750 V IGBTs for Mild Hybrid Vehicles

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ABSTRACT

In mild hybrid cars, 600 V IGBT (insulated gate bipolar transistor) modules have often been used. Recently, however, in order to improve fuel efficiency and acceleration performance further, there has been growing demand for higher system voltages. In response to this demand, Fuji Electric has developed a 750 V IGBT and FWD (free wheeling diode) chip, and an IGBT module. A prototype of the module was evaluated and the following results were obtained. The module can be used safely with systems having power supply voltages of up to 500 V even when surge voltage is superimposed. When the 750 V IGBT is utilized, total loss can be decreased by approximately 28% compared to 1,200 V devices.

1. Introduction

Efforts to protect the global environment by reducing CO_2 emissions are mainly being carried out through the governmental policies of countries throughout the world. CO_2 emissions in the transportation sector, which includes automobiles, presently accounts for about 20% of the total amount of CO_2 emissions. The number of registered vehicles is expected to be higher the future, mainly due to increases in developing countries. To reduce CO_2 emissions, there is an urgent need to increase the proportion of environment friendly vehicles. Hybrid cars are highly practical and have the potential to contribute significantly as environment friendly vehicles. With governments and municipalities incentivizing the introduction of hybrid cars, as well as the development of hybrids to multiple types of vehicles by automobile manufacturers, expansion of this market is expected in the future.

Fuji Electric's 1,200 V IGBT-IPM (insulated gate bipolar transistor intelligent power module) for use in boost converters and 1,200 V chips having a plated structure for double-side cooling that are installed in LEXUS*[1] models LS600h and RX450h that have been commercialized for use in hybrid cars are highly regarded. In systems that use 1,200 V chips, the battery voltage is boosted and the DC voltage is increased to improve the output and efficiency. Moreover, in systems not requiring voltage boosting, such as mild hybrid systems, 600 V chips are used. Recently, however, boosting of the battery voltage or boosting of the output current has been requested even in systems that do not require voltage boosting. Intermediate-voltage IGBTs are used in such applications and are the optimal solution for applications in which 600 V chips provide an insufficient margin of voltage blocking capability, but 1,200 V chips would provide too great of a margin and would be over-spec.

Fuji Electric has accumulated experience with two series (600 V and 1,200 V) of automotive IGBT products. To meet the needs of our customers, Fuji Electric has additionally established and developed a new 750 V series as an intermediate-voltage series. The 750 V series of chips has been optimized by designing the active area, the edge termination area and the Si crystal specifications for intermediate voltages so as to maintain the high-speed and low-loss characteristics of 600 V chips, combined with the proven stable voltage blocking performance of 1,200 V chips.

2. Overview of Development

2.1 Need for 750 V series of IGBTs

Fig. 1 shows schematic diagrams of motor driving systems. Fig. 2 shows the applicable range of each voltage class of IGBT modules in terms of the relationship between maximum motor output and system voltage.

In a mild hybrid system, the system shown in Fig. 1(a) is widely used. In this system, DC current from the battery is converted into AC current by an inverter to drive a three-phase AC motor. In this case, the battery voltage is the system voltage. When using a motor of maximum output 30 kW or less, which is mostly used with mild hybrid systems, the system voltage is commonly set at 300 V or less, and 600 V IGBT modules are generally used.

On the other hand, in the case of a relatively large motor output of about 100 kW, the system of Fig. 1(b)

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*1: LEXUS is a trademark or registered trademark of Toyota Motor Corporation.

is typically used to avoid an increase in motor current. In this system, since the battery voltage of 300 V is boosted to 600 V or more, a 1,200 V series IGBT module is used. Recently, however, improved fuel economy and acceleration performance have been requested of mild hybrid vehicles.

