IGBT Modules

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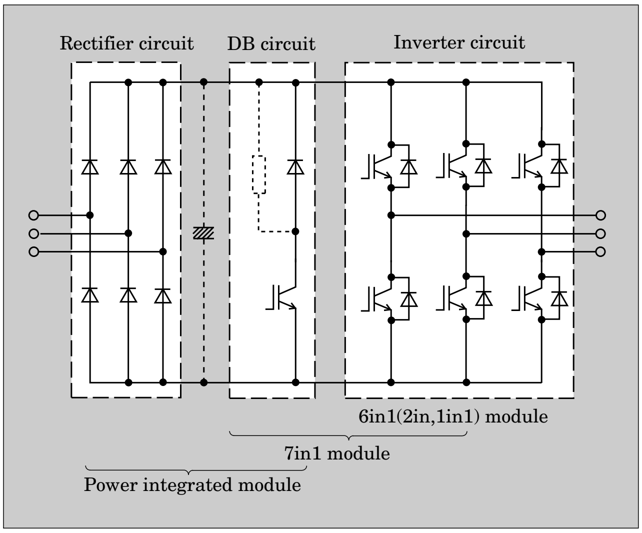
1. Introduction

Power electronics, in which power control and conversion are the main technologies has rapidly progressed in recent year. Application examples include general purpose inverters, uninterruptible power supplies (UPS) and numerical control (NC) machines. Market needs for these power converting systems always require small size and light weight, higher efficiency and lower noise. Therefore, technical innovations of power semiconductor devices (power devices), such as higher performance, advanced function and more power, are required from the market.

In these circumstances, the IGBT (insulated gate bipolar transistor) attracts attention because of its low loss, ease of driving circuit design, high blocking voltage, and development of high power devices. In 1993, Fuji Electric released the third generation IGBT (J series), leading all other companies. We then developed new third generation IGBTs (the N series and G series) which aim at lower price, improved usability and higher reliability. These IGBTs have been adopted in various fields.

In this paper, we will introduce the semiconductor device technology now developing, together with the present state of the newest IGBT modules.

Fig.1 Main configuration of the inverter circuit



2. The Present IGBT Module Series

2.1 Configuration of the inverter's main circuit and module

The configuration of the inverter's main circuit is shown in Fig. 1. This circuit is comprised of a converter circuit that converts (rectifies) alternating current (AC) to direct current (DC), an electrolytic smoothing capacitor to remove ripple voltage and an inverter circuit to get an AC output from a DC input. Furthermore, in the case of the motor control inverter, a dynamic brake (DB) circuit is necessary to suppress a rise of the smoothing capacitor voltage by regenerative operation.

Except the smoothing capacitor and a resistance of the DB circuit, all components in this configuration are power devices. Module products of this insulation type are widely used as power devices because of their ease of mounting.

2.2 The present IGBT module series

The above mentioned IGBT modules include various products such as a 6-in-1 (6 elements in one module), 2-in-1 or 1-in-1 for the inverter circuits, 7-in-1 for the DB + inverter circuit and a power integrated module for the converter + DB + inverter. Fuji Electric has mass-produced and brought these products to the market as the line-up for the new third generation IGBTs. This broad line-up is shown in Table 1, and the products are compatible with past company products as well as products of the other companies.

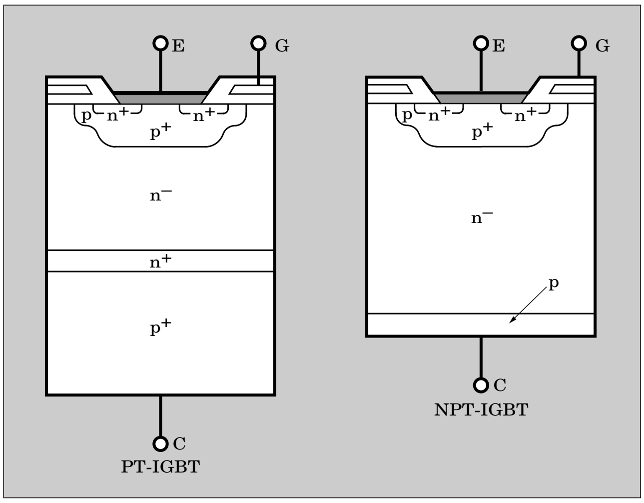
3. Present Problems and Subjects

We believe that the new third generation IGBTs (N and G series) comply with the market's needs by balancing low loss, soft switching characteristics, high withstand capability and an abundant product line-up. However, technological innovation for higher performances, advanced function and larger capacity is always necessary to comply with the ever-changing market needs, described previously. Using the exam-

