Microstructure Study of Mix Assembly Lead-free Sn-Ag-Cu Ball Grid Array and Sn-10Cu Solder Paste

Rita Mohd Said¹, Kalaiarasi A/P Sulwarajan¹2, Nurul Razlina Abdul Razak³, Flora Somidin¹, Nur Syahirah Muhammad Zaimi¹

¹Center of Excellence Geopolymer & Green Technology (CeGeoTech), Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Taman Muhibbah, 02600 Jejawi, Perlis, Malaysia
²Faculty of Chemical Engineering Technology, Universiti Malaysia Perlis (UniMAP), Taman Muhibbah, 02600 Jejawi, Perlis, Malaysia
³Nihon Superior Centre for The Manufacture of Electronic Materials (NS CMEM), School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, QLD 4072, Australia.

Abstract. In recent years, electronic technologies have been striving to minimize the use of lead in their manufacturing and production. As a result, the electronic packaging industry is slowly transitioning from lead solder to lead-free solder. Though environmentally lead-free solders are advantageous, there still needs some work in meeting current technological demand and requirements. In this study, the microstructure analysis on lead-free Sn-Ag-Cu Ball Grid Array (BGA) and Sn10Cu solder paste was done. The main aim of this study is to investigate the effect of isothermal aging on the microstructure of the solder paste joint and evaluate the intermetallic compound (IMC) thickness on the solder joint reliability. Optical Microscope (OM) and ImageJ software have been utilized to study the bulk solder microstructure. The results show that the bulk microstructure consists of β-Sn and CuSn5 / β-Sn eutectic phases. The IMC layer has undergone rapid growth with increasing aging temperature and time. The two main IMC layers (CuSn and CuSn3) grew thicker due to high temperature. The growth kinetic of Sn10Cu resulted in 16.70 kJ/mol activation level. Therefore, the significance of the findings from this study might provide a potential answer for future development for highly reliable solder joint applications.

1 Introduction

In the microelectronic packaging process, the soldering process plays a vital role as a metallurgical joining method which is done by utilizing filler metals and solders that require a melting point below 425 °C. The soldering technique is vastly used in silicon die as an assembly and one of interconnection methods. Solder joint reliability is very much dependent on the solder material as it offers electrical, mechanical, and thermal continuity in electronic assembly [1]. In a modern electric circuit, companies have switched from using the tin-lead (Sn-Pb) to Pb-free Sn-Ag-Cu (SAC) BGA due to component availability issues faced. As companies are stepping up to become lead-free, many leading corporates are experimenting with the formation of mixed assembly lead-free BGA and lead-free solder paste [2]. One of the main reasons for this drastic change in the electronic industry is due to the recent trends of worldwide environmental legislation for toxic materials and the constant demand from consumers for “green” and environmental-friendly products. Researchers are also constantly coming up with promising Pb-free solders such as Sn-0.7Cu, Sn-3.5Ag, Sn-3.8Ag-0.7Cu, and Sn-3.5Ag-4.8Bi (in wt.% and slight variations in composition) [3].

The microstructure formation is known to have a significant impact on the properties of solder joints. Microstructural formation and the intermetallic layer influence the solder joint reliability in the long run as it contributes to the significant properties. Generally, soldering is essential in electronic packaging as it ensures the formation of the permanent joint. Among the various types of the soldering process, reflow soldering is one of them [4]. In the electronic industry, reflow soldering is a common approach to form solder interconnects. Understanding the effect of isothermal aging on solder joint formation, growth and reliability is a key factor in the fundamentals of soldering [5].

This paper will focus on the effect of isothermal aging on the microstructural formation of mix assembly Sn-Ag-Cu BGA and Sn10Cu solder paste. The development and growth of the interfacial intermetallic layer heavily contributes to
the reliability of the solder joint. Therefore, the aim here is to investigate the growth of IMC layer due to the differential aging conditions and how it affects the solder joint reliability.

## 2 Experimental Procedure

In this research study, the matrix materials were comprised of two different materials. The materials are Sn-Ag-Cu/SAC and Sn-0.7Cu solder powder. To place the punched solder sheets, solder paste flux type XF-07-03 were also utilized. The Sn-0.7Cu solder paste was mixed with 9.3 wt. % copper powder to fabricate Sn-10Cu (SC10) solder paste. To ensure the homogeneity of the reinforcement particles in the SC10 paste, the process of mixing was executed using a solder paste mixer with a duration of about 30 minutes. The Sn10Cu solder paste was fabricated by adding copper (Cu) powder with an average particle size > 45μm into the SC solder paste.

For the solder joint, the solder balls were subjected to a soldering process on a 600 μm ball pitch size of Cu substrate printed circuit board (PCB) with organic soldering preservative (OSP) surface finish with the aid of flux in a small amount. The solder joint is then subjected to isothermal aging at 75 °C, 125 °C and 150 °C for 24, 72 and 168 hours. The subjected samples were then placed in a 4.5 cm diameter mould and embedded in epoxy resin and hardener. Further preparations such as grinding, and polishing were done to the finished samples.

