Improvement of High Power Cycling Reliability having Sn-Cu Based Solder

Miyazaki Takaaki, Ikeda Osamu
Hitachi, Ltd., Research and Development Group
Address
292, Yoshida-cho, Totsuka-ku, Yokohama-shi, Kanagawa-ken, 244-0817, Japan
Ph: +81-50-3135-2262; Fax: +81-50-3135-3477
Email: takaaki.miyazaki.ko@hitachi.com

Abstract

Demands of the raising operation temperature of power modules have been increasing in recent years. However, the power cycle capability is insufficient when used in a high temperature environment to apply the conventional Sn-based solder. In this study, we have developed a highly reliable bonding technology that improves the characteristics of the Sn phase by adding additional elements Bi, In, Sb to the Sn-7Cu solder. Power cycling test(Tjmax175℃) was carried out to evaluate the reliability. Power cycling reliability of Sn7Cu3Bi, Sn7Cu10Sb is approximately 3 times, 6 times higher than Sn7Cu.

Key words: Lead-free solder, Power cycling reliability, high temperature,

1. Introduction

The development of power modules that can control power with high efficiency has been progressing in recent years in response to energy-saving needs. A schematic illustration of a typical power module for use in hybrid electric vehicles (HEV) and electric vehicles (EV), railroad systems, etc. is shown in **Fig. 1**. Additionally, the development of wide-bandgap semiconductors using materials such as SiC and GaN that can operate at high temperatures and contribute to compact and light devices is becoming a trend in power semiconductors. While conventional Si semiconductor devices have a maximum operating temperature of approximately 175°C, SiC semiconductor devices can be used at temperatures above 175°C [1]. So the need for lead-free, high heat-resistant joints is growing. Against this background, we have come to develop Sn-Cu based solder as a high heat-resistant solder [2]. The bonding mechanism of Sn-Cu based solder is shown in **Fig. 2**. When bonding by Sn-Cu based solder, a Cu-Sn inter metallic compound(IMC) is selectively deposited at the bonded interface. This high heat-resistant Cu-Sn IMC acts as a barrier layer protecting the bonded interface, so reactions at the bonded interface can be suppressed even in a high-temperature environment. In this report, we study Sn-7Cu solder as a basic composition that can achieve a stable bonded interface even under high-temperature conditions.

With the above in mind, we here report on a study we made on improving the power cycling reliability at 175°C of Sn-Cu based solder as an Sn based solder.

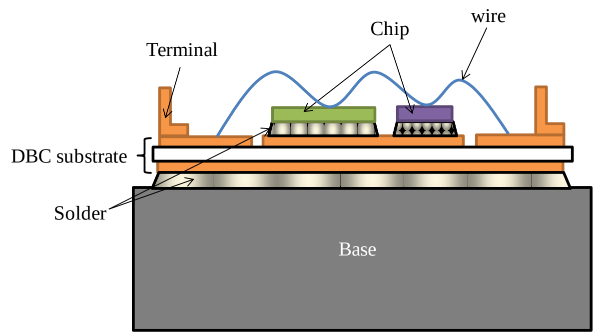


Fig.1 Schematic illustration of Power modules.

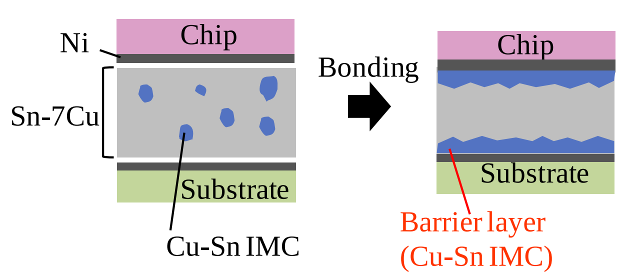


Fig.2 Schematic illustration of Sn-7Cu bonding mechanism .

