# Silver bonding wire – an alternative for mechanical sensitive chip configurations in automotive electronics packaging

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*Abstract*— **Silver (Ag) bond wires are mainly used in consumer products as a reliable low-cost alternative to gold (Au) bond wires. In previous investigations, we have shown that silver wires also have potential for use in the automotive sector [1, 2, 3, 4], where the materials are exposed to particularly harsh environmental conditions. In order to understand the influence of these conditions in the electronic package on the silver-aluminum material system, we carried out extensive studies on test packages built on laboratory level. For the future development of challenging automotive devices, it will be important to have a cooperation between semiconductor package developer and material supplier with an assist of characterization specialists. In this project, we formed a three-party project in which characterization specialists, package developer, and wire manufacturer collectively conduct a feasibility study of a new Ag wire material for automotive application. Two wire types (standard Ag wire and new type of Ag wire GX2s) were chosen for the investigation in direct comparison regarding long-term reliability. Samples were built under mass production conditions and then subjected to various reliability tests following AEC-Q006 requirements. Subsequently, mechanical characterizations by means of ball shear and pull tests as well as high resolution SEM microstructure analyses on cross-section samples are applied.**

**In the paper, results of the different tests will be summarized, but a more in-depth analysis will be given to the temperature cycle test (TCT), where the most significant differences between the sample variations occurred. Overall, the results show the importance of the knowledge for the material reliability upfront a device qualification process (robustness validation) and give further guidance for material selection.**

***Keywords— silver wire bonding, TCT, temperature cycle test, long term reliability, automotive electronics packaging***

## I. Introduction & Motivation

In the past decade, gold has been widely replaced by copper as a bonding wire material for ultrasonic ball-wedge bonding. The main driver here was the cost factor due to the enormous difference in the price of the raw materials. Copper is ideal as a bonding wire contact material because it has very good electrical and thermal conductivity as well as high stiffness. However, the copper wire material also has disadvantageous properties. Due to the higher hardness and stiffness, there is an increased risk of chip cratering effects when bonding on particularly thin semiconductor metallization or for chip-to-chip bonding. Silver wire materials can bridge the gap between gold and copper bond wires here. Like copper, it has very good electrical and thermal properties, but has more favorable mechanical characteristics for wire bonding applications. Table 1 compares relevant properties of the three bonding wire raw materials [1, 2, 3].

Typically, silver wire materials are used in LED applications, where copper wires cannot be applied due to the necessary reflectance and in consumer electronics for challenging chip configurations, where the mechanical properties of the copper material can become a problem. In our previous publication [4], we have already investigated the reliability of silver wire bond contacts under harsh conditions, such as automotive applications, and were able to show that specially enhanced silver wire materials can also perform reliable in such application scenarios. The study now available is a follow-up to the results of the last publication. Based on the positive findings of the investigations on dummy samples manufactured at the laboratory level, an extensive study was now carried out on functional standard packages manufactured under mass production conditions. These were subjected to a variety of reliability tests based on the requirements of the AEC-Q006 standard. The aim is to demonstrate the reliability of a silver wire bonded mass production component for automotive applications.

## II. Silver Wire Bonding

Silver wire bonding in the ball-wedge process is carried out in the common process steps as also known from gold or copper wire bonding. Due to its tendency to oxidize, the Free

TABLE I. Comparison of bond wire raw materials [1, 2, 3]

| Property / Material | Gold | Copper | Silver |
|---|---|---|---|
| Electrical resistivity [µΩm] | 0.024 | 0.017 | 0.016 |
| Thermal conductivity [W/(m*K)] | 318 | 401 | 428 |
| Elastic modulus [$10^{11}$Pa] | 0.88 | 1.36 | 1.01 |
| Ultimate strength [MPa] | 100 | 210 | 170 |

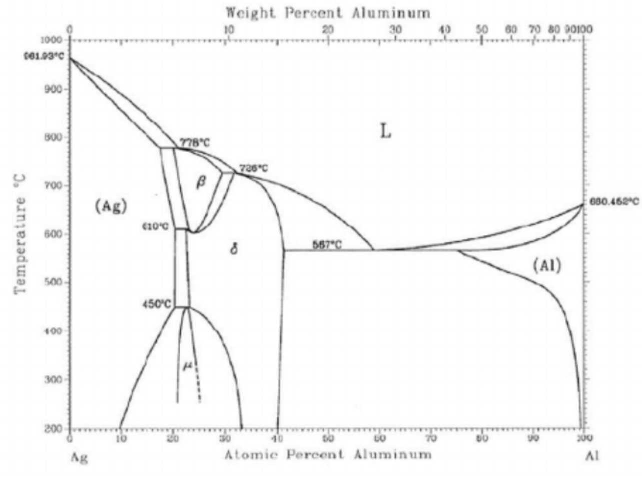


*Fig.1 Silver-Aluminum binary phase diagram [5]*

Air Ball (FAB) is formed under inert gas (forming gas $N_2$ + 5% $H_2$ or pure $N_2$). All common chip-side metallization and substrate-side bond metallization used for the gold and copper wires can be considered as bond surfaces.

