

Review

An Introductory Overview of Various Typical Lead-Free Solders for TSV Technology

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Abstract: As semiconductor packaging technologies face limitations, through-silicon via (TSV) technology has emerged as a key solution to extending Moore’s law by achieving high-density, high-performance microelectronics. TSV technology enables enhanced wiring density, signal speed, and power efficiency, and offers significant advantages over traditional wire-bonding techniques. However, achieving fine-pitch and high-density interconnects remains a challenge. Solder flip-chip microbumps have demonstrated their potential to improve interconnect reliability and performance. However, the environmental impact of lead-based solders necessitates a shift to lead-free alternatives. This review highlights the transition from Sn-Pb solders to lead-free options, such as Sn-Ag, Sn-Cu, Sn-Ag-Cu, Sn-Zn, and Bi- or In-based alloys, driven by regulatory and environmental considerations. Although lead-free solders address environmental concerns, their higher melting points pose challenges such as thermal stress and chip warping, which affect device reliability. To overcome these challenges, the development of low-melting-point solder alloys has gained momentum. This study examines advancements in low-temperature solder technologies and evaluates their potential for enhancing device reliability by mitigating thermal stress and ensuring long-term stability.

Keywords: packaging; solder; low melting temperature; lead-free; integration



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1. Introduction

Given the limitations of current semiconductor packaging technologies, TSV technology represents a promising solution for high-density packaging, enabling the extension of Moore’s law in the microelectronics industry [1,2]. As Moore’s law of miniaturization approaches its limits, significant research is being conducted to identify solutions to overcome its constraints [3]. To address this challenge, a technology that is gaining traction in the electronics industry is the TSV method. Although wire bonding is a prevalent technique for semiconductor packaging, the necessity for enhanced electrical properties and compact form factors has prompted the industry to embrace TSV technology. Compared to wire

bonding, TSV technology offers several advantages, including high density, high electrical performance, fast signal speed, and low power consumption [4–6]. The TSV interconnect process consists of three principal stages: molding, insulation/seed layer deposition, and filling. One of the ways to improve TSV technology is therefore the development and assembly of fine-pitch and high-density solder microbumps.

The use of solder flip-chip microbumps for interconnects has the potential to enhance the wiring density of silicon carriers compared to organic or ceramic substrates [7]. Furthermore, this technology enables the establishment of high-performance signal and power connectivity. The necessity for high-performance microelectronics is driving advances in electronic packaging, with ongoing research focusing on performance, functionality, miniaturization, the integration of heterogeneity, and reductions in power consumption. Consequently, the requirement for superior solders is on the rise. Sn-Pb solder alloys have become standard materials in various soldering methods, and offer many advantages, including excellent electrical conductivity, good wettability, and good mechanical strength. However, Pb has been found to be harmful to both the human body and the environment [8]. As awareness of environmental protection has grown, interest in and research on lead-free solders has been promoted, which has significantly limited the use of lead. As a consequence of environmental regulations on hazardous substances, the transition from traditional Sn-Pb-based solders to lead-free alternatives has resulted in the utilization of alternative solders such as Sn-Ag- [9], Sn-Cu- [10], Sn-Ag-Cu- [11], Sn-Zn- [12], and Bi- [13] or In-based solders in chip- and board-level interconnect applications. Because a variety of lead-free solders are utilized in electronic components or modules employed in electronic devices, including those used in mobile and automotive applications, conducting research on the reliability of these solders is essential, particularly with regard to system safety, to facilitate their use in diverse industries. Therefore, several studies have been conducted to assess the reliability of lead-free solder joints for system safety by employing a range of reliability tests, including mechanical and thermodynamic reliability tests [14].

However, the fusion of conventional lead-free solders requires elevated temperatures. The application of elevated temperatures results in thermal stress between the chip and substrate, which is attributable to disparities in the coefficient of thermal expansion [15]. Furthermore, in the context of computing trends, thermal stress can result in severe warping, ultimately leading to chip damage. The development of alloys capable of low-temperature bonding is expected to enhance device reliability by mitigating the risk of heat-induced warping and ensuring stability over extended periods. The implementation of a low-melting-point solder is the most effective method for mitigating warping issues, because it enables the attainment of lower reflow temperatures. Consequently, this review presents papers on the development of lead-free solders to improve TSV technology, including low-temperature solders.