In electric vehicles, increasing the battery to extend the travel distance will result in the vehicle becoming heavier. To drive such heavy vehicles, increased motor output is being requested. To increase the motor output without using a booster system requires that the battery voltage be increased. This corresponds to the intermediate voltage region in Fig. 2, and system voltages in the 400 to 500 V range presented a challenge in that a 600 V module would provide insufficient voltage blocking capability, while a 1,200 V module would result in excessive generated loss in the chip. Thus, Fuji Electric developed a 750 V IGBT chip and IGBT module that provide intermediate voltage blocking capability compared to the 600 V and 1,200 V models.

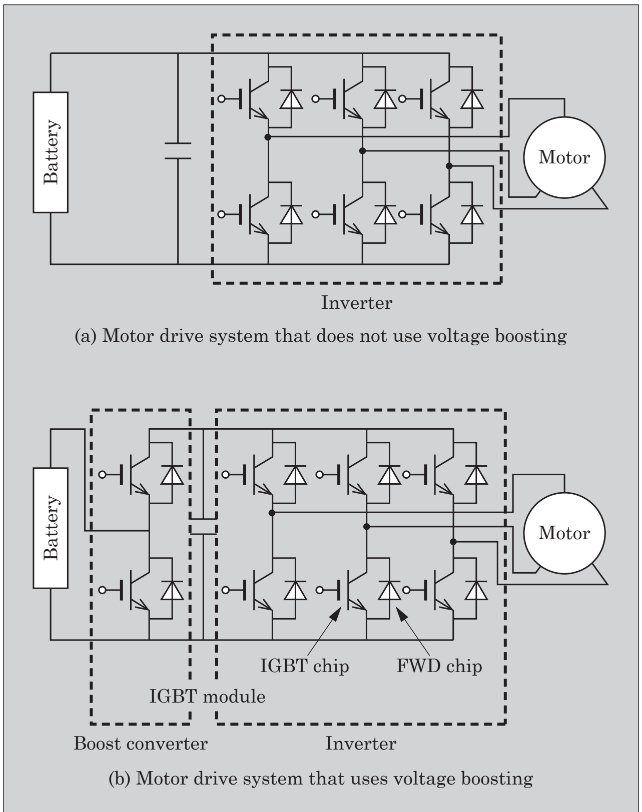

Fig.1 Schematic of motor drive system

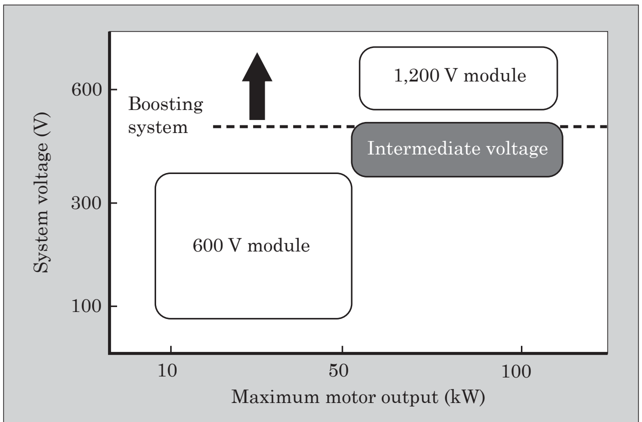

Fig.2 IGBT module application map per voltage class

2.2 Chip design objectives

The design objectives of the new 750 V series IGBT and FWD (free wheeling diode) chip were set as follows to solve the challenge described in section 2.1.

- ○ Guaranteed voltage blocking capability:
  At room temperature or above, 750 V or higher
  At −40 °C, 650 V or higher
- ○ Switching loss: 600 V chip +20% level
- ○ System voltage: 500 V
- ○ High reliability for automobile use

