In-air Cu sintering with Partial Encapsulation System for SiC Power Module

YehRi Kim, Eunjin Jo, and Dongjin Kim*
Korea Institute of Industrial Technology (KITECH)
156, Gaetbeol-ro (Songdo-dong), Yeonsu-gu,
Incheon Metropolitan City, 21999, KOREA
*Ph: +82-32-850-0159; *Fax: +82-38-850-0210
*Email: dongjinkim@kitech.re.kr

Abstract
This study was carried out to realize Cu sintering in the air atmosphere and investigate the driving force of oxidation-free Cu sintering. Cu sintered joints were successfully achieved at the temperature of 250 °C in the air with a uniform pressure below 10 MPa. A mechanism was applied in which oxygen was instantaneously blocked from the entire volume of the die-attach specimen during the sintering process. Consequently, we achieved bonding strengths exceeding approximately 36 MPa with a Cu particles size of 0.3 μm. In particular, it is interesting to note that no oxidation layer was observed at sintered bonding at 250 °C in the air atmosphere. The bonding strength was fundamentally attributed to the interfacial connected ratio between the Cu substrate and Cu sintered layer. This study systematically investigated the Cu-sintered joints structure involved in the size of Cu particles and the mechanism of bonding strength, considering the relationship between microstructures and mechanical behavior.

Key words
Cu sintering, double side power module, in-air atmosphere, mechanical strength, pressure bonding process

I. Introduction

Over the past decade, the growing necessity to reduce the greenhouse gas emissions have led to the rapid growth of the electric vehicles in automotive industry. This growth is accompanied by an increased demand for reliable and high-performance power electronics in the powertrains of electric vehicles. Such Si-based power semiconductor modules have been optimized over decades to satisfy the needs of industrial applications. However, the continually increasing demand for higher reliability, functionality, power density, and efficiency of electric vehicles which required improvements in power semiconductors and power conversion systems. Wide band-gap (WBG) semiconductors power devices such as silicon carbide (SiC) metal-oxide-semiconductor field effect transistors (MOSFETs) with exceptional physical and mechanical properties are particularly in high demand since Silicon (Si)-insulated gate bipolar transistor (IGBTs) encounter the limitation due to their inherent material properties [1]. The SiC semiconductors have emerged as promising candidates which offer significant improvement of the high- temperature operation (>250 °C), high thermal conductivity (> 400 W/mK), high blocking voltages, high switching frequencies, and low power dissipation resulting in higher power densities in a smaller size.

The dominance of SiC semiconductors in the automotive power module market from 2017 to 2019 has led the original equipment manufacturers (OEMs) to adopt the SiC semiconductor power module in the Tesla Model 3. Since the development of automotive-qualified SiC power modules has accelerated, new models with SiC power modules have been introduced. Automakers and industries are primarily focused on designing and packaging solutions with high efficiency and high reliability power module while reducing cost, resulting in the development of the SiC MOSFETs double-sided cooling (DSC) power modules [2]. The DSC power module can dissipate the heat through both sides of the power semiconductor device, improving heat transfer and reducing the effective thermal resistance. Namely, the DSC power module can provide advantages over single-sided cooled modules, including improved heat dissipation, enhanced electrical performance, reduced inductance, increased lifespan, and smaller packaging size. The Infineon launched the DSC power module HybridPACK and Denso introduced the power sandwich, providing a 33% reduction in junction thermal resistance, a 70% lower inductance, and a 40% higher power density [2]. However, the conventional

DSC power module was based on Si-IGBT. To respond to the development of a complete electrification vehicle, a SiC double-side cooling power module must be developed.

The SiC semiconductor power modules comprise several components, including terminals, a SiC die, a direct bonded copper (DBC) substrate, an interposer, and a heat sink. The packaging of the DSC power module requires attachment between a substrate and power devices (die-attach), power devices and interposer, and substrate to the heatsink. The properties of attachment material including the melting temperature, thermal conductivity, and electrical conductivity are important that these factors affect the performance degradation during thermal cycling. Currently, Cu sintering is emerging as a prominent die-attach technology for SiC DSC power modules due to its high thermal conductivity (i.e 400W/mK), high melting point(1083°C), thermal mechanical performance, and abundant material compared to Ag[3]. Furthermore, the key to determining bonding performance is the surface finish of the substrate, and the industry is paying attention to improve or simplify the process for mass production. The industry desired to commercialize the bare Cu substrate rather than metal-coated Cu substrate due to its cost and high adhesion with EMC molding [4].

