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Exploring Pressureless Nano-Copper Sintering for Power Chip Interconnection

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Abstract

This study explores the potential of pressureless nano-copper sintering for power chip interconnections. As electronics evolve towards miniaturization and higher power density, traditional interconnection materials such as nano-silver, despite their excellent thermal and electrical properties, face challenges like high cost and susceptibility to electromigration. Nano-copper, with comparable electrical conductivity and superior thermal performance at a lower cost, emerges as a promising alternative. The study examines the impact of sintering atmosphere and temperature on shear strength. Results show that nitrogen-protected environments significantly enhance bonding by preventing oxidation, while samples sintered in air exhibit minimal strength due to surface oxidation. Additionally, sintering at 230°C provides stronger bonds compared to 200°C, indicating improved diffusion and bonding at higher temperatures. SEM analysis of samples sintered at 300°C demonstrates optimal bonding, with minimal voids, making 300 ° C an ideal sintering temperature for reliable power chip packaging using nano-copper.

Introduction

As electronic components continue to evolve toward miniaturization, integration, and high performance, the demand for interconnect materials in medium and high-power chips is steadily increasing. In this context, nano-metal sintering technology[1-3], particularly for its excellent thermal conductivity, electrical conductivity, and high-temperature reliability, has emerged as a critical process in chip interconnection[4-6], gaining widespread attention. Among these, nano-silver sintering technology has shown remarkable performance in semiconductor packaging, radio frequency chips, and power chips, especially for handling high heat flux and high-frequency operating conditions in electronic devices.

Despite the excellent thermal and electrical properties of pressureless sintered nano-silver, its high cost and susceptibility to electromigration have limited its broader application[7]. As a precious metal, silver's price fluctuates significantly, hindering its feasibility for large-scale industrial adoption. Furthermore, electromigration leads to performance degradation under prolonged high current densities, posing a significant limitation for power electronic devices requiring high reliability.

To address these challenges, researchers have increasingly focused on copper[8][9], particularly pressureless nano-sintered copper technology. Compared to silver, copper offers a significant cost advantage, as it is abundant and relatively stable in price. Additionally, copper's electrical conductivity is close to that of silver, while its thermal conductivity is even superior. More importantly, copper exhibits much higher resistance to electromigration than silver, making nano-copper an ideal candidate for high-power chip packaging applications.

Although nano-copper typically requires higher sintering temperatures, advances in surface modification techniques and the development of novel sintering additives have significantly improved pressureless nano-sintered copper technology, reducing the sintering temperature and enhancing its feasibility in practical applications. For instance, surface modification of nano-copper particles can effectively lower the activation energy required for sintering, enabling efficient sintering at lower temperatures, thereby meeting the thermal constraints of packaging processes.

Moreover, pressureless nano-sintered copper technology demonstrates clear advantages in environmental sustainability. Copper is abundant and easily recyclable, and compared to silver, it entails lower environmental costs, aligning well with current industrial demands for greener, more sustainable solutions.

Overall, pressureless nano-sintered copper technology, with its low cost, superior performance, and environmentally friendly characteristics, is gradually becoming the preferred solution for power chip packaging. Although challenges remain, such as further reducing the sintering temperature and improving interface bonding strength, ongoing research is expected to drive the widespread adoption of pressureless nano-sintered copper technology in the field of electronic packaging.

Method

In this experiment, we used dummy substrates (with a silver plating thickness of 1 μm) and dummy chips with dimensions of 3×3×1 mm and a silver plating thickness of 1 μm. First, we investigated the effect of different sintering atmospheres (nitrogen and air environments) on the shear strength between the chip and substrate after pressureless copper sintering. After determining the appropriate sintering atmosphere, we further studied the effect of different sintering temperatures on the shear strength between the chip and substrate after pressureless copper sintering. Once the optimal sintering temperature was identified, we conducted an in-depth characterization of the sintered fracture surface and cross-section, followed by a mechanistic analysis of the related phenomena.

