

New Assembly Technologies for $T_{jmax}=175^{\circ}\text{C}$ Continuous Operation Guaranty of IGBT Module

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ABSTRACT

In order to meet the needs for miniaturization and cost reduction of inverters, IGBT modules are required to offer higher power density than ever. Fuji Electric has developed a new aluminum wire, solder alloy and surface electrode protection layer to improve the continuous operating temperature of an IGBT module from the conventional 150°C to 175°C , thereby realizing higher power density. A power cycle lifetime has been more than doubled compared with the conventional products in all temperature ranges, and thus 20% improvement of inverter maximum output can be expected.

1. Introduction

General-purpose inverters are widely used and demand for them is expanding as they contribute to significant energy saving. There is a strong market need for energy efficiency and miniaturization as well as for a comprehensive reduction of costs including system development costs⁽¹⁾.

In order to meet such market demand, Fuji Electric has been working on loss improvement and miniaturization of insulated gate bipolar transistor (IGBT) chips, which are a main component of an IGBT mounted on a general-purpose inverter. The “V-Series” of IGBT modules has improved the guaranteed continuous operation at 150°C , which is 25°C higher than the IGBT module operation temperature of the “U-Series.” This has been done to support miniaturization and cost reduction of inverter systems as a whole. Figure 1 illustrates the transition of rated IGBT module chip area (1,200 V; 50 A). As there is limited room for further improving the power losses of IGBT

chips, we considered miniaturizing and higher power density of IGBT modules by raising the upper limit of the operating temperature. It is estimated that a 20% improvement in the output of a general-purpose inverter is expected when the upper limit of the operating temperature is raised to 175°C from the conventional 150°C . This article will describe the assembly technology for IGBT modules that realizes highly reliable and continuous operation at T_{jmax} 175°C .

2. Technical Challenges to Guarantee Continuous Operation at 175°C

One of the important elements in realizing guaranteed continuous operation at 175°C is power cycle lifetime. Raising the maximum operational temperature from the conventional 150°C by 25°C means there is an increase of thermal stress on component materials. It also increases the temperature fluctuation range between operation and downtime. Thus the materials need guaranteed resistance against more thermal fatigue than the previous product.

Figure 2 shows the power cycle lifetime of previous modules at fixed maximum operational temperature T_{jmax} with a cumulative failure rate of 1%. The lifetime is reduced by 30% to 50% as T_{jmax} increases to 175°C from 150°C . It is therefore essential to create a highly reliable assembly that guarantees a power cycle lifetime equal to that of previous 150°C -range products and yet is operable at a T_{jmax} of 175°C .

It is generally considered that fractures in an IGBT module incurred in the power cycle test are mainly due to fatigue from repeated stress applied between components differing in coefficient of thermal expansion during temperature fluctuations⁽²⁾. In a continuous operation at T_{jmax} 175°C , the effect from a metallic microstructure change in the components

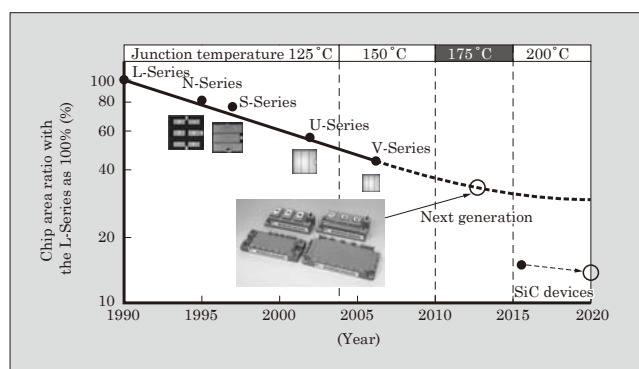


Fig.1 Transition of IGBT chip area (1,200 V/50 A)

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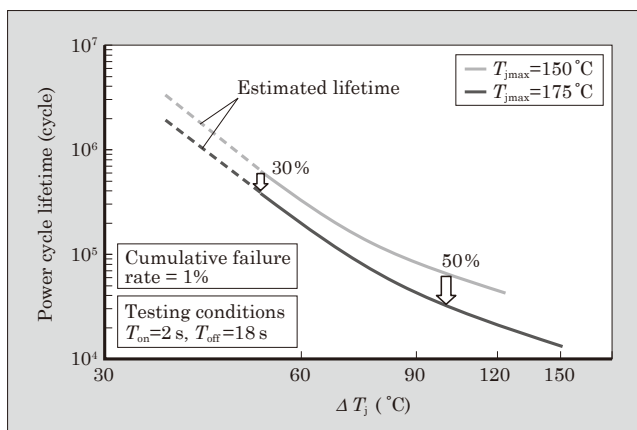


