

Room Temperature Wedge-Wedge Ultrasonic Bonding using Aluminum Coated Copper Wire

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Abstract

The purpose of our study is to evaluate the feasibility of room-temperature wedge-wedge bonding using commercially available 25 µm copper wires, coated with aluminum. Bonding quality, reliability and aging resistance of the wire bonds have been investigated using standard wire pull tests immediately after bonding and after accelerated life tests, including temperature storage at 125 °C and 150 °C for up to 2000 hours. Using focused ion beam (FIB-) preparation and high resolution electron microscopy (SEM, TEM combined with EDX x-ray analysis), results of microstructure investigations of the Al-coating / Cu wire interface as well as of the bonding interconnect formed between the coated wire and the gold metallization on LTCC substrate will be presented. These investigations provide background information regarding the binding mechanisms and material interactions, and contribute to assess and to avoid potential reliability risks. Due to the found advantageous bond processing behavior and increased reliability properties, our results indicate that room temperature wedge-wedge bonding of coated copper wires has a remarkable application potential, for instance in medical and other high reliability applications. It combines all known advantages of usual copper bonding like excellent contacting behavior, high reliability and favorable material price with the possibility of processing temperature damageable components and considerable improved storage capability. Therefore, room temperature bonding using coated copper wire can also reduce cycle time, manufacturing and material costs and will be conducive to new products.

Key words: Wire bonding, wedge-wedge, copper wire, room temperature, LTCC

Introduction

Common trends in the microelectronics industry are towards miniaturization, higher performance, and lower costs. These trends are driving the development of novel materials for bonding wires. With gold price continuously soaring on the one hand and requested packaging cost competitiveness on the other hand, copper wire is widely regarded as an alternative interconnection material that serves as a competitive successor to gold wire due to many advantages in mechanical and electrical characteristics as well as cost efficiency. The wire bonding industry is looking towards extending the use of Cu as a new wire material to replace Au, but uncoated Cu wires show oxidation [2], [3] and room temperature bonding issues [1]. In

addition, a well-known disadvantage of copper bonding wires, higher hardness, offers a main challenge to the introduction of copper wire bonding on high-end integrated circuits. The focus of this paper is the use of copper wires in a wedge-wedge process at room temperature in air solving the problems mentioned above.

The advantages of bonding at room temperature are for instance shorter manufacturing cycles for components with a large heat capacity because heating is not required and the possibility to process very temperature sensitive substrates. We could show that it is possible to obtain reliable wedge-wedge bonds at room temperature using aluminum coated copper wire.

Investigated wires

Room temperature wedge-wedge bonding is well established for AlSi1 wires. In many cases, aluminum wires can not be used, however.

In this study we investigate wedge-wedge bonding of commercially available copper wires with aluminum coating at room temperature.

The bonding wires used for the experiments are listed in table 1:

Experiment	Bonding Wire	Breaking Load	Bonding Temperature
A *	Source 1, 25 μ m	>10.6 gf	23 °C
B *	Source 1, 25 μ m 10-26 nm Al	>10.6 gf	23 °C
C *	Source 2, 25 μ m	>10.5cN	23 °C
D *	Source 2, 25 μ m 10-26 nm Al	>10.6cN	23 °C
E *	Source 1, 25 μ m 20-40 nm Al	>10.6 gf	23 °C
F **	AlSi1, 30 μ m ⁺	>21.4cN	23 °C

* Tool SPT FP45A-W-1520-1.0-GCG

** Tool SPT FP45A-W-2015-C-CBF

+ For comparison only

1 cN = 1.019716213 gf 23 °C = 73.4 °F

Table 1: Bonding wires used in this study

Aluminum coated copper wires can be stored over an extended period of time in nitrogen [3], [4].

