/w
	Diode	$R_{th(j\text{-}c)}$				0.13	°C/w

2.2 Rating characteristcs

Tables 1 and **2** list the main product specifications.

Though the IGBT module is able to withstand a high voltage of 2,000V, the saturation voltage of the IGBT is 3.5V (typical) and V_F of the bult-in high speed recovery diode is 2.2V (typical).

The switching characteristics of t_{off}=1.5 μs and t_f= 0.8 μs are about one tenth of those of a GTO with the same rating.

The isolation voltage of the IGBT complies with JIS E 5004. So that the isolation will be compatible with the power supply of 1,500V, the absolute maximum rating is set to AC 5,400V for 1 minute.

The isolation voltage of the clamping high speed recovery diode is rated at AC 5,400V, the same as that of the IGBT module, and its t_{rr} is 0.6 μs.

2.3 External appearance

Figure 1 shows the external appearance of the IGBT module (model 1MBI400L-200) which includes one IGBT unit and was developed based on the conventional module.

Fig. 1 Photograph of IGBT module (1MBI400L-200)

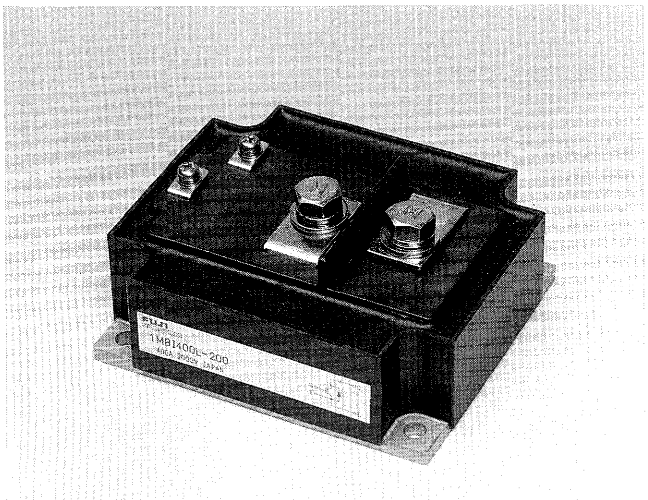
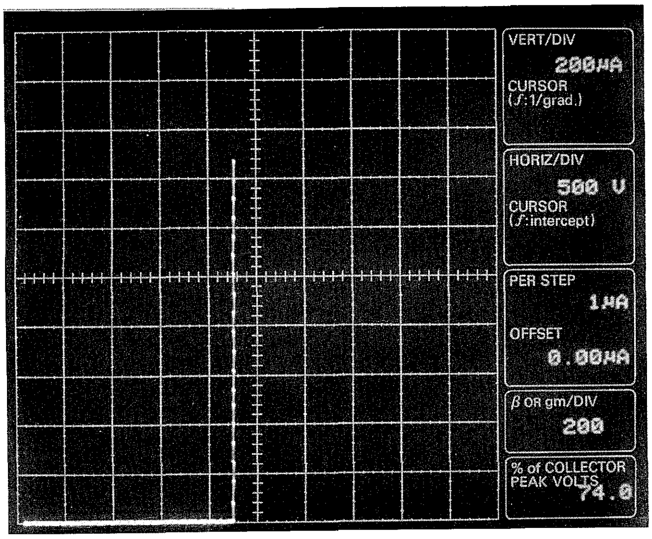


Fig. 2 Voltage characteristics of IGBT module (1MBI400L-200)



3. Characteristics

3.1 High withstand voltage

Power is supplied to the vehicle through a DC 1,500V rated trolley wire. Voltage varies greatly along this wire and reaches 1,900 to 2,000V at the maximum.

Here, 1,000V is applied to each constituent element of the three-level inverter. Considering both of the surge voltage caused by stray inductance of the main circuit during switching transients and the voltage rise across the snubber circuit, these must be added to the applied voltage of

