Power Semiconductor Devices for Traction Inverter Application

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1. Introduction

Electric railways are indispensable in this day and age as a means of rapid mass transportation for everyday passengers and cargoes. Ensuring safety and high reliability during operation are basic requirements. In addition, from the point of view of rapid transit, comfort, economy, and the environment, the following demands have recently intensified:

(1) To increase transport capacity by quickening acceleration and deceleration, as well as increasing maximum speed
(2) To improve the passenger's comfort by improving air conditioning functions, intercommunications media, and providing a smooth ride
(3) To improve economy by saving energy and reducing maintenance
(4) To decrease repercussions influences on the environment by reducing noise and suppressing vibration

To satisfy these requirements, improvement in the performance of power semiconductor devices used for traction inverter systems must be achieved.

To meet the needs of the traction inverter market, Fuji Electric has marketed power semiconductor devices and expanded its product line.

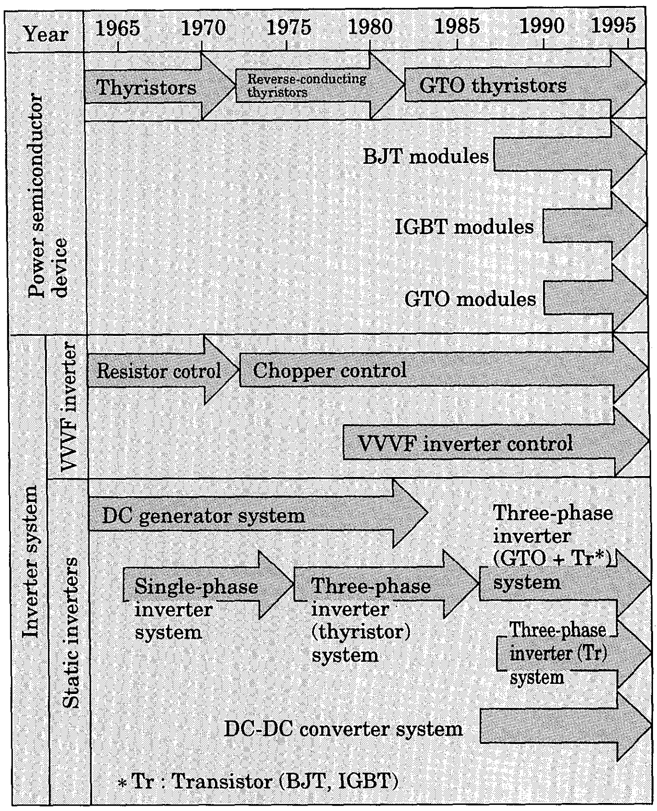
This paper introduces the technical trends of power semiconductor devices and inverter systems as well as Fuji Electric's product line of power semiconductor devices for traction. Although use of the IGBT (Insulated Gate Bipolar Transistor) for traction inverter applications is progressing, the newly developed 1,800V/600A IGBT module (1MBI600PN-180) will be introduced in this paper.

2. Trends of Traction Inverter Application

2.1 Technical trends of power semiconductor devices and inverter systems for traction

The progress of power semiconductor devices and inverter systems for traction is shown in Fig. 1. The traction inverter system consists of VVVF (Variable Voltage Variable Frequency) inverters for the generation of running power during operation and static inverters that supply power for air conditioning, lighting, and control circuitry. Typical circuits of both inverter systems are shown in Figs. 2 and 3.

Fig. 1 Progress of power semiconductor devices and inverter systems for traction



The application of power semiconductor devices to traction inverter systems began with the application of thyristors to operating drive power supply equipment in the 1960s. This was followed by the application of large capacity, reverse-conducting thyristors used in chopper control for DC electric trains in the 1970s. Subsequently high-voltage and large capacity GTO (Gate Turn-Off) thyristors were used in VVVF inverters in the 1980s. Now, the GTO thyristor is the mainstream of power semiconductor devices for traction, high-speed trains like the Shinkansen, and ordinary trains. On the other hand, with regard to static inverters, conventional DC generator systems first gave way

