

# IGBT Modules for Hybrid Vehicle Motor Driving

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## 1. Introduction

Influenced by international efforts to curb global warming, automobile manufacturers are focusing on environmental issues and are working to reduce CO<sub>2</sub> emissions. Hybrid vehicles, currently being mass-produced as ecologically friendly cars having low CO<sub>2</sub> emissions, enjoy high public recognition and have rapidly become popular over the past several years.

In a gasoline hybrid system, an electric motor that assists the combustion engine in the range from start-up to low speeds, for which the engine has poor efficiency, and regenerative brakes that efficiently recharge the battery when decelerating are used to improve fuel efficiency.

The main components of a hybrid system are an electric motor, a battery and an inverter. The inverter is used as an electric power conversion system for supplying electrical energy from the battery to the motor, and for storing energy generated by the motor in the battery. IGBT (insulated gate bipolar transistor) modules are generally used as the main switching device in this electric power conversion system.

IGBT modules first began to be used about 20 years ago, primarily in industrial equipment, and are now being used in electric power conversion systems for controlling motors in a wide range of fields, ranging from household appliances such as air conditioners to applications in the railroad industry. In recent years, the range of automotive applications has been expanded and development is aiming to realize IGBT modules having even higher levels of performance.

Hybrid systems can be broadly categorized as either a dual-motor system (traction motor and generation motor) focused on travel performance or a single-motor system that combines traction and generation functions and that is focused on miniaturization. The single-motor hybrid system, known as a parallel hybrid system (hereafter referred to as a parallel hybrid), is expected to increase in popularity with application to small vehicles where the parallel hybrid advantages of small size and light weight can be fully appreciated.

This paper introduces Fuji Electric's automotive IGBT modules that are ideally suited for inverters in parallel hybrids.

## 2. Power Devices for Hybrid Vehicles

To achieve hybridization by installing an inverter, an electric motor and a battery within the limited space of an automobile, the system must be made lighter in weight. To popularize parallel hybrid technology, the capacities of the expensive inverter, motor and battery must be reduced to their respective minimum requirements, and the motors generally used have a capacity of 20 kW or less. To fully utilize the performance advantages of power devices, the rise in device temperature due to the transient maximum current flowing to the motor during acceleration must be limited within an allowable range. Additionally, for the case where the allowable temperature is exceeded, an embedded control that constantly monitors the chip temperature and limits the motor output and a safety design that prevents heat damage to the device due to excessive current must also be provided.

Moreover, the use of electrical regenerative braking (refer to the explanation of regenerative braking on page 50) during deceleration enables energy, which previously was emitted as heat from hydraulic brakes, to be collected as electrical energy and reused in order to improve the fuel economy. The capability to collect as much electric power as possible during the short braking time from the beginning of deceleration until stopping is important, and for this purpose, devices capable of conducting large currents for short time durations are required.

## 3. Characteristics of IGBT Modules for Automobiles

### 3.1 Product specifications

Figure 1 shows the external appearance and Fig. 2 shows an internal block diagram of a Fuji Electric IGBT module. The main characteristics are listed in Table 1, and product features are described below.

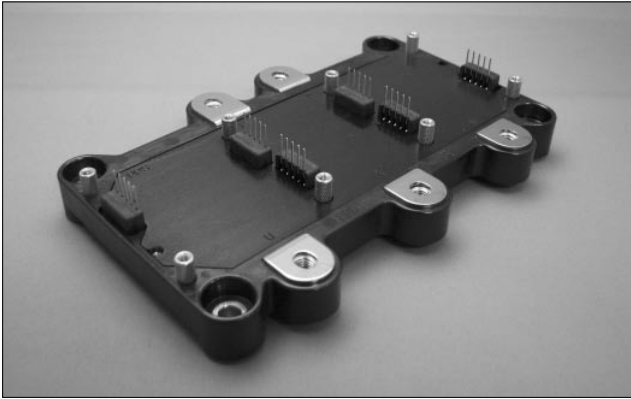
(a) 600 V/300 A chip required for inverters that

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drive 20 kW or smaller 3-phase motors is mounted in a custom 6-in-1 package