Experimental set-up

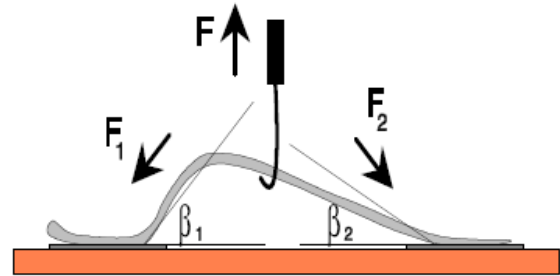
For our experiments we used thick-film gold paste, silver paste, and AgPd paste on DuPont®951 tape using a test pattern shown in [1]. We did not employ special cleaning procedures or plasma treatment for the substrate.

Paste	1	2	3	4	5	6
Material	Au	Au	Ag	Ag	Ag	AgPd

Table 2: Thick film paste used in this study

For the experiments, we bonded wire loops with a length of 1 mm and a height of 0.3 mm (Figure 1) using a BondJet 710 wire bonder from Hesse & Knipps.

The used loop geometry is conducive to a correction factor of 1.0 for the wire pull test as outlined in Figure 1. Details can be found in the literature [5], [6].



$$\text{If } \beta_1 = \beta_2 = 30^\circ \text{ then } F_1 = F_2 = F$$

Figure 1: Wire pull test -geometric relationship [5]

Figure 2 shows a single wire bond contact made with an unused bonding tool on the LTCC test substrate.

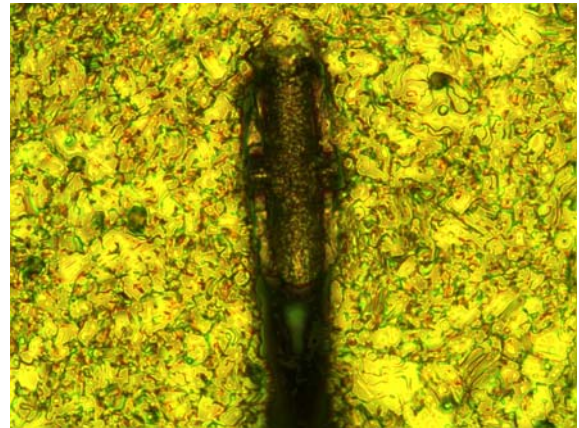


Figure 2: Wire D on LTCC (magnification 500x), new tool

Figure 3 shows a single wire bonded with a bonding tool after 26000 bonds on the LTCC test substrate.



Figure 3: Wire D on LTCC (magnification 500x), tool after 26000 bonds

Figure 4 shows the bond tool used for the nano-coated copper wires after 24000 bonds. Only marginal amounts of Al built-ups at the wedge tool contact area could be observed.

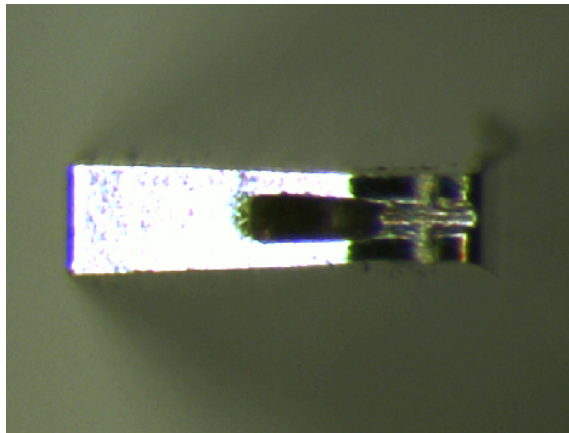


Figure 4: Bond tool after 24000 bonds

For every experiment, we pulled 30 wires each after 0 h, 137 h, 250 h, 560 h, 1030 h, and, in some cases, 2000 hours of high temperature storage conditions at 125 °C (257 °F) and 150 °C (302 °F), respectively, using a pull tester Dage BT28. The results were compared to the specifications and reliability criteria described in the relevant guide lines of the German Welding Association DVS 2811 [6]. In this publication, only the results after storage at 125 °C for paste 1 to 6 will be considered.

Results obtained on LTCC

Bonds with uncoated copper wires did not meet the reliability requirements as described in the DVS 2811 guide lines [6].

