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Effect of Cryogenic Storage on Reliability of the BGA Interconnect Solder Joint

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Abstract. The inhibitory effect of cryogenic factor on the migration rate of Cu atoms resulted in the formation of granular Cu_6Sn_5. The cryogenic temperature greatly reduced the active ability of atoms and vacancies leading to the even dispersion of lead atoms. The mismatch in the thermal expansion coefficient between the IMCs and the solder matrix promoted the propagation of tiny cracks. The thicker IMCs induced larger residual stresses and serious mismatch, resulting in the generation of microcracks and peeling.

1. Introduction

With the further exploration of the external space, the electronic components applied on spacecraft will experience more severe environment, such as ultra-low temperature and large temperature change conditions. Mechanical-stress, thermal-stress and radiation are the main factors that lead to failure of components in deep space environment [1]. For example, Mars has a minimum ambient temperature of -125℃ while Venus has an atmospheric temperature of over 500℃. The latter also needs to be able to withstand high pressure and corrosive gases. The working temperature required by the asteroid Nereus probe ranges from -180℃ to 100℃. The average temperature experienced by the Saturn ring probe is -183℃. The deep space probe working near Pluto has to work at a low temperature of -229℃ [2-4]. The difference in thermal expansion coefficient between the substrate and the solder in the packaged device will cause serious mechanical stress. At the same time, microcracks caused by temperature-dependent stress and IMC migration caused by thermal migration have gradually become the main causes of component failure [5]. The reliability of the micro-interconnect structure is significantly reduced by the shear and tensile stress failure caused by the long-term temperature varying [6]. Satellites and detectors serving in outer space will undergo a long period of low and high temperature storage. The failure mechanism of interconnect under high temperature storage conditions has been studied and reported by relevant scholars [7, 8]. However, the performance degradation and failure mechanism of the micro-interconnect structure in low cryogenic storage have not been investigated comprehensively at present.

In this paper, cryogenic storage experiments were carried out on micro-interconnect solder joints to investigate the microstructure evolution of the bumps and interfaces. The mechanism of the

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mechanical properties degradation of micro-interconnect solder joints was analyzed and characterized in detail.

2. Experiment

The cryogenic storage test of mixed solder joints with different Pb contents (0%, 4.67%, 22.46% and 37% was conducted under the temperature of －196°C. The period of storage was set to 10 days, 20 days, 30 days to investigate the microstructure evolution and mechanical degradation of the tin-based solder joints. The test samples were designed in a typical BGA package with bumps and pads of diameter in 550μm and 420μm respectively. Scanning electron microscopy (SEM) was applied to characterize the microstructure at the cross-section interfaces of the solder bumps after the cryogenic storage. Dynamic thermomechanical analysis was applied to analyze the degradation of mechanical properties of solder joints with different lead contents.

3. Results and Discussion

3.1. Precipitation of Cu_6Sn_5 Phase during Cryogenic Temperature Storage

Fig.1 shows the SEM morphology of the cross section of the SnPb (Pb: 22.46%) solder bumps after cryogenic storage at －196°C for different durations. As can be seen from the Fig.1(a), granular Cu_6Sn_5 (identified by energy spectrum analysis) IMCs began to sprout after 10 days cryogenic storage, and more granular Cu_6Sn_5 IMCs were characterized in the bumps with the extension of storage time shown in Fig.1(a), Fig.1 (b), Fig.1(c) and Fig.1(d). The formation of Cu_6Sn_5 IMCs should be related to the copper atoms diffusion migration from pads on both sides of the bumps into the matrix. The granular shape of IMCs may be due to the inhibitory effect of cryogenic factors on the migration rate of Cu atoms and the growth of IMCs. In addition, more Cu_6Sn_5 IMCs were prone to generated after cryogenic storage of 30 days. It can be attributed to the decrease in solid solubility of Cu atoms at cryogenic temperature. A small amount of copper atoms precipitated at low temperature and combined with Sn atoms in the matrix to form the granular Cu_6Sn_5 IMCs. In addition, compared with the mico-interconnect solder joints stressed at ambient and high temperature conditions, the microstructure evolution at cryogenic temperature was not performed obviously as shown in Fig.1. It indicates that the cryogenic temperature factor inhibited the atomic activity to a certain extent.

