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The Development of Low-Temperature Lead-Free Solders using Sn-Bi Solders Alloys

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Abstract—Lead-free solders have been the substructure innovation of electronic interconnections for many decenniums due to the widespread utilization of electronic contrivances. Sn-Ag–Cu (SAC) is presently seen as the popular lead-free solder alloy for bundling interconnects in the electronics industry. In this review, the study on the development of low-temperature Pb-free solders using Sn-Bi solder alloys will be discussed regarding thermal behaviour and wettability. The impact of alloying on these compounds is depicted as far as basic microstructural changes, mechanical properties, and reliability. The review closes with a perspective for cutting edge electronic interconnect materials.

Index Term—SAC, Sn-Bi, intermetallic compound, lead-free solder

I. INTRODUCTION

Minimizing the melting temperature of solder has been shown to be one of the main factors required for achieving lead-free electronics packaging. A low processing temperature is desirable for avoiding heat damage to electronic devices during soldering, and this is a reason for the adoption of other low-melting temperature alloys, i.e., Sn–Bi, Sn–Zn–Bi and Sn–Ag–Bi [1].Recently, the soldering processhas been a key perspective in the acknowledgment of every electronic item since the beginning of the electronic age, and it is expected that it will remain the essential gathering and interconnection innovation for quite a while to come. It has for some time been perceived that solder joints epitomize a potential purpose of shortcoming in every single electronic item: paying little mind to the consistently expanding complexity of present-day electronic frameworks, they won't work if their segment interconnections fall flat. Until this point, the best solders have been founded on Sn–Pb composites, and to be sure their remarkable blend of synthetic, physical, thermal, and mechanical properties have given tough and dependable usefulness to numerous decades[2].Conventional Sn-rich lead-free solders have liquefying temperatures just a couple of degrees lower than the melting point of unadulterated Sn at 232 °C [3][4][5].

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Interfacial reactions between molten solder and thesubstrate occur forming intermetallic compounds (IMCs) during the soldering process. IMC formation advances holding between the solder and the substrate. In any case, large IMCs present at the interface will be reduced the mechanical properties of the whole solder joint because of their brittle nature [6][7][8]. Chen et al.[9] mentioned that a lower Young's modulus

(YM) andlittle coefficient of thermal extension (CTE) are not suites between the board and segment just as an increasingly adjusted IMC surface morphology improvessolder joint reliable quality. Interfacial reactions and the properties of surface layers can be controlled by alloying the element [10], which will explained detail in the up and coming areas.

Post reflow solder joints are in charge of both electrical and mechanical associations, one of the real worries for ball grid arrays (BGA) and flip-chip innovation is the unwavering quality of the solder joint. Solder joints are exposed to fluctuating strains due to CTE crisscrosses between the chip transporter and the circuit board [11][12]. The interfacial IMC formation between solder, substrate, component and its failure after aging is shown as described in**Fig 1**. Along these lines, the mechanical properties of solder joints, for example, fatigue and shear strengths, are an urgent issue in deciding the reliability and uprightness of electronic packaging [13][14].Coyle *et al.*detail the influence of soldering process variables on microstructural evolution and IMC morphology for accurate prediction of the reliability of solder joints [15]. In addition, the wettability andmechanical properties of such alloys need to be considered and enhanced.The expansion of further alloying components gives a chance to control mechanical properties. Until now, different alloying components have been examined including Ag, Bi, Cd, Cu, In, Sb, Zn, Al [16][17][18].

Another capacity for reliability quality hazard with high-Sn-content lead-free solder alloys (of around 95-99.3 wt.%) is related to undercooling in the innovation where solder bumps are a point to irregular solidification times because of the high undercooling of the b-Sn stage [10][19]. This outcome in certain knocks being solidified while others are not, prompting pressure fixations and ensuing early precisely initiated disappointments[20]. Therefore, Sn-Bialloys have far lower undercooling compared to Sn-rich Pb-freealloys, therefore, negating this ability issue[21][22].

As indicated bythe Sn-Bi binary phase diagram shown in **Fig.2**[23], the Sn-Bi is a simple eutectic system with the eutectic temperature at 139°C and the eutectic composition at Sn-57Bi (wt.%, same below). The low eutectic temperature enables one to perform patching at a much lower temperature contrasted with customary Sn rich without lead solders.