The results for samples, bonded with 10-nm-Al-coated Source 1 wire and stored at 125 °C dry heat, are shown in Figures 5 and 6:

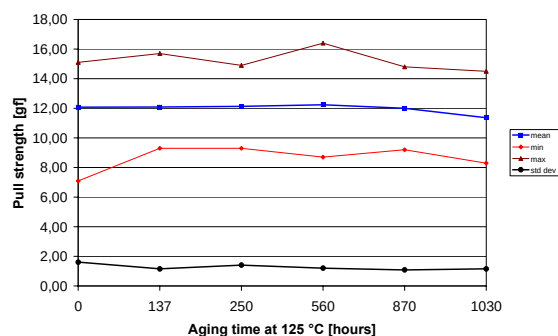


Figure 5: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 1, wire B)

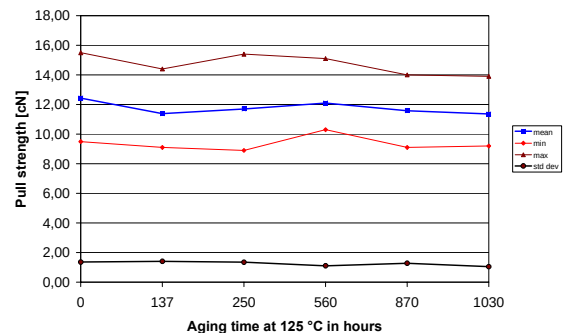


Figure 6: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 2, wire B)

The results for samples, bonded with 10nm-Al-coated Source 2 wire and stored at 125 °C dry heat, are shown in Figures 7 to 12:

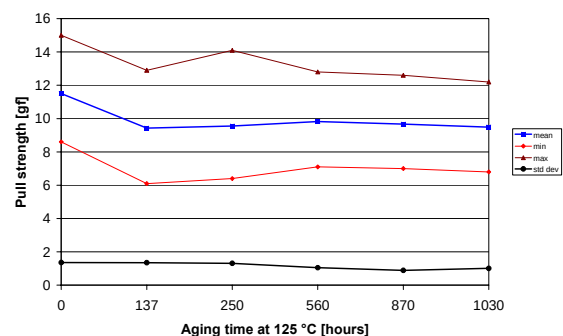


Figure 7: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 1, wire D)

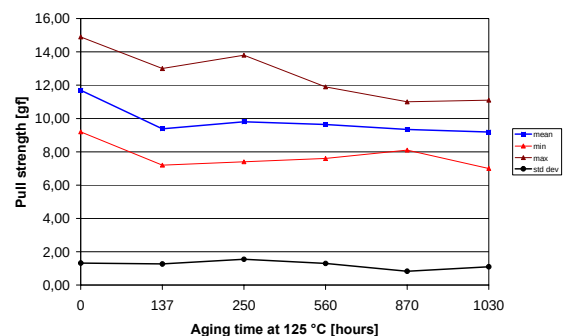


Figure 8: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 2, wire D)

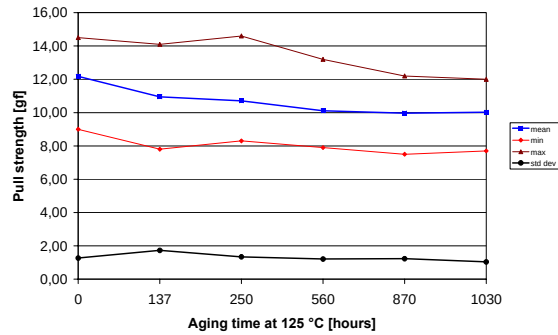


Figure 9: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 3, wire D)

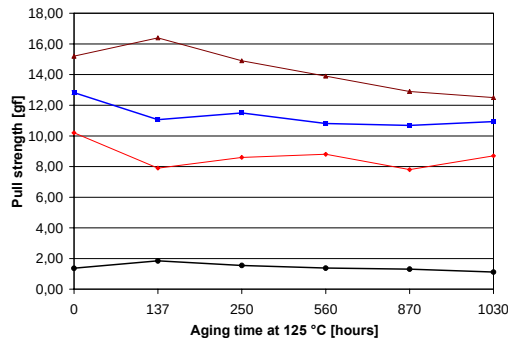


Figure 10: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 4, wire D)

