Thermomechanical Reliability of Bi-Based Solders for HTP

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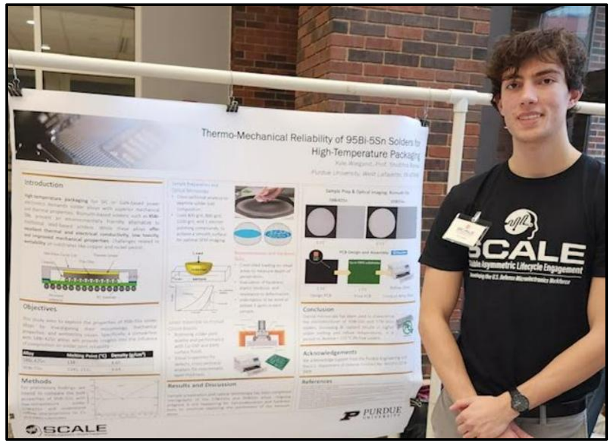
About Me: Kyle Wiegand

Journey into Advanced Packaging



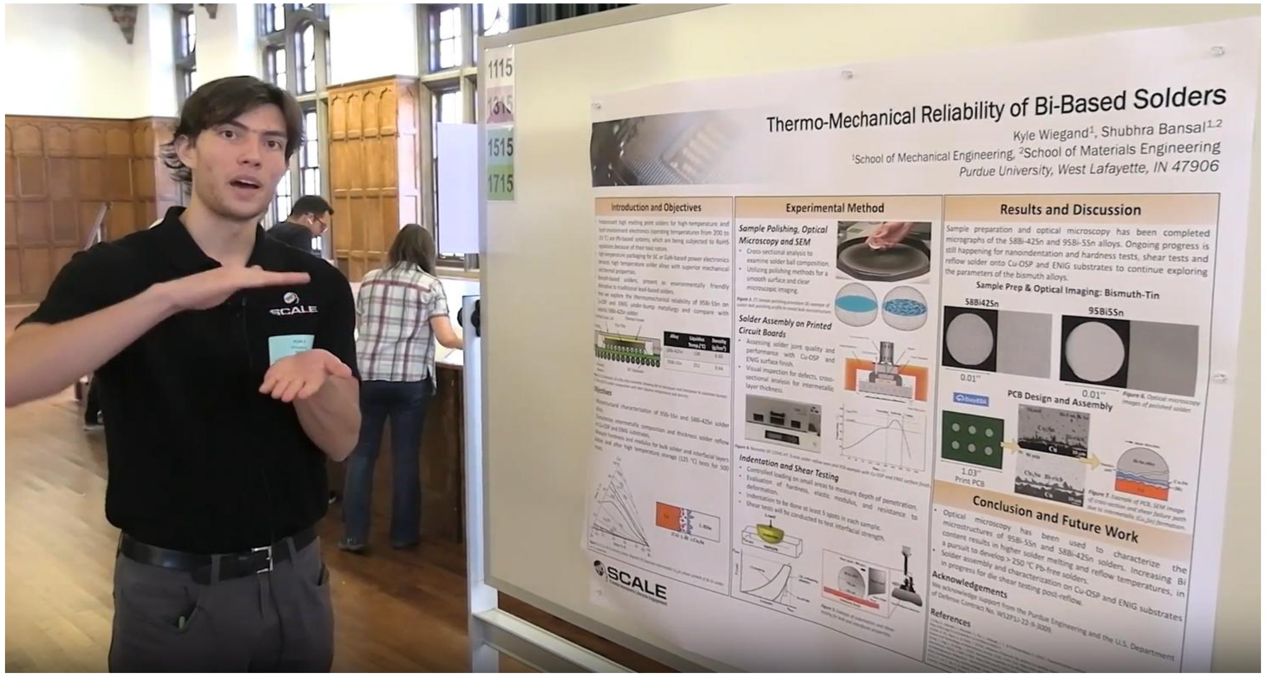
- Currently an undergraduate student at **Purdue University**. Graduating May 2025 with a Mechanical Engineering (ME) major with an Electrical & Computer Engineering (ECE) minor.
- Became involved in advanced packaging research through the **SCALE** program May 2023. Worked with a team of graduate students mentored by Shubra Bansal, Associate Professor of Mechanical Engineering and Materials Engineering.
- Post-graduation, I will continue to work in the advanced packaging field with **HRL Laboratories** for the innovation and development of 2.5D and 3D semiconductor integration processes for RF and high-speed mixed-signal electronics applications.

What is SCALE?

Program Motivation & Goals

- **Scalable Asymmetric Life Cycle Engagement** (SCALE) is an immersive educational program that combines government/DIB internships with aligned research and mentoring to deepen understanding and relationship building for undergraduate and graduate students.
    - Growing to over 2,000 students and 40 universities.
    - Achieving sustainable K-12 classroom engagements across the U.S.
    - Enhancing the microelectronics curriculum at community colleges and offering continuing education programs for practicing professionals

<u>SCALE Directors</u>: Peter Bermel, Kerrie Douglas.



2024 – 2025 SCALE HIAP Scholarship Winners

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SCalable Asymmetric Lifecycle Engagement
Developing the U.S. Defense Microelectronics Workforce

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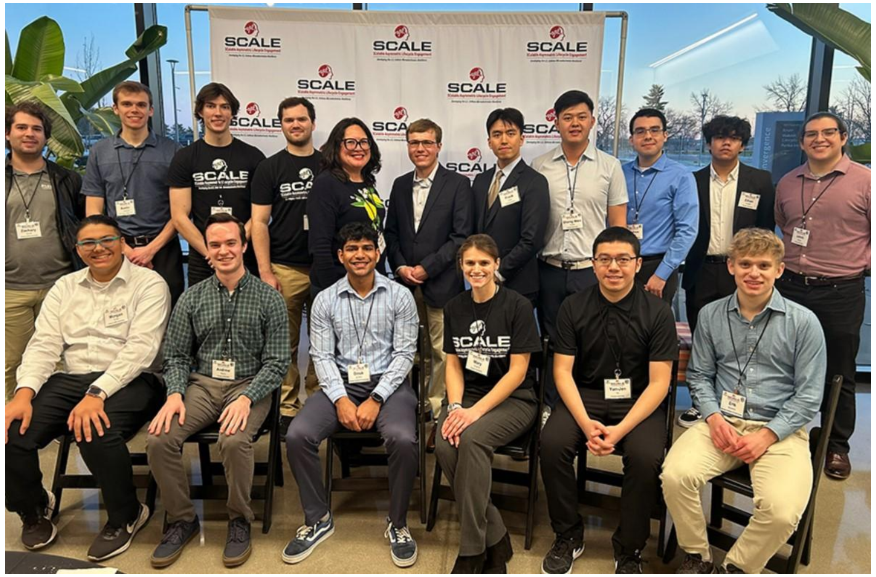

Fall 2024 SCALE HIAP Poster Awards

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Introduction to Bi-Based Solders

Background Information, Research Objectives, & Relevant Work.

