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The Application of Low-temperature Copper Sintering in Power Devices of New Energy Vehicles

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Abstract:
With the growing demand for high-reliability, lead-free interconnection materials in power devices for new energy vehicles and related fields, copper particle sintering has emerged as a viable solution. This study presents a systematic analysis of copper sintering technologies at the micro, nano, and bimodal scales. Micro-copper particles provide economic advantages and mechanical stability but require high-temperature processing and specific atmospheric conditions, which limit their energy efficiency. Nano-copper particles, by contrast, offer superior low-temperature sintering due to their high surface energy and uniform morphology. However, they face challenges such as oxidation, high synthesis costs, and limited industrial validation. Bimodal copper systems, combining micro- and nano-sized particles, strike a functional balance by reducing sintering temperature and enhancing bonding strength while maintaining reasonable cost and structural integrity. Despite their potential, issues related to mixing uniformity and oxidation control remain unresolved. The paper concludes that although each copper system presents distinct benefits, no single approach fully meets all practical demands. Future development should prioritize the integration of particle design, atmosphere-independent sintering, and performance optimization to support scalable, cost-effective applications in power electronic packaging.

Keywords: Cu sintering, micro-Cu, nano-Cu, bimodal-Cu

1. Introduction

With the increasing popularization of new energy vehicles, large-scale construction of 5G base stations, and rising performance demands for the power units of high-speed rail trains, power devices, serving as their core components, are experiencing growing market demand. Under the imperative for energy

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conservation and resource saving, metal plates are employed as the mold material for these power units. Surface Mount Technology (SMT) packaging stands as one of the most prevalent interconnection technologies within power electronics packaging[1]. However, the high-temperature solders utilized in conventional SMT, encompassing both high-lead solders and lead-free alloy solders (such as gold, bismuth, and zinc-based alloys), face significant challenges including toxicity, high cost, low thermal conductivity, and poor corrosion resistance. Crucially, the most commonly used tin-based lead-free solder cannot satisfy operational requirements exceeding 250 °C due to remelting issues. Consequently, there is a pressing need to develop novel lead-free interconnection materials to meet the packaging technology demands of next-generation power devices. In recent years, metal particle sintering materials have attracted considerable attention in the field of power device packaging owing to their high reliability and excellent thermal dissipation properties. High-temperature resistant soldering materials, such as low-temperature sintering materials, are anticipated to become viable substitutes for traditional soldering filler metals.

Nanoparticles possess higher surface energy compared to their bulk counterparts, enabling their sintering temperature to be reduced to levels comparable to that of conventional solder. As a result, sintered joints formed from metal nanoparticles with melting points exceeding those of solders have consistently garnered significant interest. Utilizing pure metal nanoparticles for these joints can potentially overcome problems associated with intermetallic compounds (IMCs). Silver nanoparticles find widespread application as conductive materials due to their low resistivity and high stability. Additionally, their relative resistance to oxidation in air facilitates storage and sintering under ambient conditions [2]. Nevertheless, drawbacks include the high cost of raw materials and difficulties in ensuring long-term reliability due to susceptibility to ion migration. These limitations have spurred research into alternative metal nanoparticles as potential replacements for silver NPs.

To address the constraints of silver nanoparticles, researchers have undertaken studies focusing on copper [3]. Copper presents distinct advantages: not only does it possess a high melting point, excellent thermal conductivity, and high electrical conductivity, but it is also relatively low-cost and exhibits strong resistance to ion migration[4]. Their investigations revealed that stabilizers composed of fatty acids and amines can decompose onto Cu nanoparticles in oxygen-free environments. It has been observed that certain metallic layers may exhibit favorable interactions with sintered copper-based materials, potentially contributing to improved interfacial bonding comparable to conventional joining methods. Moreover, they successfully synthesized copper nanoparticles (NPs) in an aqueous phase without organic ligands at room temperature and under atmospheric conditions, employing nickel salts during the reduction of leaf-shaped copper oxide particles.The synthesized copper nanoparticles generally fall within a particular size range, and it appears that particles of certain dimensions may facilitate sintering at relatively lower temperatures, possibly due to specific structural or surface characteristics. These nano-copper particles were subsequently applied to formulate nano-copper paste demonstrating low-temperature sintering capability. The resistivity of copper electrodes annealed from this paste reached 64 μΩ·cm and 27 μΩ·cm after treatment at 150 °C and 200 °C for 30 minutes, respectively. Importantly, bonding oxygen-free copper plates achieved a strength of 32 MPa following pressure-less sintering at 260°C for 30 minutes in a nitrogen atmosphere [5]. Advanced implementation of this developed copper nanoparticle manufacturing process offers a sustainable and low-CO_2-emission pathway for producing copper electrodes and achieving robust bonding on flexible films. However, a current limitation is the absence of a unified standard governing the particle size of copper sintering raw materials. Therefore, investigating the influence of copper particle size on sintering performance is critically necessary.

