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Reduced total cost of ownership with copper sintering

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Abstract

For copper sintering to be attractive to the industry and adapted on a large scale, not only the material costs, but also the overall cost of ownership should be low. The sintered interconnect must ensure improved reliability over silver, high thermal conductivity and most importantly compatibility with existing silver sintering equipment. This paper presents a novel microscale copper sinter paste with excellent thermo-mechanical fatigue resistance and details the overall process flow, starting from paste storage up to sintering which are substantially simplified compared to a traditional silver sinter process. Enhanced surface modifications on microscale particles together with the use of innovative organic binder chemistry offers excellent low temperature, low pressure sintering capabilities and an average shear strength of ~ 40MPa across the standard metallizations, namely gold (Au), silver (Ag) and copper (Cu) and the capability to also sinter at temperatures as low as 220°C, thereby allowing for a single solution for both die-attach and substrate attach. The material are observed to sustain harsh thermal shock conditions of +175/-65°C for die-attach and +125/-40°C for substrate attach with zero delaminations after 1500 cycles.

1 Introduction

Interconnect materials are critical for improved performance and enhanced reliability of power electronics packages. Different solutions are available as shown in Figure 1. Conventional lead free-based solders have a low melting point (220-230 °C), thereby limiting the reliable temperature use to below 150 °C.

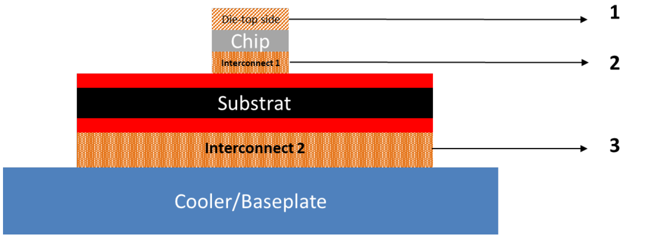

Figure 1 - Simplified view of a power module and the existing interconnect material solutions for the three interconnect levels, namely; (1) wire bonding, ribbon bonding, clip attach or foil-based solutions, (2) soldering, TLP bonding or sintering and (3) soldering or sintering.

With the advent of SiC and GaN devices for die-attach where the junction temperatures and the operating temperatures are beyond 175°C, new die-attach materials are necessary. Similarly, for package/module attach onto coolers/baseplates, interconnect materials with very good thermal conductivity are necessary, more so with the increased use of high-performance ceramic substrates.

Standard solders achieve ~60W/mK, while sintered interconnects achieve > 180W/mK, therefore atleast a factor 3 higher than traditional solders, while allowing for high temperature operability.

Therefore, in recent years, solid state sintering has shown a high rate of adaptability by the industry. Ag sintering under pressure is industrialized in power electronics packaging for die-attach with SiC and GaN based devices and marginally also for Si IGBTs. Pressureless Ag sintering is widely used in high-power optoelectronics packaging (automotive LEDs and laser diodes). However, for second level interconnects soldering still remains the technology of choice, with a limited few innovators in the automotive field using Ag sintering for module attach as well. With a clear performance advantage shown by these innovators using Ag sintering, the trend is slowly but surely moving towards evaluating sintering as a viable alternative also for second level interconnects.

Ag is expensive and is highly prone to electromigration [1–3]. Ag majorly exists in combination with elements such as sulphur, arsenic, and antimony among others and thereby in ores such as argentite (Ag_2S) or silver chloride (AgCl). Galena is a lead ore which has significant amounts of Ag. Therefore, the extraction process of Ag is either through amalgamation or electrolysis. Therefore, the carbon footprint of Ag is also much higher than that of Cu which is abundantly available and can be easily recycled as well [4]. These

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factors have necessitated the scientific community and industry alike to look for a suitable alternative that offers comparable/better performance, at a fraction of the cost and is a sustainable alternative. Among the metals, Cu offers the next best alternative due to its excellent thermal and electrical properties, improved creep resistance, low cost, easy recyclability, and a substantially lower carbon footprint. Cu has also been reported to be more robust against electrochemical migration due to the lower solubility product constant of Cu ion hydroxides compared to Ag [5]. Cu sintered interconnects have also shown very good corrosion resistance [6]. Cu sintering, therefore, has been the focus of R&D over the past years [7].

