COMPARATIVE PERFORMANCE EVALUATION OF COPPER WIRE COMPOSITIONS UNDER GRADE 0 RELIABILITY CONDITIONS

Ginbert C. Manalo
Tonton C. Pinili
Isiah N. Gregorio

Central Engineering
onsemi, Golden Mile Business Park, SEZ Governor's Drive, Maduya, Carmona, Cavite, Philippines
Ginbert.Manalo@onsemi.com, Ton.Pinili@onsemi.com, Aicee.Gregorio@onsemi.com

ABSTRACT

"Grade 0" reliability represents the most stringent level of performance demanded in critical applications. It signifies near-perfect operation with minimal tolerance for errors or degradation. Copper is one of the best options for bonding wire, but their performance can be significantly impacted by its composition, especially under extreme operating conditions. This study investigates the behavior of various copper wire compositions under these extreme conditions. By understanding these limitations, we can pave the way for the development of next-generation materials that push the boundaries of performance and reliability, ultimately fostering groundbreaking advancements in technology.

A comparative analysis of T_0 wire bond data, facilitated by statistical tools, allows us to understand the wires' behavior before stress. Finally, the employment of Scanning Electron Microscopy (SEM) and Energy-Dispersive X-ray Spectroscopy (EDX) in failure analysis from reliability results enables the identification and characterization of degradation mechanisms at the microscopic and elemental levels, respectively. The study revealed that both standard copper (4N) and copper alloys (2N) exhibited limitations under the extremely high temperatures of Grade 0 environments. It exposed the vulnerability of bare copper (Cu) to sulfur corrosion at high temperatures. While copper alloys offer some benefits over bare copper, they still aren't reliable enough to sustain necessary readouts of reliability. The big winner is palladium-coated copper with Au flash (2N Au PCC). The palladium layer protects the copper from corrosion and reduces weak connection formation even at very high temperatures. This makes AuPdCu wires the most reliable choice for applications requiring top performance and durability under extreme conditions.

1. 0 INTRODUCTION

Grade 0 certification signifies the highest level of reliability in the automotive industry. Our focus is on conquering the hurdle of Grade 0 qualification, a critical step towards fulfilling the evolving demands of our customers. By accurately creating a robust process that adheres to these stringent reliability standards, we aim to unlock a new frontier of business opportunities. This research represents a significant leap forward in our ongoing development efforts, giving way for a future where our product portfolio includes not only our existing Grade 1 offerings but also Grade 0-qualified devices that push the boundaries of performance and reliability.

This research explores the potential of copper wire as a viable alternative to gold for achieving "Grade 0" reliability in wire bond interconnects. By leveraging advanced material science and data analysis, we aim to bridge the gap between affordability and peak performance.

1.1 Grade 0 Reliability Requirements

The Automotive Electronics Council's (AEC) Q100 standard defines Grade 0 as the category with the most extreme operating temperature range (Table 1). Consequently, Grade 0 devices require the most stringent qualification conditions (Table 2). It's important to note that the standard mandates zero defects across all qualification tests for Grade 0 components [1].

Table 1. Part Operating Temperature conditions per Grade level as per AECQ100

Part Operating Temperature	
Grade	Ambient
0	-40°C to +150°C
1	-40°C to +125°C
2	-40°C to +105°C
3	-40°C to +85°C

Table 2. Qualification test methods per Grade Level

Grade	Qualification Test Methods		
	TC	HTSL	HTOL
0	-55°C to +150°C 1500 cycles	+175ºC Ta 1000hrs or +150ºC Ta 2000hrs	+150ºC Ta 1000hrs
1	-55°C to +150°C 1000 cycles	+150ºC Ta 1000hrs or +175ºC Ta 500hrs	+125ºC Ta 1000hrs
2	-55ºC to +125°C 1000 cycles	+125ºC Ta 1000hrs or +150ºC Ta 500hrs.	+105ºC Ta 1000hrs
3	-55°C to +125°C 500 cycles	+125ºC Ta 1000hrs or +150ºC Ta 500hrs.	+85ºC Ta 1000hrs

1.2 Copper Wire

The initial adoption of copper wire for bonding in the semiconductor assembly market began with bare copper (Cu) wires. Shortly thereafter, palladium-coated copper (PdCu) wires were introduced. These early iterations of fine copper wire components were primarily used in consumer electronics. These products typically underwent less stringent reliability testing, often excluding voltage-humidity stress tests (biased HAST, THB), extended temperature cycling (TC), or extended high-temperature storage life (HTSL) evaluations. As field returns for consumer electronics are generally less frequent compared to products with stricter reliability requirements, issues related to copper wire bonding were not widely identified during this initial phase [2].

The primary factor driving the switch from gold to copper bonding wire was its significant cost advantage. However, the move from copper wire to palladium-coated copper wire stemmed from the need for enhanced anti-oxidation properties and the stringent reliability requirements of the automotive industry [3]. Refer to Figure 1.

