Package Technology for Achieving Higher Power Density in IGBT Modules for xEVs

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ABSTRACT

In the automotive field, electrified vehicles are expected as a measure of reducing greenhouse gas emissions. Their power modules in the inverter are required to have a higher power density, that is, small, thin and high output. To meet these market demands, Fuji Electric has developed the “M677,” an industry-leading ultra-compact IGBT module for xEVs. We have improved the short-circuit capacity of this small, thin IGBT by bonding the lead frame wiring on the flat surface of the chip to reduce the stress per unit volume that has increased with the growth of the power density. In addition, the solder joints have sufficient resistance to the electromigration lifetime to meet the market needs.

1. Introduction

In order to solve the issue of climate change, global efforts to reach carbon neutrality by the year 2050 are accelerating. In the automobile field, electrified vehicles powered by electric motors (xEVs), which include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EV), are considered to be one of the most effective ways to reduce greenhouse emissions.

To contribute to the fulfillment of this social demand, Fuji Electric has developed an industry-leading ultra-compact IGBT module, the “M677”[1],[2] (see Fig. 1) for xEVs, targeted for 100-kW class inverters as a key component of xEV power trains. The M677, which is designed to provide high power density, has successfully achieved a compact module size that meets the market demand.

This paper describes the packaging technologies that achieve higher power density.

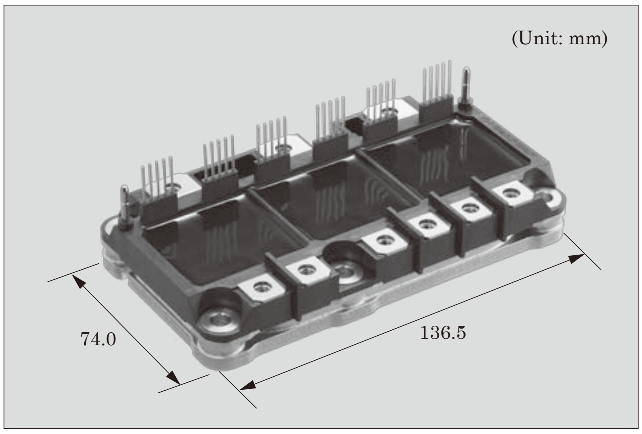
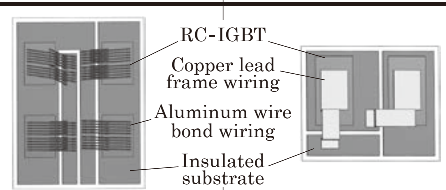


Fig.1 IGBT module M677 for xEVs

2. Challenges for Higher Power Density

To achieve reduced size and increased output power in the newly developed M677, we adopted the 7th-generation reverse conducting insulated gate bipolar transistor (RC-IGBT). And also in order to reduce conduction losses, we reduced the chip thickness and optimized the surface structure[1]. In addition, compared to the predecessor “M653,” which is configured with two chips per arm*1, we achieved a smaller chip footprint with the new circuit configuration that uses one chip per arm. The result shows that the footprint of the main circuit has been reduced by half that of the predecessor M653, and as a consequence, the power density is almost double compared to the predecessor M653,[1],[2] as shown in Table 1. On the other hand, as an effect of the chip being made more compact and thinner than its predecessor, there is an inevitable decrease in thermal capacity due to the reduced chip

Table 1 Internal circuit comparison between the M653 and M677

	M653	M677
Internal circuit configuration		
Circuit area (arb. unit)	1.00	0.49
Power density (arb. unit)	1.00	1.98

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*1 Arm: Refer to “Supplemental Explanation 1” on page 209 volume as well as an increase in thermal resistance due to the reduced surface area of the chip. Since the junction temperature must be kept below a specified value during operation to prevent module performance degradation, it is necessary to improve heat dissipation from the chip.

In addition, further measures against electromigration are required as power density increases. A phenomenon as electromigration in solder can occur when a high current flows in a narrow wiring area at high temperature. As metal atoms are transported by momentum exchange with conducting electrons, voids are formed, the increase of which leads to increased electrical and thermal resistance. As this can eventually lead to wire breakage, it is necessary to provide the high current density areas with adequate resistance to electromigration.

3. Improved Short-Circuit Capacity of Lead Frame in Thin Wafer RC-IGBTs

3.1 IGBT short-circuit failure modes

In power modules, short-circuit faults are caused by chip damage, abnormality in the control or driving circuit, malfunction due to noise, wire connection mistakes, ground fault, and other issues. In short circuit conditions, current conducting a chip raise up to is applied thousands of amperes of high with in a few microseconds while high voltage is being applied, and the IGBT will eventually fail if these conditions continue.

