IGBT Modules for Electric Hybrid Vehicles

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1. Introduction

Due to society's increasing requests for measures to curb global warming, and benefiting from the skyrocketing prices of petroleum products, the sales volume of hybrid cars is growing rapidly. By combining the two main types of power sources, gasoline engines and electric motors, and optimizing the load sharing according to the driving conditions, hybrid systems achieve improved fuel economy. These hybrid systems had an extremely high cost when mass-produced cars were first being sold and their sales volume was limited. Subsequently, however, by improving the performance and reducing the cost to car manufacturers, electric equipment manufacturers and component manufacturers, hybrid system costs have fallen and, at present, the sales volume is increasing.

In a gasoline hybrid system, an electric power conversion system that includes an inverter and converter is used to convert the power generated by the engine into electrical energy, to charge and discharge a battery, and to drive the motor. The electric power conversion system typically uses an IGBT (insulated gate bipolar transistor) module as its main switching device. IGBT modules have been used mainly in industrial facilities for the past 20 years, but the development of IGBT modules having higher reliability and higher performance is being advanced for application to automobiles.

This paper introduces the core technologies and examples of product applications relating to the performance and reliability of IGBT modules used in hybrid cars.

2. Reliability Technology for Automotive-use IGBT Modules

2.1 Difference from modules for industrial use

The IGBT module product group used for many years in industrial applications forms the basis for the automotive-use IGBT modules. However, the environment and conditions under which automotive-use products are used are much more severe than those of conventional industrial-use products, and the required levels of long-term reliability are significantly different. For this reason, automotive-use electric equipment is required to provide long-term reliability, and such equipment often requires two or more years from the start of development until mass production. Efforts to eliminate lead usage are being advanced in order to address environmental issues, but since the desired reliability levels are different for industrial-use[1] and automotive-use IGBT modules, the materials used therein will also differ.

2.2 Requested reliability and compliant technology

An example comparison of the reliability levels required for industrial-use and automotive-use IGBT modules is shown in Table 1. Because automotive-use modules are water-cooled and have a large temperature variation, their required temperature cycle tolerance is an order of magnitude greater than that of the industrial-use modules. If the number of temperature variations (temperature cycles) exceeds the device capability, cracks will appear in the solder layer bonding together the power chips and the insulating substrate and create defects that increase the thermal resistance. Accordingly, the technology that provides the requested level of temperature cycle tolerance must relieve stress at the solder layer. Assuming use in a high temperature and high humidity environment, the migration tolerance of the printed circuit board is also an important issue.

Table 1 Comparison of required levels of guaranteed reliability

Item \ Category	Industrial use	Automotive use
Temperature cycle test	100 cycles Temperature conditions : –40 to +125°C	1,000 cycles Temperature conditions : –40 to +125°C
Power cycle test	15,000 cycles Temperature conditions: ΔT_j = 100°C	30,000 cycles Temperature conditions: ΔT_j = 100°C
Vibration test	Acceleration = 10 G 2 h for each of X, Y and Z axes	Acceleration = 20 G 2 h for each of X, Y and Z axes

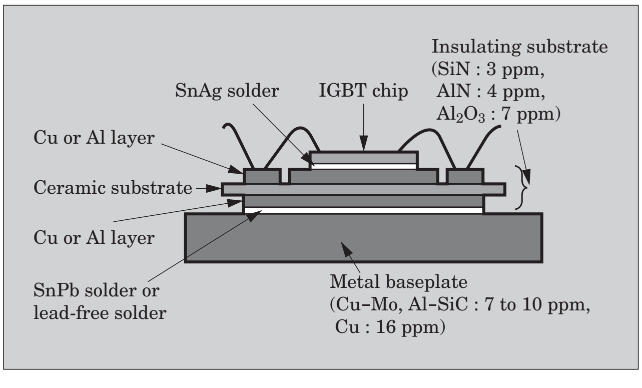
2.3 Reliability technology for lead-free compliance

The automotive industry is addressing environmental issues by working to develop lead-free technology in support of the ELV (end of life vehicles) directive. As described above, however, the high level of required reliability for automotive applications is a restriction that has not resulted in all lead-free automotive electronic components. Figure 1 shows a typical cross-section of an IGBT module. The module is configured bottom-up from a metal baseplate, solder, an insulating substrate (ceramic substrate bonded to metal layers on both sides), solder, an IGBT chip, and bonded wire. Lead-free solder for use underneath the IGBT chip has been developed and is being utilized in industrial-use modules[2][3].

