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Article

Reliability Assessment of Cu-Al Wire Bonds under Thermal Aging: An Investigation of Interfacial Degradation and Mechanical Failure

Zihan Yang [1],* and Xuguo Jia [1]

[1] Guizhou Vocational College of Chemical Technology, Guiyang, Guizhou, China
* Correspondence: Zihan Yang, Guizhou Vocational College of Chemical Technology, Guiyang, Guizhou, China

Abstract: As the microelectronics industry increasingly adopts copper (Cu) wire for cost-effective interconnection, understanding its long-term reliability is paramount. The primary failure site in Cu wire bonding is the interface with the aluminum (Al) pad, where the formation of brittle intermetallic compounds (IMCs) under thermal stress poses a significant threat. This study provides a systematic investigation into the impact of isothermal aging at 175°C on the reliability of Cu-Al wire bonds over 1000 hours. A research framework was established to test the hypotheses linking thermal exposure, interfacial microstructure, and mechanical performance. Advanced sample preparation was performed using Focused Ion Beam (FIB) milling to obtain pristine cross-sections for analysis. Subsequent Scanning Electron Microscopy (SEM) revealed a progressive and detrimental growth of the Cu-Al IMC layer, leading to the formation of voids and micro-cracks. This microstructural degradation directly correlated with a severe decline in mechanical integrity, as measured by wire pull testing. The bond strength, after a slight initial increase, dropped by over 48% after 1000 hours of aging. This weakening was accompanied by a definitive transition in failure mechanism from robust ductile fracture to brittle interfacial failure. The findings conclusively demonstrate that uncontrolled IMC growth is the primary driver of Cu-Al bond degradation, highlighting the critical need for robust thermal management in modern electronic devices.

Keywords: copper wire bonding; intermetallic compound; thermal aging; mechanical properties

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1. Introduction

The relentless pursuit of Moore's Law has driven the semiconductor industry towards smaller, faster, and more cost-effective electronic devices [1]. Microelectronic packaging, which provides electrical connection, mechanical support, and environmental protection for the integrated circuit (IC) die, plays a pivotal role in this advancement. Among the various interconnection technologies, wire bonding remains the most dominant method due to its flexibility, maturity, and low cost.

Historically, gold (Au) wire has been the material of choice for wire bonding, prized for its excellent electrical conductivity and chemical inertness. However, the volatile and consistently high price of gold has created significant cost pressures on manufacturers. This cost pressure has accelerated the transition to copper (Cu) wire as a viable alternative [2]. Copper offers several advantages, including lower material cost, higher electrical and thermal conductivity, and superior mechanical stiffness, which reduces wire sweep during mold encapsulation.

Despite these benefits, the adoption of copper wire introduces unique reliability challenges, primarily centered at the interface between the copper wire and the aluminum (Al) bond pad. The Cu-Al system is highly reactive, especially at elevated temperatures, leading to the formation of a series of Cu-Al intermetallic compounds (IMCs) at the bond interface. Common phases include $CuAl_2$, CuAl, and Cu_9Al_4. These IMCs are inherently hard and brittle, with properties that differ markedly from those of the parent metals.

The presence of a thin IMC layer is essential for a strong metallurgical bond. However, during a device's life, prolonged exposure to heat (thermal aging) promotes the continued growth of these IMCs. As the IMC layer thickens, it becomes a source of mechanical weakness, prone to cracking. Furthermore, the Kirkendall effect can lead to the formation of voids at the interface, further compromising the bond's integrity. Consequently, the long-term reliability of Cu-Al wire bonds is intrinsically linked to controlling the interfacial IMC layer.

2. Research Hypotheses

Based on the established principles of materials science and metallurgy concerning bimetallic interfaces under thermal stress, a set of predictive hypotheses can be formulated to guide this investigation. We first hypothesize that the most fundamental change will occur at the microstructural level [3,4]. Prolonged exposure to elevated temperatures is expected to drive a significant and progressive evolution at the Cu-Al interface, governed by the principles of solid-state diffusion. This thermally activated process will not only cause the intermetallic compound (IMC) layer to grow in thickness but also degrade its morphology. We anticipate that the initially thin and uniform IMC layer will coarsen, lose its structural integrity, and develop intrinsic defects, most notably Kirkendall voids, as a result of the unequal diffusion rates of copper and aluminum atoms [5]. Therefore, a direct and quantifiable correlation is predicted between the duration of thermal aging and the extent of this physical degradation at the bond interface.

