Investigation of Cu-Cu Stitch Bonding Reliability on Cu Leadframe Substrate Using Ultrathin Cu-Selective Passivation

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Abstract

Despite advances in 2.5D and 3D packaging, wire bonding remains the industry's most widely used interconnect method due to its cost-effectiveness. Ultrasonic wedge bonding, also known as stitch bonding, is a critical interconnection technique that links IC dies to external circuits for power and signal transmission, where precise control of bonding parameters is essential to ensure reliable connectivity. However, as the industry transitions from traditional gold (Au) wire to cost-effective copper (Cu) and palladium-coated copper (PCC) wire, new challenges have emerged in ensuring second bond (stitch) reliability, particularly on modern leadframe substrates with silver (Ag) coatings. While Ag plating helps suppress Cu oxidation, it adds to material cost and raises environmental concerns due to its bioaccumulation potential. To address this, we developed a low-cost, ultrathin Cu-selective passivation coating that effectively suppresses Cu oxidation and enables direct Cu-Cu stitch bonding without the need for Ag. This passivation layer is fully compatible with standard IC packaging processes and does not interfere with surrounding dielectrics or interconnects. This paper discusses the application of this ultrathin coating on copper-based leadframe (LF) and is subjected to stitch bonding with 25 µm (1 mil) aluminum (Al-1wt%Si) and palladium-coated copper wire (PCC) under different heating conditions (170°C-200°C). The bonding power, time, and force are kept constant throughout the work. Coated Cu leadframes demonstrated a substantial improvement in pull strength and reliability. Notably, bonds on bare-Cu LF failed at the interface due to oxidation, while passivated-Cu LF exhibited failure at the wire neck, indicating stronger bond integrity. Preliminary data with PCC wire at 125°C further support these findings. This work highlights a promising, environmentally sustainable alternative to Ag plating, enabling reliable Cu-Cu stitch bonding for next-generation, low-cost IC packaging solutions.

Key words

Ag-free LF package, Cu-Cu Stitch Bonding, Cu-oxidation suppression, Ultrathin Cu-selective passivation technology.

I. Introduction

Wire bonding has been the dominant interconnection method in microelectronics for over five decades, offering low cost, high throughput, strong electrical performance, and adaptability across package types from traditional dual-in-line packages (DIPs) to fine-pitch surface-mount and multi-chip modules [1]. Despite the rise of advanced interconnects like flip-chip and TSV-based 2.5D/3D integration, wire bonding remains essential for high-reliability, cost-sensitive applications such as automotive, industrial, and consumer electronics [2]. As a mature and efficient process, it annually enables trillions of electrical and mechanical connections with high production speeds and near-perfect yields [3], [4]. Among the various wire bonding techniques, ultrasonic wedge bonding, particularly the second bond or "stitch bond", plays a critical role in completing the electrical path from the die to the leadframe or substrate [5]-[7]. Unlike ball bonding, which forms the first bond at the die pad, wedge bonding creates the second bond on a metal-coated leadframe, a more mechanically vulnerable site prone to failure under thermal and environmental stress. Therefore, ensuring robust bonding strength is critical for long-term package reliability [6].

The Quad Flat Package (QFP) remains a widely adopted format in high-volume semiconductor packaging due to its low cost, ease of board-level assembly, and suitability for medium-to-high I/O count devices. In QFP designs, leads extend outward from the package body, with wire bonds typically routed from the die center to the peripheral leadframe paddles [8]. Cu-based leadframes (LF) are widely used in QFPs alongside silicon die, bonding wire, and epoxy molding compounds due to their superior electrical and thermal conductivity and lower cost. Compared to traditional iron-based alloys like Alloy 42 (Fe-42 wt% Ni), they are the preferred choice for plastic IC packages [9]. As the semiconductor industry advances toward finer pitches, thinner profiles, and higher operating currents, the second bond in QFPs formed at the leadframe becomes increasingly critical. This site is particularly susceptible to mechanical and electrical stress, especially in automotive-grade applications where extended temperature exposure is common [10].

