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Failure characters and damage mechanism of Sn3.0Ag0.5Cu/Cu solder joints under shear thermal cycling

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Abstract. The failure characters and damage mechanism of Sn3.0Ag0.5Cu/Cu as-reflowed solder joints under shear thermal cycling were investigated by special shape design for the experiment sample in this paper. The results indicate that fatigue damage mainly occurred within the solder far from the interconnection interface of edge solder joints. The microcracks initiated and propagated along the grain boundaries of β-Sn. The thermal damages of as-reflowed solder joints were attributed to the anisotropy of β-Sn in the coefficient of thermal expansion and the geometry constraint of substrates and interfacial intermetallics compounds layer.

Introduction

Solder joints which provide mechanical interconnections and conduct paths of currents have been widely applied in electronic packing field. Traditionally, Sn-Pb alloy has been used for a solder material in soldering procedure for many years. However, the Pb in electronic device waste can pollute the soil and underground water. Up to now, several types of lead-free solder alloys have been investigated [1-4]. Among the numerous lead-free solders, Sn-Ag-Cu solder alloys, which are regarded as the most promising candidate to replace the Sn-Pb solder [5]. Whereas the change in solder alloy components may lead to new properties of solder joints. Since a single destroyed solder joint may lead to the fatal damage of a whole device, the high reliabilities of solder joints are of utmost importance. Solder joints usually experience repeated thermal stress due to the coefficient of thermal expansion mismatch between solder and substrate, as a consequence of temperature excursions encountered during service. Thermal fatigue is a major source of failure of solder joints. Both thermal fatigue behaviors and its damage mechanism are critically important in high reliabilities of solder joints. The resistance to thermal fatigue of solder joints depends on the microstructure and temperature conditions. The microstructures of solder joint mainly conclude β-Sn, compounds in solder, substrate and interfacial intermetallics compounds layer that primarily is composed of Cu_6Sn_5. Many investigations on thermal fatigue adopted a high upper temperature, for example, 150°C during a temperature cycling, which could induce an obvious microstructure evolution especially the thickness of interfacial intermetallics compounds (IMC) layer, leading the response properties of microstructure to periodic thermal stress not being exhibited completely. In this study, the failure characters of Sn3.0Ag0.5Cu/Cu as-reflowed solder joints under the temperature cycling between -20°C and 70°C were investigated and the damage mechanism was discussed.

Experiments

A cold-drawn polycrystalline Cu and Sn3.0Ag0.5Cu solder paste were chosen as substrate and solder respectively. Firstly, the polycrystalline Cu were cut into the designed shape illustrated in Fig.1 by electricity spark cutting machine. The Cu substrates were ground with 800#, 1200#, 2000# SiC sandpaper and polished carefully with 2.5μm, 1.0μm and 0.5μm diamond polishing pastes, respectively. Secondly, Sn3.0Ag0.5Cu solder paste was spread on the surface of polished Cu substrates to form Cu/solder/Cu sandwich structure, and then was put into an oven with a constant temperature of 240 ^{o}C for 2 minutes and was cooled in air to room temperature. Then the samples were ground and polished again for the observation of microstructure. The sectional area of solder

joint is 2mm×2mm. The height of solder h is 470μm. Total length of sample L is 16 mm. Finally, the sample was put in to the BE-TH-80M8 programmable temperature cycling oven for accelerated temperature cycling test. The temperature changed from -20 ºC to 70 ºC. The increase rate of temperature and decrease rate are 5.5 ºC /min and 1.5 ºC /min, respectively. Each dwell time at ultra temperature is 30 minutes. The microstructure and surface microcracks of joints were observed by LEO supra 35 scanning electron microscopy (SEM).

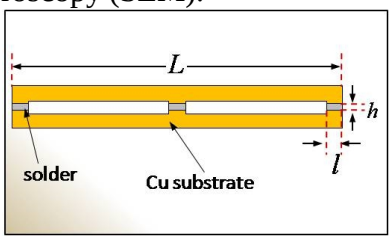

Fig. 1 Design of Sn3.0Ag0.5Cu/Cu solder joint.