For observation of IMC morphology formed at the interface of the solder joint, the cross-sections of the soldered samples were polished and observed under an Optical Microscope (Motic Digital Microscope). At least 5 images were taken to analyse the IMC thickness. The fraction of area Sn and Cu-Sn IMC at bulk solder area and interfacial IMC thickness were measured using the ImageJ software.

## 3 Results and Discussion

### 3.1 Bulk Microstructure Evolution

Fig. 1 shows the optical microscope (OM) images for the bulk microstructure of as-reflowed mixed assembly solder joint and solder joints that subjected to different isothermal aging temperature for 24 hours. The microstructure of the mixed assembly solder joint is generally composed of β-Sn and Cu₆Sn₅ / β-Sn eutectic phase. The bulk microstructure of the as-reflowed solder joint undergoes coarsening of the Cu₆Sn₅ phase when subjected to different temperature of isothermal aging. Based on the observation, at 150 °C the β-Sn phase undergoes reduction. With the increase of aging temperature, the Cu₃Sn phase disintegrates which allows the Cu₆Sn₅ phase to rapidly grow. This observation is heavily associated with the Ostwald ripening theory.

![Fig. 1. Bulk microstructure evolution of mix assembly solder joint (a) as reflowed and isothermally aged at (b) 75, (c) 125 and (d) 150 °C at 24 h.](image)

### 3.2 Interfacial IMC Layer

In this study, compared to the as-reflowed solder joint, the solder joints subjected to isothermal aging had significant growth in their IMC. Based on the observation, at low temperature (75 °C), there is no visible growth in the Cu₃Sn phase. However, as the aging temperature increased, the two main IMC layers (Cu₃Sn and Cu₆Sn₅) grew thicker. The elevated thickness of IMC layer during isothermal aging can be contributed by solid state-state diffusion between the Cu and Sn atoms [6]. Based on the observation, at low temperature (75 °C), the IMC morphology is mostly scallop type compared to the IMC morphology at high temperature (125 – 150 °C). Though there might be changes in lattice structure for Cu₃Sn, but morphologically it remains as planar type with escalating aging temperature and time. The
evolution of interfacial intermetallic compounds (IMC) of the reflowed mixed assembly solder joints that underwent isothermal aging are presented in Fig. 2 for 168 h.

![Fig. 2. Intermetallic formation of mixed assembly solder joint (a) as reflowed and isothermally aged at (b) 75, (c) 125 and (d) 150 °C for 168 h.](image)

### 3.3 Growth Kinetic

The average intermetallic layer thickness against the aging time is presented in Fig. 3. The graph displays a linear pattern between the relationship of the aging temperature and interfacial IMC thickness which shows bulk diffusion as its primary mechanism during IMC growth. The comparison of the IMC thickness indicates that higher aging temperature will contribute to a higher IMC growth which increases its thickness.

![Fig. 3. Graph of intermetallic compound thickness against aging time for SAC/SC10.](image)

Fig. 4 shows the Arrhenius plot of ln k against the 1/T for the solid-state IMC growth kinetics for SC10 solder joint. For a better comparison, the activation energy of Sn-0.7Cu is analysed based on a previous literature studied by Mohd Said et al., [7] Based on the result, the activation energy calculated was 16.70 kJ/mol. Meanwhile, the activation energy of Sn-0.7Cu (SC) solder joint calculated was 16.24 kJ/mol [7]. In comparison to SC solder joint, SC10 solder joint has a slightly lower activation energy. The higher activation energy indicates that IMC present is larger than in the SC solder joint. The large CuSn IMC present will restrict the interfacial IMC growth when subjected to prolonged aging conditions. Therefore, SC10 has shown better thermodynamic stability due to its higher activation energy.
Conclusions

The conclusions made from the findings are briefly outline:

i. The microstructures of the mixed assembly solder joints are generally comprised of β-Sn and Cu₆Sn₅ / β-Sn eutectic composition. With an increasing aging temperature, the Cu₆Sn₅ phase disintegrates which allows the Cu₆Sn₅ to grow rapidly.

ii. The solder joints subjected to isothermal aging had significant growth in their IMC thickness. As the temperature increased, two main IMC layer (Cu₃Sn and Cu₆Sn₅) grew thicker.

iii. The growth rate of the solder connections increased with elevated temperature. Overall, the SAC/SC10 solder joint possessed higher activation energy (16.70 kJ/mol) compared to the Sn-0.7Cu (SC) solder joint which had activation energy of 16.24 kJ/mol.

The authors wish to express their sincere gratitude to the Ministry of Higher Education Malaysia and University Malaysia Perlis for their financial support (Research Materials Fund (RESMATE) 9001-00628) throughout the research project.

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