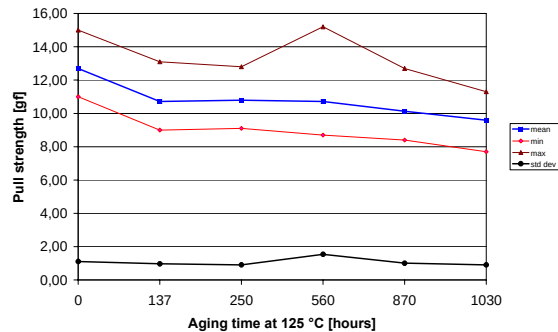


Figure 11: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 5, wire D)

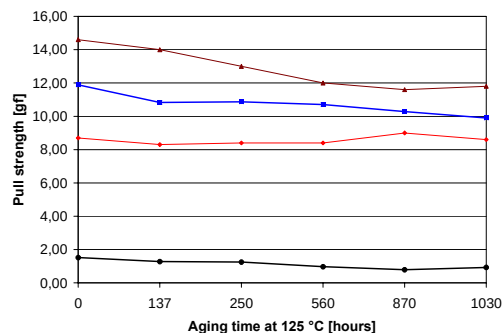


Figure 12: Mean, min, max, and standard deviation of the pull strength in dependence on the aging time at 125 °C (paste 6, wire D)

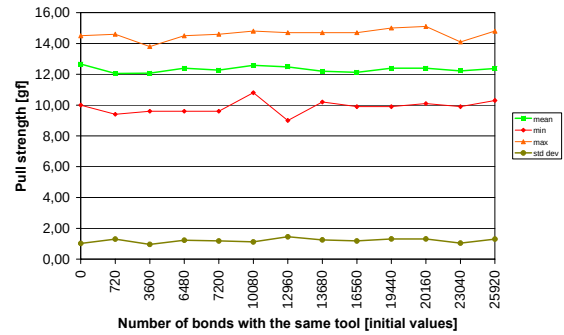


Figure 13: Mean, min, max, and standard deviation of the pull strength in dependence on the increasing number of wedge contacts produced with the same tool (paste 1, wire D)

It can be seen easily, that wire B (from source 1, coated with >10 nm Al at the TU Dresden) bonded on LTCC metalized with paste 1 shows the best stability during high temperature storage at 125 °C. No lift-offs could be found. All bonds meet the requirements according to [6].

Wire D (source 2, coated with >10 nm Al) bonded on metalized LTCC shows good stability during high temperature storage at 125 °C as well. No lift-offs could be found using gold paste (1, 2) and silver paste 3, thus meeting the required reliability specifications [6]. With wire D one pull lift-off on paste 4, one pull lift-off on paste 5, and six pull lift-offs on paste 6 were found after bonding, respectively.

Using aluminum coated copper wire, also tool life and process stability are sufficiently high for manufacturing processes (Figure 13).

The results obtained suggest, that bonding with wire C on LTCC, metalized with paste 2, no high quality bonds can be obtained.

Results with reference wire F were found to be similar to those published in [1].

The reliability tests have been supplemented with storage of test coupons at 85 °C / 85 % relative humidity which also revealed successful results (not shown here).

Process capabilities

The process capability values for aluminum coated copper wires from source 2 bonded at room temperature on gold metalized LTCC are listed in table 3 and table 4:

	C_p	C_{pk}	Sigma level
Initial*	2.148	1.965	5.895
1030 h	2.888	1.977	5.931

LSL = 3.5 gf

Table 3: Values for C_p , C_{pk} , and Sigma level after 0 hours and after 1030 hours storage at 125 °C dry heat (paste 1)

	C_p	C_{pk}	Sigma level
Initial*	2.209	2.068	6.204
1030 h	2.652	1.724	5.173

LSL = 3.5 gf

Table 4: Values for c_p , c_{pk} , and Sigma level after 0 hours and after 1030 hours storage at 125 °C dry heat (paste 2)

Results obtained on PCBs

Our experiments on printed circuit boards with proprietary metallization using aluminum coated copper wires yielded very reliable bonds as well. All requirements according to [6] have been met.