Fig. 2 Typical circuits of traction VVVF inverter systems

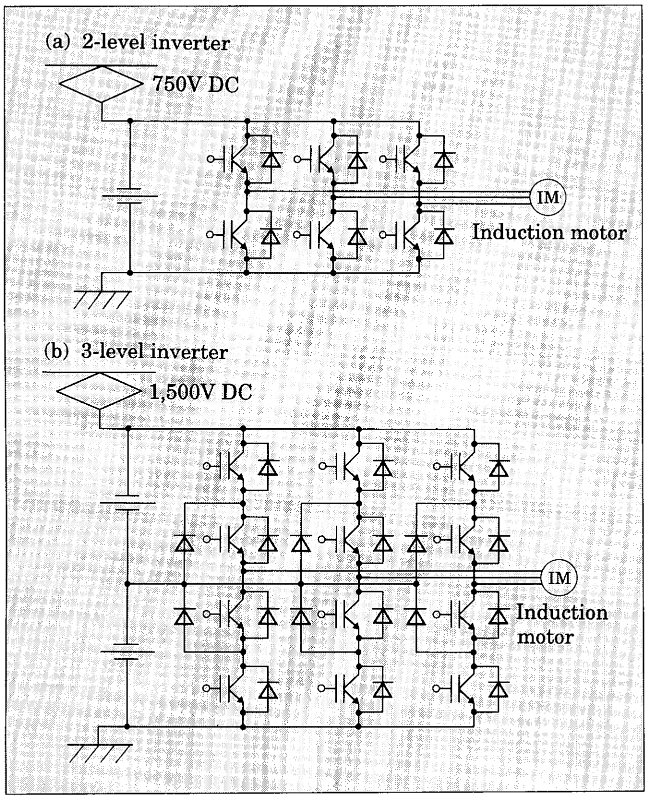
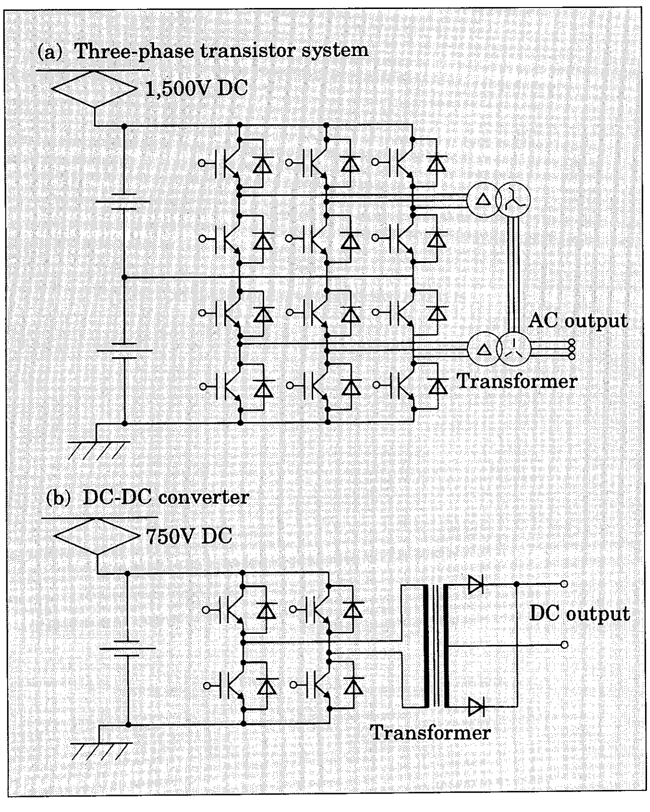


Fig. 3 Typical circuits of traction static inverter systems



to three-phase AC inverter systems utilizing power semiconductor devices and then to DC supply systems utilizing DC-DC converter systems.

Because of these trends, power semiconductor devices with insulated module construction have been used in power inverter systems for subway and suburban DC trains since the 1990s. The reason is that when compared with flat package structures, insulated construction requires no pressure connection mechanism, and maintenance and handling are simple. At the moment, because of such characteristics as high-speed switching and facilitated control, insulated IGBT modules are attracting attention in Japan as well as abroad.