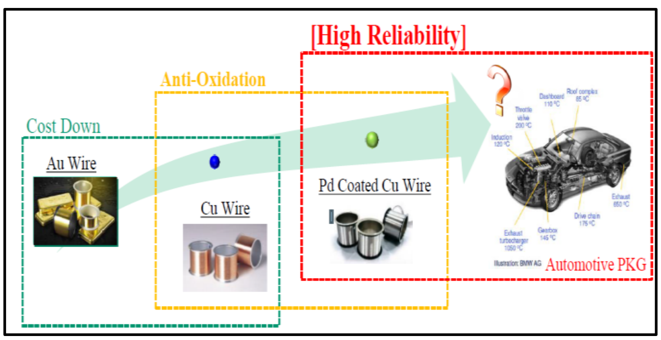

Fig. 1. Evolution of bonding wires to improve oxidation resistance. The evolution starts with gold (Au) wire, then progresses to bare copper (Cu) wire, and finally to palladium (Pd) coated copper wire.

2. 0 REVIEW OF RELATED WORK OR LITERATURE

Several studies for a variety of bonding wire options were established. The succeeding paragraphs contain a comparative summary of available options in the semiconductor industry.

A. Copper versus Palladium Coated Copper

The reported work shows bare copper has equal performance to palladium-coated copper wire under Automotive Electronic Council (AEC) reliability grade 1 in specified package types when the bonding process, substrate/lead frame design, and mold compound have been correctly optimized [2].

Previous research investigating the behavior of copper wires with different molding compound compositions suggests that palladium-coated copper (Pd-Cu) wires may offer improved humidity reliability. While chloride ions (Cl^-) originating from molding compounds have been identified as a primary contributor to corrosion, the specific failure mechanisms remain unclear, particularly for Pd-Cu wires [4].

3.0 METHODOLOGY

Discussed in this section are the materials and equipment used throughout the study and a general description of the methods involved.

A. Materials & Equipment

To ensure exceptional reliability under "Grade 0" conditions, the device was chosen based on its ability to endure harsh environments. The selected device features Bond Over Active Circuit (BOAC) die technology, a 90µm Bond Pad Opening (BPO), and 0.8µm Front Metal Thickness (FMT), all contributing to its high mission profile. This device is fabricated on an industry-standard 8-inch wafer and then packaged in a TSSOP format during assembly. For a more comprehensive performance evaluation, we utilized three distinct copper wire compositions (Table 3). These compositions included: 4N bare copper, a 2N copper alloy containing dopants of nickel, iron, manganese, and platinum, and 2N palladium-coated copper (PCC) with an additional gold (Au) flash layer and platinum dopant.

Table 3. Technical Data Sheet (TDS)

Type			4N Bare Cu	2N Cu Alloy	2N Au PCC	Units
Diameter			1.0			mil/s
General	Breaking Load		6 ~12	10 ~ 16	8.2 - 15.9	gf
	Elongation		8 ~16	9.0 ~ 21.0	5 - 20	%
Physical	Hardness	Free Air Ball	85 – 95	90 – 100	60 - 80	Hv
		Wire	85 – 95	95 – 105	85 - 105	
	Density		8.92	8.93	8.99	g/cm3
	Thermal Conductivity		401	405	333	W/m K
	Elastic Modulus		80 – 90	90 – 100	60 - 85	Gpa
	Melting Point		1083	1054	1086	degC
	Fusing Current		0.455	0.46	1.03 (L=3mm,10s)	A
	Resistivity (20 degC)		1.69	1.74	2.3	µΩ.cm

Before the wire bonding process, careful machine selection was conducted to guarantee the best possible outcomes when comparing different wire types. The wire bonders evaluated were Conn X from KNS, GoCu from ASM, and UTC5k from SKW. The deciding factors for choosing the best machine were bonding accuracy, the resolution of the Z-axis on the bond head, and the specifications of the XY table. The analysis revealed that the UTC5000 from SKW emerged as the superior choice due to its three key features; Screwless transducer, precise bond force calibration, and Controlled XY table vibration.

B. Methods & Design of Experiment

At wire bond, the formation of the Free-Air Ball (FAB) of the three copper wire types was evaluated. Electrical Flame Off (EFO) current and time were identified as critical factors influencing the final FAB shape and visual quality. To prevent copper oxidation during FAB formation, a forming gas mixture of 95% nitrogen (N2) and 5% hydrogen (H2) was used at a constant flow rate of 0.5 liters per minute (LPM).

The overall quality of the FABs was evaluated using high-magnification microscopes and Scanning Electron Microscopy (SEM) for both 4N bare copper and 2N copper alloy. For the 2N AuPCC wires, an additional method was implemented to specifically assess the thickness and uniformity of the palladium layer. The following procedure is based on chemical etching of the copper bulk; thereby exposing the thickness and distribution of the surrounding Pd coating.

1. Mechanically cross-section units.
2. Prepare the copper etchant solution composed of the ff.: (remember add acid to water, NOT water to acid)
    - 2 ml FeCl3 (36%)
    - 23 ml H2O
    - 6 ml HCl
3. Dip the cross-sectioned sample into the solution for 3-5 seconds.
4. IMPORTANT: Immediately wash samples with running DI water. Aim the sample surface parallel to the direction of water flow.

Dry samples and observe under a high-magnification microscope to check the quality of etch.

Thickness measurement on FAB is divided into four (4) areas, as shown in Figure 2. Four (4) data points are taken in each area. This is done for three (3) ball bonds to achieve 12 data points per area.

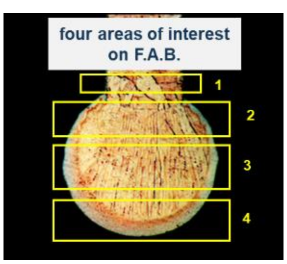

Fig. 2. Sample image of etched 2N AuPc Free-Air-Ball (FAB). The areas of interest for palladium (Pd) thickness measurement are highlighted.