This essay analyzes the current landscape of copper sintering technologies, specifically micro-scale, nano-scale, and hybrid micro-nano approaches, and explores the impact of copper particles of varying sizes on the resultant properties. It systematically summarizes recent research progress domestically and internationally, analyzes prevailing challenges, and introduces and anticipates the future application of copper particle sintering technology within the electronic packaging domain. Simultaneously, it compares the advantages and disadvantages of these three primary methods, further aiming to contribute to the advancement and practical implementation of copper particle sintering technology. The expectation is to furnish valuable reference information to support more in-depth research and broader application of this technology.

2. Case

The sintering behavior of copper particles is fundamentally governed by their size distribution, with micron-scale (1–100 μm), nano-scale (<100 nm), and hybrid micro-nano systems each demonstrating unique sintering mechanisms and resulting material properties. Micron-scale copper particles exhibit relatively low surface energy and sinter primarily through conventional solid-state diffusion and grain boundary migration mechanisms. This leads to moderate densification with typical porosity levels of 10–20%, as the large particle size limits atomic mobility and leaves interconnected pore networks. While these systems provide adequate mechanical strength for many structural applications, their performance is constrained by residual porosity and coarse microstructures. From an economic standpoint, micron powders are highly favorable due to their low production costs and compatibility with standard powder metallurgy equipment, though their high sintering temperatures and prolonged processing times increase energy consumption.

In contrast, nano-scale copper particles possess dramatically higher surface energy, enabling densification through enhanced surface diffusion and plastic deformation at much lower temperatures (200–400°C). This results in near-theoretical density (<5% porosity) and exceptional mechanical strength due to ultra-fine grain structures. However, the benefits of nano-sintering are partially offset by challenges including rapid grain growth during sintering, agglomeration tendencies, and the high costs associated with nanoparticle synthesis and handling. Furthermore, the need for precisely controlled atmospheres (e.g., inert or reducing gases) to prevent oxidation adds to processing complexity and expense.

Hybrid micro-nano systems strategically combine the advantages of both size regimes by incorporating nanoparticles within a micron-particle matrix. The nanoparticles fill interparticle voids, improving packing density and enabling lower-temperature sintering compared to micron-only systems, while reducing the overall nanoparticle content to maintain cost efficiency. These systems typically achieve intermediate porosity (8–12%) and mechanical properties, as the nanoparticles enhance localized bonding without fully replicating the microstructural refinement of pure nano-sintered materials. Economically, hybrid sintering represents an optimal compromise, reducing energy consumption through lower processing temperatures while minimizing material costs by limiting nanoparticle usage. This makes hybrid systems particularly attractive for applications requiring a balance between performance and cost, such as electronics packaging or structural components. Ultimately, while nano-sintering provides the highest performance, its economic barriers restrict widespread adoption, whereas micron sintering remains limited by material properties. Hybrid sintering thus emerges as the most practical solution for industrial applications demanding both reliability and cost-effectiveness.

3. Analysis & challenge

3.1 Micro-Cu

Micro-Cu materials can be effectively fabricated through a controlled pre-oxidation and low-temperature sintering process[6]. Copper powder with an average particle size of approximately 1.5 μm was first pre-oxidized in air at 250 °C to generate a Cu_2O surface layer, enhancing surface reactivity. The treated powder was then mixed into a paste, screen-printed onto the substrate, and sintered under a formic acid atmosphere at 300 °C with 20 MPa pressure for 20 minutes. This process yielded a dense, well-bonded Cu–Cu interface with improved mechanical integrity [7]. The process is shown in Fig. 1.