Metal-plated leadframes are commonly employed to enable reliable second bonding in QFPs and other advanced packaging formats. These leadframes typically feature a 5-12 µm thick silver (Ag) layer deposited over a Cu substrate [11], [12]. The Ag layer serves dual purposes: it acts as a bondable surface for wedge (stitch) bonding and functions as a diffusion barrier, delaying oxidation of the underlying Cu during thermal processing [13]. While Ag plating has been widely adopted in industry, it presents several limitations. (a) Ag is an expensive noble metal, and its use over a large area significantly increases material and processing costs. (b) Ag is associated with environmental and regulatory concerns, including its bioaccumulative nature and challenges in industrial waste management [14]. Lin et al. have also shown that Ag is not an effective long-term barrier against Cu diffusion [15]. During high-temperature steps such as die attach (~175°C) and second wire bonding (~200°C), Cu migrates through the Ag layer, forming oxide-rich Cu domains at the bond interface. These oxides interfere with metallurgical bonding, reducing pull strength, interfacial delamination, and early-life reliability failures. Alternative metallization strategies have been explored and studied. Among them, Ni plating has received attention for its ability to retard Cu diffusion [16]. However, Ni-plated Cu leadframes suffer from poor interfacial adhesion, particularly at the Cu-Ni and Ni-Ag interfaces, resulting in mechanical instability and delamination under thermal cycling. Moreover, both experimental and microstructural analyses have demonstrated that Cu can still diffuse through Ni layers, especially at elevated temperatures, thus undermining its long-term effectiveness as a diffusion barrier [17], [18]. These studies collectively emphasize that conventional metal-based diffusion barrier systems (Ag, Ni) are inadequate for preventing Cu migration and oxidation during extended thermal exposure.

To address these limitations, we developed a Cu-selective passivation strategy based on the surface modification of Cu substrates as proposed in Fig. 1. This approach offers two critical advantages: (1) it effectively suppresses Cu oxidation at elevated temperatures (~200°C), thereby enabling robust Cu-Cu stitch bonding, and (2) it provides a low-cost, environmentally sustainable alternative to electroplated Ag pad, aligning with industry trends toward green and cost-efficient packaging solutions. In our recent study [19], we demonstrated that a 10 nm Cu-selective passivation layer significantly reduced Cu (I) oxide formation by up to 75% during thermal annealing at 200°C

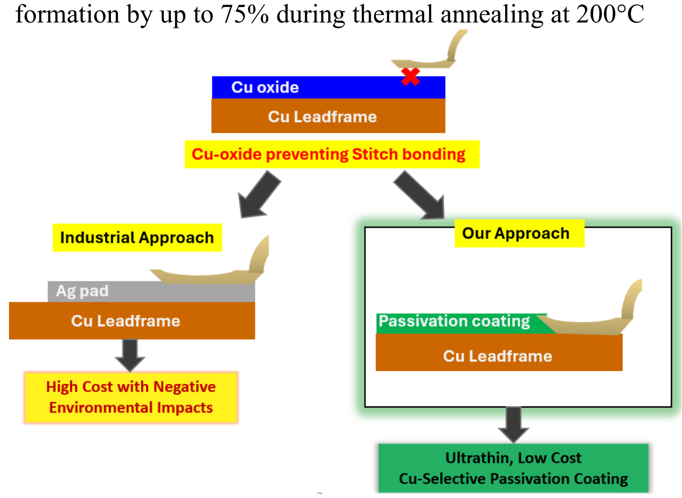

Fig.1: Proposed Plan for reliable Cu-Cu stitch bonding.

in ambient air. This was confirmed via Reflection Absorption Infrared Spectroscopy (RAIRS) and Quartz Crystal Microbalance (QCM) measurements. The passivation coating enabled >99% Cu–Cu ball bonding yield, with minimal non-stick-on-pad (NSOP) defects and shear strengths surpassing those of conventional Cu-Al bonds. Furthermore, in accelerated corrosion tests conducted in 100 ppm chloride solution, unprotected Cu-Al wire-bonded devices exhibited complete wire lift-off within hours. In contrast, Cu-Cu bonded samples coated with our passivation layer remained structurally intact even after 40 days of immersion in 100 ppm chloride solution, demonstrating the coating's inhibition of corrosion defects and suitability for automotive-grade, high-reliability applications.

