Low-Temperature Soldering (LTS) in the Electronics Industry: a Brief Review

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Abstract**—**Soldering is still the main joining technology of the electronics industry; thus, the quality and reliability of the solder joints determine the whole circuit's quality and reliability. The low-temperature soldering (LTS) is a new and emerging trend in the electronics industry, and it means that the melting temperature of the solder alloy is typically below the melting point of the classical eutectic Sn63Pb37 alloy (183°C). The LTS solder alloys are usually composed of tin (Sn), bismuth (Bi), or Indium (In), but not exclusively. The exact composition, additives, and, finally, the characteristics of the LTS solder alloy depend more on the manufacturer than in the case of classical SnAgCu lead-free alloys. They are usually applied to thermally sensitive components and circuit boards to mitigate warpage defects and reduce energy costs. In our review article, we would like to give an overview of the history and the current status of LTS technology in the electronics industry.

Keywords**—***Soldering, BiSn, LTS, biodegradable substrate, sustainability*

I. Introduction

The main problem of the lead-free change in the soldering technology was always the high melting temperature of the lead-free alloys, which is typically between 221–230°C. The higher melting temperature increased the peak temperature of the soldering thermal profile to 245-250°C, which is close to the maximum temperature (~260°C) that an average component can endure. The reduction of the process window of the thermal profiles required sophisticated thermal management during the soldering process, which practically meant the need for much more sophisticated and expensive soldering ovens. By the way, the increased peak temperature increased the energy costs as well. A further technological problem in the application of classical lead-free solders is the warpage defect typically found in large-size BGA components [1].

In the past years, component manufacturers have tended to produce even large-size BGAs with plastic interposers instead of ceramics due to cost reduction. These BGAs can suffer considerable thermal deformation during the soldering, as shown in Fig. 1. This defect is called BGA warpage, and it can lead to the formation of open joints or head-in-pillow defects [1]. The recent advance of biodegradable PCBs, which cannot tolerate high technological temperatures, also makes it necessary to have reliable LTS alloys

[2]. So, LTS technology can protect thermally sensitive components and printed circuit boards, mitigate warpage defects, and reduce the energy costs of the soldering technology.

Although the LTS is a new trend but, its fundamentals have a long history, which was partially initiated by the lead-free ambitions of the electronics industry. Suganuma et al. [3] have already investigated the microstructural properties of Sn-Bi solder joints even before 2000. Sn-Bi or Bi-Sn alloys are still the base of most of the LTS alloys. The most popular LTS alloys are 57.6Bi42Sn0.4Ag (melting temperature 146°C) and the 57Bi42Sn1Ag (151°C). The addition of Ag enables the formation of Ag_3Sn intermetallic particles (IMCs) in the solder bulk, which enhances the mechanical parameters of the LTS solder joints [4].

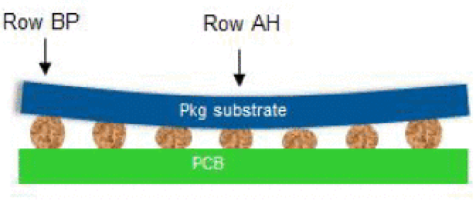

Fig. 1. BGA warpage defect during the reflow soldering process [1].

Most of the market-leading solder alloy manufacturers offer these alloys, usually under various nicknames, which hide the real composition, but the melting temperature and phase diagram of Bi-Sn-Ag (Fig. 3) indicate the exact composition.

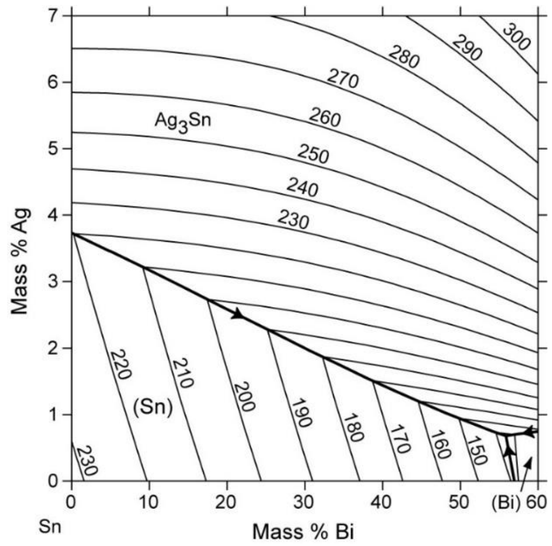

Fig. 2. Phase diagram of Bi-Sn-Ag.