The test is to change low-temperature Sn-Bi composites into combinations that can be utilized at higher temperatures by the interfacial response. In the writing, a few investigations on the responses between the Sn-Bi patches and Cu had been distributed [24][25][26][27][28].

Subsequently, this present study aimed to explore the impact of low-temperature lead-free solders on the improvement of Sn–Bi solder alloys regarding thermal behavior and wettability. The resulting microstructure of the modified alloys and IMCs formed at the interface among the solder and Cu substrate were additionally reviewed. It was normal that the recently created Sn–Bi alloys system could be a promising option of the Sn–Pb alloys as low-temperature lead-free solder in electronic assemblies[29].

II. MELTING TEMPERATURE FOR SN-BI BASED ALLOYS

With a low dissolving temperature of 138°C, the utilization of 42Sn-58Bi solders are increasing impressive consideration in the electronic business. It is accounted for following measure of rare earth (RE) element (0.1 wt.% Ce and La), while 0.5 wt.% Ag, or 0.5 wt.% Co has little impact on the dissolving temperature of Sn-58Bi based solders, each showing a short pale scope of under 4°C, which guarantees the development of a solid joint[28][30]. Shen *et al.*[31] discovered that follow Cu expansion (0.1 wt.%) diminishes both liquefying point and pale scope of Sn-Bi based solder while Zn (2 wt.%) plays a turnaround impact.Meanwhile, Shlaby [32] reported that the addition of 2 wt.% In or Ag into the Sn-Bi reduces the melting temperature of the solder.Alloying effects on warm properties of Sn-Bi based combinations has been summarized in**Table 1**.