2. Various Solder Alloys

2.1. Sn-Bi Solder

Sn-Bi solder is a low-melting-point solder with advantages such as low cost, good solderability, and a lead-free nature, which makes it environmentally friendly. In addition, the Sn-Bi solder exhibits excellent wettability and favorable mechanical properties. The melting point of the Sn-Bi solder can vary significantly depending on the specific alloying components. By contrast, the melting temperatures of lead-free alternatives such as Sn-Ag, Sn-Cu, and Sn-Ag-Cu exceed 220 °C, thereby conferring a significant advantage to Sn-Bi solder over SnAg, SnCu, and SnAgCu solder. Many studies employ the use of Sn-58Bi solder, which exhibits a melting point of approximately 138 °C [16–25]. The addition of various elements to Sn-58Bi solder alters its melting point and associated properties. Con-

sequently, numerous researchers have examined the potential for incorporating additional elements [26–28].

However, Bi segregation at the SnBi/Cu interface after prolonged aging has been identified as a significant reliability issue, particularly given that the substrate is predominantly Cu. To address this challenge, Hu et al. [16] examined the effects of Ag incorporation into a Sn-58Bi solder on the SnBi/Cu interface reaction in SnBiAg/Cu solder joints. They observed that the interfacial morphology was similar in the soldered joints, confirming the presence of a thin lamellar structure in the solder. In addition, they identified the intermetallic compound (IMC), which was observed to be Cu_6Sn_5 and was approximately 2 μm thick. Following a 7 day aging period, the Cu_6Sn intermetallic compound thickness increased to 6 μm . Researchers have observed that the morphologies of the SnBi/Cu and SnBiAg/Cu interfaces underwent alterations over time. This study also confirmed the progression of IMC growth over time following the addition of Ag. Furthermore, the elements present in the solder could diffuse into the Cu substrate during the process, creating a surface-alloying effect that could help suppress IMC growth.

As well as the addition of Ag, studies have also demonstrated the efficacy of incorporating two additional elements (In, Ni) to improve the Sn-Bi solder. Mokhtari et al. [29] incorporated 0.5 wt% In and 1 wt% Ni into Sn-58Bi solder. The addition of indium and nickel was not as effective as anticipated, because the inhibition of IMC growth during reflow did not reach the expected level. However, the results demonstrated that the incorporation of 0.5 wt% In and Ni during thermal aging proved effective in impeding IMC layer growth.

Furthermore, the addition of a modest quantity of In resulted in a significant reduction in the coarseness of the Bi phase within the alloy. Moreover, studies have employed the addition of alloys to Sn-58Bi solder. Yang et al. [30] incorporated micro-CuZnAl particles into a Sn-58Bi solder at concentrations ranging from 0 to 0.4 wt%. The solder alloys were produced by subjecting the Sn-58Bi solder to mechanical mixing with varying amounts of CuZnAl particles, varying from 0 to 0.4% by weight, for 30 min. A total of six samples were prepared, with CuZnAl additions of 0, 0.05, 0.1, 0.2, 0.3, and 0.4 wt%, respectively. Researchers have discovered that the alteration in the microstructure is contingent upon the introduction of CuZnAl. Figure 1 shows the microstructures of Sn-58Bi-xCuZnAl after reflow. In the initial state, Sn-58Bi exhibited a lamellar structure. The addition of CuZnAl particles to the Sn-58Bi solder enhanced the solder microstructure. The addition of CuZnAl at concentrations of 0.1% and 0.2% resulted in a significant reduction in the Bi-phase aggregation. However, the addition of a greater quantity of CuZnAl particles resulted in the gradual coarsening of the microstructure. Moreover, when the CuZnAl content reached 0.4%, the microstructure exhibited a greater degree of coarseness than that observed for the older Sn-58Bi. This phenomenon can be explained by the fact that, as the amount of CuZnAl particles increased, the flowability was negatively affected by the formation of agglomerates. The refinement effect on the microstructure of the Sn-58Bi solder diminished, indicating that the optimal content with the highest degree of refinement was between 0.1% and 0.2%.

In addition, the inclusion of CuZnAl particles significantly reduced the thickness of the intermetallic compound layer. Figure 2 shows the average intermetallic compound layer thickness of Sn58Bi-xCuZnAl solder joints. Without the CuZnAl particles, the intermetallic compound thickness was measured at 1.62 μm . When 0.05 wt% CuZnAl was added, the IMC layer thickness decreased to 1.28 μm . The reduction in thickness continued when 0.1 and 0.2 wt% of CuZnAl particles were added. The addition of 0.2% CuZnAl particles reduced the IMC layer thickness to 1.03 μm , accompanied by an increase in the flatness of the interface. However, a higher concentration of CuZnAl particles led to a

slight increase in the thickness of the IMC layer between the composite solder and Cu substrate. This is a result of the diffusion of CuZnAl particles into the Sn-58Bi solder and at the interface between the solder and Cu substrate. Consequently, we can conclude that the addition of 0.1 to 0.2 wt% CuZnAl to the Sn-58Bi solder resulted in further improvements to the microstructure, including a lower melting temperature and thinner IMC. The inevitable growth of these IMCs between solder and substrate can impact reliability as solder sizes shrink.