However, Cu is highly prone to oxidation and Cu oxides are diffusion barriers and hence hinder sintering. By virtue of the higher melting point of Cu (~1085°C) compared to Ag (~ 962°C), Cu particles when having the same morphology as Ag particles, will need a higher sintering temperature. This is undesirable for two reasons, namely; (1) higher sintering temperatures will results in higher stress in the components and warpage thereby compromising reliability and (2) for second level interconnects, i.e. molded packages, the glass transition temperature of the mold material limits the sintering temperature to a maximum of 220°C, thereby rendering any material solutions beyond this temperature not suitable for application.

2 State of the art

2.1 Materials

A review of the state of the art in Cu sintering reveals the various approaches adopted by researchers towards Cu sintering, with the main goal to reduce sintering temperature. These can be broadly classified as:

- Cu nanoparticles (NPs) and nanoporous materials [8–11]
- Ag or Sn shell Cu NPs and Ag-Cu mixed hybrid pastes [12–17]
- Coating of Cu NPs / Cu NPs with passivation layer [18,19]
- Cu salts [20,21]

Cu NPs have been the material of choice for researchers for Cu sintering. The enhanced sinterability is attributed to the high surface energy of NPs resulting from a high surface area to volume ratio. However, Cu NPs with high specific surface energy are highly prone to oxidation and require specific product (e.g. passivation layers, anti-agglomerates) & process adjustments (e.g. reducing sintering atmosphere)

The use of special capping agents and/or anti-agglomerates in the paste formulation is a limitation to achieve low temperature sintering (< 250 °C), as the capping agents need higher temperatures and/or eventually high bonding pressure to burn off completely to enable sintering [22]. Further, the use of Cu NPs leads to environmental and health safety issues not only during the chemical synthesis of these particles but also during the use of the same [23].

To counter the issue of oxidation, typically a reducing sintering atmosphere is recommended, i.e, sintering either under formic acid enriched nitrogen, forming gas or pure hydrogen. This makes the use of such sinter paste unsuitable for standardized Ag sintering equipment. Further, the use of hydrogen adds additional costs concerning safety within the working environment and use of formic acid enriched nitrogen leads to challenges of corrosion and contamination due to formate sublimation. Therefore, not only do material costs increase, but also process costs.

Cu salts are at least factor 5 more expensive than Cu particles, are toxic and also have a low metal loading content (e.g. ~28 wt% of copper(II) formate tetrahydrate is pure Cu), which leads to a high-volume shrinkage and degassing of organic compounds during the sintering process, leading to high voiding and localized/island type sintering. Further, contamination due to formate sublimation is a major challenge, similar as in the case of using formic acid enriched nitrogen during sintering, more on which is detailed in the following sections.

3 Cost factor

As discussed earlier, for Cu sintering to be attractive to the industry and adapted on a large scale, not only the material costs, but also the overall cost of ownership should be low. Therefore, it is essential to consider the entire value chain of the sintering process, from paste storage up to sintering to ensure that Cu sintering brings a substantial advantage over Ag sintering.

3.1 Storage

Ag sinter pastes are typically stored under refrigeration (2 to 8°C) or in deep freeze (-20 to -40°C). Such conditions add additional costs for transportation, storage and other operating costs While the costs pertaining to the former two are obvious, the costs concerning the latter are typically hidden quality costs that do not reflect in the final product costing.