Building on the success of our Cu-selective passivation in ball bonding, we extended the study to stitch bond the critical second bond in quad flat package (QFP) assemblies. We evaluated two industry-standard wires: 25 µm aluminum (Al–1wt%Si) wire for cost-effectiveness, and palladium-coated copper (PCC) wire for enhanced reliability. Bonding was performed on bare and passivated Cu leadframes, which were pre-annealed at 170–200°C to simulate typical wire bonding conditions. With Al wire, passivated Cu LF showed significantly higher pull strength and interfacial integrity than bare Cu LF, with failure shifting from the bond interface to the wire neck, indicating strong adhesion. Similar trends were observed with PCC wire bonded at 125°C, where passivated Cu LF again outperformed bare Cu LF in pull strength. These results confirm the effectiveness of passivation in enabling reliable, Ag-free stitch bonding across different wire materials and bonding conditions.

II. Experimental

A. Surface Activation and Coating of Cu-Leadframe Substrates

Copper leadframe (Cu-LF) substrates provided by our industrial collaborators were used throughout the study. To remove surface contaminants and activate the Cu surface, the substrates were treated using a reducing plasma (95% Ar and 5% H_2) with different gas flow rates (SCCM) controlled using the PROTEK PC-540 MFC readout instrument. Harrick Plasma PDC-001 benchtop plasma cleaner was used to perform the plasma treatment before the coating process.

B. Wire Used for Stitch Bonding

Stitch bonding was performed using 25 µm (1 mil) diameter aluminum (Al-1wt% Si) wire and palladium-coated copper (PCC) wire (4N Cu 99.99%) with Pd coating and gold flashing. The materials were sourced from AMETEK Engineered Materials and Topline (Tanaka) Corporation, respectively.

C. Conformal Coating of the Cu-Leadframe Substrate

Using a previously established liquid-phase deposition method, an ultrathin Cu-selective passivation layer was applied to Cu-LF substrates [20]. In this study, passivated substrates are denoted as "p-Cu LF," whereas uncoated, native bare Cu LF are referred to as "b-Cu LF." To examine how passivation film thickness affects bonding performance, we prepared samples with varying thicknesses and systematically characterized them.

This study employs attenuated total reflectance (ATR) spectroscopy to accurately quantify the thickness of the passivation layer, using our earlier RAIRS-based coating thickness calibration method as a reference [19]. The chemical characteristic of the passivation coating was further analyzed using a Bruker Vertex 70 spectrometer, equipped with a Platinum ATR accessory and a deuterated triglycine sulfate (DTGS) detector. Surface roughness and coating conformality were evaluated using a Nanosurf Mobil S Atomic Force Microscope (AFM) in contact mode. Scans were acquired over a 10 µm x 10 µm area at 256 x 256 pixels resolution. Roughness parameters were extracted using Gwyddion software with at least three spots per sample to ensure reproducibility.

D. Studying Cu-oxide Suppression at High Temperature

To evaluate oxidation suppression capabilities, both p-Cu LF with varying coating thicknesses and b-Cu LF substrates were individually annealed in a programmable Lindberg/Blue 1-inch tubular furnace at 170°C and 200°C, simulating typical wire bonding manufacturing conditions. Different air annealing times, such as 1, 3, 5, and 10 minutes, were tested to assess the time-dependent effect. The extent of Cu oxide formation was measured using ATR spectroscopy for each sample. AFM analysis was carried out to check the surface roughness of the Cu LF post annealing.

E. Stitch Bonding Reliability on Pre-Annealed Cu-LF and Postmortem Analysis

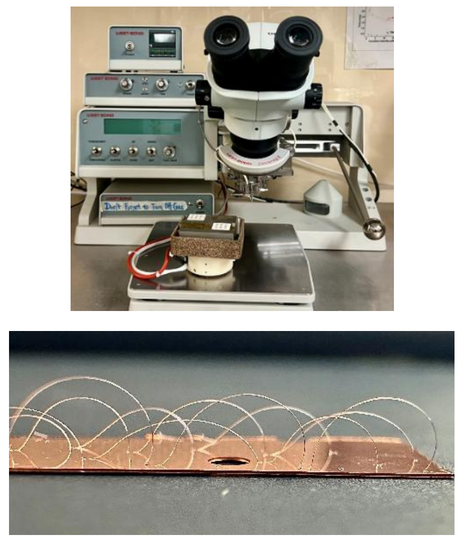

Fig. 2: (top) Manual Wedge bonder from WEST-BOND Inc., and (bottom) A series of Al wire stitch bonded on a passivated Cu LF (p-Cu LF) edge sample.

