Formation behaviour of reaction layer in Sn-3.0Ag-0.5Cu solder joint with addition of porous Cu interlayer

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Abstract. The morphology and growth of interfacial intermetallic compound (IMC) between Sn-3.0Ag-0.5Cu solder alloy and Cu substrate metal of solder joint is reported. The IMC morphology and IMC thickness layer were observed at three different porosities of porous Cu interlayer. The results revealed that during soldering process, Cu$_6$Sn$_5$ compound with scallop like morphology was formed at the interface of both the solder alloy and Cu substrate and at solder alloy and porous Cu interlayer. By adding porous Cu interlayer at the solder joint, the IMC thickness increased with increasing soldering temperature and the number of pores in porous Cu interlayer. The effect of porosity on increasing the IMC layer was also due to the slower cooling rate during solidification of molten solder.

1. Introduction

It is reported that Sn-Pb eutectic solder has been widely used for a long period of time [1]. However, due to the environmental and health concerns over the toxicity of lead, research activities to find suitable lead-free solders has intensified [2]. Various investigations have been made with regard to characterization of lead-free solder including solder joint microstructure and its interfacial reaction [3,4]. For instance, the interfacial reactions between Sn-Ag alloys and Cu substrate have been investigated in some details in order to obtain an understanding of the reactions at the micro level [5]. It has been acknowledged that in Sn-based joint soldered with Cu substrate, the solder will bind
through the formation of a Cu-Sn intermetallic compound (IMC) layer. The IMC layer basically consists of Cu$_6$Sn$_5$ which will also be altered significantly by increasing the cooling time of the molten solder [6,7]. The rate at which a solder joint solidifies depends on how fast the molten solder solidifies. The solidification of molten solder will subsequently affect the growth of IMC layer.

Recent developments in automotive electronic industries demand electronic components that can withstand high temperature. Therefore researchers have been searching for potential lead-free solder for use in the assembly of heat tolerance electronic components. There are also studies which showed that cellular structure like metal foam or porous metal can be applied as the heat transfer medium in semiconductor application where in actual practice, high thermal resistance of the system is very crucial [8].

Thus, in the present studies, the porous metal which is known for its high thermal conductivity was used as the heat dissipation agent in the solder joint. The main purpose of this research is to investigate the formation behavior of reaction layer especially on their microstructure features in Sn-3.0Ag-0.5Cu solder joint with addition of porous Cu interlayer.

2. Experimental procedures

Sn-3.0Ag-0.5Cu (wt%) of lead free solder paste with the constant amount of 0.1g was used to join two Cu rods (99.99%) with diameter and length of 8 mm and 30 mm respectively as illustrated in Figure 1. The porous Cu interlayer was inserted in the middle of joining part as shown in the figure. Three different porosities namely at 15 ppi – pores per inch (P15), 25 ppi (P25) and 35 ppi (P35) were used where the pore size was smaller at higher ppi. Prior to be inserted in the middle of joining part, the porous Cu interlayer was rolled to obtain a uniform thickness of 0.1 mm. Figure 2 shows the microstructure of the porous Cu interlayer after rolling process. The soldering process was conducted in the furnace with an Argon gas flow. The holding temperature was controlled at 267ºC and 287ºC with a holding time of 60 s. Solder joint without adding porous Cu interlayer was also prepared as the control sample. The in-situ temperature measurement was conducted during the soldering process by positioning the end of thermocouple at the spot where the porous Cu interlayer was located or directly at the solder layer for the control. After the sample was soldered, it was cut perpendicular to the joint and the cut surface was polished to observe the interface of joining part. Scanning electron micrograph (SEM) was used to observe the IMC thickness at the interfaces between the solder and Cu rod as well as between solder and porous Cu. Energy dispersive X-ray spectroscopy (EDS) was utilized to determine the elemental composition of IMC layer.

![Figure 1. Configuration of solder joint.](image)
3. Results and Discussion

3.1. Cross-sectional morphology

Micrographs from typical cross-sections of the sample soldered with or without porous Cu interlayer are shown in Figure 3. It is observed that the thickness of soldered sample without porous Cu interlayer (Figure 3a) is thicker compared to the soldered sample with porous Cu interlayer (Figures 3b, c and d); a constant amount of solder alloy being used in both conditions. A thinner solder layer was further observed at the soldered sample with P15 of porous Cu interlayer when compared to those of the soldered sample with P25 and P35 of porous Cu interlayer. The bigger pores at P15 of porous Cu interlayer caused the molten solder alloy to penetrate easily inside the interlayer. In contrast the solder layer for soldered sample with P25 and P35 were thicker. This is because the molten solder was unable to penetrate into small pores. It was observed that the solder layer with P25 and P35 porous Cu interlayer have almost similar thickness of approximately 80 µm.

Figure 2. SEM image of porous Cu interlayer with porosity of (a) P15, (b) P25 and (c) P35 after rolled.

Figure 3. Cross-section of solder joint of Sn-3.0Ag-0.5Cu solder alloy and Cu rod at 287ºC, 60 s. (a) no porous (b) P15, (c) P25 (d) P35.
3.2. Formation of IMC layer

Figure 4 shows IMC layer for solder joint without porous Cu added and soldered at temperature and time of 287°C and 60 s respectively. Elemental analysis of the IMC layer at Table 1 showed the main element that exists is Cu₆Sn₅. It was observed the IMC layer for solder joint without porous Cu appeared as rough and scallop-like structures. Similar result was obtained for the soldered sample at the same soldering time of 60 s and a lower temperature of 267 °C except that the IMC/ solder layer appeared slightly thinner.