Bonding of semiconductor chips

A well-known disadvantage of copper bonding wires, higher hardness and increased strain hardening during deformation, offers a main challenge to the introduction of copper wire bonding on high-end integrated circuits. Our experiments indicate that high-quality bonds using aluminum coated copper wires (Figure 14) are feasible. The aluminum coating will be conducive to lower ultrasonic power [7], which helps to prevent cratering, peeling and underlying crack of bond pads.

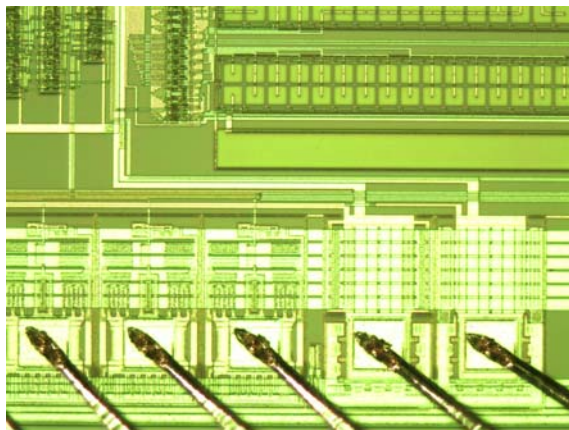


Figure 14: Integrated circuit, bonded with aluminum coated copper wire

Microstructural Investigations

A holohedral coverage and a good adhesion of the aluminum coating are essential for a successful bonding process and thus, also for the formation of a reliable and stable interconnect. These qualities, and also the homogeneity of the coating layer thickness, were analyzed by Transmission Electron Microscopy (TEM) after sample preparation using Focused Ion Beam techniques (FIB).

Figure 15 shows a TEM image of the aluminum coated bonding wire surface. A Pt protection layer has been used for sample preparation. The aluminum layer thickness varies locally between about 10 to 30 nm. The Al polycrystalline structure is clearly visible. An intermediate layer is located between the copper bonding wire surface and the aluminum coating. This film is significantly smaller than the surface film formed on non-aluminum coated copper wires (Figure 16 B).