- (b) 6th generation 600 V V-series IGBT (realizing a 25% improvement in current density compared to the prior series) is used to realize lower loss and higher current density
- (c) An IGBT with built-in current sensing function and an on-chip temperature sensing diode is used
- (d) Required installation space is reduced through the use of a small and thin module package
- (e) Combination with Fuji Electric's Fi009 gate drive IC enables easy configuration of overheating protection, short-circuit protection and over-current protection functions for the IGBT chip
- (f) Design support is provided by an IGBT module drive evaluation circuit board that facilitates circuit design by the customer

Fig.1 External appearance of IGBT module



- (g) Simultaneous realization of lead-free content and in-vehicle reliability

### 3.2 V-series IGBT chip

The IGBT chip uses Fuji Electric's 6th generation 600 V V-series IGBT chip. A characteristic of this chip is its use of a field-stop (FS) structure and a trench gate, which have a proven track-record with Fuji Electric's 1,200 V IGBTs, to realize a lower collector-emitter saturation voltage. A comparison of output characteristics with conventional products is shown in Fig. 3. For the same chip size, the collector-emitter saturation voltage is reduced by approximately 25% and this new chip is expected to contribute to improved efficiency.

Devices used in automobiles are directly affected by changes in the ambient air temperature and the capability to endure temperature changes (hereafter re-

Fig.2 Internal block diagram

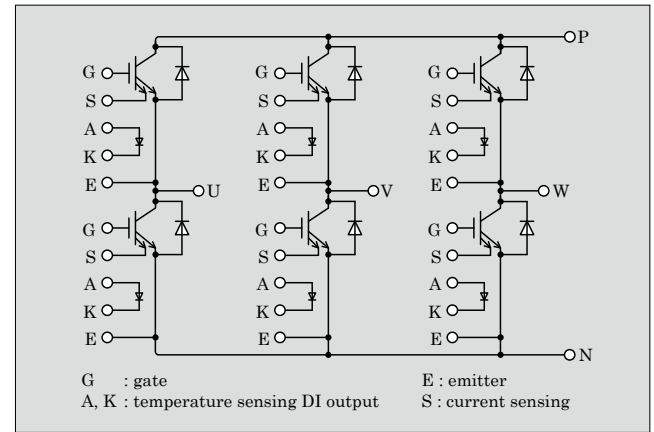


Table 1 Main characteristics

(a) Absolute maximum ratings (unless specified otherwise,  $T_j = T_c = 25^\circ\text{C}$ )

Item	Symbol	Condition	Rating	Unit
Collector-emitter voltage	$V_{CES}$	$V_{GE} = 0\text{ V}$	600	V
Gate-emitter voltage	$V_{GES}$	—	$\pm 20$	V
Collector current	$I_C$	Continuous	300	A
Max. allowable loss	$P_C$	1 device	595	W
Max. junction temp.	$T_{j(\text{max})}$		150	$^\circ\text{C}$
Operating temp.	$T_{op}$		$-30$ to $+125$	
Storage temp.	$T_{stg}$		$-40$ to $+125$	

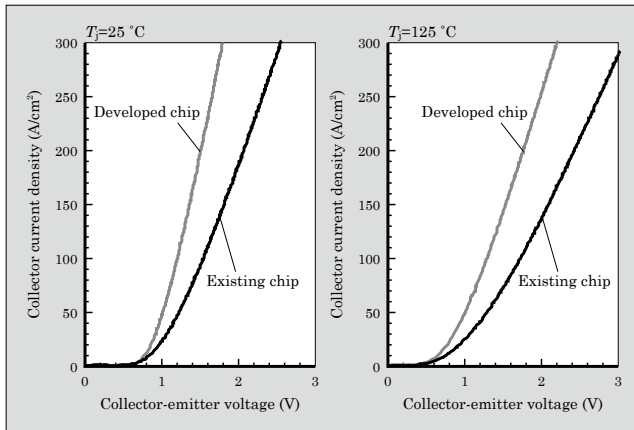
(b) Electrical characteristics (unless specified otherwise,  $T_j = T_c = 25^\circ\text{C}$ )

Item	Symbol	Test condition	Min.	Typ.	Max.	Unit
Collector cutoff current	$I_{CES}$	$V_{GE} = 0\text{ V}, V_{CE} = 600\text{ V}$	—	—	1.0	mA
Gate-emitter leakage current	$I_{GES}$	$V_{CE} = 0\text{ V}, V_{GE} = \pm 20\text{ V}$	—	—	200	nA
Gate-emitter threshold voltage	$V_{GE(\text{th})}$	$V_{CE} = 20\text{ V}, I_C = 300\text{ mA}$	—	6.2	—	V
Collector-emitter saturation voltage	$V_{CE(\text{sat})}$	$V_{GE} = 15\text{ V}, I_C = 300\text{ A}$	—	2.10	2.63	V
Forward voltage drop	$V_F$	$I_F = 300\text{ A}$	—	1.96	2.40	V

