On-Chip Sensor Built-In IGBT Modules for Driving xEV Motors

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ABSTRACT

In recent years, the switch to electric vehicles (xEV) has been increasing, and the xEVs are equipped with inverters for driving electric motors. Therefore, there has been growing demand for inverters and their component IGBT modules for xEVs. Fuji Electric has developed an IGBT module that integrates an on-chip sensor for driving motors of xEVs. The on-chip sensor is equipped with temperature and current sensors. The temperature sensor directly monitors the temperature of the IGBT chip to improve the permissible current of the module. The low-loss current sensor monitors large current and enables protective operation when there is an overcurrent caused by short circuit or other accidents.

1. Introduction

In recent years, in accordance with energy saving and CO_2 emission regulation, switching vehicles to electric vehicles (xEV), such as hybrid electric vehicles (HEV) and electric vehicles (EV), is accelerating even faster all over the world. The xEV is equipped with an inverter for driving an electric motor. Therefore, there is increasing demand for inverters and insulated gate bipolar transistors (IGBT) for xEVs, which are components of inverters.

The IGBT module for xEVs that Fuji Electric is developing achieved a small module having a high current density by using reverse-conducting IGBTs (RC-IGBTs), on-chip sensors, and a structure in which a cooler is built in(1). In this article, the properties and characteristics of the IGBT module having a built-in on-chip sensor are described.

2. On-Chip Temperature Sensor

2.1 Characteristics

Figure 1 shows the circuit diagram of the IGBT module. In this circuit diagram, 2 IGBTs are config-