The price of the LTS alloys is generally twice as high as the price of the simple SnAgCu alloys. This is caused by the higher price of Bi (compared to Sn) and the lower size of the market. In our brief review, we would like to give an overview of the history and the current status of LTS technology in the electronics industry.

II. Change to Lead-free or the Beginnings of LTS

As discussed above, the evolution of LTS technology was also initiated by lead-free changes in the electronics industry. Thus, the first results were published in 90s'. Mei and Morris [5] compared the soldering properties (wettability, under cooling, creep, and low cycle fatigue) of 58Bi42Sn to 60Sn-40Pb solder, and with three low-temperature solders, 52In-48Sn, 43Sn-43Pb-14Bi, and 40In-40Sn-20Pb. In the case of 58Bi42Sn, they observed 35° wetting angle on Cu and 15°C undercooling during solidification. It was also found that 58Bi42Sn has the best creep resistance but the poorest fatigue strength among the investigated ones. Suganuma et al. [3] found that below 21 wt% of Bi, it segregated to Bi islands in the Sn-matrix. In the case of soldering a through-hole circuit, he observed voids between the Cu_6Sn_5 IMC and the Bi segregation layer. Before the lead-free changes, the effect of Bi alloying was studied in SnPb alloys as well. Yoon and Lee [6] determined the phase diagram of the Sn-Bi-Pb ternary system by calculations and experiments.

One of the major handicaps of the eutectic BiSn alloy is that it is prone to failure by brittle fracture at high strain rates. Mccormack et al. [4] found that alloying of Ag (~0.5wt%) into BiSn can significantly improve the ductility of eutectic BiSn. The increase of ductility was found to be more than threefold in tensile elongation, even at high strain rates like $0.01s^{-1}$. So, the reduction of the strain-rate sensitivity is beneficial for enhancing the joint's reliability against sudden impacts suffered during device packaging, shipping, or thermal cycling.

Jang and Paik [7, 8] compared the possible replacement of SnPb bumps to BiSn bumps on BGA components in the function of four different types of UBM metallurgy. They concluded, according to a series of bump shear tests, that three UBMs (Al/elNi/Au, Al/NiV/Cu, and Al/Ti/elCu) showed good stability in the case of BiSn bumps. Fig. 3 illustrates the applied solder bumping process.

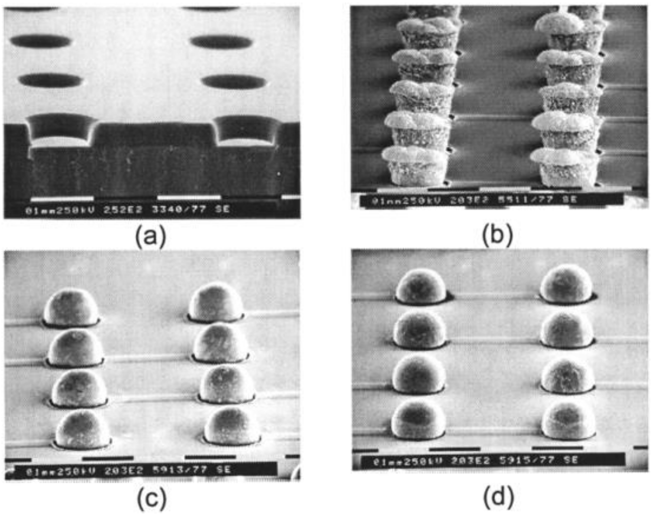

Fig. 3. Solder bumping process steps: (a) patterned photoresist, (b) plated Bi/Sn bumps, (c) eutectic Pb/Sn bumps, and (d) eutectic Bi/Sn bumps [7].

Hua et al. [9] investigated the possible change of eutectic 63Sn37Pb to 58Bi42Sn from a lot of aspects. They reported that most of the no-clean fluxes developed for 63Sn37Pb are not suitable for 58Bi42Sn due to the higher activation temperature. Although, at room temperature, 58Bi42Sn and 63Sn37Pb have similar mechanical properties, but 58Bi42Sn becomes much softer as temperature increases to 110°C. It also has smaller fatigue resistance, which can be improved with a small addition of Ag or Au.

