T-series and U-series IGBT Modules (600 V)

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1. Introduction

The IGBT (insulated gate bipolar transistor) module is the most popular power device in power electronics fields such as motor control applications. The reason for the IGBT's popularity is the market values of its excellent reliability due to reduction of generated loss and increase of withstand capability, etc., in addition to the fact that it can be easily driven. The 600 V IGBT modules play an especially important role as key devices in a wide market area including the Japanese domestic market where 220 V industrial power supplies are used and overseas such as in Europe where 200 V public power supplies are used as general-purpose power supplies.

Under these circumstances, Fuji Electric has also been developing a 600 V IBGT module product series, and has continued to improve their characteristics ever since first developing the series in 1988. In 2001, the development of thin wafer processing technology enabled NPT (non-punch through) structure to be applied to 600 V devices. This made possible the development of T-series IGBTs, having low switching loss and being especially suitable for high frequency applications.

While development of NPT technology mainly involved by development of the structure at the back of the chip, improvements of the chip's front structure have also been implemented since 2002. By applying trench-gate-structure, increase in channel density and elimination of the unnecessary voltage-drop component was achieved, thereby enabling the reduction of on-state loss. This made the development of U-series IGBTs successful, as the device having the smallest loss among products of its class, and at present, we are in the process of producing various rated current series and sample modules.

For the FWD (free wheeling diode) packed in IGBT modules, enhanced soft-recovery characteristics as well as decreased loss is demanded. These demands are not only for the sake of preventing equipment malfunction, but also to preventing possible ill effects of noise emission on the surrounding equipment and on the human body. To satisfy these requirements, FWDs having a new structure were developed and adopted for the above new IGBT modules. This paper presents these device techniques and the product series.

2. T-series IGBT Modules

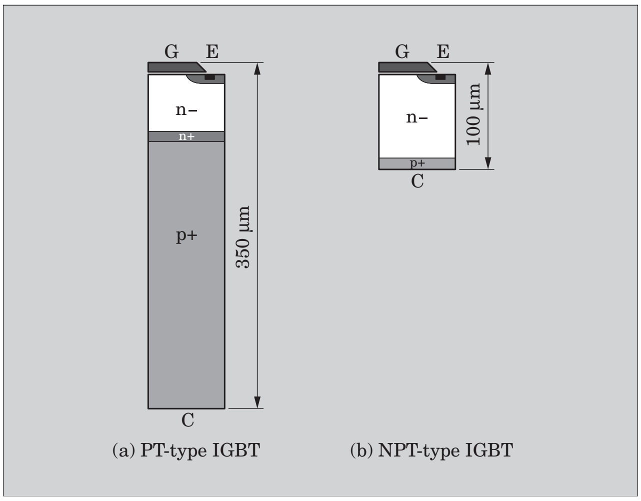
2.1 Features and challenges of T-series IGBT modules

The cell structure of an NPT-type IGBT and the unit cell of PT (punch-through)-type device are shown in Fig. 1. Their features are as follows:

(1) Since injection from the collector-side can be suppressed, lifetime control is unnecessary and the switching loss does not increase even at a high temperature.
(2) Because the temperature dependence of output characteristics is positive (the saturation voltage increases at higher temperatures), these devices are well suited for parallel applications.
(3) Withstand capability including load short-circuit capacity are higher than those of a PT-type device.
(4) Use of an FZ (floating zone) wafer makes the price cheap and the reliability high owing to its low crystal defects.

The challenge is to establish a thin wafer processing technique. It is important for NPT-type devices to suppress saturation voltage while maintaining the collector-emitter (CE) forward blocking voltage. This

Fig.1 Comparison of unit cell structures



requires keeping the depletion layer end thick enough so there is no punch-through even when the maximum CE voltage is applied. The optimal thickness is thinner for devices having lower CE forward blocking voltage, making their manufacturing even more difficult.

2.2 Fuji Electric approach to NPT devices

Fuji Electric has been involved in developing NPT technology earlier on as shown in Fig. 2, and is working to extend the application of this technology to more challenging devices having lower forward blocking voltages.

Although the optimal thickness for 600 V-NPT IGBTs application is said to be about 100 µm based upon various investigations, Fuji Electric has made it possible to set the thickness lower than that of the other companies through improved precision of back-grinding process technology. This was effective in reducing saturation voltage and turn-on loss, which were factors contributing to generated loss or inverter loss.