Table 1 Product lines of power semiconductor devices for traction

Device	Structure	Model	Rated voltage/ current (T_j=25°C)
GTO thyristor	Flat package	EF3003AM-45	4,500V/3,000A
Reverse-conducting GTO thyristor	Flat package	EF2301RH-45	4,500V/2,300A
Free wheeling diode	Flat package	ERS21-45	4,500V/640A
IGBT module	Insulated module	1MB1400L-200	2,000V/400A
	Insulated module	1MB1600PN-180*	1,800V/600A
Clamp diode module	Insulated module	1F1600A-200	2,000V/600A
Fast recovery diode for snubber	Stud	ER25SM-20FR/R	2,000V/25A

* : newly developed

2.2 Fuji Electric's power semiconductor devices for traction

Fuji Electric's product line of power semiconductor devices for traction are shown in Table 1. The products are arranged in a series so that they can meet the above-mentioned technical trends and be used for everything from the subway to the Shinkansen. The company is making a special effort to develop an insulated IGBT modules, which has been recently attracting attention.

The overhead line voltage for DC trains now uses 1,500V and 750V, as shown in Fig. 2. For the 1,500 V overhead line, 3-level inverters [Fig. 2 (b)] are generally used so that harmonic noise, torque ripple, and magnetic noise can be reduced. For the 750V overhead line, 2-level inverters [Fig. 2 (a)] are generally used. However, because the overhead line voltage sometimes increases to a maximum of approximately 1,200V, high-voltage power semiconductor devices are required. In inverter systems using BJT (Bipolar Junction Transistor) modules, the maximum collector-emitter blocking voltage is 1,200V; therefore, 3-level inverters are used.

The 3-level inverters with BJT modules for 750V DC overhead lines are used especially overseas, where the demand for IGBT application, which reduces the number of devices and improves performance of inverter systems, is strong. The newly developed

Table 2 Typical ratings and characteristics of the 1,800V/600A IGBT module

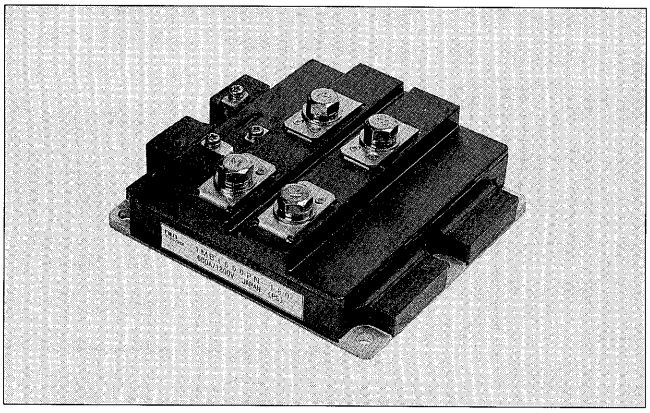
(a) Absolute maximum ratings ($T_j = T_C = 25°C$)

Item	Symbol	Max. ratings	Units
Collector−emitter blocking voltage	V_{CES}	1,800	V
Collector current (DC)	I_C	600	A
Isolation voltage	V_{iso}	4,000AC	V
Junction temperature	T_j	+150	℃
Storage temperature	T_{stg}	−40 to +125	℃

(b) Electrical characteristics ($T_j = 25°C$)

Item	Symbol	Condition	characteristics	Units
Collector−emitter leakage current	I_{CES}	$V_{CE}=1{,}800V$ $V_{GE}=0V$	Max. 1.0	mA
IGBT saturation voltage	$V_{CE(sat)}$	$V_{GE}=15V$ $I_C=600A$	Typ. 3.8	V
FWD forward voltage	V_F	$I_F=600A$ $V_{GE}=0V$	Typ. 3.5	V
IGBT turn−off time	t_{off}	$V_{CE}=750V$ $I_C=600A$ $V_{GE}=\pm15V$ $R_G=1.5\Omega$ Inductive load	Typ. 1.5	μs
	t_f		Typ.0.5	μs

Fig. 4 External view of the 1,800V/600A IGBT module



1,800V/600A IGBT module (1MBI600PN-180) aims to meet these requirements. An outline of the product is described below.