(1) Solder underneath the insulating substrate

Various trials were carried out on the solder connecting the metal baseplate and insulating substrate in order to solve the problem of cracking caused by the stress of temperature cycles. The metal baseplate and insulating substrate have different rates of thermal expansion, and a change in temperature causes thermal stress to be generated in the solder layer. The elongation of cracks in the solder layer due to this stress is a problem when using lead-free solder. In hybrid vehicle-use IGBT modules, composite materials such as Cu-Mo and Al-SiC that have a small thermal expansion rate (i.e., a thermal expansion rate of 7 to 10 ppm, compared to Cu which has a thermal expansion rate of 16 ppm) have been used previously for the metal baseplate, and this is one way to prevent the abovementioned problem. However, the problems with these materials are that their thermal conductivities (indicating exothermicity), in the range of 150 to 250 W/m·K, are lower than that of copper (Cu having a thermal conductivity of 390 W/m·K), and their cost is several times that of copper. Figure 2 shows an example of a thermal stress simulation (with a 1/4 model) performed for the purpose of using copper, which has a relatively low cost and good exothermicity, as the baseplate material. Also, Fig. 3 shows the results of temperature cycle testing using a sample in which the solder material was changed.

Fig.1 Cross section of IGBT module



From Fig. 2, the deformation and stress in the given model can be inferred. In Fig. 3, the actual state of an elongating crack, according to the solder composition, can be verified. This type of three-dimensional analysis was carried out in detail, and by comparing the analysis results to actual experimental results, we found that a structure using a copper baseplate and lead-free solder would be able to provide the required level of reliability for automobile applications.

(2) Improved reliability of printed circuit boards

Since the reflow temperature increases when lead-free solder is used to mount electronic components, care must be taken when using the conventional FR-4 circuit board which has low heat-resistance. The migration and temperature cycle tolerances required of automotive-use devices are gradually becoming more severe. The use of higher heat-resistance and halogen-free low thermal expansion rate circuit boards enable improvement in both the migration tolerance and the temperature cycle tolerance. Figure 4 shows the change in insulation resistance during high temperature high humidity bias testing in which a voltage of 1,200 V is applied to a pattern having a narrow spacing of 0.5 mm. It can be seen that this halogen-free substrate has excellent capability to withstand 2,000 hours or more of testing.

Fig.2 Thermal stress simulation of IGBT module (1/4 model)

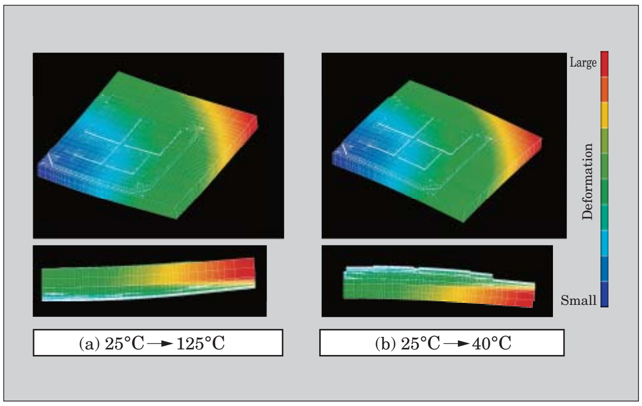
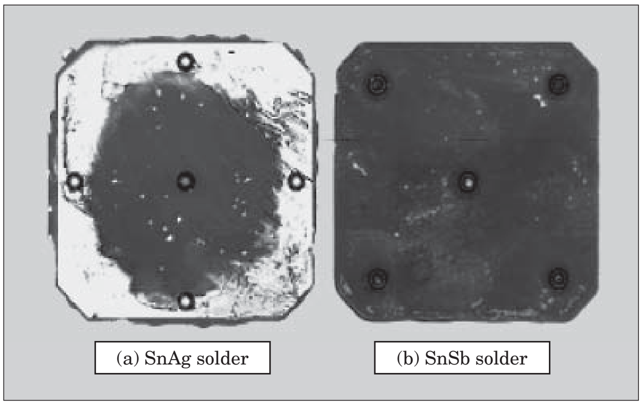


Fig.3 Ultrasound photograph focused underneath the substrate after 2,000 cycles of a temperature cycle test (The white area is the solder crack.)