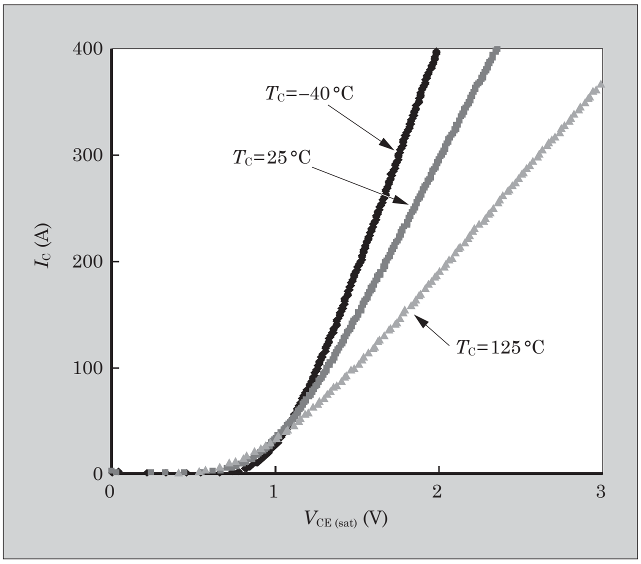

Fig.3 Output characteristics of 750 V/200 A IGBT chip

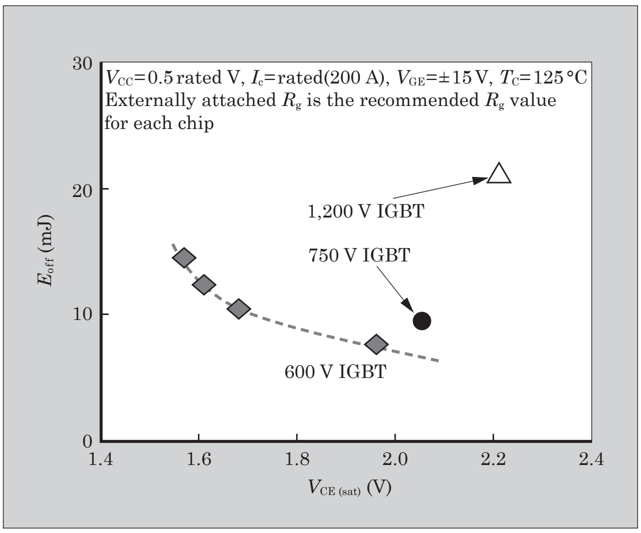

Fig.4 E_{off}–$V_{CE(sat)}$ characteristics of IGBTs for various blocking voltages

3. IGBT and FWD Chip Characteristics

The 750 V chip was designed by incorporating technology from both the 6th generation "V Series" 1,200 V chips and 600 V chips currently being mass-produced.

3.1 IGBT chip

IGBT chips are typically designed by separating the edge termination area required for ensuring the voltage blocking capability of the chip peripheral components and the active area for conducting or blocking current flow, and optimizing the design of each area and then combining them. The edge termination of the 750 V chip is based upon the proven success of Fuji Electric's 1,200 V automobile-use chips, and was designed so as to be realized in as small an area as possible. The design was made using a device simulator to optimize the electric field distribution to achieve high reliability. Moreover, by using a high density cell structure, which has a proven track record with 600 V chips, and a FS (field stop) structure in the active area, the Si wafer is made as thin as possible and the design is optimized for 750 V use to realize a switching loss that is close to that of the 600 V chip. Fig. 3 shows the output characteristics and Fig. 4 shows the turn-off loss E_{off} vs. $V_{CE(sat)}$ characteristics, respectively, of the 750 V chip.

Additionally, Fuji Electric has also developed an IPM-use IGBT chip that contains an on-chip temperature sensing diode and a built-in current sensing function capable of sensing abnormal conditions and implementing protective operations in cases where the temperature, current or the like become excessively large.

3.2 FWD chip

As in the case of the IGBT chip, the FWD chip was also designed with a separate edge termination area and active area. However, because the resistivity of the Si crystal used in the FWD differs from that of the IGBT, the edge termination area had to be designed independently. The edge termination of the FWD is de-

