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Interface characterization of Cu—Cu ball bonds by a fast shear fatigue method

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ABSTRACT

A highly accelerated shear fatigue testing method is presented to test the long-term reliability and reveal the bonded interface of thermosonic Cu—Cu ball bonds. The method is an adaptation to a new industrial fatigue tester (BAMFIT) and can be conducted without an intricate specimen preparation. This method induces mechanical cyclic shear stresses to the Cu nailhead in order to initiate fatigue fracture until lift-off, revealing the actual bonded interface. This study compares the fatigue resistance of Cu wire bonded to coarse and fine grained Cu and Al metallization. The fatigue experiments are accompanied by nano indentation tests, shear tests and finite element analysis. The fatigue results showed the best performance for Cu bonds on coarse grained Cu pads (metallization), followed by those bonded on fine grained Cu while the Cu—Al nailheads failed at least a decade earlier than Cu—Cu bonds. Annealing the specimens prior to testing resulted in slight increases in the number of loading cycles to failure (N_f) for Cu bonds as well as for Cu—Al bonds, while the scattering in N_f for Cu bonds increased. Nevertheless the calculated endurance limit of the fatigue data decreases with increasing annealing stages, due to a change in the fracture probability curve. With the ability to compare the fatigue behaviour of the bonded interface within minutes, this method is most suitable for rapid qualification at an early stage of development.

1. Introduction

The semiconductor industry is constantly developing new wire material combinations and innovative design concepts in order to improve the performance of devices at higher operation power, elevated temperatures and less electrical losses to increase their reliability. That is also the case for ball bond connections in semiconductor modules switching to Cu wires bonded onto Cu metallization [1]. But determination of the quality of these bond connections by means of standard static ball shear/pull tests, does not draw any conclusions about the cyclic loading capacity. At present their long-term reliability can only be estimated by time-consuming tests such as temperature cycling or high temperature storage tests [2]. Thus fast and reliable testing methods for rapid evaluation of the bonding quality subjected to cyclic loads are essential.

The only known fatigue investigation regarding the interface was done by Lassnig et al. [3]. They used as well a highly accelerated mechanical testing setup that worked at 20 kHz and obtained lifetime curves of Cu—Al nailheads with the failure mode being wire bond lift-off. The method is based on the mechanical stresses which are induced at the interface of two vibrating coupled parts. As described in detail in [3], two different sample preparation methods consisting of single bond and multiple bond testing procedures were developed to increase the mass of the nail heads and induce sufficient cyclic stresses at the bonding interface during the vibration. Applying these two methods resulted in a slight difference between the loading modes of the nailheads which was analyzed by using FEM. This was an interesting study where the fatigue resistance of thermosonic ball bonds was investigated for the first time. The only drawback in this method is the intricate and time consuming sample preparation.

In this study the interface reliability and bonding quality of Cu wire bonds to Cu and Al pads was evaluated by using a highly accelerated fatigue test (BAMFIT) [4–6,18] adapted for thermosonic ball bonds. Shear tests and nano indentation tests were performed to compare the hardness and static material behaviour to the obtained fatigue values.

The BAMFIT method applies a vibrational load via the resonating tweezers to the nailhead in a certain direction and with a constant displacement amplitude to facilitate a fatigue crack growth in the interface. This mechanically induced load is not exactly the same as a multiaxial thermo-mechanical load due to the CTE mismatch. This difference and the influence of the testing frequency for the BAMFIT tests were investigated in [5,18] for heavy Al wedge bonds and compared to thermally induced fatigue failure by power cycling tests. In order to put the results of this method into perspective and to compare different nailhead sizes and materials, finite element analysis (FEA) were conducted to calculate the stress and strain conditions in the interface.

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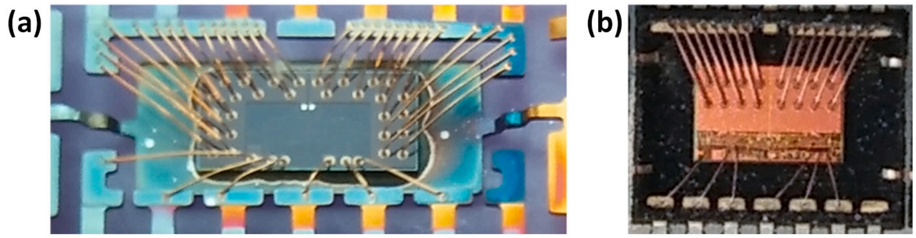

Fig. 1. Overview of the decapsulated samples (a) Cu—Al, (b) Cu—Cu wire bonds.

2. Specimen and testing methods

Cu ballbond connections from decapsulated devices, depicted in Fig. 1, with two different types of Cu metallization and as a reference an Al pad metallization were subject of this study. 4 N Cu wires with a diameter of 65 μm were thermo-sonically bonded to a Cu metallization of 20 μm thickness and 50 μm Cu wires to a 5 μm Al pad metallization. Two kind of Cu—Cu bonds with different electrochemically deposited Cu metallization layers, one showing a fine grain (~3 μm) and the other a coarse grain structure (~20 μm) were investigated. The former is further mentioned as Cu-Cu_{fine}, the latter as Cu-Cu_{coarse} and the ballbonds on the Al pad metallization as Cu—Al. The etched cross section of the initial state of the two Cu—Cu specimens is shown in Fig. 2. Each thermo-sonic bonding process was optimized to their type of metallization and wire. Those three types of bond connections were tested in the initial state at room temperature and after annealing for 100 h and 200 h, exposed to 200 °C. Cu—Al bonds performance are well covered in literature regarding the intermetallic phase formation [2,7], shear performance [8,9], and recently also fatigue resistance [3,10]. The same Cu—Al specimen as Lassnig et al. [3] used, only with an additional shelf life of 5 years, were tested in this study as a direct reference.

Conventional shear tests and nano indentation tests were conducted to evaluate the properties of the ball bond connections at conditions stated above and compare them with the proposed BAMFIT test.