2. Test Method

2.1 Deformation test

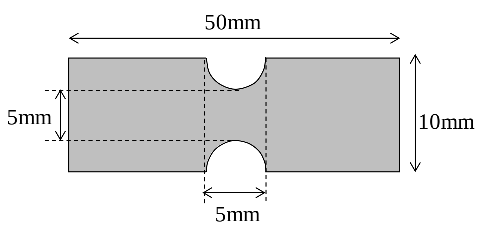
In this test, we used Sn-3Ag-0.5Cu, Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-3In, Sn-7Cu-5Sb, and Sn-7Cu-10Sb as solder evaluation specimens (each with dimensions of 50 mm × 10 mm × t0.1 mm). To evaluate deformability under high-temperature conditions, we applied stress of 2 MPa to each specimen in a 175°C environment and compared the amount of specimen elongation up to the point of breaking. A schematic illustration of this deformation test is shown in **Fig. 3.**

2.2 High-temperature storage test

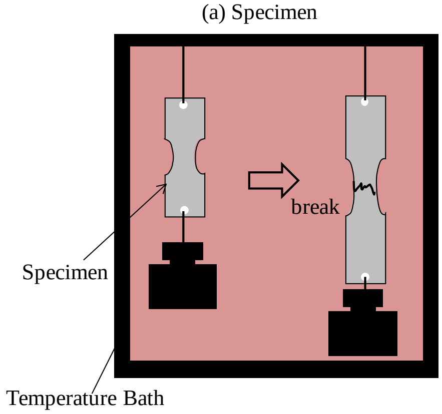
In this test, we used Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-3In, Sn-7Cu-5Sb, and Sn-7Cu-10Sb solder foil as bonding material and a nickel-plated invar plate (10 mm × 10 mm × 0.5 mm; Ni plating thickness: 5 µm) and nickel-plated oxygen-free copper plate (15 mm × 15 mm × 1 mm; Ni plating thickness: 5 µm) as bonded material. Bonds were made in an N_2 atmosphere. Each specimen was prepared by placing a nickel-plated invar plate and a 10 g weight on top of solder foil to perform pressurized bonding. The specimen was then heated up to 300°C at a rate of 60°C/min, held at that temperature for 4 min, and cooled in N_2. Finally, after storing the specimen fabricated in the above way at 200°C for the desired time, its 200°C heat resistance was evaluated in terms of change in the bonded interface and solder composition over time.

2.3 Thermal cycling test

For this test, we used a nickel-plated invar plate (10 mm × 10 mm × 0.5 mm; Ni plating thickness: 5 µm) and nickel-plated anoxic copper plate (15 mm × 15 mm × 1 mm; Ni plating thickness: 5 µm) as bonded material. The thermal expansion coefficients of invar and Cu are 4.5 ppm/K and 17 ppm/K, respectively. Bonding two types of materials with a large difference in their thermal expansion coefficients accelerates deterioration in the bonded section during a thermal cycling test. Here, we used Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-5Sb, and Sn-7Cu-10Sb solder foil with a thickness of 0.1 mm as bonding material and performed bonding in an N_2 atmosphere. First, a 10-mm-square solder foil was placed above the nickel-plated copper plate, and next, the nickel-plated invar plate and a 10 g weight were placed on top of the solder foil to form the bond. Prepared specimens were heated up to 300°C at a rate of 60°C/min, held at that temperature for 4 min, and cooled in N_2. Finally, each specimen was subjected to a thermal cycling test of up to 500 cycles under temperature-cycling conditions of -55°C (15 min) and 200°C (15 min).

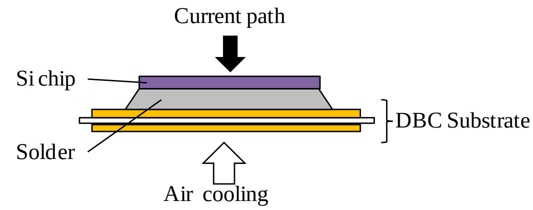


(a) Specimen

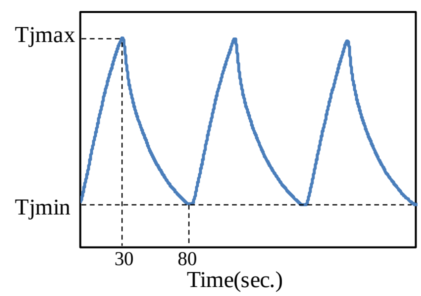


(b) Experimental condition

Fig. 3 Schematic illustration of Deformation test.