The IGBT failure modes associated with short-circuit faults can be divided into the four major modes shown in Fig. 2.[(4)-(8)] In mode A, a latch-up is caused by a high-amperage current when high voltage is being applied, and after turn-on, the IGBT fails immediately. In mode B, thermal destruction occurs due to rapid temperature rise caused by power loss during short-circuit operation. In mode C, destruction occurs due to the effect of current concentration caused by inhomogeneous operation inside the IGBT during turn-off operation. In mode D, the IGBT fails due to thermal runaway that occurs as a result of an abnormal leak current after a short circuit. The time an IGBT takes to fail when such short-circuit faults occur is defined as the short-circuit capacity.

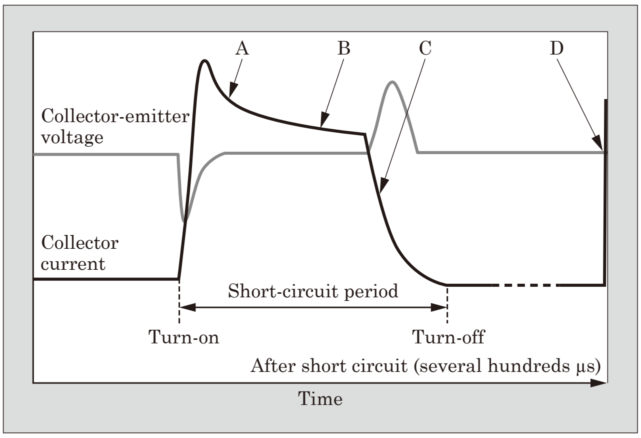

Fig.2 IGBT short-circuit failure modes

3.2 Relationship between the active volume of the IGBT and mode D short-circuit capacity

The cause of mode D short-circuit faults is the thermal runaway that occurs as a result of an abnormal leak current, which is produced after a short-circuit, causing the chip's internal temperature to rapidly rise.[(6)] This short-circuit capacity is reduced as the chip is made thinner. Thinner chips have a reduced volume and smaller thermal capacity, which is believed to be the reason why chip temperatures tend to rise dramatically against thermal runaway after a short circuit.[(9)] Figure 3 shows experiment results of between the active volume of an IGBT and short-circuit failure energy. The active volume of the IGBT is proportional to the short-circuit capacity with respect to mode D. In other words, size reduction and increased withstand capacity have a trade-off relationship.

3.3 Short-circuit capacity improved with lead frame wiring

While the thermal capacity decreases as chips are made thinner, the rise in temperature can be minimized by improving heat dissipation performance by increasing the area of the junction between the chip and the wiring.[(10)]

If the aluminum wire bond wiring used in the predecessor M653 is applied to the newly developed M677 chip, the short-circuit capability for mode D is 30% lower than that of the M653. To address this issue, we adopted a structure in which the copper lead frame wiring, which have a greater thermal capacity than aluminum wire bond wiring, are bonded to the chip's flat surface.

Figure 4 shows the comparison of short circuit capability between a wire bond wiring package and a lead-frame wiring package. Short circuit capability in the lead-frame wiring package dramatically increase

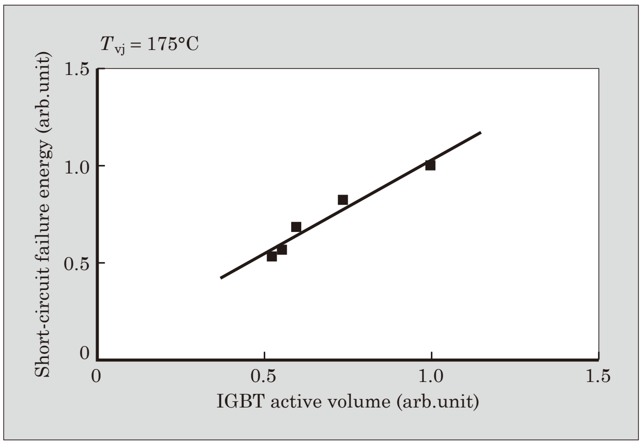

Fig.3 The experiment results of the relationship between IGBT active volume and short-circuit failure energy