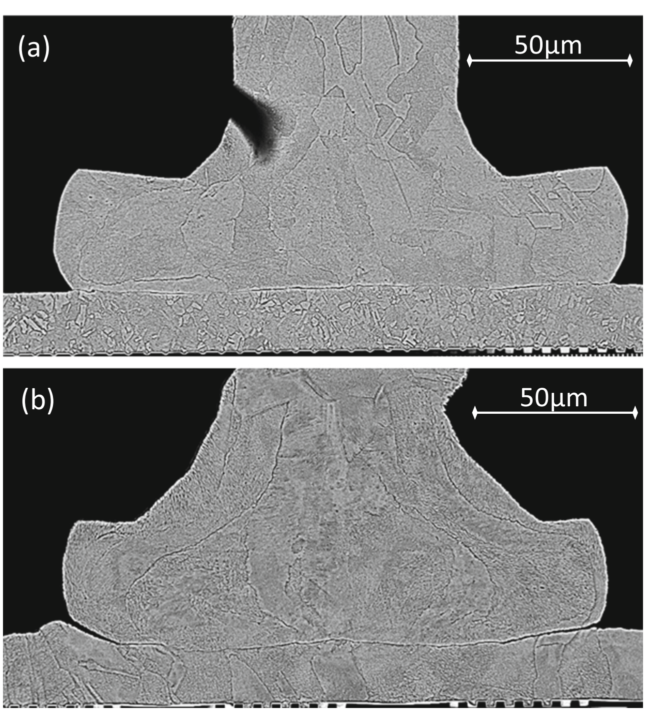

Fig. 2. SEM images of the etched cross sections of (a) Cu-Cu_{fine} and (b) Cu-Cu_{coarse} nailhead bonds in the initial state.

2.1. Shear test

The shear test is the most common test to validate a bond quality and to optimize the bonding process parameters. It is a static evaluation of the shear resistance of the interconnect, which can result in different failure modes such as ball lift, pad lift, ball shear, and cratering. The test procedure is described in detail in the ASTM, JEDEC standard [11,12] for Au and Cu ball bonds.

In this study shear tests were performed in order to compare the static performance of the ballbond interconnects with an established qualification tests to the presented accelerated fatigue test. The shear tests were performed on a BONDTEC 5600 at a shear height of 10 μm and a velocity of 200 μm/s. The results are shown in Fig. 3 for each type of connection and annealing stage. Cu-Cu_{fine} and Cu-Cu_{coarse} show similar levels, which increases after annealing up to 200 h at 200 °C. The measured shear force for Cu—Al with a peak value at 100 h at 200 °C are comparable to the results given in [7], but showing an overall reduction of ~40 cN, which is still in the 3 sigma limit. This can be explained due to a five years shelf storage of the samples at ambient condition. Shear test results of Cu—Al bond and the influence of interfacial intermetallic phase growth was not perused in this study, since they are well covered literature [7–9].

Since the bond area varies for each type, due to the wire diameter, material properties and bonding parameters, it is more appropriate to consider the shear stress for a direct comparison. The shear stress is calculated by the max. shear force divided by the total area of the bond interface, which itself was measured by outlining the perimeter visible in the fracture surface after BAMFIT testing for each type. The Cu—Al bonds seem to have an equal shear resistance compared to Cu-Cu_{fine}. with respect to the size difference. Cu-Cu_{coarse} shows a slightly smaller interface area and hence enhanced shear resistance comparing with Cu-Cu_{fine}.

Shear fracture occurred in the Al pad for Cu—Al and for the Cu—Cu in the interface and through the Cu wire nailhead. With increasing aging time, the area of the remaining Cu nailhead on the pad increases and the shear tool cuts more through the wire material, as illustrated in Fig. 4 for Cu-Cu_{coarse} bonds. This improvement of the bond quality may be caused by a stimulated interdiffusion due to the heat treatment and possible local recrystallization, as reported for Cu—Cu bonding in [13,14].

2.2. Nano indentation

The material properties in the region of the nailhead differ greatly from the wire, due to free air ball forming and thermosonic bonding. Hence nano indentation tests were performed around the bond connection in rows of ~10 measurement starting from the metallization layer into the nailhead in the cross section, by an ASMEC Unat with a Berkovich indenter. In Table 1 the average hardness values for the investigated Cu metallization and the nailheads are listed. These measurements and the grain size structure were used to select the material model for the FEM simulations of the fatigue test.

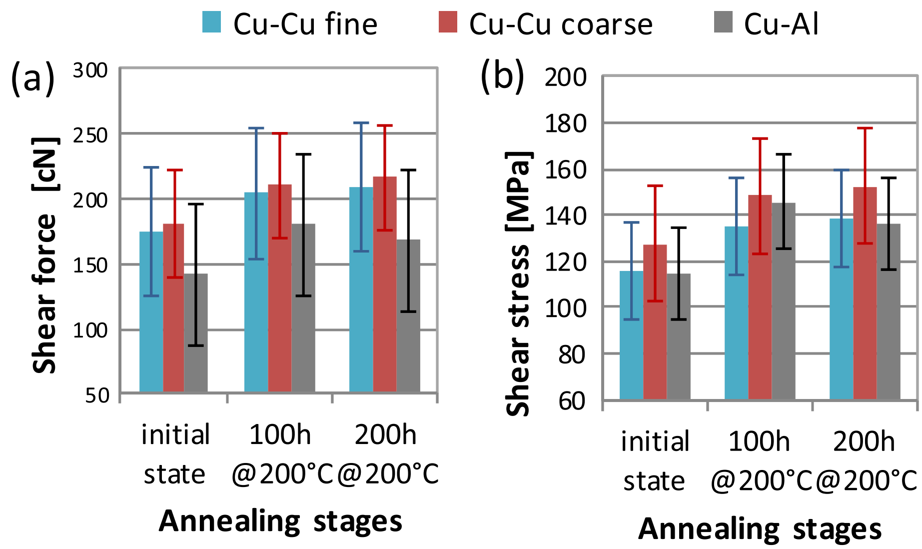

Fig. 3. Shear test results plotted as (a) the maximum reached shear forces and (b) calculated shear stresses for all wire bonds and conditions.