2.3 Characteristics of T-series IGBTs

An overview of the characteristics of T-series IGBTs is presented below. Figure 3 compares V_{CES} waveforms, namely the CE-forward blocking voltages, in which the forward blocking voltage of the NPT device is about 800 V, similar to that of the PT device, and higher than the maximum rated voltage of 600 V.

Figure 4 shows a comparison of turn-off waveforms. In PT-type devices, which are injected more from the collector side, lifetime control is implemented to promote the recombination of carriers at the time of turn-off. However, because this effect decreases as the temperature increases, the loss tends to increase caused by the increase of tail current. For NPT-type devices, on the other hand, no lifetime control is applied and therefore these temperature dependence do not exist, resulting in no change in the turn-off waveform and no increase in turn-off loss.

The load short-circuit waveforms are shown in Fig. 5. When the load is short-circuited, devices breakdown due to the temperature rise resulting from the generated energy loss.

However, the NPT-type device, having a thick n– drift layer, can support the voltage with its wide n– drift layer, and the temperature rise which causes breakdown can be suppressed, resulting in high short-circuit withstand capability. Compared with the withstand capability of 15 µs of a PT-type device, the NPT-type device has a real capability of 22 µs, which is

Fig.2 Changes in Fuji Electric's application of NPT technology

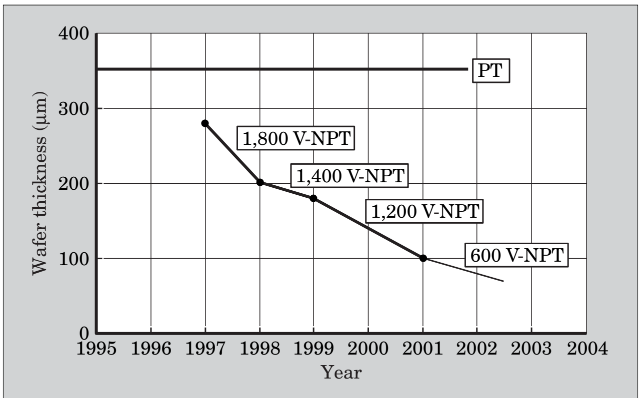


Fig.3 Comparison of V_{CES} waveforms of PT-type device and NPT-type device

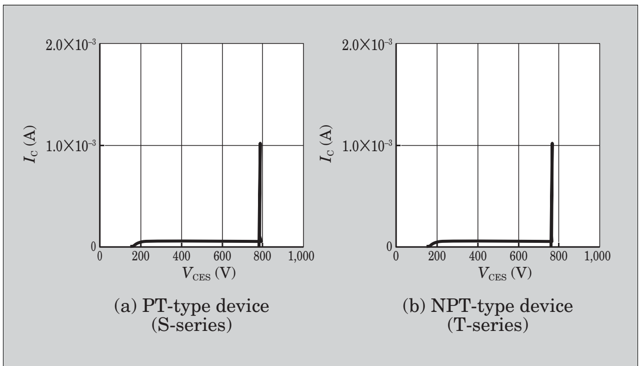


Fig. 4 Comparison of turn-off waveforms

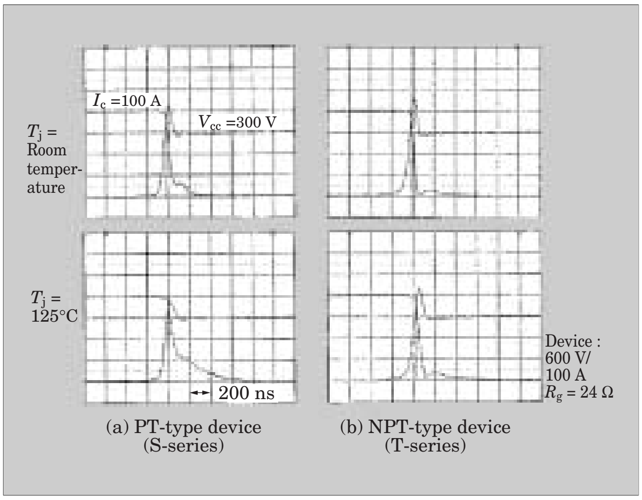
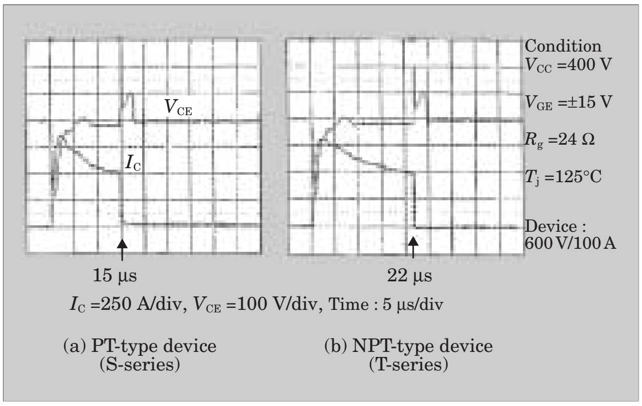


Fig.5 Comparison of load short-circuit waveforms



sufficiently above the usually required 10 μs.