Results and discussions

Fig.2 (a) and (b) are SEM images of Sn3.0Ag0.5Cu/Cu solder joints before thermal cycling experiment corresponding to the microstructures near the interface and far from the interface respectively. An intermetallic compound layer formed at the interface between Cu substrate and solder in soldering process. The intermetallic compounds layer is mainly composed of Cu_6Sn_5 compounds [6,7]. Sn-Ag-Cu solder alloys consist of β-Sn dendrites, Sn-Ag_3Sn or Sn-Cu_6Sn_5 binary eutectic structure and Sn-Ag_3Sn-Cu_6Sn_5 ternary eutectic structure. The β-Sn provides good ductility for solder and the Ag_3Sn compounds are crucial to reinforce the solder strength.

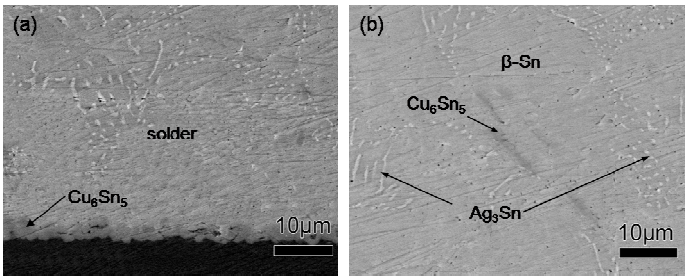

Fig. 2 Scanning electron microscopy images of Sn3.0Ag0.5Cu/Cu solder joint after reflow: (a) at interface; (b) the solder far from the interface.

Fig.3 shows the surface morphologies of edge solder joint after 300 cycles under the thermal cycling loading. Fig.3 (a) and Fig.3 (b) are the deformation morphologies near interface and far from the interface of edge joint. Some wave deformation bands appeared in the solder near the interface. Even some solder close to the solder/Cu_6Sn_5 interface was extruded. It was noted that some microcracks have initiated in β-Sn in Fig.3 (b).

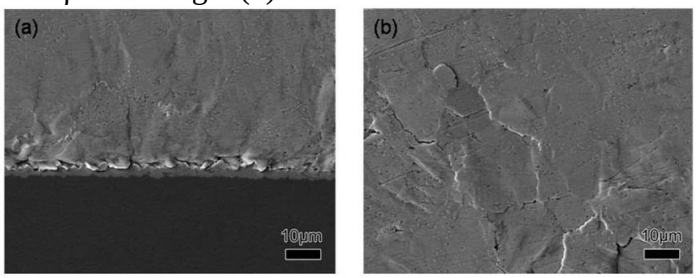

Fig. 3 (a) Interfacial deformation morphologies of edge solder joint after 300 cycles; (b) Microcracks in solder of edge joint after 300 cycles.

As the increase of thermal cycling, the damages of solder joints became more severe. The thermal damages of edge joint after enduring 500 cycles of thermal cycling were shown in Fig. 4 (a) and (b). It is seen in Fig.4 (a) that a long microcrack along the diagonal direction appeared in the edge solder joint. Some fracture stages were observed on β-Sn surface, suggesting that the microcracks initiated in

300 thermal cycling cycles become deeper and propagate inside solder. Fig.4 (b) is the deformation morphology in the region where no obvious deformation was observed in prior 300 circles of thermal cycling. Now a large number of deformation bands were found in this region after 500 cycles of thermal cycling, indicating severe plastic deformations have occurred in β-Sn.