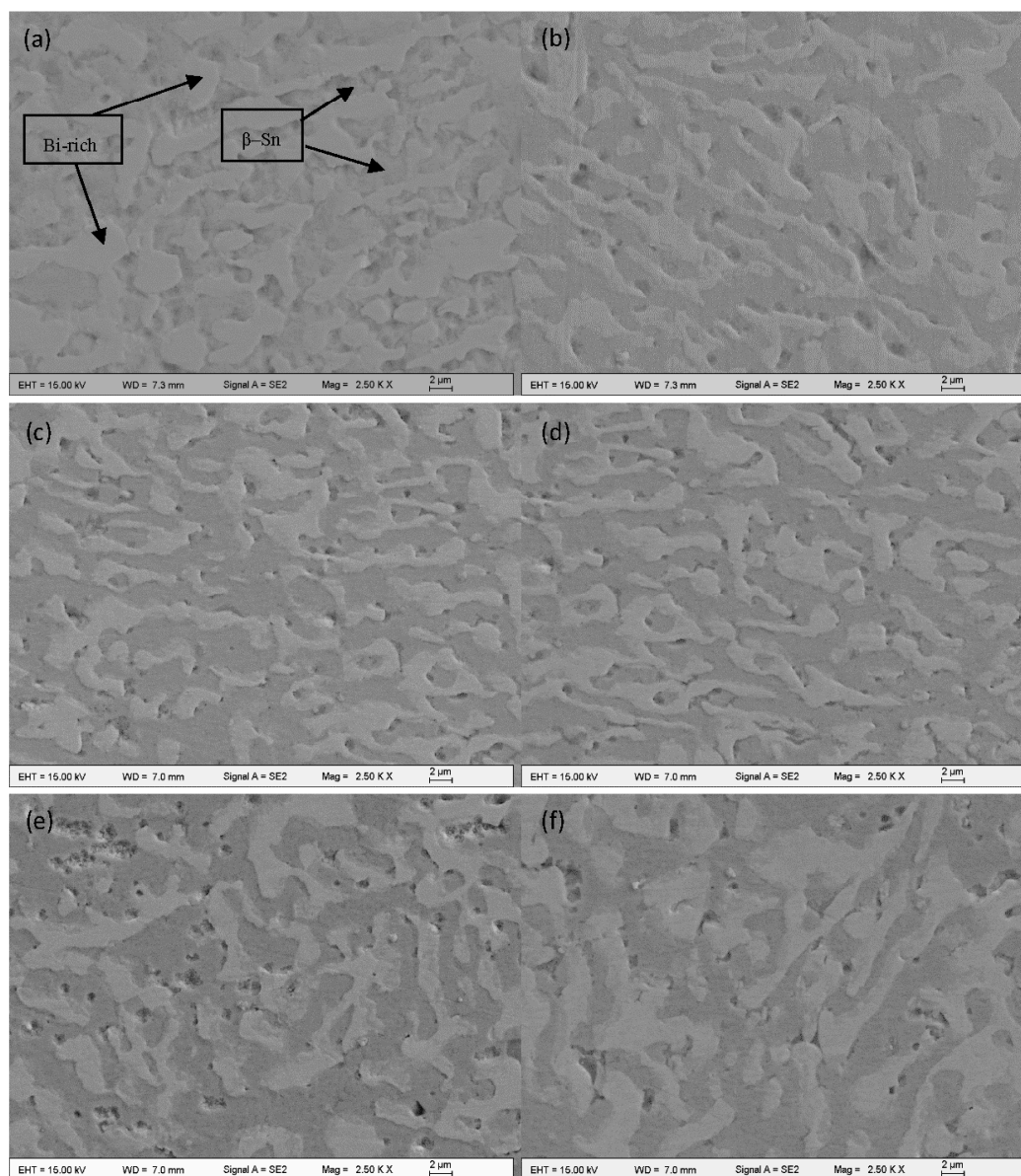


Figure 1. Microstructures of Sn-58Bi- x CuZnAl after reflow: (a) $x = 0$; (b) $x = 0.05$; (c) $x = 0.1$; (d) $x = 0.2$; (e) $x = 0.3$; and (f) $x = 0.4$. Reprinted/adapted with permission from Ref. [30], 2017, Fan Yang.

The Sn-Bi solder's most significant advantage is its low melting point, which allows for more efficient and controlled melting during the soldering process. However, this solder's Bi-rich aggregation contributes to relatively low shear and tensile strengths when compared to other solder types. To address this, the addition of other elements or the integration of Sn-Bi with other particles can be employed to enhance the mechanical properties. The integration of Sn-Bi with other particles or the addition of other elements is a viable solution to address its relatively low shear and tensile strengths. The combination of a

simplified processing method and enhanced mechanical strength is anticipated to undergo widespread industry adoption, particularly in technologies such as TSV technologies utilizing microbumps, given Sn-Bi's extremely low melting point.