2.3. BAMFIT

The BAMFIT method is designed for a commercial bondtester (BONDTEC 5600) to reproduce the thermo-mechanical shear stresses by mechanical means and invoke lift-off failure at the bond interface. This method, which was originally developed for heavy Al wire wedge bonds as described in [4], is further developed for evaluation of fine thermosonic wire ballbonds in the current study, by adapting the resonance tweezers gripping tool.

The mechanical stresses are induced by mechanically gripping and exciting the bond wire near the bonded interface in one direction with very small cyclic shear loads and simultaneously holding the substrate static. Gripping the ball-bond is realized by a special tweezers fabricated out of one piece of spring steel, which operates in resonance at 60 kHz. Due to the tweezers design the gripping force of < 1 N is always constant. A camera pattern recognition unit provides precise positioning with less than 5 µm offset error and a touch-down sensor keeps a defined gripping height of 5 µm above the surface. The tip is machined in a way to maximize the pinching contact to the nailhead, as illustrated in Fig. 5. The oval, micro scaled shape was cut into the tip with a plasma focus ion beam. The grippers are excited at a constant sinusoidal amplitude at 60 kHz during fatigue testing until a complete wire bond lift-off occurs, while a small tensile preload is applied in Z-direction in order to prevent re-bonding or grinding in the interface. Each step of the described BAMFIT test process, the positioning and opening of the tweezers (I), the touchdown (II), the retraction to the clamping height and closing of the tweezers (III), the static preload and ultrasonic excitation (IV) and the final lift off (V), is illustrated in Fig. 6. The excitation amplitude was measured using a differential laser Doppler vibrometer (LDV) at the nailhead and the metallization to determine the displacement amplitude (dx).

Table 1
Hardness investigation of Cu-Cu ballbonds and metallization.

H (GPa)	Initial state	100 h @ 200 °C	200 h @ 200 °C
Fine metallization	1.45 ± 0.18	0.95 ± 0.06	0.94 ± 0.08
Coarse metallization	0.77 ± 0.03	0.93 ± 0.05	1.08 ± 0.07
Nailhead fine met.	0.95 ± 0.07	0.79 ± 0.22	1.03 ± 0.12
Nailhead coarse met.	0.96 ± 0.08	0.96 ± 0.09	0.96 ± 0.05

The pinching of the ball bond and the ultrasonic softening effect during testing causes a slight deformation of Cu nailhead within the first few ms of the fatigue test. This deformation can be seen in Fig. 7a and remains in most cases above the unbonded region. The few cases ($< 10\%$), where the nailhead deformed significantly during BAMFIT testing, were excluded for the evaluation, since very high unrealistic N_f and occasional slipping of the tweezers tool were observed.

The tests were conducted for nailhead bonds with cut wires at the neck for a better clearance and visibility of the tweezers tool during testing to the neighbouring bonds. Nevertheless with the designed tweezers tip shape it is well possible to reach and test the nailheads with intact wires (Fig. 5), in which case the testing direction has to be aligned with the wire direction. Hence investigating the fatigue resistance of the bonded interface of such ~50 µm Cu ballbonds is possible without special specimen design and can be performed directly after bonding. This BAMFIT method is an extremely fast reliability test, designed to reveal the interface structure and determine the fatigue behaviour of ballbond connections.

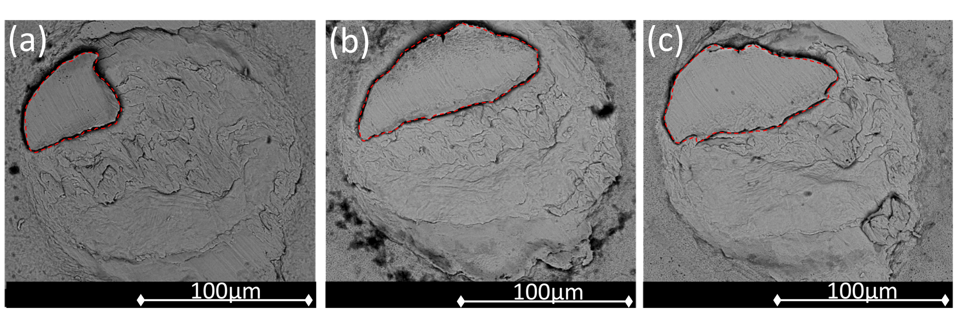

Fig. 4. Shear fracture surface for Cu-Cu_{coarse} in (a) the initial state, after annealing for (b) 100 h and (c) 200 h at 200 °C.