3. U-series IGBT

3.1 Chip front cell structure of U-series IGBT

Improvements were applied to the emitter side structure of the T-series IGBT chip, having already had its back structure improved, for the purpose of further collector side performance enhancement. Fuji Electric is producing trench-gate type power MOSFETs (metal oxide semiconductor field effect transistors), to which design and process technologies have been applied, to ensure sufficient reliability to permit installation in motor vehicles. The U-series IGBT is the result of applying these techniques to IGBTs. Figure 6 compares this cell structure with that of the T-series planer type.

The trench type IGBT allows drastic increase in cell density, resulting in suppression of the voltage drop at the channel part to a minimum. Since the distinctive J_{FET} region, sandwiched between channels of the planer type device, does not exist in the trench type device, the voltage drop at this region can be completely eliminated. However, a standard cell design cannot be applied to power MOSFETs having a low blocking voltage below 100 V, and instead, a new cell pitch and trench depth appropriate for 600 V IGBTs should be applied. The optimal values for U-series IGBTs were investigated using simulations and experiments, and then applied to the cell design.

Fig.6 Comparison of planar and trench type cell structures

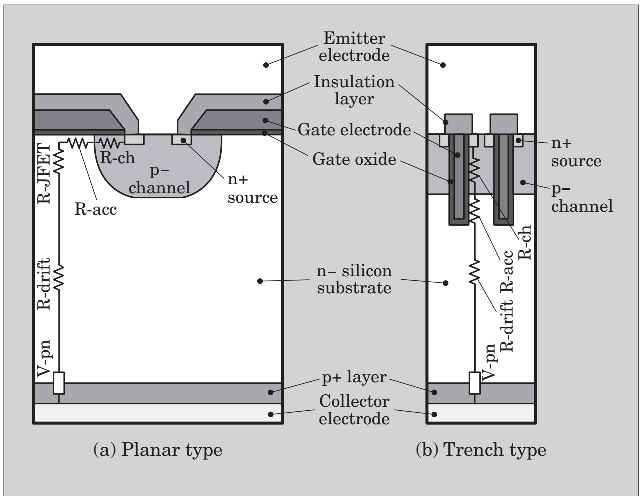
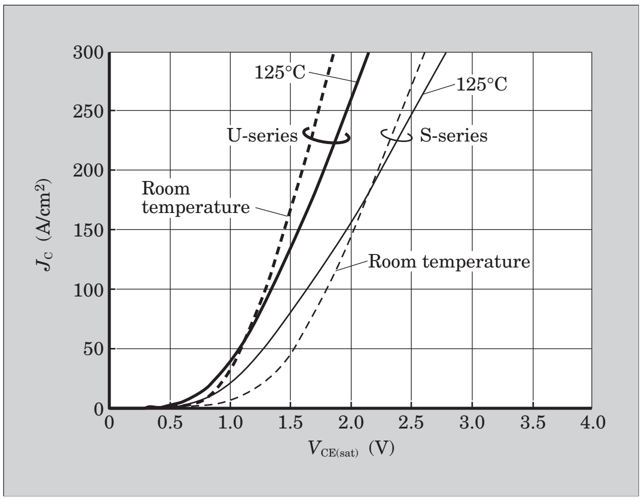


Fig.7 Comparison of saturation voltages between collector and emitter, and of collector current output characteristics



3.2 Characteristics of U-series IGBTs

Characteristics of U-series IGBTs, designed based upon the aforementioned techniques, are described below. First, the output characteristics of saturation voltage between collector and emitter ($V_{\text{CE (sat)}}$) and collector current are shown in Fig. 7.