The bonding performance of the bare Cu substrate to the Cu sinter joint exhibited a high shear strength compared to other metal-coated Cu substrates due to the same chemistry and lattice constant. Despite these advancements, the die-attach bonding process at a temperature exceeding 250 °C subjects the Cu to severe oxidation, which significantly degrades mechanical, thermal, and electrical properties. The easy oxidation of Cu in the air has been reported [5],[6]. In response, previous studies proposed the use of a reductive or protective sintering atmosphere to prevent the oxidation of Cu nanoparticles (NPs) [7],[8]. However, tier 1 electric component companies and automobile OEMs exhibit significant interest in enhancing price competitiveness and establishing a dependable structure through oxidation-free Cu sintering in an air atmosphere. To ensure practical implementation and proper production, it is necessary to comprehend the mechanism of Cu sintering in an air atmosphere and to investigate the driving force of oxidation-free Cu sintering. In this study, pressure-assisted Cu sintering was conducted at a temperature of 250 °C. Different size of Cu particle paste was examined to discern the potential driving force of Cu sintering based on the size of Cu particles. This study quantitatively analyzed to reveals the crystallographic behavior of Cu sintered joint structure involved in the size of Cu particles and the mechanism of bonding strength, considering the relationship between microstructures and mechanical behavior.

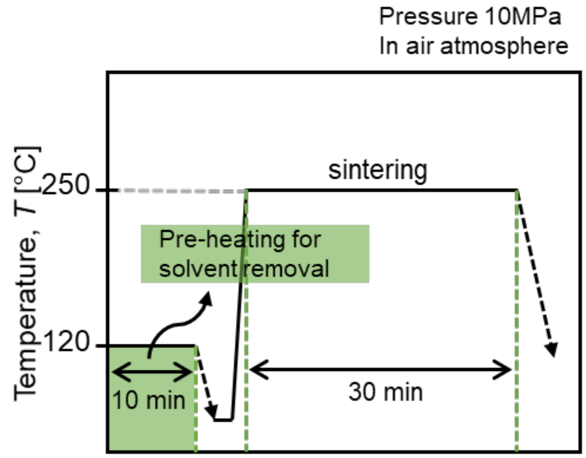

Fig. 1 Die-bonding conditions

II. Experiment procedures

A. Materials

In this study, two distinct types of copper powders with particle sizes of 2 µm and 0.3 µm, respectively, were utilized and mixed with trimethylene glycol (TEG) organic solvent to prepare two types of Cu pastes. The bare Cu dies (3 mm × 3 mm × 1 mm) and bare Cu substrates (10 mm × 10 mm × 2 mm) were applied as a die and substrate material, respectively.

B. Experimental procedures

The pre-heating process was conducted using a hot plate at 120 °C for 10 min in an air atmosphere. After the pre-heating process, the die bonding process was conducted in an air atmosphere using a wafer bonder at a temperature of 250 °C for 30 min with a low pressure of 10 MPa. The detailed sinter bonding conditions are displayed in Fig. 1.

C. Characterization

To investigate the interfacial microstructure of Cu sintered joints, the cross sections of Cu sintered die-attachment were polished by a mechanical auto-polishing machine (Labopol-30, Struers) and an ion-milling polishing system (IB-09020CP, JEOL, Tokyo, Japan). The interfacial microstructures and fracture surfaces were characterized by scanning electron microscopy (SEM, Inspect F50, FEI, USA) and energy dispersive spectroscopy (EDS). The crystallographic characteristics of the sintered Cu structure were quantitatively analyzed by the electron backscattered diffraction (EBSD, Velocity Super, EDAX, USA) detector. The bonding strength of the Cu sintered die-attach joint was evaluated by a shear tester (Dage4000, Nordson, UK).