For example, all pastes that are refrigerated or deep freezed need to be allowed to stabilize at room temperature before usage. This is referred to as thawing time and it varies from 1 to 3 hours. This means, any production run planned with the pastes need to consider this thawing time additionally and the quality costs that consequently follow. However, in case of any disruption in the production plans or other unforeseen factors that lead to the pastes having to be stored back, the performance of the paste is

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compromised, i.e. such type of pastes can only see a specific number of exposure cycles before a drop in performance is seen.

Further, once used for stencil/screen printing, excess pastes on the stencil/screen cannot be recycled back into the original containers and this is typically limited to ~20% used content as maximum allowed.

Therefore, we propose a novel solution where the Cu sinter pastes can be stored at room temperature. This drastically reduces the transportation costs, the quality costs and the operation costs. No thawing time is necessary for the pastes before usage and they can be stored in a clean room atmosphere (20 to 24°C and controlled humidity). Therefore, an important factor on the cost of ownership of the paste is addressed, wherein all the challenges/issues mentioned above are not relevant for these Cu pastes.

3.2 Equipment

Sintering equipment have matured and developed over the years, mainly targeting Ag sintering [24–28]. The traditional approaches therefore involved sintering Ag or Au metallized dies onto Au or Ag metallized substrates with Ag based sintering materials (either paste or films). Therefore, sintering is mainly performed in air or vacuum. With the advent of use of Cu substrates, sintering under N_2 and vacuum have gained prominence. Further, for mainly R&D purposes, sintering under reducing atmosphere (formic acid enriched nitrogen, forming gas or H_2) are commonly implemented.

The industrialized solutions available in the market for series production however can be categorized as following:

- Sintering under vacuum
- Sintering in an inert atmosphere
- Sintering with inserts/punches
- Soft tool sintering set-up

Each one of the above technologies has their own advantages and challenges and it is clear from the market research that no specific solution is the preferred solution, either for Ag sintering or for Cu sintering. Therefore, when designing a Cu paste, it must be considered that the compatibility with majority of the equipment is satisfied. This is essential considering the fact that it is not foreseen that the industry will transition from Ag sintering to Cu sintering in a disruptive fashion but in a phased manner and therefore, there will continue to be an overlap in the production lines between Ag and Cu sintering. Hence, any Cu sintering product that is targeting to replace Ag sintering must be compatible with the equipment as well as the established processes for Ag sintering.

3.3 Sintering process

A typical pressure sintering process involves paste printing, pre-drying, pick and place, sintering.

Typical chip backside metallization is Ag or Au. Latest trends are also investigating nickel (Ni) and palladium (Pd) as possible backside metallization. Similarly, direct bonded copper (DBC) or active metal brazed (AMB) substrates are used, usually plated with Ag or Au, but the trend is moving towards bare Cu surfaces, firstly for cost reductions and secondly to have a uniform material stack after sintering.

Stencil and screen printing are the most widely used paste application technologies within the industry. For the scope of this paper, transfer films and dispensing technologies are not considered. With all pressure sinter processes for die-attach applications, a drying process step is performed after printing and before pick & place. This step ensures that specific organics within the pastes, for example having a functionality to maintain rheology of the paste or to ensure efficient printing processes are sufficiently removed before pick & place of the die. This ensures that the paste does not squeeze out during pick & place and excessive degassing of the organics during sintering process which can lead to high voiding and/or inhomogeneous sintering is avoided.

In case of module/package attach, wet placement is preferred. This is to ensure that the large packages do not move during the process steps and any warpages and inhomogeneities can be sufficiently considered. But, this also results in long pre-drying times, typically exceeding 30min.