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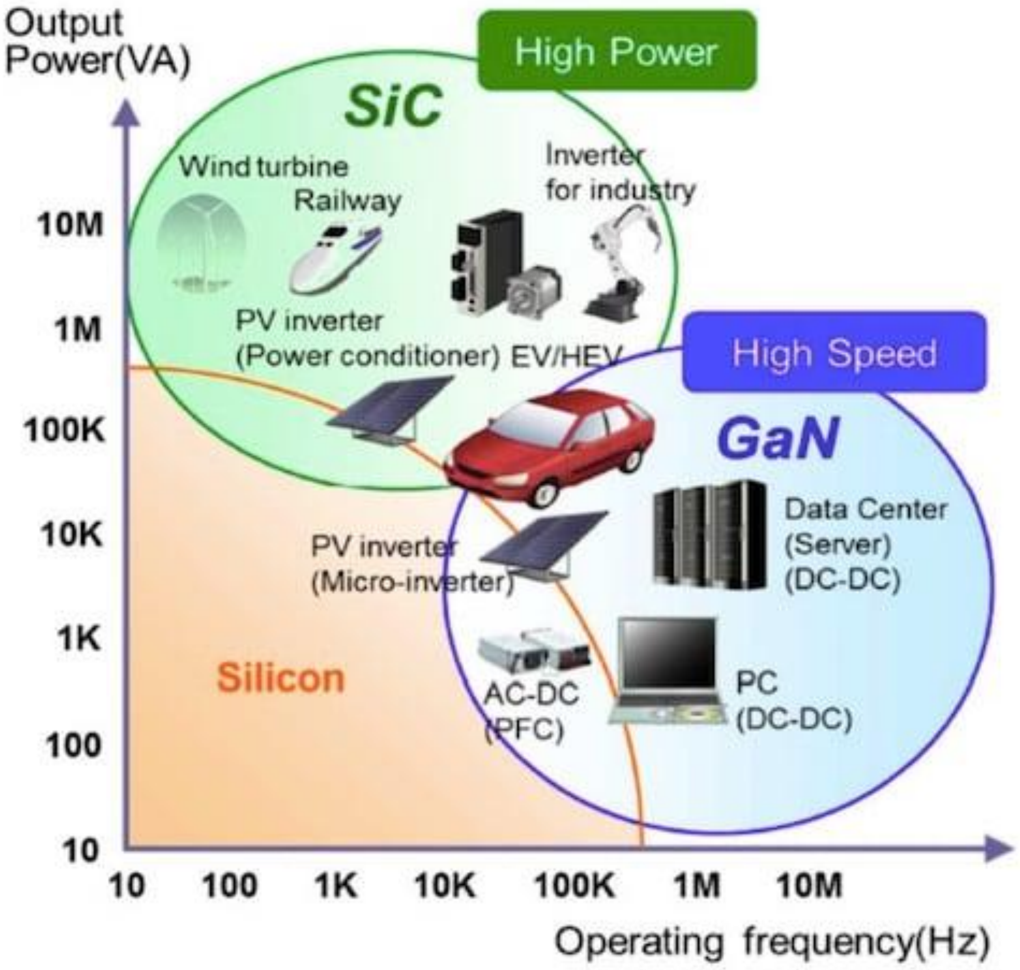
Reliability of Bismuth-Based Solders: Motivation

Background Information and Research Objectives

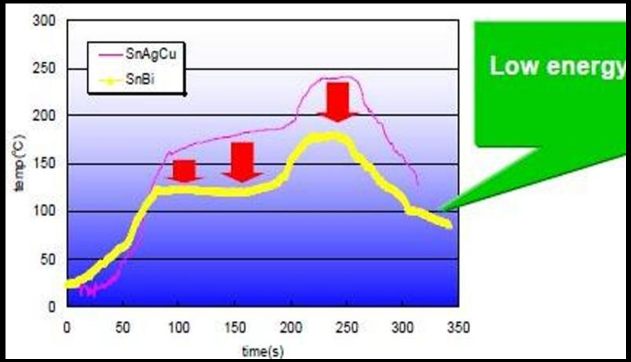
- The semiconductor industry's need for materials that can withstand high temperatures (200–250°C) has driven the development of advanced solder alloys, especially for SiC and GaN-based power electronics.
- RoHS regulations have led to a transition from traditional lead-based solders to environmentally friendly, lead-free alternatives, which are now matching the performance of lead-based solders while offering environmental benefits.



Advantages of Bismuth-Based Solders

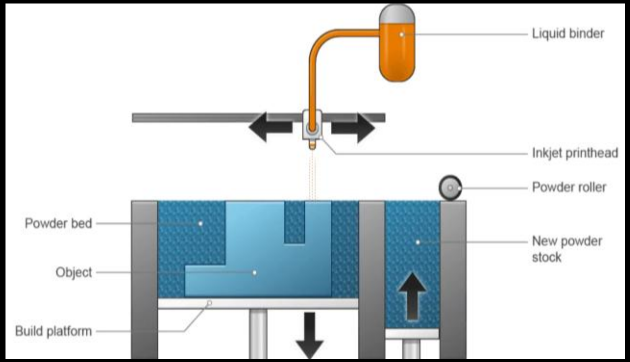
Low Melting Point

Defects such as delamination can be minimized or eliminated by using lower temperature solders. With Eutectic Sn58Bi have a melting point of 138°C, the reduced thermal stress during reflow help prevent damage to sensitive components and substrates.



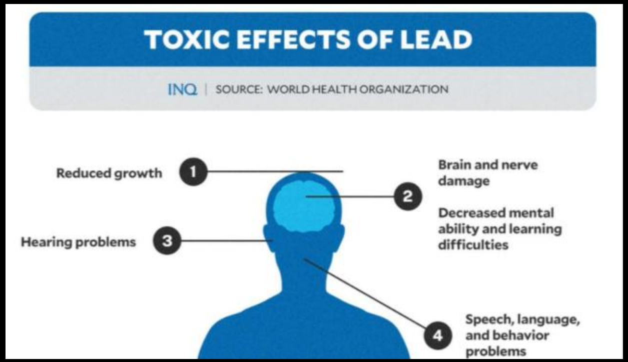
Additive Manufacturing & Printing

Lead solidifies quickly and tends to warp, making it difficult to maintain print precision, detail, and integrity. Bismuth has a stable and predictable cooling behavior that enhances precision and quality for these types of applications.