IGBT modules are high voltage devices, and high voltage lines lay side-by-side on the printed circuit board connected to the module. To ensure safety, ion-migration on the substrate surface must not degrade electric strength, and the resulting large margin of safety provides a sense of security.

(3) Lead-free solder for through-holes

IGBT modules are used in combination with a drive circuit and protection circuit, and therefore, the solder technology for connecting the printed substrate to the module is extremely important. Moreover, since in an IPM (intelligent power module), a printed circuit board is attached inside the module package, the lead-free solder used is required to be capable of withstanding the same number of temperature cycles as the IGBT module. The use of lead-free solder is also required at the location of the through-hole connecting the printed circuit board and the module, and lead-free solder has been developed for this purpose. Figure 5 shows a cross section after temperature cycle testing of a through-hole joint structure in which SnAg lead-free solder having improved durability was used. Due to the low rate of thermal expansion in the thickness direction of approximately one-half that of the FR-4, cracking is limited even after 2,000 cycles, and the required level of durability is achieved.

Fig.4 Change in insulation resistance during high temperature high humidity bias test

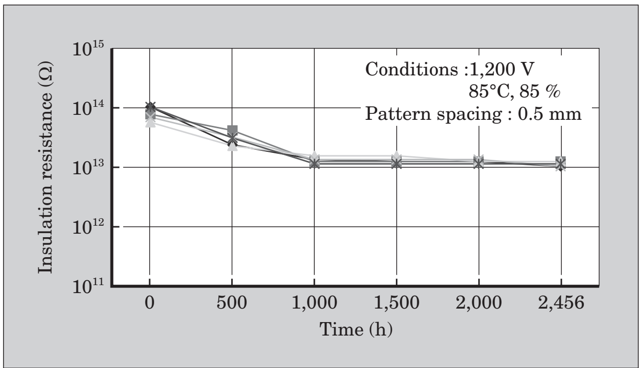
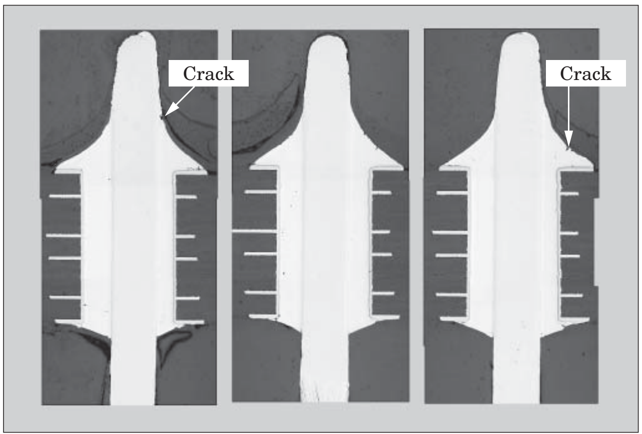


Fig.5 Cross section of through hole joint (after 2,000 temperature cycles)



3. IGBT-IPM for Electric Hybrid Vehicles

An overview of the hybrid vehicle-use IGBT-IPM, as developed based on the above-described core technologies for IGBT modules, is presented below. Figure 6 shows views of the exterior and interior of the hybrid vehicle-use IGBT-IPM.

3.1 IPM overview

The IPM is a switching device rated at 600 A and 1,200 V for use in an up/down converter, and is configured from an upper arm and a lower arm. Each arm is provided with four IGBT chips and four FWD (free wheeling diode) chips connected in parallel configuration, gate drive circuits, protection circuits, chip temperature output circuits are also provided on the printed circuit board inside the IPM.

