Transient liquid phase bonding for solder-a short review

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Abstract. The issues on the replacement of high Pb solder for high power module application has been a major concern among researchers since Pb could caused toxicity to the environment. Alternatively, transient liquid phase (TLP) has becomes a potential bonding technology for high power module devices. Typical TLP bonding for solder is a bonding method that using an interlayer of low and high temperature metal. However, a new transient liquid phase bonding which dealing with solder in the form of powder and paste has been developed. Both bonding methods have successfully increased the melting temperature of the bonded alloys higher than the bonding temperature as will be discussed further.

1 Introduction

A challenge for the packaging of the power devices in electronics manufacturing is to find the suitable robust die attach materials. Robust die attach materials is the materials that capable of surviving extreme environment such as high temperature and high pressure. In recent years, the demand for high power electronics module, which requires highly reliable and stable functionality, has been rapidly increasing in particular for applications such as automotive, aerospace, deep-well drilling and energy production industries [1]. Previously, high melting points materials that can withstand high operation temperature (>300 °C) are Pb10Sn and Pb5Sn solder. However, the usage of Pb is banned for their toxicity and it has become a challenge for researcher and also manufacturer to find the suitable replacement for Pb-free robust die attach materials. Till now, the successful of finding the high Pb solder replacement is still limited [2]. Nevertheless, the replacement candidates that have gain researcher’s attention are Au-Sn, Au-Ge, Zn-Al and Bi based solder alloys [2,3]. However, there are limitations for these solders. Table 1 summarize the strength and weaknesses of the solders.

Melting behaviour and soldering temperature are the critical issues that should be considered in designing the replacement for High Pb solders. A high melting temperature solder alloy would leads to a higher soldering temperature. Higher soldering temperature/parameter could be detrimental to the polymer that being used as die electric materials in the substrate [4]. The melting temperature should be 400 °C and above since

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the operation temperature for high temperature application is more than 300 °C. [5]. Thus, it will leads to the high processing temperature as well as a higher cost to the solder’s manufacturer. Not just that, the high temperature during reflow / soldering process can lead to high thermal stresses on the whole electronic circuit, accelerating a range of failure mechanisms to the components and reducing circuit lifetime [2].

Table 1: Strength and weakness of High-Pb solder replacement [2].

| Solder      | Strength                          | weakness                              | Cost     |
|-------------|-----------------------------------|---------------------------------------|----------|
| Zn-Al based | does not form IMCs                | high corrosion                        | cheap    |
| Bi based    | Good solidification criteria and hardness properties | Poor thermal & electrical conductivity | cheap    |
| Au-Sn based | Narrow solidification range       | Formation of brittle phase ζ Au5Sn   | very expensive |
| Au-Ge based | does not form IMCs, and good thermal conductivity | Too high in hardness and must be alloyed with other elements | very expensive |

Therefore a soldering method that could use the existence soldering temperature yet could withstand a high operational temperature has been established [6,7,1]. The method is known as transient liquid phase (TLP) bonding. Transient liquid phase (TLP) bonding or commonly termed as Solid Liquid Inter diffusion (SLID) process is a method that enable a solder joint to be processes at a lower temperature while still resulting in the formation of a joint with a higher re-melting point [3]. This bonding method involved completely consumption of low-melting-point metal and formation of high-melting-point intermetallic [8].

The TLP bonding offers various processing advantages over conventional soldering process including rapid densification, lower soldering or bonding temperatures, reduce microstructural coarsening, void free interface and reduce cost by avoiding the use of expensive pre-alloyed powders [9,10,11].

2 Methodology

2.1 TLP bonding process for solid solder alloys

In the TLP bonding process, typically, a full intermetallic compounds (IMCs) joint can be obtained at low temperature through the diffusion reaction between high-melting metal substrate such as Cu and Ag and low-melting interlayer such as Sn [1,9]. During heating at above the liquidus temperature of Sn, low melting layer (Sn) diffuses into the high-melting metal substrate and form an intermetallic phases [9,10] as illustrated in Fig 1. The heating temperature is just around 280 °C if low melting point metals such as Sn, Bi, In and etc are chosen as the interlayer [2]. The sandwiched layers were then being hold at the bonding temperature until the liquid phase has solidified due to diffusion process and another type of peritectic IMCs (as stated in the phase diagram of the alloy) will form as can be seen in Fig 1 b). Additional heating such as annealing heat treatment will increase the size / number of the peritectic phases as shown in Fig 1 c). Once the TLP bonding process is completed, the melting temperature of the alloys is raised. The resultant alloys will not melt if the same heating temperature is used. It will only remelt if higher heating temperature is used.
2.2 TLP bonding process for solder powder / solder paste.

There is also a research on the TLP bonding process for metal alloys in the form of powder and paste [2] since the application of solder alloys are in the form of solid, powder and paste [4]. Fig 2 illustrate the bonding mechanism of solder powder/paste. Basically, the TLP soldering principles is as follows: the bonding material used a mixture of high and low melting point metal powders. The low melting-point metal powder melts and react with the high-melting-point metal powder to form high-melting-point intermetallic compounds or solid solution and finally subsequent heating will allow the IMCs achieve a high-temperature-resistance bonding [12].