According to the phase diagram (see Fig.1), in the silver-aluminum wire bond system, there are two types of intermetallic compound (IMC), $Ag_2Al$ ($\delta$) and $Ag_3Al$ ($\mu$). Each IMC exhibits different property and thus different sensitivity to certain degradation mechanisms. In our previous publication [4], we have identified and investigated these IMCs intensively by means of transmission electron microscopy (TEM) and have discussed relevant corrosion inducing/suppressing mechanisms.

## III. Reliability Study

In automotive applications, the materials are exposed to particularly harsh environmental conditions. In order to understand the influence of these conditions in the electronic package on the silver-aluminum material system, we carried out this extensive study. The focus is on the correlation beween the mechanical stability of the chip-side wire bond contacts and the material interaction processes in the interface depending on the silver wire material and the epoxy mold compound (EMC).

### A. Sample Preparation

For the present study, two silver wire materials with 25µm in diameter were contacted to an Al-0.5wt%Cu chip metallization (1.0 µm thickness) by thermo-sonic ball/wedge bonding using forming gas. The first wire material is a commercially available standard silver wire, denoted as stdAg. The second material is the GX2s wire from Nippon Micrometal Corporation (NMC) which has optimized corrosion resistance by additive elements and a low resistivity (2.4 $\mu\Omega$cm). The used component is a QFN32L5 package provided by ELMOS with two silicon-based dies (see Fig. 2). Two different EMC were used – a low halide containing standard EMC (<<5ppm) and a sulfur-free variant. The complete assembly (die placement and attach, wire bonding, molding, singulation etc.) was processed in a standard ELMOS mass production assembly line. Fig. 2 shows the package configuration and the wire bond layout.

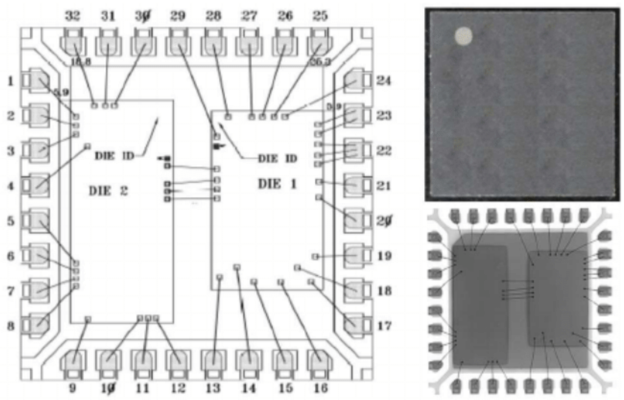


*Fig 2 Scheme of QFN component used for the study (left), optical image and 2D x-ray image with wire bonding layout visible (right)*

TABLE II. Reliability test conditions

| Reliability test | Test conditions |
|---|---|
| MSL-1 | 125°C for 24 hours → 85°C + 85%rh for 168 hours → 3x 270°C reflow |
| AC | 121°C + 100%rh + 29psig for 96/192 hours |
| TCT | -55/150°C (30 min/cycle) for 1,000/2,000/3,000 cycles |
| Biased HAST | 0-3.3V bias Voltage at 130°C + 85%rh for 96/192 hours |
| HTSL 1 | 150°C for 1,000/2,000/3,000/4,000 hours |
| HTSL 2 | 175°C for 1,000/2,000 hours |

### B. Reliability Testing

The components were subjected to various reliability tests following AEC-Q006 requirements. Table I lists the tests performed with the individual conditions. Samples of all variations (both wire types and both EMC) were investigated in initial state by pull and shear testing as well as by means of microstructural cross section analyses to ensure sufficient and comparable starting condition of interface quality. Moisture sensitivity level (MSL-1) was performed as pre-conditioning before autoclave testing (AC) testing, temperature cycle testing (TCT) and biased highly accelerated stress test (bHAST). High temperature storage (HTSL) was applied at 150°C and 175°C.