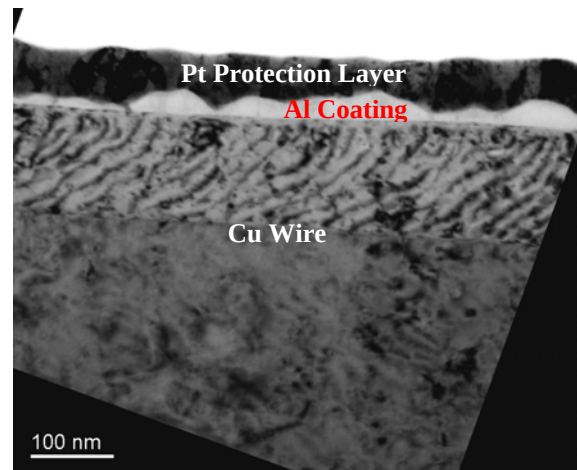


Figure 15: TEM image of an aluminum coated copper bonding wire top surface

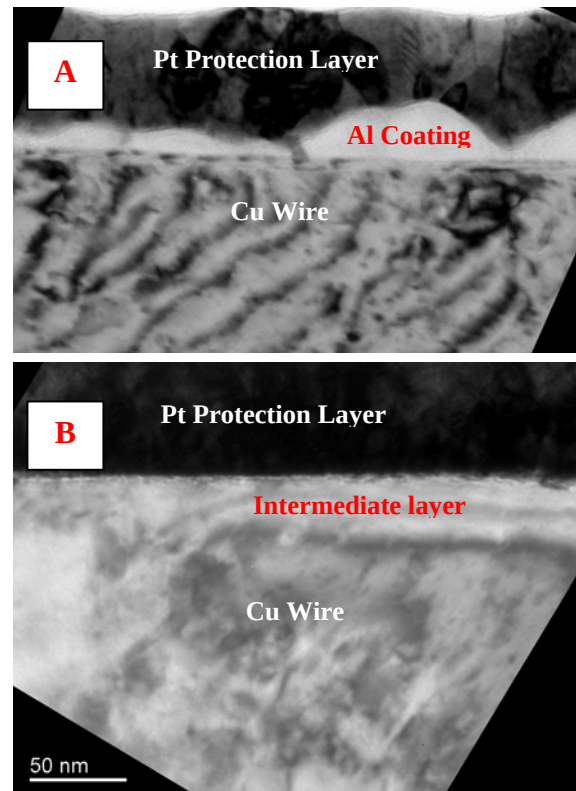


Figure 16: TEM images of bonding wire top surface: A: aluminum coated copper wire, B: non-aluminum coated copper wire

To analyze the microstructure of the bonding interface, wedge contacts were cross sectioned using FIB techniques and afterwards inspected by SEM. Figure 17 shows an overview of such a FIB cross section.

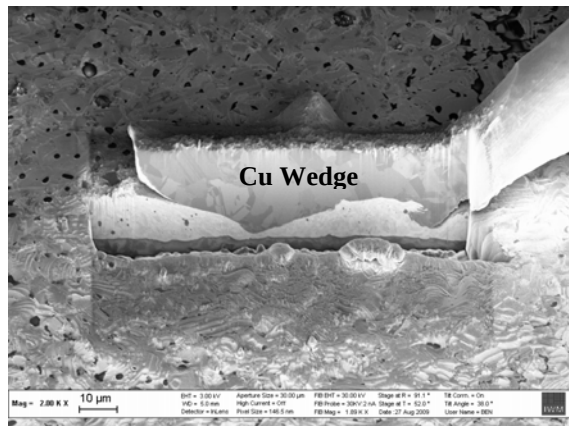


Figure 17: SEM image of an ultrasonic bonded Al coated Cu wedge contact after cross sectioning by FIB

The high magnification SEM analyzes show an excellent contact interface formation directly after the bonding process (Figure 18). No voids, delaminations or other defects are detectable. Only very small inclusions could be found at some isolated sites in the bonding interface (see arrows in Fig. 20). It is assumed that these inclusions are residues of the aluminum coating which have not been completely removed towards the contact periphery during the bonding process.

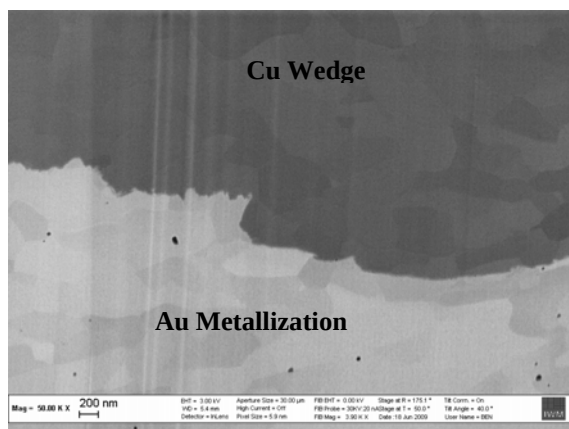


Figure 18: High magnification SEM image; detail of the contact interface between copper wedge and gold metallization directly after bonding

Similar effects have been found for a reference process using Al-coated Au wires bonded to flash-Au substrate, Figure 19. In this case, the TEM analysis revealed the presence of amorphous aluminum oxide particles together with very small regions of crystalline aluminum. However, the

hypothesis of a similar behavior for the Al-coated Cu wires has to be verified by further TEM analysis yet.