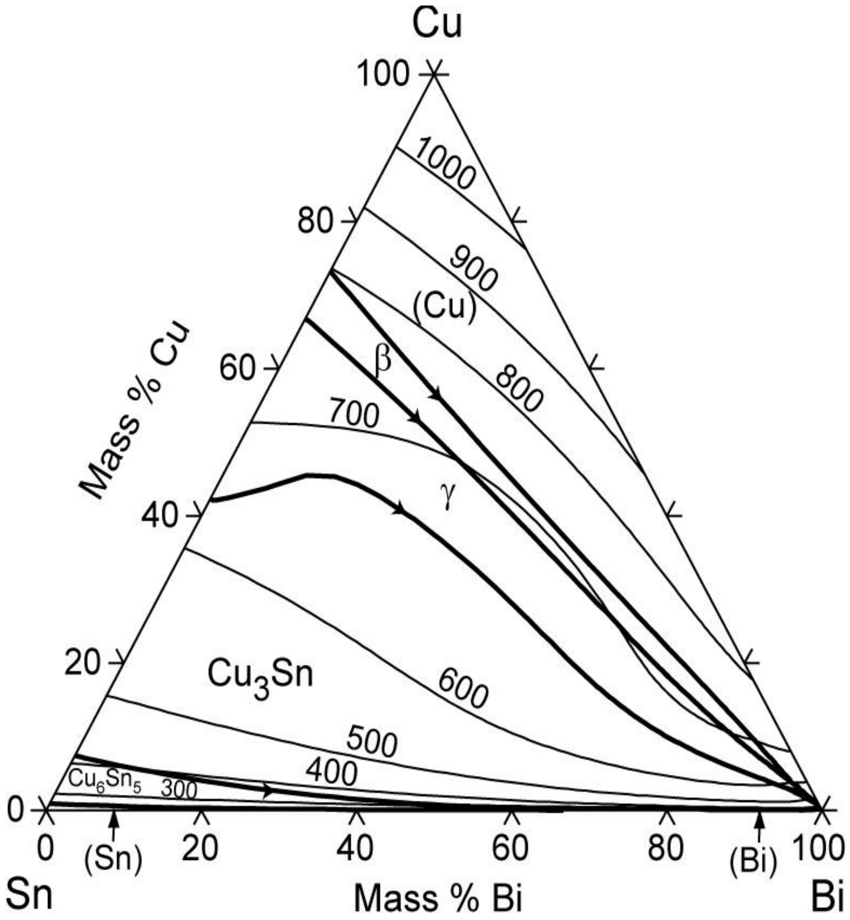
Health & Environmental Benefits

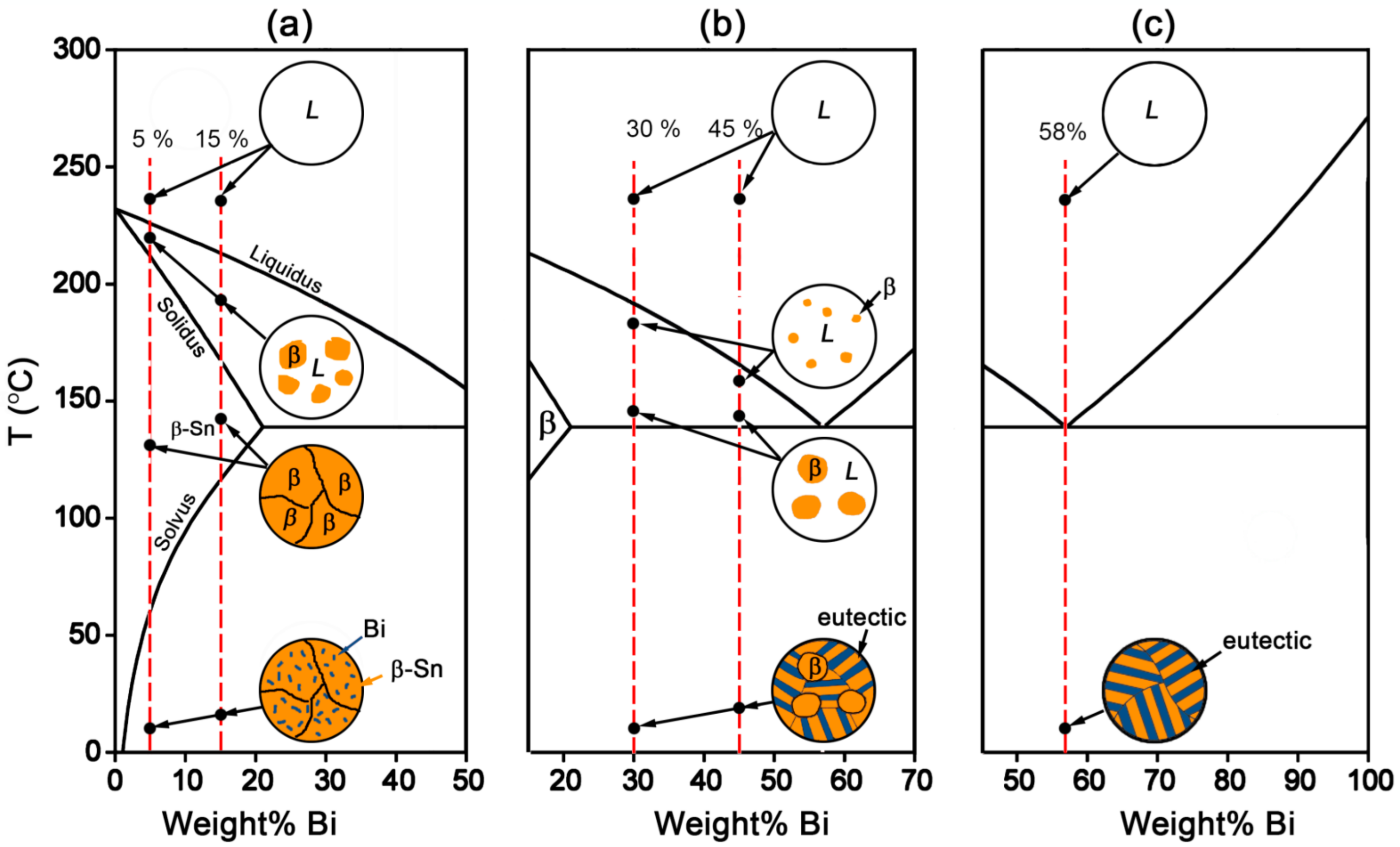
Lead can create toxic vapor or dust, which necessitates extensive safety protocols. Bismuth is a lower-risk option for high traffic environments; it's also easier to dispose of or recycle.



Tin-Bismuth (Sn-Bi) Microstructural Properties

Characterize intermetallic composition and thickness solder reflow on different substrates.





Relevant Work: Bi-Based Alloy Evaluation

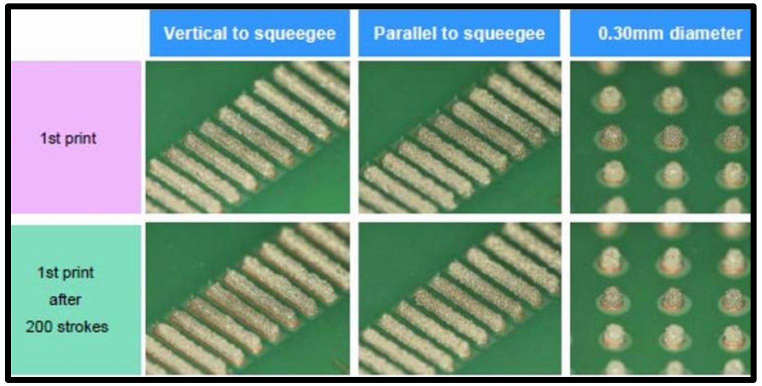
"An Investigation into Low Temperature Tin-Bismuth and Tin-Bismuth-Silver Lead-Free Alloy Solder Pastes for Electronics Manufacturing Applications" by Bath et al. (2024)

The high reflow temperatures required for Sn3Ag0.5Cu can damage sensitive materials and increase energy consumption. To address this, tin-bismuth (Sn-Bi) and tin-bismuth-silver (Sn-Bi-Ag) alloys, with lower melting points (138°C) and reflow temperatures (around 180°C), were developed as alternatives. Bath et al. (2024) conducted a comprehensive investigation into low-temperature Sn-Bi and Sn-Bi-Ag solder pastes, focusing on their performance in electronics manufacturing applications.

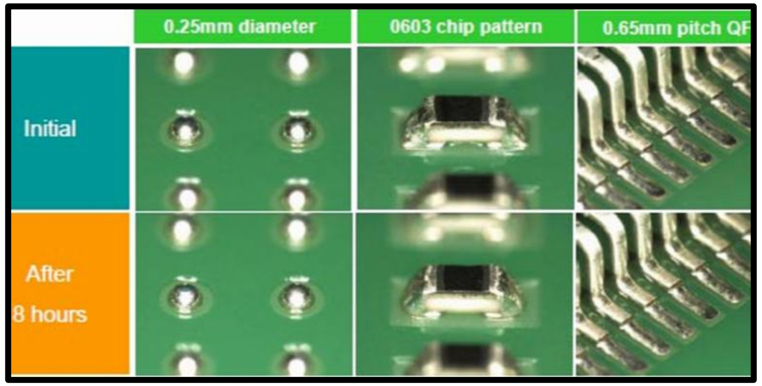
Experimental Analysis: Paste Printing → Reflow & Wetting → Head-in-Pillow & Pin-in-Paste → Voiding → Solder Joint Bond Strength

Relevant Work: Experimental Findings

Bath et al. (2024)

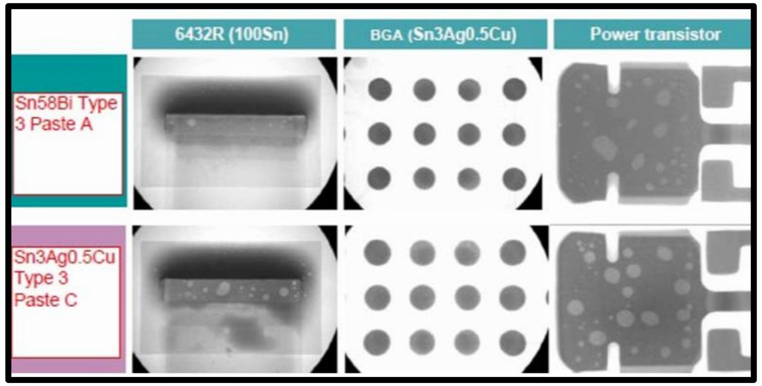


Paste Printing

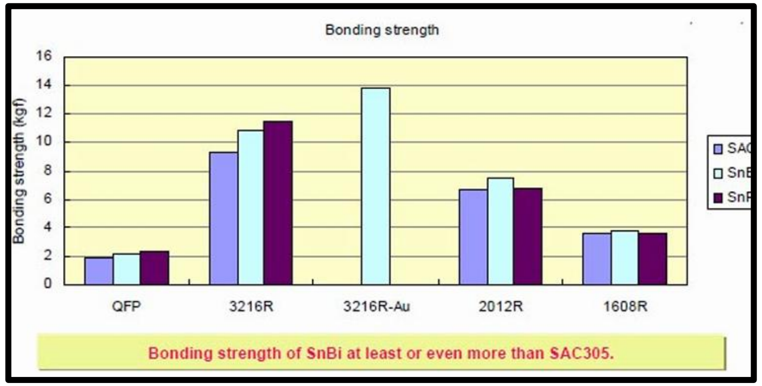


Reflow & Wetting

Head-in-Pillow & Pin-in-Paste



Voiding



Solder Joint Bond Strength

Relevant Work: Experimental Findings

Bath et al. (2024)

Paste Printing	Reflow & Wetting	Head-in-Pillow & Pin-in-Paste	Voiding	Solder Joint Bond Strength
Sn58Bi and Sn57.6Bi0.4Ag pastes demonstrated excellent printability, with minimal viscosity variation over 3,000 prints and consistent performance.	Sn58Bi paste exhibited good spreading on copper and brass substrates, with partial wetting on harder-to-solder surfaces like Alloy 42 and nickel. The paste also showed reliable wetting on 0603 chip and 0.65mm pitch QFP components.	Sn-Bi pastes outperformed SAC305 in head-in-pillow tests, with complete solder sphere merger achieved at lower temperatures. Pin-in-paste tests also demonstrated superior wetting for Sn57.6Bi0.4Ag paste compared to its counterparts.	Sn58Bi paste exhibited lower voiding compared to SAC305, attributed to its lower surface tension during reflow. Voiding studies on power transistor components further confirmed the minimal impact of silver additions on voiding behavior.	Bond strength with Sn58Bi was equivalent or better than Sn3Ag0.5Cu or Sn37Pb. Results indicated minimal differences in pull & shear test results between Sn58Bi, Sn57.6Bi0.4Ag and Sn57Bi1Ag solders.