Characterization of factors affecting wire bonds was performed. The responses for the DOE were Wire Pull Strength (WPT), Ball Shear Strength (BST), Mashed Ball Dimension (MBD), Intermettalic-Coverage (IMC), Pad Metal Displacement ratio (PMDr), and bond pad damage check (i.e., crater test). The ball dimensions and remaining Al were characterized by optical microscopy and scanning electron microscopy (SEM). These techniques were also used to look for possible damage to underlying structures after removing the bond pad metallization (i.e., crater test).

After defining the wire bonding process for each of the three copper wires, evaluation samples were subjected to reliability testing under stress levels higher than Grade 0 conditions.

- Highly Accelerated Stress Test (HAST) - 110°C, RH 85%, 18.8psi for 264hrs – 528hrs
- Unbiased Highly Accelerated Stress Test (UHAST) - 110°C, RH 85%, 18.8psi for 264hrs
- Temperature Cycle (TC) – (-)55°C / 175°C for 1000cys – 2000cys
- High-Temperature Operating Life (HTOL) – Ta 170°C / Tj max 183°C for 1000hrs
- High Temperature Storage Life (HTSL) – 190°C for 504hrs – 1008hrs – 2016hrs

To assess the performance of the wire bonds under various conditions, custom Destructive Physical Analysis (CDPA) techniques were employed. These analyses focused on comparing the growth of Intermetallic Compounds (IMC) and the extent of corrosion after (HTSL) testing, uHAST /HAST, and a final bond integrity check following Thermal Cycling (TC). The data comparison will cover the entire testing period, from initial measurements (Time 0) to the final reliability results.

4.0 RESULTS AND DISCUSSION

4.1. Free-Air-Ball (FAB)

The FAB data confirms similar dimensions and spherical shapes for all three copper wires (Figure 3). No irregularities were detected.

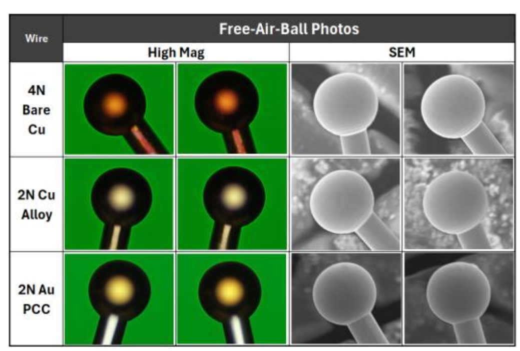

Fig. 3. High magnification and SEM photos of Free Air Ball. No abnormalities were observed on all wire compositions.

In addition to conforming to the dimensional specifications and showing no visual defects, the Au PCC wires demonstrated a uniform distribution of palladium when bonded using the defined EFO parameters (Figure 4). As expected, results verified that the thickest Pd coating will be on area 4 where the EFO firing occurred. This is critical to be able to serve the purpose of palladium in Au PCC wire.

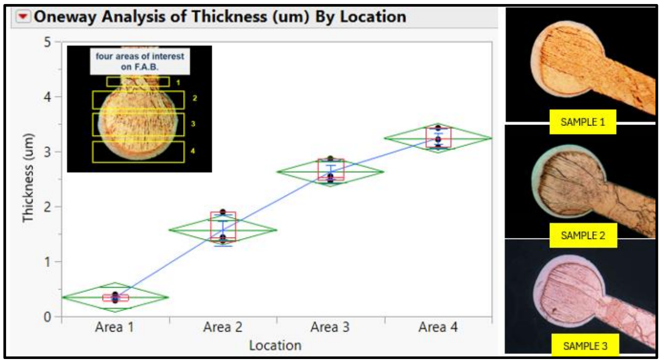

Fig. 4. Graphical data on the palladium (Pd) thickness measurement of 2N AuPCC and sample images of the etched Free-Air-Ball. Thickest Pd measurements were observed on the bottom part of the FAB.

4.2 Time 0 Wire bond responses

All wires met the pre-stress requirements at Time 0: BST $\geq$ 19.2 gms WPT $\geq$ 3.0 gms shown in Figure 5, IMC $\geq$ 70% (Figure 6). No cracks or craters were observed during the crater test, and the target aluminum remaining was obtained with good ball flatness during cross-section analysis (Figure 7).

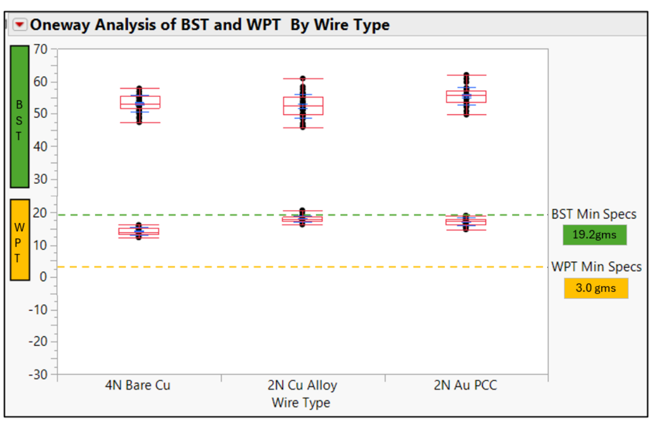

Fig. 5. Ball Shear Test (BST) and Wire Pull Test (WPT) at Time 0. All three wires indicate that they meet the required minimum requirements.