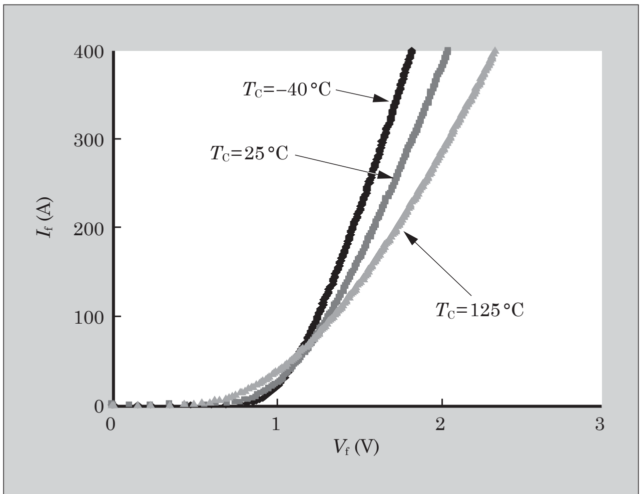

Fig.5 Output characteristics of 750 V/200 A FWD chip

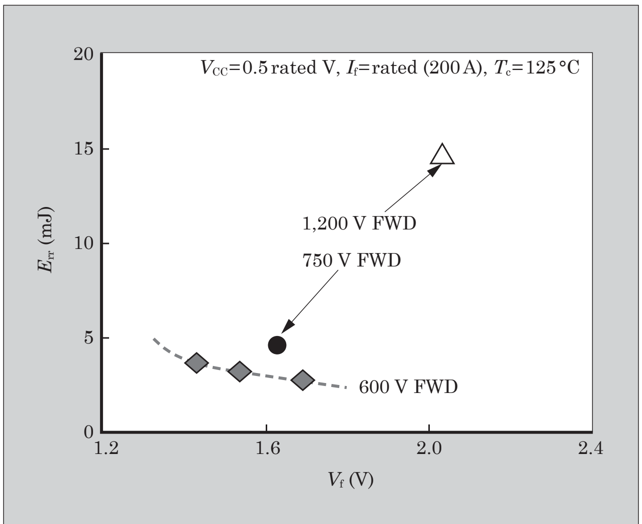

Fig.6 E_{rr}–V_f characteristics of FWDs for various blocking voltages

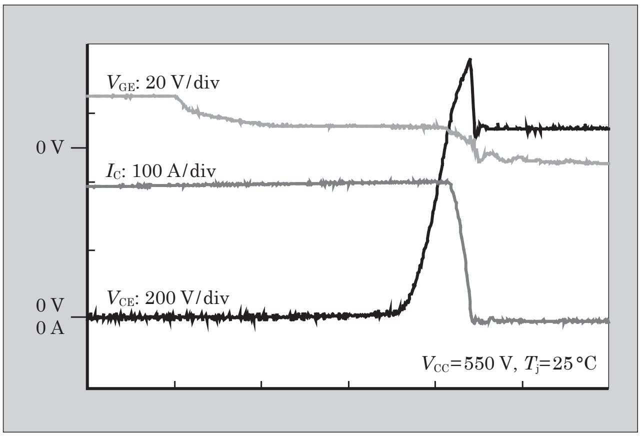

Fig.7 Switching waveform of 750 V IGBT chip

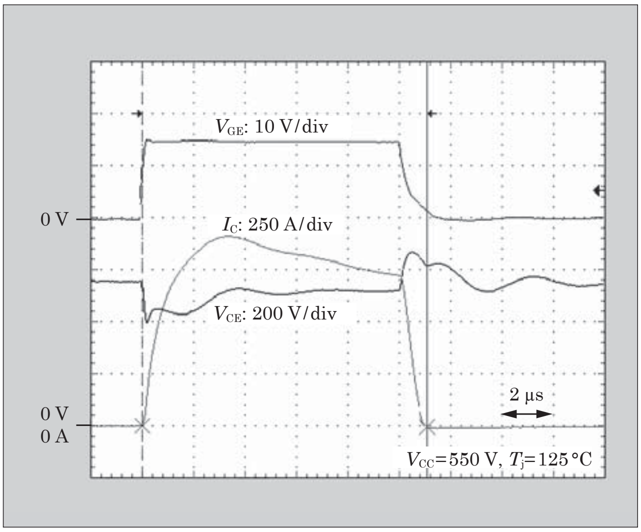

Fig.8 Short-circuit waveform of 750 V IGBT chip

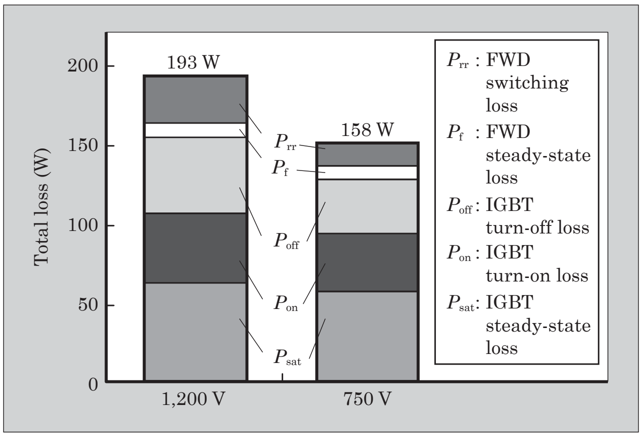

Fig.9 Comparison of module loss when motor is driven

signed based upon the proven track record of Fuji Electric's automobile-use 1,200 V chip. For the active area, the resistivity and thickness of the Si wafer, and the amount of minority carrier injection were optimized to reduce loss. As a result, reverse recovery loss E_{rr} vs. forward voltage V_f characteristics, that are close to those of the 600 V chip, were obtained. Fig. 5 shows the output characteristics and Fig. 6 shows the E_{rr} vs. V_f characteristics, respectively, of the FWD chip.

3.3 750 V module

A prototype module was built using an IGBT and FWD optimized for ensuring 750 V voltage blocking, and the characteristics were evaluated as follows. Fig. 7 shows the turn-off waveform when driven by a DC voltage of 550 V. Although dependent upon the inductance of the DC smoothing circuit and the snubber circuit design, in this example, the surge voltage rose to nearly 750 V, indicating that 750 V voltage blocking capability is needed. Moreover, Fig. 8 shows the waveform of a short-circuit