Expanding from Prior Findings

How can our research further characterize the thermomechanical properties?

- Bath et al.'s study highlighted the advantages of low-temperature Sn-Bi and Sn-Bi-Ag solder pastes, such as reduced energy consumption and compatibility with temperature-sensitive components.
- This study explores the thermomechanical reliability of the 95Bi-5Sn solder alloy on Cu-OSP and ENIG under-bump metallurgy, with a comparative analysis against the eutectic 58Bi-42Sn solder. The questions to answer are:

1. How do the microstructural and compositional properties of bismuth-based solder alloys (Sn58Bi and Sn95Bi) influence their thermomechanical reliability in high-temperature applications?
2. What are the mechanical properties of bismuth-based solder alloys, and how do they perform under thermal stress?
3. How do bismuth-based solder alloys perform on common substrates like Cu-OSP and ENIG, and what are their long-term stability and degradation mechanisms?

Methodology

Material Characterization & Thermomechanical Reliability Testing Methods.

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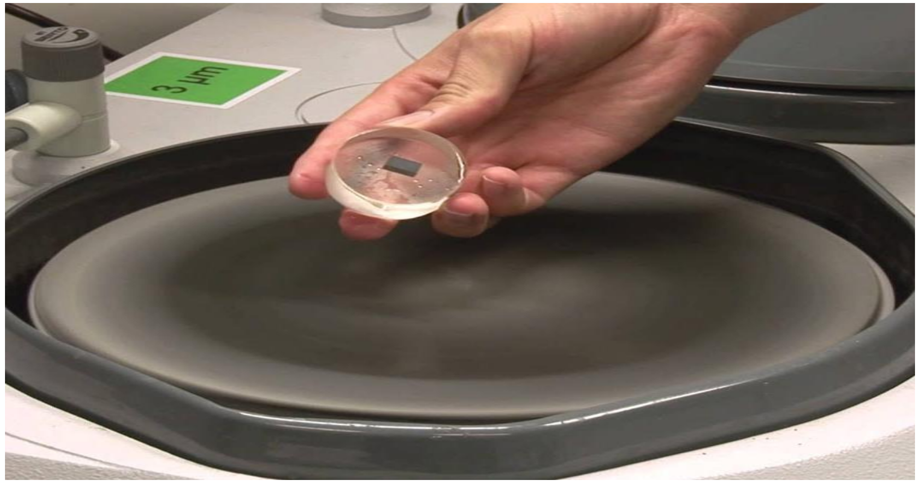
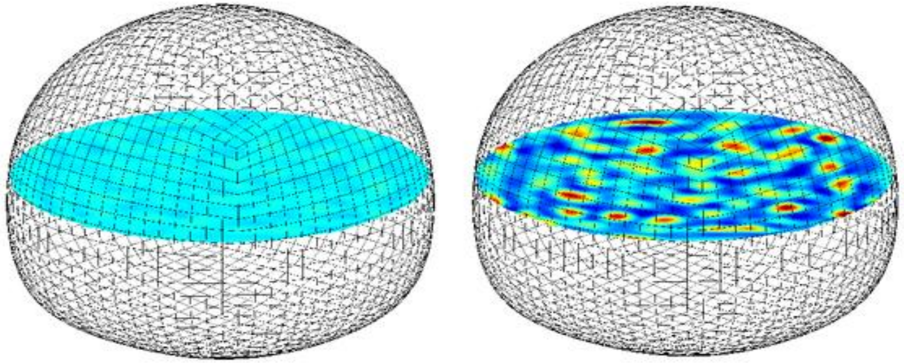
Optical Microscopy & Cross-Sectional Analysis

Polishing and Cross-Sectional Analysis for Sn-Bi Phase Characterization

- The polishing process involved using a series of abrasive papers and diamond suspensions to create a smooth surface on the solder balls, ensuring clear and high-resolution imaging for detailed microscopic analysis of the Sn-Bi phases.
- Optical microscopy analyzed 42Sn-58Bi and 5Sn-95Bi solder balls, focusing on Sn and Bi phase distribution.
- Cross-sectional analysis revealed internal microstructure and phase arrangement, ensuring high-resolution imaging of Sn-Bi homogeneity and composition.

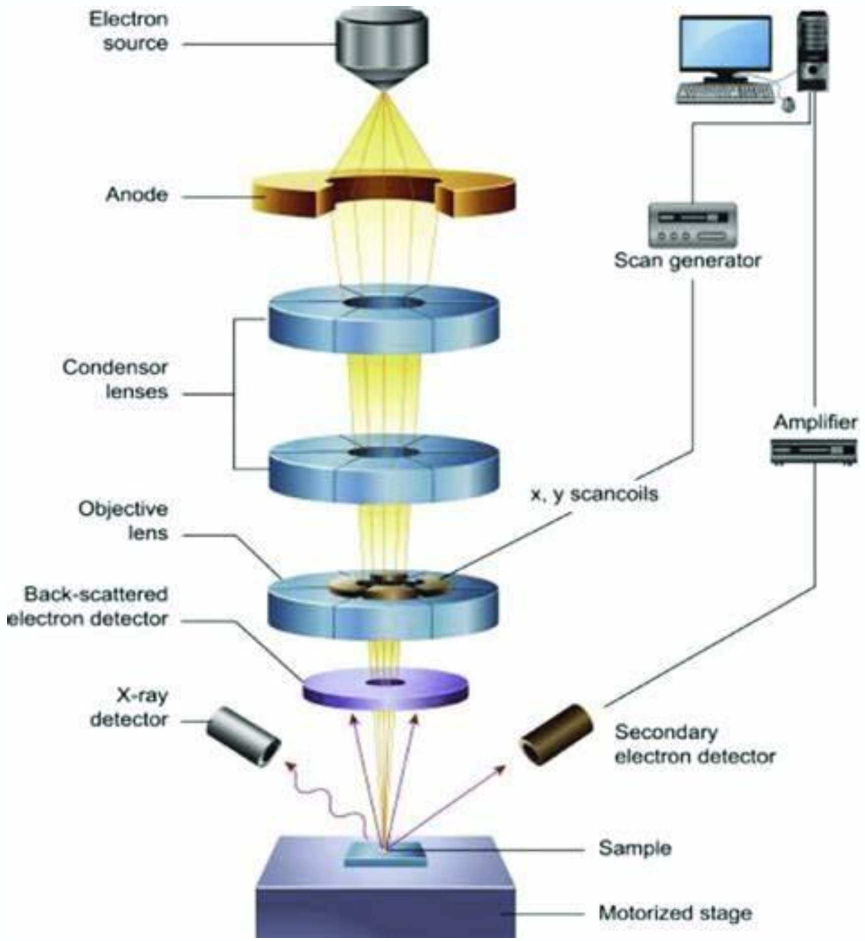




SEM/EDS Analysis

Elemental Mapping and Homogeneity Analysis of Sn-Bi Solder Alloys

- SEM-EDS analyzed 0.01′′ Sn58Bi and Sn95Bi solder balls to quantify Sn and Bi distribution.
- Spectra collected from multiple points revealed variations in elemental composition, highlighting regions with differing Sn and Bi concentrations.
- By averaging these spectra, the study determined phase distribution and compositional homogeneity, providing insights into the material's microstructure and its reliability in high-temperature applications.