(a) Specimen



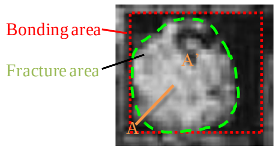
(b)Temperature image

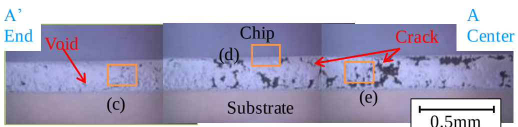
Fig.4 Schematic illustration of power cycling test.

2.4 Power cycling test

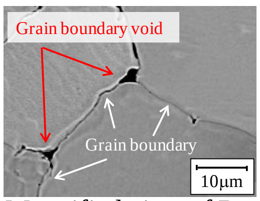
In this test, we used a ceramic substrate (dimensions: 55 mm × 45 mm; layer configuration: Cu: 0.3 mm, AlN: 0.6 mm, Cu: 0.2 mm, Ni plating: 5 µm) and a Si diode chip (0.2 mmt, Ni/Ag metallization) as bonded material and Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, and Sn-7Cu-10Sb solder foil with a thickness of 0.2 mm as bonding material. We layered the above materials in the order of ceramic substrate, solder foil, and Si chip and formed the bond by heating up to 300°C at a rate of 60°C/min in an N_2 atmosphere, holding at that temperature for 4 min, and cooling in N_2.

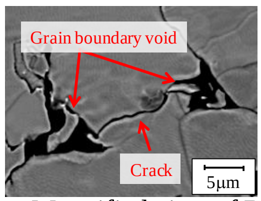
We performed a power cycling test on each bonded specimen to evaluate its reliability. A schematic illustration of the power cycling test and its temperature profile are shown in **Fig. 4**. In this test, a 35A current is made to flow through the specimen thereby heating the Si chip. While measuring the temperature of the ceramic substrate directly under the chip, the current is turned on until this temperature reaches 150°C so that the initial temperature of the joint reaches 175°C. The current is then turned off until the temperature drops to 50°C.



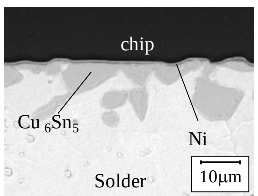


(b)Cross sectional view (Line





Magnified view of Region Magnified view of Region



Magnified view of Region

Fig.5 Image of Chip/Substrate joints using Sn-7Cu after power cycling test.

This process constitutes one cycle. At this time, the generation of cracks in the solder joint will degrade heat dissipation from the chip, which is a heating element, to the outside causing the temperature of the chip to rise. It is therefore possible to indirectly evaluate the progression of cracking within the solder by measuring forward voltage ΔVf. In this study, we took the point at which ΔVf rises by 20% of its initial value to be solder joint life. In this regard, a rise in Tjmax from 150°C to 175°C causes joint life to drop to approximately 2/3 its usual value. Thus, to obtain a level of reliability at a Tjmax of 175°C the same as that at 150°C, we set out to develop an Sn based solder having a power cycling life 1.5 times that of Sn-7Cu

3. Improving Power Cycling Reliability

3.1 Fracture mode under power cycling test

To begin with, we investigated the fracture mode under a Tjmax-150°C power cycling test using Sn-7Cu. A cross sectional view of the specimen after the power cycling test is shown in **Fig. 5**. As shown in **Fig. 5 (e),** stability is maintained in the bonded interface even after the test through a (Cu, Sn) IMC formed at the interface. However, as shown in **Fig. 5 (a)**, significant fracturing occurred at the center of the solder joint in contrast to fracturing from the end of the solder joint as in ordinary thermal cycling. On making more detailed observations, it was found that many voids had arisen at grain boundaries of the crystal Sn phase and that cracks had formed so as to connect those grain boundary voids as shown in **Fig. 5 (c)** and **(d)**.