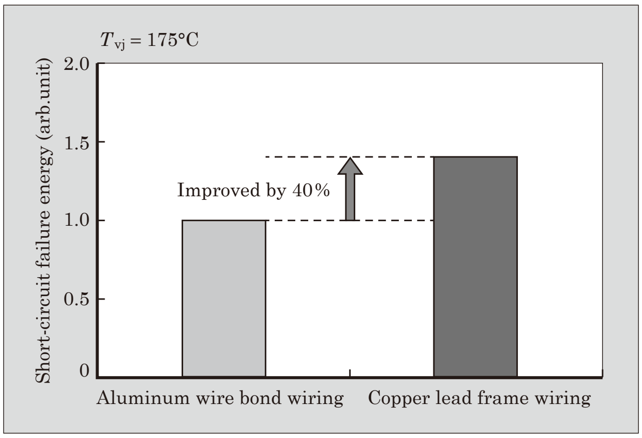

Fig.4 Effect of short-circuit capacity improved with lead frame wiring

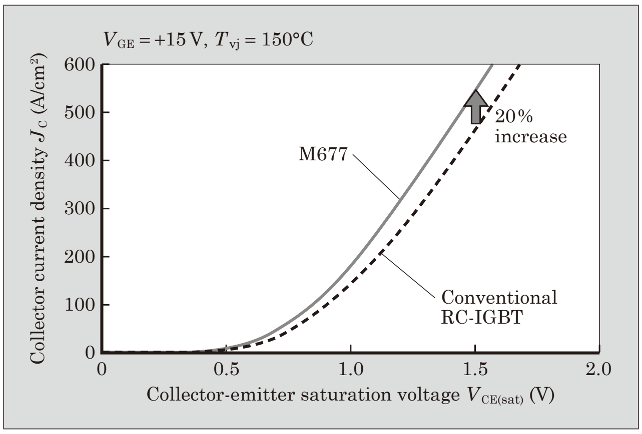

Fig.5 Collector-emitter saturation voltage $V_{CE(sat)}$

by 1.4 times compared to the one in the wire bond wiring package. The increase of short circuit capability allows to achieve the ruggedness to short circuit event in a thinner and smaller chip. The results show an improvement of 40% compared to the conventional aluminum wires.

In the M677, the measures above ensure short-circuit capability in thinner chips, which is effective in reducing conduction loss. In addition, the conduction loss has been reduced by optimizing the surface structure of the RC-IGBT. Figure 5 shows the collector-emitter saturation voltage $V_{CE(sat)}$. The collector-current density of M677 is higher than that of the conventional design by 20 % at the same saturation voltage.

4. Electromigration and Reliability Evaluation Method

4.1 Electromigration

The mean time to failure (MTTF) model of electromigration described in Chapter 2 can be estimated with the Black's equation shown in Equation (1) with current density and temperature as the main factors.[11]

$$\text{MTTF} = AJ^{-n} \exp\left(\frac{Ea}{kT}\right) \quad \text{......(1)}$$

A : Constant
J : Current density
n : Current density exponent
Ea: Activation energy
k : Boltzmann constant
T : Absolute temperature

According to Equation (1), the MTTF due to electromigration is shorter at higher current densities and temperatures. Since among the components of power modules, the current density is greatest at the solder used as bonding material, we verified the electromigration resistance of the solder bonding areas during the development of the M677.

4.2 Effects of current density and temperature

We used test pieces that simulated the M677's solder bonding areas, which connect the lead frames and insulated substrate to the chip in order to evaluate their electromigration resistance. Figure 6 shows the overview of the test circuit. To decrease the distortion in the bonding areas caused by changes in temperature during power module operation, the M677 is designed with solders A and B, which have different characteristics, and in the test, we evaluated the test pieces for each of them.

In the test method we used, a constant current was continuously applied to the test pieces, and the ambient temperature was controlled in a temperature-controlled chamber. The current density and temperature, which are the determinants in the Equation (1) above, were compared as test conditions. Furthermore, as a criterion of electromigration lifetime, we used the time it takes for the resistance of the test piece to be increase by 20%.

As a result of the test, the electromigration lifetime with respect to current density is shown in Fig. 7, and the electromigration lifetime with respect to temperature is shown in Fig. 8. As was predicted by Black's