Table 1 The new third generation IGBT line-up

I_c rating	600V	1,200V
10A	6MBI10GS-060	7MBR10NE120 7MBR10NF120
15A	6MBI15GS-060	7MBR15NE120 7MBR15NF120
20A	6MBI20GS-060	
25A		7MBR25NE120 7MBR25NF120
30A	7MBR30NE060 7MBR30NF060	
40A		7MBI40N-120
50A	7MBR50NE060 7MBR50NF060 2MBI50N-060	7MBI50N-120 2MBI50N-120
75A	7MBR75GE060 7MBI75N-060 2MBI75N-060	2MBI75N-120
100A	7MBI100N-060 2MBI100N-060	2MBI100N-120 2MBI100NB-120 2MBI100NC-120 2MBI100NE-120
150A	2MBI150N-060 2MBI150NC-060	2MBI150N-120 2MBI150NB-120 2MBI150NC-120 2MBI150NE-120
200A	2MBI200N-060	2MBI200N-120 2MBI200NB-120 2MBI200NE-120 1MBI200N-120 1MBI200NB-120
300A	2MBI300N-060 2MBI300NB-060	2MBI300N-120 1MBI300N-120 1MBI300NB-120 1MBI300NP-120 1MBI300NN-120
400A	2MBI400N-060	1MBI400N-120 1MBI400NB-120 1MBI400NP-120 1MBI400NN-120
600A	2MBI600NT-060 1MBI600NP-060 1MBI600NN-060	

Fig.2 Cross section of the NPT and PT chips



ple of general purpose inverters, the following must be considered:

(1) A blocking voltage of 1,400V for North America
(2) A wider reverse bias safe operating area (RBSOA) to simplify the snubber design.
(3) Soft switching characteristics to comply with EMI (electromagnetic interference)
(4) Specification of parallel connection or high blocking voltage and large current to increase inverter capacity

Furthermore, for power supply equipment in DC electric cars for subway and suburban trains, isolated type of IGBTs are considered an alternative to the present GTO (gate turn-off) thyristors from the viewpoints of ease of maintenance, high-speed switching and drive ease, and required high blocking voltage.

At present, Fuji Electric is investigating and developing the basic technology for these requirements. We will present some examples on the above subjects in and after the next section.

4. Results of New Technology

4.1 Technology and characteristics of the NPT-IGBT chip

4.1.1 NPT structure and features

The NPT (non punch-through)-IGBT has a structure designed for optimum thickness of the n^- layer so as not to elongate the depletion layer to the p layer. It is shown in Fig. 2 compared with the conventional structure (PT: punch-through).

The NPT-IGBT has attracted attention in recent years due to the following three items:

(1) A high blocking voltage IGBT can be designed by setting the thickness of the n^- layer.
(2) As shown in Fig. 3 (a), collector-emitter saturation voltage $V_{CE(sat)}$ increases as the temperature rises. Therefore, when chips or modules are connected in parallel, current imbalance is smaller and it is easy to increase inverter capacity using them in parallel.
(3) Cost/performance is high because FZ (floating zone) silicon wafers can be used.

