Lead-free IGBT Modules

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1. Introduction

In response to environmental issues, lead-free solder (in compliance with the RoHS*1 directive) is being promoted for use instead of conventional Sn-Pb solder in the mounting of electronic components. Under these circumstances, there is also desire for IGBT (insulated gate bipolar transistor) modules to be made lead-free.

Fuji Electric has been using lead-free solder in the soldered connections underneath silicon chips since 1998, and has succeeded in improving power cycle reliability. This paper reports a new established technique for using lead-free solder instead of Sn-Pb solder for joining a ceramic insulated substrate to a metal base in an IGBT module.

2. Challenges to Achieving Lead-free Status

Figure 1 shows a schematic diagram of the IGBT module, and lists the coefficients of thermal expansion for several component materials. Generally, in an IGBT module, a metal base and ceramic substrate having significantly different coefficients of thermal expansion are joined by soldering. During the soldering process and due to changes in the ambient temperature, the metal base deforms and stress is generated in the area of the soldered joint. This stress causes cracks in the soldered joint. As a result, with lead-free solder, it is difficult to ensure sufficient reliability during thermal cycle testing.

*1: RoHS is Restriction of the use of certain hazardous substances in electrical and electronic equipment.

Fig.1 Conventional IGBT module structure

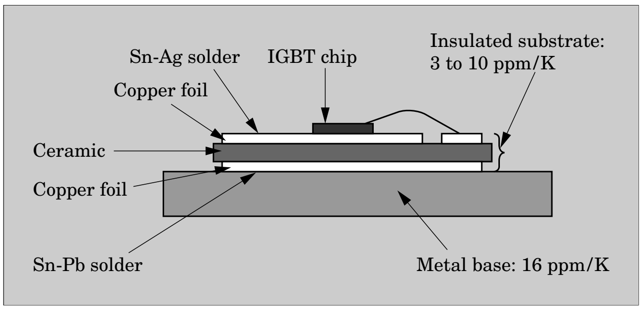


Fig.2 Relationship between ambient temperature and deformation of the metal base

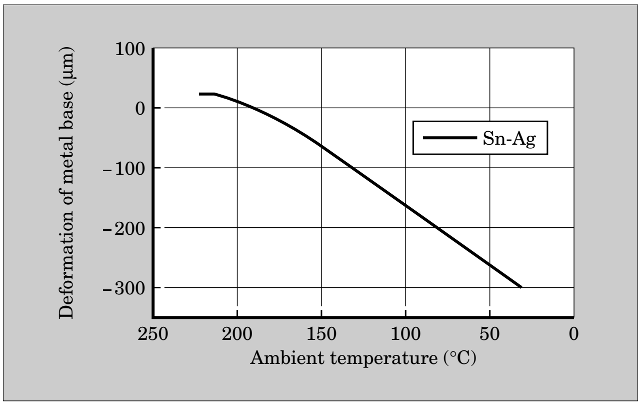


Table 1 Characteristics of various ceramics and copper

Type of material		Coefficient of thermal expansion	Thermal conductivity
Ceramics	Alumina	7 ppm/K	20 W/(m·K)
	Aluminum nitride	4 ppm/K	170 W/(m·K)
	Silicon nitride	3 ppm/K	70 W/(m·K)
Metal base	Copper	16 ppm/K	390 W/(m·K)

Figure 2 shows the relationship between ambient temperature and deformation of the metal base. From this figure it can be understood that deformation of the metal base is caused only by the difference in thermal expansion coefficients of the insulated substrate and metal base. In other words, by reducing the amount of metal base deformation after soldering, the ability to withstand thermal cycle testing can be increased.

3. Considerations in the Structural Design

The structural design was evaluated in order to suppress the amount of metal base deformation due to the difference in thermal expansion coefficients.

Table 1 lists characteristics of various ceramics used in a typical insulated substrate and of the copper in the metal base. Alumina substrates, which are inexpensive and durable, and aluminum nitride substrates, which are characterized by good thermal conductance, are used as the insulated substrates in IGBT modules.

The use of alumina, which has a coefficient of thermal expansion that is close to that of the metal base, is thought to be effective in increasing the ability of a lead-free IGBT module to withstand thermal cycle testing.

4. Experimental Results

4.1 Alumina ceramic substrate

Figure 3 shows the amount of deformation of the metal base after soldering to various insulated substrates.