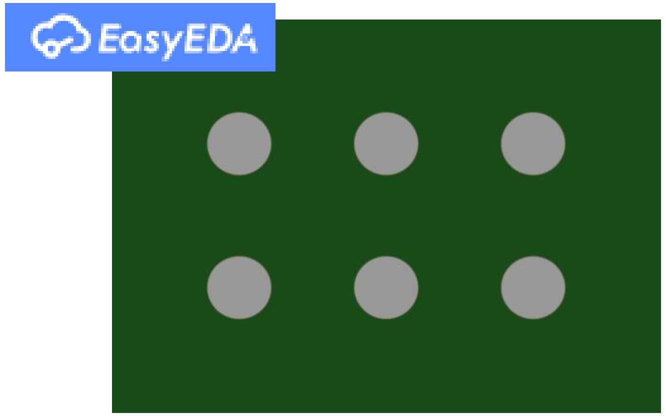


Reflow Testing

Optimizing Solder Joint Formation

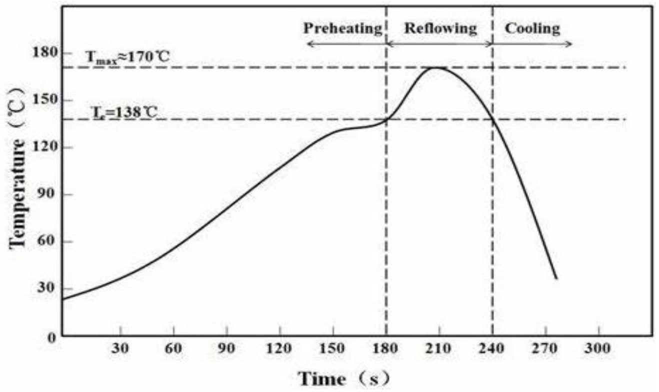
Composition	Melting Temp (°C)	Reflow Temp (°C)
Sn58Bi	138	170
Sn95Bi	262	322

Reflow testing begins with designing a test board that includes the desired substrate materials (Cu-OSP and ENIG). The solder alloy (Sn58Bi and Sn95Bi) is applied to the board after flux. The reflow process involves heating the assembly in a controlled DDM Novastar oven to melt the solder, allowing it to wet the substrate and form joints. A reflow profile is generated by defining key parameters, including ramp-up rate, peak temperature, dwell time, and cooling rate, tailored to the specific solder alloy and substrate.



Design Test Board

Reflow Fluxed Solder Alloy



Generate Reflow Profile

Results & Discussion: Material Interactions

Analyzing Micromaterial Interactions.

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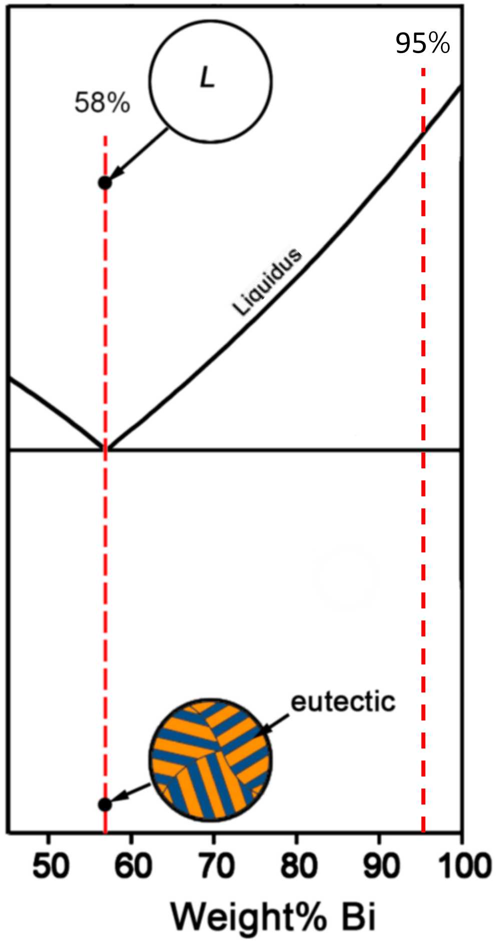
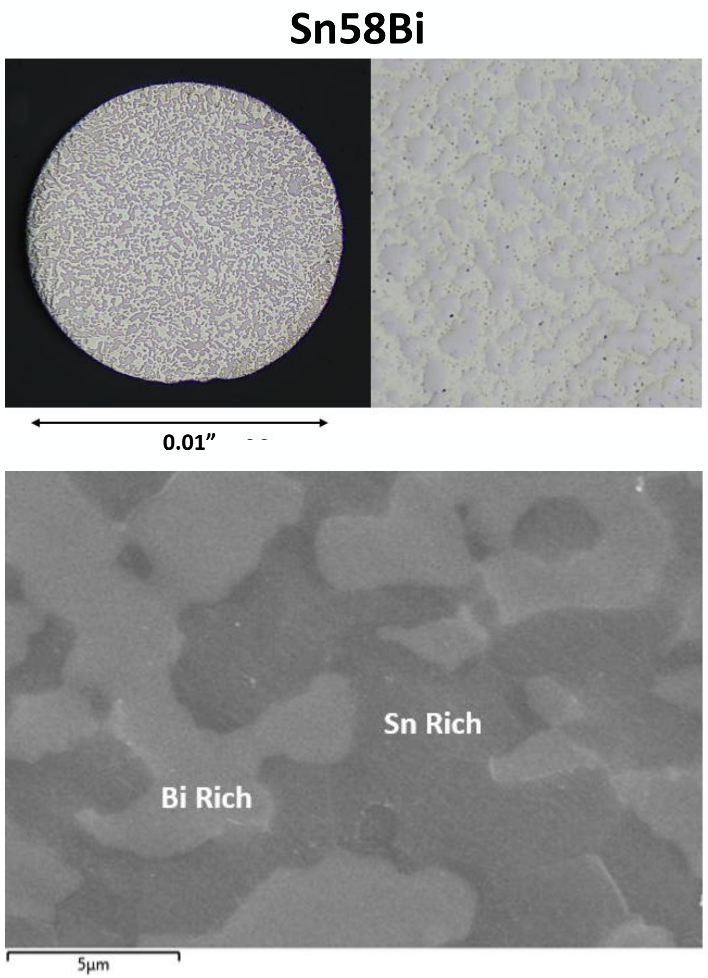
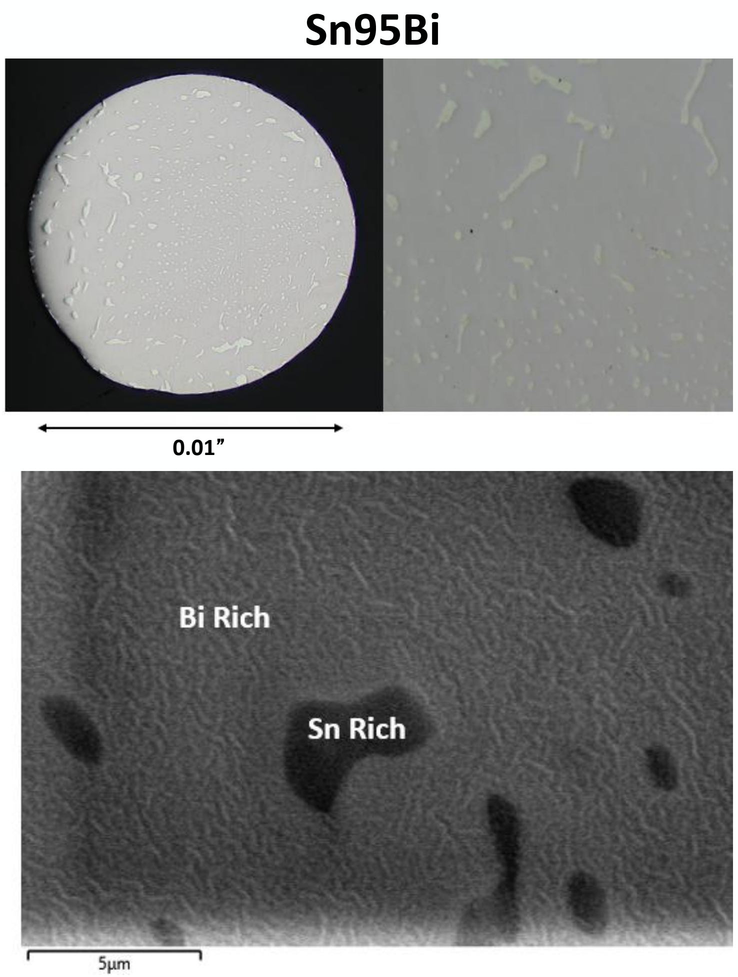
Material Interaction Analysis