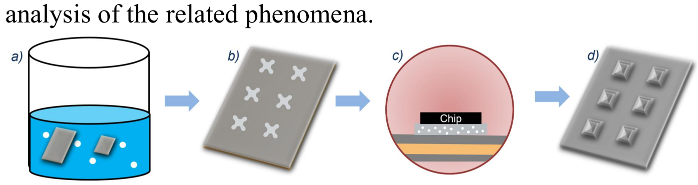

Fig. 1. The process of pressureless nano-copper sintering. a) Cleaning; b) Dispensing; c) Pressureless sintering; d) Pressureless sintered Sample

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Before being used, the dummy chips and substrates need to be cleaned in an ultrasonic cleaner to remove surface oil and other contaminants. The solvent used for cleaning is anhydrous ethanol, and the cleaning time is 30 minutes (Fig. 1(a)). After thorough cleaning, the materials should be removed, dried with a nitrogen gun, and wiped clean with a lint-free cloth for later use. Next, adhesive dispensing needs to be performed on the clean dummy substrate (Fig. 1(b)), and the dispensing amount should be adjusted according to the size of the chip (typically, the dispensing volume can be adjusted indirectly by controlling the air pressure and dispensing time). After dispensing, to ensure full contact between the chip and the pressureless copper paste, a vertical force must be manually applied to the surface of the dummy chip. In this experiment, a force of 20g was applied. Subsequently, the sample is placed in a chamber where protective gas can be introduced, and the temperature profile can be programmed for the sintering step (Fig. 1(c)). After the sintering process is completed, the pressureless copper sintered sample is obtained (Fig. 1(d)).

Experimental Process and Results

Firstly, we verified the effect of different sintering temperatures on shear strength. In the experiment, the temperature profile (Fig. 2) was set as follows: the chamber temperature of the oven was heated to 160°C over a period of 60 minutes, then held at that temperature for 45 minutes. Afterward, the temperature was increased to 200°C (or 230°C) within 15 minutes, and once it returned to room temperature, the shear strength of the sample was tested using a pull-push tester (Dage 4000). By comparing the shear strength of the samples sintered at these two temperatures, the optimal sintering temperature was determined.

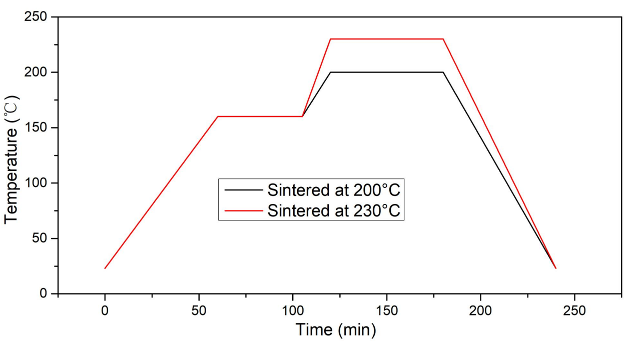

Fig. 2. Diagram of different sintering curves

The shear strength results demonstrate a clear difference in the mechanical performance between samples sintered at 200°C and those sintered at 230°C. Specifically, the samples sintered at 230°C consistently exhibit significantly higher shear strength values, ranging from 35 to 38 MPa, across all five samples. In contrast, the shear strength of the samples sintered at 200°C remains consistently low, with values varying between 2 to 5 MPa.

This significant disparity indicates that the higher sintering temperature of 230°C leads to a much stronger bond formation between the dummy chip and the substrate. The nearly uniform shear strength values observed at 230°C across the samples suggest that the sintering process is both reliable and repeatable, providing consistent mechanical strength in the copper-sintered joints. On the other hand, the samples sintered at 200°C not only exhibit much weaker bonding but also show greater variability in shear strength, highlighting that the lower temperature is insufficient for achieving the desired mechanical properties in the pressureless copper sintering process.

The consistently higher shear strength at 230°C implies that this temperature promotes better diffusion and bonding at the interface between the copper particles and the substrate, likely leading to improved densification and fewer defects. Conversely, the low shear strength at 200°C suggests that this temperature does not provide enough energy for adequate sintering, resulting in weaker bonding and a less cohesive joint.

In conclusion, the experimental results clearly favor 230°C as the optimal sintering temperature for achieving strong and reliable bonds in pressureless copper sintering. This temperature ensures a significant improvement in shear strength, with more consistent results, making it a preferred choice for applications where mechanical strength is critical.