test at the DC voltage of 550 V. Because this test is non-destructive, even if blocking begins 10 µs after the start of the short-circuited state, the module was found to have sufficient capability to withstand short-circuits. Thus, in consideration of a given margin, this device can be used safely with systems having supply voltages of up to 500 V.

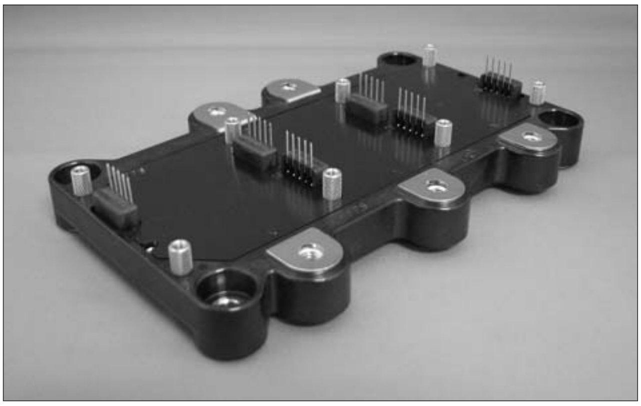

Fig.10 External view of 750 V/200 A inverter module

The generated loss when operating the inverted was estimated from the aforementioned evaluation results of the prototype inverter module characteristics. As shown in Fig. 9, when a motor is driven with a system voltage of 500 V, the total loss of the module was approximately 28% less than in the case when using a 1,200 V module. Fig. 10 shows the external appearance of the 750 V/200 A inverter module prototype.

4. Postscript

Through their use in a diverse range of industrial to consumer applications, the technical development of IGBT modules has continued to date, and industrial and consumer demand is not expected to diminish in the future. Meanwhile, the growth of the automobile drive sector has been remarkable, and there is no doubt that this market will rival or surpass that of conventional sectors.

As a device manufacturer, Fuji Electric considers itself obligated to continue to supply compact high-performance power devices in the automotive industry, and intends to continue to develop such devices together with its customers.