3.2 Inference of destruction mechanism under power cycling test

While a number of factors can be considered, we examined the phenomenon of Sn grain boundary destruction under a power cycling test in the manner shown in **Fig. 6**. In a power cycling test, destruction of Sn grain boundaries progresses from the center of the solder joint. It has been reported that applying current to the chip creates a temperature distribution in which temperature is highest at the center of the chip dropping off progressively from the center to the end of the chip [3)]. As a result, a significant jump in temperature occurs particularly at the center of the solder joint under the chip when current is applied causing the temperature of Sn solder to rise as well. This, in turn, increases the concentration of atomic vacancies introduced in Sn. The relationship between temperature T and vacancy concentration Cv is given by Eq. (1) [4)]. Here, A, Ev, and k_b denote a constant, the vacancy activation energy, and the Boltzmann constant, respectively. It can be seen that a rise in temperature of Sn solder means a rise in the concentration of atomic vacancies introduced in Sn. In such a case, it is easier for vacancies to occur at grain boundaries than within the grains themselves, and as a result, vacancies at grain boundaries where vacancy concentration is high tend to aggregate and form voids. Furthermore, it is thought that applying thermal stress repeatedly to the solder by turning the current on and off causes grain boundary voids to link up and cracks to progress. The characteristics of grain boundary voids caused by atomic vacancies are determined by joint temperature and metal melting point. However, making a significant improvement in the melting point of Sn based solder is difficult, and since our target here is a solder joint temperature of 175°C, the suppression of grain boundary voids is likewise difficult. We therefore decided to focus on crack progression caused by repeated application of thermal stress and considered that improving solder deformability could reduce the stress applied to grain boundaries and suppress crack progression. This would have the effect of improving power cycling reliability.

$$C_v = A\exp\left(-\frac{E_v}{k_b T}\right) \qquad (1)$$

3.3 Study on adding additional elements to Sn-7Cu

We aimed to improve the deformability of Sn solder in a high-temperature environment by adding additional elements to Sn-7Cu solder. To this end, we selected Bi, In, and Sb as additional elements to be tested considering that they are elements that are solid-soluble in Sn and that can result in an increase in slip systems. Using these additives, we evaluated

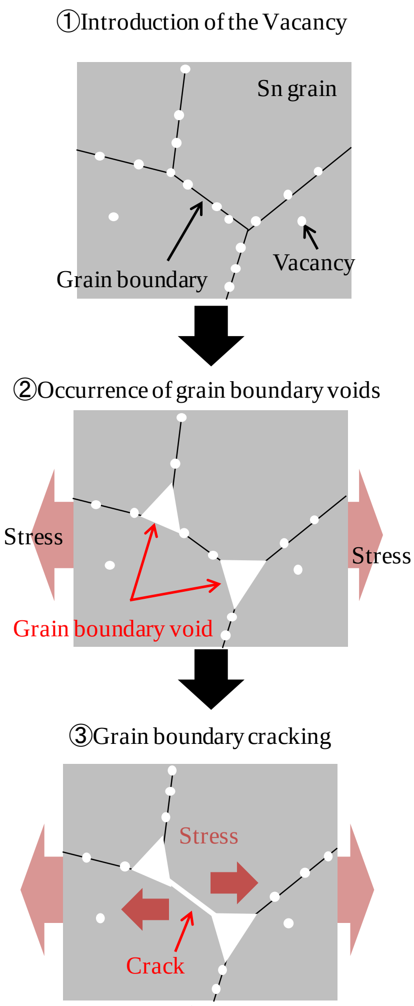


Fig.6 Schematic illustration of Sn destruction mechanism under power cycling test.

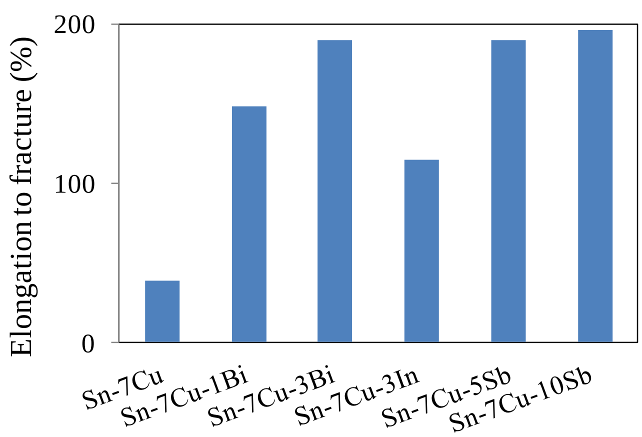


Fig.7 Fracture elongation by 175°C deformation test using Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-3In, Sn-7Cu-5Sb, Sn-7Cu-10Sb at 175°C.

solder deformability in a 175°C environment and obtained the results shown in **Fig. 7**. These results show that adding Bi, In, and Sb to Sn-7Cu can improve deformability. They also show that increasing the amount of additive improves deformability in the case of the Bi and Sb additional elements. For the above reasons, we chose Bi, In, and Sb as additional elements that can be expected to improve power cycling reliability.