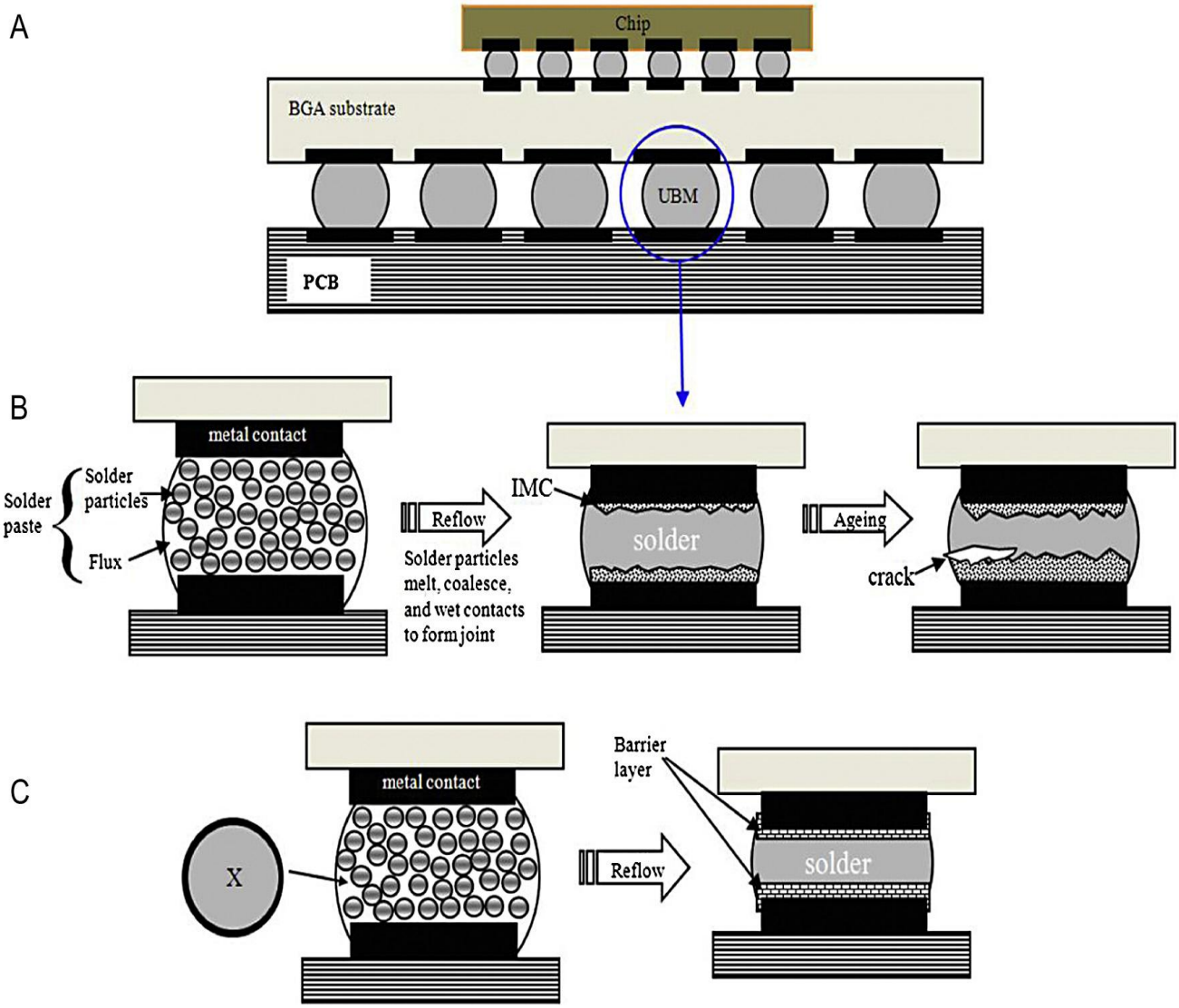

Fig. 1. A schematic drawing showed: (A) flip-chip solder joints, (B) solder joint formation, and failure, and (c) formation of barrier layer after addition of elements (X) [31].

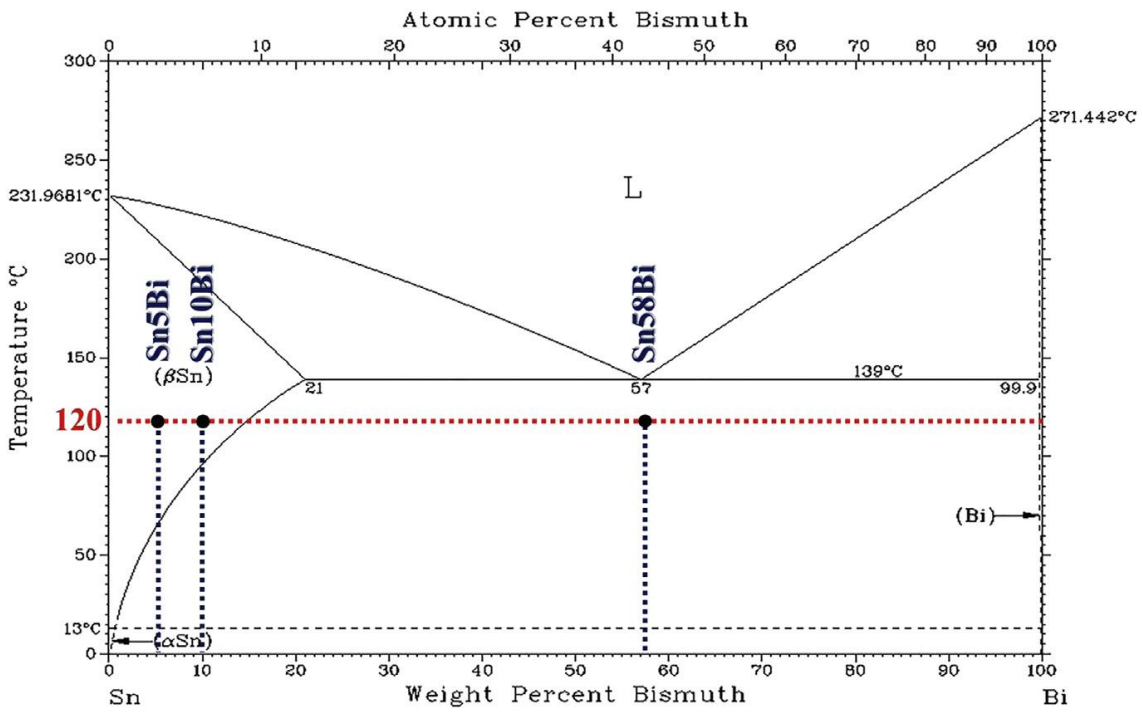

Fig. 2. Sn-Bi binary phase diagram. The diagram is taken from Baker [23]. The compositions of the alloys, Sn5Bi, Sn10Bi, and Sn58Bi, are marked.

Table 1 Influences of alloying on thermal properties of Sn-Bi based alloys.