Fig.3 I_C - V_{CE} characteristics of the NPT-IGBT

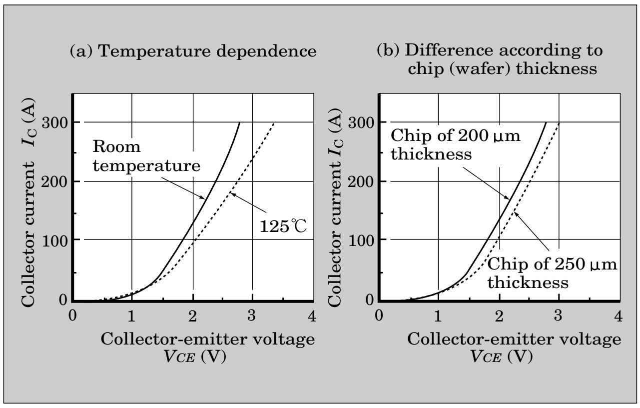


Fig.4 Reducing E_{off} by a thinner chip of 20µm thickness

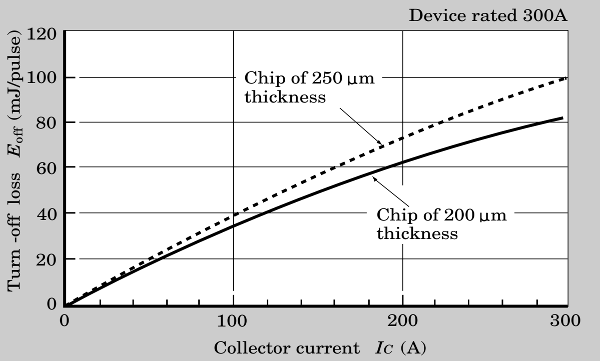


Fig.5 Reducing short-circuit current with a chip of higher $V_{GE(th)}$ (for a 100A device)

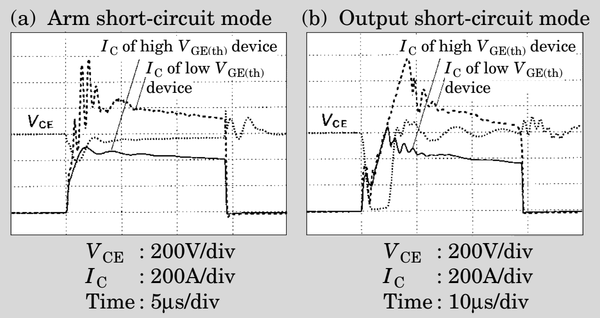
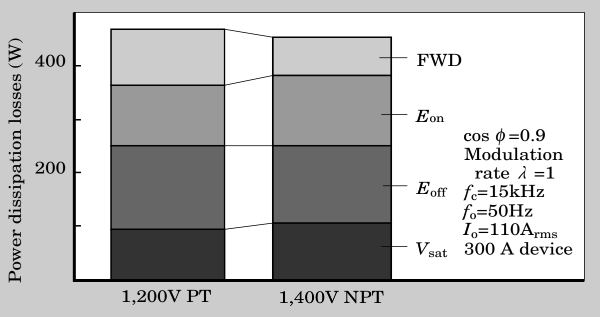


Fig.6 Comparison of power dissipation losses between PT and NPT



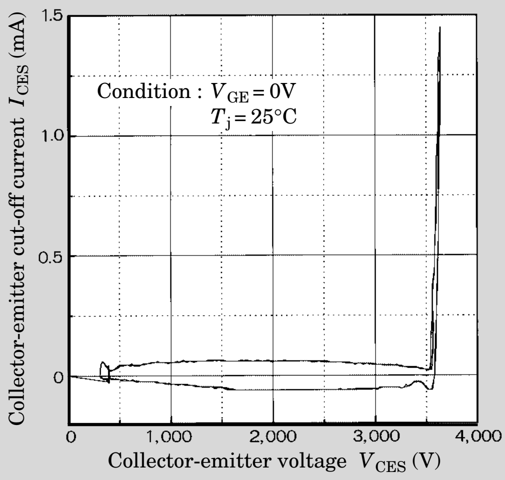
4.1.2 Features of Fuji Electric's NPT-IGBT

When using the IGBT as main switching device in an inverter equipment, dissipitation loss is an important item to be evaluated. Dissipitation loss is generally classified into conduction loss and switching loss. These losses have a close relationship with $V_{CE(sat)}$ and turn-off characteristics respectively. The thinner the n^- layer is, the smaller the $V_{CE(sat)}$ and tale current at turn-off become. It is necessary to then optimize the thickness of the n^- layer, taking into consideration the trade-off with the device's blocking voltage. On the other hand, when the inverter has short-circuit trouble, the devices are specifically required to have a short-circuit withstand capability to tolerate a certain minimum short-circuit period by reduction of short-circuit current.