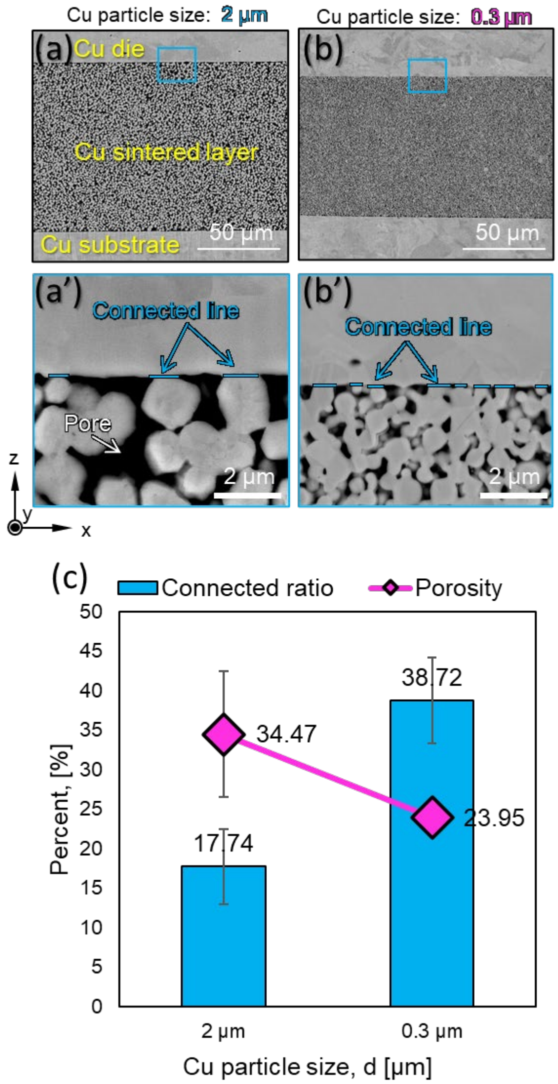

Fig. 2 Cross-sectional SEM images of the Cu sinter joint. (a, a') Cu particles size of 2 µm, (b,b') Cu particles size of 0.3 µm, (c) connected ratio and porosity change plot depending on the size of Cu particles.

III. Results and discussion

A. Cu bonding interfaces

Fig. 2 represents the cross-section of the Cu sintered joints depending on the size of Cu particles, and the microporous Cu structure was formed after sintering regardless of the size of Cu particles. Fig 2(a) and (b) depict the SEM images of the Cu sinter joint bonded by the Cu particles size of 2 µm and 0.3 µm, respectively, in which structurally sound bonding was achieved and no Cu oxidation layer was observed. Fig. 2(a') shows a high-magnification image of the particle size of 2 µm interfaces, which revealed inadequate connection between the Cu substrate and the Cu sintered layer. When the size of Cu particles decreased to 0.3 µm, the increased connected portion between the Cu substrate and the Cu sintered layer was observed (see Fig. 2(b')). Fig. 2(c) summarizes the interfacial connected ratio and porosity of the sintered layer depending on the size of Cu particles. The connected ratio increased by 54 % on Cu particle size of 0.3 µm compared to particle size of 2 µm. The porosity of Cu particles with a diameter of 0.3 µm decreased by 31 % compared to particles with a diameter of 2 µm. Therefore, Cu particle size was a critical factor in substantially increasing the interfacial connected ratio and decreasing the porosity.

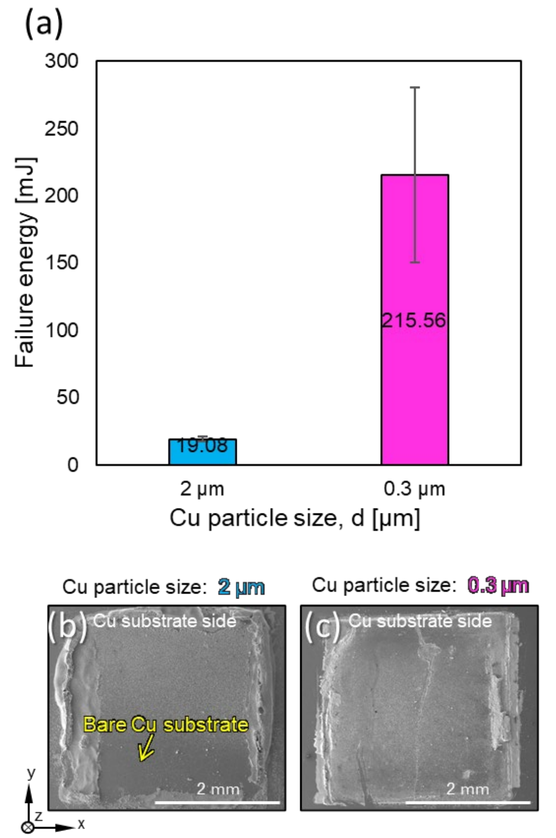

Fig. 3 Failure energy and fracture surface analysis results. (a) Failure energy depending on the size of Cu particles, the fracture surface of Cu sinter joints with Cu particles size of (b) 2 µm and (c) 0.3 µm