Fig.2 Power cycle lifetime in the conventional structure

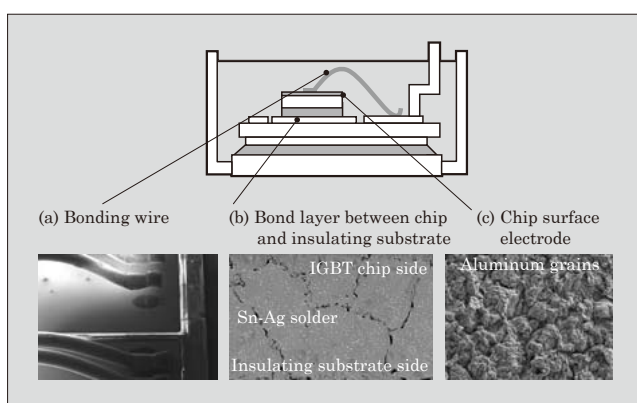


Fig.3 Fractures after power cycle testing ($T_{jmax} = 175^{\circ}\text{C}$)

must be taken into account in addition to the repetitive stress. The components in question are solder and aluminum. We therefore observed fractures in a module subject to the power cycle test at the continuous operational temperature of $T_{jmax} 175^{\circ}\text{C}$.

Figure 3 illustrates fractures under power cycle testing ($T_{jmax}=175^{\circ}\text{C}$). There are mainly three parts susceptible to fracture.

(a) Bonding wire

Shear stress created by the difference in coefficient of thermal expansion between aluminum wire and silicon (Si) chip causes cracks in the base material, and eventually the wire detaches.

(b) Bonding between chip and insulating substrate

The solder used between the chip and insulating substrate undergoes microstructural changes and thermal fatigue, which exacerbate the development of cracks in the solder bonding portion.

(c) Chip surface electrode

Cracks are caused in the chip surface electrode due to coarsening of aluminum grains and the fact that aluminum has a coefficient of thermal expansion that is different from that of silicon. In order to secure continuous operation at $T_{jmax} 175^{\circ}\text{C}$, lifetime of material in these three fracture areas need to be improved.

3. New Bonding Technology to Achieve High Reliability

3.1 New aluminum wire

Figure 4 shows a cross-section of aluminum wire after a power cycle test ($T_{jmax}=175^{\circ}\text{C}$; $\Delta T_j=75^{\circ}\text{C}$). The bond was broken as the cracks developed within the aluminum wire material. This suggests that the lifetime primarily depends on the material strength of the aluminum wire.

Power cycle test at $T_{jmax} 175^{\circ}\text{C}$ suggests that aluminum particles in the wire coarsen as they recrystallize because the temperature is within the recrystallization temperature range of the material.

The following Hall-Petch Equation expresses the relationship between metallic grain diameter and strength⁽³⁾.

$$\sigma_y = \sigma_0 + k d^{-1/2} \dots \dots \dots (1)$$

σ_y : Yield stress

d : Average grain diameter of the metal

σ_0, k : Material dependent constants

The Hall-Petch Equation indicates that growth in metal grain size weakens the material. Therefore, Fuji Electric has developed new aluminum wire that has a recrystallization temperature higher than 175°C . Figure 5 illustrates a cross-section of aluminum wire

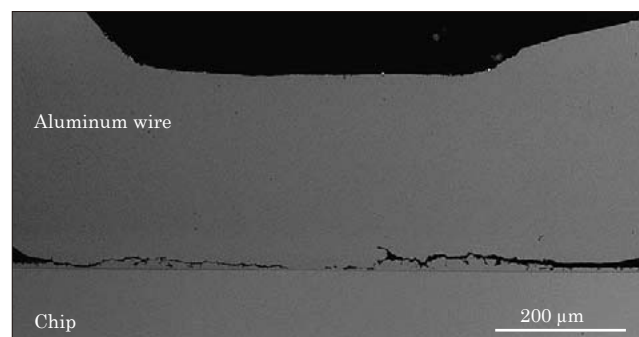


Fig.4 Cross-section of the bonding wire after power cycle testing

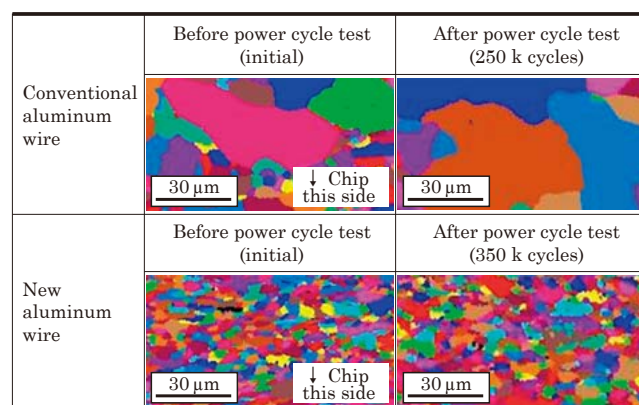


Fig.5 Cross-section of aluminum wire before and after power cycle test ($T_{jmax} = 175^{\circ}\text{C}$)