As Ni is a popular surface finish metallization in the electronics industry, its chemical compatibility with Bi was an important issue since, theoretically, Ni and Bi are possible to form $NiBi_3$ IMCs, which are soft and brittle. The fear was unfounded since Tao et al. [10] studied the reactions between Ni and 58Bi42Sn at various soldering temperatures, 180, 240, 300, 360, and 420°C from 0.5 to 48 h. They observed only the formation of Ni_3Sn_4 in all cases, no sign of $NiBi_3$ was detected. Chen et al. [11] got the same results in a similar study. Mei and Holder [12] investigated the thermal fatigue failure mechanism of 58Bi42Sn solder joints by thermal cycling (500 cycles −45°C-100°C). They found that the felt of the solder joints was caused by the dissolving of Pb from the surface finish of the component leads or the PCB. It formed a 52Bi32Pb16Sn eutectic phase that can melt at 95°C, which caused a significant reduction in mechanical strength. Thus, they highlighted the possible compatibility problems between lead-free and lead-containing components and materials.

Raeder et al. [13] created a continuum mechanics composite creep model to describe the deformation of eutectic 58Bi42Sn solder joints. The model was only partially effective because it assumed continuity across the grains and the other phases, and this is invalid when phase boundary sliding occurs, McCormack and Jin [14] studied Bi43Sn2.5Fe LTS alloy melting point ~137°C) and found that the dispersion hardening by magnetically distributed Fe particles suppressed both microstructural coarsening and high-temperature deformation, which can widen the application of BiSn eutectic alloys. Poon et al. [15] investigated the shear properties of Sn50Bi alloy after different thermal shock loads (-25 – 125°C and -25 – 85°C), and they observed weaker performance at the stronger thermal shock conditions due to fine cracks which appeared along the boundary of the Bi-rich phase. In the case of the weaker thermal shock, these cracks were not observed, and then the performance of the Sn50Bi alloy was close to the performance of the reference Sn3.5Ag.

Vianco et al. [16] investigated the solid-state IMC layer growth between eutectic Bi42Sn and Cu under thermal aging between 55 and 120°C for 1 to 400 days. They observed that the IMC layer was composed of sublayers containing the traditional Cu_6Sn_5 phase as well as one or more complex CuSnBi phases. The number of sublayers increased with aging temperature and time. The amount of Sn at the solder – Cu interface determined the thickness of the IMC layer. Suganuma et al. [17] studied the thermal stability QFP components soldered with Sn58Bi-(0/0.5/1.0)Ag and their microstructural properties. The addition of Ag resulted in the formation of large dispersed Ag_3Sn IMC in the solder bulk over 0.8wt% Ag. Thermal loading under 100°C did not cause degradation of the solder joints, but at 125°C, the shear strength of the joints decreased considerably.

Some exotic alloys also appeared in the early age of LTS. Moreland et al. [18] optimized the quaternary system BiInSnZn alloy by the CALPHAD (Computer Coupling of Phase Diagrams and

Thermochemistry) method. All calculated liquidi, isothermal, vertical sections, and thermodynamic properties were compared and agreed with experimental data from the literature. The obtained thermodynamic description could be very useful in the future design of BiInSnZn solders. Brunetti et al. [19] studied the thermodynamics of BiInSn solder alloys by torsion–effusion and differential scanning calorimetry. They found that the system is non-ideal with the general composition, which is 20Bi58In22Sn. Noor et al. [20] studied the melting temperature of BiInSn solder alloys and the BiSn IMCs in the solder joints. They found that the melting temperature can be reduced to under 100°C mainly due to the very low melting point (61°C) of In. Fig. 4 shows the microstructure of a BiInSn solder joint.

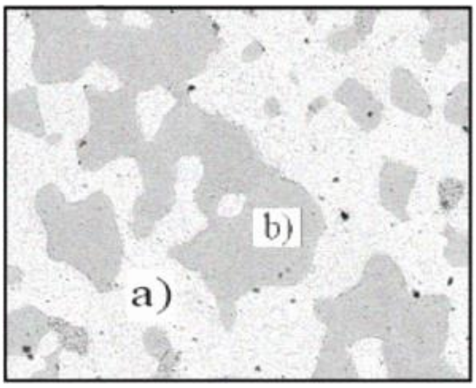

Fig. 4. SEM micrograph of Bi-In-Sn solder joint at 1000X a) bright color (BiIn rich b) dark color (Sn rich) [20].

III. PROTECTING THERMAL SENSITIVE COMPONENTS BY LTS

The second momentum of the development of LTS technology was the fight against the BGA warpage and general protect any kind of thermally sensitive components like biodegradable PCB substrates. In order to reduce the production fees, the component manufacturers started to produce the BGAs with plastic interposers, even the large ones, whose components are much more sensitive to warpage during the elevated reflow temperature of the generally used SAC lead-free alloys.