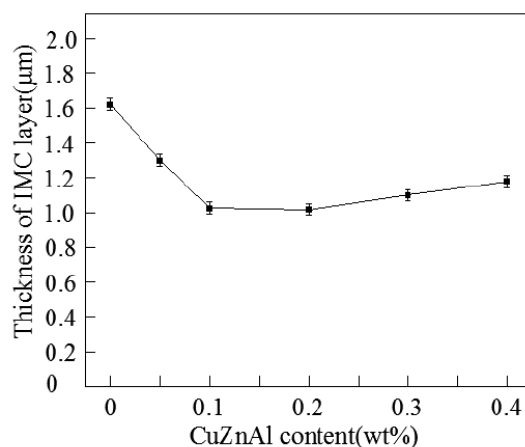


Figure 2. Average intermetallic compound layer thickness of Sn58Bi-xCuZnAl solder joints. Reprinted/adapted with permission from Ref. [30], 2017, Fan Yang.

2.2. Sn-Zn Solder

Sn-Zn solder can be used as an alternative to conventional Sn-Pb solder without increasing the process temperature. The eutectic temperature of Sn-Zn solder alloys is 198 °C, which is 20 °C lower than that of Sn-Ag-Cu systems. This temperature is sufficient to replace the Sn-Pb solder. However, the Sn-Zn solder suffers from reliability issues and susceptibility to oxidation, making it difficult to commercialize [31]. To overcome these drawbacks, many researchers have studied the addition of various elements to the Sn-Zn solder [31–38].

Kim et al. [39] examined the effects of diverse environmental conditions on the oxidation state of Sn-Zn solder. Bi, Al, and P have been introduced into the solder to enhance its performance. The addition of Bi to Sn-Zn solder at 80 °C and 85% humidity was observed to result in the formation of ZnO at the interface, which was found to reduce the overall shear strength. This was presumed to be because the addition of Bi accelerated the diffusion process. However, the addition of Bi to Sn-Zn was found to have no significant effect on the bond strength, even when the samples were exposed for an extended period (1000 h) at relatively low temperatures (60 °C) and humidity levels (90%). Furthermore, the incorporation of Bi resulted in enhanced resistance to oxidation compared to that of the conventional Sn-Zn solder. Researchers have introduced Bi into the Sn-Zn solder along with trace quantities of Al and P. This resulted in a solder with enhanced oxidation resistance. The addition of Al and P prevented oxidation by forming a dense oxide layer that inhibited further oxidation, whereas P continued to oxidize and absorb oxygen atoms, preventing the oxidation of Sn and Zn.

Oxidation also proceeds well at high temperatures, so we investigated the paper on preventing oxidation at high temperatures. Zhang et al. [33] investigated the addition of various elements to enhance the oxidation resistance of Sn-Zn solder at high temperatures. The incorporation of Ga and Al significantly enhanced oxidation resistance, whereas the introduction of other elements, including Ge, Ni, and Ce, did not demonstrate a comparable improvement.

Many studies have been conducted to improve the mechanical properties of Sn-Zn solders. Zhou et al. [40] investigated the impact of varying the Bi content on the mechanical properties of Sn-Zn solders. Their findings indicated that the mechanical properties of the solder deteriorated when the Bi content exceeded 4 wt%. This deterioration

is presumed to be the result of an increase in the Bi phase content of the alloy. This Bi phase has been the subject of several studies that have demonstrated its capacity to weaken mechanical strength.

A recent study revealed that Sn-Zn solder with a low Zn content exhibited superior corrosion resistance in comparison to solder with a high Zn content. This finding suggests that Zn is vulnerable to corrosion [41]. Sn-Zn solder exhibits a notable drawback in terms of its mechanical strength, which is attributed to its susceptibility to oxidation and reduced wettability [42]. Qu et al. [43] focused on improving low-temperature wave soldering in the industry using Sn-9Zn-2.5Bi-1.5In alloys and setting the suitable process parameters. Researchers developed a nitrogen protection device to improve the Sn-Zn-based solder, which is vulnerable to oxidation. This device enabled cold wave soldering, reaching the IPC standard and finding room for industrial application. The lower soldering temperature of Sn-Zn solder enhances its compatibility with PCBs, suggesting its potential for widespread industrial application [44].