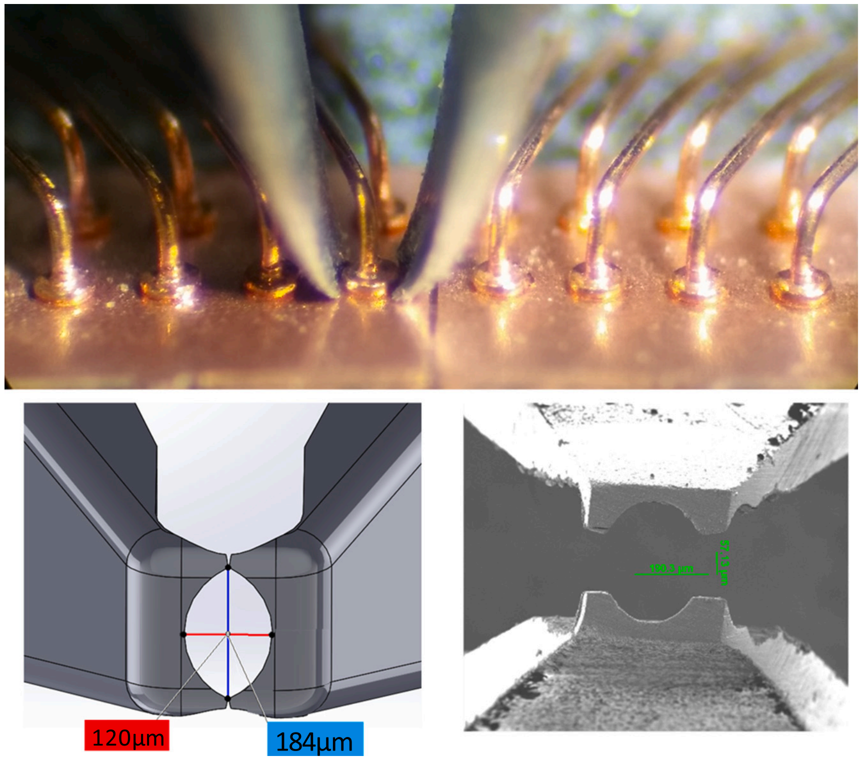

Fig. 5. Tool tip geometry and design to reach the nailhead between the bond connections.

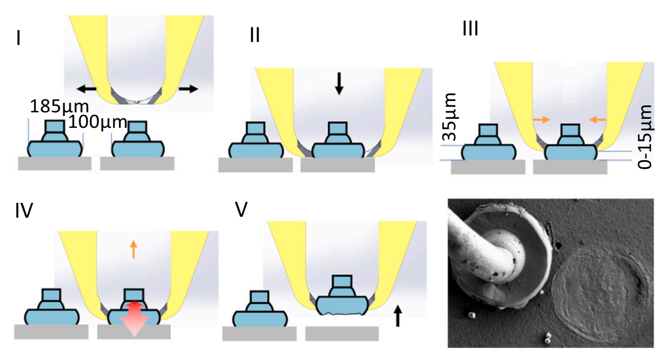

Fig. 6. Schematic illustration of the gripping and testing process with the BAMFIT method.

3. BAMFIT results

The cyclic excitation of the nailhead leads to a fatigue crack propagating in the interface of the bond, which exposes the actual bonded interface over the whole bonding area. This is in most cases not completely visible after shear testing due to the remnant of the sheared nailhead, as in Fig. 4. The fracture surface of the completely lifted nailheads can be seen in Fig. 7. For Cu—Al the fracture occurs in the Al metallization layer as in Fig. 7b where a layer of Al remains on the lifted nailhead.

The fracture surfaces for $Cu\text{-}Cu_{coarse}$ and $Cu\text{-}Cu_{fine}$ are shown in comparison in Fig. 8. The magnified images of the interface of $Cu\text{-}Cu_{fine}$ show the actual bonded areas and some smooth areas where the metallization grain structure in the backscattered electron image can be distinguished (Fig. 8b). This indicates that the actual bonded interface of the Cu-Cu is not bonded completely over the whole interface area.

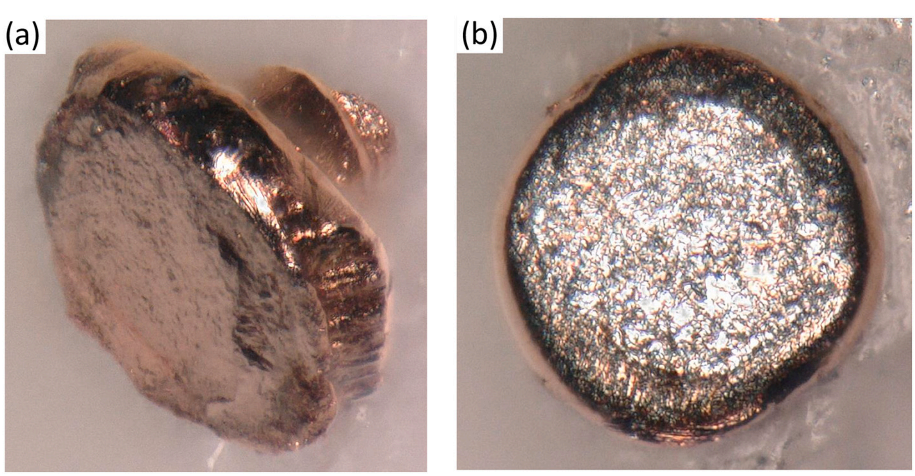

Fig. 7. Lifted Cu nailhead of a) Cu-Cu and b) Cu—Al thermo-sonic bond connection.