### C. Analysis Methods

Ball shear and pull tests were conducted on samples in initial condition (as bonded) as well as in intermediate steps and at the end of each reliability test. Two parts with 35 wire bond contacts each were prepared for both pull and shear tests. For this, the mold compound was removed with laser IC opener and mixed acid followed by acetone wash to gain access to the wire bond contacts. Fig. 3 shows the sample condition after mold compound removal exemplarily. For microstructural analysis the test specimens were cross sectioned using broad ion beam preparation. The method uses an argon ion beam to mill cross sections with a high surface

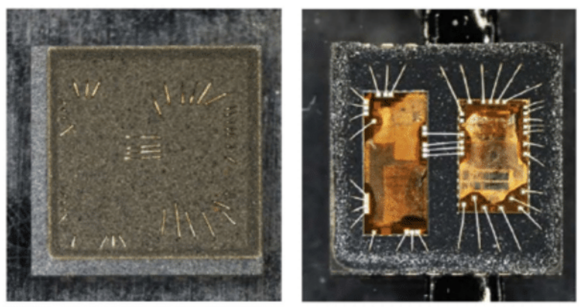

*Fig 3 Decapsulation prior pull and shear testing: condition after laser opening (left); condition after chemical removal of EMC (right)*

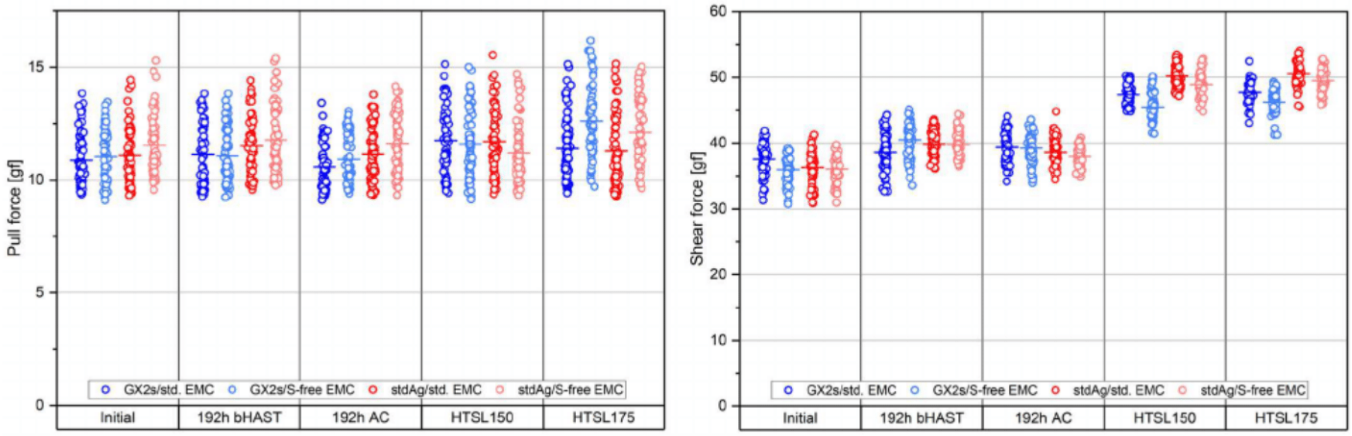


*Fig. 4 Results of wire pull testing (left) and ball shear testing (right) in initial state and after different reliability tests.*

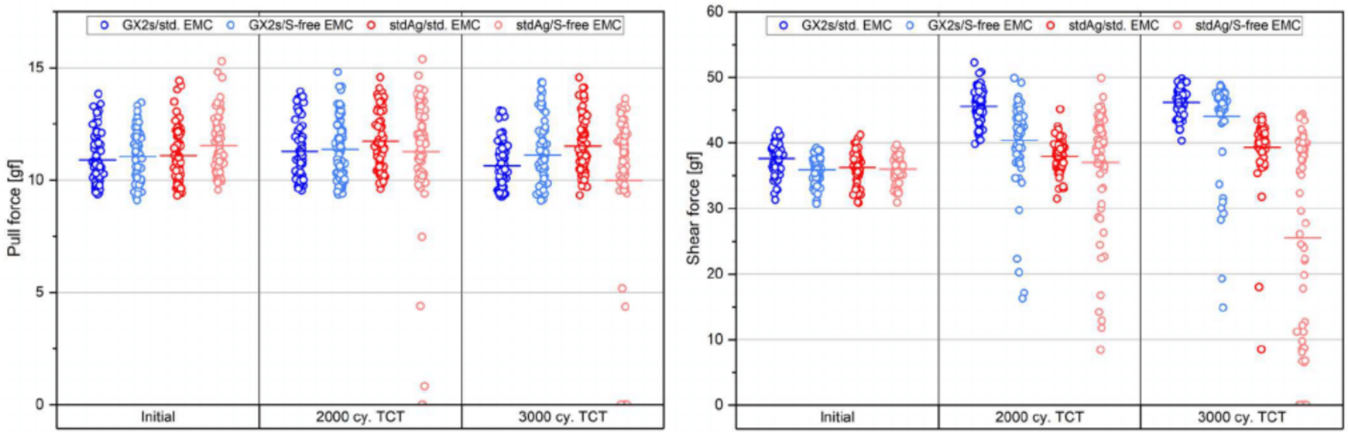


*Fig. 5 Results of wire pull testing (left) and ball shear testing (right) in initial state and after 2000 resp. 3000 cycles of TCT.*

quality and to obtain cleanly polished surfaces of the interface between the wire bond materials and substrate metallization. Following the preparation, high resolution microstructural analyses were performed by SEM.