Ultrasonic stitch bonding was performed on both passivated (p-Cu LF) and bare (b-Cu LF) Cu leadframes at room temperature (RT) using a WEST-BOND Manual Wire Bonder with 45° wire feed as shown in Fig. 2 (top). Prior to stitch bonding, both types of leadframes were pre-annealed at 170°C and 200°C for 1, 3, 5, and 10 minutes in air. Fig. 2 (bottom) shows a series of Al stitch bonds on the p-Cu LF edge sample. Bonding conditions were kept constant: 80 ms bonding time, 400 W ultrasonic power, and 23 g bonding force. 5-15 bonds were formed for each condition with uniform loop height and bond length to ensure reliable pull strength measurements. Pull testing was performed using an in-house hook setup, where a tensile force was applied perpendicular to the stitch bond until failure occurred. The corresponding pull strength values were then recorded and compared for analysis. Post-bond failure analysis, including optical imaging using a Keyence VK-X3000 confocal microscope, was carried out to check the wire breakage point (whether from the Cu LF substrate or the wire neck). The stitch-bonded samples were cross-sectioned by embedding them in resin, followed by polishing using standard metallurgical sample preparation methods as outlined in [21]. Cross-sectional SEM analysis of Al stitch bonding was performed on a JEOL IT200 at 5 kV under high vacuum. A backscattered electron detector in composition mode (BED-C) was employed to enhance image contrast and resolution.

III. Results and Discussion:

A. Characterization of Cu-selective Passivation film on Cu-LF substrate

In our prior reported work [19], the 788 cm^{-1} RAIRS peak, attributed to the characteristic peak of the Cu-selective passivation, was established as a chemically distinct and reliable spectral marker for coating thickness due to its well-defined peak shape and strong linear correlation with film thickness. Fig. 3 shows representative ATR spectra from

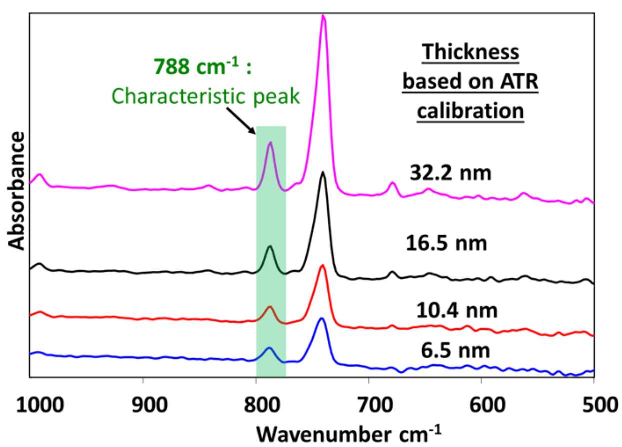

Fig. 3: ATR Spectrum showing different passivation coating thicknesses based on calibration.

passivated Cu LF substrates, where the progressive increase in peak intensity at 788 cm^{-1} aligns with increasing film thickness. The explored thickness range of 6 to 32 nm was selected to span the functional window relevant for subsequent reliability studies, allowing us to probe both the threshold of oxidation suppression and bonding interface integrity under elevated temperature conditions like 170-200°C. AFM measurements were also carried out as shown in Fig. 4 by performing three different spots to assess the surface morphology for both b-Cu LF and p-Cu LF samples. The b-Cu LF exhibited an average surface roughness of 29.3 ± 4.0 nm, while the p-Cu LF, with a coating thickness of less than 20 nm, showed an increased roughness of 44.4 ± 0.1 nm. This increase indicates a change in surface morphology following passivation and provides insight into the uniformity of the applied coating.