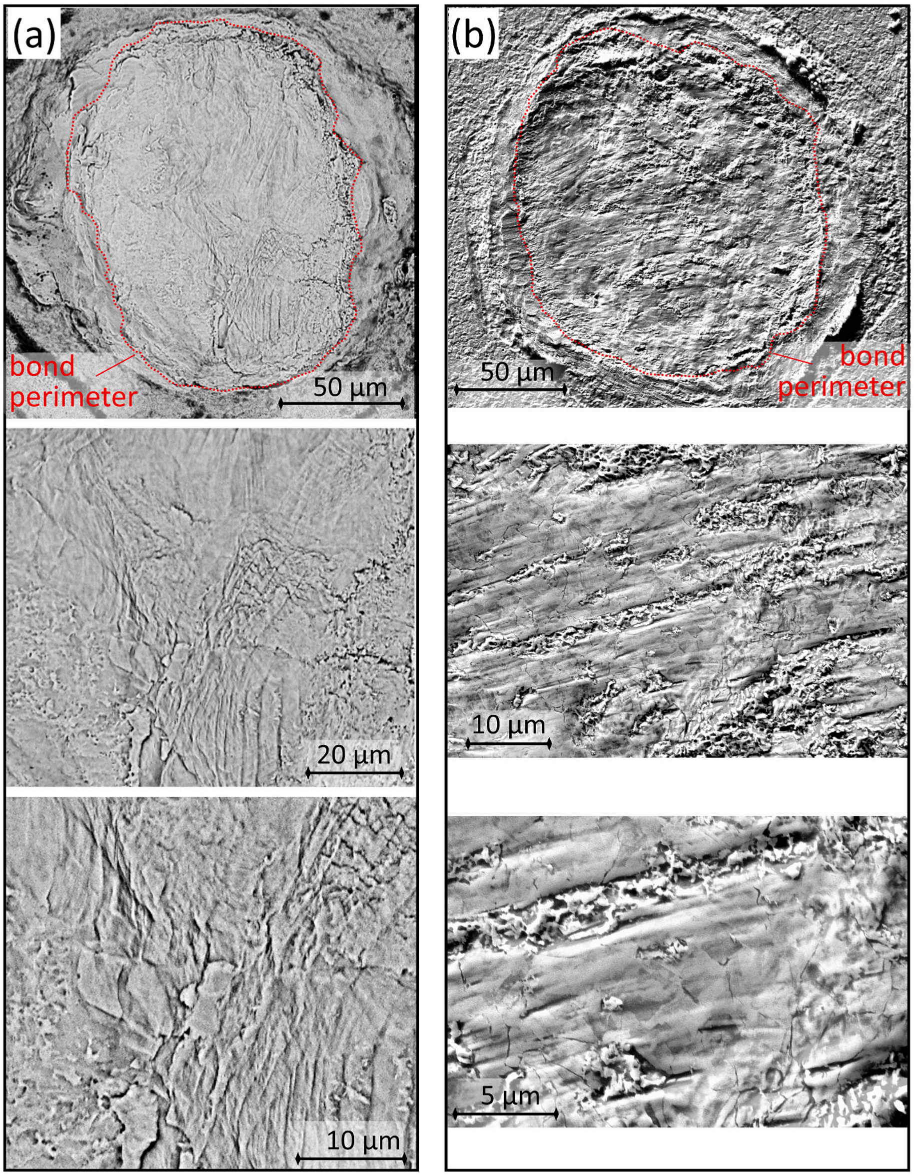

Fig. 8. Fracture surface after BAMFIT testing on the metallization side for (a) Cu-Cu$_{coarse}$ and (b) Cu-Cu$_{fine}$, indicating in red the perimeter of the overall bond area used for shear stress calculations and FEM models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For Cu-Cu$_{coarse}$ the interface in Fig. 8a seem to be bonded over a larger area. The large grain structure of the metallization is also visible.

The BAMFIT fatigue test detects the cycles to complete lift off failure (N_f) for an applied excitation amplitude (dx). The tests were conducted in the range of 1e3 up to 1e8 loading cycles. The results shown in Fig. 9 depicting dx in nm against N_f for Cu—Cu and Cu—Al for each annealing stage separately. More than 600 nailhead bonds were tested for all 3 types of ballbonds at 4 stress levels, each with an average of 16 bonds per level, providing enough data for a statistical analysis and calculating the percentile S-N curves. In this plot the size differences of the wires and interconnects are not taken into consideration, but will be covered in the next FEM section. The 50% fracture probability (P_f) and endurance limit from the fatigue data of each bond at each state was calculated using the profatigue software [15]. The software uses a Weibull model for calculating the endurance limit (C) for $N \rightarrow \infty$ and the percentile curves are hyperbolas with the asymptote $\Delta x = \exp(C)$. The larger Cu—Cu bonds can withstand much higher amplitude until failure compared to the smaller Cu—Al bonds with data for Cu-Cu$_{coarse}$ being slightly above Cu-Cu$_{fine}$ despite the smaller interface area of Cu-Cu$_{coarse}$. The endurance limit for all bonds drops with increasing annealing time. That is not due to a reduction in N_f, but due to a decreasing curvature of the calculated fatigue curves. The endurance limit drops about 1/3 of its value for Cu—Al from 55 to 35 nm. BAMFIT test of the annealing stages actually shown a slight increase in N_f. This can be seen in more detail in the Weibull plots in Fig. 10, where P_f is displayed against N_f for one overlapping excitation amplitude of 90 nm. The shift in N_f for 50% P_f can be seen for all bonds. For both Cu—Cu bonds the scattering of the fatigue results increases as well, as evident due to a rotation of the fit curve.