## IV. Results After Reliability Testing

### A. Results After AC Testing, Biased HAST and HTSL

Both in the initial condition after bonding and molding, and after reliability testing, ball pull and shear testing was performed to determine the contact strength. The diagrams in Figure 4 show the results after AC testing, bHAST and HTSL at 150°C/ 175°C. For all these test conditions a very similar behavior could be determined for the different material variations. No significant differences in the stability of the wire bond contacts were found, neither depending on the wire types nor with regard to the epoxy mold compounds. For both the pull test and the shear test, the mean values are at a very comparable level and also with regard to the scatter there are only minor differences. All variants showed very stable and reliable interface connection. The microstructure analyses after ion beam cross-section preparation confirmed these results. All contacts showed good formation of intermetallic phases. In no case significant degradation phenomena, such as void formation or corrosion damage, were detected.

### B. Results After TCT

The condition of the contact interfaces after thermal cycling differs significantly from the results of the other reliability tests (see Fig. 5). With sulfur-free EMC, the scatter of shear strengths for the contacts of both wire materials increases noticeably already after 2000 cycles. There are a few outliers with significantly reduced values, whereby this trend is more pronounced for the std.Ag wire. With the standard EMC, both wire types show no changes in the shear test after 2000 cycles compared to the initial values. For pull testing, both EMC variants with GX2s wire behave completely inconspicuously, and the std.Ag wire with standard EMC also shows no decrease in force compared to the initial condition.