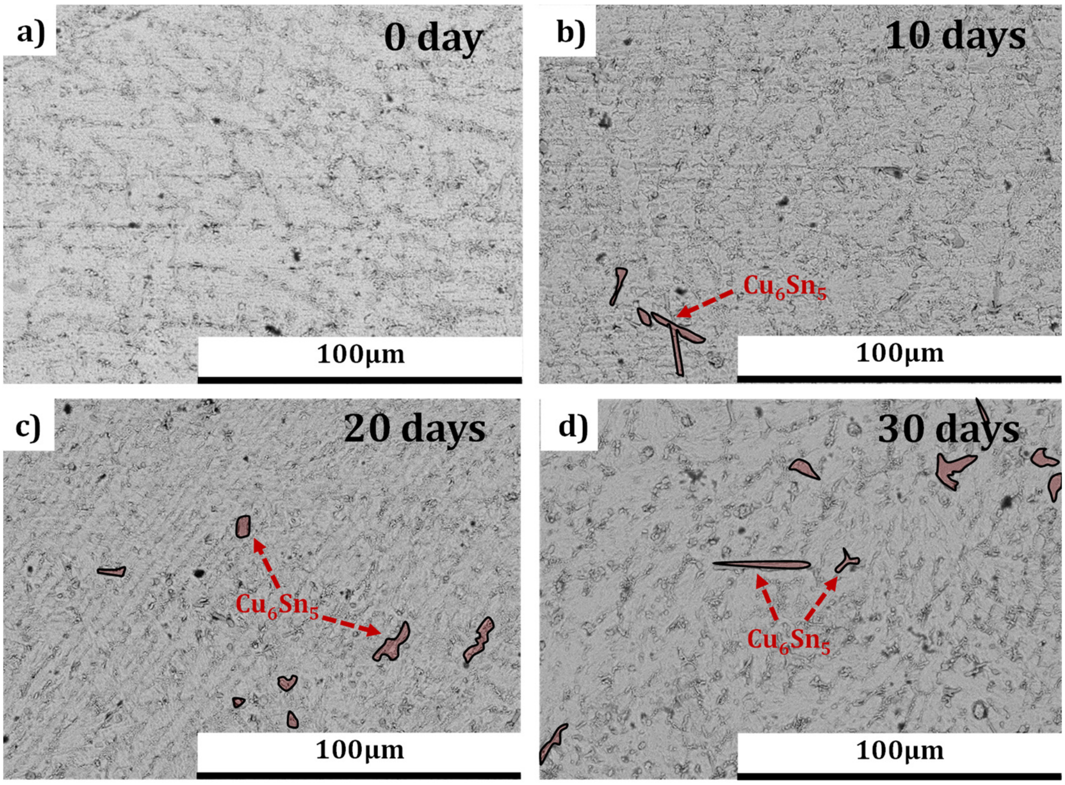

Fig.1 SEM morphology of SnPb (Pb: 22.46%) solder matrix after different durations of storage at －196 °C
(a) 0 day (b) 10 days (c) 20 days (d) 30 days

3.2. Dissolution of Lead-Rich Phase during Cryogenic Temperature Storage

Fig.2 shows the SEM morphology of the cross section of the SnPb (Pb: 37%) solder bumps after cryogenic storage for different durations at －196℃. Fig.2 (a) illustrates that Pb elements (identified by energy spectrum analysis) were abundantly enriched inside the bumps and distributed in a fishbone shape before cryogenic storage stressing. However, the lead-rich phase evenly dissolved and diffused with the extension of storage duration as shown from Fig.2 (b) to Fig.2 (d). After cryogenic storage of 30 days, only a small amount of lead-rich phase can be observed at the cross section of the bump in Fig.2 (d). The previous studies have reported that atoms and vacancies tended to reach equilibrium at the lowest energy state [9]. Lead atoms originally concentrated and distributed slowly diffused to reach the lowest energy state in the form of uniform distribution.