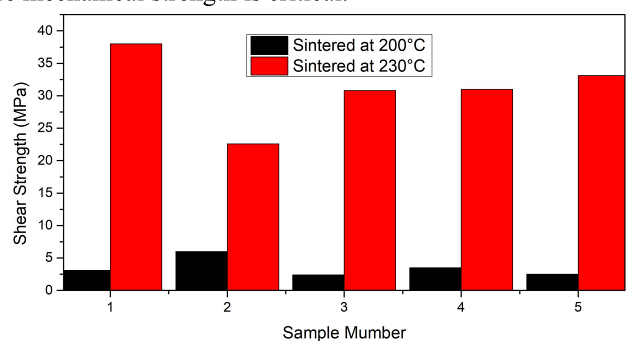

Fig. 3. Shear strength results of samples sintered at 200°C and 230°C

In the subsequent experimental study, we explored the effect of the sintering atmosphere on the shear strength of the samples. The specific experimental content included conducting pressureless copper sintering under nitrogen-protected and non-nitrogen-protected conditions, followed by a comparative analysis of the shear strength of the sintered samples. The experimental results showed that when sintering was performed without nitrogen protection, the shear strength of the samples was almost undetectable. This indicates that sintering in air likely leads to severe surface oxidation of the samples, which hinders the effective bonding between copper particles, preventing the formation of stable conductive or mechanical connections. The presence of this oxide layer not only impedes the diffusion and adhesion between copper particles but may also form fragile structures at the interface, significantly weakening the overall mechanical performance of the samples.

In contrast, when sintering was performed under a nitrogen protective atmosphere, oxidation was effectively prevented, allowing copper particles to fully diffuse and bond, forming a dense sintered structure that significantly enhanced the shear strength of the samples. Thus, nitrogen as a protective gas plays a crucial role in the pressureless copper sintering process. It not

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only ensures good metal bonding but also greatly improves the mechanical performance and reliability of the samples.

This research highlights the importance of controlling the atmosphere during the sintering process, particularly for materials like copper that are prone to oxidation. The use of a protective atmosphere is key to preventing the formation of an oxide layer, thereby ensuring the quality and strength of the sintered joints. This provides important guidance for future optimization of pressureless copper sintering technology and its application in fields such as electronic packaging.

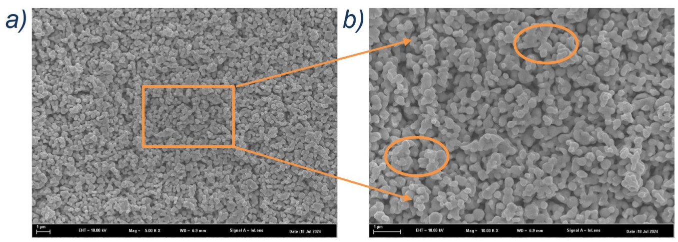

Fig. 4. a) Cross-sectional SEM image and b) its magnified local region

Next, to further analyze the reasons for the high shear strength of samples sintered at 300°C, we conducted SEM analysis of the cross-sections. Under the sintering condition of 300°C, the copper particles exhibited excellent bonding and diffusion behavior. As shown in Fig. 4(a), the overall surface structure appears uniform, with tightly distributed particles. This phenomenon indicates that at this temperature, stable diffusion connections have been formed between the copper particles. The localized region magnified in Fig. 4(b) shows the bonding interfaces between the particles, where clear neck formations can be observed. The presence of these necks suggests that diffusion during the sintering process was relatively sufficient, significantly reducing the voids between the particles. This tight bonding provides the sample with good mechanical stability, particularly in terms of shear strength, where the sintering temperature of 300°C can significantly enhance the material's load-bearing capacity.

In addition, the sintering temperature of 300°C provides the copper particles with sufficient kinetic energy, promoting surface atom diffusion and filling the voids between the particles. This solid-state diffusion is a critical step in the sintering process, with the formation and expansion of diffusion necks making the bonding between particles more solid. Although high-temperature sintering may cause some materials to experience excessive grain growth or oxidation, these risks are effectively avoided at 300°C. This means that this temperature not only ensures effective diffusion between the particles but also prevents adverse effects caused by excessive temperatures (such as oxidation and over-sintering), resulting in a good microstructure.

The bonding interface in the images shows a small amount of microporosity, indicating that the sintering process is not yet fully densified, but these small voids do not significantly affect the overall mechanical properties of the structure. Under the conditions of 300°C, the sample has achieved sufficient density, and its shear strength is expected to be significantly enhanced. These small voids may be related to localized insufficient diffusion, but overall, the diffusion bonding between particles is very complete, suggesting that the sintering performance at this temperature provides excellent mechanical strength and electrical properties.

In summary, the sintering conditions at 300°C provide an ideal diffusion environment for copper particles, allowing them to form a dense structure. Compared to sintering at higher temperatures, 300°C ensures densification while avoiding problems like excessive grain growth or surface oxidation caused by higher temperatures, making it an ideal sintering temperature. Observing the quality of the microstructure and bonding interfaces, it can be predicted that samples sintered at this temperature will exhibit excellent mechanical properties, such as high shear strength and good fatigue resistance. These characteristics make 300°C a highly recommended temperature choice in pressureless copper sintering processes.