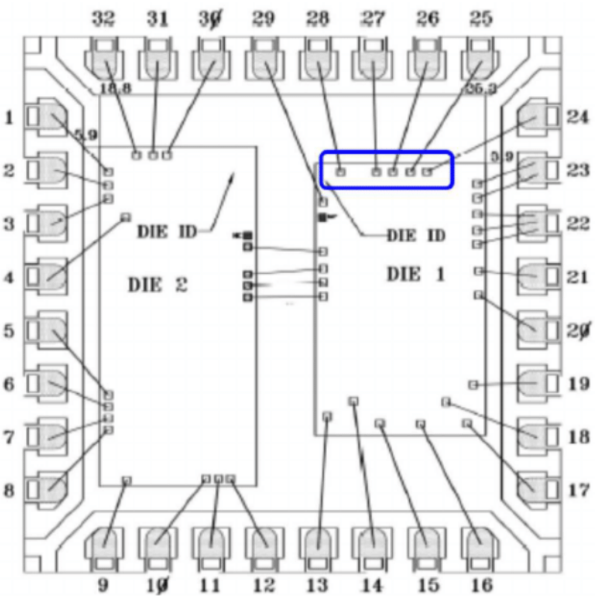


*Fig. 6 Package layout with marked area of increased damage potential*

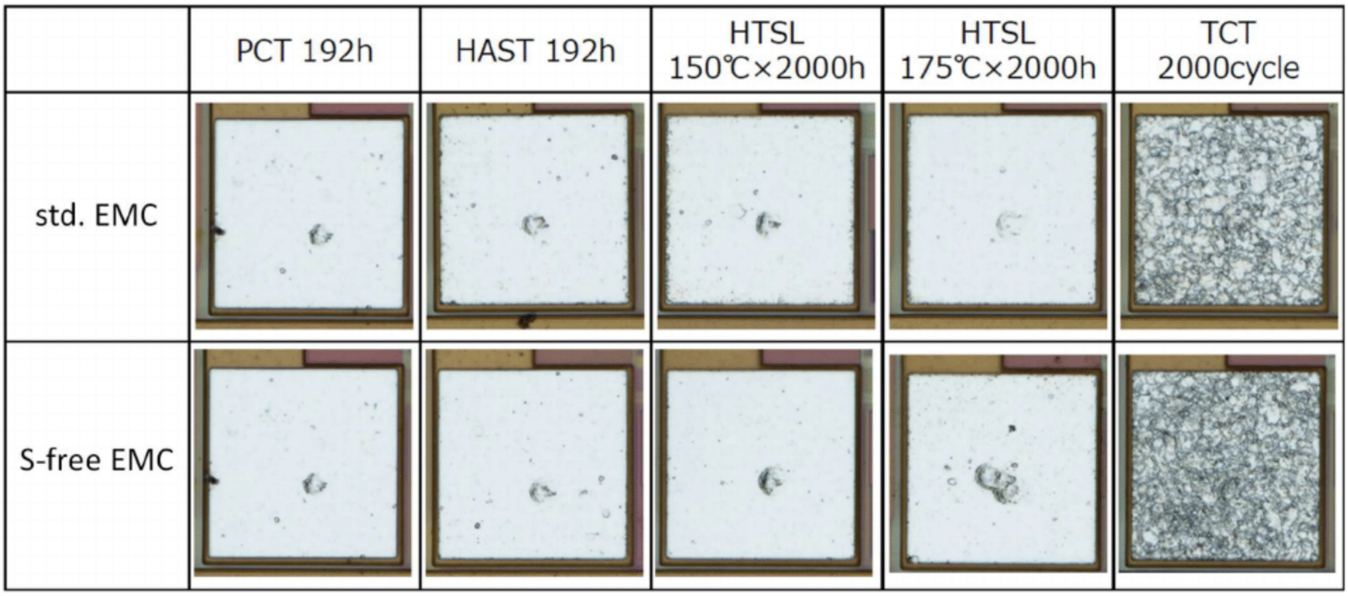


*Fig. 7 Differences in surface appearance of non-bonded Aluminum pad metallization depending on reliability test condition.*

In contrast, the std.Ag wire with S-free EMC exhibits sporadic outliers with low pull forces.

After 3000 cycles of thermal cycling, the interface stability continued to degrade significantly. In the pull test, the GX2s wire with both EMC variants and the std.Ag wire with the standard EMC again show no changes from the initial state. In the combination of std.Ag wire with S-free EMC, as in the condition after 2000 cycles, a few outliers with significantly lower values occur. The development of the shear strength shows the clearest differences. The GX2s wire with the standard EMC is the only combination where the bond contacts show stable test values. The std.Ag wire with standard EMC shows some outliers with significantly reduced values. With the S-free EMC, both wire types show a partly drastic reduction in shear strength, although the behavior is significantly more pronounced with the std.Ag wire and also results in sporadic lift-off.

Two aspects were particularly striking in the development of the contact strengths under load with temperature cycling. Firstly, the differences as a function of the EMC were unexpected. Secondly, the question arose as to why some bond contacts show a significant reduction in strength, while the majority remain in a very stable condition. The correlation of the reduced strength values with the position in the package