Fig. 3 V_{CE}-I_C characteristics

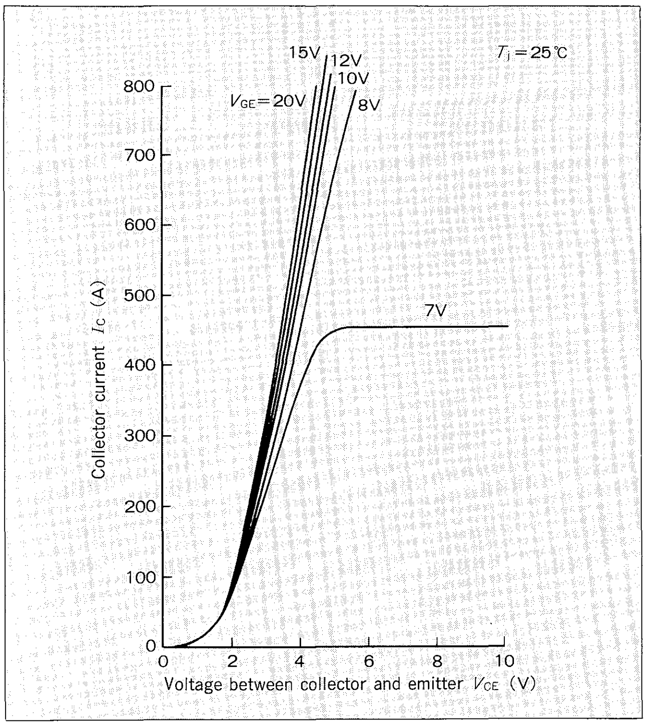
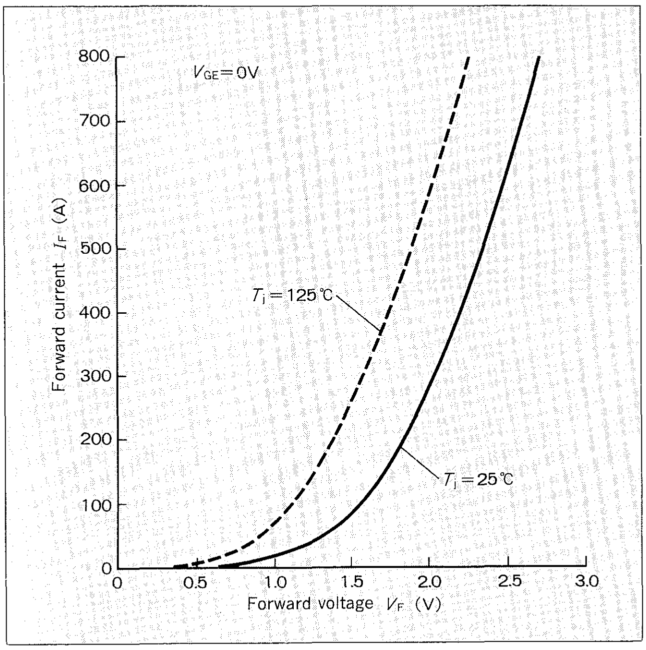


Fig. 4 V_F-I_F characteristics

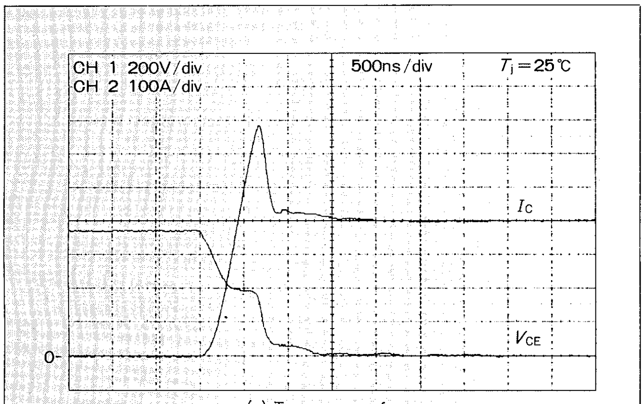


1,000V, whithstand voltage of IGBT is required that each element be able to withstand 2,000V.

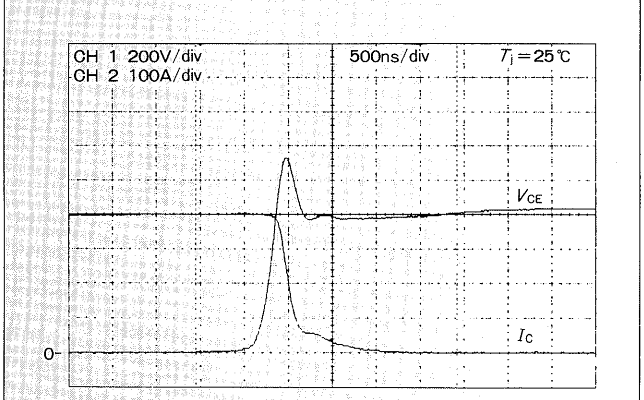
The IGBT and diode chips were developed to withstand voltage of more than 2,000V with excellent reliability by optimizing the field plate structure and silicon wefar parameters.