Alloy type	Solidus temperature (°C)	Pasty range (°C)	Ref.
Sn-37Pb	183	0	[32]
Sn-58Bi	139.6	7.8	[32]
	130.2	27.2	[33]
	136.1	3.0	[30]
	140.3	5.7	[21]
Sn-58Bi-0.05Co	140.3	6.7	[21]
Sn-58Bi-0.5Co	140.1	4.9	[21]
Sn-58Bi-2In	129.8	5.2	[32]
Sn-58Bi-2Ag	139.1	6.3	[32]
Sn-58Bi-2In-2Ag	131.2	4.8	[32]
Sn-58Bi-0.5Ag	135.7	2.5	[30]
Sn-58Bi-0.1RE (RE = Ce & La)	136.2	3.5	[30]
Sn-58Bi-0.5Ag-0.1RE (RE = Ce & La)	136.6	2.5	[30]
Sn-40Bi-0.1Cu	125.1	22.0	[33]
Sn-40Bi-2Zn-0.1Cu	127.7	23.1	[33]

III. WETTING AND INTERFACIAL REACTION FOR SN-BI BASED ALLOYS

Hua *et al*. [34] evaluates the 42Sn-58Bi as a swap for 63Sn-37Pb in Surface Mount Technology(SMT)and found that with recently created noclean transitions which actuate at a lower temperature, Sn-58Bi solder wets well on natural covered copper surfaces making a decent metallurgical bond, however not just as eutectic Sn-Pb patch.

As surface-dynamic rare earth element (RE) components can undoubtedly agglomerate at the interface among solder and transition during liquefying, this can diminish the interfacial surface pressure between the fluid patch and the substrate and quicken the wetting process. Dong *et al.*[30] confirmed that the addition of 0.1 wt.% RE (Ce and La) improves the wettability of Sn-58Bi and Sn-58Bi-0.5Ag solder alloys on Cu substrate. Adding a trace amount of Ag (0.5. wt.%) also improves the wettability of Sn-58Bi solder alloy.

Li *et al.*[28] examined the interfacial response energy between liquid Sn-58Bi patch and Cu substrates and found that at temperatures somewhere in the range of 200 and 240°C, development of η-Cu_6Sn_5 is trailed by the development of the ε-Cu_3Sn and η-Cu_6Sn_5. Moreover, they included 1-2wt.% Al, Cr, Cu, Si, Zn, Ag, Au, Pt, and Nb into the base Sn-58Bi patch, trying to deliver an obstruction layer that backs off IMC development, and found that expansion of 1 wt.% Zn brings about the arrangement of γ-Cu_5Zn_8IMC layer at the interface. Different increments either neglect to shape a proper obstruction or are ineffective in backing off IMC development.

IV. SN–BI SOLDER ALLOYS

Sn–Bi composites show guarantee as without Pb solder frameworks.

The expansion of 58 wt.% Bi into Sn structure a eutectic with a moderately low softening temperature of 139°C, and at room temperature Sn–Bi patch composites display improved yield and break quality in correlation with Sn–Pb alloys [10]. Sn–Bi exhibits a negative volume change upon melting and is cheaper than the comparable In–Sn solders which have similarly low melting points [10]. Furthermore, the properties of Sn–Bi composites are surely known and described because of their basic use in soldering applications, and they are monetarily accessible in glue structure [28]. The primary downside to the framework is the low working temperatures that farthest point Sn–Bi fastens (even 100°C compares to a homologous temperature of 0.90).

The Sn–Bi alloy is a basic eutectic framework, displaying periods of Sn rich, Bi rich, and Sn-Bi eutectic. Fig. 3 demonstrates a SEM image of a Sn–Bi/Cu test, where the microstructure of the Sn–Bi combination comprises an essential b-Sn stage and a Sn–Bi eutectic mixture [34]. The limitation of solid solubility of Sn in Bi is partial completely clear, and the values reported in the literature vary, [35] ranging between 0.2 and 4.1 at.% Sn [36]. The Sn–Bi system initially forms Cu_6Sn_5 IMC on a Cu substrate, followed by Cu_3Sn during subsequent aging. On Ni–P substrates, Ni_3P, and Ni_3Sn_4 layers, as shown in **Fig. 3**. The $NiBi_3$ phase only occurs when the Bi content is over 98 wt. %, whereas the Ni_3Sn_4 phase is formed in most Sn–Bi/Ni systems.