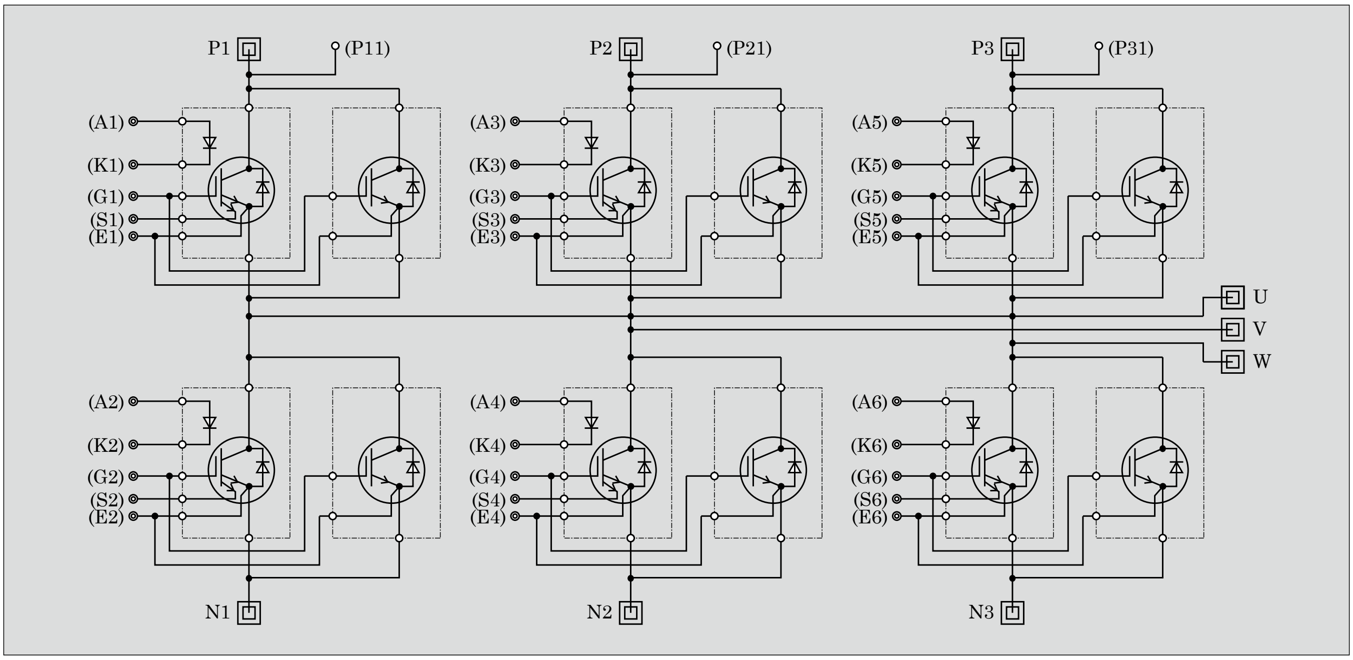

Fig.1 Circuit diagram of IGBT module

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ured in parallel in 3-phase upper and lower arms. The IGBTs in the 3-phase upper and lower arms are operated by switching, and convert the DC voltage of the battery into AC voltage to drive the motor. The temperature sensor diode (a diode between A and K terminals in Fig. 1) embedded in the IGBT chip monitors the chip temperature to protect from overheating. The conventional module had a structure for overheating protection in which a negative temperature coefficient (NTC) thermistor is mounted on the insulating substrate away from the chip in the module. However, the NTC thermistor cannot directly monitor the chip temperature. Therefore, the thermal design had to be created considering the variations of product characteristics, such as device characteristics and the thermal resistance of packages. Large safety margins had to be taken for this factor, and this had been a disadvantage for satisfying requirements (small, lightweight and large current) modules for automotive applications.

Using the on-chip temperature sensor can greatly reduce these safety margins. When the IGBT and the free wheeling diode (FWD) have different chip structures, only the temperature of the IGBT region can be monitored. However, the combination of the RC-IGBT and the temperature sensor allows the chip temperature to be monitored in a way that reflects both the IGBT region and the FWD region. This also protects against overheating when an unexpected reverse current is generated from the motor and the current flows into the power module (in this case, FWD).

2.2 Structure and characteristics

Figure 2 shows a schematic cross-sectional view of an RC-IGBT. This structure not only simply decreases the number of chips but also brings advantages like smaller element areas and thermal resistance reduction. Thus, smaller and more lightweight inverters are expected to be manufactured at low costs.

We have realized lower power dissipation of large capacity RC-IGBT chips, which had been technically difficult, and mass-producing high power RC-IGBTs with low power dissipation for vehicles and industrial use.

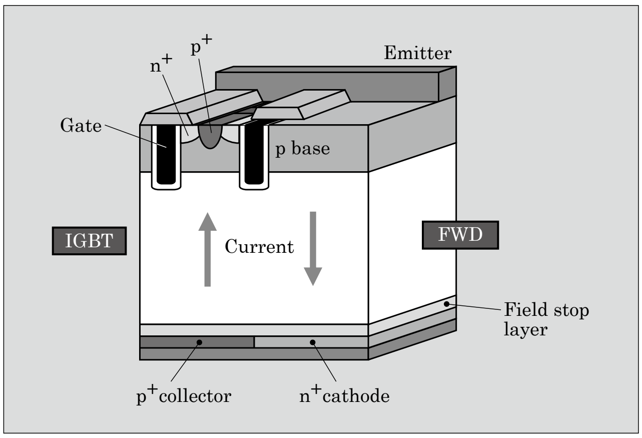

Fig.2 Schematic cross-sectional view of RC-IGBT

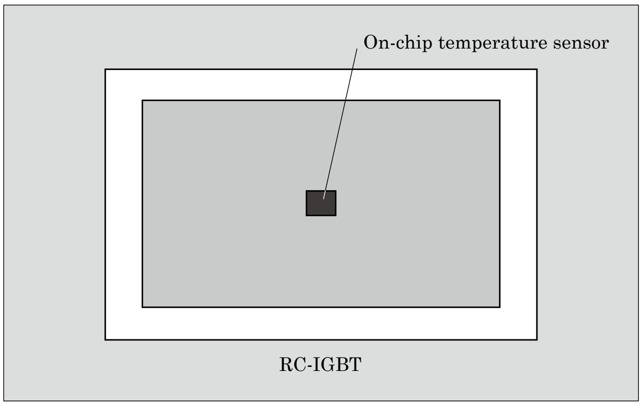

Fig.3 Planar schematic view of on-chip temperature sensor

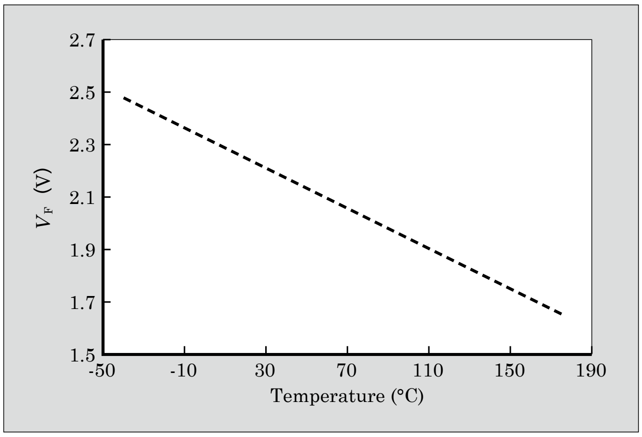

Fig.4 Temperature characteristics of on-chip temperature sensor

Figure 3 shows a planar schematic view of an on-chip temperature sensor. An on-chip temperature sensor is a pn diode placed on the chip via an insulating oxide film. A sensor is positioned in the vicinity of the center of the RC-IGBT chip to monitor the maximum temperature of the chip.