Figure 2 shows the measured withstand voltage characteristics with a transistor curve tracer.

Fig. 5 Switching waveform at 750V and 400A

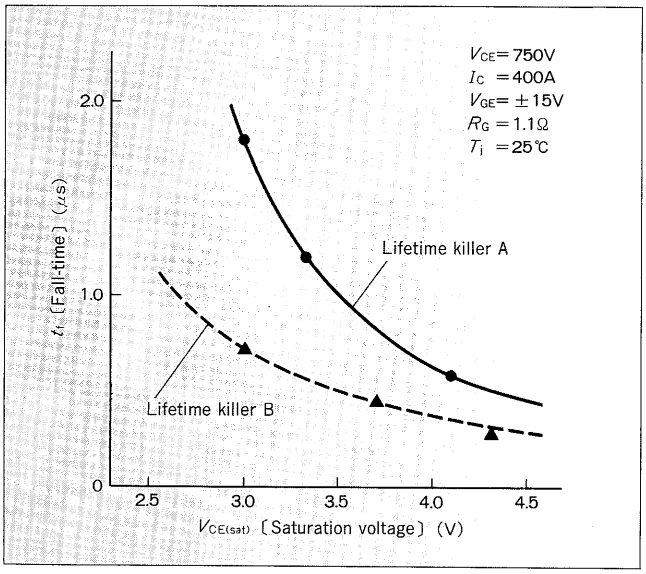


(a) Turn-on waveform



(b) Turn-off waveform

Fig. 6 Relation between fall-time t_f and saturation voltage $V_{CE(sat)}$



3.2 Output characteristics

Figure 3 shows the typical output characteristics of the IGBT and **Fig. 4** shows the typical V_F characteristics of the FWD (Free Wheeling Diode) connected in anti-parallel to the IGBT.

3.3 Switching characteristics

Figure 5 shows the current and voltage waveforms in inductive load, when the rated current is switched on and off.

The turn-on waveform, accompanied by neither surge voltage nor oscillation as shown in **Fig. 5**, is obtained from an FWD designed to have reduced reverse recovery current and soft recovery characteristics through the optimization of silicon wefar parameters, lifetime killers, diffusion impurity concentrations, and diffusion depth.

Figure 6 shows the trade-off relation between the t_f and $V_{CE(sat)}$ of the IGBT. Deterioration of the trade-off characteristics from high withstand voltage is prevented by selecting an optimum lifetime killer.

Figure 7 shows the turn-off waveform observed at maximum load, at a high temperature with a power supply voltage of 1,000V and the current of 800A. As **Fig. 7** shows, two times of rated current is cut-off in safety.

3.4 Safe operating area

Conventional GTOs were subject to switching frequency limitation and complexity in their circuit design caused by large power loss in the charge/discharge type snubber circuit adopted to avoid dv/dt limitations.