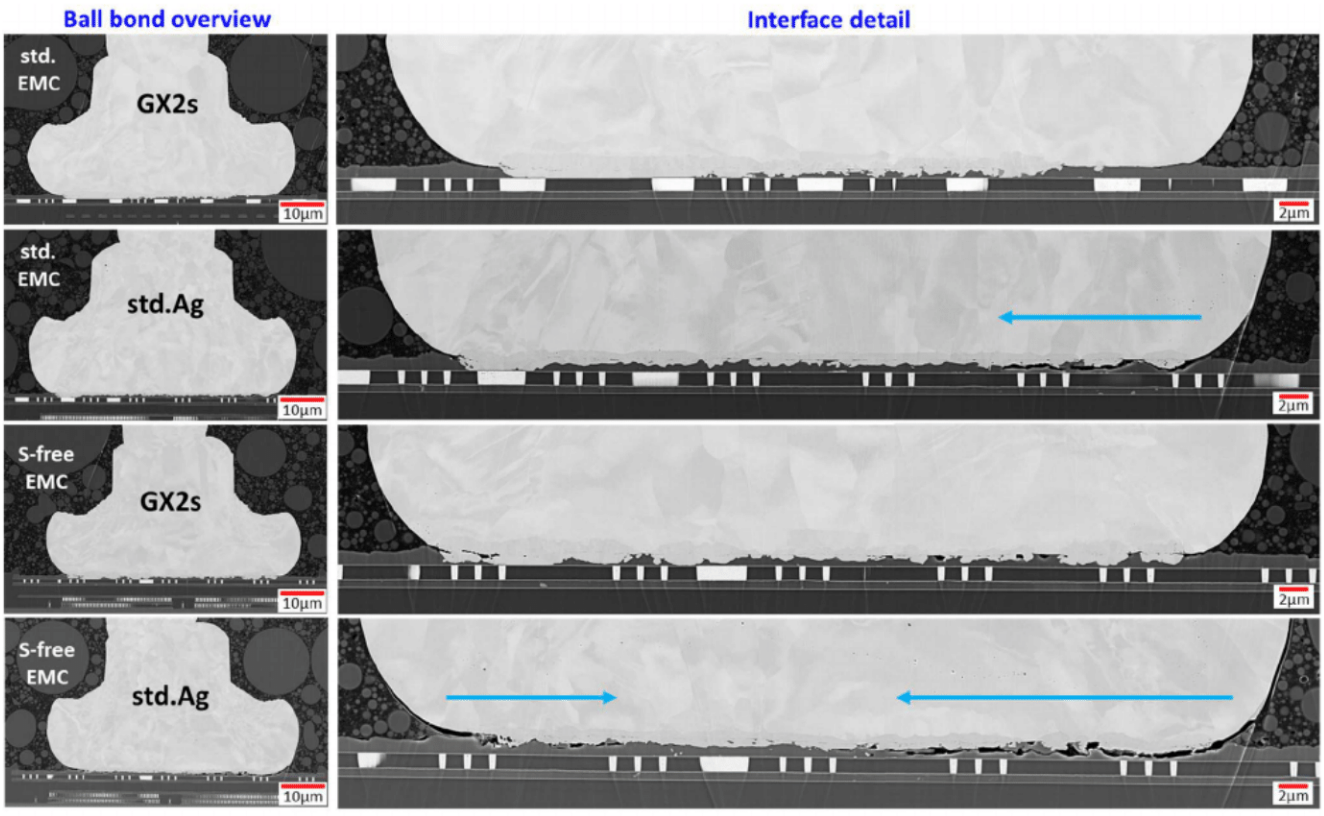


*Fig. 8 Results of SEM cross section analyses on wire bond contacts after 2,000 cycles of TCT (-55°C/ 150°C).*