Fuji Electric has optimized the NPT-IGBT to make the chip's thickness thin while securing the device's blocking voltage and establishing the manufacturing technology. As a result, reducing $V_{CE(sat)}$ (as shown in Fig. 3) and reducing E_{off} (as shown in Fig. 4) became possible. Furthermore, the short-circuit current is reduced by setting $V_{GE(th)}$ somewhat higher and the short-circuit oscillation is suppressed by adopting a terrace-gate structure. The comparison of waveforms is shown in Fig. 5.

A comparison of inverter losses using the newly developed IGBT and the conventional IGBT is shown in Fig. 6. Surpassingly the 1,400V NPT-IGBT shows an equivalent total power dissipation loss as the 1,200V PT-IGBT. Furthermore the NPT-IGBT can have short-circuit withstand capability of about twice or more that of the PT-IGBT.

Fig.7 Blocking voltage of the 3,300V prototype



4.2 Technology and characteristics of the high blocking voltage chip

As described in section 3, higher performance of semiconductor devices is indispensable for the power supply equipment of DC electric cars used by subway and suburban trains. Especially in recent years, semiconductor devices with an insulated module structure are positively investigated because of their ease in handling and maintenance. They are also widely noted as an alternative to GTO thyristors from the viewpoints of high-speed switching and driving ease. Fuji Electric plans to introduce high blocking voltage IGBTs, thus enlarging the product series.

We have developed an IGBT with a high blocking voltage applicable to 2-level inverter for overhead traction wire with voltages of 750V or 1,500V. We will

Fig.8 Output characteristics of the 3,300V prototype

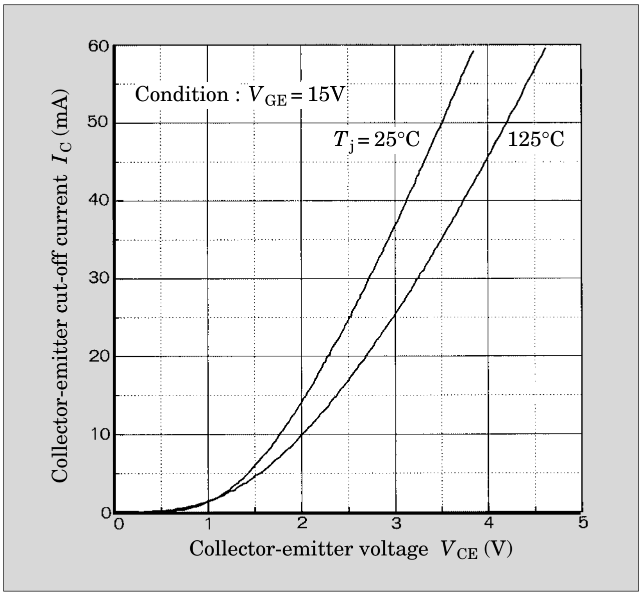
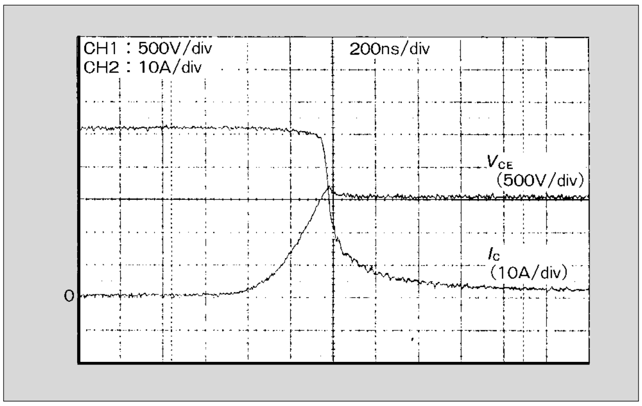


Fig.9 Turn-off waveform of the 3,300V/50A prototype



explain the features and characteristics of this IGBT.