4 Die-attach

4.1 Novelty & Performance

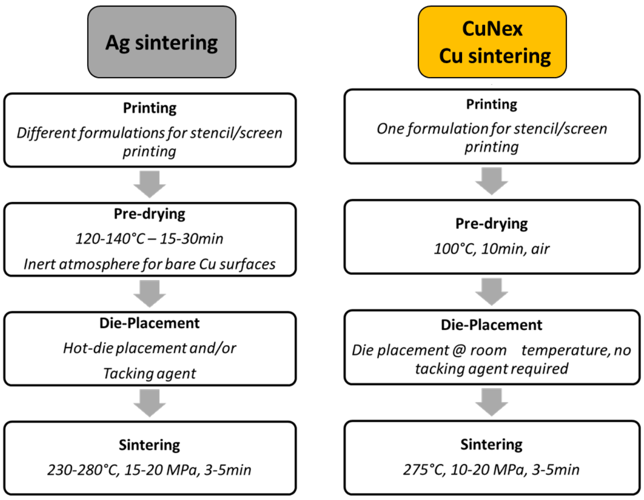

Figure 2 – Die-attach process parameter comparison between industrialized Ag sinter paste solutions and the novel CuNex Cu sinter solutions.

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A Cu sinter paste formulation is presented, composed of surface enhanced microscale particles. These improved surface modifications on the particles enable nanoscale sintering capabilities even with microscale particles. The novel binder chemistry in combination with this surface treatment of the flakes in the paste allows for a fast-pre-drying process in air through a hot-in/hot-out process and an efficient countering of copper oxides during the sintering process. Therefore, sintering in an open bond chamber under constant N_2 flow or when under 1 min, sintering in air can also be performed. The pastes also show very good compatibility to Au and Ag end metallization and an average shear strength averaging 40 MPa across the different metallization.

As can be seen from Figure 2, in comparison to a traditional Ag sinter process, ever single process step is simplified. Starting with printing, a single formulation is capable of both stencil and screen printing. Further, it can address die-sizes from 0,5mm² flip-chip LEDs up to large IGBTs with a typical footprint of 100mm² to 225mm².

The pre-drying of the paste is performed in air through a hot-in/hot-out process and within a very short time of 10min. This substantially reduces the process times compared to Ag sintering and more importantly, eliminates the need for an inert atmosphere or a controlled atmosphere oven for pre-drying as necessitated by Ag sintering, specially while sintering on Cu surfaces, since the high pre-drying temperatures otherwise will lead to severe oxidation of the Cu surfaces.

Ag sintering typically requires either hot die-tacking or a tacking agent during pick & place process to hold the die in place. Further, a high pick & place force is needed. This is detrimental when working with LEDs or Si IGBTs which are typically 80 to 120µm thick. Any placement force in excess of 5N can lead to cracking of the dies. These challenges are addressed with the new CuNex pastes where die placement is made with a low force of 0.1N and without the use of either hot die tacking or tacking agent. The die placement is made at room temperature.

Finally, sintering is performed at 275°C for 3min with 10MPa bonding pressure. The pastes are composed purely of microscale particles, i.e. no nanoparticles. As can be seen from Figure 3, a uniformly sintered interconnect with a dense and homogeneous microstructure is obtained even while sintering for only 3min at 275°C with 10MPa bonding pressure.

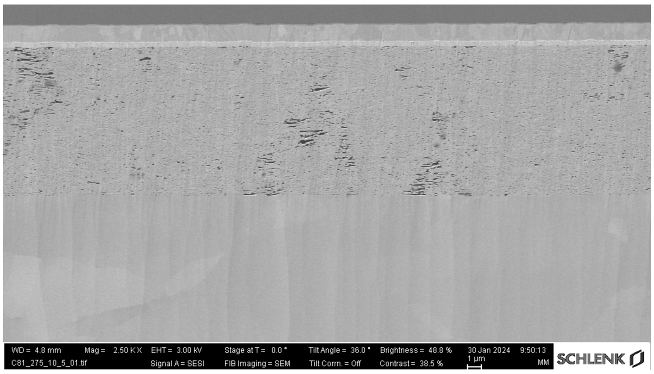

Figure 3 – SEM analysis of the sintered interconnect after sintering at 275°C for 3min with 10MPa bonding pressure using a AMX P100 sinter press, showing a homogeneous sinter microstructure.