before and after a power cycle test ($T_{jmax}=175^{\circ}C$). This is a cross-section image using electron back scatter diffraction (EBSD). The aluminum grain growth was observed in the conventional wire after the power cycle test, but there was no change in the grain in the new aluminum wire. Therefore, it is supposed that the base material strength of the aluminum wire is not compromised by the power cycle test.

3.2 New solder

There is a concern that the degradation of solder layer between the chip and substrate due to heat and thermal fatigue is accelerated during the continuous operation at T_{jmax} 175°C. We attempted to reinforce the soldering material against high temperature, based on microstructural considerations.

There are two methods to strengthen metal with additional elements: precipitation strengthening and solid-solution strengthening. Figure 6 shows structural models of solder before and after a thermal aging process^{*1}. The diagrams depict microstructural changes in the metal caused by the strengthening methods. Sn-Ag solder is the representative of precipitation strengthening.

In this case, Ag₃Sn minuscule inter-metallic compounds precipitate between Sn particles, reinforcing the yield point of the grain boundary and preventing the development of cracks. However, Sn grains grow and Ag₃Sn aggregates under high temperature, resulting in cracks. On the other hand, Sn solder with added Sb and In within the solid solubility limit is the model for the solid-solution strengthening. The particles of Sb and In dissolve in the Sn grains to suppress coarsening under high temperature.

Figure 7 is an illustration of the tensile strength variance in solder after thermal aging test. Stored under the conditions of 150°C and 175°C for 1,000 hours, Sn-Ag solder significantly weakens from its initial

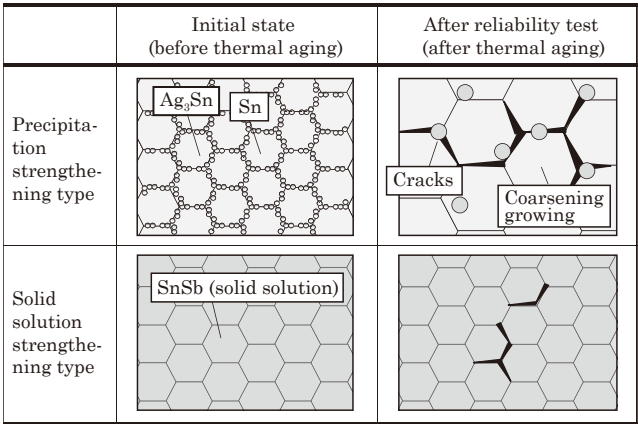


Fig.6 Structural diagram of solder before and after thermal aging

^{*1}: Aging: a phenomenon in which metallic properties (for example hardness) change over time.



Fig.7 Tensile strength variance in solder after thermal storage test

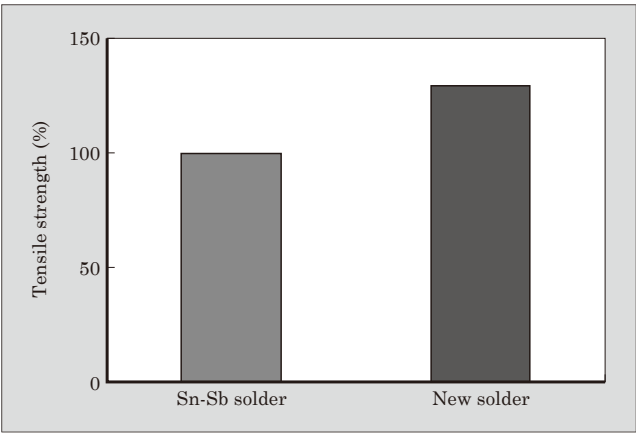


Fig. 8 Tensile strength of Sn-Sb and new solder

state while Sn-Sb maintains its strength. We also conducted a power cycle test ($T_{jmax}=175^{\circ}C$) using samples of both Sn-Ag and Sn-Sb solder to compare the effects on the power cycle lifetime. As a result, we verified that Sn-Sb had superior improvement of power cycle lifetime over Sn-Ag. Furthermore, by adding Sb in excess of the solid solubility limit, residual Sb precipitates as SnSb, creating an effect of the solid-solution strengthening and precipitation strengthening combined⁽⁴⁾.