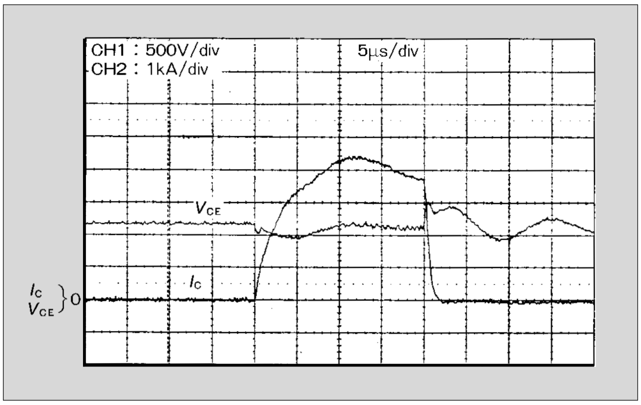
4.2.1 High blocking voltage

Setting the thickness of the n⁻ layer and specific resistance and design of the blocking voltage structure are important for high blocking voltage in the NPT structure. Recently, prototypes developed and produced were chips of 3,300V based on the design of 2,500V flat type IGBTs. By optimizing the structure and number of guard rings and length of the field-plate, blocking voltage of a 3,300V/50A prototype are achieved stably and its characteristic is shown in Fig. 7. The avalanche voltage is nearly 3,600V.

4.2.2 Saturation voltage characteristics

Since the module for traction cars is required to be 400 to 1,200A per module, chips of about 50 to 100A should be connected in parallel in a module. Therefore, NPT-IGBT chips having a positive temperature coefficient of saturation voltage characteristics are optimum in securing a good current sharing between the chips inside the module and between them. The output characteristics of this chip are shown in Fig. 8. The characteristics show about 3.5V at the rated

Fig.10 Short-circuit waveform of 1MBI800PN-180



current of 50A by improving the trade-off between blocking voltage, switching characteristic and the short-circuit withstand capacity and by optimizing the process conditions.

4.2.3 Turn-off characteristics

The turn-off waveform is shown in Fig. 9. This waveform shows turn-off of rated current at 1,500V and demonstrates useful characteristics that surge voltage is smaller by suppressing the $-di/dt$.

4.3 Packaging technology and its reliability

When applying IGBT to inverter equipment, long-term reliability is required for traction cars in particular. In this section, we will explain package technology focusing mainly on securing reliability.

4.3.1 Securing isolation voltage

The required isolation voltage in electric railways is 4,500V AC or more in an overhead traction wire of 1,500V DC. The IGBT module satisfies this requirement by optimizing the material and thickness of the isolation substrate and the design of the edge part.

4.3.2 High current module

The reliability of semiconductor devices depends on their heat dissipation, which decreases as the temperature increases. Therefore, the current sharing of the chips should be equalized to suppress temperature imbalance when structuring a module with a high current rating with plural chips connected in parallel. It was found that the current sharing largely depends on the geometrical form of the current path in the module. Then, it becomes possible to equalize the current sharing by equalizing the arrangement of the chips and designing the wiring layout symmetrically inside the module.

On the other hand, to reduce surge voltage in the module, the inductance or current value between the terminals inside the module should be greatly reduced. It is then required to reduce the inductance for making the current high. This is attainable by utilizing mutual induction of parallel conductors and putting the collector and emitter electrodes close together to reduce the inductance. We have acquired the patent to reducing inductance by utilizing the mutual induction of parallel conductors (Japan Patent No. 2046854).

4.3.3 Reducing loss and securing reliability

Reducing loss and the short-circuit withstand capability have a trade off relationship. The short-circuit withstand capability is reduced when the saturation voltage and switching loss are improved. We have secured the short-circuit withstand capability