$V_{\text{CE (sat)}}$ for a current density of 185 A/cm^2 (at T_{j} = 125°C) was significantly reduced from 2.15 V down to 1.70 V. The intersects of the output characteristics at room temperature and at high temperature lies in the lower current area, and the temperature dependence

Fig.8 Comparison of loss generation of various devices

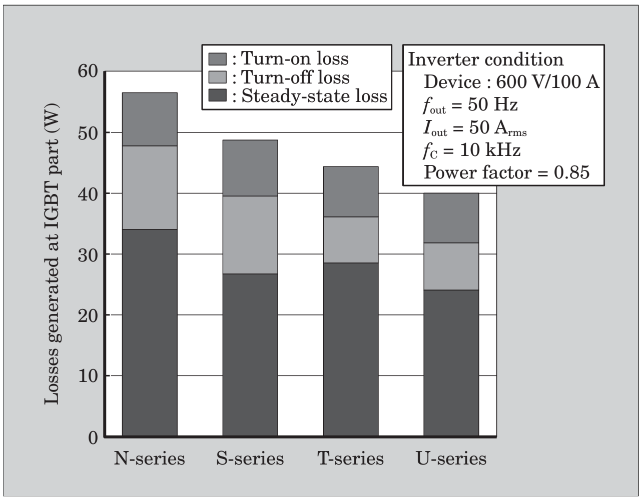


Fig.9 FWD output characteristics

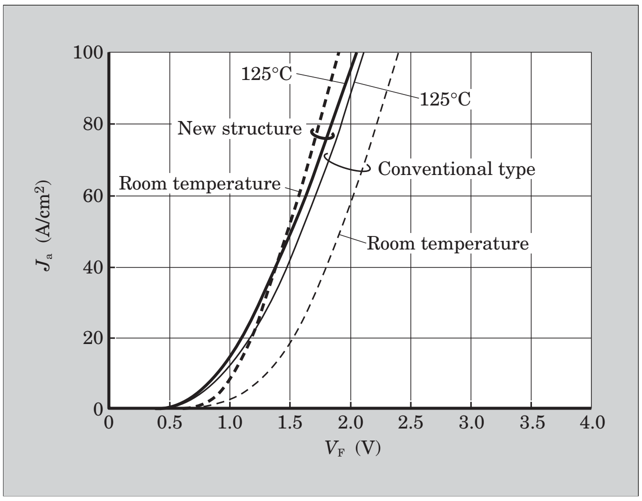
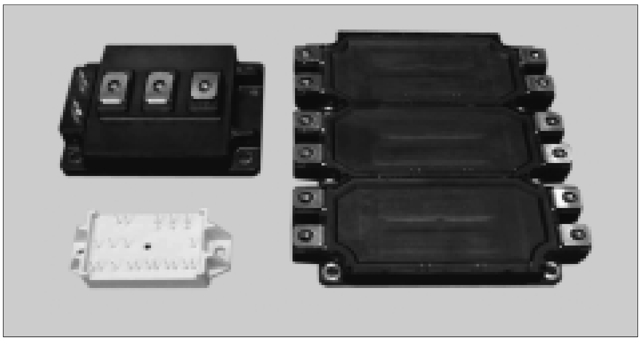


Table 1 U-series IGBTs

Package	Rated current	Model	Product release date
Small capacity PIM	8 A	7MBR8UE060	April 2003
	10 A	7MBR10UE060	
	15 A	7MBR15UE060	
	20 A	7MBR20UE060	
	30 A	7MBR30UE060	
EP2	20 A	7MBR20UA060	
	30 A	7MBR30UA060	
	50 A	7MBR50UA060	
EP3	50 A	7MBR50UB060	
	75 A	7MBR75UB060	
	100 A	7MBR100UB060	
HEP2	20 A	7MBR20UC060	
	30 A	7MBR30UC060	
	50 A	7MBR50UC060	
HEP3	75 A	7MBR75UD060	
	100 A	7MBR100UD060	
7in1 (M631 or M621)	100 A	7MBI100UD-060	
	150 A	7MBI150UD-060	
	200 A	7MBI200UD-060	
	300 A	7MBI300UD-060	
M232	150 A	2MBI150UA-060	
	200 A	2MBI200UA-060	
M233	300 A	2MBI300UB-060	
	400 A	2MBI400UB-060	
M238	600 A	2MBI600UE-060	
M629	400 A	6MBI400U-060	
	600 A	6MBI600U-060	

Fig.10 Typical package of U-series IGBT



in the normal-use area are positive. These positive temperature dependence can reduce the behavior unbalance between devices when using large capacity modules parallel, and can elongate the lifespan of the products. These characteristics result from the facts that lifetime control is not implemented and that the n-drift layer is thick, which are common features of the T-series and U-series.