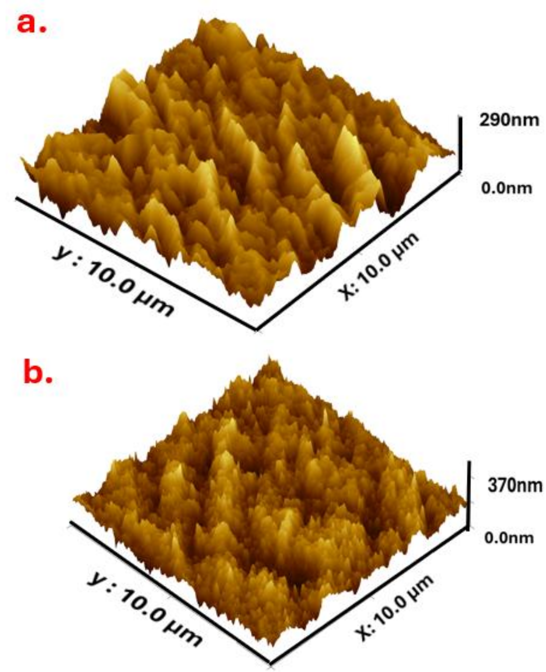

Fig. 4: AFM images of (a) b-Cu LF and (b) p-Cu LF.

B. Cu-Oxidation Suppression using Passivated Film at Elevated Temperature.

Copper surfaces are inherently prone to oxidation when exposed to air, a phenomenon that accelerates significantly at elevated temperatures relevant to microelectronic packaging processes. Specifically, temperatures more than 150°C facilitate the rapid formation of Cu(I) oxide (Cu_2O), the dominant oxide phase below 300°C [10], [22]. In this study, we evaluated the oxidation resistance of our Cu-selective passivation coating using Cu leadframe (Cu LF) edge samples, under temperature and time conditions representative of typical wire bonding processes. Cu LF samples were passivated with varying average film thicknesses: 6.5 nm (Type A), 10.4 nm (Type B), 16.5 nm (Type C), and 32.2 nm (Type D) were subjected to air annealing at 170°C and 200°C for 1, 3, 5 and 10 minutes, alongside uncoated (bare) Cu LF as a control. To assess the oxide suppression capability of the passivation coating under more stringent elevated thermal treatment, i.e., samples air annealed at 170°C and 200°C for 10 minutes were selected for evaluation. As shown in Fig. 5(a), all passivated Cu LF samples exhibited substantial suppression of Cu oxide