Fig.11 Cross section of wire bonding after 800,000 power-cycles

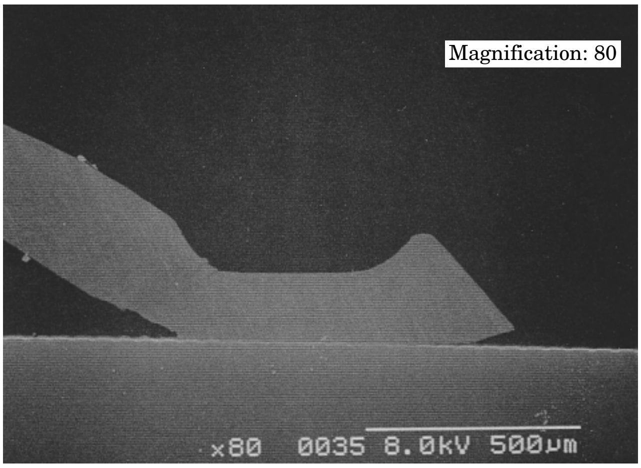


Fig.12 Change of transient thermal resistance during heat cycle (ΔT_j) test

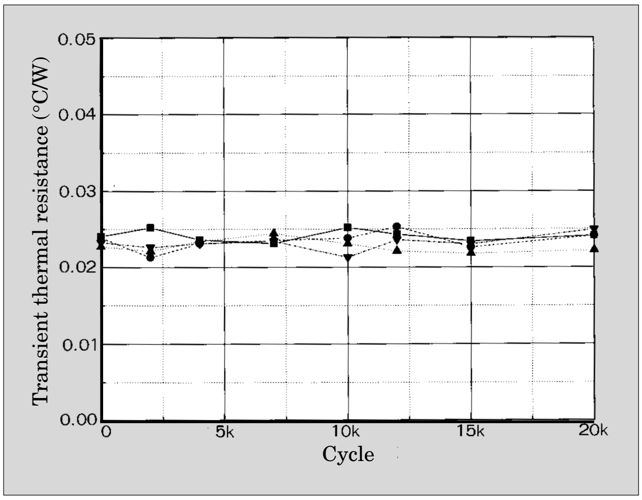


Fig.13 View of Fuji Electric's NPT-IBPT

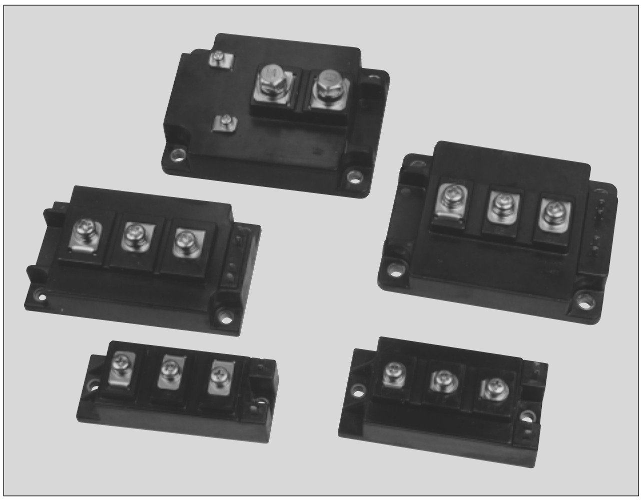


Table 2 Fuji Electric's NPT-IGBT series

Model	No. of elements	V_{CES}	$I_{C(DC)}$	$V_{GE(th)}$ (typ.)	$V_{CE(sat)}$ (typ.)	V_F (typ.)
2MBI50P-140	2	1,400V	50A	8.0V	2.8V	2.4V
2MBI75P-140	2	1,400V	75A	8.0V	2.8V	2.4V
2MBI100PC-140	2	1,400V	100A	8.0V	2.8V	2.4V
2MBI150PC-140	2	1,400V	150A	8.0V	2.8V	2.4V
2MBI200PB-140	2	1,400V	200A	8.0V	2.8V	2.4V
2MBI300P-140	2	1,400V	300A	8.0V	2.8V	2.4V
1MBI600PX-120	1	1,200V	600A	8.0V	2.9V	2.5V

Table 3 Ratings and characteristics of 1MBI800PN-180

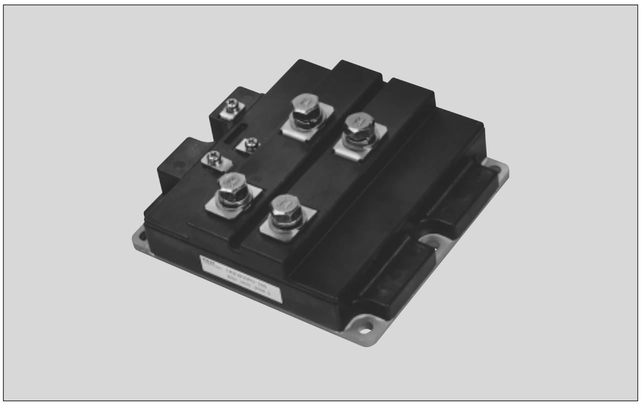
(a) Absolute maximum rating ($T_j = T_c = 25$°C)

Item	Symbol	Maximum rating	Unit
Collector-emitter voltage	V_{CES}	1,800	V
Collector current (DC)	I_C	800	A
Isolation voltage	V_{iso}	5,400 AC (1 minute)	V
Junction temperature	T_j	150	°C
Storage temperature	t_{stg}	– 40 to +125	°C