Figure 4 shows the temperature characteristics of an on-chip temperature sensor. It shows the diode voltage at each temperature when a forward current of 1 mA flows through a temperature sensor diode. It shows good linearity from −40 °C to 175 °C.

2.3 Comparison with NTC thermistor

We verified how superior an on-chip temperature sensor is with respect to an NTC thermistor. Specifically, we calculated and compared the allowable current value of the IGBT module using an NTC thermistor with that using an on-chip temperature sensor under the conditions shown in Table 1.

The NTC thermistor was put on the insulating substrate, and the chip temperature was estimated from the measured temperature. Therefore, we needed to calculate the values considering the characteristic and dimension variations of the IGBT module components such as the chip and the package.

Table 1 Calculation condition of allowable current estimates

Item	Condition
Bus voltage V_{CE}	450 V
Output frequency	100 Hz
Switching frequency	10 kHz
Power factor	0.8
Modulation factor	1.0
Flow rate	8 L/min

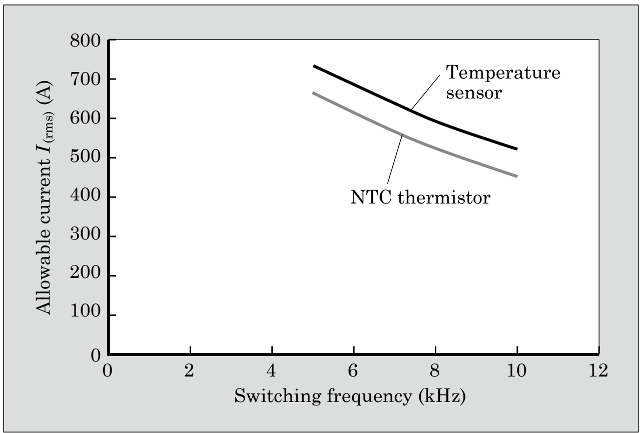

Fig.5 Relationship between switching frequency and allowable current

Figure 5 shows the result of comparing the allowable current $I_{(rms)}$ with respect to switching frequency between the on-chip sensor and the NTC thermistor. When the switching frequency was 8 kHz, the NTC thermistor showed $I_{(rms)}$ of 521 A, whereas the on-chip temperature sensor showed $I_{(rms)}$ of 589 A under the same condition. This estimated calculation shows that adopting an on-chip temperature sensor can increase the allowable current by about 13% compared with the case in which an NTC thermistor is used. This indicates that the same allowable current can be achieved with a 12% smaller chip. The size of the module itself can also be reduced by reducing the chip area; therefore, the on-chip temperature sensors are effective for making smaller and more lightweight modules.

2.4 Protection with respect to reverse current

As motors for xEVs are increasingly required to be more lightweight and provide higher output power, their operating voltage is increased so the cables can be made more lightweight. Figure 6 shows an xEV motor drive circuit. For example, the IGBT may turn off after detecting some trouble when the motor is rotating at high speed. At this time, if the counter electromotive force of the motor is larger than the battery voltage, a short-circuit current in a reverse direction flows from the motor to the IGBT module. The short-circuit current flows through the FWD, and the FWD needs to withstand the short-circuit current until the protection is applied[(2)]. To prevent module breakage, it is necessary to improve the short-circuit current

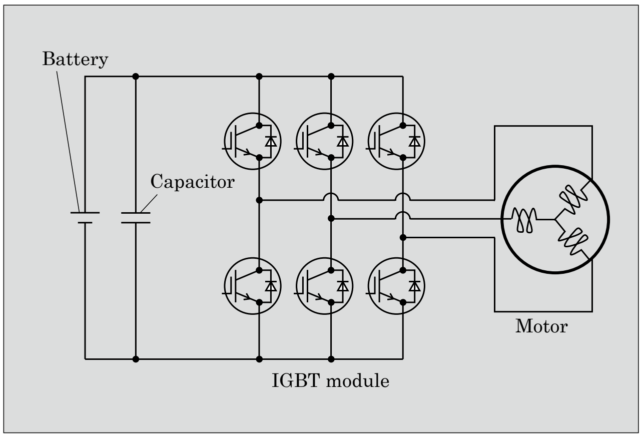

Fig.6 xEV motor drive circuit

capability of the FWD and at the same time immediately detect the failure and protect the module. When the IGBT and the FWD are different chips or when an on-chip temperature sensor is not embedded, the abnormality of the FWD cannot be directly detected. However, the combination of the RC-IGBT and the temperature sensor can detect abnormal heat generation of the FWD and apply protection.