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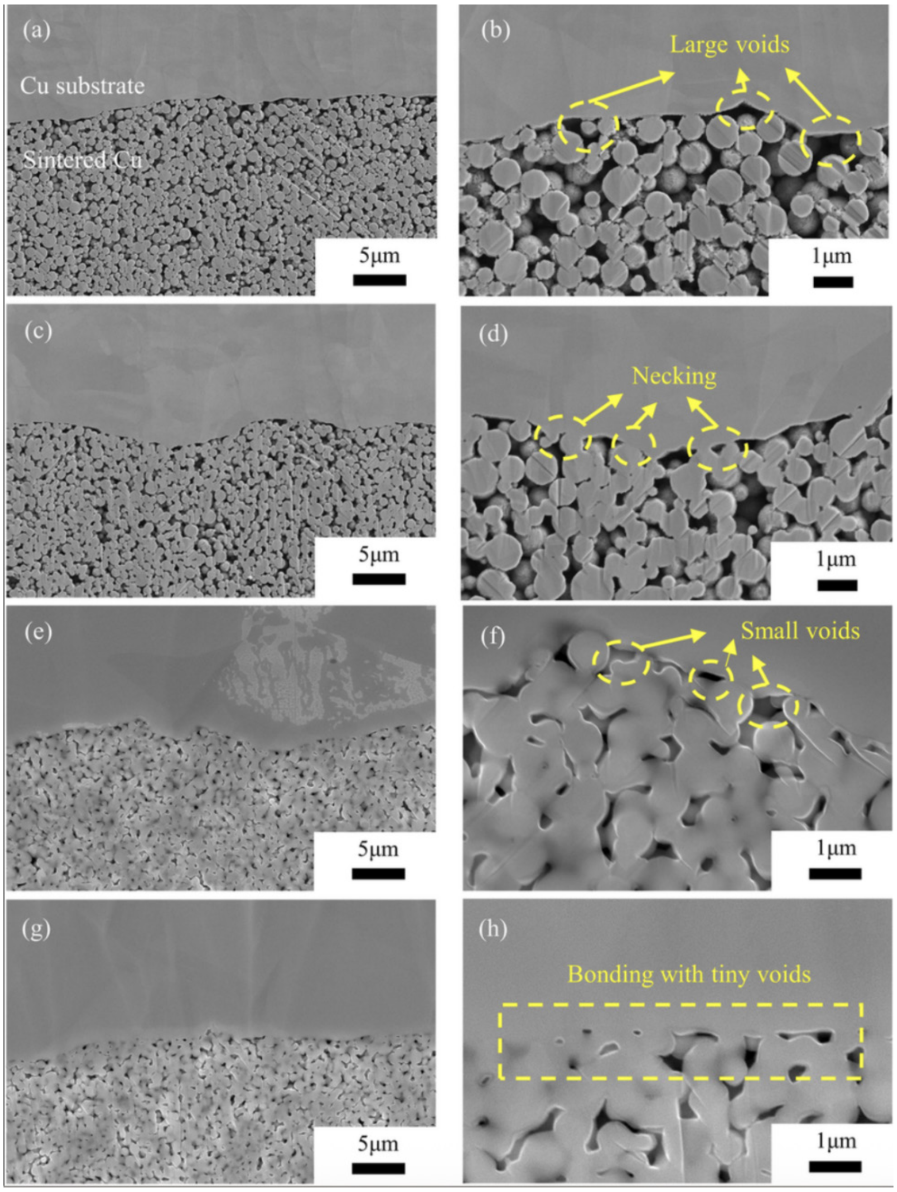

Fig. 1 SEM cross-sections of Cu nanoparticles sintered with Pt-catalyzed formic acid at a, b 180 °C 5 MPa; c, d 180 °C 20 MPa; e, f 250 °C 5 MPa; and g, h 250 °C 20 MPa for 15 min [7]

The Micro-Cu paste, which is prepared from 1.5 μm copper particles and processed under optimized conditions, exhibits excellent bonding performance. After sintering at 300 °C for 20 minutes under a 20 MPa pressure in a formic acid atmosphere, the Cu–Cu joints achieved an average shear strength of 131 MPa, significantly higher than conventional solder joints. Cross-sectional SEM images revealed a dense and continuous bonded interface with minimal voids or cracks, indicating high interfacial integrity. The resistivity of the sintered joints was measured at 8.2 μΩ·cm, which is close to bulk copper, suggesting good electrical conductivity. Thermogravimetric analysis (TGA) confirmed the stability of the oxide layer formed during pre-oxidation, which plays a key role in enhancing sintering activity. These results highlight the potential of Micro-Cu materials for reliable low-temperature bonding, offering a promising alternative to lead-free soldering in high-performance electronic packaging applications.