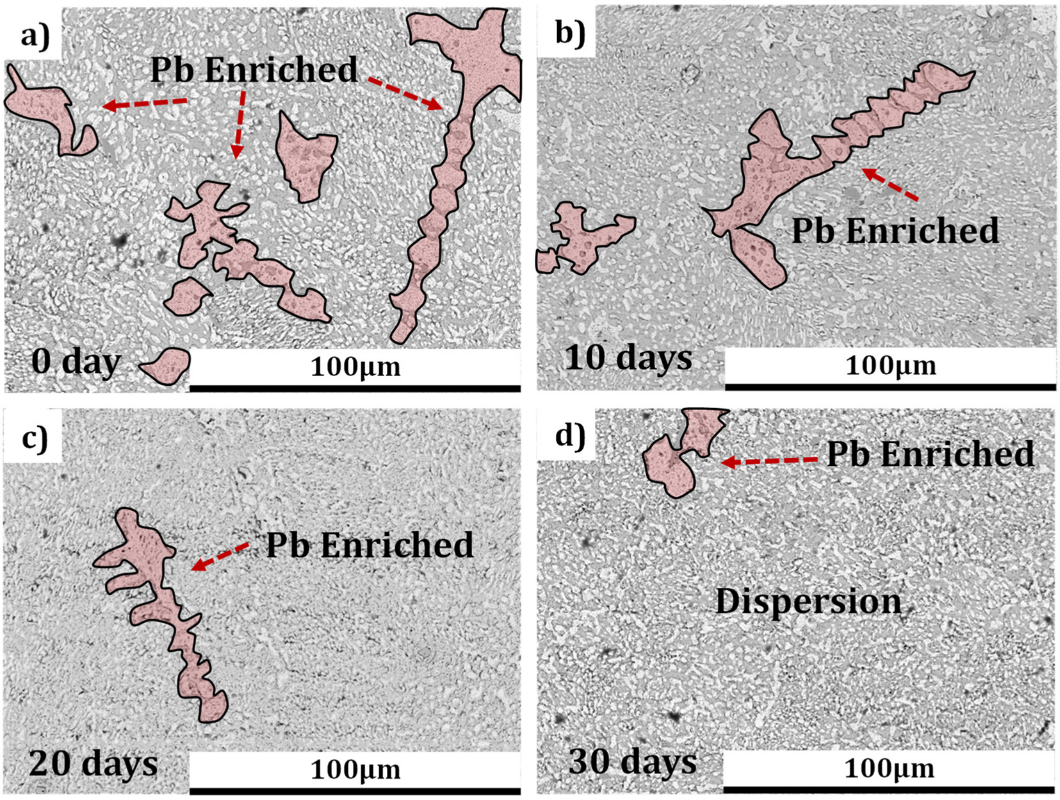

Fig.2 SEM morphology of SnPb (Pb: 37%) solder matrix after different durations of storage at −196℃
(a) 0 day (b) 10 days (c) 20 days (d) 30 days

3.3. Interface Evolution of Interconnect Solder Joints during Cryogenic Storage

Fig.3 shows the interface topography of the Sn3.0Ag0.5Cu solder joints after stored of 30 days at −196℃. The results compared the microscopic evolution of the interfaces between nickel-containing and nickel-free coatings at the temperature of −196℃. Fig.3 (a) shows that IMCs kept intact contact at the interface of nickel-containing coating. However, obvious microcrack and slight peeling occurred between IMC and Cu pad at the interfaces without nickel coating as shown in Fig.3 (b). The thickness comparison of IMC layers at the two interfaces was illustrated in Fig.3 (a) and Fig.3 (b). The thickness of IMC layer on the nickel-containing coating side was significantly thinner than that on the nickel-free coating side with about 3μm. $(Cu_xNi_{1-x})_6Sn_5$ IMCs were found in both solder bumps, however, the number of IMCs in Fig.3(b) was significantly higher than that in Fig.3(a). As a result, we can conclude that Ni coating acted as a barrier layer to prevent the Cu pad from reacting with the Sn-based solder. The mismatch in the thermal expansion coefficient between the IMC and the solder matrix promoted the propagation of tiny cracks [10]. The thicker IMCs induced larger residual stresses and serious mismatch, resulting in the generation of microcracks and peeling as shown in Fig.3 (b).