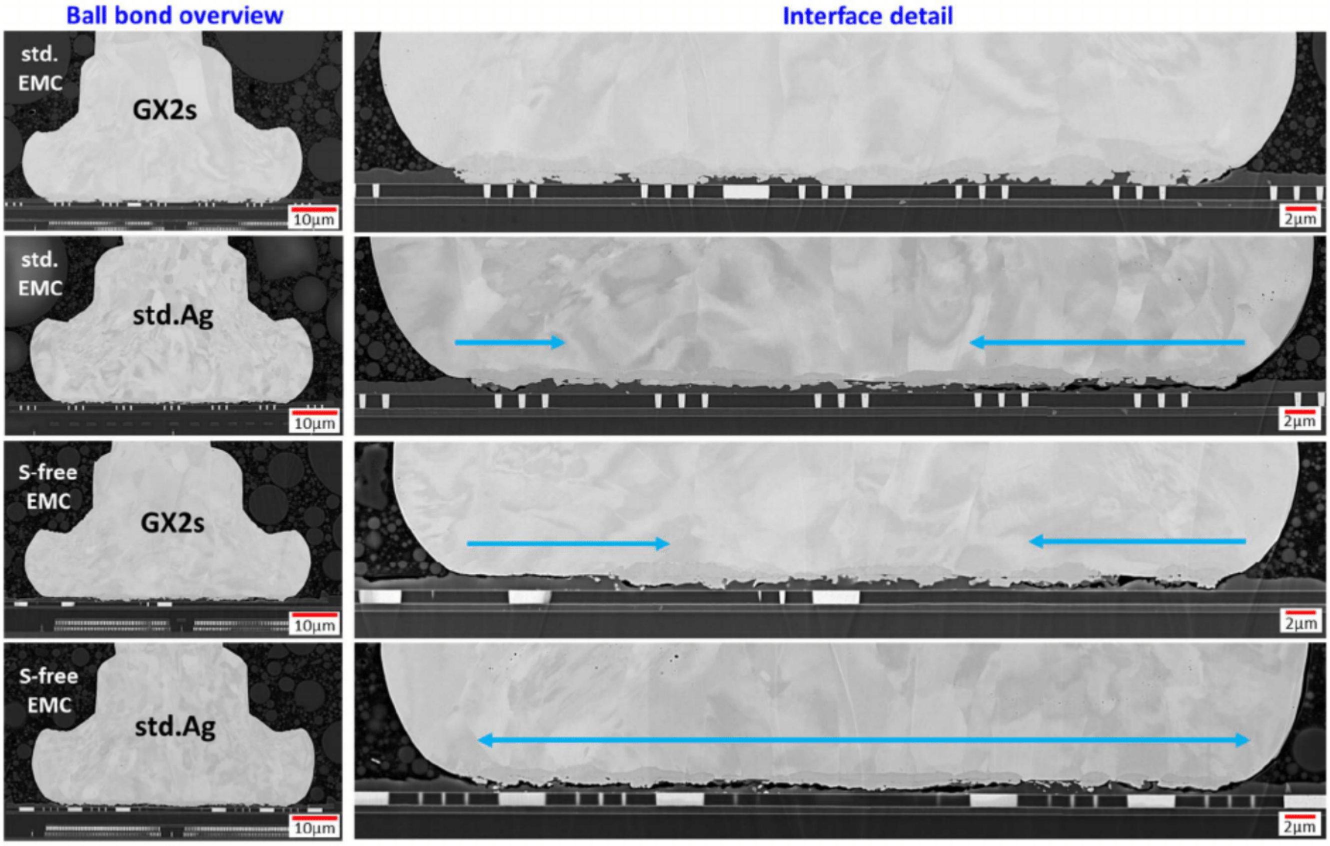


*Fig. 9 Results of SEM cross section analyses on wire bond contacts after 3,000 cycles of TCT (-55°C/ 150°C).*

revealed that there is an accumulation of lower values in the area of pins 25 to 28 (see Fig. 6). Furthermore, it was noticed during the investigation that an neighboring bond pad, which is not contacted, shows a significantly higher roughness after loading with temperature changes than after all other reliability tests. Figure 7 shows these differences as a function of the loading condition. Based on these findings, additional cross-sections were prepared on this contact sequence using ion beam technology and subsequently the damage pattern was analyzed microstructurally using SEM.

Figures 8 and 9 show the interface degradation on one exemplary wire bond contact per material variation from the relevant chip area after 2000 and after 3000 cycles of TCT, respectively. After 2000 cycles, no degradation can be seen for the contacts of the GX2s wire with either EMC variant. In contrast, the std.Ag wire already shows clear damage at this stage, especially in combination with the S-free EMC. The blue arrows in the figures mark the progress of degradation. The condition after 3000 cycles shows a significant increase in damage. The std.Ag wire shows a complete lift-off in combination with the S-free EMC. The GX2s wire also shows significant interface weakening with this EMC, but the contact is not completely separated. With the standard EMC, The contacts of the std.Ag-wire show progressive damage, while

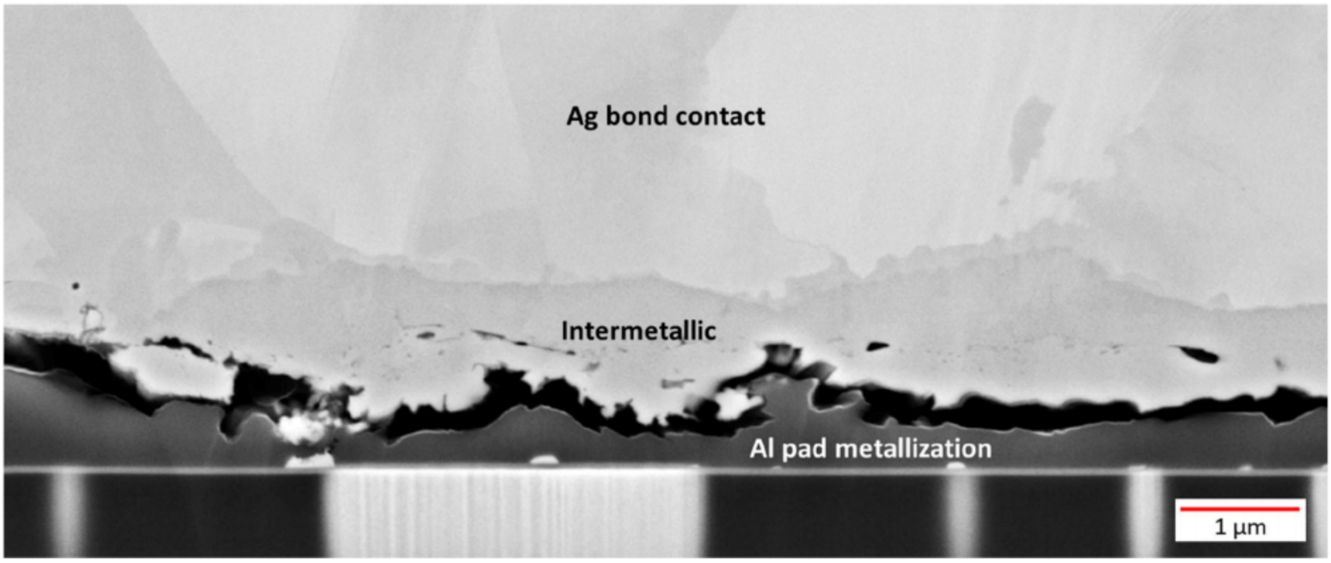


*Fig. 10 Degraded interface of wire bond contact after 3000 cycles TCT; std.Ag wire and S-free EMC*

no degradation is evident for the GX2s. These results correlate excellently with the results of the pull and shear tests.