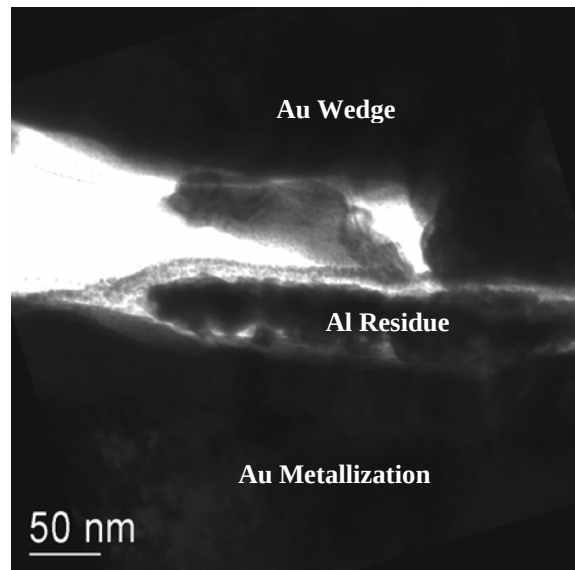


Figure 19: TEM investigation of an aluminum residue in the bonding interface between gold wedge of a reference wire and gold metallization

Also, after temperature storage at 125°C for 1030 hours an excellent quality of the contact interface has been found. Figure 20 and Figure 21 document these results for the bonded and annealed contact of Wire D and Wire B, respectively.

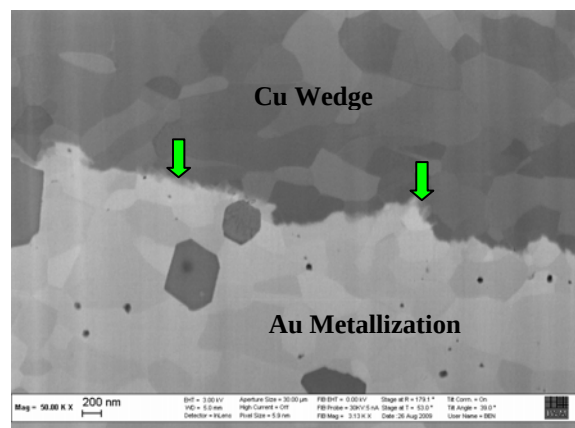


Figure 20: High magnification SEM image; detail of the contact interface between copper wedge and gold metallization (Wire B after 1030 hours @ 125°C) arrows indicate hypothesized residues of Al coating in the bonding interface

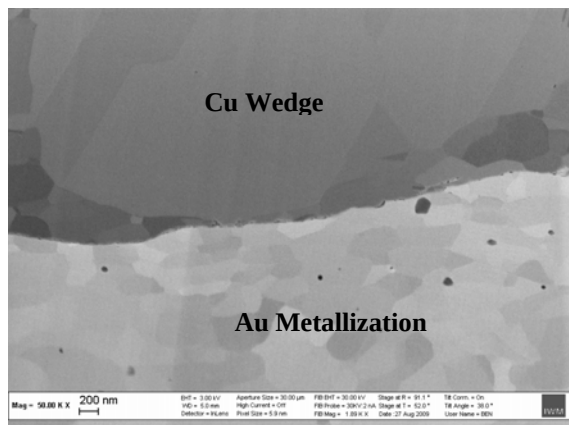


Figure 21: High magnification SEM image; detail of the contact interface between copper wedge and gold metallization (Wire D after 1030 hours @ 125°C)

Also the contacts bonded with aluminum coated copper wire on silver metallization present very good interface morphologies (Figure 22). No defects and delamination-like failures have been found in the bonding contact.