3. Development of the 1,800V/600A IGBT Module

3.1 Product outline

The typical ratings and characteristics of the 1,800V/600A IGBT module are shown in Table 2. This new product is a one-pack module incorporating IGBTs and FWDs (Free Wheeling Diodes). The voltage and current ratings were set at 1,800V/600A, ensuring a necessary isolation voltage and a large enough current to safely cut off the current in case of fluctuations in the overhead line voltage. Figures 4 and 5 show the external view and a sketch of the new module. This module has the maximum rating capacity and is the largest in size among Fuji Electric's IGBT modules.

Considerations during design of the module structure included the following:

Fig. 5 Outline drawing of the 1,800V/600A IGBT module

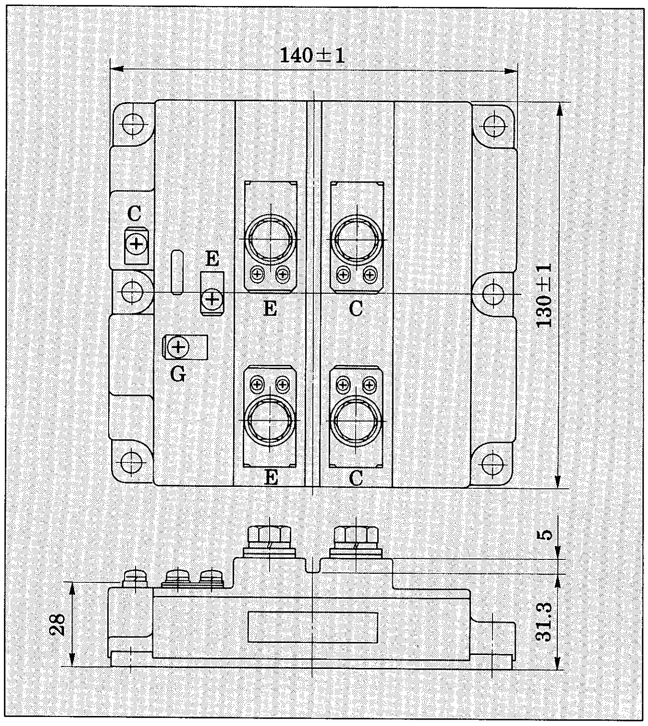
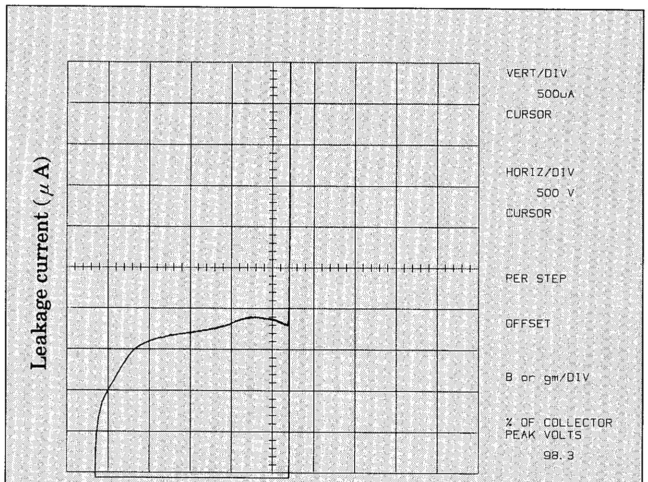


Fig. 6 Blocking voltage characteristics of the module structure



Collector-emitter blocking voltage (V)
Current : 500μ A/div, Voltage : 500V/div

(1) Ensuring isolation voltage

Modules for 750V overhead lines require the design of an isolation structure that can secure an isolation voltage of at least 4,000V AC.

(2) Uniformity of current sharing and thermal conductivity

Because the chips are connected in parallel to carry a large current, it is necessary to equalize current sharing and thermal conductivity between the chips.