(1) By changing from an aluminum nitride to alumina substrate, the amount of deformation after soldering was reduced from 640 µm to 460 µm.

(2) By changing the thickness of the alumina ceramic from 0.635 mm to 0.25 mm, the amount of deformation after soldering was reduced from 460 µm to 330 µm.

When made thinner, the ceramic substrate deforms more easily due to stress. Consequently, the amount of metal base deformation decreases as a result of the ceramic substrate deformation due to stress generated by the difference in thermal expansion coefficients.

Stress is generated due to a difference in thermal expansion coefficients of the insulated substrate and metal base, and to investigate this phenomenon, we conducted thermal cycle tests using various ceramic substrates.

Figure 4 shows the relationship between the number of thermal cycles tested and the solder crack length. Compared to an aluminum nitride insulated substrate, an alumina substrate results in less deformation of the metal base, fewer solder cracks, and greater ability to withstand thermal cycle testing.

4.2 Consideration of the solder material

Figure 5 shows the relationship between the solidus temperature of various types of solder and the amount of deformation of the metal base. It can be seen that the solidus temperature and metal base deformation have a proportional relationship. To reduce the amount of metal base deformation it is effective to select solder that has a low melting point. For this purpose, we selected and examined low-melting point Sn-Ag solder and Sn-Ag-In solder.

Fig.3 Relationship between various insulated substrates and deformation of the metal base

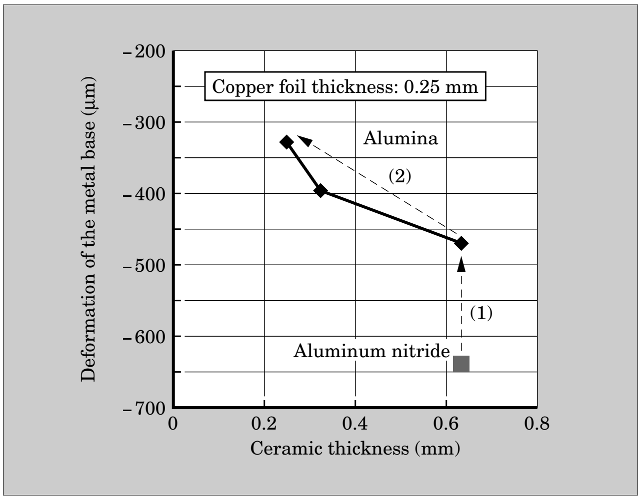


Fig.4 Relationship between the number of thermal cycles tested and solder crack length

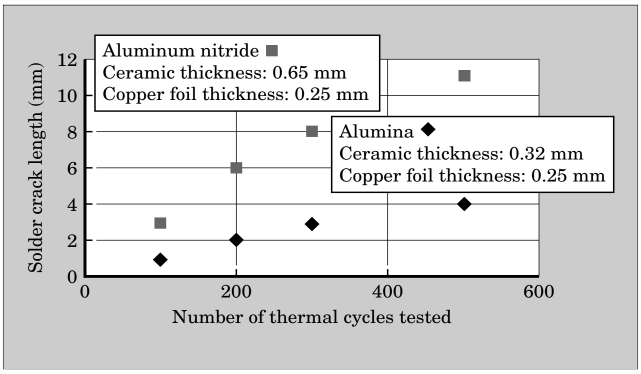


Fig.5 Relationship between the melting point of solder and deformation of the metal base

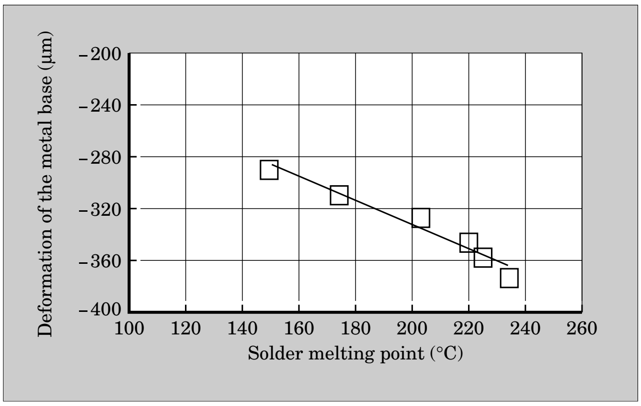


Fig.6 Stress-strain curve for Sn-Ag solder and Sn-Ag-In solder at room temperature