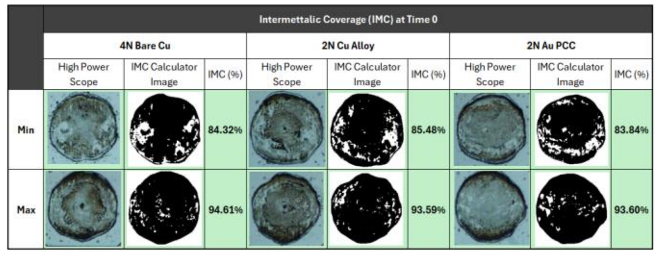

Fig. 6. Intermetallic Coverage (IMC) data at Time 0. All three wires measured IMC greater than 70% minimum requirement.

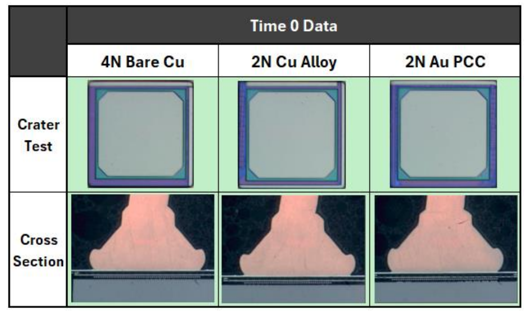

Fig. 7. Crater test and ball cross-section data at Time 0. All three wires confirm no crack and have good ball formation.

4.3 Reliability Results

4.3.1 Highly Accelerated Stress Test (HAST) and Unbiased Highly Accelerated Stress Test (uHAST)

Both the Highly Accelerated Stress Test (HAST) and the Unbiased Highly Accelerated Stress Test (uHAST) produced the same reliable results: all three wire types passed. There was minimal growth in the Intermetallic Coverage (IMC), and no signs of corrosion were found (Figure 8).

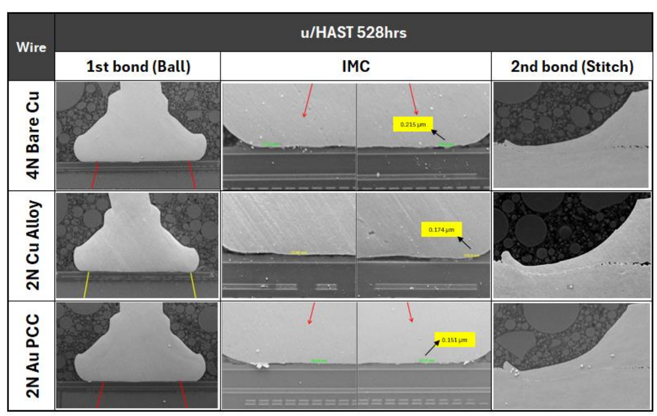

Fig. 8. SEM cross-section photos after u/HAST 528hrs. The data revealed no abnormalities and minimal intermetallic growth.

4.3.2 Temperature Cycle (TC)

The Temperature Cycle (TC) testing also yielded positive results. There were no significant changes in IMC growth even after 2,000 cycles as shown in Figure 9. The 4N bare Cu and 2N Cu alloy showed a significant increase in BST readings with a p-value of 0.001 for both. In contrast, the shear strength of 2N Au PCC inhibits no significant difference with a p-value of 0.9992 (Appendix A). Refer to Figure 10 for the BST graphical representation.

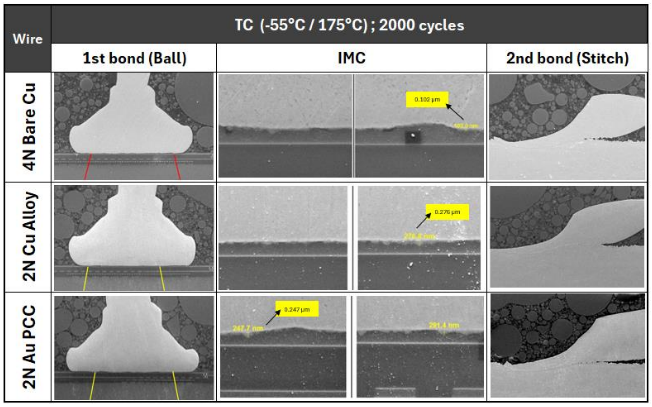

Fig. 9. SEM cross-section photos after TC 2000 cycles. The test results showed everything was normal and with very little IMC growth.

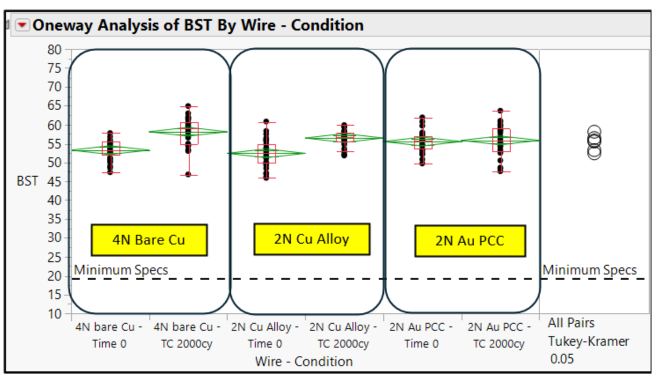

Fig. 10. Ball Shear Test (BST) readings after TC 2000 cycles. Data showed a significant increase from 4N bare Cu and 2N Cu Alloy while no change from 2N Au PCC.