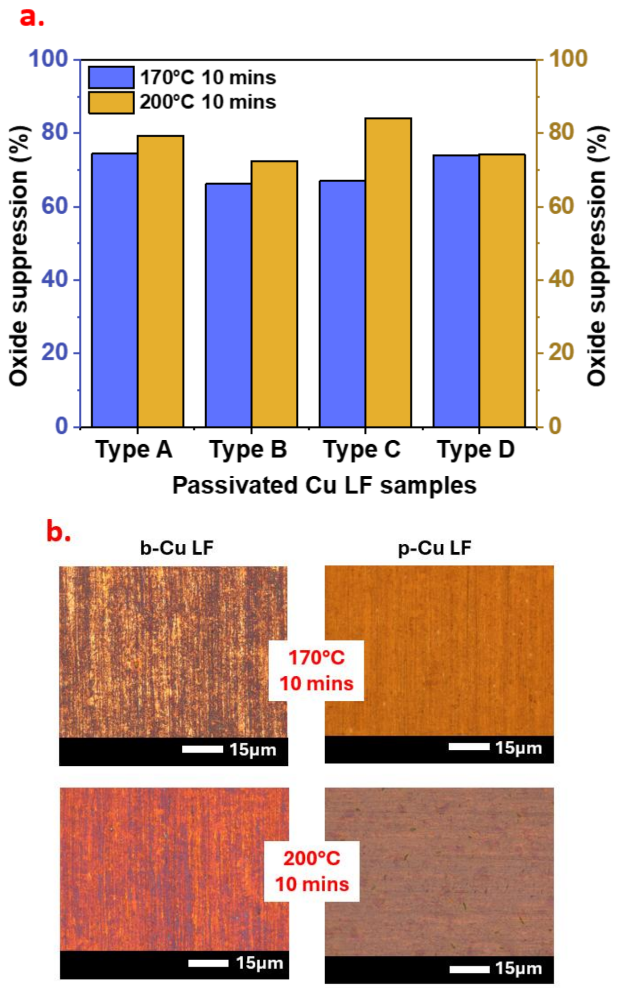

Fig. 5: (a) Cu-oxidation suppression across different coating thicknesses in 170°C and 200°C 10 min annealed samples. (b) Microscopic images of b-Cu LF and p-Cu LF post 10 mins of 170 and 200°C air annealing.

formation compared to the bare Cu LF substrate after 10 minutes of air annealing at 170°C and 200°C. The oxide suppression efficiency varied between 70% to 84%. This variation in the oxide suppression may be attributed to coating inhomogeneity, which can eventually lead to oxygen diffusion onto the Cu surface. Fig. 5(b) provides visual evidence that b-Cu LF shows significant surface darkening due to heavy oxidation. In contrast, the p-Cu LF retains a much lighter appearance, indicating effective protection and minimal oxide formation.

C. Al stitch bonding results with preliminary pull strength data acquired with PCC wire.

Although slight surface oxidation was detected on the p-Cu LF samples after pre-annealing at 170°C, stitch bonding formed using 25 µm Al wire consistently achieved strong and reliable bonds. In comparison, pre-annealed b-Cu LF samples exhibited poor bonding performance. The hook method was utilized to pull the wire stitched onto the Cu LF surface. The pull strength results demonstrate a clear correlation between thermal oxidation suppression and bonding performance on Cu LF substrates. Figure 6(a)

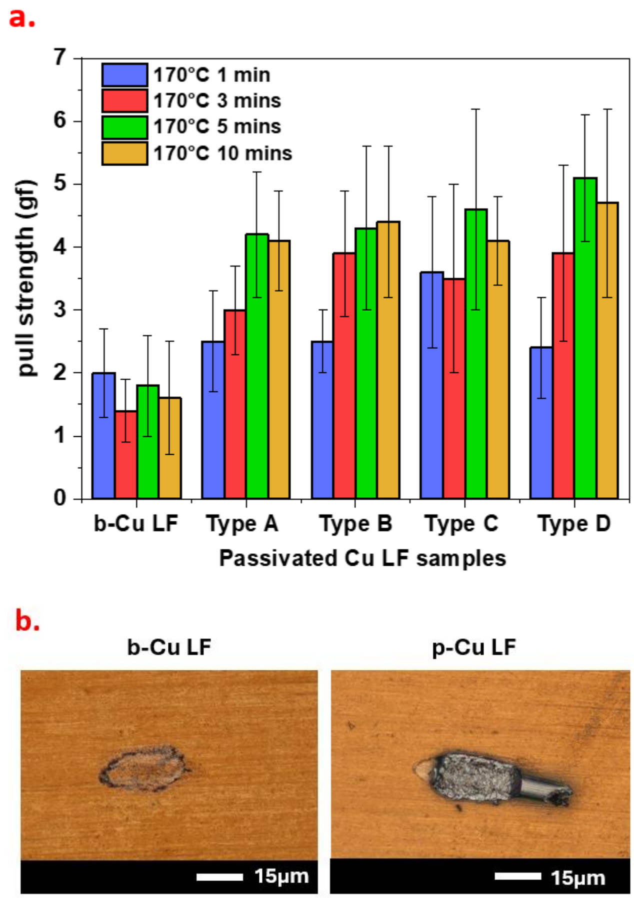

Fig. 6: (a) Pull strength of Al stitch bonds on passivated (Type A-D) vs. b-Cu LF after pre-annealing at 170°C for various time intervals. (b) Microscopic evidence showing the Al wire breakage point post-pull test process.