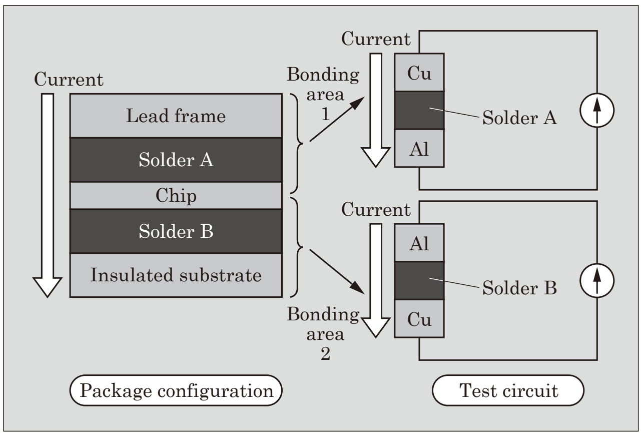

Fig.6 Test sample structures and set up in evaluation of electromigration

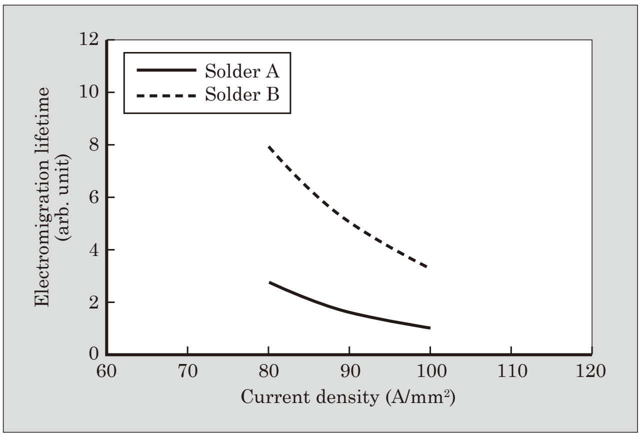

Fig.7 Current density dependence of electromigration lifetime

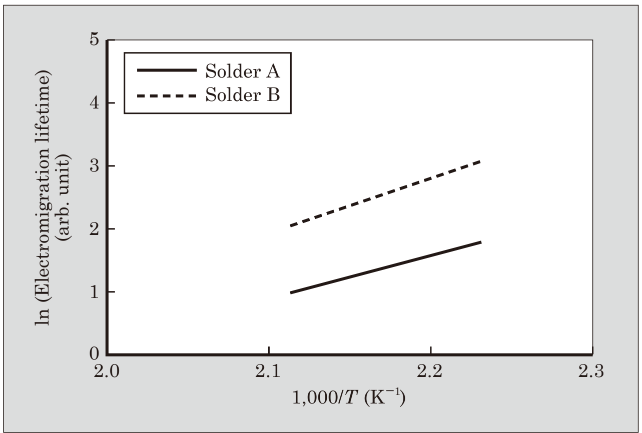

Fig.8 Temperature dependence of electromigration lifetime

equation, the electromigration lifetime is shorter at higher current densities and temperatures. We confirmed that solder B has a higher electromigration resistance than solder A.

4.3 Electromigration resistance of the M677

The M677's chip size, solder material, internal wiring and other features are designed to meet the target values for electromigration lifetime. The target electromigration lifetime was determined by the MTTF of the solder material obtained from Equation (1) based on the results for current density and temperature described in Section 4.2 and the stress expected when the power module is actually used in an xEV.

In verifying the electromigration resistance of the M677, we conducted a continuous heat run test with real equipment. Figure 9 shows the cross-sections of the solder bonding areas observed after the continuous heat run test. These are the cross-sections of solder bonding areas 1 and 2 after each of them were continuously subjected to currents for three times as long as the target lifetime. The cross-sections observed after the test showed no void caused by increases in wiring resistance or thermal resistance, and from these results, we determine that the M677 is durable enough to meet the target electromigration lifetime.

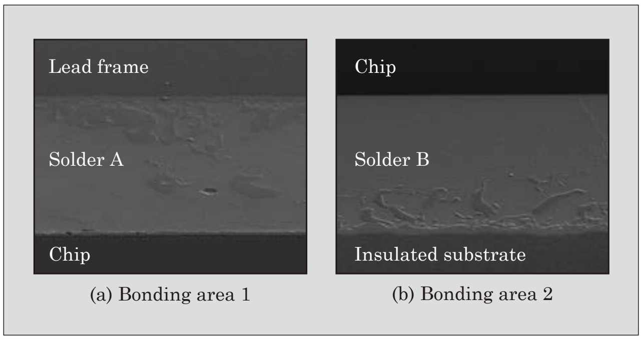

Fig.9 Solder bonding area cross-sections SEM image after the electromigration test in M677 tests

5. Postscript

This paper has described the improvement of short-circuit capacity and resistance to electromigration as part of our efforts to realize higher power density IGBT modules for xEVs. These efforts have made it possible for us to offer the "M677," the 100-kW class ultra-compact RC-IGBT module for xEVs.

We will continue developing technologies for lower power loss, higher power density, and higher reliability to meet the requirements for power semiconductors for xEVs, which will continue to growing rapidly, and by providing power modules that meet the market demand, we intend to contribute to the realization of carbon neutrality.

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