Chen et al. [33] enhanced the mechanical properties of Sn-Zn solders by adding Ga and Ag. They determined that an optimal microstructure was achieved at a Ga content of 0.5 wt%. Furthermore, different quantities of Ag were added to Sn-9Zn, and the resulting effects were investigated. These findings indicate that the addition of Ag is crucial for the solderability and structure of the solder, as well as for the mechanical properties of the soldered joint. The research indicates that the optimal Ag addition is 0.3 wt%, which significantly enhances solderability and increases oxidation resistance. In addition, the Sn-9Zn-0.3Ag solder exhibited a microstructure superior to that of the conventional Sn-9Zn solder. However, the formation of IMCs at Ag concentrations above 1 wt% has been observed, leading to a notable decline in the mechanical properties. The formation of these IMCs has the potential to impact the mechanical reliability of the solder. Shiliang et al. conducted a study on the microstructure and fracture mechanism of Sn-9Zn-2.5Bi-1.5In (Sn-Zn) joints with Cu substrates. Their findings indicated that aged Sn-Zn joints exhibit a propensity to fracture at the solder/IMC interface [45]. Consequently, the optimal levels of Zn and other additive ratios for microjoints and IMC formation must be properly considered for improved TSV technology.

2.3. Sn-Cu Solder

Sn-Cu solder is more environmentally friendly than Sn-Pb solder, and is significantly more cost-effective than other solder alternatives without Pb, such as Sn-Ag and Sn-Bi. Price competitiveness is likely to be a significant factor in this industry in the future. However, a previous report indicated that Sn-Cu solder has lower mechanical properties than and inferior wettability to other lead-free solders [46]. One of the important properties of solder alloys is their melting point. Although the melting point of Sn-37Pb solder is 183 °C, the melting point of Sn-Cu solder is generally higher. For example, the melting point of Sn-0.7Cu-5In is reported to be between 213 °C and 217 °C, whereas that of Sn-0.7Cu-4In-0.5Ga is between 215 °C and 219 °C. A typical Sn-0.7Cu solder has a melting point of 227 °C. The melting point of the solder alloys is a critical factor that must be considered during the soldering process. The maximum temperature attainable during the soldering process is constrained by the potential warping of the components and devices on the substrate. This limitation impedes the capacity to execute high-temperature bonding. By contrast, the minimum temperature is determined via the melting behavior of the solder and the necessity of forming a robust bond with the substrate. This frequently results in the incorporation of an additional alloying element, typically a low-melting-point substance such as Zn [47], Bi [48], or In [49], to reduce the melting point by a few degrees.

Furthermore, various elements can be introduced to enhance the microstructure, which significantly influences the solder bonding.

Sn–0.7Cu solder is widely used for industrial applications due to its cost and mechanical behavior. Many elements, i.e., Zn, Ni, and Bi, have been added to the solder for the purpose of enhancing its performance, but it is necessary to define these alloys specifically. It has been determined via research that small additions of Zn to Sn–0.7Cu improve oxidation resistance and microstructure stability without altering its inherent nature as an Sn–Cu-based solder [46,47].

Zeng et al. (2015) investigated the impact of Zn additions on Sn–0.7Cu solder joints and determined that small Zn additions ($\leq 1\%$) enhance oxidation resistance and microstructure, without changing the classification of Sn–Cu-based solders [47]. Similarly, the addition of Bi, according to Huang et al. [48], results in mechanical property enhancement in Sn–Cu alloys, demonstrating that Sn–Cu-based systems can be effectively modified for enhanced performance without reclassification.

The microstructure and intermetallic compound (IMC) growth at the substrate/solder interface play a key role in influencing the reliability of Sn-based solder joints. With the aim of enhancing the performance of Sn–0.7Cu solder joints, research work has been conducted to investigate the effects of alloy additions such as nickel (Ni) and zinc (Zn) on microstructural development and phase transformation. Zeng et al. studied the impact of additions of Ni and Zn on the microstructure and phase transformation in Sn–0.7Cu/Cu solder joints. The results confirmed that both elements are accountable for refinement in the microstructure, as Ni promotes the growth of $(\text{Cu,Ni})_6\text{Sn}_5$ IMCs that are finer and more uniform compared to the normal Cu_6Sn_5 phase.

In addition, Zn addition caused the formation of Cu–Zn IMCs, which further enhanced the microstructure and impacted the interfacial reactions. Regarding phase transformations, Ni was observed to stabilize $(\text{Cu,Ni})_6\text{Sn}_5$, while inhibiting the growth of the Cu_3Sn layer, which is commonly linked to brittle failure in solder joints. Zn, on the other hand, modified intermetallic layer formation by encouraging the growth of Cu–Zn IMCs, influencing diffusion paths and minimizing unwanted IMC thickening. These microstructural modifications had a significant impact on the mechanical properties of the solder joints, with improved shear strength and thermal fatigue life. The thinner IMC layers assisted in attaining improved mechanical stability, which is crucial for long-term electronic packaging reliability. The study concludes that the addition of Ni and Zn to Sn–0.7Cu solders is a promising method to improve the mechanical properties and reliability of solder joints. These findings are priceless for creating new lead-free solder alloys with improved durability for electronic devices.