3.2 Composition of packaging

Since copper is used for the metal baseplate, the difference in thermal expansion rate compared to the insulating substrate causes bending stress to be generated. The use of an insulating substrate made of aluminum oxide, a high-strength ceramic able to resist bending stress, makes it possible to use a copper baseplate. SnSb is used as the lead-free solder underneath the insulating substrate in order to strengthen the resistance to cracking. Since the solder layer stress caused by bending stress is largest in the area around the insulating substrate, the shape of that area is designed to resist solder cracking.

The aluminum wires that electrically connect the power chip have a diameter of 400 µm, which provides excellent power cycle performance, and ensures a strong connection with low resistance. A halogen-free circuit board with improved heat-resistance is used as the printed circuit board, thereby ensuring sufficient temperature cycle tolerance and migration tolerance.

3.3 U series IGBT chip and FWD chip

Fuji Electric’s 1,200 V U series chips, having a good market performance in industrial applications, are being used as the IGBT chip and FWD chip in the

Fig.6 Hybrid vehicle-use IGBT-IPM

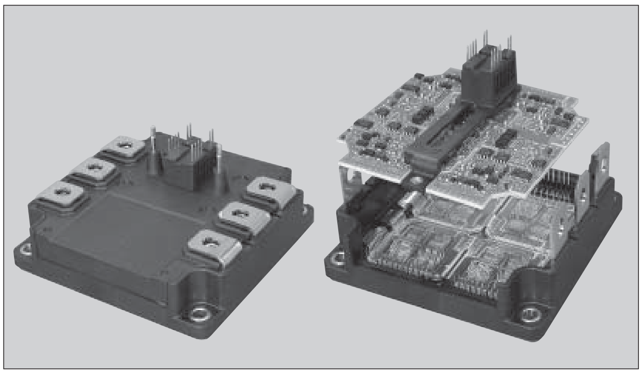
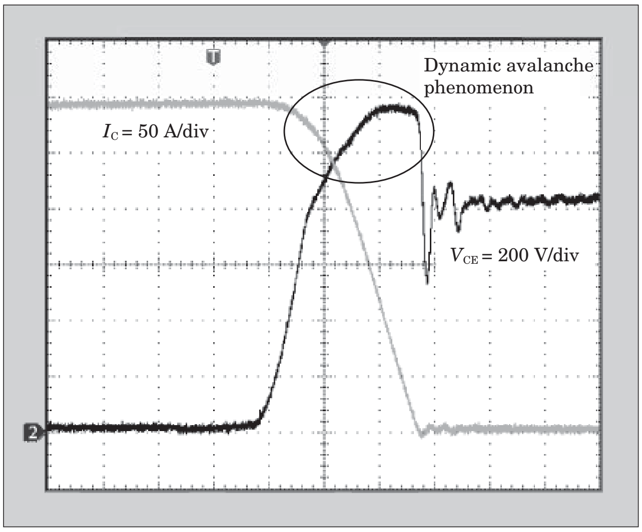


Fig.7 Dynamic avalanche waveform of U series IGBT chip



IGBT-IPM. The U series IGBT chip is a trench gate type chip, corresponding to a 5th generation IGBT, and has characteristics of both a low $V_{CE(sat)}$ and high tolerance of dynamic avalanching. Figure 7 shows the dynamic avalanche waveform of the U series IGBT chip. The dynamic avalanche phenomenon absorbs the surge voltage energy emitted at the time when a large current turns off. The U series FWD has a low injection efficiency type anode structure and higher transfer efficiency. V_F characteristic has a positive temperature dependence and low variation.

3.4 Protective functions

All IGBTs are provided with overcurrent protection and overheating protection functions to prevent damage to the IGBT. Moreover, as a special function for automotive-use IGBTs, a function that externally outputs as an analog signal of the IGBT chip temperature in each of the upper and lower arms is provided to enable monitoring from an operating situation.

4. Conclusion

The core technologies that make possible the realization of highly reliable and lead-free IGBT modules for hybrid vehicle use and Fuji Electric's product line have been introduced. The sales volume of hybrid vehicles will continue to increase and IGBT modules will continue to be used for electric power conversion for the foreseeable future. Accordingly, manufacturers who have not previously produced such modules are expected to enter this market, and the competition to develop new technology is expected to intensify. In the future, Fuji Electric intends to continue to develop modules that provide even higher reliability, smaller size and higher heat dissipation, and that are easier to use.

References

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