B. Mechanical and fracture behavior

The bonding results of Cu sintered joints was depended on the size of Cu particles. When the size of Cu particles was decreased to 0.3 µm, the shear strength exceeded about 36 MPa, which was about 182% higher than the Cu particle size of 2 µm. Fig. 3(a) depicts the failure energy depending on the size of Cu particles. The failure energy was achieved by 19mJ in the case of Cu particles size of 2 µm and significantly increased to 215 mJ in the case of Cu particles size of 0.3 µm. Consequently, the bonding strength and failure energy were significantly dependent on the interfacial connected ratio and porosity. Fig. 3(b) and (c) depict the fracture surface of the substrate after the die-shear test. The fracture path depended on the size of Cu particles, which bare Cu substrate was observed in the case of Cu particles size of

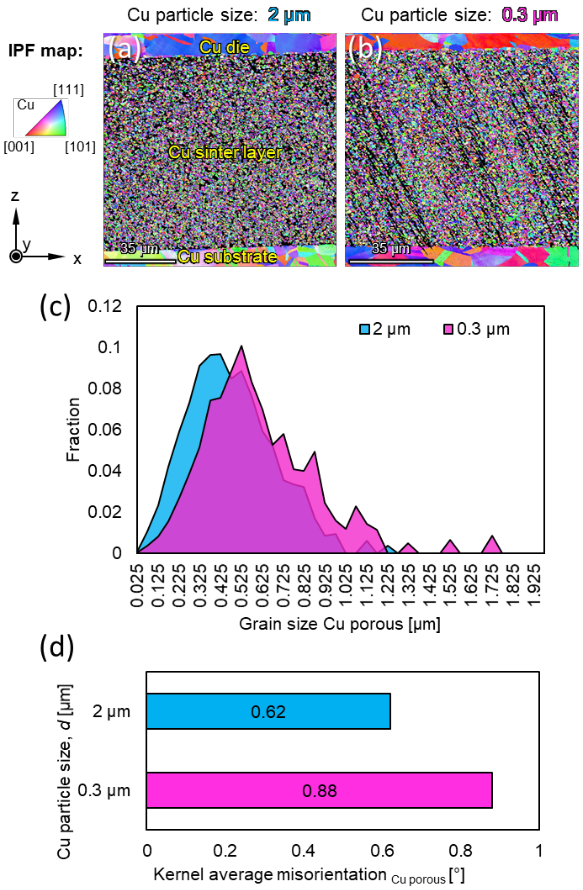

Fig. 5 EBSD analysis results of Cu sintered joints depending on the size of Cu particles. IPF map of Cu sinter joints with Cu particles size of (a) 2 μm and (b) 0.3 μm, (c) grain size distribution of Cu sintered layer, (d) plot of KAM, kernel average misorientation within Cu

2 μm (see Fig. 3(b)) and Cu sintered layer was observed in the case of Cu particles size of 0.3 μm (see Fig. 3(c)) at the surface of the fracture. Therefore, the porosity of the Cu sintered layer and the connected ratio between the Cu substrate and Cu sintered layer interface had a dominant influence on the robust bonding mechanism.

C. Microstructure of Cu sintered joints

The Cu sintered joints were observed using EBSD to investigate the crystallographic behavior of Cu sintered joint structure involved in the size of Cu particles. We exhibit the EBSD-IPF of cross-sectional Cu sintered joints in the case of particle sizes of 2 μm and 0.3 μm. The orientation of the grains was randomly distributed regardless of the size of Cu particles. The grain size of the Cu sintered layer was observed, with a Cu particle size of 0.3 μm achieved a 1.3 times larger grain size compared to a Cu particle size of 2 μm. Therefore, decreasing the size of Cu particles further increased the densification and coarsening between Cu particles. The kernel average misorientation (KAM) value of the Cu sintered layer was analyzed. The higher KAM value was achieved in the case of a Cu particle size of 0.3 μm compared to a Cu particle size of 2 μm, which strain was highly formed in the case of a Cu particle size of 0.3 μm. The increase in KAM value is correlated with the deformation of the Cu sintered layer, which resulted in the high shear strength of the Cu sintered joints.

IV. Conclusion

In conclusion, the Cu sintered joint was successfully achieved by a uniform pressure of 10 MPa for 30 min at 250 °C in an air atmosphere. A correlation was identified between the size of Cu particles and the features of the Cu joint structure. As the size of Cu particles decreased from 2 μm to 0.3 μm, porosity decreased by 31% and the connected ratio increased by 54%, respectively. The die shear strength of Cu sintered joints showed a significant increase when the Cu grain size was reduced to 0.3 μm, reaching 182% of the strength when the Cu grain size was 2 μm. The smaller size of the Cu particles led to an increase in total interfacial energy, resulting in densification and coarsening in the Cu sinter layer. Furthermore, the accumulation of strain in the Cu sinter layer and the interface of the substrate led to an enhancement in the bonding strength.

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