Gan et al. [50] discovered that the microstructure of Sn–xCu solder exhibits notable variation with changes in the Cu content. Researchers have investigated the microstructures of Sn–xCu solders. Figure 3 shows the phase analysis of Sn–xCu solders. The microstructures exhibited the presence of Sn-rich phases, eutectic Sn–Cu phases, and Cu_6Sn_5 intermetallic compounds. The intermetallic compound (Cu_6Sn_5) exhibited a proportional increase in concentration with increasing Cu wt%. In addition, as the Cu content increased, the Sn-rich phase became progressively finer.

The formation of various IMCs on a bonding surface is a common phenomenon when a Sn–Cu solder is subjected to high-temperature bonding with diverse substrates. For example, a solder composed of tin and copper with a copper substrate will form an intermetallic compound known as Cu_6Sn_5 . Similarly, solder comprising tin, copper, and nickel will form an intermetallic compound designated as $(\text{Cu,Ni})_6\text{Sn}_5$. In addition, the Sn–Cu solder with a Ni substrate forms $(\text{Cu,Ni})_6\text{Sn}_5 / (\text{Ni,Sn})_3\text{Sn}_4$, whereas the Sn–Cu–Ni solder forms $(\text{Cu,Ni})_6\text{Sn}_5 / (\text{Ni,Sn})_3\text{Sn}_4$. The formation of these IMCs can reduce the

mechanical reliability of the solder, particularly if it becomes excessively thick. A significant body of research has established a clear correlation between IMC formation and shear strength. Alam et al. developed a Sn-0.7Cu solder by incorporating varying quantities of nanoscale copper particles into tin via microwave-assisted powder metallurgy. The resulting solder showed 233% and 159% increases in yield and tensile strength, respectively, compared with the conventional Sn-0.7Cu solder. In addition, the resistivity properties were comparable to those of the conventional Sn-0.7Cu solder. These findings suggest that these methods can be employed to develop a solder with enhanced mechanical reliability for the Sn–Cu solder.