However, a major drawback lies in their inherently high sintering temperatures and extended processing durations, which significantly increase energy consumption. The main drawback, is that micron copper powders require high sintering temperatures and long processing times. This is primarily due to their larger particle size, which slows down the atomic diffusion process required for strong Cu–Cu bonding. Unlike nanoscale particles, micron powders exhibit slower surface diffusion, requiring temperatures often exceeding 300 °C and long dwell times to achieve sufficient Cu–Cu bonding[6]. This not only raises operational energy costs but also limits their application in temperature-sensitive or energy-efficient manufacturing environments. Moreover, the need for prolonged thermal exposure can introduce additional challenges, such as grain growth or interfacial degradation. As a result, more energy is consumed, both in heating and in maintaining the high temperature over an extended time.This increases production cost and reduces environmental efficiency, especially when compared to nanoscale powders that sinter more readily at lower temperatures.

3.2 Nano-Cu

Nano-Cu particles were synthesized via a straightforward and environmentally friendly two-step chemical reduction method in aqueous solution [8]. Copper(II) chloride dihydrate ($CuCl_2 \cdot 2H_2O$) was used as the copper precursor. L-ascorbic acid acted as both a reducing agent and a mild capping agent, while polyvinylpyrrolidone (PVP) was added to stabilize the nanoparticles and prevent agglomeration. Sodium hydroxide (NaOH) was introduced to adjust the pH of the solution, facilitating the formation of metastable intermediate complexes. The reduction reaction proceeded under constant stirring at room temperature, ultimately yielding uniformly dispersed, nearly spherical copper nanoparticles with an average diameter of around 34 nm. The synthesized Nano-Cu displayed high purity, excellent dispersibility, and long-term colloidal stability (over one month without sedimentation). As shown in Fig.2, this method is notable for its simplicity, low cost, and absence of toxic reagents or high-temperature processing, making it suitable for scalable and green production of copper nanoparticles.