4.3.3 High Temperature Operating Life (HTOL)

All three wire types successfully passed electrically the 1000-hour high-temperature operation (HTOL) life test. However, after the CDPA data, the 2N Au PCC wires exhibited an advantage. Their IMC growth appeared controlled, staying within the aluminum layer's thickness (0.8um). In contrast, the other two wire types showed significant IMC growth exceeding the aluminum thickness (Figure 11).

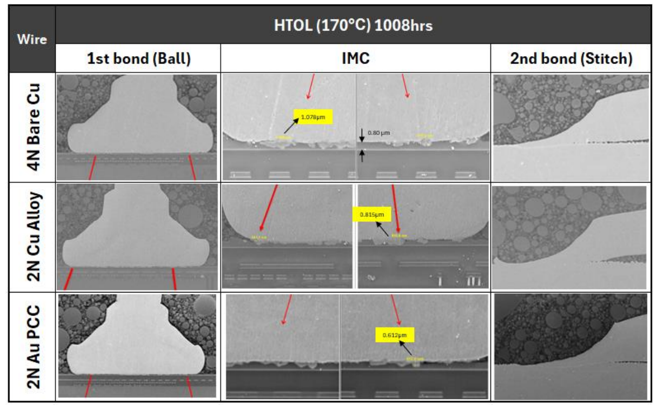

Fig. 11. SEM cross-section photos after HTOL 1008hrs. Faster growth of IMC was observed on 4N bare Cu and 2N Cu Alloy compared to 2N Au PCC.

Bond strength (BST) readings supported these observations. The first two wire types displayed notably higher individual BST readings, indicating a potential correlation with excessive IMC growth. While the 2N Au PCC wires also saw an increase in BST readings, it was less severe compared to the other two as shown in Figure 12. Although statistically, all wire types' BST readings increased significantly with a p-value of 0.0001 (Appendix B).

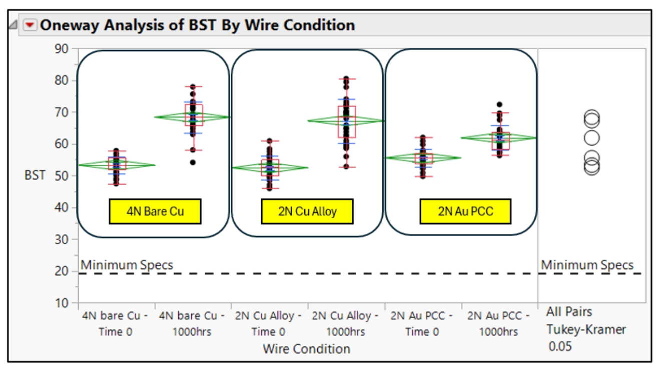

Fig. 12. Ball Shear Test (BST) readings at 1000 hours of HTOL testing show a significant increase in bond strength for all wires. However, the increase is less noticeable for the 2N AuPCC wire compared to the other compositions.

4.3.4 High-Temperature Storage Life (HTSL)

While prior testing revealed minimal performance differences between the wire types, high-temperature storage life (HSTL) exposed a clear distinction. At the extreme temperature of 190°C, 4N bare copper (Cu) experienced gross electrical failures early in the qualification process, at the 504-hour mark. Notably, 19 out of 77 units failed for 4N bare Cu, whereas both 2N Cu alloy and 2N Au PCC achieved a perfect pass rate.

From the Failure Analysis (FA) report, cross-sections on the failed units revealed an interfacial gap between the wire and the bond pad surface at 1st bond. IMC growth was also measured at 2.01µm consuming the entire aluminum thickness of 0.8µm. On the other side, the second bond's cross-section showed signs of corrosion (Figure 13).

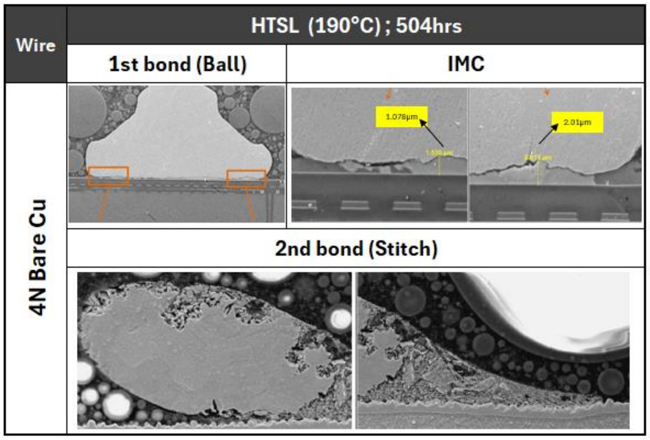

Fig. 13. 4N bare Cu SEM cross-section photos after HTSL 504hrs. A gap between the wire and the bond pad was observed on 1st bond with probable corrosion on 2nd bond.

Energy-dispersive X-ray Spectroscopy (EDX) mapping identified sulfur in the corroded area as shown in Figure 14. Sulfur is a known corrosive element commonly found in mold compounds. This finding suggests that bare copper's vulnerability to halide attack increases at extremely high temperatures. Since the same mold compound was used for all wire types, we anticipated that the 2N Cu Alloy and 2N Au PCC would also be susceptible to sulfur attack.