3.4 Study of solder composition

We evaluated, in particular, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-1In, Sn-7Cu-3In, Sn-7Cu-5Sb, and Sn-7Cu-10Sb reflecting different amounts of Bi, In, and Sb solid-soluble in Sn. For each of these solder compositions, we evaluated stability of the bonded interface under a 200°C high-temperature storage test and resistance to cracking progression under a -55°C/200°C thermal cycling test with the aim of further narrowing down desirable solder compositions. Finally, we evaluated the reliability of those solder compositions for which desirable results were obtained by subjecting them to a Tjmax-175°C power cycling test.

3.5 Evaluation of interface stability under high temperature storage test

The disappearing thickness of Ni metallization under a 200°C high-temperature storage test is shown in Fig. 8 and the cross-sectional microstructure near the bonded interface after 1000h at 200°C is shown in Fig. 9. Here, we used as an evaluation standard the fact that the 1 μm thickness of the Ni metallization layer in an ordinary chip is not consumed after 1000h at 200°C. The Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-5Sb, and Sn-7Cu-10Sb solder compositions that add Bi and Sb to Sn7Cu satisfied this standard. However, Ni metallization in the case of Sn-7Cu-3In that adds In was greatly consumed as shown in Fig. 9 (c) and consequently did not satisfy this standard. We infer that the reason for this is that the In comes to be contained in the Cu-Sn IMC formed as a barrier layer at the bonded interface thereby forming $Cu_6(Sn, In)_5$, which has an effect on the rate of Ni disappearance [5]. Based on the above results, we narrowed down our selection of solder compositions to Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-5Sb, and Sn-7Cu-10Sb.

3.6 Evaluation of thermal fatigue resistance under thermal cycling test

We performed a -55°C/200°C thermal cycling test on Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-5Sb, and Sn-7Cu-10Sb and evaluated the thermal cycling resistance of each of these solder compositions. The relationship between bonding rate and number of cycles in the thermal cycling test is shown in Fig. 10 and the areas exhibiting crack progression after 500 cycles are shown in Fig. 11. The results of Fig. 10 show that adding Bi and Sb to Sn-7Cu achieves high thermal cycling

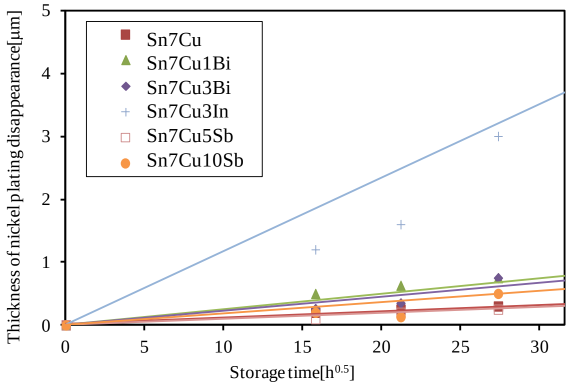


Fig.8 Changes of thickness of nickel plating disappearance using Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-1In, Sn-7Cu-In, Sn-7Cu-5Sb, Sn-7Cu-10Sb,Sn-7Cu-15Sb through aging test at 200℃.

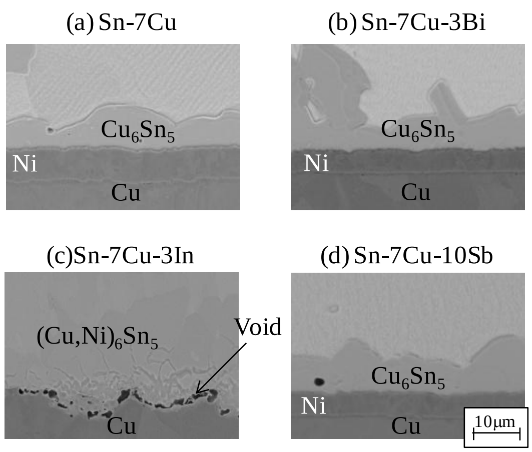


Fig.9 Cross-sectional microstructure near bonded interface using Sn-7Cu, Sn-7Cu-3Bi, Sn-7Cu-10Sb after storage test 1000h at 200℃.