presents the pull testing results with associated error margins. The unprotected b-Cu LF exhibited significantly lower pull strength, ranging from 1.4 ± 0.5 gf to 2.0 ± 0.7 gf. In contrast, stitch bonds formed on the passivated p-Cu LF (Types A to D), pre-annealed at 170°C for various durations, showed noticeably improved pull strengths. The lowest value was 2.5 ± 0.8 gf for Type A (coating thickness =

6.5 nm), while the highest was 5.1 ± 1.0 gf for Type D (coating thickness = 32.2 nm). These values are comparable to or exceed the minimum bond strength of 2.5 gf specified by MIL-STD 883E, Method 2011, Test Condition D, for 1 mil Al wire bonds [23]. As per the MIL-STD 883 Method 2011.9 failure code 2 and 9 [24], p-Cu LF samples show the wire breaking point in the neckdown region on the stitch bond, whereas the b-Cu LF sample follows the failure code of 4, which means the lift off is happening from the LF substrate, clearly evident from Fig. 6(b). To gain deeper insight into the bonding quality underlying the observed mechanical performance, cross-sectional SEM imaging was

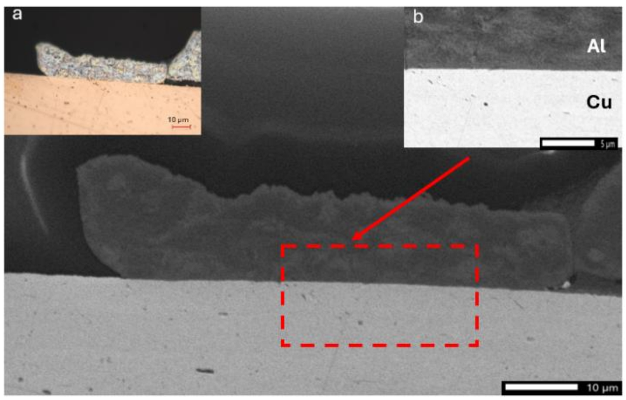

Fig. 7: Cross-sectional SEM image showing Al stitch bonded on pre-air annealed Cu LF substrate with insets (a) microscopic image and (b) zoom-in SEM view shows clear bonding interface between the Al wire and Cu LF.

performed at the Al-Cu stitch bond interface, as shown in Fig. 7. It shows high-magnification evidence of a well-structurally intact Al stitch bond on a passivated Cu LF sample pre-annealed at 170°C. The interface appears continuous and free from cracks or delamination, indicating strong mechanical integrity. A closer view in Fig. 7(b) highlights the flat and intimate bonding of the Cu LF beneath the stitch bond, consistent with bonding performed at room temperature. The top surface of the Al wire also appears relatively flat and uniform, further confirming the absence of damage or bonding defects. These observations suggest that the passivated Cu LF maintains sufficient surface conditions even after thermal exposure to enable reliable Al stitch bonding without interfacial degradation.

Similarly, the passivation effect becomes more evident for 200°C pre-air-annealed Cu LF samples, where the risk of oxidation is more severe. The b-Cu LF failed under prolonged exposure, consistently showing the lowest wire pull strength of 2.4 ± 1.0 gf for 1 min. In contrast, all passivated samples (Type A-D) showed significantly