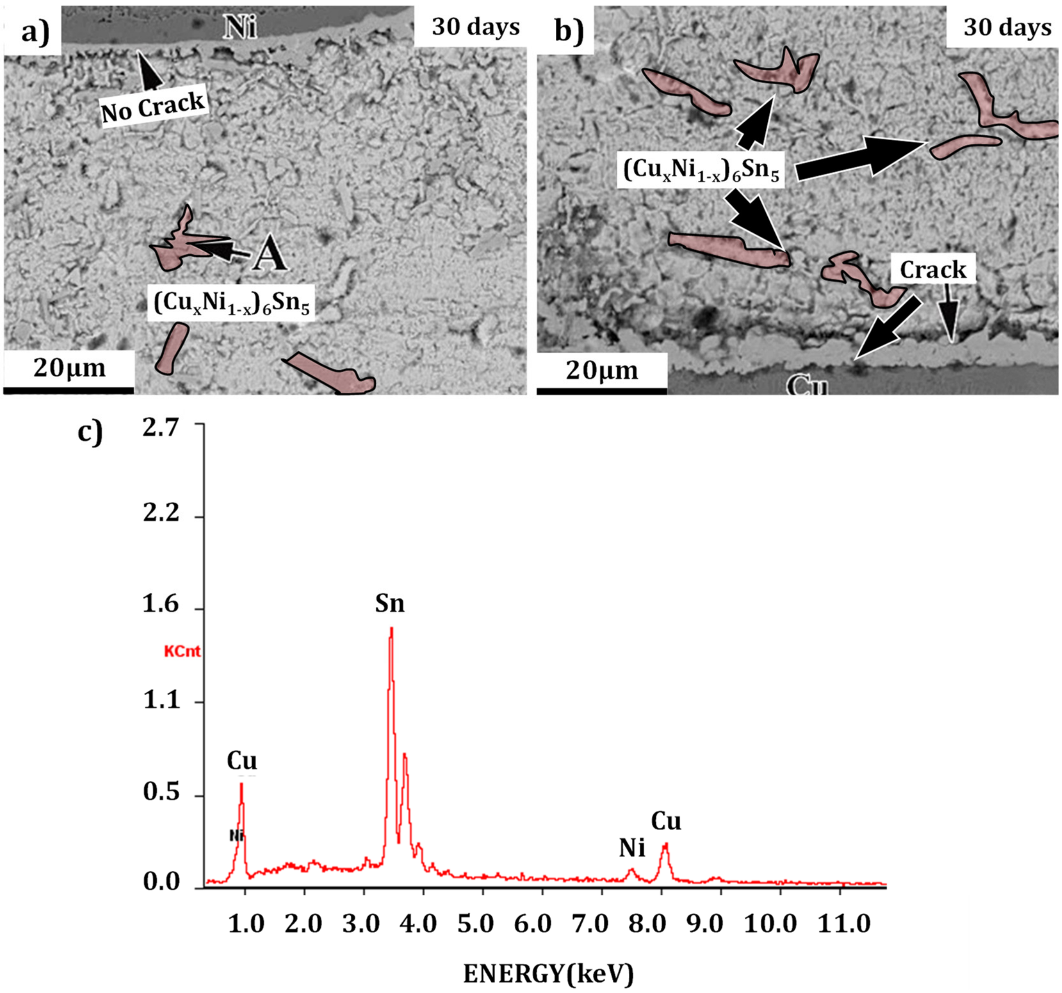

Fig.3 SEM topography of Sn3.0Ag0.5Cu interfaces of the solder joints after cryogenic storage at －196 °C for 30 days