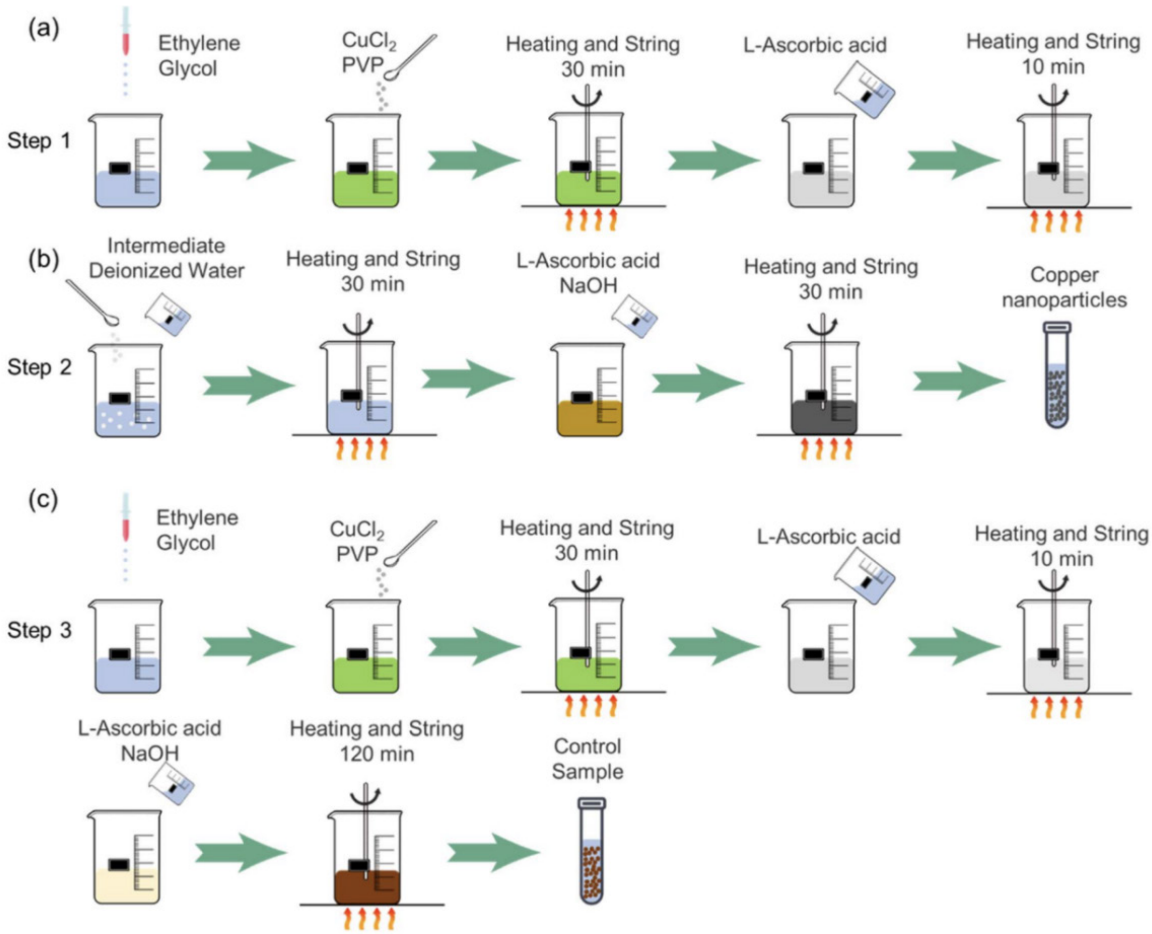

Fig. 2 Schematic diagram of copper nanoparticle synthesis method of (a) Step 1; (b) Step 2 and (c) Step 3 [8]

One of the most significant advantages of nano-sized copper (nano-Cu) particles is their high chemical reactivity, which makes them highly attractive for advanced electronic packaging and interconnection applications. As demonstrated by Lu et al., the unique surface characteristics of nano-Cu, including a high surface-area-to-volume ratio and enhanced surface energy, promote rapid diffusion and bonding even at temperatures below 200 °C. In their

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study, Lu et al. developed a simple and scalable method for synthesizing copper nanoparticles from metastable intermediates, yielding highly pure and uniform particles. These nano-Cu particles exhibited superior thermal and chemical reactivity, which are crucial for achieving strong Cu–Cu bonding under mild processing conditions. This low-temperature sintering behavior not only reduces overall energy consumption but also enables integration with temperature-sensitive substrates such as polymers or flexible circuits. Therefore, the outstanding low-temperature processability of nano-Cu, enabled by its nanoscale features and reactive surfaces, stands out as a key benefit in next-generation microelectronic and flexible device manufacturing [8].

The most critical drawback of Nano-Cu,, is its extreme tendency to oxidize, especially during storage and handling. The high surface area-to-volume ratio of copper nanoparticles makes them thermodynamically unstable in ambient conditions, leading to rapid formation of Cu_2O or CuO surface layers. This oxidation significantly reduces the particles' sintering activity and electrical conductivity, which undermines their performance in electronic applications. Even short-term air exposure caused measurable oxidation in Cu NPs, affecting interfacial bonding quality in printed electronics. Oxidation can also lead to agglomeration and loss of uniformity in nanoparticle dispersions, further degrading reliability and consistency in device fabrication. This oxidation issue remains the primary bottleneck preventing the broader commercial application of Nano-Cu materials, especially in environments where long-term storage or thermal cycling is involved.

3.3 Bimodal-Cu

Bimodal Cu paste was prepared by combining micro-sized Cu particles (typically 1–5 μm) with nano-sized Cu particles (20–100 nm) to achieve a denser packing structure and enhanced sintering performance.[9] The Cu particles were mixed in specific weight ratios, often around 7:3 (micro:nano), using a three-roll mill to ensure uniform dispersion. Organic solvents, binders, and in some cases reducing agents were added to form a printable paste. The paste was screen-printed onto substrates and sintered under a reducing or inert atmosphere at temperatures ranging from 250 °C to 300 °C. This approach leverages the high surface reactivity of nano-Cu for neck formation and the volume stability of micro-Cu for mechanical strength and shrinkage control.