The sintered interconnects are also put through very reliability tests. Ag metallized SiC devices are sintered onto Ag metallized AMB substrates. Under a non-encapsulated condition, the sintered interconnects are subjected to the harsh thermal shock conditions. A thermal shock profile of +175/-65°C with a dwell time of 30min (air-air, two chamber system) is performed. As can be seen from scanning acoustic microscopy analysis, no delamination is observed even after 1500 cycles (Figure 4). This is very good reliability, especially considering the fact that the samples were non-encapsulated. Therefore, the newly developed paste and the simple sinter process results in a sintered interconnect that ensures comparable reliability over state-of-the-art silver sintering solutions as has been detailed in previous publications [29].

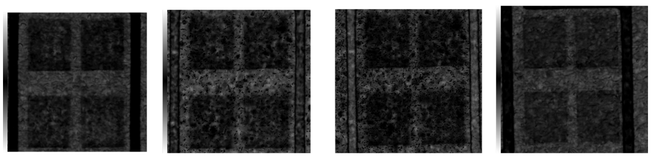

Figure 4 - SAM backside scans of samples through TST showing zero delamination after 1500 cycles under test conditions of +175/-65°C. SiC devices with Ag end metallization were sintered onto Si_3N_4 based AMBs with Ag plating.

5 Substrate-attach

Large area sintering is critical for reliable module attach. Ag sintering for package attach has shown robust performance and reliability [30]. However, very few studies are available that show the performance of such interconnects when the sintering temperature is lowered to < 220°C at the interconnect. Recent publications concentrating on the feasibility of Cu sintering for large area sintering, including performance under high stress conditions [31], still relied on high sintering temperature. Si_3N_4 based AMBs from Rogers Curamik were sintered onto 5mm Cu baseplates. Crack propagation and delamination was limited to <5% even after 1000 cycles under harsh testing conditions of +200/-40°C as can be seen from SAM analysis shown in Figure 5.

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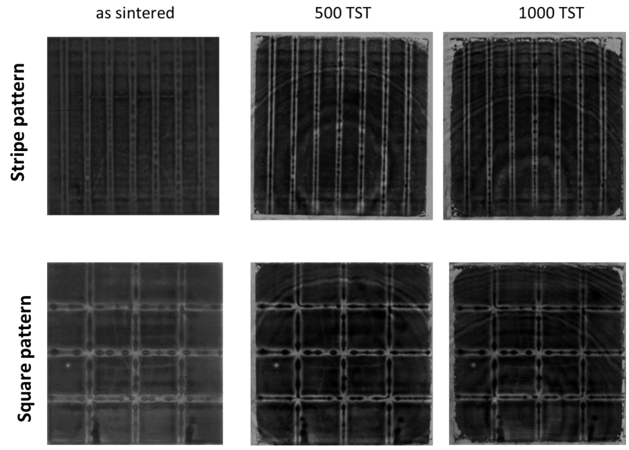

Figure 5 – Backside SAM analysis of the sintered interconnects of Cuprum 80 sinter paste after 1000 TST under +200/-40°C, showing negligible delaminations.

SEM analysis of the sintered microstructure (Figure 6) shows a uniform and homogeneous sintered microstructure with well defined porosity. This material innovation of porosity engineered into the interconnect allows for excellent thermo-mechanical stress relaxation even under high stress conditions. Thereby the fatigue resistance and reliability of the sintered interconnect are improved. The preliminary studies thereby showed the feasibility of Cu sintered interconnects for large area sintering.

