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Reliability-Oriented Design of Low-Temperature Sn–Bi Solder Interconnects for Advanced Packaging Systems

Eunsung KIM[1], Heebo HA[1], Yuntae LEE[1], Dragan MARINKOVIC[2,3], and Byungil HWANG[4,*]

[1]Department of Intelligent Semiconductor Engineering, Chung-Ang University, 06974 Seoul, Republic of Korea
[2]Department of Structural Analysis, Technical University Berlin, 10623 Berlin, Germany
[3]Mechanical Science Institute, Vilnius Gediminas Technical University—VILNIUS TECH, Plytines St. 25, LT-10105 Vilnius, Lithuania
[4]School of Integrative Engineering, Chung-Ang University, 06974 Seoul, Republic of Korea
Email: dltnals9902@cau.ac.kr, hhb2348@cau.ac.kr, lyt0076@cau.ac.kr, dragan.marinkovic@tu-berlin.de, bihwang@cau.ac.kr*
* Corresponding author

Abstract. The rapid growth of artificial intelligence, electric vehicles, and high-performance computing has accelerated the demand for miniaturized and thermally reliable electronic packages. As front-end scaling approaches its physical limits, advanced packaging has become central to improving system performance. However, heterogeneous integration, 2.5D/3D packaging, and chiplet architectures intensify thermomechanical reliability concerns because materials with different coefficients of thermal expansion are integrated within confined structures. Conventional Sn–Pb solders offered low processing temperatures and excellent ductility, but their toxicity drove the transition to lead-free systems. Sn–Ag–Cu solders, especially SAC305, have been widely adopted for their mechanical strength and fatigue resistance; nevertheless, their high melting temperature aggravates warpage, interfacial delamination, and thermal stress. In this context, Sn–Bi solders have attracted attention as low-temperature candidates, since eutectic Sn–58Bi melts near 138–139 °C. Despite this advantage, they suffer from brittleness, Bi-rich phase segregation, microstructural coarsening, electromigration-related degradation, and excessive interfacial intermetallic growth. This manuscript reviews the evolution of conventional solder systems, the metallurgical characteristics of Sn–Bi alloys, and recent strategies including micro-alloying and nanocomposite reinforcement for improving the reliability of low-temperature solder joints in advanced packaging applications.

Key-words: Advanced packaging; intermetallic compound; lead-free solder; low-temperature solder; micro-alloying; nanocomposite solder; Sn–Bi solder; thermal reliability.

1. Introduction

In recent years, the electronics industry has been driven by the rapid development of artificial intelligence (AI), electric vehicles (EVs), high-performance computing (HPC), and the Internet of Things (IoT) [1], all of which simultaneously demand higher integration density, higher performance, and further miniaturization [2]. As the conventional approach of improving semiconductor device performance through front-end-of-line (FEOL) feature scaling alone has approached its physical limits, packaging technology has emerged as a key factor that determines overall system performance [3], evolving beyond the role of simple electrical interconnection to simultaneously address thermal management [4], signal integrity, and mechanical stability [5]. Despite these advances, several issues at the solder joint, such as the growth of interfacial intermetallic compounds (IMCs) and thermal fatigue driven by coefficient of thermal expansion (CTE) mismatch, have remained unresolved key challenges. To overcome the scaling bottlenecks of conventional architectures, advanced packaging technologies such as 2.5D/3D packaging, through-silicon via (TSV), fan-out wafer-level packaging (FOWLP), and heterogeneous integration have been rapidly developed [7], but interfacial delamination, warpage, and microcrack formation under repetitive thermal cycling are now recognized as critical variables that govern the reliability of next-generation packaging [6].