In the review by Tamura et al., Bimodal-Cu sintering materials, composed of a mixture of micro- and nano-sized copper particles, demonstrated superior performance in both mechanical and electrical aspects [9]. By optimizing the micro\:nano Cu ratio (typically 7:3 by weight), the resulting sintered joints exhibited a high shear strength of up to 125 MPa after sintering at 275 °C for 20 minutes under a pressure of 10–20 MPa. [9] SEM analysis showed a well-packed microstructure, where nano-Cu particles filled the interstitial spaces between micro-Cu particles, forming robust necks and minimizing porosity. The electrical resistivity of the sintered bimodal structure was reported as low as 7.8 μΩ·cm, approaching that of bulk copper. Moreover, thermal cycling and humidity tests revealed that bimodal Cu joints retained over 90% of their mechanical strength after 1000 cycles, indicating excellent reliability. The bimodal approach effectively combines the sinterability of nano-Cu with the volume stability of micro-Cu, reducing overall shrinkage and void formation, thus making it a promising candidate for next-generation high-performance, lead-free interconnect materials.

The main drawback of Bimodal-Cu, is inhomogeneity in particle mixing and persistent oxidation issues that limit its performance[10]. Even with careful blending of micro- and nano-sized particles, achieving uniform dispersion throughout the paste remains difficult; this can lead to regions of high porosity or uneven neck growth in the sintered material, undermining mechanical strength and conductivity. Moreover, copper's inherent tendency to oxidize during mixing, printing, or sintering continues to be a major concern. For instance, oxidation and void formation in bimodal Cu pastes significantly hamper the uniformity of die-attach layers and suppress interparticle bonding. In a similar vein, ACS research has shown that even nanoscale Cu particles exist in mixed oxidation states—ranging from metallic Cu to Cu_2O and CuO—which exacerbates the problem and leads to inconsistent overall performance. In summary, despite its strengths in combining micro- and nano-scale advantages, Bimodal-Cu still suffers from reproducibility issues and degradation due to oxidation—issues that must be resolved before it can be considered a practical, high-reliability alternative in power electronics.

4. Summary and suggestion

Micro-copper materials continue to be widely utilized in interconnection technologies because of their high sintering strength, fast densification behavior, and compatibility with standard powder metallurgy techniques. Their relatively large particle size facilitates easier handling and reduces production costs, while enabling effective sintering when exposed to controlled atmospheres such as formic acid or hydrogen. When processed under optimized conditions, including pre-oxidation followed by low-temperature, pressure-assisted sintering, micro-Cu systems are capable of forming dense, well-adhered Cu–Cu interfaces with favorable electrical and mechanical properties. However, these positive outcomes are highly sensitive to the sintering environment, which can introduce variability and limit scalability in industrial settings. Additionally, although the short-term bonding performance of micro-Cu is well documented, its long-term reliability under thermal cycling, oxidation, and mechanical stress remains uncertain. To address these limitations, future research should explore alternative sintering atmospheres that are more stable and cost-effective, and less dependent on narrow process conditions. Furthermore, extended reliability testing and aging studies under simulated service environments are necessary to confirm long-term performance. Lowering sintering parameters without compromising bond quality could also expand micro-Cu's applicability in electronics manufacturing, particularly in high-volume or thermally sensitive applications.

Nano-copper has attracted significant interest due to its high surface energy and excellent reactivity, which allow sintering to occur at much lower temperatures and pressures compared to traditional micro-Cu powders. Its synthesis is generally straightforward and, in many cases, environmentally friendly, offering fine control over particle size and shape. Moreover, the resulting nanoparticles typically exhibit excellent dispersion and colloidal stability, making them highly suitable for use in printed electronics, flexible circuitry, and other low-temperature applications. However, the practical deployment of nano-Cu still faces considerable challenges. The high production cost of nanoparticles remains a major barrier, particularly for large-scale implementation. More importantly, the functional properties of nano-Cu, such as electrical conductivity, oxidation resistance, and reliability under operating conditions, have not been adequately tested or confirmed. In addition, the same high surface energy that enhances sintering can also lead to agglomeration and premature oxidation, which may compromise performance. Therefore, future work should focus on comprehensive evaluation of sintered nano-Cu films under real-world stress conditions, including thermal, mechanical, and chemical environments. Efforts to develop protective coatings, core–shell structures, and flux additives could further improve nano-Cu's stability and reliability in industrial applications.