Fig. 7 Turn-off waveform at 1,000V and 800A

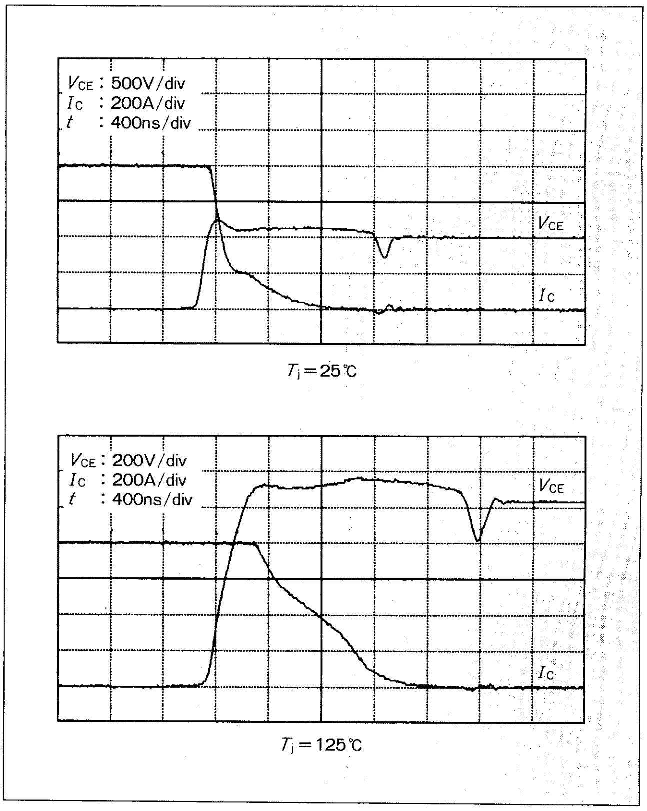
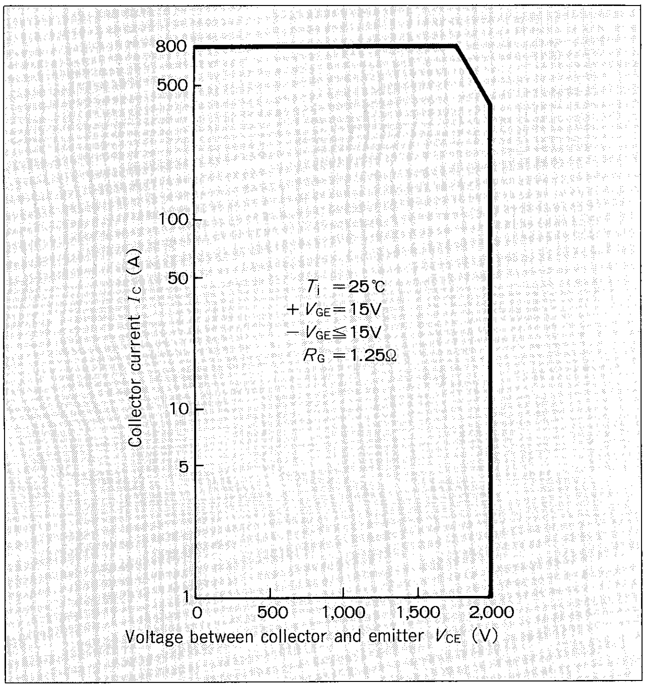


Fig. 8 RBSOA characteristics



As illustrated in **Fig. 8** which shows the reverse-bias safe operating area (RBSOA), the developed IGBT is guaranteed as withstand voltage of 2,000V up to the rated current.

Thus, as described above, in addition to the applied voltage (max. 1,000V), there is another 1,000V of margin in the design of the main circuit.

4. Package Design

The package was designed with the following principle in order to achieve a higher voltage capability than conventional and to realize the largest capacity IGBT in the world.

4.1 Reduction of internal wiring inductance and equalization of current sharing

Because of the utilization of a module structure, each electrode terminal is soldered to the isolating substrate. The main terminal structure is optimized to relieve stress at the soldered location caused by generated heat during operation and to reduce inductance of the internal wiring terminal.

Table 3 Specified creeping and space distances, and product dimension

Item	JEM spec.	2,000V IGBT module		Unit
Creeping distance	20	Distance between collector and emitter terminals	24.0	mm
		Distance between gate and emitter terminals	20.5	
Space distance	10	Distance between collector and emitter terminals	22.0	
		Distance between gate and emitter terminals	20.5	

In order to achieve large capacity, the chips are connected in parallel internally. Current is shared equally into these chips through the use of a symmetrical layout.

4.2 Maintaining creeping and space distances

The creeping and the space distances were designed in accordance with the JEM 1103 standard specification.

Table 3 lists the pertinent JEM specifications and the dimensions of the product. All the dimensions of the product meet JEM specifications. The IGBT module is well suited for application in the inverter circuits of electric trains.

5. Conclusion

This paper has summarized the main characteristics and the important aspects in the package design of the newly developed high-voltage IGBT module (2,000V/400A). This IGBT module has been developed mainly for use in inverters which is applied to electric trains, a new area of application for the IGBT. Compared to conventional GTOs, this IGBT will undoubtedly contribute to the improved performance and easier design of power equipment.

Fuji Electric is continuing its effort to develop and improve power devices and their application equipment.

Reference

(1) Uchida, Y. et al. "New IGBT Modules with Improved Power Loss at High Frequency PWM Mode", Electronica (1990).