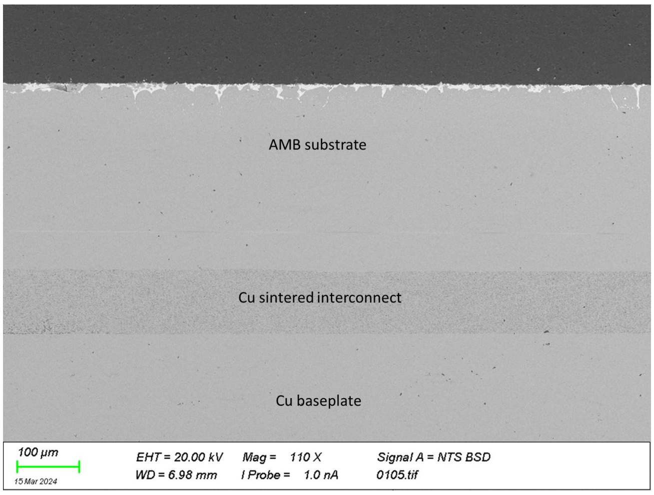

Figure 6 – SEM analysis of the sintered interconnect sintered at 275°C for 5min with 10MPa using budatec SP300 sinter press, showing a uniform and dense sintered microstructure.

5.1 Low temperature & low-pressure sintering

However, unlike die-attach bonding where higher sintering temperature, i.e. 250-275°C might still be acceptable, the glass transition temperature of the mold compound is a limitation when working with large area sintering. Therefore, the top tool temperature in a sintering press can be set to a maximum of 180°C and not more and similarly the bottom tool temperature to 240°C and not more. The applied pressure can also not exceed 15MPa.

Therefore, a novel paste is developed which allows for sintering precisely under the limitation mentioned above, while still working with microscale particles. Precise understanding of oxidation of the particles and the interaction between the organics and the microscale particles, including specific surface modifications on the particles help in a residue-free sinter process. As can be seen from Figure 7, a dense and homogeneous interconnect can be clearly observed in the SAM analysis with no delamination or high porosity. Similar results were also observed while sintering under vacuum as shown by the SEM microstructure in Figure 8 and the SAM analysis of large ceramic substrates sintered in an inert atmosphere (Figure 9).

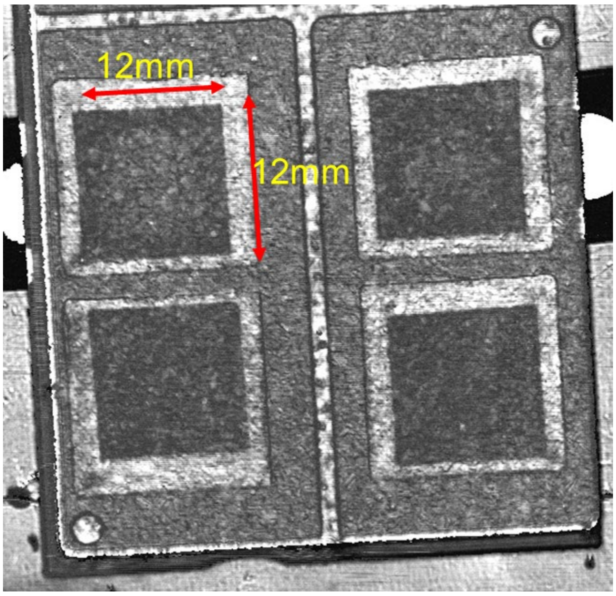

Figure 7 – SAM analysis of dummy Si test chips sintered onto test AMB substrates using the soft tool of the PINK SIN 20 sinter press with a top tool temperature of 180°C and bottom tool at 230°C for 10min with 15MPa bonding pressure.