Figure 8 compares the calculated results of loss generation for various devices when the current density is kept at the same value. Application of an NPT-type structure reduced the turn-off loss drastically in the T-series module, resulting in an approximate 10 %

Table 2 Major ratings of 2MBI400UB-060 (tentative)

(a) Absolute max. ratings (T_c = 25°C unless specified otherwise)

Item	Symbol	Condition	Max. rating	Unit
Collector-emitter voltage	V_{CES}		600	V
Gate-emitter voltage	V_{GES}		±20	V
Collector current	I_C	Continuous	400	A
	$I_{C\ pulse}$	1 ms	800	
	$-I_C$		400	
	$-I_{C\ pulse}$	1 ms	800	
Maximum power dissipation	P_C	1 device	1,135	W
Junction temperature	T_j		150	°C
Storage temperature	T_{stg}		–40 to +125	°C
Isolation voltage (package)	V_{iso}	AC : 1 min	2,500	V
Screw fastening torque	Mounting		3.5	Nm
	Terminals		3.5	

(b) Electrical characteristics (T_c = 25°C unless specified otherwise)

Item	Symbol	Condition		Characteristics min.	typ.	max.	Unit
Zero gate voltage collector current	I_{CES}	V_{GE} =0 V, V_{CE} =600 V		–	–	2.0	mA
Gate-emitter leakage current	I_{GES}	V_{CE} =0 V, V_{GE} =±20 V		–	–	0.4	μA
Gate-emitter threshold voltage	$V_{GE(th)}$	V_{CE} =20 V, I_C =400 mA		–	6.0	–	V
Collector-emitter saturation voltage	$V_{CE(sat)}$ (Terminal)	V_{GE} = 15 V, I_C = 400 A	T_j =25°C	–	1.8	–	V
			T_j =125°C	–	1.9	–	
	$V_{CE(sat)}$ (Chip)		T_j =25°C	–	1.6	–	
			T_j =125°C	–	1.7	–	
Input capacitance	C_{ies}	V_{GE} =0 V, V_{CE} =10 V, f =1 MHz		–	40	–	nF
Turn-on time	t_{on}	V_{CC} =600 V, I_C =400 A, V_{GE} =±15 V, R_g =0.5 Ω		–	–	1.2	μs
	t_r			–	–	0.6	
Turn-off time	t_{off}			–	–	1.0	
	t_f			–	–	0.35	
Diode forward voltage	V_F (Terminal)	I_F = 400 A	T_j =25°C	–	1.8	–	V
			T_j =125°C	–	1.7	–	
	V_F (Chip)		T_j =25°C	–	1.6	–	
			T_j =125°C	–	1.5	–	
Reverse recovery time	t_{rr}	I_F =150 A		–	–	0.3	μs

(c) Thermal resistance characteristics

Item	Symbol	Condition	Characteristics min.	typ.	max.	Unit
Thermal resistance of device (1 device)	$R_{th(j-c)}$	IGBT	–	–	0.11	°C/W
		FWD	–	–	0.18	
Case to fin thermal resistance	$R_{th(c-f)}$		–	0.025	–	

reduction in total IGBT loss, compared with the S-series. For U-series IGBT modules, in which on-state energy loss has been decreased due to a reduction of $V_{CE\ (sat)}$, an additional 10 % reduction of loss has been realized.

4. Improvement of FWD

An FWD is packed into an IGBT module together with an IGBT, and the FWD is required to have soft recovery characteristics and reduced levels of generated loss. The improvements include optimization of wafer specifications, injection control from the anode at the chip's front structure and implementation of optimal lifetime control. Fuji Electric has developed FWDs with a revised new design. The output characteristics are shown in Fig. 9. As a result, the forward voltage (V_F) has been reduced and positive temperature dependance have been realized. Because carrier injection is suppressed, the peak current at reverse recovery has been reduced, loss generation has been reduced, and soft-recovery characteristics have been achieved. These improvements led to the realization of an FWD having low generated loss and low noise, and enabled its application to the U-series module.

5. Introduction of Product Series

Details of the U-series IGBT product lineup are as follows. The U-series IGBT product lineup and product release date are shown in Table 1, and the external view of a typical package is shown in Fig. 10. The major ratings and characteristics of U-series IGBTs are shown in Table 2.

6. Conclusion

The T-series and U-series of IGBTs for 600 V-NPT modules were introduced. Fuji Electric will continue to advance the high performance of these modules by developing specific technology for IGBTs and by incorporating technologies of other types of semiconductors, and will strive to contribute to the overall development of power electronics.