It has been demonstrated that even follow measures of some alloying components can frame an obstruction layer which smothers the arrangement of interfacial IMCs at high temperatures. However, the elements Al, Cr, Si, Nb, Pt and Cu (at 1–2 wt.%) appear to have no significant effect on the IMC growth under high-temperature storage[28]either neglecting to form an appropriate barrier or failing to slow down the IMC growth.

By adding 1 wt.% Ag into the fundamental Sn–Bi solder it is conceivable to somewhat decrease the utilization pace of the Cu substrate. This might be expected to Ag_3Sn gatherings shaping and being caught at the outside of the Cu_6Sn_5grains so as to decrease the interfacial energy, which backs off IMC development. Yu *et al.*[37]reported that nano-particulate Ag_3Sn apparently precipitated on the surfaces of Cu_6Sn_5grains in the Sn–3.5Ag/Cu framework, and on the Ni_3Sn_4grains in the Sn–3.5Ag/Ni. It has been demonstrated that even little increases of Ag or Au into 58Bi–42Sn can fundamentally improve the isothermal weariness obstruction because of grain refinement. Increasing Au content additionally quickly increase the melting temperature in Bi–Sn–Au patches, yet no critical contrast is seen with Ag addition[10].

The addition of 0.05–0.5 wt.% of Co to the Sn–Bi solder framework shapes a Cu_6Sn_5IMC interfacial layer with low Co solvency, an impact which isn't seen with Zn addition. The Co suppresses the arrangement of $Cu_3Sn$and the development pace of Cu_6Sn_5increments with expanded Co expansion. This Cu_6Sn_5IMC layer displays a permeable structure with solder filled voids[21].

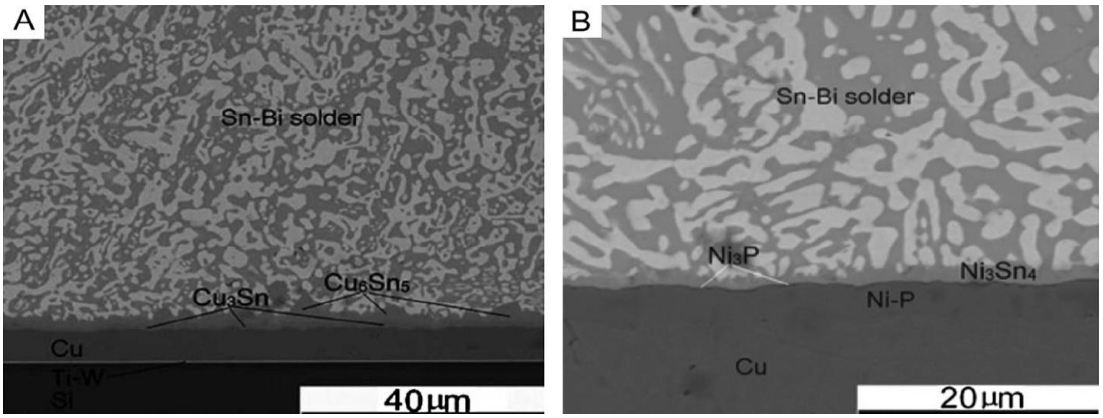

Fig. 3. Representative SEM images of (A) Sn–Bi/Cu system [28] and (B) Sn–Bi/Ni–P system [34]

V. MICROSTRUCTURES AND MECHANICAL PROPERTIES

The benefits of Sn-Bi solder incorporate great joint quality, astounding drag obstruction, low CTE, great wettability, and minimal cost [38]. 42Sn-58Bi solder is stronger but more brittle than 63Sn-37Pb on a Cu substrate at room temperature and the fatigue resistance of 42Sne58Bi is less than that of 63Sn-37Pb, but can be increased to a comparable level by alloying a small amount of Ag (2wt.%). Apart from the low melting point, the eutectic Sn/Bi has a low CTE value (15 ppm/°C) which is 1/3 lower than eutectic Pb/Sn[39]. The low CTE of eutectic Sn-Bi decreases the local thermal confound while soldering on low CTE material surfaces, for example, Alloy 42 (42Ni-58Fe), along these lines expanding the thermal fatigue life of solder joint [40].