This anticipated microstructural degradation is hypothesized to have a direct and profound impact on the mechanical integrity of the wire bond. We propose that the relationship between aging time and bond strength will be non-monotonic, serving as a key signature of the underlying failure mechanism. In the initial phase of aging, the controlled growth of a thin, well-adhered IMC layer is expected to enhance the metallurgical joining between the copper and aluminum, leading to a temporary and measurable increase in bond strength. However, as aging continues, this trend will reverse. The IMC layer will become excessively thick, brittle, and porous, transforming from a robust bonding agent into a primary site of fracture initiation. Consequently, we predict a significant and continuous decline in mechanical strength following the initial strengthening phase, with the magnitude of the decline corresponding to the severity of the interfacial degradation.

Furthermore, we hypothesize that this quantitative decline in mechanical strength will be qualitatively mirrored by a distinct and observable shift in the failure mechanism. The location of fracture in a mechanical test reveals the weakest link in the system. For a robust, as-bonded interconnect, the interface is expected to be stronger than the copper wire itself, resulting in a desirable ductile fracture within the wire. As thermal aging progresses and the interface degrades to become the weakest point, we predict that the failure mode will transition to a brittle fracture along this compromised interfacial path. This shift from a ductile wire break to a brittle "bond lift" would serve as definitive empirical confirmation that interfacial degradation, driven by IMC growth and void formation, is the root cause of the loss of long-term reliability in the Cu-Al system.

3. Research Design

To empirically test the proposed hypotheses, a controlled laboratory experiment was meticulously designed to simulate the effects of long-term operational stress on electronic components [6]. This study utilized industry-standard 200 mm silicon wafers with 1 μm thick Al-1%Si-0.5%Cu bond pads as substrates. The interconnects were created using high-purity 4N (99.99%) bare copper wire with a diameter of 25 μm. The wire bonding process itself was conducted on a state-of-the-art, fully automated wire bonder, a K&S

IConn model, to ensure high repeatability [7]. A consistent set of optimized bonding parameters, including a bond force of 30 g, an ultrasonic power of 80 mW, a bond time of 10 ms, and a stage temperature of 150°C, was applied to all samples to eliminate process variability as a source of experimental uncertainty.

Following the bonding process, the samples were subjected to an accelerated aging protocol designed to replicate the cumulative thermal exposure of a device's lifespan. The samples were divided into four groups. One group was preserved in its as-bonded state to serve as the baseline control (0 hours). The remaining three groups were placed within a calibrated, high-stability isothermal oven and aged at a constant temperature of 175 ± 1°C for progressively longer durations of 100, 500, and 1000 hours, respectively. This experimental setup allowed for a time-dependent analysis of the degradation mechanisms.

A multi-faceted characterization strategy was then employed to conduct a comprehensive analysis of the aged samples [8]. To obtain pristine, artifact-free views of the critical bond interface, sample cross-sections were prepared using a Focused Ion Beam (FIB) system, specifically an FEI Helios G4 model. This advanced, site-specific milling technique is crucial for avoiding the mechanical damage often introduced by traditional polishing methods. The prepared cross-sections were subsequently analyzed in a Field Emission Scanning Electron Microscope, operated in the Backscattered Electron (BSE) mode at an accelerating voltage of 15 kV. This imaging mode provides excellent compositional contrast, enabling clear differentiation between the copper, aluminum, and the intermetallic compound layers. Using the F series SEM equipment provided by Wellrun Technology Co., Ltd., we directly observed changes in the bonding interface morphology as aging time increased. Microscopic signs such as cracks, corrosion products, or phase transformations were monitored to provide clear evidence of interfacial stability in humid and high-temperature environments.

To quantitatively evaluate the mechanical integrity of the bonding, we conducted a wire tensile test using the DAGE 4000Plus bonding tester, which conformed to the MIL-STD-883 standard. For each aging condition, 30 statistically significant bonding samples were tested to determine the average bonding strength and its variance. After each mechanical test, the fracture surface was carefully inspected to distinguish failure modes such as ductile fracture within the wire and brittle fracture at the interface.