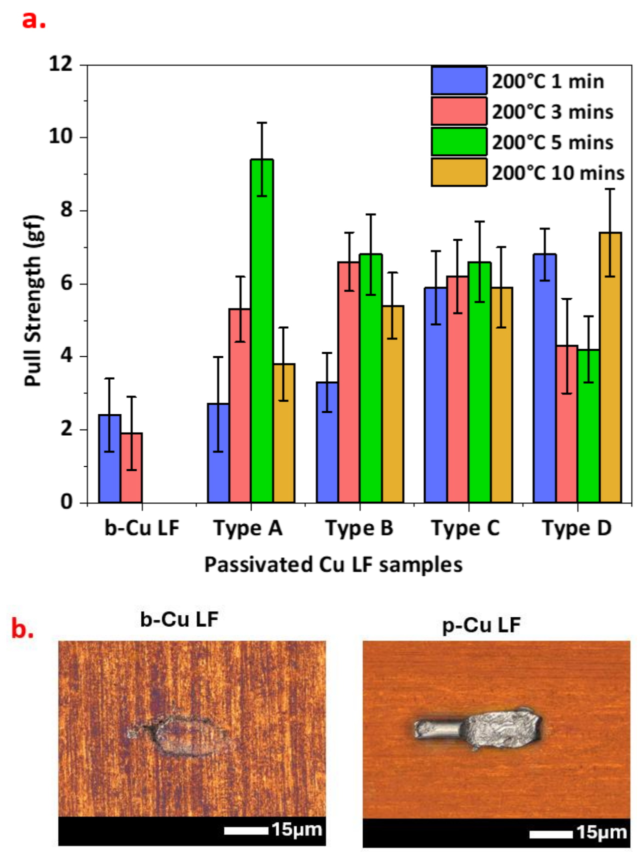

Fig. 8: (a) Pull strength of Al stitch bonds on passivated (Type A-D) vs. b-Cu LF after 200°C annealing at various times. (b) Microscopic images show the Al wire breakage point post pull test process.

improved pull strength, as shown in the bar graph of Fig. 8(a). Notably, the sample with 6.5 nm thickness (Type A) showed a pull strength of 9.4 ± 1.0 gf, the highest recorded among the varied thickness samples, followed by 7.4 ± 1.2 gf, which was recorded for the sample with 32.2 nm (Type D) passivation film thickness. Type B and Type C samples consistently achieved pull strengths of 5-6 gf range, which is still higher than b-Cu LF. Fig. 8(b) shows the wire breaking point, which follows a similar trend to that we observed in 170°C pre-annealed Cu LF. After 5 and 10 minute anneals, the b-Cu LF developed a thick oxide layer so that successful stitch bonding was impossible; the Al wire rebounded from the surface, resulting in a high non-stick-on-lead (NSOL) rate. At the applied bonding power (400 W) and bonding time (80 ms), this oxide layer prevented proper adhesion, resulting in complete bond failure.

In addition, using 25 µm PCC wire, a similar trend of wire breaking point after pull tests was observed as that of the Al wire counterparts reported earlier (Fig. 9). Here, the stitch bonding was performed on LF substrates heated at 125°C, rather than the room temperature process we performed for Al wire. Despite the stitch bonding of PCC wire at a higher temperature, our preliminary data showed that a high pull strength of 7 gf can be achieved. This pull strength exceeds the standard of MIL-STD 883E method 2011 and Qin et al.

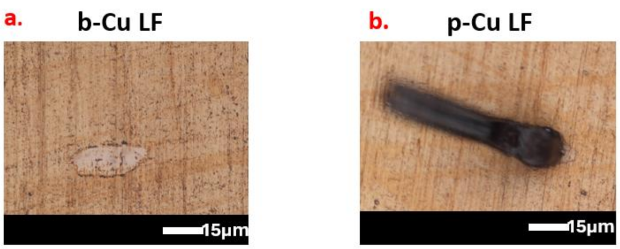

Fig. 9: Microscopic images showing PCC-wire breaking patterns in (a) b-Cu LF and (b) p-Cu LF.

reported a value of 3.7 gf [25]. The results demonstrate that the Cu-selective passivation coating significantly enhances stitch bond reliability by mitigating surface oxidation. This leads to higher pull strengths, indicating that robust bonding can be achieved.

IV. Conclusion:

This study investigates a novel Cu-selective passivation strategy developed to tackle two major challenges in Cu-based LF packaging: (1) high-temperature oxidation and (2) stitch bonding reliability. By leveraging ATR and RAIRS-based calibration methods, precise control over passivation thickness was achieved, enabling a systematic investigation of the relationship between oxide suppression and bond performance. The results clearly show that passivated Cu LF (p-Cu LF) samples exhibit substantially reduced Cu-oxide formation and notably higher pull strengths compared to bare Cu LF (b-Cu LF), even under extended thermal exposure, as confirmed based on the microscopic and cross-sectional SEM imaging. Successful stitch bonding using Al and PCC wire further confirms the coating's versatility.

These findings establish Cu-selective passivation as a promising, scalable, and cost-effective silver-free solution for enabling reliable Cu-Cu stitch bonding in thermally demanding microelectronic packaging applications.

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