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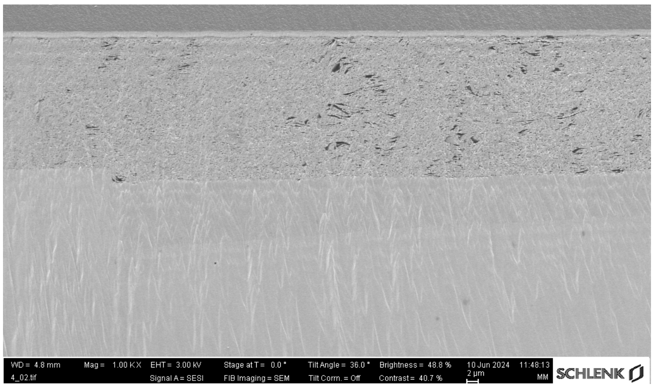

Figure 8 – SEM analysis of the sintered interconnect of Cuprum 85 sintered using the ASMPT Silver SAM. Sintering under vacuum of 0.1mbar, at 230°C for 5min with 10MPa bonding pressure.

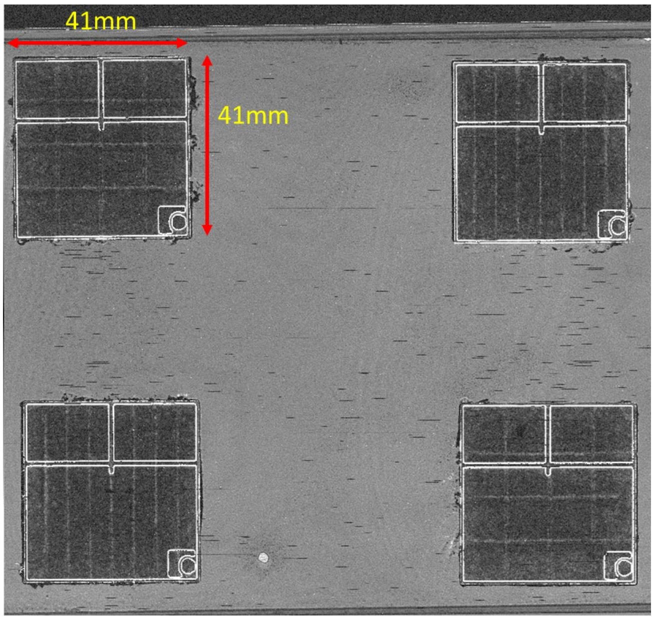

Figure 9 – SAM analysis of Si_3N_4 based AMBs from Rogers Curamik sintered onto Cu baseplate using a Budatec SP300 sinter press.

Therefore, the new development of the pastes, allows for low-temperature and low-pressure sintering with a top tool temperature limited to a maximum of 180°C and bottom tool to 230°C and a sintering time of maximum 10min and sintering pressure of at most 15 MPa. The pastes continue to be room temperature storable, capable of drying in air for < 15 min, even for large printed thicknesses of ~400µm. Furthermore, wet placement is not necessary and the pastes allow for semi-dry or dry placement with sufficient tack to hold even the large components in place. Reliability analysis of the interconnects are ongoing, where the first TST results following the AQG324 norms for molded packages on Al coolers with pin-fin structures, show very promising results, with delamination limited to under 10% and thermal conductivity of the material of 220 W/mK.

6 Conclusions

Novel Cu sinter paste formulations with substantially simplified sintering processes and their reliability and performance are presented. A dense and homogeneous sintered interconnect with porosity < 10% can be obtained with sintering at 275°C with just 10MPa bonding pressure and sintering time of 3 min for die-attach application and sintering with 180°C top tool and 230°C bottom tool temperature for 10 min and 10MPa for large area interconnects.

The Cu sinter pastes and processes are compatible with existing Ag sintering production lines and do not need additional process adaptations such as reducing pre-drying and/or sintering atmosphere, high sintering temperatures, long sintering times and/or high bonding pressure. Therefore, not only material costs but the process costs are substantially reduced and the process steps are simplified, especially storage, pre-drying and pick & place. With the new low temperature and low pressure sinterable pastes, an attractive and reliable low-cost alternative for large area interconnects is presented.

With the novel solutions and the material and process savings, Cu sintering is advantageous for the reduced total cost of ownership over state-of-the-art Ag sintering.

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