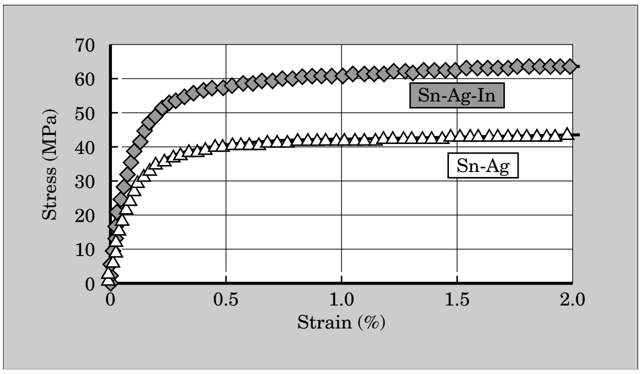


Figure 6 shows the stress-strain curve for Sn-Ag solder and Sn-Ag-In solder at room temperature. The strength of Sn-Ag-In solder has been increased to approximately 1.5 times that of Sn-Ag solder, and the strengths of these materials exhibit similar tendencies even at 125°C. To investigate the effect of solder type on the ability to withstand thermal cycling, we conducted thermal cycling tests (using an alumina ceramic thickness of 0.32 mm and a copper foil thickness of 0.25 mm) in products that currently use alumina substrates.

Figures 7 and 8 show the results of ultrasonic inspection of the solder joints. When Sn-Ag solder was used, cracks occurred over approximately 30 % of the solder joint area after a test of 300 thermal cycles, but with the newly developed Sn-Ag-In solder, there were almost no cracks and reliability was nearly the same as that of conventional leaded solder.

Figure 9 shows the relationship between solder thickness and crack length. It can be seen that the effect of solder thickness is less for Sn-Ag-In than for Sn-Ag.

Figure 10 shows the microstructure of the solder, before and after the thermal cycle testing. As a result of the thermal cycle testing, the Sn-Ag solder exhibits grains aggregate. However, the microstructure of Sn-Ag-In solder does not change. Strength generally decreases due to an increase in the grain size. The addition of Indium to Sn-Ag prevents an increase in the grain size and is thought to be one reason for the improvement in ability to withstand thermal cycle testing.

Fig.7 Ultrasonic monitoring of thermal cycling test results

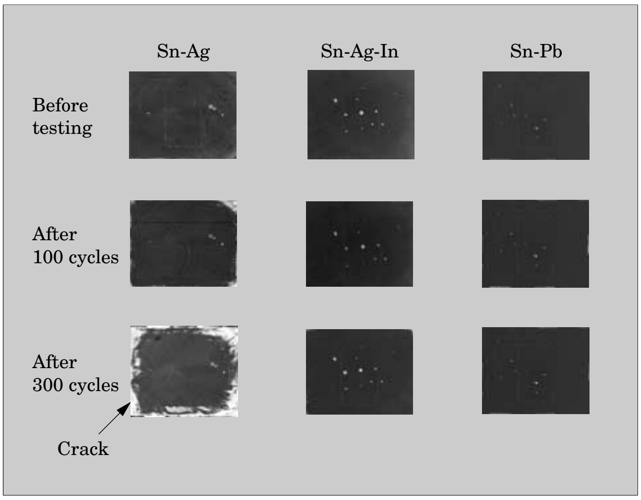


Fig.8 Relationship between the number of thermal cycles tested and solder crack length