Soldering Bi-containing solders on Cu substrates causes the effect of Bi isolation at the Cu/Cu_3Sn interface, which can significantly diminish the mechanical properties of the solder joints. Hu *et al.*[41]clarify that at higher fastening temperatures (over 280 °C), diffused Bi isolation collect at the Cu_3Sn/Cu interface, prompting Bi isolation at the Cu_3Sn/Cu interface and segregated Bi particles are framed on cooling [41]. Be that as it may, Gao *et al.*[42]announced that including La_2O_3(0.1-1.5 wt.%) into Sn-58Bi brings about the controlling of the isolation of Bi-rich stages during the cooling procedure and furthermore IMC grain development is smothered,

subsequently decreasing the fragility of the solder alloy. Properties are additionally improved by grain refinement reinforcing systems with a small melting point impact.

The slip planes cannot move openly which results in an absence of malleability [33]. Noteworthy Bi-rich stage coarsening can be seen in the parallel eutectic Sn-Bi solder joint during thermal aging at 120°C. In any case, the coarsening rate can be generously decreased by including 1 wt.% Cu into 42Sn-58Bi solder, with both Cu and Pt-Ag metalized Al_2O_3 substrate[26]. It was discovered that the expansion of RE components (0.5 wt.% Ce and La) to Sn-58Bi solder compound not just refines the microstructure and the molecule size of IMCs yet additionally diminishes the thickness of the IMC layer. The expansion of a follow measure of RE additionally improves the shear quality of Sn-58Bi based solder joint and altogether diminishes its weakening brought about by high-temperature aging. The expansion of RE conceivably brought about the change of microstructure, where the portion of net-like eutectic increments and the molecule size of IMCs diminishes[30]. Alloying influences on the mechanical properties of Sn-Bi based alloys have been summarized in **Table 2**.

Table 2
Influences of alloying on mechanical properties of Sn-Bi based alloys.

Alloy type	Condition	Young's modulus (GPa)	Shear modulus (GPa)	Stress exponent	Vickers hardness (Hv)	Tensile strength (MPa)	Elongation (%)	Ref.
Sn-Pb	Melt-spun, 10gf load, 90 s	40.21	14.78	4.302				[32]
Sn-58Bi	Melt-spun, 10gf load, 90 s	42.72	15.9	4.546				[32]
	Annealed at 50 °C, drawing speed 1 mm/min at 25 °C				18.58	73.24	24.8	[33]
Sn-58Bi-2In	Melt-spun, 10gf load, 90 s	45.5	16.97	4.802				[32]
Sn-58Bi-2Ag	Melt-spun, 10gf load, 90 s	46.15	17.18	5.234				[32]
Sn-58Bi-2In-2Ag	Melt-spun, 10gf load, 90 s	48.22	17.95	5.403				[32]
Sn-40Bi-0.1Cu	Annealed at 50 °C, drawing speed 1 mm/min at 25 °C				21.36	82.45	35.4	[33]
Sn-40Bi-2Zn-0.1Cu	Annealed at 50 °C, drawing speed 1 mm/min at 25 °C				22.28	89.31	13.3	[33]

VI. RELIABILITY

According to Table 2, 58Bi-42Sn is more vigorous but more brittle than 63Sn-37Pb at room temperature. Due to its lamellar structure as shown in **Fig. 4**, the fatigue life of eutectic Bi-Sn is poor compared to Sn-Pb. However, a small addition of Ag or Au into eutectic Bi-Sn dramatically ameliorates the thermal fatigue resistance. The alloy 58Bi-42Sn-2Ag lasts significantly longer than the 58Bi-42Sn and is comparable to 63Sn-37Pb. Au has a homogeneous effect, yet too much Au causes embrittlement. Sn-Bi solder with 1.5 wt.% Ag or 0.5 wt.% Au also provides stronger adhesion on Alloy 42 component lead surfaces[40]. As reliability is emphatically impacted by microstructural development.

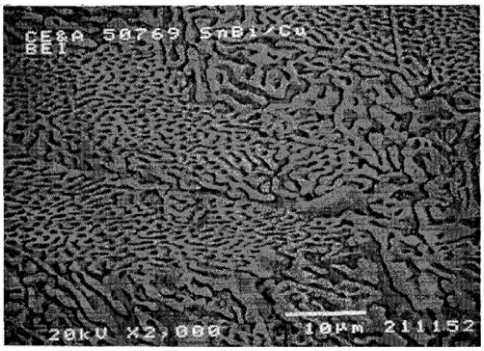

Fig. 4. The lamellar structure of eutectic Sn-Bi on Cu finished surfaces, reproduced with permission from Ref.[40].