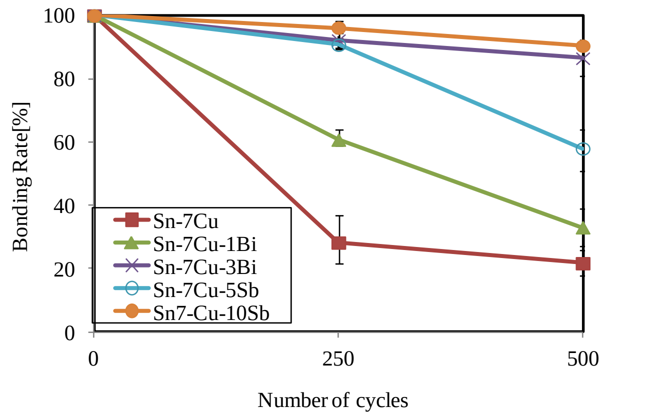


Fig.10 Changes of bonding rate of Invar-to-Cu/Ni substrate joints using Sn-7Cu, Sn-7Cu-1Bi, Sn-7Cu-3Bi, Sn-7Cu-5Sb, Sn-7Cu-10Sb, Sn-7Cu-15Sb through -55/200°C thermal cycling test .

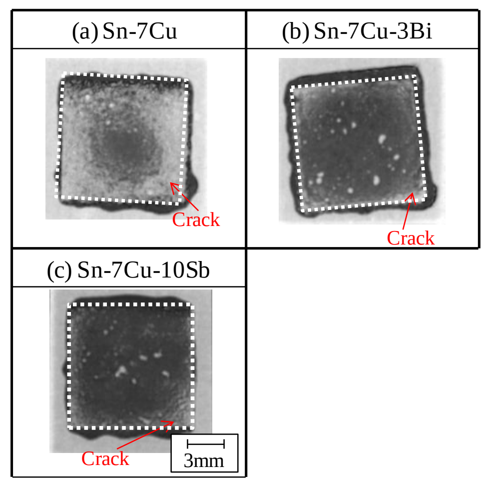


Fig.11 SAM images of joint of Invar-to-Cu/Ni substrate joints using Sn-7Cu, Sn-7Cu-3Bi, Sn-7Cu-10Sb, through thermal cycle test between -55℃ and 200℃.

reliability compared with Sn-7Cu and that good reliability is particularly obtained with Sn-7Cu-3Bi and Sn-7Cu-10Sb having a relatively large amount of additional elements. We consider the reason for this to be that adding Bi and Sb to Sn-7Cu improves deformability thereby easing the thermal stress generated under the thermal cycling test.

3.7 Evaluation of solder joint under power cycling test

We performed a Tjmax-175°C power cycling test on Sn-7Cu-3Bi and Sn-7Cu-10Sb, which exhibited good reliability under a 200°C storage test and -55°C/200°C thermal cycling test, and for comparison purposes, on Sn-7Cu and Sn-7Cu-1Bi, the latter of which differs in the amount of additional elements. Percent change in ΔVf versus number of cycles in the power cycling test is plotted in Fig. 12. In this Tjmax-175°C power cycling test, the number of cycles corresponding to a 20% increase with respect to the initial value of ΔVf was 3975 for Sn-7Cu. However, when adding Bi, this number became 9050 for Sn-7Cu-1Bi and 12600 for Sn-7Cu-3Bi showing that solder joint life improves by increasing the amount of Bi additive. Furthermore, when adding Sb, the longest solder joint life was obtained at 23000 cycles for Sn-7Cu-10Sb. A cross-sectional SEM image of the Sn-7Cu-10Sb solder joint after testing is shown in **Fig. 13.**

For the Sn-7Cu-10Sb solder, it was found that no voids had formed at the bonded interface on completion of the test thereby maintaining interface stability and that cracks had arisen in the center of the joint layer progressing in the vertical direction. This progression of cracks in the vertical