The team of iNEMI executed a comprehensive study about the application of BiSn-based solder pastes with BGA, FCBGA, and QFN components. They observed similar stencil printability and solder profile shape of BiSn solder pastes to the reference SAC solder paste. Some wetting and hot tearing problems were found in mixed SAC-BiSn solder joints of FCBGA, located in the die shadow area [21]. They also proved that the solder joint stand-off height (SJH) in the case of SAC-ball + BiSn joint structure (Fig. 5) was considerably less than that for simple SAC solder joints. The void ratio of mixed SAC-BiSn joints was below 5%.

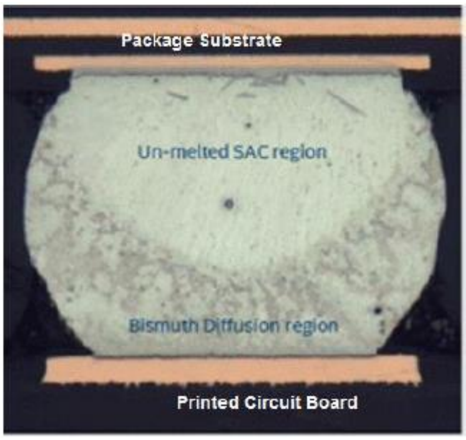

Fig. 5. Cross-section of a mixed SAC-BiSn BGA solder joint illustrating two distinct microstructure regions. [1]

The amount of encapsulation of the solder joint was between 25 and 55%, depending on the tested BiSn solder paste composition [1].

Later, they observed that the BiSn-SAC solder joints of Package on-Package (POP) component (Fig. 6) have lower reliability in the strain rates suffered during mechanical drop tests than simple SAC joints.

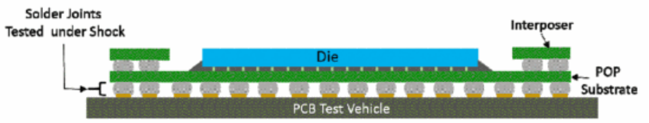

Fig. 6. Assembly stack-up of the POP component test vehicle soldered on the PCB test vehicle [22].

However, the addition of polymeric reinforcement (resin) into the BiSn-SAS solder significantly (115%) improved the mechanical shock reliability, according to the characteristic life earned from Weibull plots (Fig. 7) [22].

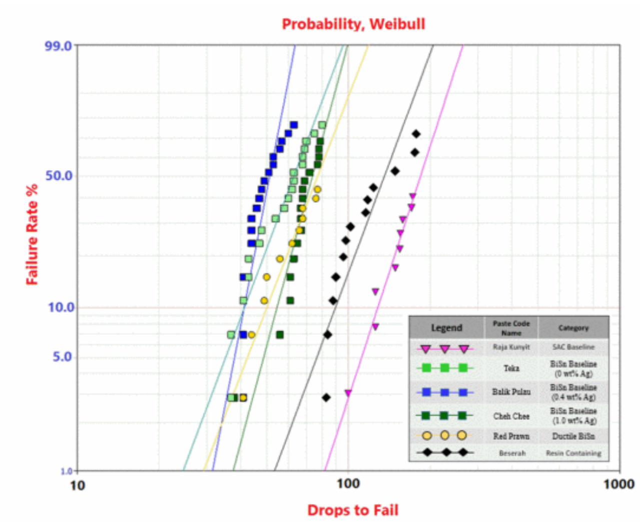

Fig. 7. Weibull of the mechanical shock reliability of POP component solder solders formed using various category solder pastes [22].

The failure interface was found to be at the solder to PCB land interface, which contained the highest weight fraction of Bi. Most of the failures were observed at the corner joints of the POP component, where the stresses were the highest during the mechanical drop test. The lands with metal design performed better results than lands with solder mask design [23].