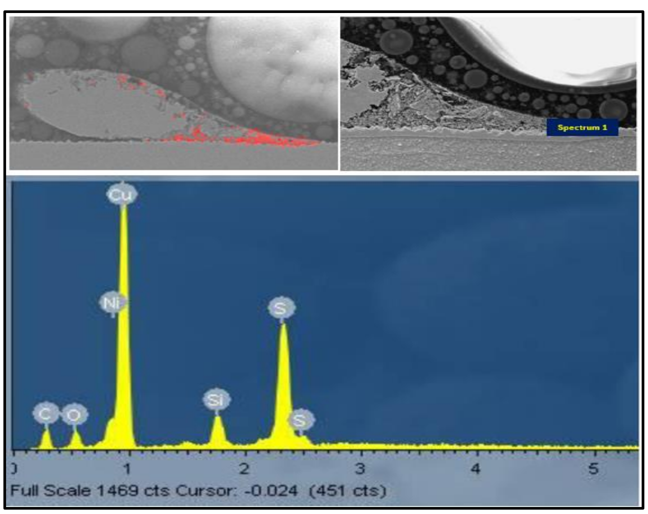

Fig. 14. Energy-dispersive X-ray spectroscopy (EDX) analysis of the corroded stitch area on 4N bare copper (Cu) after HTSL 504hrs. Testing revealed the presence of sulfur (S).

We continued evaluating the two remaining wire types, which had passed previous tests, until the next data point at 1,008 hours of high-temperature storage life (HTSL). Although both wires maintained electrical functionality after 1,008 hours, the custom Destructive Physical Analysis (CDPA) revealed a key difference.

The 2N Cu Alloy wires exhibited a thicker layer of IMC growth compared to the 2N Au PCC wires (Figure 15).

.

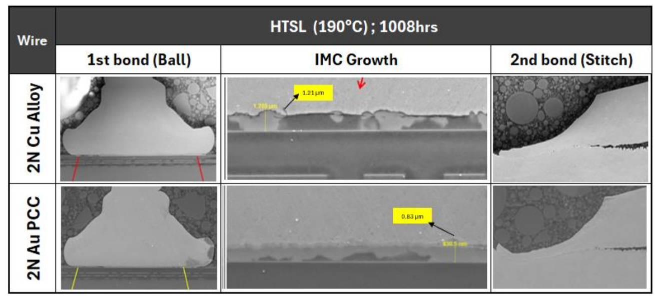

Fig. 15. SEM cross-section photos after HTSL 1008hrs. IMC growth of 2N Cu Alloy was thicker and not uniform compared to 2N Au PCC.

The IMC growth in the 2N Cu Alloy (1.21µm) entirely consumed the 0.8µm aluminum layer. In contrast, the 2N Au PCC wires maintained an IMC layer of 0.83µm, matching the aluminum thickness. We also saw more uniform IMC distribution across the bonded ball on 2N Au PCC compared to 2N Cu Alloy. Additionally, gaps were observed between the copper wire and the aluminum bond pad in the 2N Cu Alloy samples, suggesting potential interfacial corrosion. These gaps were not observed in the 2N Au PCC wires.

Discussed growth in Intermetallic Compound (IMC) thickness corresponds to a significant rise in ball shear strength readings for both wires as illustrated in Figure 16. This is also supported by the comparative p-value of 0.0001 for both wires (Appendix C).

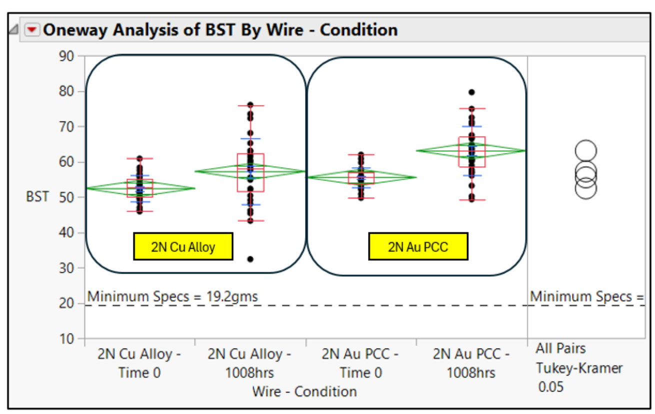

Fig. 16. Ball Shear Test (BST) readings after 1008hrs HTSL. Analysis showed a significant increase in bond strength for both wires.

This excessive IMC growth in the 2N Cu Alloy wires negatively impacted their Wire Pull Test (WPT) results. While both of them show significant degradation in terms of WPT readings with a p-value of 0.0001 (Appendix D), the break mode of 2N Cu alloy failed. Nine out of thirty (9/30) samples failed the pull test due to lifted metal, compared to zero (0/30) failures for the 2N Au PCC wires. Figure 17 illustrates the characteristic appearance of lifted metal and WPT readings.