VII. DISCUSSION

For the case the Sn-Bi solder is utilized to accumulate a region cluster bundle with a higher melting point solder, it is additionally essential to assess its change into the fluid stage. Since early exchanges on the probability of embracing Sn-Bi alloy as a Pb-free solder, plainly their poor mechanical properties, eminently inordinate fragility and lower elongation, would be an impediment. Figure 5 shows the tensile properties of Sn-Bi alloys with the decrement of Bi content. It showed that the low Bi content elongation of Sn-Bi alloy during the tensile test.From the perspective of reliability, the moderate development pace of interfacial IMCs can be accomplished by giving a decent dispersion boundary layer of low-temperature lead-free solders.

Another alternative for improving Sn-Bi alloys mechanical properties is the utilization of alloying increments. As discussed before, alloying increments can be utilized to improve eutectic Sn-Bi execution, for example, mechanical properties, drop shock and thermal cycling [40].The impacts of contaminations on intermetallic responses are additionally noteworthy in all frameworks. The components can affect solidification of the solder and on interfacial IMC development, with mechanical properties either improving or corrupting relying upon the stage arrangement. Due to their lower processing temperature (<200 °C) and raw material cost (40%-50% the cost of SAC) Sn-Bi solder alloys offer technical advantages and cost-effectiveness over standard SAC based lead-free solders in consumer electronic applications.Finally, a reasonable compound organization is key for accomplishing the ideal execution results.

All things considered, solder alloy composition and properties must be painstakingly assessed. Other related works can be found in[43][44][45][46][47][48][49].

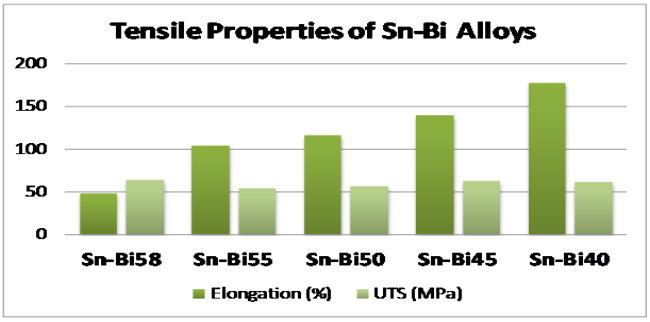

Fig. 5. Tensile properties of Sn-Bi alloys [50].

VIII. CONCLUSION

In this article,a diagram of the present best in class in Pb-free solder, with an accentuation on the impacts of different substrates and alloying components, before moving onto spread how the approach of component increases has opened up new open doors for novel approaches to improve solder quality and reliable quality. Framing reliable solder without Pb is an imposing undertaking, regardless need further understanding from physical metallurgy to propel our insight into ternary and quaternary Pb-free solder frameworks to enable us to really proceed onward from the double Sn–Pb patch of the past. Besides, expanding weight is being set on the nature of patch by cutting edge bundling models that request ever better execution from interconnections. Consequently, proceeding with an investigation into understanding the mind-boggling connections of metallurgy, mechanical conduct, and dependability, for all classes of solders, is basic to drive development in the electronics application.Future patterns in the electronics industry manage that these interconnect materials will be required for applications in portable, scaled-down, incorporated and wearable customer gadgets.Other potential applications for these materials are in warmth touchy units, for example, optoelectronic segments.So as to understand these goals various specialized difficulties stay to be tended.These incorporate new motion frameworks that will empower oxide evacuation, the satisfactory timeframe of realistic usability and suitable wetting for these materials; reliability testing to decide segment lifetimes and failure components related to new intermetallics shaped with copper substrates, and alloying to tailor property/preparing connections inside these alloys.Moreover, this result give a detailed clarification of the development of interfacial IMCs in Sn-Bi solder alloys, which are known to assume a vital job in joint structure, and development between different solders and substrates. As an interfacial response happens, one, for the most part, anticipates that the substrate should break up into the fluid solder, trailed by a compound response between the solder and substrate alloying components, and then lastly solidification happened. The significance of each stage differs between frameworks relying upon the dissolvability of components.The characteristics of the interfacial IMCs are essential in characterizing the reliable quality of solder joints of Sn-Bi as a result of the impacts that the diverse IMCs have on the mechanical properties.

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