**Figure 4.** IMC morphology for Sn-3.0Ag-0.5Cu solder and Cu rod without porous Cu interlayer.

**Figure 5.** Observation of IMC layer at interface of the solder joint soldered with P15 of porous Cu interlayer (a) solder alloy – rod Cu, (b) solder alloy – porous Cu.

It is observed that the IMC layer between Cu rod and the solder alloy also appeared rough with scallop-like undulating shape (Figure 5a). EDS analysis confirmed (Table 2) that the elemental composition of the IMC layer is Cu₆Sn₅. The IMC layer which consists of Cu₆Sn₅ is also formed at the interface between porous Cu and solder alloy as shown in Figure 5b. It can be speculated that during the soldering process the porous interlayer have reacted with solder alloy at atomic level which also influence the IMC growth at the porous Cu interface. Similar results are obtained for the solder joint with P15 porous Cu interlayer when soldered at 267°C and soldering time of 60 s.

**Table 1.** Elemental analysis of the IMC layer.

| Element | Atomic (%) |
|---------|------------|
| Cu      | 52.21      |
| (Ag)    | (0.73)     |
| Sn      | 47.06      |

**Table 2.** Elemental analysis of the IMC layer for sample joined with P15 of porous.

| Element                          | Atomic (%)     |
|---------------------------------|----------------|
| solder alloy – Cu rod           | 57.29          | 51.42     |
| solder alloy – porous Cu        | (0.36)         | (0.35)    |
| Sn                               | 42.35          | 48.23     |
Figure 6 shows the IMC layer for the solder joint with P25 of porous Cu interlayer soldered at 
温度 and time of 287°C and 60 s respectively. In this instance, the solder layer is thicker than 
that of solder joint with P15 of porous Cu interlayer. The scallop-like grains at IMC layer is similarly 
observed at the interface of the Cu rod with solder alloy (Figure 6a) as well as between the porous Cu 
interlayer with solder alloy (Figure 6b). The EDS also confirmed the IMC layer consists of Cu₆Sn₅ on 
both sides of the IMC layer. Similar results are obtained for the solder joint with P25 porous Cu 
interlayer when soldered at 267°C and soldering time of 60 s except that the solder layer appeared 
slightly thinner.

![Figure 6. Observation of IMC layer at interface of the solder joint soldered with P25 of porous Cu interlayer (a) solder alloy – Cu rod, (b) solder alloy – porous Cu](image)

**Table 3.** Elemental analysis of the IMC layer for sample joined with P25 of porous.

| Element | Atomic (%) | solder alloy – Cu rod | solder alloy – porous Cu |
|---------|------------|-----------------------|-------------------------|
| Cu      |            | 59.68                 | 52.09                   |
| (Ag)    |            | (0.53)                | (0.41)                  |
| Sn      |            | 39.79                 | 47.5                    |

Effect of pore size interlayer on the IMC thickness is shown in Figure 7. It was found that the 
IMC thickness increased with increasing pore size of porous Cu interlayer. This shows that the molten 
solder is getting more difficult to penetrate the porous Cu with increasing pore size and finally 
solidified at the point between porous Cu and solder alloy.

It has also been reported that the cooling rate had a significant effect on the thickness of the IMC 
layer [6,9]. In the present study, the cooling rate for various solder joints is as shown in Figure 8. 
Since all the porous Cu has nearly similar weight, it can be deduced that the pore sizes have influence 
on the cooling rate. It appears that the smaller pore sizes of porous Cu interlayer (P25 and P35) results 
in longer cooling time for solidification of molten solder than that observed for P15. This slower 
cooling rates had allowed more time for Cu₆Sn₅ to grow and develop at the interface layer of molten 
solder. This results in thicker IMC layer for P25 and P35 as compared to P15. In contrast, the cooling 
time for the solder joint without porous Cu was shorter. As a result a thinner IMC layer was formed 
compared with solder joint joined with porous Cu interlayer.

The difference in the cooling rate can also be explained by differences in thermal conductivity provided by the porous Cu interlayer inside the solder joint. Thermal conduction through the Cu metal 
during cooling process will dissipate heat into molten solder that flow through them. This will 
eventually have a bearing on the solidification of solder alloy which ultimately affect the growth 
of IMC layer in the solder joint.
4. Conclusions
The effect of adding porous Cu interlayer to Sn-3.0Ag-0.5Cu solder alloy on IMC growth and morphology have been studied. The IMC layer which consists of Cu₆Sn₅ compound was observed at the interface between Cu substrate and Sn-3.0Ag-0.5Cu solder, and also between porous Cu layer and the solder alloy. It was found that increase in soldering temperature and the number of pores inside porous Cu interlayer resulted in increasing thickness of the IMC layer. Results further showed that cooling rate after soldering process have significant effect on the IMC thickness. It was also observed that the cooling time for the sample soldered with the porous Cu interlayer was longer compared to that for the solder joint without the porous interlayer. The cooling rate decreased with increase in number of pores of the porous Cu interlayer.

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