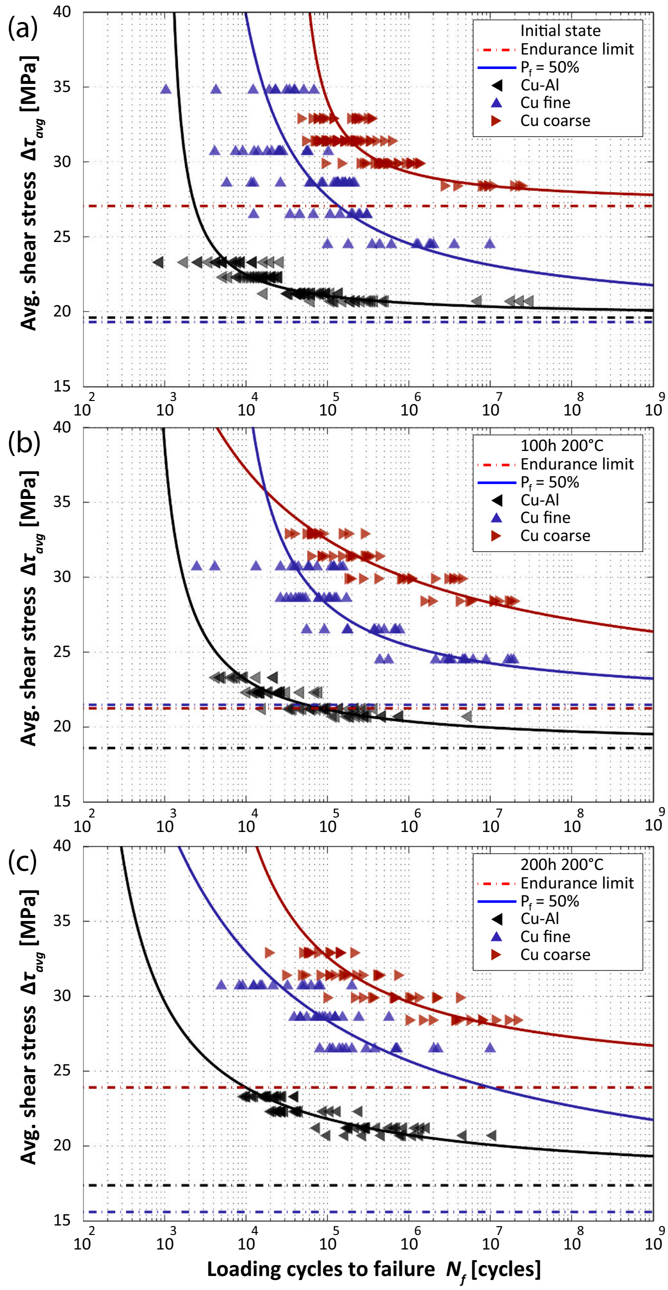

Fig. 9. BAMFIT results plotted dx against N_f for Cu-Cu_{fine}, Cu-Cu_{coarse} and Cu—Al for (a) the initial state and after annealing for (b) 100 h and (c) 200 h at 200 °C.

3.1. FEM analysis

Finite element analysis of the BAMFIT test was conducted to convert the applied mechanical vibrational loads into shear stresses in the interface. The dynamic conditions were simplified by consecutive static simulations of the clamping, the preload and the excitation phases. Nonlinear kinematic hardening models were used for the Cu nailhead, Cu and Al metallization, obtained from previous investigations on 25 μm Cu wires with different microstructures [16,17,19]. The data from tensile tests of fine and coarse grained polycrystalline wires were chosen for the fine metallization and the nailhead. For the coarse

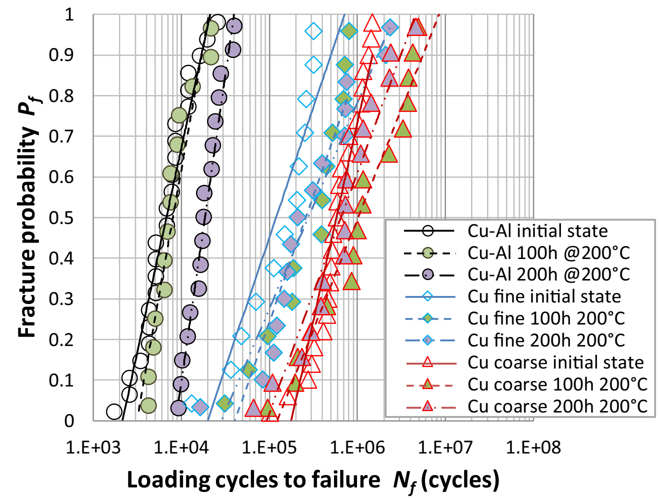

Fig. 10. Comparison of BAMFIT fatigue results at 90 nm excitation plotting the fracture probability.

metallization, where the grains exceed the layer thickness, data from a bamboo structured wire were selected. The mesh size at the contacts and interface was refined to 5 μm.

The experimental test conditions were replicated by a displacement movement of the tip of the tweezers in X-direction against the nailhead on a Si chip metallization. As boundary conditions, frictionless contacts between the nailhead and the tweezers tool and a fixed support at the bottom of the silicon chip were defined. The movements of the tweezers tip are indicated in Fig. 11. The clamping of the tweezers at 5 μm distance to the chip metallization resulted in a local plastic deformation of the nailhead, then the vertical preload of 5 g was applied and finally a displacement in the range of 50–150 nm in y direction of the tweezers tip induces shear stresses in the interface.

Since in the experiments the movement at the bottom of the Si chip can't be restrained to absolute 0 as in the FEA, the differential displacement (*dx*) was measured at the bottom of the nailhead neck and on the chip metallization using a LDV with a laser spot size of ~3 μm, as indicated in Fig. 11. The same positions were evaluated in the FEA to match the excitation displacement amplitudes from the experiments, at which point the stresses in the interface were calculated. In Fig. 12a the von Mises stress distribution of the wire and in 12b the equivalent plastic strain distribution of the interface for Cu-Cu_{fine} at 90 nm excitation (*dx*) is displayed. The interfacial shear stress distributions (XZ-plane) for all wires at 90 nm excitation are displayed in Fig. 13, showing the highest gradient from center to the edge for Cu-Cu_{coarse}.

Evaluating the average shear stresses in the interface for each excitation amplitude and wire, as is plotted Fig. 14, provides a linear conversion of the displacement to the shear stress. By converting the excitation amplitudes from Fig. 9 with this FEA method to shear stress levels, the BAMFIT results can then be plotted as conventional S—N curves, in Fig. 15. In the S—N plot the difference between Cu_{fine} and Cu_{coarse} increases, since due to the smaller bonding interface of Cu-Cu_{coarse} the shear stress increases for the same excitation level. The trend of the S—N curves and the endurance limit don't differ much from the excitation plot (Fig. 9), but the larger difference between Cu-Cu_{fine} and Cu-Cu_{coarse} brings the endurance limit for Cu-Cu_{coarse} above the others for all conditions. More investigations at higher and lower stress amplitudes would be necessary for a better prediction of the curve trends and endurance limits at very high cycles. Although the Cu—Al bonds had the smallest interface, due to the much softer Al the shear