(c) Thermal characteristics ( $T_c = 25^\circ\text{C}$ )

Item	Symbol	Test condition	Min.	Typ.	Max.	Unit
Thermal resistance	$R_{th(j-c)}$	IGBT	—	—	0.21	K/W
		FWD	—	—	0.25	

Fig.3 Comparison of IGBT output characteristics (comparison with chip characteristics)



ferred to as temperature cycles) is strongly requested. When an IGBT module is exposed to a temperature cycle environment, thermal stress generated at the solder layer in the junction between the insulating substrate and the IGBT chip causes cracks to form and expand. Because the V-series IGBT chip is thinner than the conventional products and deforms flexibly in response to thermal stress, cracks in the solder are less likely to occur even when temperature cycles are added.

### 3.3 Internal temperature during electrical regeneration

During acceleration, a hybrid system requires a large amount of electric power and therefore the battery must always store electrical power. Moreover, during deceleration, the deceleration energy must be converted efficiently into electrical power by electrical regenerative braking. Electrical regenerative braking converts kinetic energy into electric power and charges the battery, and the amount of energy generated is proportional to the mass of the vehicle. In the case where a small motor has been selected, efficiency is increased by regenerating larger amounts of electric power, but the upper limit on the amount of electric power that can be regenerated is constrained by the allowable temperature of a highly conductive FWD chip. Figure 4 shows the internal temperature distribution for the assumed maximum continuous load during electric power regeneration.

By optimizing the chip size and staggering the chip layout in order to improve efficiency during electric power regeneration, the temperatures of the IGBT and FWD chip will be limited to equal values, and the module will simultaneously realize both higher efficiency and smaller size.

### 3.4 On-chip temperature sensing function

If an IGBT is exposed to an environment of anomalous temperature or if the temperature of an IGBT rises suddenly as a result of an abnormal operation, in order to prevent system failure, abnormal heat generation from the IGBT must be sensed and the operation

Fig.4 Internal temperature distribution for assumed regenerative braking

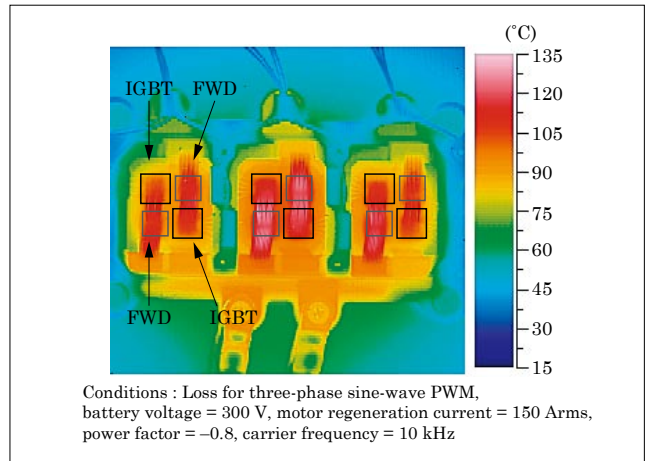
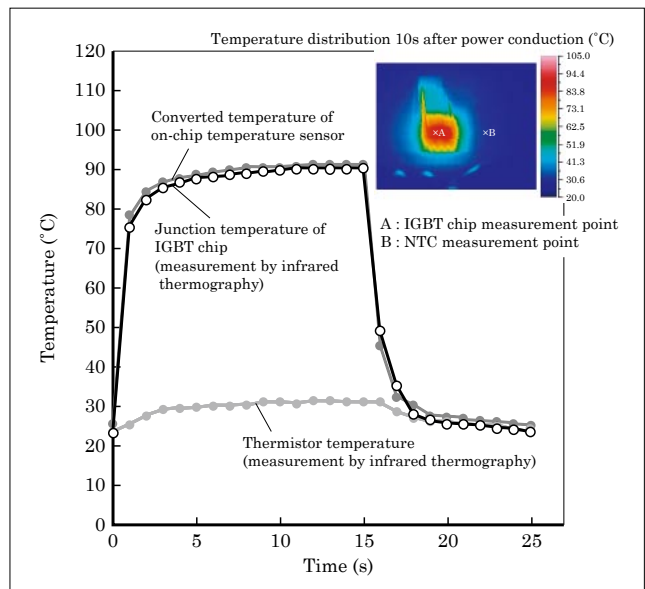