Bimodal-copper systems, which combine both micron-sized and nano-sized copper particles, offer a promising balance between the mechanical strength found in micro-Cu and the high reactivity characteristic of nano-Cu. This combination enables sintering at moderate temperatures and pressures, potentially reducing processing energy requirements while maintaining structural integrity. The presence of nano-Cu accelerates densification, while the larger particles help preserve mechanical stability and reduce the risk of surface oxidation. As a result, this dual-particle approach shows potential for applications that require low-temperature, low-pressure sintering, such as flexible electronics and compact device packaging. Nevertheless, current research on bimodal Cu remains largely qualitative, with limited empirical studies that examine sintering kinetics, interface morphology, and long-term performance. Additionally, the blending process introduces further complexity, as the ratio of nano to micro particles must be carefully optimized to ensure uniform packing and bonding. Future research should prioritize quantitative analysis using advanced imaging techniques and thermal analysis, in order to better understand interface evolution and diffusion behavior. Computational simulations could also aid in optimizing the mixture design. Through systematic experimentation and careful process refinement, bimodal Cu can be developed into a scalable and reliable interconnection material.

Micro-Cu, nano-Cu, and bimodal-Cu each offer distinct advantages suited to different application scenarios, although they also exhibit specific limitations that require further research. Micro-Cu is low-cost and structurally robust, but it relies heavily on specialized sintering environments and lacks long-term performance validation. Nano-Cu supports low-temperature processing and stable dispersion, but it remains costly and lacks comprehensive functional testing. Bimodal-Cu provides a promising middle ground by combining strength and reactivity, yet it requires improved control over formulation and deeper empirical study. Moving forward, the development of copper-based interconnects will benefit from a combination of materials design, process innovation, and cross-disciplinary collaboration. Researchers should focus on long-term reliability evaluation, optimization of sintering conditions that are independent of specialized atmospheres, and the establishment of performance benchmarks across material types. Integrating computational modeling with in situ experimental characterization will be essential to accelerate progress. Ultimately, these efforts will support the advancement of high-performance, energy-efficient, and scalable copper interconnection technologies for future electronic systems.

5. Conclusion

This study presents a comprehensive evaluation of copper particle sintering technologies across three particle size regimes, micro, nano, and bimodaL, in the context of high-reliability interconnection for power electronic devices in new energy vehicles and related systems. The analysis reveals that micro-copper materials, while

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offering advantages such as strong mechanical integrity, low material cost, and compatibility with existing powder metallurgy processes, are constrained by their need for high sintering temperatures and specific atmospheric conditions. These requirements result in elevated energy consumption and reduced suitability for thermally sensitive packaging applications. Moreover, the long-term stability and structural reliability of micro-Cu joints under conditions such as thermal cycling and oxidation remain insufficiently validated, indicating the need for continued research into more adaptable sintering environments and extended performance testing.

On the other hand, nano-copper materials demonstrate exceptional sinterability at significantly lower temperatures, owing to their high surface energy and small particle size, which promote rapid atomic diffusion and dense microstructure formation. This makes nano-Cu especially suitable for next-generation flexible electronics and miniaturized assemblies. However, this approach also faces serious challenges, particularly regarding its high production cost, vulnerability to oxidation during storage and processing, and limited industrial-scale validation. To bridge this gap, further efforts should focus on enhancing oxidation resistance through surface modifications, improving storage stability, and conducting real-condition reliability assessments. Meanwhile, bimodal copper systems, which integrate both micron- and nano-sized particles, offer a promising balance. The smaller particles enhance densification and interfacial bonding, while the larger ones contribute mechanical stability and reduce oxidation sensitivity. These systems allow moderate sintering temperatures and lower nanoparticle usage, providing an effective compromise between performance and cost. Nonetheless, issues such as poor dispersion uniformity, persistent oxidation, and lack of standardized process control still limit their widespread adoption.

In conclusion, while each copper sintering approach offers distinct strengths aligned with specific application demands, none currently satisfies all criteria required for universal implementation. Future development should prioritize atmosphere-independent sintering strategies, optimized particle size distributions, and long-term performance evaluation under operational conditions. Cross-disciplinary research integrating materials science, thermal processing, and electronic reliability testing will be key to advancing copper-based sintering technologies toward scalable, energy-efficient, and high-performance interconnection solutions.

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