For decades, Sn–Pb solders have been used as the standard joining material in the electronics industry. However, due to the severe toxicity of Pb to human health and the environment, the strict enforcement of the European Union's Restriction of Hazardous Substances (RoHS) directive has made the transition to lead-free solders mandatory [8]. Against this background, Sn–Ag–Cu (SAC) solders have emerged as a primary lead-free alternative; nevertheless, they also have drawbacks, as their melting temperature is relatively high, ranging from approximately 217 to 221 °C, which significantly increases the thermal budget of electronic packaging processes [9]. Moreover, in next-generation applications such as wearable electronics, flexible displays, and bioelectronic devices, conventional high-temperature soldering is becoming increasingly difficult [10].

To address these technical requirements, extensive research has focused on low-temperature solders capable of forming stable interconnects, among which Sn–Bi-based solders have attracted significant attention as a promising low-melting-point alternative [11], and their solidification behaviour for electronic packaging has been actively investigated [12]. The eutectic Sn–58Bi composition exhibits a low melting temperature of approximately 139 °C, allowing the soldering process to be carried out more than 80 °C lower than that of conventional SAC solders, which not only minimizes thermal damage and improves compatibility with various substrates [14] but also effectively reduces the thermal stress arising from CTE mismatches [13]. Despite these advantages, Sn–Bi solders suffer from inherent microstructural limitations: they exhibit a eutectic microstructure consisting of an Sn-rich phase and a highly brittle Bi-rich phase [15], and the excessive growth of interfacial IMCs with Cu pads serves as another major mechanism compromising long-term reliability [16]. To overcome these limitations, recent studies have proposed diverse metallurgical approaches, including micro-alloying, ceramic and metallic nanoparticle reinforcement, interfacial diffusion barrier engineering, transient liquid phase (TLP) bonding, and hybrid bonding [17].

The remainder of this manuscript is organized as follows. Section 2 reviews conventional Sn–Pb and SAC solder systems and discusses their metallurgical characteristics and the reliability limitations that motivate the move to low-temperature alternatives. Section 3 examines metallurgical reinforcement strategies for Sn–Bi solders, covering Ag addition (Section 3.1), Zn and Ni additions (Section 3.2), In addition for ultra-low-temperature processing (Section 3.3), and nanocomposite solders reinforced with ceramic nanoparticles (Section 3.4). Section 4 outlines the remaining challenges and future research directions for applying these approaches to advanced packaging architectures, and Section 5 summarizes the main conclusions of the review.

2. Conventional Solder Systems and Their Limitations

In the early stages of electronic packaging technology, Sn–Pb-based solders were the most widely used, owing to their excellent wettability, low process temperature, and high ductility [18]. From a microstructural perspective, Sn–Pb solders exhibit a dual-phase structure in which a Pb-rich phase is dispersed within an Sn-rich matrix [19], which is a key factor that improves both the impact resistance and the thermal fatigue resistance of solder joints [20]. Despite these superior thermomechanical properties, the severe toxicity of Pb has acted as a decisive factor restricting the use of Sn–Pb solders [21], and the strict enforcement of global regulations such as the RoHS directive has made the transition to lead-free solders mandatory.

Among the lead-free alternatives to Sn–Pb solders, the SAC alloy—particularly the SAC305 composition—has emerged as the industry standard [22], owing to its high mechanical strength and excellent thermal fatigue performance. IMCs such as Ag_3Sn and Cu_6Sn_5 precipitate within the Sn matrix during solidification. Moreover, when a thermal gradient is present across the solder joint, the Cu_6Sn_5 growth becomes highly asymmetric: in Cu/Sn/Cu joints reflowed at 280 °C under a simulated thermal gradient of ∼154.5 °C/cm, the Cu_6Sn_5 layer at the cold end grows markedly thicker than that at the hot end, owing to the rapid thermomigration (TM) of Cu atoms from the hot side to the cold side. This highlights that interfacial reliability in SAC joints is governed not only by isothermal diffusion kinetics but also by directional mass transport driven by local temperature gradients [23]. The growth behavior of interfacial IMCs is governed by a diffusion-controlled mechanism, where x is the thickness of the IMC layer, D is the diffusion coefficient, and t is time:

$$x = (D \cdot t)^{1/2}. \tag{1}$$

An appropriate IMC layer is essential for forming a strong metallic bond, but excessive growth is harmful; in particular, Kirkendall voids often form at the Cu_3Sn/Cu interface due to the asymmetric diffusion rates of Cu and Sn during solid-state aging [24]. In addition, owing to the relatively high melting temperature of 217–221 °C, the heat required for the packaging process is significant, and this excessive heat induces thermomechanical stress caused by the CTE mismatch between the substrate and the chip, which can be expressed as [25]:

$$\sigma = E \cdot \Delta\alpha \cdot \Delta T, \tag{2}$$

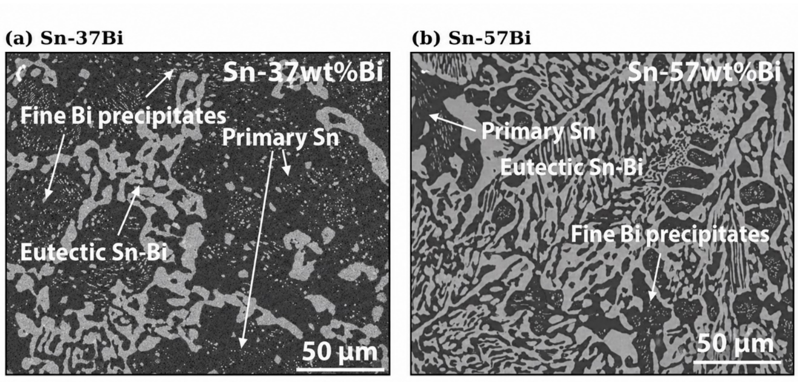

Fig. 1. Microstructural comparison of (a) hypoeutectic Sn–37Bi and (b) near-eutectic Sn–57Bi alloys. In (a), large primary β-Sn dendrites disrupt the continuity of the Bi-rich eutectic network, whereas (b) is dominated by a continuous lamellar Sn–Bi eutectic structure. The disruption of the Bi network by primary β-Sn in hypoeutectic compositions is the key microstructural origin of improved ductility and impact resistance in Sn–Bi solder joints. Adapted from Ref. [26] under CC BY 4.0.

where E is the elastic modulus, $\Delta\alpha$ is the difference in CTE between the materials, and ΔT is the temperature change.

Recent advances in electronic packaging have moved beyond conventional 2D packaging to 2.5D/3D integration, TSV, FOWLP, heterogeneous integration, and chiplet-based architectures. These architectures integrate materials with very different CTEs, such as silicon, copper, polymers, and underfill, within an extremely limited space, and during high-temperature reflow and subsequent operation these mismatches generate severe thermomechanical stress. The resulting shear stress concentrates at the solder interconnects and gives rise to three representative failure modes—pad-matrix failure at the substrate-side Cu pad, bulk solder failure within the solder ball, and UBM/IMC failure at the die-side under-bump metallization—each of which can act as a dominant degradation pathway depending on the local stress distribution. To address these interconnected problems, Sn–Bi-based low-temperature solders are emerging as a very promising alternative.

With a eutectic melting point of approximately 139 °C, Sn–Bi solder enables reflow at temperatures significantly lower than those required for conventional SAC alloys. However, despite this process advantage, Sn–Bi solder possesses inherent microstructural vulnerabilities: during repeated thermal cycling and long-term aging, the Bi-rich phase becomes severely coarsened along with the continuous growth of interfacial IMCs, ultimately degrading long-term reliability. Fundamentally, the inherent brittleness of this Bi-rich phase is a primary point of crack propagation under dynamic shock or thermomechanical loading [27]. The lamellar spacing of such a eutectic microstructure is generally described by the Jackson–Hunt relation:

$$\lambda^2 \cdot V = C, \tag{3}$$

where λ is the lamellar spacing, V is the growth velocity, and C is an alloy-system-dependent constant. Because the continuous, coarse Bi-rich network provides a low-energy path for crack propagation, hypoeutectic compositions with reduced Bi content are often used: the primary precipitation of ductile β-Sn dendrites physically interrupts the continuity of the brittle Bi-rich network, significantly improving the macroscopic ductility and drop-impact resistance of the joint. This microstructural contrast is clearly demonstrated in Fig. 1, where the hypoeutectic Sn–37Bi alloy (Fig. 1a) exhibits coarse primary β-Sn regions that interrupt the eutectic matrix, whereas the near-eutectic Sn–57Bi alloy (Fig. 1b) is dominated by a continuous lamellar eutectic structure that provides a connected pathway for crack propagation through the brittle Bi-rich phase [26].

3. Metallurgical Reinforcement Strategies for Sn–Bi Solders

3.1. Effect of Ag addition

Ag is an important trace alloying element for controlling the microstructure of Sn–Bi solders and improving their thermomechanical properties. Yang et al. [28] reported that adding 5 wt.% Ag near the eutectic point of Sn–Bi alloys precipitates needle-shaped Ag_3Sn IMCs; quantitative analysis showed that this increased the Vickers hardness of the binary $Bi_{60}Sn_{40}$ alloy from 14.59 $\pm$ 1.69 HV to 17.33 $\pm$ 2.79 HV for $Bi_{60}Sn_{35}Ag_5$. This enhancement of approximately 18.8% is primarily attributed to precipitation hardening, and trace Ag additions were also shown to reduce the contact angle by approximately 15%, improving solder spreadability and initial bond strength. From a thermodynamic perspective, Ag exhibits a duality in diffusion kinetics governed by the Arrhenius relationship [29]:

$$D = D_0 \exp\left(-\frac{Q}{RT}\right), \tag{4}$$

where D is the diffusion coefficient, D_0 is the frequency factor, Q is the activation energy, R is the universal gas constant, and T is the absolute temperature. Ag increases the activation energy Q required for diffusion (e.g., from 76.6 to 86.8 kJ/mol for 0.4 wt.% Ag), acting as an initial barrier against the nucleation of harmful IMCs; however, it simultaneously increases D_0 (from 5.7×10^{-6} to 7.7×10^{-6} m^2/s), implying that if the thermal activation threshold is exceeded during long-term aging, Ag can accelerate atomic mobility and promote interfacial IMC overgrowth. The intrinsic resistivity of the Bi phase is exceptionally high at approximately 129.9 $\mu\Omega$·cm, whereas the Sn phase exhibits approximately 11 $\mu\Omega$·cm and the Ag_3Sn phase only 6.08 $\mu\Omega$·cm, so finely dispersed Ag_3Sn can provide low-resistance pathways through the Bi-rich matrix. The optimal Ag content is, however, strongly dependent on the base composition: as shown in Fig. 2 for a dilute Sn–Bi alloy, a moderate Ag addition refines the eutectic, whereas beyond roughly 1.0 wt.% the Ag_3Sn coarsens into rough, brittle plate-like phases that act as stress concentration points and increase both the joint resistance and the interfacial IMC thickness under thermal aging [30].

3.2. Effect of Zn and Ni additions

As a cost-effective microalloying strategy, Zn addition has been studied to mitigate the inherent brittleness of Sn–Bi solders and improve interfacial stability. Nishikawa et al. [31] demonstrated that adding 2.6 wt.% Zn to Sn–45Bi alloys near the eutectic point effectively destroys the continuous layered Bi network and increases the volume fraction of the ductile β-Sn phase. At the Cu interface, the conventional shell-shaped Cu_6Sn_5 IMC was replaced by a highly flat Cu_5Zn_8 reactive layer; however, since Zn is highly sensitive to oxidation, a highly active flux must be used in the reflow process, and the resulting alloy generally has poor corrosion resistance that limits