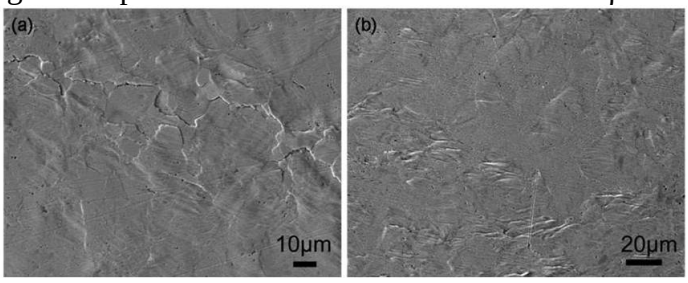

Fig. 4 (a) Distribution of microcracks of edge joint after 500 cycles; (b) Deformation morphologies of solder far from interface after 500 cycles.

The thermal fatigue of solder joint was controlled by stress and the strain produced at temperature increasing and decreasing stages due to the mismatch of thermal expansion coefficient between solder and substrates. Stress relaxation would occur during temperature remaining periods of temperature cycling process. The stress in bulk materials usually released in a short time. However, in terms of solder joint with small size, the stress could not release completely in the geometry constrained regions. Residual stress and strain were produced in each thermal cycling. With the increase of thermal cycling the stress accumulated continuously. As a consequence, severe plastic deformation bands formed in the solder near the interface. Therefore, the thermal fatigue damages of solder near the interface were mainly attributed to the geometry constraint.

The thermal stress in the solder far from interface should release faster than that in the solder near interface. However, the microcracks initially appeared in the solder far from interface, which should be relative closely to the anisotropy of β-Sn in thermal expansion coefficient. Each β-Sn grain can be considered as a single crystal which exists in a body centred tetragonal structure with lattice constants a=b=0.5831nm and c=0.3182nm. The thermal expansion coefficient of c axis was approximately twice as much as that of a or b axis [8,9]. As a result, thermal stress occurred at the boundaries of Sn grains with different orientation at temperature increase and decrease periods. The thermal stress can be divided normal component force which is vertical to the grain boundary and tangential component forces which is along grain boundary. The microcracks initiated at grain boundaries when the normal stress accumulated to a critical value. Analogously, the accumulation of tangential stress would induce the boundary sliding forming some deformation stages at the Sn grain boundaries. Actually, the boundary sliding was easy to be induced because of the high homologous temperature of solder. Since the melting point of Sn3.0Ag0.5Cu solder is 217°C, the homologous temperature even reached 0.7 at 70°C. The grain boundary sliding played an important role in deformation mechanism to decrease strain energy.

The thermal fatigue fracture of as-reflowed solder joints occurred in solder, not at the interface between Cu_6Sn_5 IMC layer and solder, which is attributed to the intense geometry constraint and the optimized orientation of β-Sn at interface. Residual stress did not release completely due to the constraint of large size substrates. Residual stress in solder accumulated continuously leading severe plastic deformation and fatigue fracture. On the other hand, the thermal expansion coefficients of a, b axes of β-Sn grain are very close to that of Cu_6Sn_5 and Cu substrate. There are indications suggesting that grains in contact with the interface layer may try to match the coefficient of thermal expansion of the intermetallics compounds [10]. For this reason a, b axes of β-Sn grains tend to contact with Cu_6Sn_5 compounds. Because the difference of thermal expansion coefficients between Cu_6Sn_5 and a, b axes of β-Sn grain is very small, no cracks occurred at the solder /Cu_6Sn_5 interface in the thermal cycling.

Conclusions

The failure characters and damage mechanism of Sn3.0Ag0.5Cu/Cu as-reflowed joints were investigated under thermal cycling between -20°C and 70°C. Microcracks mainly initiated and propagated within the solder far from the interfacial IMC layer of edge joint. The thermal fatigue damages of as-reflowed joints were attributed to the anisotropy of β-Sn in thermal expansion coefficient and geometry constraint of substrates and IMC layer. At the stages of temperature increase and decrease, thermal stress appeared near the grain boundaries of β-Sn due to the thermal expansion anisotropy of a, b and c axes. Although these stress would relax at the temperature dwell time, the stress did not completely be released due to the geometry constraint. As the cycle number of thermal cycling increasing the stress and strain accumulated continuously, leading the formation of microcracks in solder joint.

Acknowledgements

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