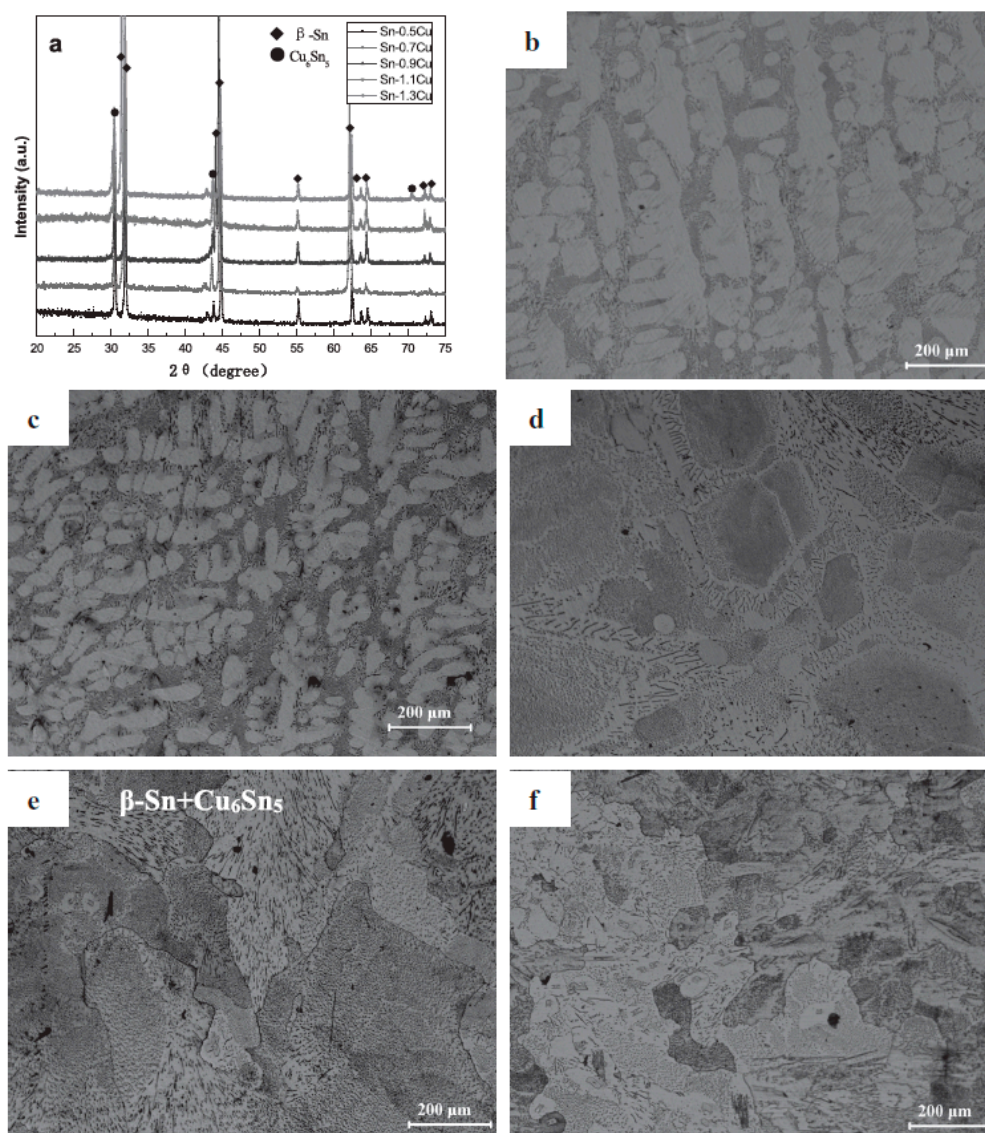


Figure 3. XRD and microstructure of Sn-*x*Cu solders. (a) XRD; (b) Sn-0.5Cu; (c) Sn-0.7Cu; (d) Sn-0.9Cu; (e) Sn-1.1Cu; and (f) Sn-1.3Cu. Reprinted/adapted with permission from Ref. [50], 2017, Guisheng Gan.

2.4. Sn-Ag-Cu Solder

Sn-Ag-Cu solder has emerged as a potential alternative to Sn-Pb solder, offering several advantageous properties. Its relatively low melting temperature, excellent mechanical characteristics, and favorable electronic compatibility have made it a subject of considerable interest.

SnAgCu solders are a type of solder prominently used, with the SAC solders composed of 3 to 4 wt% Ag and 0.5 to 1 wt% Cu being the most prevalent [51]. This is illustrated in Figure 4. The rationale behind this three-alloy composition is that the incorporation of Cu enhances the wettability, interfacial properties, and mechanical properties of the solder compared with the Sn–Ag solder. Furthermore, a critical observation is that the SAC solder has a lower melting point than the Sn–Ag solder, which is significant because the microstructure and mechanical reliability of the SAC solder undergo notable changes contingent upon the Ag content. Keller et al. [52] examined the mechanical properties of an SAC solder by varying the Ag content to 0.1, 2, 3, 3.7, 4.5, and 5 wt%. The Sn–0.4Cu composition devoid of Ag exhibited the lowest shear strength (less than 20 MPa), with the maximum value (32.5 MPa) observed at 3 wt%. The optimal bonding temperature was determined to be 300 °C.

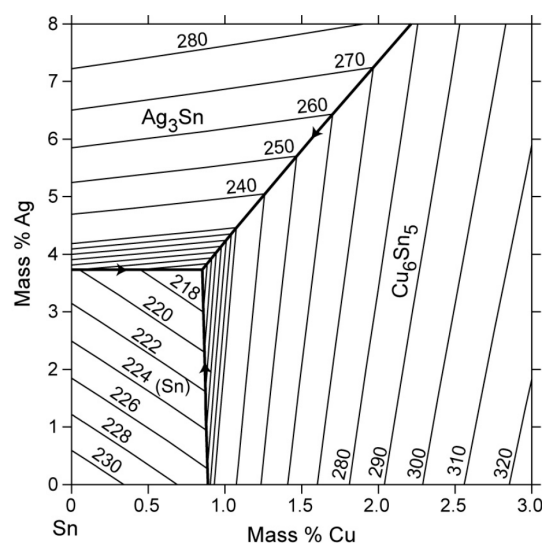


Figure 4. Ternary phase diagram of Sn–Ag–Cu. Reprinted/adapted with permission from Ref. [53], 2012, Dhafer Abdulameer Shnawah.