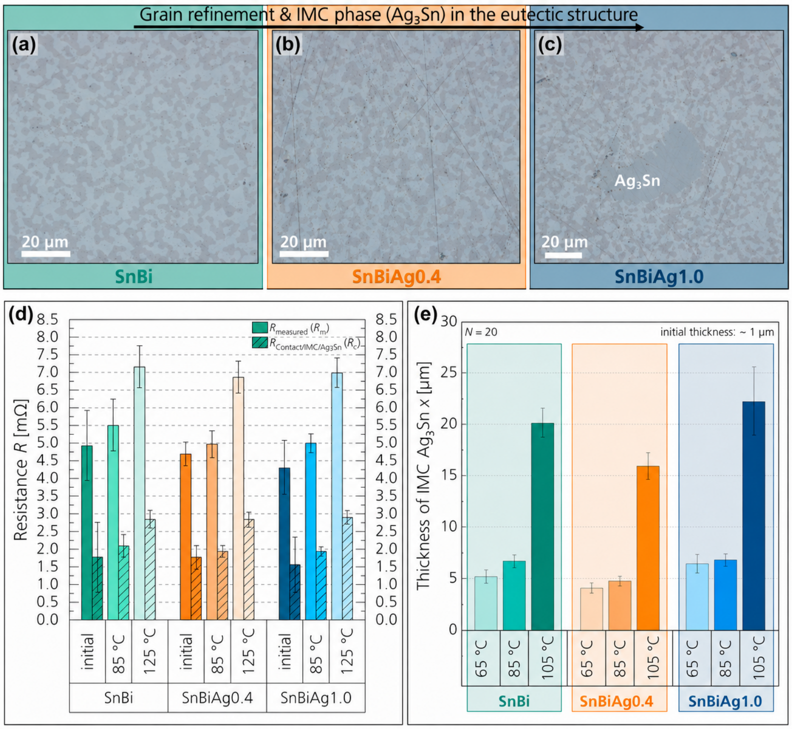

Fig. 2. Microstructural and reliability effects of Ag micro-alloying in Sn–Bi solder. (a–c) Optical micrographs of (a) SnBi, (b) SnBi–0.4Ag, and (c) SnBi–1.0Ag, showing progressive grain refinement and a coarse plate-like Ag_3Sn IMC at 1.0 wt.% Ag. (d) Measured (R_m) and contact/IMC (R_c) resistance after aging at 85 and 125 °C. (e) Interfacial Ag_3Sn IMC thickness after aging at 65–105 °C. Adapted from Ref. [30] under CC BY 4.0.

its widespread use. To overcome these chemical limitations, Ni microalloying has emerged as a strong alternative offering excellent chemical stability, enhanced electromigration (EM) resistance, and superior high-temperature reliability. Jawad et al. [32] reported that adding 0.25–1.0 wt.% Ni to a Sn–30Bi matrix precipitates Ni_3Sn_4 IMC, increasing the tensile strength from 56 MPa for untreated Sn–30Bi to 68, 72, and 75 MPa at 0.25, 0.5, and 1.0 wt.% Ni, respectively, although the elongation correspondingly decreased from 28% to 25%, 23%, and 22%. Trace Ni additions also markedly improve EM resistance: at a current density of 2,000 A/m^2, the time to failure of Sn–30Bi–0.5Ni surged from about 3,000 to 54,000 seconds, an improvement of more than ten times, and adding 0.1 wt.% Ni to eutectic $Sn_{58}Bi$ at 100 °C increased the indentation hardness from 14.67 to 21.05 MPa while suppressing creep. Fig. 3 summarizes these effects of Ni: the simultaneous gains in tensile strength, EM resistance, and melting-point stability, set against a controlled trade-off in ductility. Despite these improvements, neither Zn nor Ni can fundamentally eliminate the brittleness of the Bi-rich phase, and because excessive addition risks inducing new stress concentration points through coarse IMCs, research is gradually shifting toward In alloys.