3.4. Interface Evolution of Interconnect Solder Joints during Cryogenic Storage

To further explore the effect of cryogenic storage on the mechanical degradation of the micro-interconnect solder joints, shear tests were conducted on the solder joints with lead contents of 4.67%, 22.46%, 37% and Sn3.0Ag0.5Cu before and after storage of 20 days. Fig.4 (a) illustrates the variation of maximum shear strength of solder joints. The maximum shear strength of solder joints subjected to cryogenic storage performed lower than those had not been stored. The solder joints with different compositions (4.67%, 22.46%, 37% and Sn3.0Ag0.5Cu) all displayed the same mechanical properties. It has reported in the previous research that Sn-based solder would subject the phase transition when the temperature was lower than 13.2℃, and the β-Sn of the body-centered tetragonal lattice would transform to the α-Sn of the face-centered tetragonal lattice. This process of the ductile-brittle transition increased the volume by 27% [11]. The lattice transformation in the solid phase would lead to residual stress in the matrix. Furthermore, the higher modulus of elasticity of the interface $(Cu_xNi_{1-x})_6Sn_5$ IMC exhibited higher brittleness at low temperatures and weakened the shear resistance as well. In addition, another interesting phenomenon was found during the shear test. The maximum shear force increased first and then decreased with the increase of lead content and reached the maximum at the lead content of 22.46 % as shown in Fig.4(a).

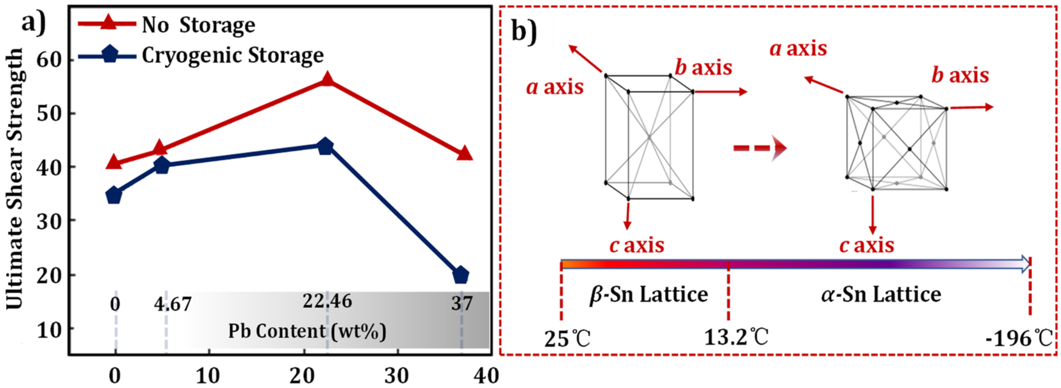

Fig.4 Variation of maximum shear strength of solder joints before and after 20 days of cryogenic storage

Considering the resistance mechanism of different dislocations, the flow stress at the interfaces can be expressed as:

$$\sigma = \sigma_p + \alpha \frac{Gb}{l} \tag{1}$$

Where σ_p is a Perine force, related to the nature of the material itself, α is a constant, usually between 0.2 and 0.5. The meaning of l varies according to different resistance mechanisms. It can be seen from equation (1) that the relationship between stress and temperature is mainly manifested by the influence of temperature on the shear modulus of the material. As the temperature decreases, the G of the material rises, resulting in an increase in the stress, resulting in an increase in the strength of the material. This theoretically explains the reason why the shear strength of solder joints increased with decreasing temperature.

4. Conclusions

1. Granular Cu_6Sn_5 IMC precipitated inside the SnPb (Pb: 22.46%) solder matrix at cryogenic storage of −196°C. It was due to the inhibitory effect of cryogenic temperature factors on the migration rate of Cu atoms and the growth of compounds, the shape of the formed Cu_6Sn_5 compound became granular. The decrease in solubility of the Cu_6Sn_5 IMCs at low temperature was another consideration.

2. Pb elements were abundantly enriched inside the bumps and distributed in a fishbone shape without cryogenic storage. The cryogenic factor greatly reduced the active ability of atoms and vacancies leading to the even distribution of lead atoms.

3. The thickness of IMC layer on the nickel-containing coating side was significantly thinner than that on the nickel-free coating side. The mismatch in the thermal expansion coefficient between the IMC and the solder matrix promoted the propagation of tiny cracks. The thicker IMCs induced larger residual stresses and serious mismatch, resulting in the generation of microcracks and peeling.

4. The maximum shear strength of solder joints subjected to cryogenic temperature storage performed lower than those had not been stored. The solder joints with different compositions all showed the same mechanical properties.

Acknowledgement

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