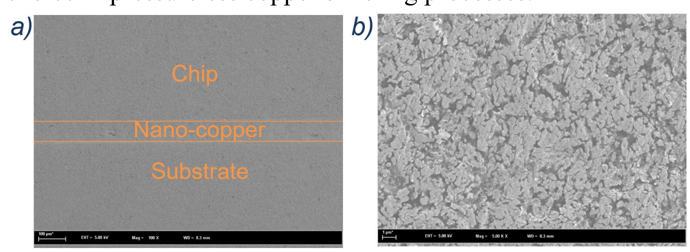

Fig. 5. Cross-sectional SEM image of a) sandwich structure of the sintered body and b) a copper layer in the middle

From the SEM cross-sectional images of the sample, Fig. 5(a) shows the overall cross-sectional structure of the chip, nano-copper, and substrate, while Fig. 5(b) is a magnified view of the sintered region. These two images demonstrate the bonding interface and microstructure formed by the nano-copper layer between the chip and substrate under the sintering condition of 300°C.

Fig. 5(a) shows three distinct regions: the chip, nano-copper, and substrate. The nano-copper layer is clearly filled between the chip and the substrate, indicating that at the sintering temperature of 300°C, copper particles were able to diffuse and bond sufficiently, forming a uniform bonding layer. This uniform bonding is crucial for enhancing the overall mechanical properties and electrical conductivity. Additionally, the thickness of the copper layer is appropriate, suggesting that the sintering process was well-controlled, and the copper particles adequately diffused and bonded within a certain range.

Then, Fig. 5(b) presents a magnified view of the nano-copper region, where the microscopic bonding structure between particles can be observed. In this image, the interfaces between the copper particles become increasingly indistinct, indicating that sufficient diffusion occurred between the particles, resulting in a tightly bonded interface. The formation of diffusion necks further confirms the good diffusion behavior of copper particles at this temperature. Although the sintering results are good, a small amount of porosity can still be seen, possibly due to localized insufficient diffusion or gas release. However, these

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pores do not significantly affect the mechanical properties of the overall structure, as the tightly bonded copper particles still provide high mechanical strength.

From the perspective of the sintering mechanism, the sintering temperature of 300°C provided the copper particles with sufficient kinetic energy, allowing surface atoms to cross particle interfaces and form diffusion necks. As sintering time increased, these diffusion necks gradually expanded, ultimately forming a dense structure. Meanwhile, the moderate temperature avoided problems such as grain growth and surface oxidation, maintaining a good microstructure, which further enhanced the bonding strength of the copper layer.

The microstructure also shows that, despite the presence of minor porosity, the overall bonding quality of the nano-copper layer is high. This dense structure helps improve the shear strength of the sample, as the tightly bonded copper particles can effectively distribute external stress, preventing cracking or interface separation. Moreover, there are no noticeable defects at the interface between the nano-copper layer, the chip, and the substrate, ensuring the mechanical stability and long-term reliability of the interface.

So, the sintering condition of 300°C provided an ideal diffusion environment for the nano-copper particles, allowing them to form a dense bonding structure and uniform bonding layer. Despite the presence of minor porosity, the mechanical performance and stability of the overall structure remain high, particularly with a significant improvement in shear strength. Therefore, 300°C is considered an optimal temperature for achieving excellent sintering results of the nano-copper layer, ensuring a strong connection between the chip and the substrate, as well as high mechanical strength and reliability.

Conclusions

In this study, pressureless nano-copper sintering was evaluated as a promising alternative for power chip interconnections. The results demonstrate that sintering conditions, particularly atmosphere and temperature, play a critical role in determining the mechanical strength of the sintered joints. The use of a nitrogen-protected atmosphere was essential in preventing oxidation, which severely compromised the shear strength in air-sintered samples. Additionally, the findings indicate that higher sintering temperatures, such as 230°C, significantly enhance particle diffusion and bonding compared to lower temperatures. Further investigation at 300°C revealed even stronger bonding, with well-formed particle interfaces and minimal porosity, confirming it as an optimal temperature for achieving reliable, high-strength connections. The study highlights the importance of optimizing sintering conditions to maximize the performance of nano-copper as an interconnection material. This research paves the way for further advancements in power electronics packaging, where cost-effective and thermally stable materials are increasingly in demand.

Acknowledgments

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