However, the concrete failure interface is unexpected. Already in the overviews, but even better in the detailed picture in Figure 10, it can be seen that the crack runs between the intermetallic compound region (IMC) and the remaining aluminum pad metallization. In contrast to halide-induced corrosion damage of wire bond contacts, it is not the IMC that is weakened here, but the remaining bond metallization appears to be degraded. A gap is formed between this and the IMC, which is not filled with reaction products. Since the phenomenon occurs only at temperature cycling, thermo-mechanical deformation of the aluminum metallization is likely. However, at this stage, the damage mechanism is not fully understood. Further analyses to clarify this will follow.

## V. Summary And Discussion

An extensive study was conducted to investigate the reliability of silver bond wires in harsh environments (e.g. automotive applications). Two different silver wire materials (std.Ag and GX2s) and molding compounds (standard EMC and S-free EMC) were selected for this purpose. Standard automotive components were assembled under mass production conditions and subsequently subjected to various reliability tests based on the AEC-Q006 standard. In the initial state without aging as well as in all test levels, mechanical characterizations of the contact strength were performed by means of pull and shear tests (after decapsulation of the package) as well as microstructural analyses of the interconnect interfaces by means of SEM (after ion beam cross-sectioning).

Except for cyclic temperature loading in the TCT, the four wire-EMC variations showed very stable and comparable contact behavior for all reliability tests. No significant reductions occurred with respect to mechanical strength. This correlates very well with the microstructure analyses, in which no relevant degradation could be detected. From 2000 cycles TCT on, a reduction of the pull forces and shear strengths can be detected for the components with the S-free EMC and the std.Ag wire. For the parts with GX2s wire, only a slight decrease in shear values can be detected, but no change can be observed in the pull test. Even after 3000 cycles, no reduction in the contact stability of the GX2s wire is evident in the pull test, and the shear strengths have only decreased marginally. The picture is different for the std.Ag wire. For this, a considerably higher number of contacts with low shear values is recorded after 3000 cycles of TCT. As already after 2000 cycles, complete contact lift-offs without detectable shear force also occur in part. The components with the standard EMC are significantly more robust. Only the std.Ag wire showed reduced shear strength after 3000 cycles.

The matching of the low contact strengths detected in the mechanical tests with the corresponding positions in the component revealed an accumulation of weakened bond contacts in a specific area. In this area, microstructure analyses were carried out on cross-sectioned wire bond interfaces in order to investigate the damage pattern and the degradation progress as a function of the number of cycles. The results regarding the degradation level correlate very well with the findings from the mechanical tests. With increasing test duration, the damage pattern shows a progressive separation between the IMC and the aluminum pad metallization remaining under the contact. Probably, starting from the contact edge, a roughening and associated pore formation occurs in the interface due to the thermomechanical stress arising from a large CTE (coefficient of thermal expansion) difference between the Al metallization and underneath Si die. With further loading, a gap forms. No signs of corrosive material degradation have been observed so far. The influence of the position, which obviously exists, has not yet been investigated further.

In summary, all material variations showed very good reliability for most stress tests and showed no relevant contact degradation. Only the cyclic temperature changes in the TCT showed a significant difference in the test variations. A particularly severe bond damage was observed for the std.Ag wire in combination with the S-free EMC. Degradation was also found for the GX2s wire, but to a much lesser extent, which was also confirmed by the microstructure analyses. Thus, the GX2s wire shows the more robust reliability behavior. The damage pattern observed still leaves some questions open with regard to the degradation mechanism. Further investigations must be carried out in this regard. The influences of the EMC material, the wire type and the position in the component also need to be examined in more detail in order to fully understand the mechanism of the damage process and to derive improvement actions.

## References


[1] ASM Metals Reference Book, 3rd Edition, ASM International 1993.

[2] Metal Data Book, 4th Edition, Japan Institute of Metals and Materials, 2004.

[3] A. M. Howatson, P. G. Lund, J. D. Todd, Engineering Tables and Data, William Clowes & Sons Ltd, London,1972.

[4] R. Klengel, S. Klengel, J. Schischka, T. Stephan, M. Eto, N. Araki, T. Yamada, "Corrosion effects and reliability improvement of silver wire bonded contacts in automotive application", Electronic Components and Packaging Conference (EMPC), 2021, pp. 1-7.

[5] T.B. Massalski, Binary Alloy Phase Diagrams, 2nd Edition, ASM International 1990.