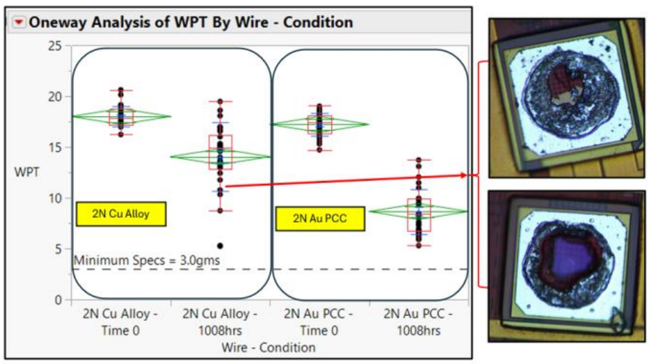

Fig 17. WPT readings and photo of break mode after pull. Both wires experienced significant WPT reading degradation but only 2N Cu Alloy has lifted metal break mode.

5.0 CONCLUSION

Our research, particularly the High-Temperature Storage Life (HTSL) testing detailed in section 4.3.4, identified the most critical findings of the study. The extreme temperatures of the HTSL test exposed a tendency for 4N bare copper to corrode rapidly due to sulfur, causing early failures. 2N Cu alloy wires, while initially promising, exhibited a concerning weakening of their internal bonds over time, ultimately resulting in similar failures. In contrast, 2N AuPCC wire emerged as the superior choice. Its unique palladium layer acts as a protective shield, effectively safeguarding the copper from corrosion and minimizing the formation of detrimental intermetallic compounds (IMC) that can weaken connections. This remarkable performance held even under the most extreme high temperatures.

By identifying these weaknesses and pinpointing the optimal solution - 2N AuPCC wire - our study paves the way for a new generation of electronics with unparalleled reliability. This wire stands out as the ideal choice for demanding applications that require top performance and durability in even the harshest Grade 0 extreme conditions.

6.0 RECOMMENDATIONS

With the extremity conditions Grade 0 can offer, it is recommended not just to study the bonding wire capability itself. This includes identifying the optimal materials for every stage, such as the die attach and mold compound, as well as establishing specific design rules fitted for Grade 0 devices. A key consideration is determining the minimum acceptable aluminum (Al) thickness to withstand the projected intermetallic compound (IMC) growth observed in HTSL testing. By considering these factors in tandem, we can create a more robust process that delivers reliable results that can pass future stringent requirements.

7.0 ACKNOWLEDGMENT

We would like to acknowledge the efforts of the following people who contributed to this study: Central Engg ETOs; Liezel Bandola, Stephanie Menor, Ruby Anne Reyes, and Angie Guatno for data gathering, Melay De Castro for the FA works and Joy De la Cruz on the reliability activities.

We also extend our appreciation to Creed Lagdameo for his guidance throughout this project.

8.0 REFERENCES

1. Automotive Electronics Council's (AEC) Q100, **"FAILURE MECHANISM BASED STRESS TEST QUALIFICATION FOR INTEGRATED CIRCUITS IN AUTOMOTIVE APPLICATIONS"** Rev J August 11, 2023

2. Chu-Chung (Stephen) Lee1, TuAnh Tran2, Dan Boyne3, Leo Higgins4, Andrew Mawer, **"Copper versus Palladium Coated Copper Wire Process and Reliability Differences",** IEEE Xplore

3. Binhai Zhang, Kaiyou Qian, Ted Wang, Yuqi Cong, Mike Zhao2, Xiangquan Fan1, Jiaji Wang **"Behaviors of Palladium in Palladium Coated Copper Wire Bonding Process",** IEEE Xplore

4. Hidenori Abea, Dong Chul Kang, Takashi Yamamoto, Takashi Yagihashi, Yoshinori Endo, Hiroyuki Saito, Takahiro Horie, Hironori Tamate, Yoshinori Ejiri, and Naoki Watanabe, **"Cu Wire and Pd-Cu Wire Package Reliability and Molding Compounds",** IEEE Xplore

9.0 ABOUT THE AUTHORS

Ginbert C. Manalo is a Mechanical Engineering graduate from the Technological University of the Philippines – Taguig. He is LSSGB trained and has more than 10 years of combined experience in the wire bond process as an equipment technician and NPD/NPI engineer. He currently holds the position of Staff Engineer under the Central Engineering group..

Tonton C. Pinili is an Electronics and Communication Engineering graduate from Don Bosco Technical College. He is LSSGB certified and has more than 15 years of experience in the semiconductor industry. He currently holds the position of Principal Engineer under the Central Engineering group.

Isiah N. Gregorio is an Electrical Engineering Technology graduate from the Technological University of the Philippines – Cavite. He is LSSYB trained and has more than 9 years of combined experience in the semiconductor industry, in both manufacturing support and the central engineering department. He currently holds the position of Process Technician under the Central Engineering group.