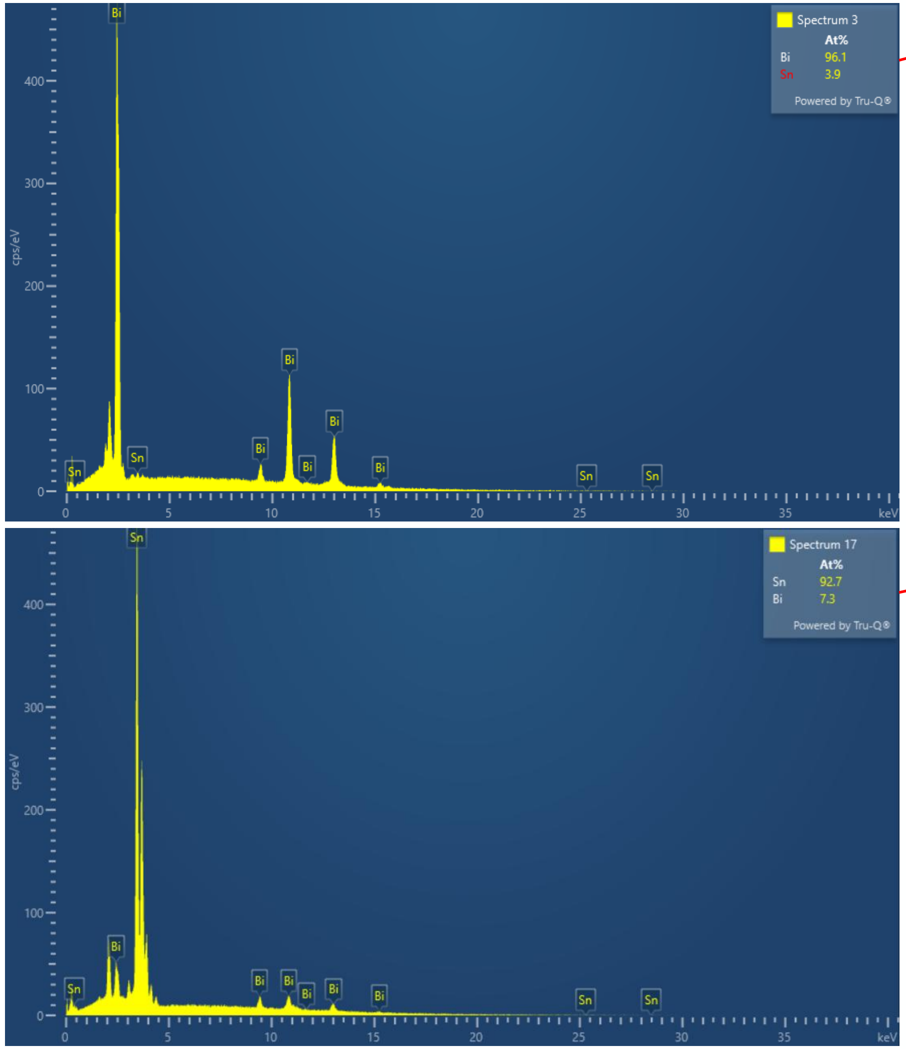
Optical (Top) and SEM (Bottom) Cross-Sectional Imaging of 0.01" Solder Alloy Spheres