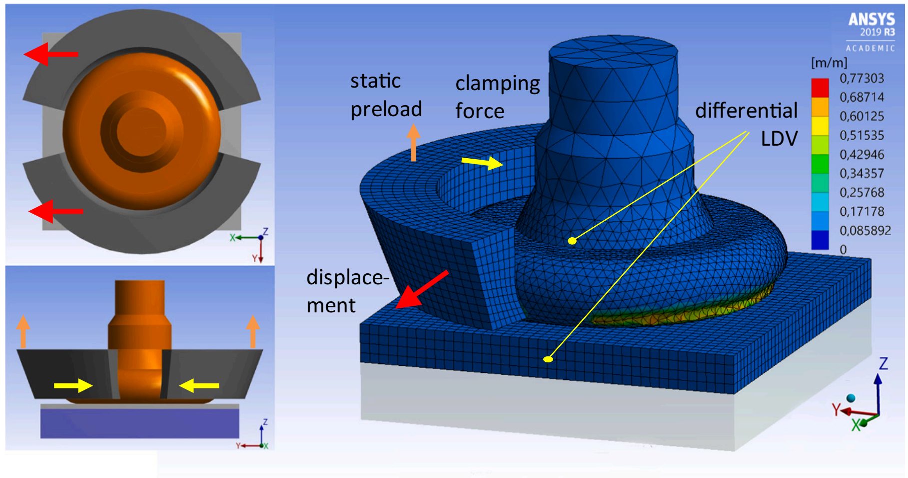

Fig. 11. (a) FEM model, (b) plastic deformation after tweezers gripping and preload of the nailhead, with indicated load directions and X displacement measurement points.

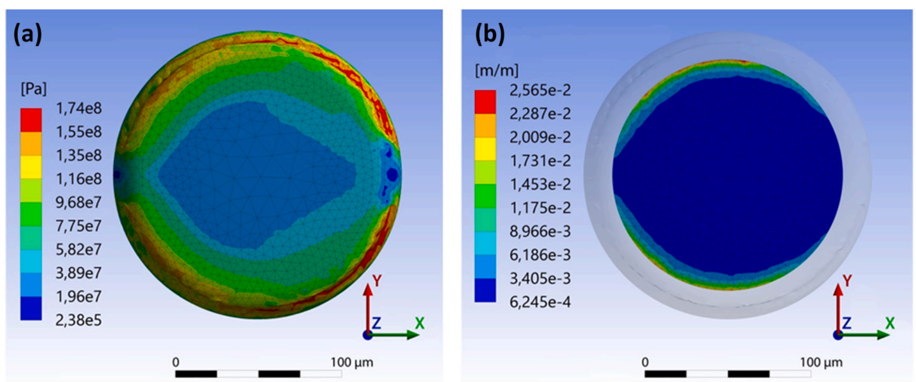

Fig. 12. (a) Von Mises stress distribution of a Cu-Cu fine nailhead (bottom side), (b) equivalent plastic strain in the interface at 90 nm displacement.

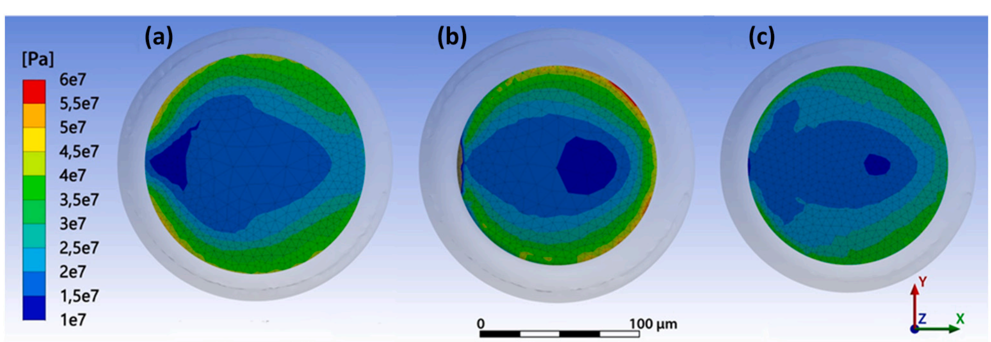

Fig. 13. The XZ shear stress in the interface of a (a) Cu—Cu fine (b) Cu—Cu coarse (c) Cu—Al at 90 nm displacement.

stresses remain comparatively low between 20 and 24 MPa. The differences in the lifetime curves between Cu—Cu and Cu—Al can be related to the lower fatigue resistance of the softer Al metallization and an effect of the intermetallic phase formation (IMC) in a Cu—Al bond [2,7,8].

These S—N curve can be directly compared to the fatigue results of Lassnig et al., since in this inertia based method they used the mass and applied acceleration to calculate the shear stresses over the interface area [3]. In that study the same Cu—Al ballbond specimen reached N_f of 1e5-1e6 at 10–15 MPa for single ball test and 30–35 MPa for multiple bond method. In comparison, the BAMFIT results for Cu—Al reach 5e3–1e6 N_f at a calculated 20–24 MPa stress level, which are right between the stress levels of the single and multiple test setups of Lassnig et al. Despite the different approach to induce the mechanical stresses, the testing frequency, the shelf life and the stress calculation, both results are in a good agreement.

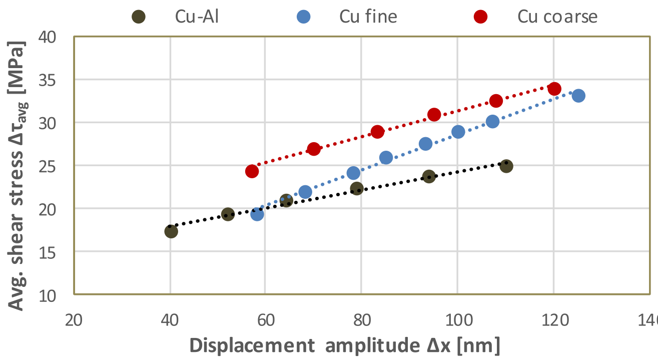

Fig. 14. Calculated average YZ shear stress of the interface against the differential displacement for all types of wire bonds.