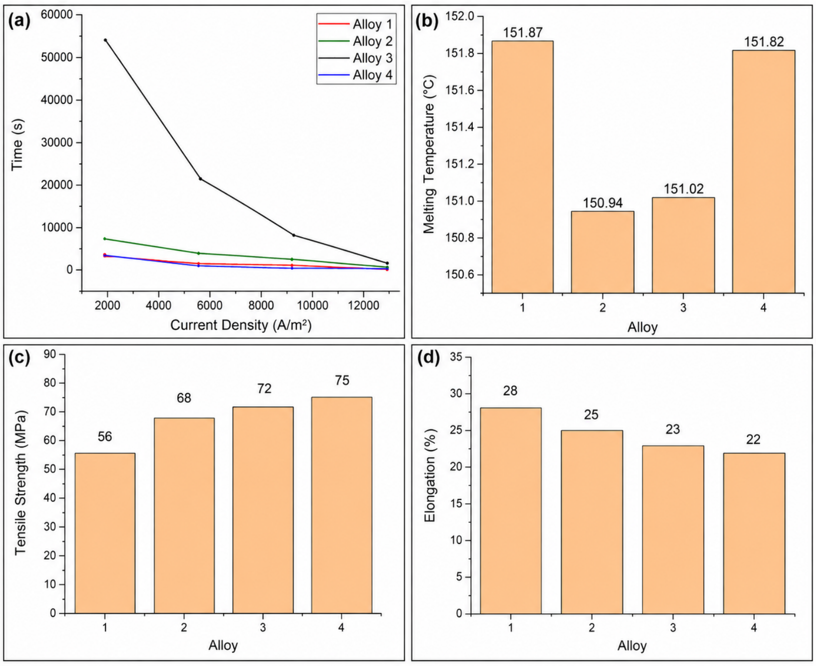

Fig. 3. Effect of Ni micro-alloying (0, 0.25, 0.5, 1.0 wt.%) on Sn–30Bi solder. (a) Time-to-failure vs. current density showing $>10\times$ improvement in EM resistance for Sn–30Bi–0.5Ni; (b) melting temperature; (c) tensile strength ($56 \rightarrow 75$ MPa); and (d) elongation ($28 \rightarrow 22\%$), highlighting the strength–ductility trade-off from Ni_3Sn_4 precipitation. Adapted from Ref. [32] under CC BY 4.0.

3.3. In addition for ultra-low-temperature processing and enhanced ductility

Adding In is an effective microalloying strategy in Sn–Bi-based systems to further lower processing temperatures while improving microstructural stability. Because In is itself a very low-melting element, its incorporation depresses the eutectic temperature of Sn–Bi alloys and broadens the available low-temperature processing window [11]; however, such hyperalloyed compositions precipitate additional brittle Bi–In intermetallic phases that act as local stress concentration points and can induce secondary brittleness. In addition, In promotes a more uniform dissolution and distribution of Bi within the β-Sn matrix, thereby mitigating the segregation and coarsening of the brittle Bi-rich phase that otherwise limits the ductility of Sn–Bi joints. In microalloying thus offers eutectic refinement, thermal-budget suppression, and Bi-segregation mitigation, but the formation of brittle Bi–In IMCs, microstructural coarsening at high In contents, and the high cost of raw In impose strict constraints on large-scale application.