Mokler et al. [24] compared the characteristic life BGA solder joints formed from SAC-BiSn and SAC-BiSnAg, and found the SAC-BiSn composition was 26% better but still weaker than the pure SAC. The application of BiSn solder paste improved the yield of the BGA solder joint and resulted in considerable energy cost savings and a reduced carbon footprint. Mokhtari and Nishikawa [25] investigated the properties of SnBi, SnBi–0.5In, and SnBi–0.5Ni solder alloys. They found that the addition of 0.5 wt% Ni can decrease the elongation property of the eutectic SnBi alloy due to the growth of Ni_3Sn_4 IMCs. They also proved that the shear strength of the BiSn solder joints (in an as-reflowed state) depends on the formation of the Bi-rich phase at the solder-IMC layer interface. However, the addition of Ni could move the fracture surface from the IMC layer into the solder bulk, mainly after thermal aging. The In-containing SnBi solder joints performed the highest shear strength due to the suppression of interfacial IMC growth and Bi coarsening. They presented a dimple-like fracture surface (in a reflowed state), indicating a ductile microstructure.

Nguyen et al. [26] characterized the Bi31.5Sn25In solder for thermally sensitive components and observed that the microstructure of the bulk solder joints composed of Sn-rich phases in Bi-rich phases with dispersed of In. The mechanical properties of the Bi31.5Sn25In solder had great strain rate sensitivity; namely, the hardness increased from 9.91 to 56.84 MPa when the strain rate increased from 0.0005 to 0.125 s^{-1}. Koide et al. [27] used Sn57Bi1Ag solder paste for mounting large CPU packages. During the reliability simulations, they obtained the results that the LTS solder reduced the built-in stress (caused by the first soldering round) of the motherboard during the second soldering by 40%.

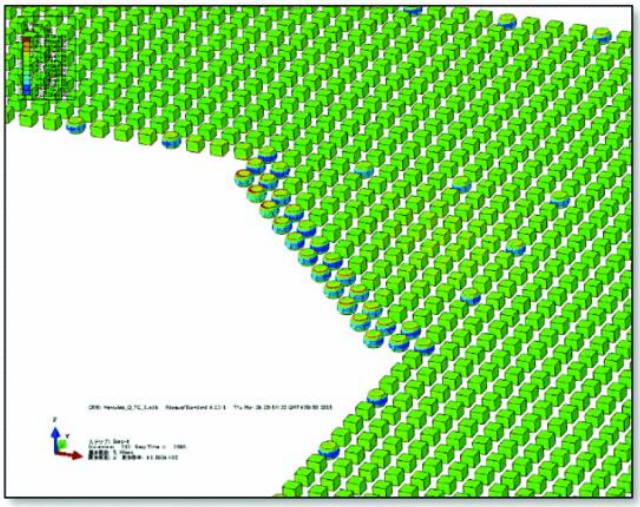

Fig. 8. BGA reliability estimation result [27].

Cai et al. [28, 29] investigated the reliability of pure Sn42Bi58, pure SAC305, and hybrid Sn42Bi58/SAC BGA balls by thermal cycling. The pure Sn42Bi58 performed the highest reliability performance, followed by pure SAC305 and hybrid Sn-Bi/SAC (Fig. 9).

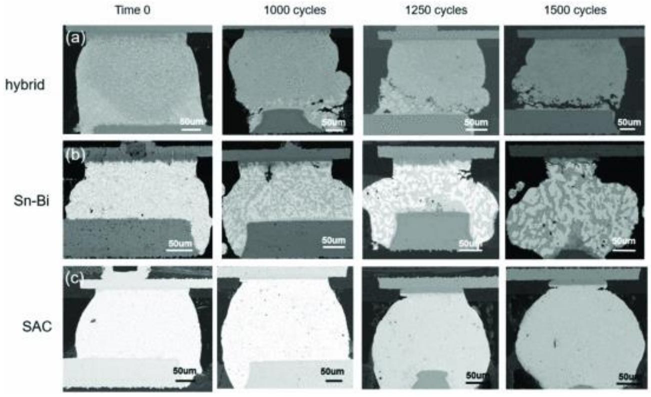

Fig. 9. SEM micrograph of the cross-sectioned solder joints during the thermal cycling test: (a) hybrid assembly,(b)SnBi assembly,(c)SAC assembly starting from time 0 after reflow till 1500 cycles of cycling [28].

A constitutive equation was also constructed for eutectic Sn42Bi58 solder, based on the Garofalo equation and accumulated SED simulations, which can calculate a fatigue life model constant, so lifetime prediction of different assemblies is possible. Wentlent et al. [30] also studied the reliability of hybrid SnBiAg/SAC BGA balls by thermal cycling. They also obtained the usual heterogeneous microstructure of the hybrid joints, namely, SnAgCu in the upper half and SnBiAg in the lower region of the ball (as shown in Fig. 5). They experienced that in the case samples soldered at 150 and 175°C, the crack propagated either along the phase boundaries of Sn and Bi or along the grain boundaries within the Bi region. In the case of the samples soldered at 200°C, slightly different failure mechanisms occurred, with separation of the upper and lower regions of the interconnect.