Fig.5 Response characteristics of on-chip temperature sensor



stopped. Hybrid vehicles have a particularly high frequency of motor acceleration and deceleration operations, and therefore are thought to be particularly susceptible to sudden temperature changes resulting from the momentary conduction of electric power. This product is equipped with a diode that is integrated into the IGBT chip as an on-chip temperature sensor. Figure 5 shows the response characteristics of the on-chip temperature sensor.

A comparison of the results of measurement of the IGBT chip surface temperature by infrared thermography with those of the temperature-converted output from the on-chip temperature sensor shows good tracking of temperature changes, even for transient periods on the order of 1 second. Moreover, the capability to compute and sense temperatures even for short durations on the order of 1 ms enables the IGBT to be protected from damage even if a sudden temperature change occurs due to a momentary load fluctuation.

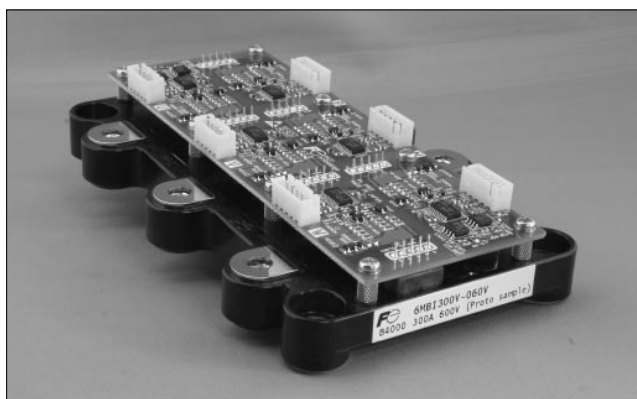
Figure 5 also shows the results of temperature measurement by a NTC (negative temperature coefficient) thermistor that has been mounted near the chip, and a temperature difference of approximately 60 °C from the value sensed by the on-chip temperature sensor can be seen. The reason for this difference is that, in the case where chip temperature rises suddenly in a short time of several tens of seconds or less, heat is radiated primarily from a copper base plate mounted on the bottom surface of the highly thermal-conductive chip package, and the copper base plate has a large thermal time constant in the lateral direction which slows the conduction of heat. However, the protection method of using an NTC thermistor to acquire the transient temperature change of an IGBT chip is limited since the slope of the temperature rise varies according to the value of current flowing into the motor. An on-chip temperature sensor capable of directly sensing the chip temperature is an effective solution for hybrid vehicle-use IGBTs.

#### 4. Drive Circuit Board for Evaluation

To extract the maximum performance from a power device, there must be cooperation between the IGBT drive circuit and protection circuit in the usage environment. Particular care must be taken to avoid incorrect operation due to difficult to discern capacitive coupling and mutual inductions. Moreover, the drive circuit for an IGBT having a built-in on-chip temperature sensor and current sensor which is made from discrete parts, is large in size, and hinders the miniaturization of the inverter and converter unit. In the past, an IGBT IPM (intelligent power module) provided an effective solution to these problems. With a black box-like configuration that makes changes difficult to implement, however, specification changes resulting from an expanded range of applicable vehicle types and the efficient utilization of space by integrating peripheral circuit parts and the printed circuit board were difficult to support.