3.4. Nanocomposite solders

Trace alloying with Ag, Zn, Ni, and In has motivated further work that seeks more precise control of the thermomechanical properties of Sn–Bi solders through additional alloying elements, including rare-earth elements such as Ce and La [33]. To move beyond the intrinsic limits of solid-solution alloying, however, recent research has increasingly turned to composite solders reinforced with second-phase particles, which strengthen the joint through physical rather than purely metallurgical mechanisms [17]. Unlike metallic additions, ceramic nanoparticles do not undergo direct interfacial alloying within the molten matrix; instead, they act as thermodynamically stable dispersed phases that preferentially segregate along grain boundaries and interfaces, exerting a strong Zener pinning effect. Small additions of ceramic nanoparticles can refine the coarse, elongated Bi network into a finer and more uniform microstructure, thereby improving wettability, shear strength, and ductility. However, such reinforcement exhibits a strict concentration threshold: only minor additions (typically below about 0.5 wt.%) are beneficial, whereas exceeding this critical amount inevitably leads to severe nanoparticle aggregation that degrades both wettability and mechanical performance.

A similar concentration-dependent trade-off is generally expected for other ceramic reinforcements such as TiO_2 and ZrO_2. In all such systems, ceramic reinforcements suppress dislocation movement and inhibit excessive IMC growth, but their interfacial bonding remains limited by their chemically inert nature.

4. Outlook and Future Research Directions

Sn–Bi solders enable low-temperature bonding that reduces the thermomechanical burden of conventional SAC soldering, but their practical application requires a careful balance between processability, mechanical reliability, interfacial stability, electrical conductivity, and long-term microstructural stability [12]. The reinforcement strategies reviewed above are summarized in Table 1. First, the brittle Bi-rich phase must be controlled; second, interfacial IMC growth must be regulated, because excessive IMC formation induces brittle fracture whereas insufficient interfacial reaction weakens metallurgical bonding; and third, EM and TM behavior must be investigated under realistic fine-pitch and high-current-density conditions. Overall, future development is likely to move toward integrated materials design, combining controlled alloy chemistry, reinforced microstructures, engineered interfaces, and process optimization.

Table 1. Summary of metallurgical reinforcement strategies for Sn–Bi solders

Strategy	Main effect	Representative benefit	Potential limitation
Ag addition	Ag_3Sn formation and eutectic refinement	Hardness and conductivity improvement	Coarse Ag_3Sn plates can increase brittleness
Zn addition	Bi network suppression and Cu_5Zn_8 interfacial layer	Lower processing temperature and improved interfacial stability	High oxidation tendency requiring active flux
Ni addition	Ni_3Sn_4 formation and grain boundary pinning	Higher strength and EM resistance	Ductility reduction at excessive contents
In addition	Lower eutectic temperature and enhanced Bi solubility	Ultra-low-temperature processing and microstructural homogeneity	High cost and Bi–In IMC formation
Ceramic nanoparticles	Grain refinement and dispersion strengthening	Improved strength and suppressed coarsening	Agglomeration and wettability degradation

5. Conclusions

Sn–Bi solders offer a clear advantage over SAC solders because their low melting temperature can reduce thermal stress, energy consumption, and substrate damage. However, the intrinsic brittleness of the Bi-rich phase, Bi segregation, microstructural coarsening, EM-induced degradation, and interfacial IMC growth remain major barriers to reliable application.

Micro-alloying with elements such as Ag, Zn, Ni, and In can refine the microstructure, improve strength, regulate interfacial reactions, and enhance thermal stability, while ceramic nanoparticle reinforcement using WO_3, TiO_2, and ZrO_2 provides additional routes for grain refinement and dispersion strengthening. A comprehensive design strategy that integrates alloying, nanoparticle reinforcement, interfacial engineering, and reliability evaluation is required to establish Sn–Bi solder as a practical low-temperature interconnect material for next-generation advanced packaging.

Looking ahead, the brittle Bi-rich network should be further suppressed through eutectic refinement, hypoeutectic composition design, and micro-alloying, while interfacial IMC growth is balanced to avoid both brittle fracture and weak bonding. Electromigration and thermomigration behaviour must be evaluated under realistic fine-pitch, high-current-density conditions, and nanoparticle reinforcement should be designed for dispersion stability through surface modification, hybrid particle systems, and optimized flux chemistry.

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