3. On-Chip Current Sensor

An overcurrent like a short-circuit current may flow in the IGBT module. The IGBT chip may break in the worst case unless appropriate protection is performed. One way of giving protection would be to detect the current flowing through the IGBT with a shunt resistor connected inside or outside the module and apply overcurrent protection. The IGBT module for automotive applications of Fuji Electric can apply short-circuit protection by detecting the current with an extremely small sense IGBT placed inside the chip.

When short-circuit protection is applied to a large capacity module, the power dissipation of the shunt resistor becomes too significant to ignore because it detects the main current that flows in the IGBT. On the other hand, an on-chip current sensor detects, for example, a sense current of about a ten-thousandth of the main current. Thus, power dissipation can be greatly reduced.

Figure 7 shows an example of a circuit configuration using an on-chip current sensor. When overcurrent like short-circuit current flows to the IGBT, a part of the current is output from the sense IGBT. This current flows through an appropriate resistor connected to the outside, and thus, the value of the voltage generated across the resistor is read and the short-circuit protection operation can be started.

Figure 8 shows waveforms at the time of short-circuit protection. The waveforms shown in the figure correspond to voltage waveform V_{CE} (1), a main current waveform I_C (2), a gate voltage waveform V_{GE} (3) and a sense voltage waveform V_{SE} (4).

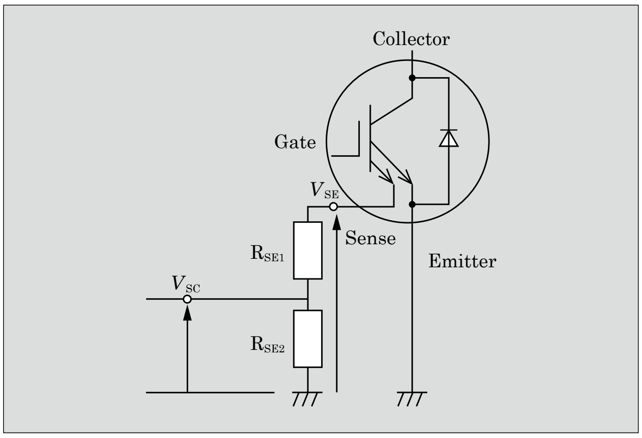

Fig.7 Circuit diagram of current sensor

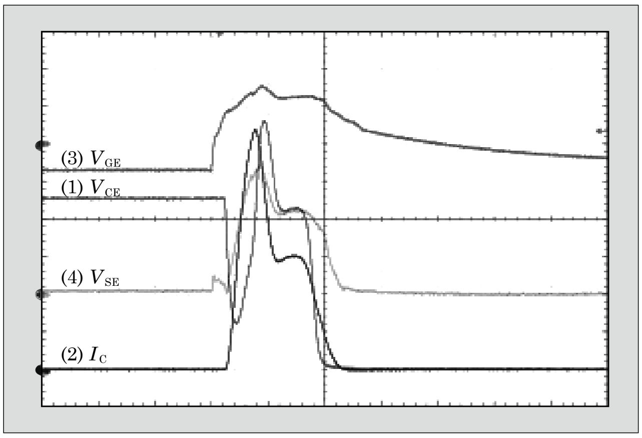

Fig.8 Waveforms at time of short-circuit protection

The waveform of V_{SE} is shown to be similar to that of I_C. Waveform V_{SE} can be used to apply protection when a certain threshold voltage is exceeded. In addition, like waveform V_{GE}, the surge voltage can be suppressed with a soft shutdown of the IGBT.

4. Postscript

An IGBT module having a built-in on-chip sensor for driving xEV motors has been described. A comparison of the temperature sensor and the NTC thermistor shows that the allowable current of the module can be improved by directly monitoring the IGBT chip temperature. Mounting the current sensor also makes it possible to monitor a large current with low power dissipation, enabling protection when an overcurrent like a short-circuit occurs.

There is an increasing demand for modules for xEVs, and we will continue contributing to global environment improvement by responding to the demand for electric vehicles.

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(2) Higuchi, K. et al. Improvement of I2t Capability for xEV Active Short Circuit Protection by Combination of RC-IGBT and Leadframe Technologies. IPEC, 2018.

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