(3) Ensuring reliability

IGBT modules for traction must have a long device level element lifetime and high reliability. In particular, it is essential to ensure reliability through load

Fig. 7 Output characteristics of the IGBT

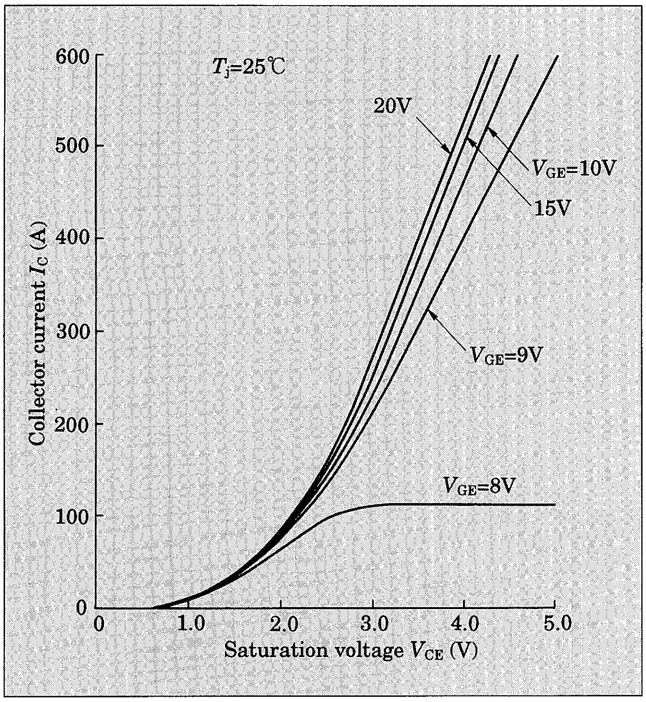


Fig. 8 Forward voltage characteristics of the FWD

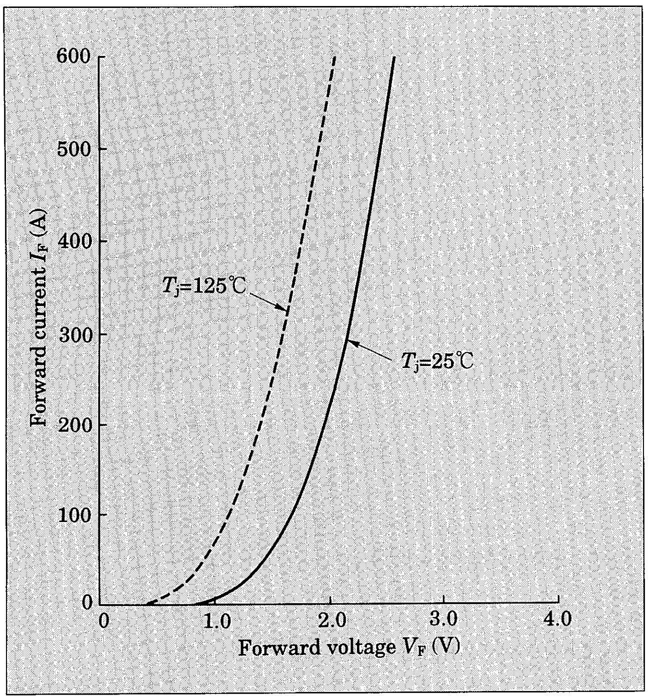
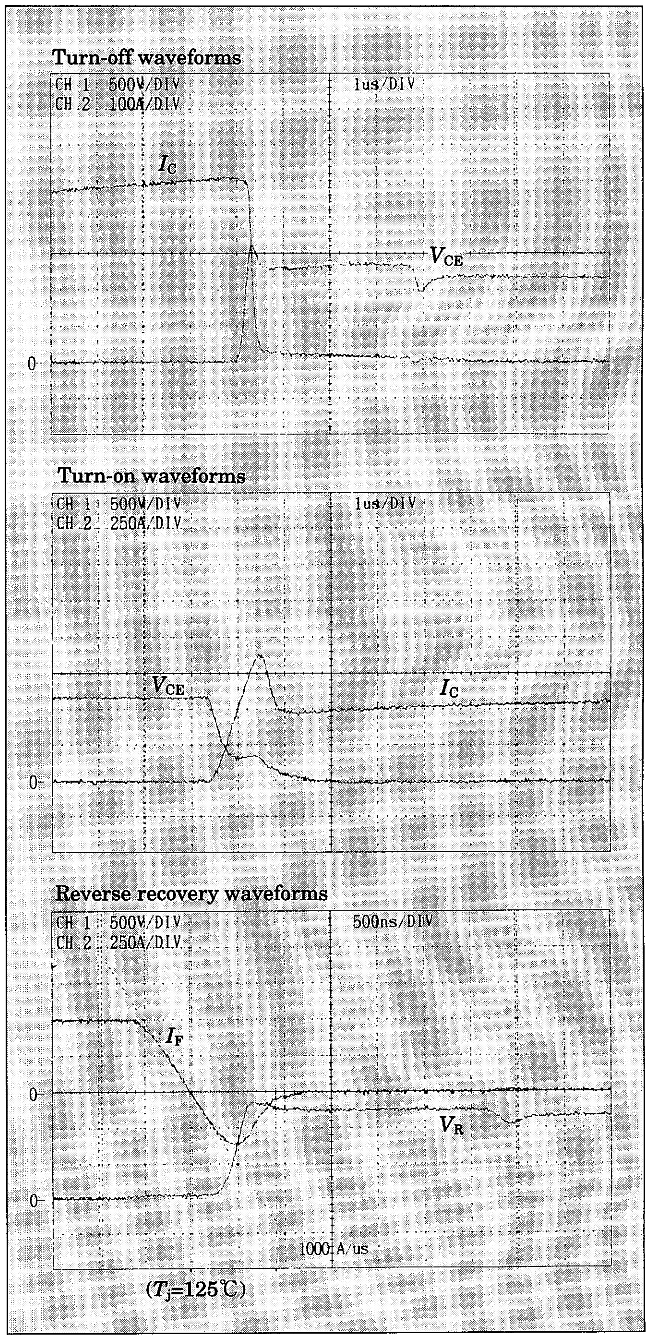