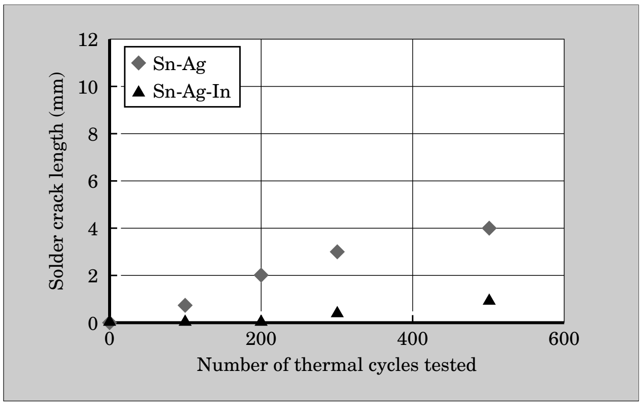
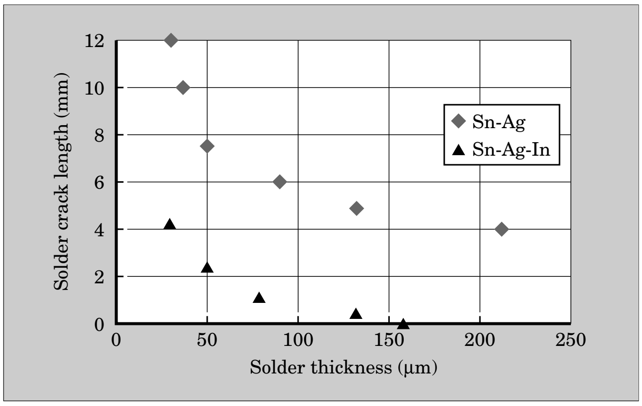


Fig.9 Relationship between solder thickness and crack length



5. IGBT Module that Uses Sn-Ag-In Solder

Figure 11 shows Fuji Electric's RoHS-compliant lead-free IGBT module. Although this product does not use lead or hexavalent chromium, it achieves the same level of product reliability as that of a module

Fig.10 Microstructure of solder

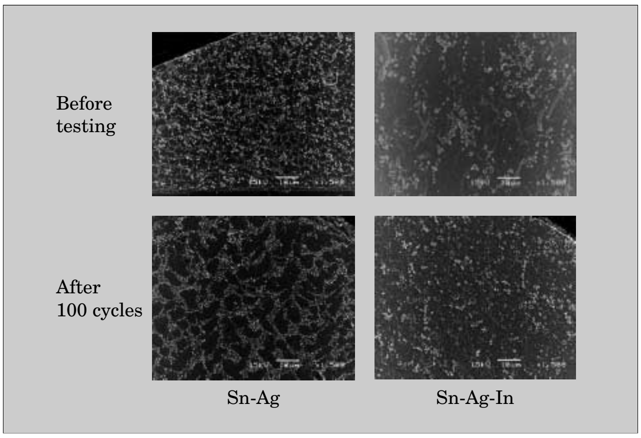


Fig.11 Fuji Electric's RoHS-compliant, lead-free IGBT module

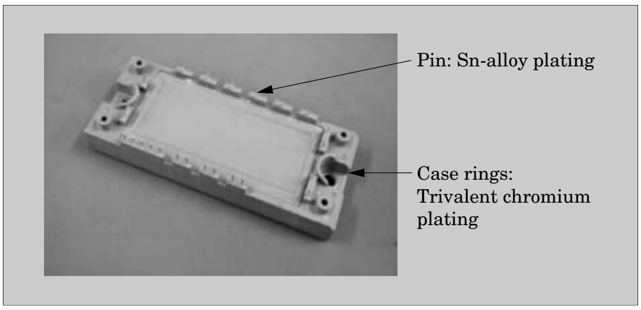


Fig.12 Relationship between copper foil thickness and thermal expansion coefficient of insulation substrate

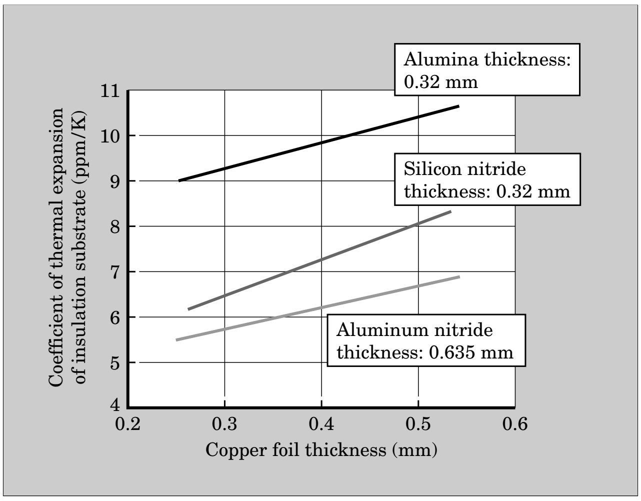
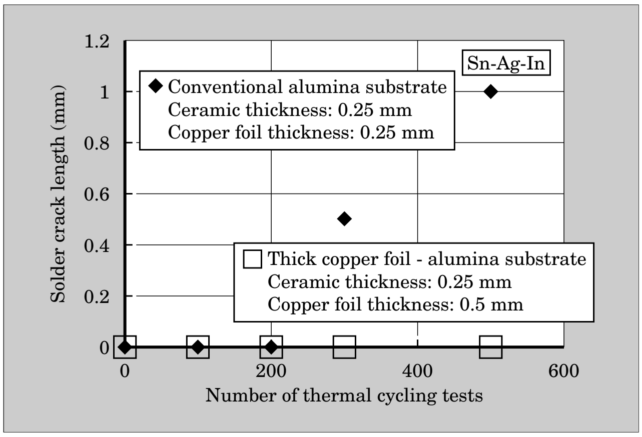