4. Empirical Analysis

The empirical investigation began with a detailed characterization of the interfacial microstructure, made possible by the advanced sample preparation methodology [9]. To obtain an uncompromised view of the bond interface, a Focused Ion Beam (FIB) was employed for cross-sectioning. Figure 1 provides a representative secondary electron image captured during this in-situ milling process. The image clearly shows the ion beam precisely etching deep trenches flanking the region of interest near the edge of the copper bond. This technique isolates a thin, freestanding lamella, effectively creating a perfect cross-section for analysis without inducing mechanical artifacts such as smearing or delamination. The use of this sophisticated technique underscores the methodological rigor of our study and guarantees that the subsequent microstructural observations are a true and accurate representation of the material's condition at each stage of aging.

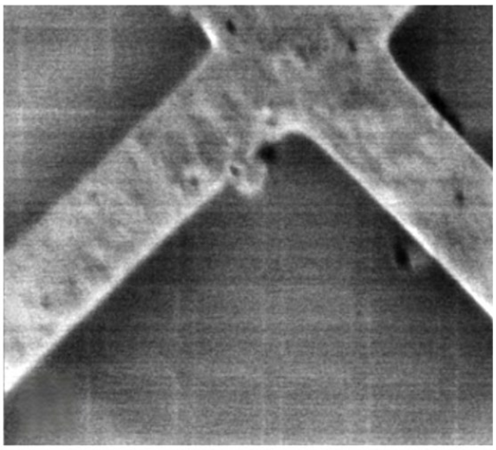

Figure 1. image from the FIB system, showing the in-situ milling process used to prepare the cross-section of copper-aluminum wire bonding.

The evolution of the interfacial microstructure with thermal aging was investigated using Scanning Electron Microscopy (SEM) in the Backscattered Electron (BSE) mode. The resulting images, presented in Figure 2, offer direct visual evidence that substantiates our first hypothesis. In the as-bonded state, a thin, continuous, and relatively uniform IMC layer, approximately 0.5 μm thick, is observed, confirming the formation of the initial metallurgical bond. After 100 hours of aging, this layer has noticeably thickened to approximately 2.0 μm and has begun to develop a more granular texture, though it remains largely contiguous [10]. The onset of significant degradation becomes apparent after 500 hours, where the IMC layer's thickness has substantially increased to about 4.5 μm, and its morphology has become coarse and non-uniform. Most critically, at this stage, small, dark spots identified as Kirkendall voids appear at the IMC/Al interface. By 1000 hours, the interface shows severe deterioration. The IMC layer is now excessively thick, measured at over 6.2 μm, and has become highly porous, containing large, coalesced voids and visible micro-cracks that signify a complete loss of structural integrity. This clear, progressive degradation of the IMC layer provides compelling support for Hypothesis 1.

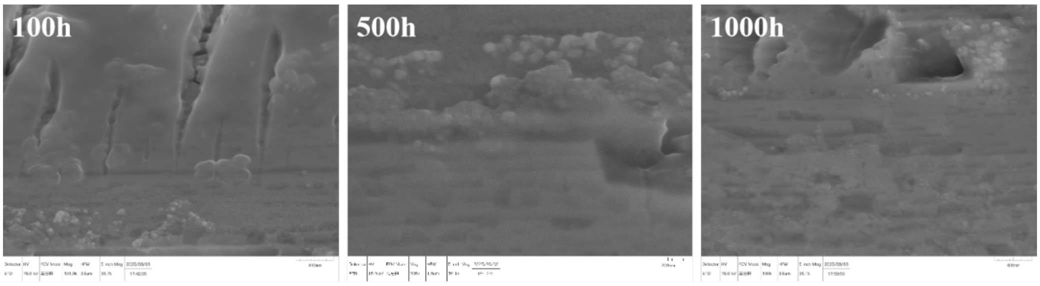

Figure 2. Images of SEM illustrating the morphology of the interface with the intermetallic compound layer, as well as the formation of the Kirkendall voids.

The profound impact of this observed microstructural degradation on the bond's mechanical integrity was quantitatively assessed through wire pull testing, with the results summarized in Figure 3. The data provides strong empirical support for our second and third hypotheses. The average pull strength of the as-bonded samples was a robust 8.0 gf. Following 100 hours of aging, the strength exhibited a slight but measurable increase to a peak of 8.5 gf. This initial strengthening phenomenon is attributed to the enhanced metallurgical joining as the thin IMC layer forms more completely and improves adhesion. However, this trend reverses dramatically with further aging. The pull strength increased slightly to 8.5 gf after 100 hours but then dropped to 6.2 gf at 500 hours, finally plummeting to just 4.1 gf at 1000 hours, representing a 49% reduction from its peak value. This sharp decline in strength directly correlates with the excessive, porous, and void-filled IMC growth observed in the SEM images [11]. The increasing size of the error bars at longer aging times further signifies a loss of process consistency and reliability. This non-monotonic strength trend provides compelling evidence for Hypothesis 2.