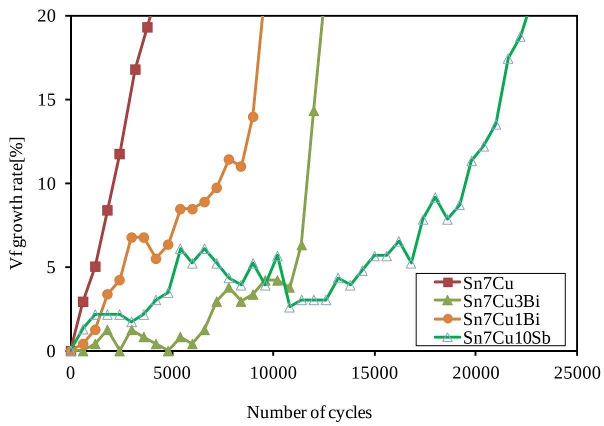


Fig.12 Changes of Vf growth rate of Chip/Ceramic substrate joints using Sn-7Cu, Sn-7Cu-1Bi、Sn-7Cu-3Bi、Sn-7Cu-10Sb through Tjmax175°C power cycling test.

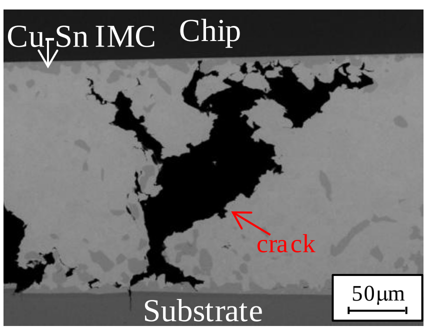


Fig.13 Cross-sectional microstructure Chip/Substrate joints using Sn-7Cu-10Sb after power cycling test.

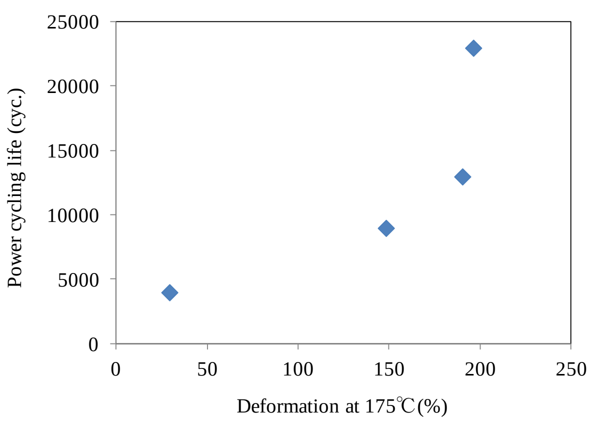


Fig.14 Relationship between Tjmax 175°C power cycling lifetime and Elongation rate under 175°C using Sn-7Cu, Sn-7Cu-1Bi、Sn-7Cu-3Bi、Sn-7Cu-10Sb.

direction. This progression of cracks in the vertical direction has a smaller effect on heat dissipation than cracks in the horizontal direction, which is considered to be the reason for the longer solder joint life.

The relationship between deformability in a 175°C environment and Tjmax-175°C power cycling life is shown in **Fig. 14.** It can be seen that Tjmax-175°C power cycling life tends to lengthen as deformability increases in a 175°C environment. We consider that these results support the inferred destruction mechanism in a power cycling test and the method of suppressing crack progression presented in section 3.2.

4. Conclusion

The results of studying high-heat-resistant, Sn-based solder for Tjmax-175°C power modules are summarized below.
(1) Adding Bi, In, and Sb to a base composition of Sn-7Cu capable of maintaining a stable bonded interface in a high-temperature environment was able to improve deformability of the Sn parent phase in a 175°C environment.
(2) Results of a 200°C-1000h high-temperature storage test and a -55°C/200°C thermal cycling test when using Sn-7Cu-3Bi or Sn-7Cu-10Sb solder showed that the amount of disappearing Ni metallization after high-temperature storage was less than 1 μm and that thermal cycling reliability was approximately four times that when using Sn-7Cu.
(3) The Sn-7Cu-3Bi and Sn-7Cu-10Sb solder compositions achieved lives approximately three times and six times longer than the life of Sn-7Cu in a Tjmax-175°C power cycling test.

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