Leveraging this feature, Fuji Electric has developed a Sn-Sb-based new solder with additional new elements having characteristics of both solid solution strengthening and precipitation strengthening. This will be followed by mass production of the next-generation IGBT modules in the near future. Figure 8 shows the tensile strength of Sn-Sb and new solder. The new solder has a higher tensile strength than Sn-Sb solder. We have also verified its enhanced power cycle lifetime over Sn-Sb in a power cycle test ($T_{jmax}=175^{\circ}C$).

3.3 New surface electrode protection layer

Si chip surface electrode is usually made of pure aluminum or with Si or Cu compounds. In power cycle test, the surface electrode sustains stress due to coarsening of aluminum grains from the heat generated in

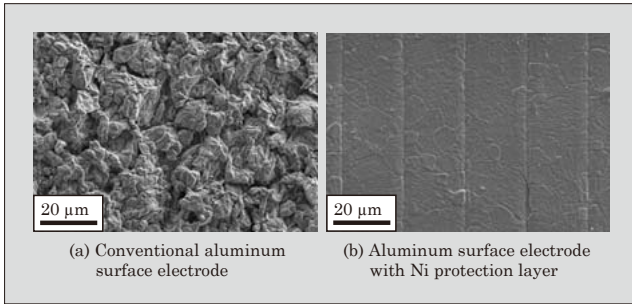


Fig.9 Surface electrode after power cycle test ($T_{jmax}=175^{\circ}\text{C}$)

the chip as well as from the difference in coefficient of thermal expansion from the Si chip, resulting in cracks caused in the surface electrode as well as in the aluminum wire bonding⁽⁵⁾. In order to prevent this, we have developed a structure with Ni, which has a coefficient of thermal expansion closer to silicon than to aluminum, forming a layer over the aluminum electrode to reduce the stress exerted upon it. Figure 9 illustrates the observation results from the power cycle test ($T_{jmax}=175^{\circ}\text{C}$) for a chip surface electrode without aluminum wire bonding. It is possible to lessen degradation by forming a protection layer over the aluminum electrode using Ni.

4. Effects of New Technology

We prepared a sample to which we applied the three new technologies described in Section 3 and conducted power cycle test.

Figure 10 shows the test results ($T_{jmax}=175^{\circ}\text{C}$). The new technology yielded a significant improvement

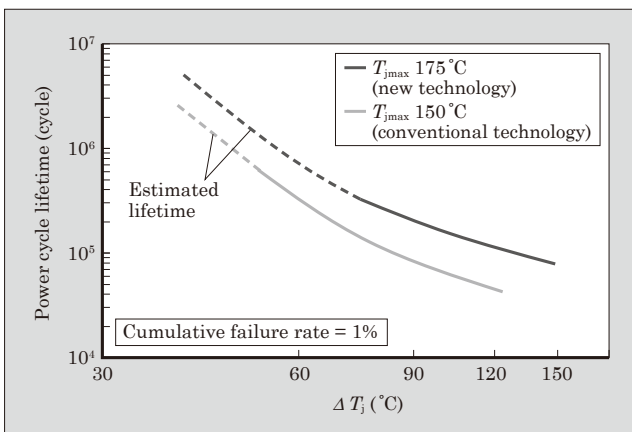


Fig.10 Power cycle test results ($T_{jmax} = 175^{\circ}\text{C}$)

at $T_{jmax} 175^{\circ}\text{C}$ over the target power cycle lifetime of conventional technology at $T_{jmax} 150^{\circ}\text{C}$. The lifetime was more than doubled at all temperature regions.

5. Postscript

We have described the IGBT module assembly technology that accomplished reliable continuous operation at $T_{jmax} 175^{\circ}\text{C}$. The developed IGBT module has guaranteed continuous operation at $T_{jmax} 175^{\circ}\text{C}$ while achieving a longer lifetime than conventional modules as a result of combining three new bonding technologies: new aluminum wire with high thermal resistance, new solder with high strength at high temperature and a new surface electrode protection layer providing high strength at high temperature and lower thermal stress between silicon and aluminum.

These technologies can be deployed without changing the current manufacturing processes at Fuji Electric, enabling easy mass production of items with guaranteed continuous operation at $T_{jmax} 175^{\circ}\text{C}$. By increasing high power density, improvements are expected to be made to the maximum power output of general-purpose inverters. We will continue our efforts with the development and expansion of offerings of the $T_{jmax} 175^{\circ}\text{C}$ continuous operation guaranteed IGBT module family, and contribute to the improvement of industrial equipment for higher efficiency and better energy saving.

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