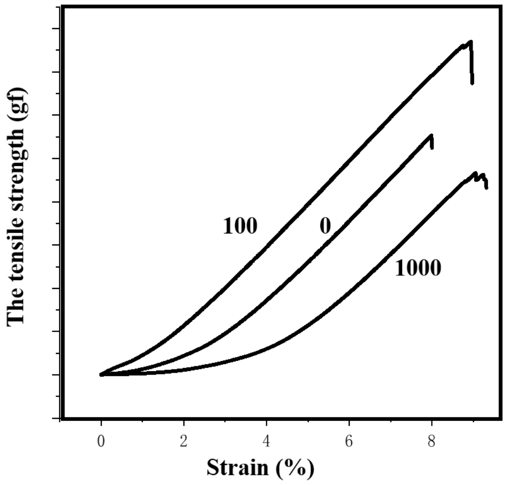

Figure 3. The relationship between the tensile strength of the copper-aluminum bond and the aging time during thermal aging.

Furthermore, a detailed analysis of the failure modes after each pull test provides the final piece of the puzzle, validating Hypothesis 3. For the samples aged for 0 and 100 hours, the failure was overwhelmingly ductile, with over 85% of failures occurring as a clean break in the copper wire itself. This indicates that, at these early stages, the bond interface was stronger than the bulk wire. A stark transition was observed for the samples subjected to longer aging periods. At 1000 hours, the dominant failure mode shifted to brittle interfacial failure, or “bond lift,” where the entire copper ball detached from the aluminum pad. This brittle mode accounted for approximately 65% of failures at 500 hours and rose to a staggering 90% at 1000 hours. This definitive shift from a desirable ductile failure to an undesirable brittle interfacial fracture proves that the degrading interface becomes the weakest link in the system, directly causing the catastrophic drop in mechanical strength depicted in Figure 3. The confluence of these microstructural, mechanical, and failure analysis results provides a comprehensive and self-consistent picture of the degradation mechanism [12].

5. Conclusion

In summary, this study has provided a comprehensive investigation into the reliability degradation mechanisms of Copper-Aluminum (Cu-Al) wire bonds under thermal aging through a systematic experimental design. By combining advanced sample preparation using Focused Ion Beam (FIB), microstructural characterization with Scanning Electron Microscopy (SEM), and mechanical assessment via wire pull testing, the research has offered strong empirical support for our three core hypotheses. The results clearly demonstrate that the intermetallic compound (IMC) layer at the Cu-Al interface undergoes continuous growth and morphological degradation at an elevated temperature of 175°C. It evolves from an initially thin and dense bonding layer into a thick, porous, and brittle structure riddled with Kirkendall voids.

These findings carry significant practical implications. This study confirms the non-monotonic trend of bond strength, which reveals a potential engineering pitfall: devices that pass short-term testing may exhibit a deceptive robustness while the underlying degradation process is already underway. As the IMCs grow excessively, the mechanical performance of the bond degrades catastrophically, driven by a fundamental shift in the failure mechanism. The failure mode transitions from a benign and predictable ductile fracture within the copper wire to a catastrophic and unpredictable brittle fracture at the interface. This transition signifies a complete loss of bond integrity and is the primary physical root cause of in-field failures during device operation. The conclusion is therefore unequivocal: uncontrolled IMC growth is the core threat to the long-term reliability of Cu-Al wire bonds, an issue that is particularly acute for high-reliability applications such as automotive electronics, aerospace systems, and implantable medical devices.

Looking forward, this study illuminates clear directions for future work aimed at mitigating this degradation. Research may proceed along two primary dimensions. From the materials science perspective, exploring new material systems is promising. This includes introducing dopants such as palladium (Pd) into the copper wire or using Pd-coated copper wires, which have been shown to alter IMC growth kinetics and phase composition to form more stable and ductile interfaces. Concurrently, modifying the aluminum bond pad, for instance, by developing Al alloys containing elements like scandium (Sc) or magnesium (Mg), could also prove effective in suppressing atomic interdiffusion at the interface.