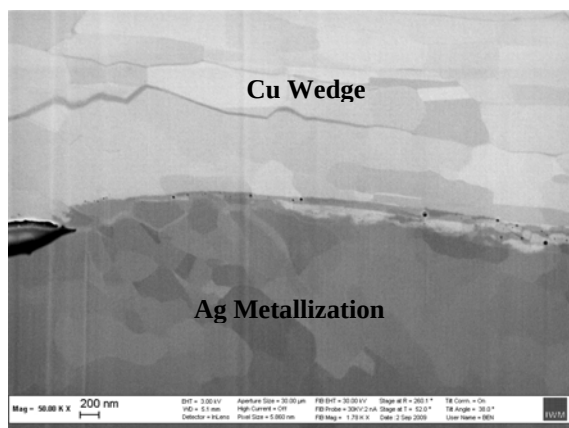


Figure 22: High magnification SEM image; detail of the contact interface between copper wedge and silver metallization (Wire D after 1030 hours @ 125°C)

Discussion

The initial pull strength obtained with the reference wire AlSi1 (bonded at room temperature) is excellent. However, like expected, we observed a rapid degradation during high temperature storage, confirming results in [1]. The Au-Al contact system has been investigated in the literature many times, for instance in [8].

Bonds with uncoated copper wires showed lift-offs, confirming results published in the literature [4].

With aluminum coated copper wires we found a superior behavior with all bonds stable at least up to 1030 h storage at 125 °C.

In comparison of the two wire sources, we obtained slightly better results in terms of reliability for wires with aluminum coating from source 1. We attribute these results to different properties of the core material [9].

The results, indicating excellent stability of the interconnects, correspond to a high-quality defect-free formation of bonding interface. Only minor very small inclusions, probably real coating residues, were found in the interface. Obviously, these residues do not have any negative influence on initial contact formation, contact stability and reliability after long time temperature storage.

Verification of the Results

Crucial experiments have been repeated, confirming the results. In order to be validated for high volume manufacturing, our results need to be verified for larger sample sizes. In addition to that, other reliability tests like temperature cycling, mechanical alternating-load tests, effect of humidity, and so on need to be carried out.

Summary and Conclusion

Two different copper wires with aluminum coating were bonded successfully on LTCC substrates at 23 °C. In addition, we used an AlSi1 wire and bare Cu wires as a reference.

When stored in air before bonding, wire bondability was maintained significantly better for aluminum coated copper wires compared to bare copper wires. Aluminum coating is effective in suppressing copper oxidation. Therefore, the longer shelf life of the copper wires due to aluminum coating is advantageous for low volume manufacturing.

Pull results using coated copper wires were significantly better than those using bare copper wires even under fresh conditions.

We did get very good initial pull values for the coated copper wires from two different sources.

During high temperature storage, only the coated copper wires, bonded at room temperature in air, performed well while the AlSi1 reference contacts showed significant degradation.

Results of the microstructure investigations support the findings of the reliability tests. TEM investigations indicate that the aluminum coating reduces the oxidation of the copper wire surface and thus, improves the storage capabilities.

The microstructure analyzes of the contact interfaces for the as bonded state as well as after the long time temperature aging experiments at 125°C also showed excellent results. For both the contacts on gold and on silver metallization, no significant defects such as voids, delaminations or significant

inhomogeneities were detected. The hypothesized very small aluminum residues in the bonded contact interfaces had obviously no negative effect on the stability and reliability of the interconnect formation. Our results suggest that aluminum coated copper wires are well suited for room temperature bonding on gold metalized and silver metalized LTCC. Here, the better electrical properties of copper in comparison to gold or aluminum wire materials provide a significant benefit particularly important for RF, microwave, and power circuit applications.

Outlook

This paper presents the current situation in the area of room temperature wedge-wedge bonding using aluminum coated copper wires with 25 micron diameter. Presently, the wire bonding processes have been demonstrated in simulated low volume production runs. Activity within supplier development settings is progressing steadily to bring it up to a production level process.

Room temperature bonding has a remarkable application potential. A few examples are the wire bonding of components with very large heat capacity, Molded Interconnect Devices (MID), and temperature sensitive semiconductors or sensors. Room temperature wedge-wedge bonding using aluminum coated copper wire can also reduce cycle time, manufacturing and material costs, making it economically viable.

Acknowledgements

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