In a related study, Kim et al. [54] examined the effects of varying the Ag composition from 3.0 to 3.9 wt% and Cu composition from 0.5 to 0.7 wt%. The elevated Ag content resulted in an increase in Ag_3Sn , which precipitated brittle fracture at the joints and the formation of crack initiation, thereby ultimately compromising the mechanical strength of the solder. In Figure 5, The formation of Ag_3Sn was not observed in alloys containing less than 3.2 wt% Ag. Therefore, utilizing SAC solder with a Ag content below 3.2 wt% is recommended to circumvent the formation of Ag_3Sn . However, Lu et al. observed that the shear strength increased until the Ag content reached 3.8 wt%. The most recently reported SAC solders that exhibit the highest shear strength are Sn–3.6Ag–1Cu (67 MPa) and Sn–3.8Ag–0.7Cu (63.8 MPa). This is because Sn has the lowest yield strength among SAC composition solders, whereas Ag_3Sn and Cu_6Sn_5 IMCs have higher strengths than SAC alloys. The concentration of Ag_3Sn IMCs increased with the addition of silver. Consequently, an increase in the quantity of Ag resulted in the formation of a thicker layer of Ag_3Sn , which in turn enhanced the yield strength. This is contrary to the prevailing opinion that cracking is initiated at the Ag_3Sn junctions [55]. An examination of the yield strength of numerous SAC solders suggests that the hypothesis that the yield strength increases with increasing Ag_3Sn is more compelling. This is because the SAC solders with the highest shear strengths in recent years have been Sn–3.6Ag–1Cu (67 MPa) and Sn–3.8Ag–0.7Cu (63.8 MPa) [56].

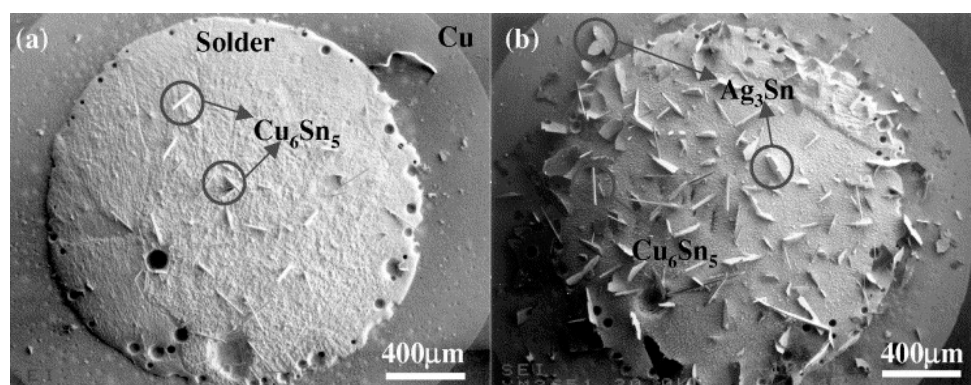


Figure 5. SEM images of Sn-Ag-Cu solder-Cu joints viewed from the top: (a) Sn-3Ag-0.5Cu and (b) Sn-3.9Ag-0.6Cu [54].

For this reason, the properties of SAC solder are subject to changes with alterations in the Ag content, which should be considered when utilizing it in practical applications and packaging [57]. One study [58] indicated that the SAC solder is not highly reliable for thermal and shock testing, limiting its use in cell phone electronics. For instance, the SAC105 solder exhibited superior performance in drop shock testing compared with SAC305, whereas the SAC305 solder demonstrated enhanced resilience in temperature cycling tests compared with SAC105. These findings highlight the necessity of comprehensive testing before employing SAC solders in practical applications [59]. SAC solder has emerged as the prevailing lead-free solder in the industry due to its numerous advantages, including its notable mechanical strength, reliability, and superior fatigue resistance. It possesses exceptional wetting properties, enabling it to form reliable solder joints on a wide range of surfaces. These properties have made SAC solder the preferred solder in the industry.

3. Conclusions

In this mini review, we introduce several representative lead-free solders, as semiconductor packaging technology has reached its limits and TSV technology has gained prominence. This improves fine-pitch and high-density solder microbumps, which are key steps in TSV technology. The hazards of lead have increased the need to replace traditional Sn-Pb solders. Therefore, the potential hazards associated with Pb have contributed to the increased popularity of lead-free solder alternatives. In this review, we focus on Sn-Bi, Sn-Zn, Sn-Ag-Cu, and Sn-Cu solder, which are representative lead-free solders. For instance, Sn-Bi solder has a notably low melting point; however, due to the presence of Bi, it exhibits comparatively reduced strength in comparison to other solders. Conversely, Sn-Cu solder offers significant cost advantages; nevertheless, its high melting point limits its suitability for industrial applications. Sn-Ag-Cu solder, unlike Sn-Cu, is one of the more expensive solders. Despite its high cost, SAC solder is widely used because of its good wettability and excellent mechanical properties. Therefore, cost is not the only consideration when choosing a solder. Each solder alloy exhibits inherent deficiencies that require further improvement. Many researchers have attempted to enhance existing solders by introducing different combustion processes or modifying processing techniques. However, the majority of solders exhibit two significant shortcomings: a high melting point and challenging processing. Nevertheless, Sn-Bi solder has the low melting point required by the industry, and despite its mechanical strength, could be widely used if it is further improved through the research described above. Furthermore, it is crucial to select the most suitable solder alloy for each application system to ensure optimal performance and reliability.

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