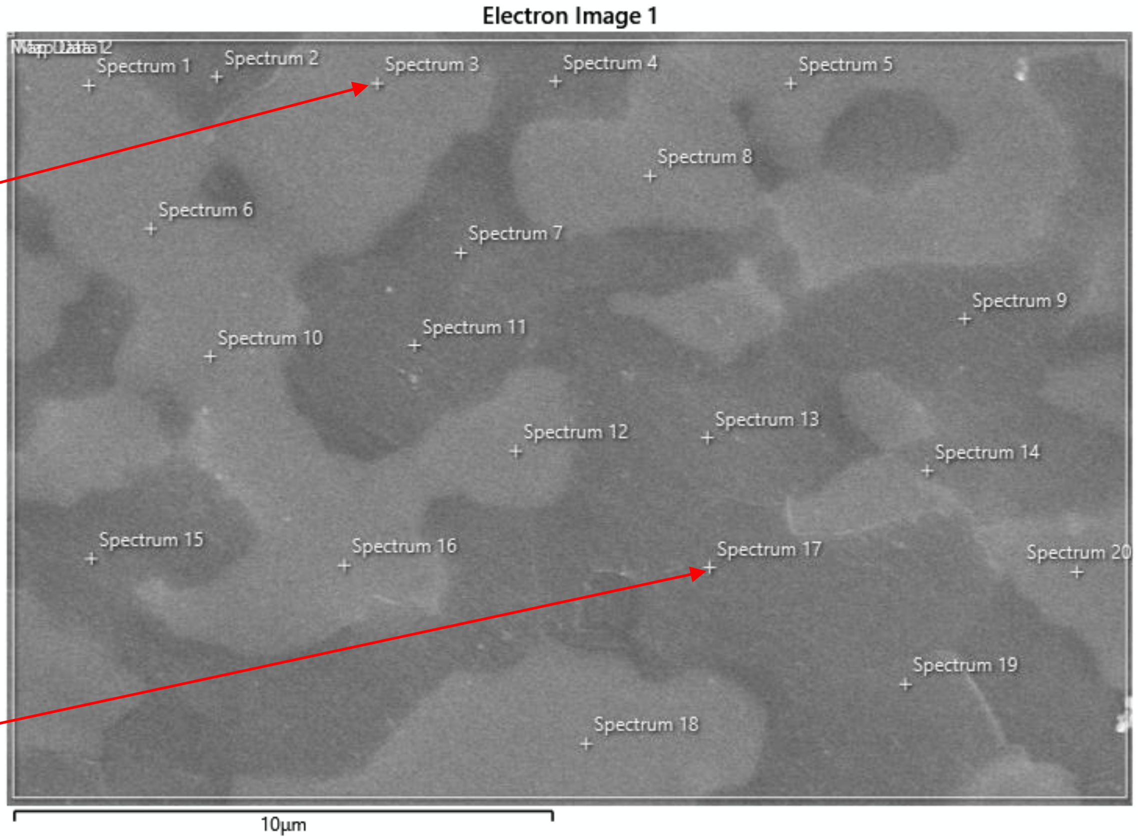


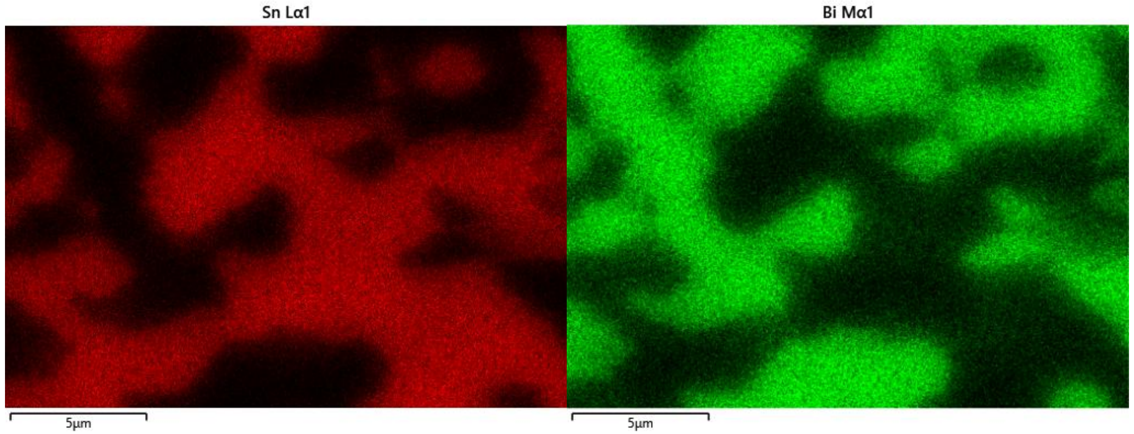




EDS Data: Sn58Bi







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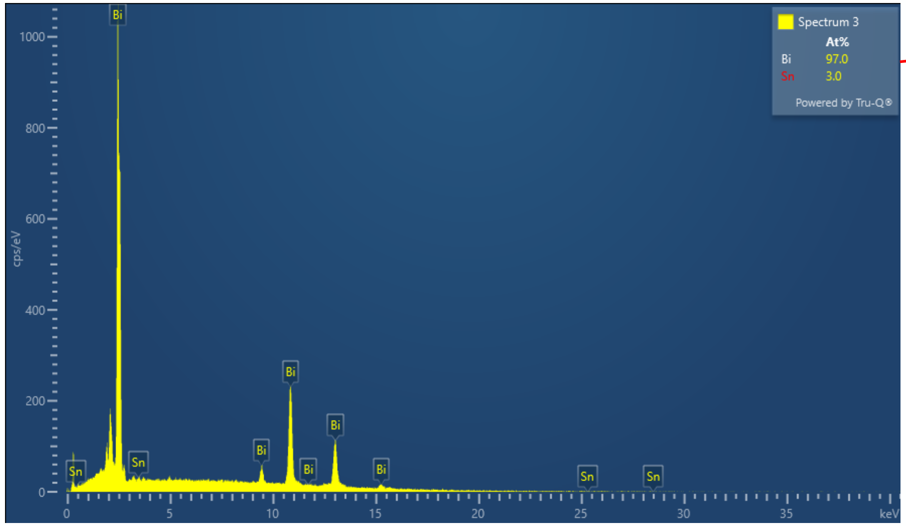
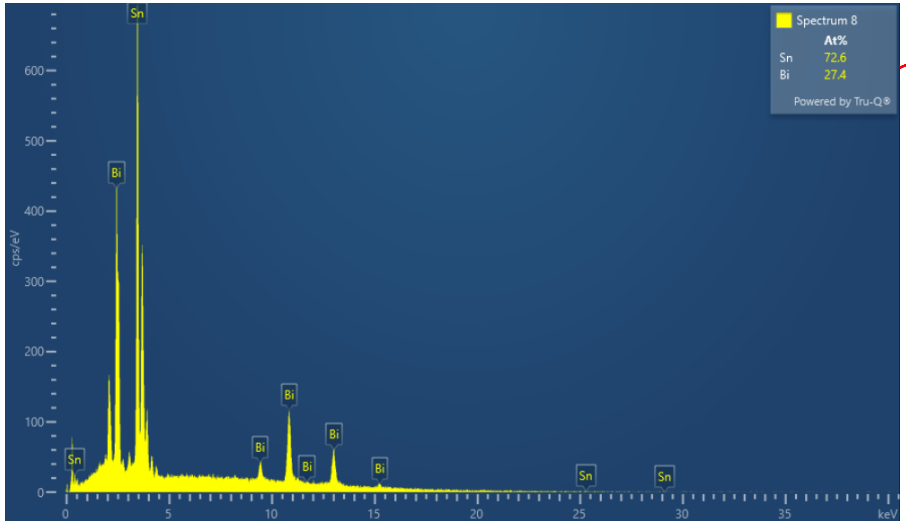
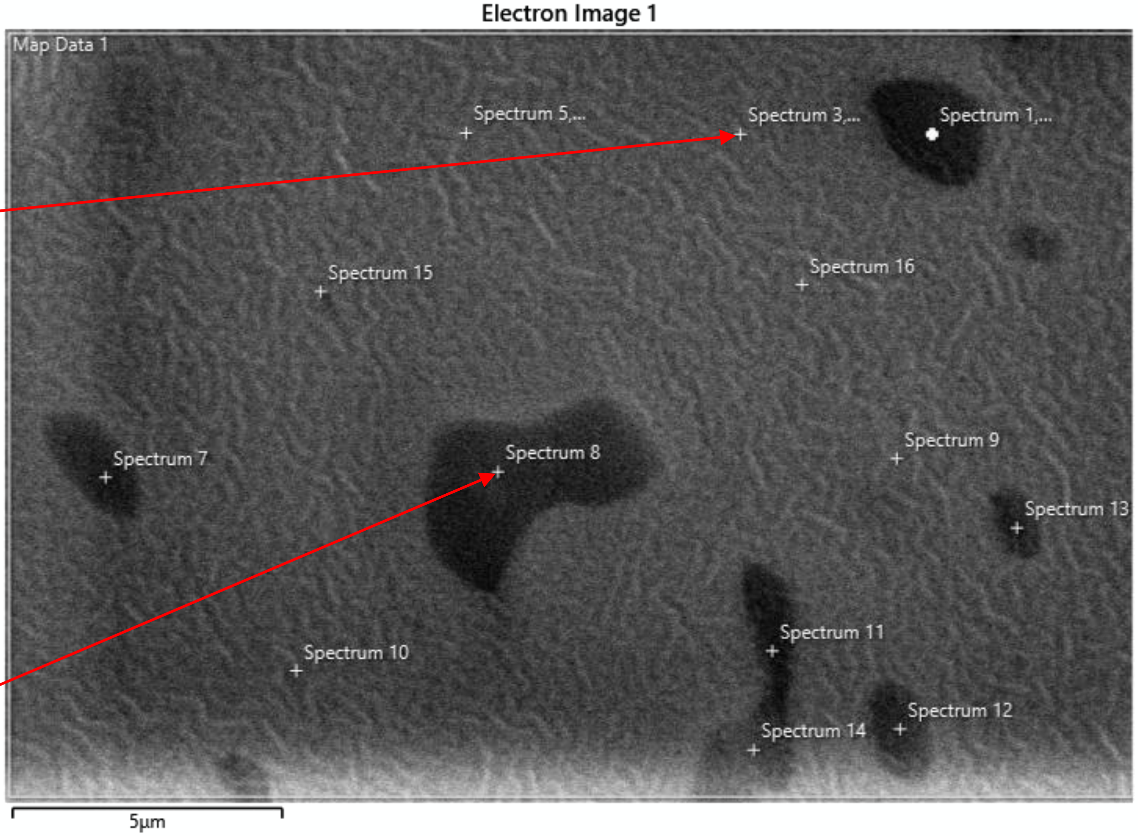
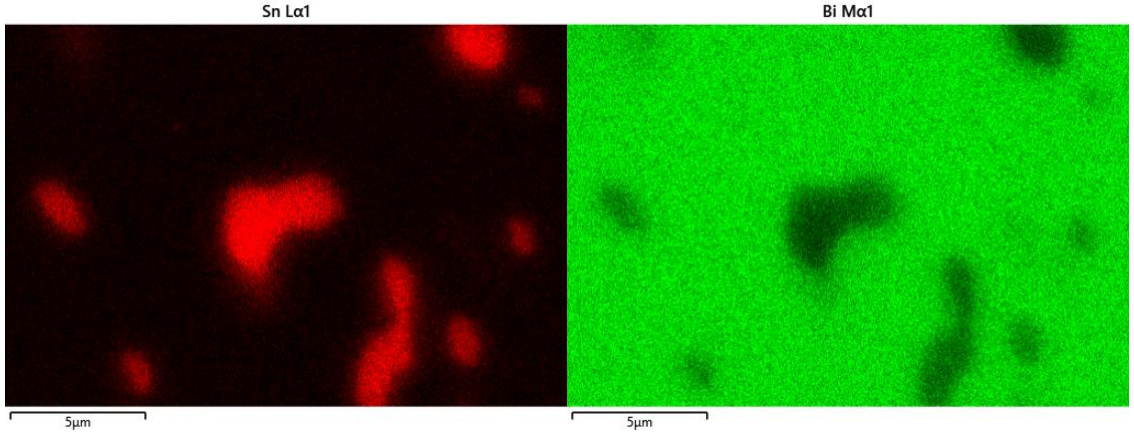
EDS Data: Sn95Bi