Ren and Huang [31] studied the drop reliability and fracture behavior of different SAC305/SnBi–X hybrid BGA balls. They concluded that the addition of Ag caused the growth of dispersed Ag_3Sn IMCs in the solder bulk with a pinning effect, while the addition of Ni and Sb suppressed the growth of interfacial Cu6Sn5/$(Cu,Ni)_6Sn_5$ IMCs. They could explain the different crack propagation mechanisms. In the case of large segregated Bi-rich phases at the solder/IMC interface, the crack propagated within Bi-rich phases. In the case of fineer Bi-rich phases, cracks propagated at the solder/IMC interface. They obtained the best drop reliability in the case of the Sn49Bi1Ag alloy.

Lee et al. [32] compared the reliability of two SnBi-based LTS solders combined with SAC305 as hybrid solder bumps by thermal cycling. They observed the sensitivity of the shape of the solder joints to the peak reflow temperature. The best reliability performance was obtained on Ni/Au surface finish when the weight fraction of Bi was between 50 and 70 % and when the paste-to-ball volume fraction was 50 % as more solder (Fig. 10). However, it has to be noted that lifetime of the hybrid LTS joints was still far from the lifetime of pure SAC305.

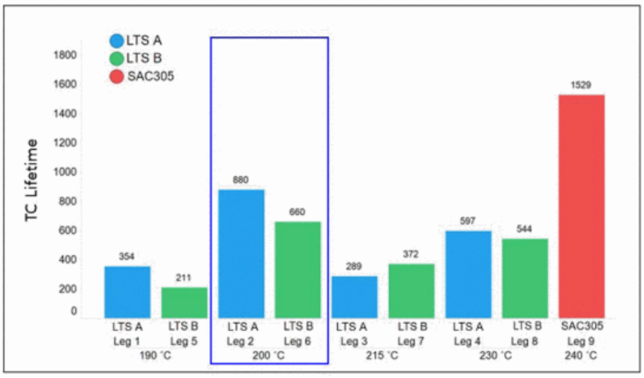

Fig. 10. Thermal cycling results by reflow peak temperature [32].

Hao et al. [32] investigated the short-term mechanical reliability of different SnBi BGA solder balls. They found an interesting and concerning phenomenon that even after some days of the soldering process, at room conditions, the shear strength of SnBi solder joints can decrease, which is caused by the precipitation of supersaturated Bi from the Sn phase.

IV. Conclusions

LTS technology was invented during the “lead-out!” efforts, and for a while, it may seemed to be an alternative to changing SnPb alloy. The most prominent LTS representative is the BiSn or SnBi systems (both sequences are frequently used in the literature). However, LTS alloys with high Bi and/or In content could compete with fastly developing SAC-based alloys, neither from the aspect of the price nor from their quality and reliability parameters. After the electronic industry could solve all the problems caused by the higher melting point of the SAC alloys, the BiSn alloys returned to the desk drawer, but only for a while! The second blossoming of the LTS technology came when the thermally sensitive components started to spread, like large-size BGA-s, POPs, or, recently, the biodegradable PCB substrates, which cannot tolerate the 250°C peak temperature of the SAC systems. According to the recent results, we can conclude the following:

- The eutectic Bi42Sn alloy does not seem to be a proper solution for the future of LTS technology due to its low quality and reliability properties. However, the alloying of a 3rd compound, like In or Ag, into Bi42Sn could improve its properties.
- The alloying of In will never be economical due to the extremely high price of this metal, and its most important feature is only the further decrease in the melting point. The alloying of Ag is the most promising way; it results in the formation of dispersed Ag3Sn IMC particles in the solder bulk, which increases the mechanical quality and reliability of the solder joints only with some (5-10°C) increase in the melting point. The alloys Bi42Sn0.4Ag and Bi42Sn1Ag are already on the market.
- The hybrid application of BiSnAg (solder paste) + SAC (solder balls) is the most promising technology for preventing BGA warpage. This technology results in a heterogeneous solder joint structure, having

a separated SAC phase up and BiSnAg phase down. This structure is the most fragile at the interface of the different phases against mechanical loads.

- Considerable improvements were achieved in the quality and reliability of LTS solder joints in the past decade, but it has to be noted that they are still very far from the classical SAC alloys, and maybe they will always be.

Acknowledgment

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