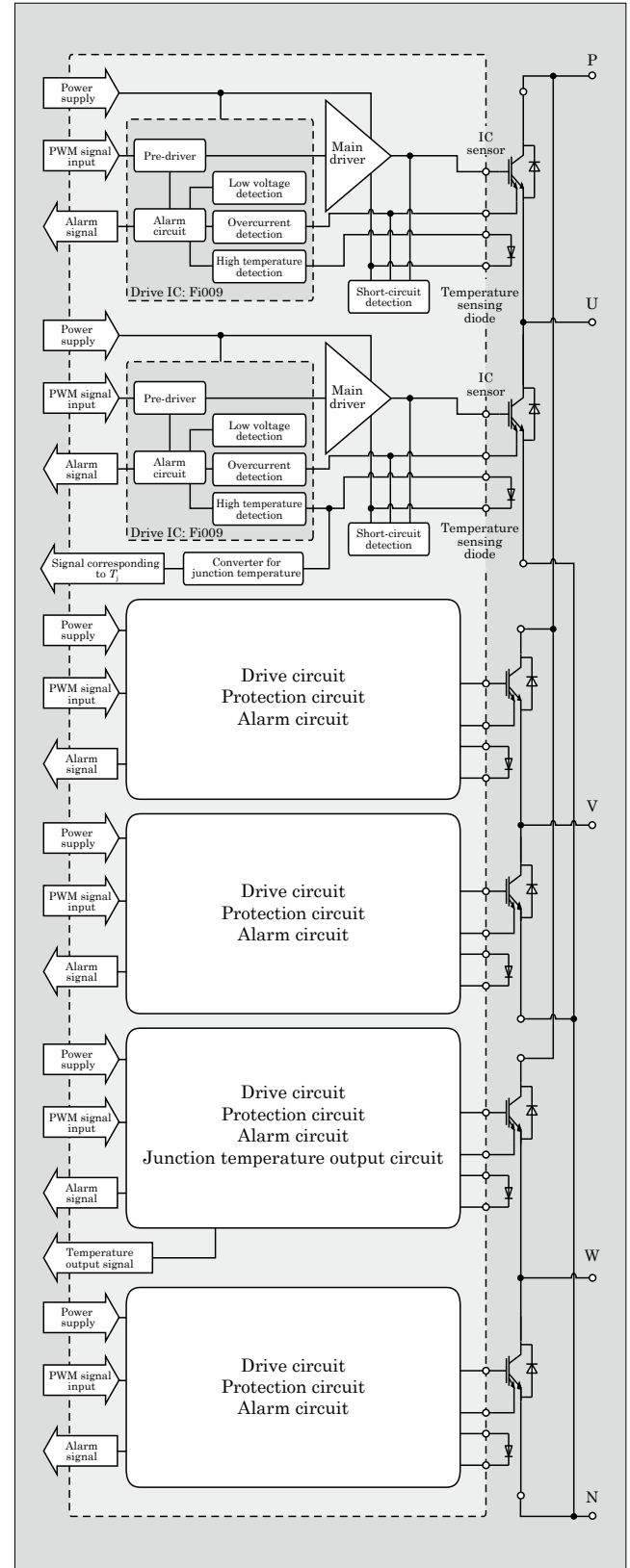
As a solution to the abovementioned problems, we introduce the example of an evaluation drive circuit

Fig.6 Appearance of drive circuit board



board designed especially for the IGBT module. Figure 6 shows the appearance when assembled, and Fig. 7 shows an internal block diagram of the evaluation drive circuit board. By using Fuji Electric's Fi009

Fig.7 Block diagram of evaluation circuit board



IGBT driver IC, which integrates the main drive functions into a single chip, this drive circuit board is configured with a fewer number of parts. The drive circuit board is extremely versatile and is also configured with discrete parts at locations where changes in the time constant are envisioned due to changes in the IGBT module specifications and in the customer usage environment. Moreover, to protect the IGBT, short-circuit protection, overcurrent protection, and overheating protection using an IGBT on-chip temperature sensor are provided, and the board is designed so that the IGBT operation can be stopped safely if necessary. A circuit for externally outputting the temperature being monitored by the on-chip temperature sensor is provided on each of the upper and lower arms. These output circuits enable observation of the IGBT chip

temperature during evaluation.

## 5. Postscript

This paper has introduced Fuji Electric's automotive IGBT modules for use in parallel hybrid vehicles. The integration of 6th generation IGBTs into custom packages for automobile use is expected to contribute to the realization of even smaller size and higher performance inverter units.

Fuji Electric intends to continue its efforts toward achieving higher performance and higher reliability elements, and to help protect the global environment by reducing CO<sub>2</sub> emissions and increasing the fuel efficiency of hybrid vehicles.



### **Explanation** Regenerative braking

Regenerative braking uses the motor as an electric generator to convert kinetic energy, emitted during deceleration as heat by hydraulic brakes, into electric power and to charge the battery. Because regenerative brakes are non-contact and

do not involve mechanical friction, a regenerative braking system is highly effective in reducing energy consumption and enables electric power to be reused without generating heat.



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