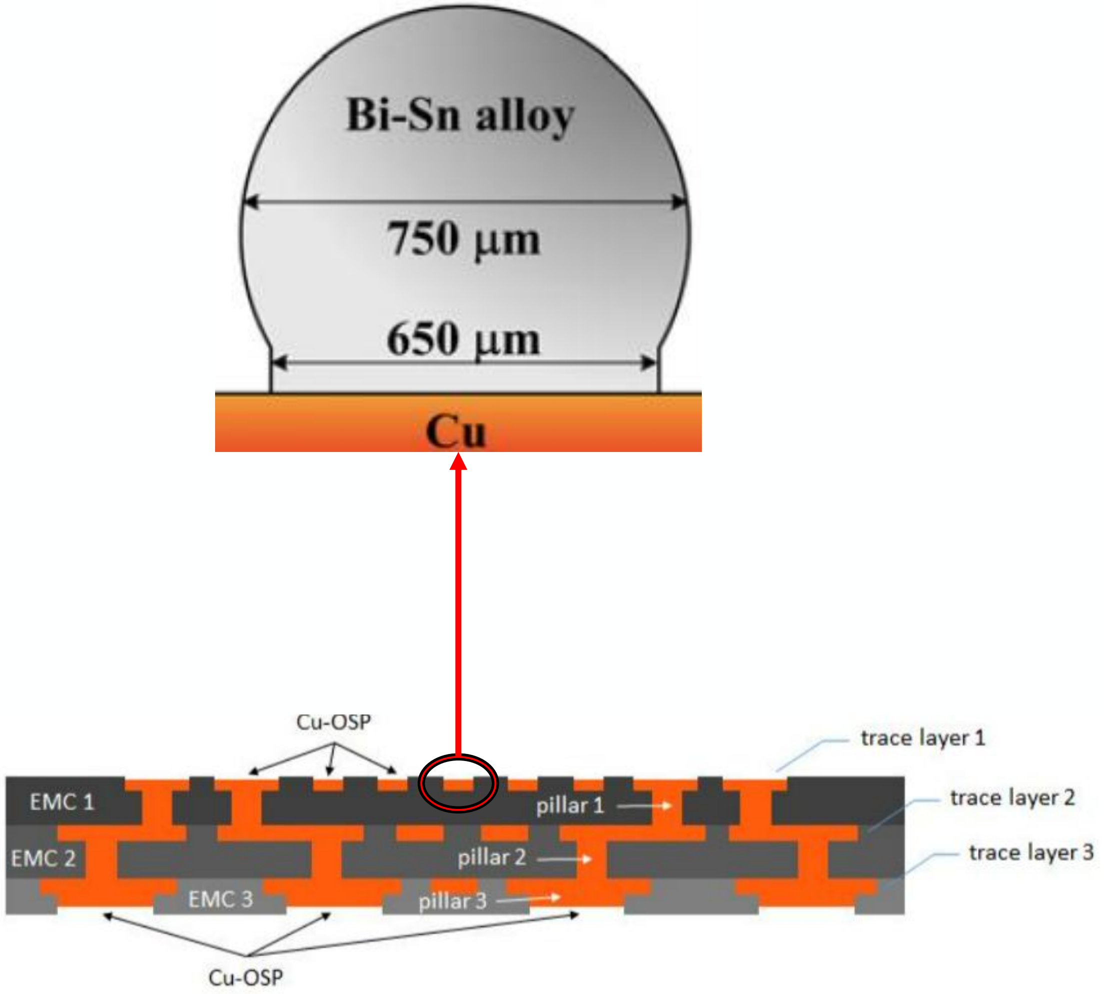




Reflow Testing

Ongoing Reflow Testing & Expected Outcomes

- Cross-sectional analysis, using optical microscopy and SEM/EDS, will reveal the microstructure, phase distribution, and elemental composition of the solder joints.
- On Cu-OSP, the formation of Cu-Sn IMCs is expected, but the bismuth content may influence their growth kinetics and morphology.
- On ENIG, the interaction with the nickel layer will be critical, with potential formation of Ni-Sn or Bi-Ni compounds.
- These findings will guide future work, including high-temperature storage tests to simulate long-term thermal aging and shear testing to evaluate mechanical performance.



Conclusion & Future Work

Where is this research going?

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Conclusion

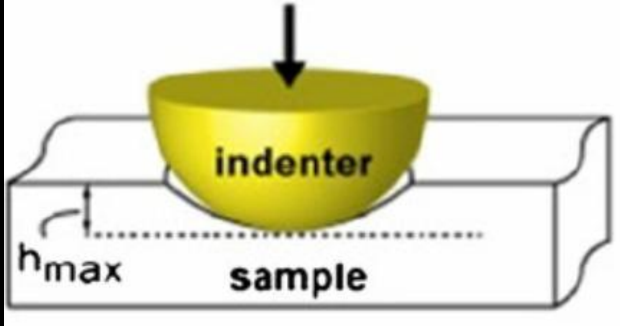
Advancing Bismuth-Based Solders for High-Temperature Reliability

This study examined material interactions in bismuth-based solder alloys, such as 95Bi-5Sn and 58Bi-42Sn, for high-temperature applications. Microstructural and compositional analyses provided a foundation for understanding thermal and mechanical stress responses. These results will be compared with future mechanical testing, including nanoindentation, shear tests, and high-temperature storage aging, to evaluate hardness, interfacial strength, and long-term reliability. Together, these methods aim to develop robust bismuth-based solders that replace lead-based systems while meeting environmental and performance standards.

Ongoing Testing: Material to Mechanical Experimentation

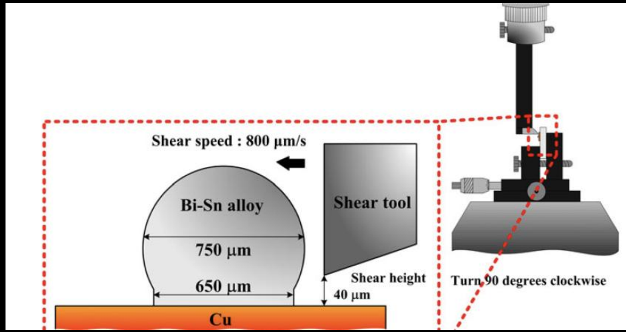
Nanoindentation Testing

Nanoindentation provides data on hardness and elastic modulus at both the bulk and interfacial levels. It enables precise measurement of material behavior under stress and evaluates solder joint reliability before and after thermal aging.



Shear Testing: Substrate Interactions

Shear testing on Cu-OSP and ENIG substrates measures the mechanical strength and reliability of bismuth-based solder joints. It evaluates interfacial adhesion and joint integrity, identifies failure mechanisms.



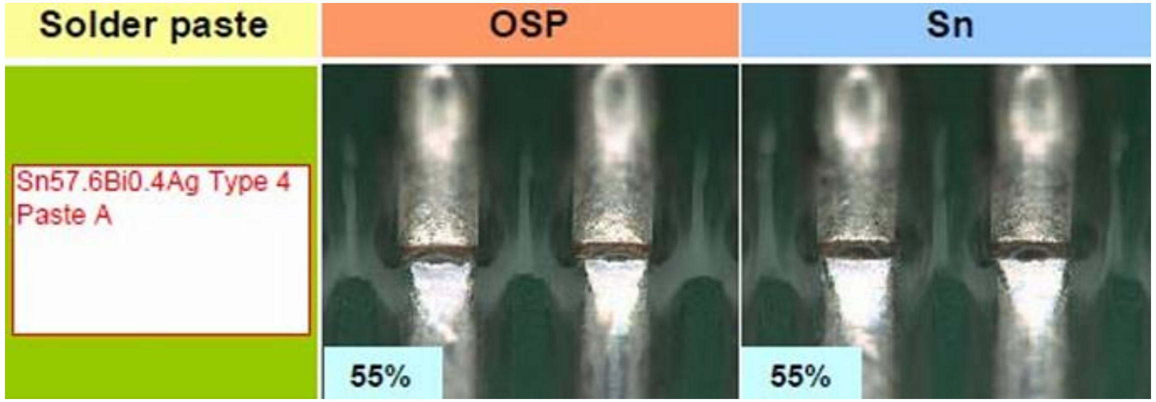
High-Temperature Storage (Aging) Tests

High-temperature storage tests simulate thermal stress by aging solder joints at 125°C for 500 hours. They assess long-term stability, degradation mechanisms, and interfacial reliability.

Considerations: Availability and Wettability

Things to Consider before Widespread Applications

Global Solder Market per year (approx.)	Global Bismuth Metal Usage per year (approx.)
180,000 tonnes solder	Global bismuth usage: 6,000 tonnes
Solder paste: 20,000 tonnes	World capacity: 10,000 tonnes
Wave solder: 160,000 tonnes	Spare Capacity: 4,000 tonnes



- Bismuth, while abundant in nature, is often produced as a byproduct of lead, copper, and tin mining, making its supply chain vulnerable to fluctuations in these industries. With global bismuth usage estimated at 6,000 tonnes annually and a spare capacity of only 4,000 tonnes, the material's limited availability poses a significant constraint for large-scale adoption in the electronics industry.

- For bismuth-based solders, wettability is often a challenge due to the material's inherent properties. Bismuth has a higher surface tension compared to traditional lead-based solders, which can hinder its ability to spread evenly across the substrate. Additionally, bismuth tends to form brittle intermetallic compounds (IMCs) at the solder-substrate interface, which can further reduce adhesion and joint strength.

The future of Bi-Based solders

What can we expect?

For more than a decade, tens to hundreds of millions of dollars have been invested in research on tin-bismuth based, low temperature lead-free solders. Implementation is already underway in niche applications, and as performance and reliability improve, broader adoption in industries like automotive, aerospace, and power electronics is likely. In the coming years, bismuth-based solders are expected to play a significant role in enabling next-generation electronics, driven by the dual demands of sustainability and technological advancement.

The key is the low-temperature nature. A low-temperature solder is advantageous over higher melting temperature alloys because lower temperature processing requirements can reduce both thermal damage and overall costs. Defects such as delamination or "pop-corning" can be minimized or eliminated by using lower temperature solders. After adequate research and reliable implementation is successful, industries and institutions can respond with a rapid growth and positive development in this change.

Thank You

IMAPS 2025 Conference.

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Acknowledgements

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