3 Results

3.1 Intermetallic compound (IMCs)

One of the most important factors that influence solder joint reliability is the formation of IMCs either at the interface of in the bulk solder areas. However, the IMCs formation mechanism by using TLP bonding process is different from the typical IMCs formation during convention soldering process.

Moktari and Nishikawa [3] in their study on TLP of Sn-Bi solder sandwiched with Cu substrate have reported that the formation of Sn-Cu IMC and Bi-rich leads to increase in the melting temperature of the solder joint. It is believed that the addition of Cu particles results in the nucleation and growth of the IMC as can be seen in Fig. 3. From the DSC analysis,
once the solder joint bonding temperature and time increase, it allows the Sn and Cu atoms to react and produce a high melting temperature of Sn-Cu IMCs as shown in Fig. 4. The valley of 667 and 700 °C represent the melting of the Cu₆Sn₅ and Cu₃Sn IMCs, respectively.

As in another case, Fig. 5 shows the back-scattered electron (BSE) micrographs of Sn-Cu based solder joints reflowed 235 °C for different bonding times studied by Sun et al, 2019 [13]. As the bonding time increased, Sn continues to be consumed to form the IMCs (Cu₆Sn₅ and Cu₃Sn). After 90 min of bonding time, the IMCs at both ends were connected. And the Sn in the liquid phase was became an island-shape/peritectic phase (surrounded by Cu₃Sn and Cu₆Sn₅) after solidification. Afterwards, the island-shape gradually decreased, and a full IMCs solder joint was formed after 150 min. At this point, the alloys has already an elevated melting temperature.

Fig. 3. The illustration of the conversion of the eutectic Sn–Bi to the Sn–Cu IMCs and Bi.[3]

Fig. 4 The DSC peak of Sn-Cu IMCs in Sn-Bi-30Cu solder paste [3]
Fig. 5. Cross-section SEM images of Cu-Sn solder joints at 235 °C for: (a) 30 min, (b) 60 min, (c) 90 min, (d) 120 min, and (e) 150 min. [13]

3.2 Peritectic reactions

The Cu-Sn binary system is used here to illustrate the TLP routes for isothermal solidification as shown in Fig 6. Sn-Cu solder with Cu composition beyond 7.6 wt. % will undergo peritectic solidification.

Fig. 6. Sn-Cu alloy phase diagram [17]

Generally, peritectic solidification involved three phases which are primary $\varepsilon$ phase, peritectic $\eta$ phase and liquid phase L. There are three main stages of peritectic solidification which are peritectic reaction, peritectic transformation and subsequent liquid precipitation of peritectic phase from the liquid melt [14]. Peng at el. in his research on peritectic reaction for sn-Cu-Ni solder has chosen Sn-10Cu solder composition as it close to 7.6 wt. % Cu, where it is still classified as a peritectic alloy. During peritectic reaction, the primary $\varepsilon$ phase reacts with liquid phase produce peritectic $\eta$ phase. The nucleation of $\eta$ phase occurs at the interface between the primary phase and the liquid. Afterwards, a lateral growth of $\eta$ phase around $\varepsilon$ phase takes place as can be seen in Fig. 7. After isolation of primary $\varepsilon$ from the liquid, the direct peritectic reaction can no longer take place. Then, the primary $\varepsilon$ transforms to the peritectic phase by peritectic transformation. Peritectic transformation is
an atomic diffusion control process and normally it takes a longer time to be completed. Due to the sluggishness of long-range solid-state diffusion, the peritectic transformation could not proceed completely. As a consequence, the final microstructure composed of both primary and peritectic phase [14,15,16]. At this time, the melting temperatures for the IMCs shifted to > 415° C.

![Peritectic microstructure of Sn-Cu based solder. Primary ε (Cu₃Sn) phase surrounded by η (Cu₆Sn₅) phase producing peritectic phase.](image)

Fig 7. Peritectic microstructure of Sn-Cu based solder. Primary ε (Cu₃Sn) phase surrounded by η (Cu₆Sn₅) phase producing peritectic phase. [18]

From the above discussion, most of the intermetallic phases that results from the TLP bonding process could precipitate between the low and high melting point metals. However, the large difference in the melting point of the involved metals could leads to the formation of kirkendall void. As we know, different diffusion rate of interdiffusion couples could lead to the formation of kirkendall voids [19]. So, having Kirkendall voids right at the joint is also a matter of great concern. Therefore, further investigation on this matter is needed.

### 4 Conclusion

TLP bonding is a good alternative soldering process for solder that could replace the usage of previous high Pb solder alloys. It results in as-soldered alloys with a higher melting temperature than that used to join the solder. TLP bonding is successfully being applied to either solid, powder or paste solder. However, there is a possibilities on the formation of kirkendall voids at the resultant peritectic IMCs since different diffusion coefficient is involved during the TLP bonding process. Therefore, further study on the physical and mechanical properties of peritectic IMCs is needed for an established experimental data.

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