Fig.13 Relationship between the number of thermal cycling tests and solder crack length



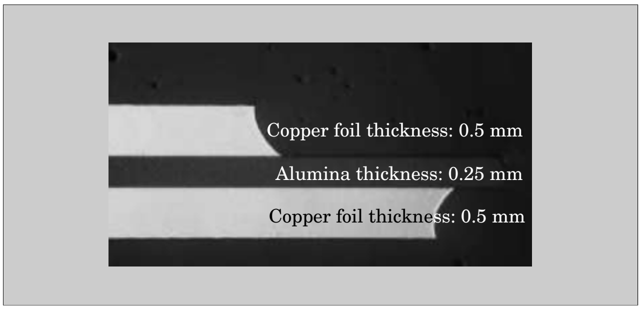
using conventional leaded solder.

6. Higher Reliability with a Thick Copper Foil and Alumina Substrate

To increase reliability even further, we considered making the thermal expansion coefficient of the ceramic insulated substrate approach that of the metal base. Figure 12 shows the results of FEM (finite element method) analysis of the thermal expansion coefficients of various ceramic insulated substrates when the copper foil thickness is changed. It can be seen that the thermal expansion coefficient of the ceramic insulated substrate increases when a thick copper foil base is used.

Using an insulated substrate having an alumina ceramic thickness of 0.25 mm and various thicknesses of copper foil, we investigated the amount of deformation in the metal base. By increasing the copper foil thickness from 0.25 mm to 0.5 mm, the amount of deformation of the metal base could be reduced by

Fig.14 Alumina DCB substrate cross-sections



approximately 100 µm. From this result, it is understood that increasing the thickness of the copper foil actually increases the thermal expansion coefficient of the ceramic insulated substrate.

We conducted thermal cycling tests on samples having an insulated substrate and thicker copper foil (Fig. 13). In a sample having a copper foil thickness of 0.25 mm, cracks occurred after 300 thermal cycles. By changing the copper foil thickness to 0.5 mm, no cracks occurred even after 500 thermal cycles. Increasing the thickness of the copper foil successfully suppressed the progress of cracks in the thermal cycle tests. Figure 14 shows cross-sections of alumina DCB (direct copper bonding) substrates in which an alumina ceramic is joined to a 0.5 mm-thick copper foil.

Furthermore, it has been shown that the use of thicker copper foil also improves the thermal resistance. Even in a structure equipped with a metal base, by increasing the thickness of the copper foil from 0.25 mm to 0.5 mm, we succeeded in decreasing the thermal resistance by approximately 15 %.

7. Conclusion

Fuji Electric has established lead-free IGBT module technology that uses an alumina ceramic insulated substrate and Sn-Ag-In solder to achieve better ability to withstand thermal cycle testing than when Sn-Ag solder is used. Moreover, by using an alumina ceramic insulated substrate and thicker copper foil, lower thermal resistance and high-reliability, even with lead-free solder, can be achieved.

Fuji Electric is committed to contributing to the protection of the global environment by developing lead-free IGBT modules that use this technology into commercial products.

References

(1) Morozumi, A. et al. Reliability of Power Cycling for IGBT Power Semiconductor Modules. IEEE Transactions On Industry Applications. vol.39, no.3, 2003-05/06, p.665-671.

(2) Nishimura, Y. et al. New generation metal base free IGBT module structure with low thermal resistance. in Proc. 16th ISPSD. 2004, p.347-350.