The calculated max von Mises stresses in the interface of the BAMFIT test reaches ~107 MPa which due to the clamping method are not as localized directly at the periphery of the bonded interface as in the study of Lassnig, where peak values of 138 MPa were calculated.

4. Conclusion

Achieving results with the BAMFIT method for the long term fatigue behaviour and revealing the actual bonding interface of Cu ball bonds is unique for this type of interconnect. Due to its flexibility, no need for intricate sample preparations and extremely fast test procedure, this new method is most suitable for rapid screening and qualification at the early stages of development and during production for lifetime evaluations and can reveal additional information to static shear or pull tests.

As the results have shown, the shear test can deviate from the fatigue behaviour. Comparing the average shear stress Cu—Al shows a lower fatigue life despite reaching similar values as Cu-Cu_{fine} in the shear test. The fatigue resistance of the Cu-Cu_{coarse} is higher than Cu-Cu_{fine} bonds and both Cu-Cu bonds show an increasing scattering after annealing. Despite an increase in N_f for all bond types for increasing annealing time up to 100 h at 200 °C the curvature of the data decreased, resulting in a lower endurance limit.

The fracture surface for Cu-Cu_{fine} revealed ribbon shaped areas in bond direction of well bonded material as well as smooth surfaces, which can't be seen by conducting static shear tests. This and the fact that a much larger Cu-Cu_{fine} bond compared to a Cu-Cu_{coarse} still feature a lower shear strength in the static shear test and a lower fatigue life in the BMAFIT test, indicates that the actual bonded area of the Cu-Cu_{fine} is not bonded uniformly over the whole interface.

The fatigue results, converted into a S—N plot by FEA, showed a good correlation to the fatigue investigation of Lassnig et al. [3] under consideration of the different method of inducing the shear stresses and different shelf life. The FEM analysis provides a better comparison to other loading conditions, since the BAMFIT test uses a unique way of inducing the shear stresses.

The BAMFIT adaptation for ballbonds is a promising addition to the conventional qualification tests, since it is a very fast testing method, needs little specimen preparation, provides lifetime fatigue results for lifetime evaluations and can reveal the actual bonding interface.

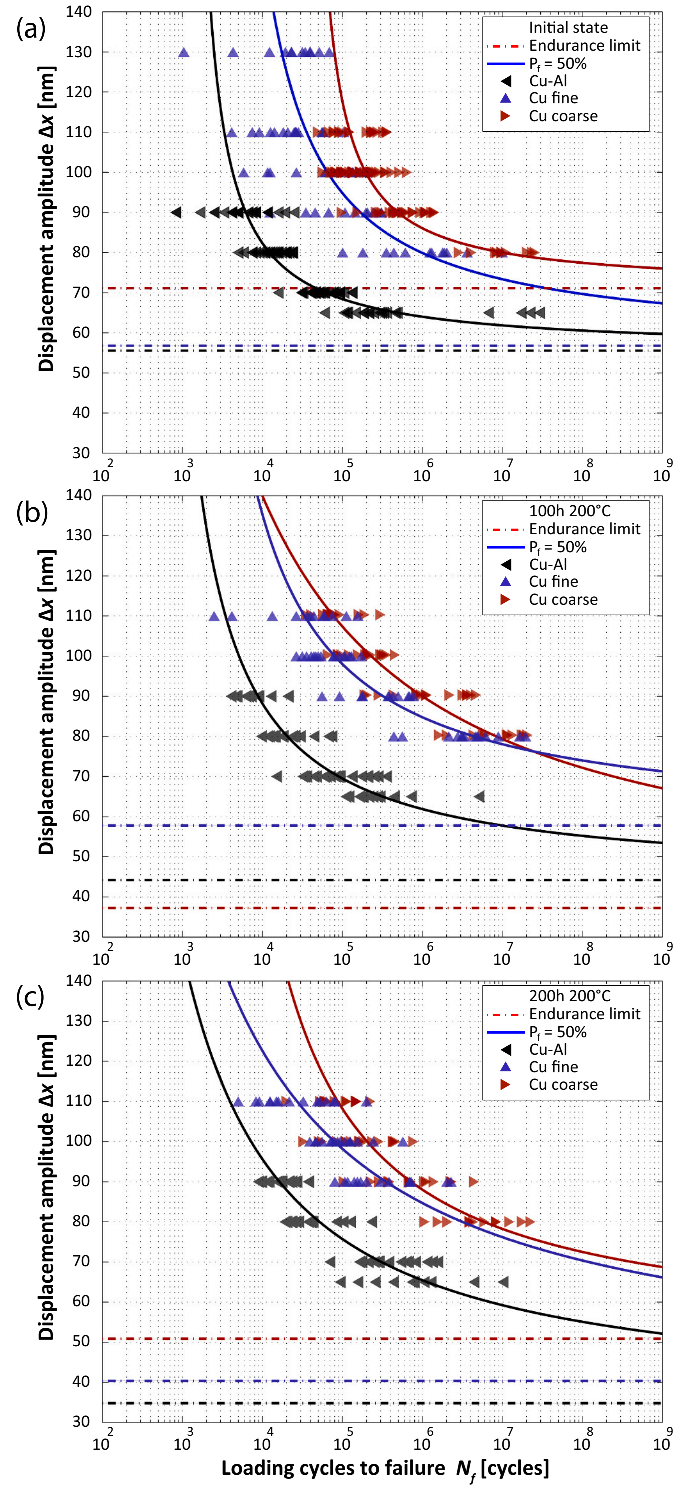

Fig. 15. S—N curves for Cu fine Cu coarse and Cu—Al for the (a) initial state, (b) after annealing for 100 h and (c) 200 h at 200 °C.

CRediT authorship contribution statement

B. Czerny: Conceptualization, Methodology, Data curation, Investigation, Project administration, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **G. Khatibi:** Conceptualization, Project administration, Funding acquisition, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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