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

Item		Symbol	Conditions	Characteristics	Unit
Collector-emitter cut-off current		I_{CES}	V_{CE}=1,800V V_{GE}=0V	Max. 1.0	mA
Gate-emitter threshold voltage		$V_{GE(th)}$	V_{CE}=20V I_C=800mA	Typ. 6.0	V
Collector-emitter saturation voltage		$V_{CE(sat)}$	V_{GE}=15V I_C=800A	Typ. 3.7	V
Diode forward voltage		V_F	V_{GE}=0V I_F=800A	Typ. 3.7	V
Thermal resistance	IGBT part	$R_{th(j-c)}$		Max.0.03	°C/W
	FWD part	$R_{th(j-c)}$		Max.0.075	°C/W
	Case-heat sink	$R_{th(c-f)}$		Typ. 0.01	°C/W

Fig.14 View of 1MBI800PN-180



without increasing dissipation loss by performing optimum design for vertical profile and process of the chip to improve this trade-off. The waveform of a 1,800V/800A device in a short-circuit test is shown in Fig. 10. The peak current became less than 4,500A when 1,200V DC was applied at $T_j = 25°C$, and a pulse width of 20μs or more was secured.

Furthermore, if the dissipation loss of the device is large, the lifetime will be shorter by the increase in temperature rise and temperature change. The lifetime of the semiconductor device required for traction cars is required to be as long as 20 to 30 years. For securing high reliability, it is important to execute the power-cycle (ΔT_j) test for the lifetime of conducting operation and the heat cycle (ΔT_c) test for the lifetime of environmental temperature change.

To improve the power cycle withstand capability, securing the strength of the wire-bonding part is important. The strength is dependent on the bonding conditions. By optimum design of the wire material and bonding part, wire bonding was confirmed not to be abnormal after 800,000 cycles of the power cycle test (acceleration test at $\Delta T_j = 100$ deg). The cross section of the wire bonding part after the test is shown in Fig. 11.

On the other hand, the generation of thermal stresses to the solder layer joint between the chip and isolation substrate and between the isolation substrate and copper base is problematic for the heat cycle. When excess thermal stress is applied to the solder layer, a problem of deteriorated thermal resistance occurs by cracks in the solder layer. As countermeasures against this stress, an analysis of the thermal stress is executed using the finite element method to reduce the stress and extend the life time. The characteristics were confirmed not to deteriorate until 20,000 cycles of acceleration test at $\Delta T_c = 70$ deg (equivalent to a lifetime of 30 years mounted on a vehicle). The results of the heat cycle (ΔT_c) test are shown in Fig. 12.

5. New Product Series

As described in section 4.1, the 1,400V NPT-IGBT realized equal or better characteristics as the existing 1,200V series. Their appearances and series contents are shown in Fig. 13 and Table 2. In the near future, Fuji Electric intends to develop a 6-in-1 module and a PIM and to expand the series to inverter applications.

As for the high voltage IGBT, a 1,800V/800A IGBT module (1MBI800PN-180) is in production. This is expected to be applied to the large capacity inverter and 2-level inverter for the 750V overhead traction wire or 3-level inverter for the 1,500V overhead traction wire in electric railways. Table 3 shows its rating and characteristics and Fig. 14 shows its appearance. An IGBT module having a blocking voltage of 3,300V is planned for development in 2-level inverters for 1,500V overhead traction wire.

6. Future Prospects

The NPT-IGBT demonstrates features for blocking voltage of 1,200V or more, but it is difficult to realize lower blocking voltage such as 600V because of difficulty to handle very thin wafers. Improvement of the present PT technology is more promising rather than that of the NPT. Expected candidates for this may be fine patterned cell structure and trench-gate IGBTs. Both are effective in reducing on-state voltage and are being investigated as elemental technologies. We are also considering other devices with new structures and new operation principles.

7. Conclusion

We have introduced a series of IGBT modules and new technology under investigation and development. We believe that these IGBTs and large capacity modules will penetrate into not only existing application fields but also new fields. They will certainly contribute to improvement of equipment performance and ease of design.

Fuji Electric will contribute to the development of power electronics by further striving to improve performance, function and reliability of power devices and to develop the products in response to diversifying market needs.