Fig. 9 Swithing and reverse recovery waveforms



cycle and temperature cycle tests.

The typical characteristics and structural design for the new module are described below.

3.2 Characteristics

3.2.1 Blocking voltage characteristics

To increase the blocking voltage of the IGBT and FWD, it is necessary to optimize the n^- layer thickness and the resistivity by trading off the switching and other dynamic characteristics. In addition, it is necessary to optimize the edge design to ensure a blocking voltage along the chip surface. For this module, they were optimized by a device simulation using IGBT and FWD chips. The blocking voltage characteristic for the module structure is shown in Fig. 6. The blocking voltage is sufficiently higher than the rated voltage.

3.2.2 Output and forward voltage characteristics

The output characteristics of the IGBT used in the newly developed module are shown in Fig. 7, and the forward voltage characteristics of the FWD are shown in Fig. 8. The typical values of the saturation and forward voltages at the rated current are 3.8V and 3.5V, respectively. These values were determined by trading off such dynamic characteristics as the blocking voltage

Fig. 10 Cross section of the isolation structures

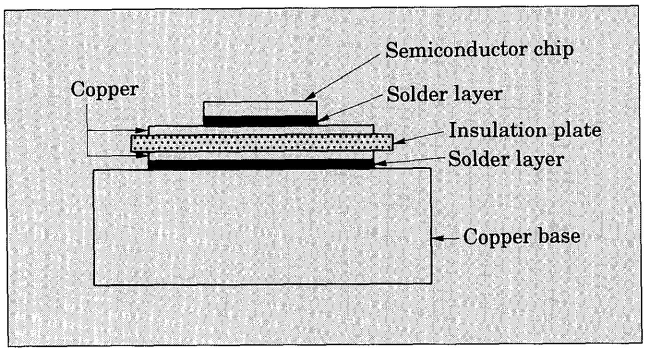
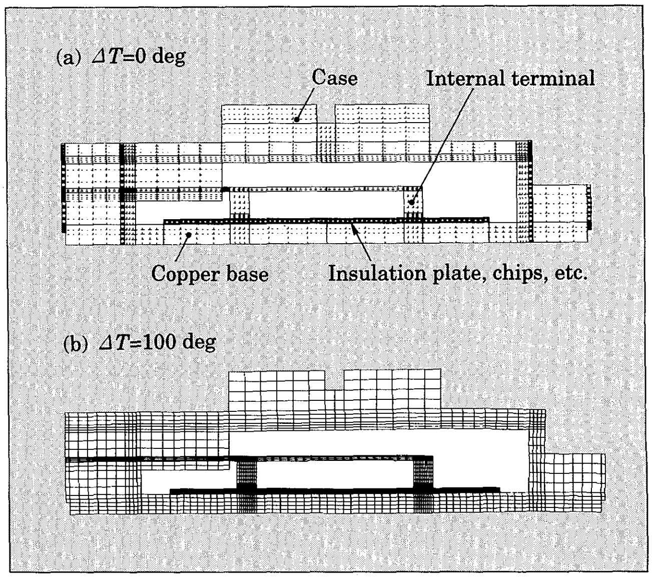


Fig. 11 Results of the two-dimensional structure simulation



and switching characteristics.