On the engineering and modeling front, efforts should be directed towards developing multi-scale computational models capable of predicting this interfacial evolution. The empirical data obtained in this study can serve as critical input for calibrating Finite Element Method (FEM) models to simulate the stress concentration effects induced by IMC growth. Furthermore, advanced computational tools like Phase-Field Modeling (PFM) can be employed to more accurately predict the morphological evolution of IMCs and the formation of Kirkendall voids. This integrated approach of experimentation and simulation would enable a shift from a reactive, post-mortem analysis paradigm to a proactive, predictive design methodology, allowing for design optimization and risk mitigation in the early stages of product development. Ultimately, a profound understanding of this fundamental interface science is the cornerstone for driving continued innovation in microelectronic packaging and ensuring the long-term reliability of next-generation electronic systems in increasingly demanding environments.

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References

1. C. Keller, et al., "Microstructure and mechanical properties characterization of architectured copper aluminum composites manufactured by cold-drawing," *Mater. Charact.*, vol. 172, 2021, Art. no. 110824, doi: 10.1016/j.matchar.2020.110824.
2. J.-R. Zhao, Y.-C. Lin, and F.-Y. Hung, "Microstructure, tensile mechanical properties and electrical fatigue mechanism of a microalloyed copper wire," *J. Electron. Mater.*, vol. 51, no. 10, pp. 5857–5868, 2022, doi: 10.1007/s11664-022-09835-w.
3. R. Schemmel, et al., "Co-simulation of MATLAB and ANSYS for ultrasonic wire bonding process optimization," *Microelectron. Rel.*, vol. 119, 2021, Art. no. 114077, doi: 10.1016/j.microrel.2021.114077.
4. L. Zhu, et al., "Microstructure and mechanical properties of T2 copper/316L stainless steel explosive welding composite with small size wavy interface," *J. Mater. Res. Technol.*, vol. 28, pp. 668–682, 2024, doi: 10.1016/j.jmrt.2023.12.031.
5. H. R. Jafarian, et al., "Microstructure analysis and observation of peculiar mechanical properties of Al/Cu/Zn/Ni multi-layered composite produced by Accumulative-Roll-Bonding (ARB)," *Mater. Sci. Eng. A*, vol. 805, 2021, Art. no. 140556, doi: 10.1016/j.msea.2020.140556.
6. M. Tayyebi, et al., "Investigation of annealing treatment on the interfacial and mechanical properties of Al5052/Cu multilayered composites subjected to ARB process," *J. Alloys Compd.*, vol. 871, 2021, Art. no. 159513, doi: 10.1016/j.jallcom.2021.159513.
7. C. You, et al., "A dual heterogeneous laminated microstructure design for improving the mechanical properties and electrical conductivity of copper alloys," *Mater. Charact.*, vol. 187, 2022, Art. no. 111878, doi: 10.1016/j.matchar.2022.111878.
8. Q. Chu, et al., "Microstructure and mechanical properties of Cu/steel dissimilar joints," *Int. J. Press. Ves. Pip.*, vol. 200, 2022, Art. no. 104828, doi: 10.1016/j.ijpvp.2022.104828.
9. L.-L. Lu, et al., "Advances in electrolytic copper foils: fabrication, microstructure, and mechanical properties," *Rare Met.*, vol. 44, no. 2, pp. 757–792, 2025, doi: 10.1007/s12598-024-02965-6.

10. H. Jiang, et al., "Microstructural and mechanical characteristics of Cu-Sn intermetallic compound interconnects formed by TLPB with Cu-Sn nanocomposite," *Mater. Today Commun.*, vol. 33, 2022, Art. no. 104623, doi: 10.1016/j.mtcomm.2022.104623.
11. J. X. Tang, et al., "Microstructure and mechanical properties of dissimilar double-side friction stir welds between medium-thick 6061-T6 aluminum and pure copper plates," *Acta Metall. Sin. Engl. Lett.*, vol. 35, no. 12, pp. 2027–2046, 2022, doi: 10.1007/s40195-022-01436-0.
12. M. D. Gholami, M. Salamat, and R. Hashemi, "Study of mechanical properties and wear resistance of Al 1050/Brass (70/30)/Al 1050 composite sheets fabricated by the accumulative roll bonding process," *J. Manuf. Process.*, vol. 71, pp. 407–416, 2021, doi: 10.1016/j.jmapro.2021.09.032.