10. APPENDIX

A. Tukey's Test: BST TC

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
4N bare Cu - TC 2000cy	2N Cu Alloy - Time 0	5.709000	0.8351351	3.30236	8.115645	<.0001*
4N bare Cu - TC 2000cy	4N bare Cu - Time 0	4.859667	0.8351351	2.45302	7.266312	<.0001*
2N Cu Alloy - TC 2000cy	2N Cu Alloy - Time 0	4.045333	0.8351351	1.63869	6.451978	<.0001*
2N Au PCC - TC 2000cy	2N Cu Alloy - Time 0	3.417333	0.8351351	1.01069	5.823978	0.0009*
2N Cu Alloy - TC 2000cy	4N bare Cu - Time 0	3.196000	0.8351351	0.78936	5.602645	0.0025*
2N Au PCC - Time 0	2N Cu Alloy - Time 0	3.114000	0.8351351	0.70736	5.520645	0.0035*
4N bare Cu - TC 2000cy	2N Au PCC - Time 0	2.595000	0.8351351	0.18836	5.001645	0.0264*
2N Au PCC - TC 2000cy	4N bare Cu - Time 0	2.568000	0.8351351	0.16136	4.974645	0.0290*
4N bare Cu - TC 2000cy	2N Au PCC - TC 2000cy	2.291667	0.8351351	-0.11498	4.698312	0.0719
2N Au PCC - Time 0	4N bare Cu - Time 0	2.264667	0.8351351	-0.14198	4.671312	0.0780
4N bare Cu - TC 2000cy	2N Cu Alloy - TC 2000cy	1.663667	0.8351351	-0.74298	4.070312	0.3511
2N Cu Alloy - TC 2000cy	2N Au PCC - Time 0	0.931333	0.8351351	-1.47531	3.337978	0.8746
4N bare Cu - Time 0	2N Cu Alloy - Time 0	0.849333	0.8351351	-1.55731	3.255978	0.9118
2N Cu Alloy - TC 2000cy	2N Au PCC - TC 2000cy	0.628000	0.8351351	-1.77864	3.034645	0.9749
2N Au PCC - TC 2000cy	2N Au PCC - Time 0	0.303333	0.8351351	-2.10331	2.709978	0.9992

B. Tukey's Test: BST HTOL

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
4N bare Cu - 1000hrs	2N Cu Alloy - Time 0	15.91500	1.129191	12.6610	19.16904	<.0001*
4N bare Cu - 1000hrs	4N bare Cu - Time 0	15.06567	1.129191	11.8116	18.31971	<.0001*
2N Cu Alloy - 1000hrs	2N Cu Alloy - Time 0	14.80367	1.129191	11.5496	18.05771	<.0001*
2N Cu Alloy - 1000hrs	4N bare Cu - Time 0	13.95433	1.129191	10.7003	17.20837	<.0001*
4N bare Cu - 1000hrs	2N Au PCC - Time 0	12.80100	1.129191	9.5470	16.05504	<.0001*
2N Cu Alloy - 1000hrs	2N Au PCC - Time 0	11.68967	1.129191	8.4356	14.94371	<.0001*
2N Au PCC - 1000hrs	2N Cu Alloy - Time 0	9.40500	1.129191	6.1510	12.65904	<.0001*
2N Au PCC - 1000hrs	4N bare Cu - Time 0	8.55567	1.129191	5.3016	11.80971	<.0001*
4N bare Cu - 1000hrs	2N Au PCC - 1000hrs	6.51000	1.129191	3.2560	9.76404	<.0001*
2N Au PCC - 1000hrs	2N Au PCC - Time 0	6.29100	1.129191	3.0370	9.54504	<.0001*
2N Cu Alloy - 1000hrs	2N Au PCC - 1000hrs	5.39867	1.129191	2.1446	8.65271	<.0001*
2N Au PCC - Time 0	2N Cu Alloy - Time 0	3.11400	1.129191	-0.1400	6.36804	0.0694
2N Au PCC - Time 0	4N bare Cu - Time 0	2.26467	1.129191	-0.9894	5.51871	0.3434
4N bare Cu - 1000hrs	2N Cu Alloy - 1000hrs	1.11133	1.129191	-2.1427	4.36537	0.9225
4N bare Cu - Time 0	2N Cu Alloy - Time 0	0.84933	1.129191	-2.4047	4.10337	0.9749

C. Tukey's Test: BST HTSL

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
2N Au PCC - 1008hrs	2N Cu Alloy - Time 0	10.64367	1.616080	6.43108	14.85626	<.0001*
2N Au PCC - 1008hrs	2N Au PCC - Time 0	7.52967	1.616080	3.31708	11.74226	<.0001*
2N Au PCC - 1008hrs	2N Cu Alloy - 1008hrs	5.84933	1.616080	1.63674	10.06192	0.0024*
2N Cu Alloy - 1008hrs	2N Cu Alloy - Time 0	4.79433	1.616080	0.58174	9.00692	0.0189*
2N Au PCC - Time 0	2N Cu Alloy - Time 0	3.11400	1.616080	-1.09859	7.32659	0.2225
2N Cu Alloy - 1008hrs	2N Au PCC - Time 0	1.68033	1.616080	-2.53226	5.89292	0.7265

D. Tukey's Test: WPT HTSL

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
2N Cu Alloy - Time 0	2N Au PCC - 1008hrs	9.344000	0.5537017	7.90068	10.78732	<.0001*
2N Au PCC - Time 0	2N Au PCC - 1008hrs	8.563667	0.5537017	7.12035	10.00698	<.0001*
2N Cu Alloy - 1008hrs	2N Au PCC - 1008hrs	5.389667	0.5537017	3.94635	6.83298	<.0001*
2N Cu Alloy - Time 0	2N Cu Alloy - 1008hrs	3.954333	0.5537017	2.51102	5.39765	<.0001*
2N Au PCC - Time 0	2N Cu Alloy - 1008hrs	3.174000	0.5537017	1.73068	4.61732	<.0001*
2N Cu Alloy - Time 0	2N Au PCC - Time 0	0.780333	0.5537017	-0.66298	2.22365	0.4961