3.2.3 Switching and reverse recovery characteristics

In IGBT modules used for traction, switching and reverse recovery actions occur at a maximum of approximately 1,200V due to fluctuations in the overhead line voltage. Therefore, it is necessary to minimize surge voltage and safely cut off the current even at a maximum of 1,200V. Figure 9 shows the switching and reverse recovery waveforms of the developed module. The surge voltage due to turn-off and reverse recovery operation is comparatively small, and the current is cut off safely within the rated voltage. This was attained by optimizing the vertical profile and wafer process condition of the chip with a trade-off between blocking voltage characteristics, power dissipation, and surge voltage characteristics.

3.3 Design of module structure

3.3.1 Internal structure

Figure 10 shows a rough cross section of the isolation structure of the new module. Electrical isolation is ensured by insertion of the isolation plate between the semiconductor chip and the copper base. The isolation voltage is determined by the isolation thickness, material, and edge design. Isolation material is also a main factor in the determination of the module's thermal conductivity. Furthermore, in a large capacity module, having a large copper base area, the amount of warping in the copper base must be given consideration. In the development of this module, optimized blocking voltage, thermal conductivity, and isolation plate strength were considered during design of the isolation structure. As a result, a module structure with an isolation voltage of 4,000V AC was attained.

In the module, IGBT and FWD chips are connected in parallel to increase capacity. In large capacity modules, the number of parallel chips increases, and uniform current sharing by the chips is important. For this module's development, the layout was designed so that IGBT and FWD chips and internal terminals were symmetrically arranged. To reduce internal inductance, a symmetrical internal layout and a structure of main collector and emitter terminals placed as close as possible were used.

3.3.2 Reliable design

IGBT modules for traction require elements with a longer lifetime and higher reliability than those for industrial inverters. Particularly important is to ensure reliability through load cycle and temperature cycle tests. The load cycle tests for IGBT modules for traction consist of ΔT_j load cycle tests for the case of a junction during the operating period between stations, and ΔT_c load cycle tests using the rise in temperature of the cooling system.

Because materials used in the module structure have different coefficients of thermal expansion, thermal deformation due to temperature changes causes internal stress. To attain high reliability in the temperature cycle and ΔT_c load cycle tests, the module structure must be designed to minimize stress on the solder layer. In the newly developed, module, module deformation due to temperature changes was analyzed by a two-dimensional structural simulation before its design. Figure 11 shows the results of this simulation for the temperature cycle tests. This structure reduces module deformation and causes little internal stress even with an accelerated temperature change.

To pass the ΔT_j load cycle tests, it is essential to ensure the strength of the wire bonding section. In the development of this module, reliability was ensured by utilizing the most suitable wire material and bonding conditions.

4. Conclusion

In the paper, the technical trends of power semiconductor devices and inverter systems for traction are described, and Fuji Electric's product line of power semiconductor devices for traction are introduced. In addition to an outline, characteristics and structural design components of the newly developed 1,800V/600A IGBT module are introduced.

This new product has the largest rated capacity among Fuji Electric's IGBT module lines. In the future, IGBT application is expected to expand, replacing GTO thyristors in traction inverter systems. Application will include not only insulated modules but also new structural devices, including flat package, high-voltage, high capacity IGBTs that enable cooling on both sides of the device. Furthermore, new MOS (Metal Oxide Semiconductor) controlled devices such as DGMOS (Dual Gate MOS) devices and ESTs (Emitter Switched Thyristors) are expected replace IGBTs in the future.

Fuji Electric will continue its technical innovations, endeavor to develop and to market power devices meeting market needs, and contribute to the development of the power electronics industry.

References:

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