

## CHARACTERISTICS OF DIE-ATTACH METHOD BY SINTER BONDING USING Ag-40Cu MECHANICALLY ALLOYED PARTICLES

Ag and Cu powders were mechanically alloyed using high-energy planetary milling to evaluate the sinter-bonding characteristics of a die-attach paste containing particles of these two representative conductive metals mixed at atomic scale. This resulted in the formation of completely alloyed Ag-40Cu particles of 9.5  $\mu\text{m}$  average size after 3 h. The alloyed particles exhibited antioxidation properties during heating to 225°C in air; the combination of high pressure and long bonding time at 225°C enhanced the shear strength of the chip bonded using the particles. Consequently, the chips sinter-bonded at 225°C and 10 MPa for 10 min exhibited a sufficient strength of 15.3 MPa. However, an increase in bonding temperature to 250°C was detrimental to the strength, due to excessive oxidation of the alloyed particles. The mechanically alloyed phase in the particle began to decompose into nanoscale Ag and Cu phases above a bonding temperature of 225°C during heating.

*Keywords:* Mechanical alloying; Ag-Cu; Die-attach; Sinter bonding; Shear strength

### 1. Introduction

Due to a growth in power electronics industries for hybrid and electric vehicles, interest in packaging technologies for power modules has increased. For example, die-attach technology for power devices such as power metal-oxide-semiconductor field-effect transistors or insulated-gate bipolar transistors has been considered crucial for the performance and reliability of these modules [1-7]. High heat generation by power devices degrades the mechanical properties of the bond-line material, especially when its melting point is low. The requirement for a Pb-free material has also expanded from the electric and electronic industries to the automotive industry [8]. Moreover, from the viewpoint of power device development, Si is increasingly being replaced with wide-band-gap semiconductor materials such as SiC and GaN, which are normally operated at higher temperatures to achieve higher power densities and efficiencies [1-6]. To keep pace with these trends, the bonding material should be changed from high-Pb and Pb-free solder alloys to metals with high melting points and good thermal conductivity.

Therefore, recent studies on alternatives to die-attach technology were focused on sinter bonding at an external pressure of 10 MPa or less, using pastes that included particles of Ag, which has a high melting point and very good thermal conductivity [3-5]. Nevertheless, the adoption of Ag sintering pastes has not rapidly expanded, due to their inherently high material cost and the Ag migration phenomena. Hence, the reduction of Ag

content in a sintering paste could be considered a crucial current research topic in the industry.

Cu exhibits high electrical and thermal conductivities approaching those of Ag [9], and it is a much less expensive material than Ag. However, pure Cu particles cannot be directly used as an alternative for Ag filler unless their oxidation can be suppressed, because Cu can be easily oxidized [10].

Therefore, in this paper, Ag-Cu alloy particles, a novel filler material with low Ag content, are suggested as an alternative filler material for sinter-bonding pastes, to reduce both material cost (in comparison with that of pure Ag) and oxidation sensitivity (in comparison with that of pure Cu). It has been reported that mechanical milling of an Ag-Cu system produces a complete solid solution for the entire composition [11-15]; hence, Ag-Cu particles were mechanically alloyed using a high-energy milling process. Subsequently, a paste containing the fabricated particles was prepared, and dies were sinter-bonded under external pressure, using the paste. The phase change in the alloyed particles was analyzed as a function of heating temperature.

### 2. Experimental

To prepare a die-attach paste containing an atomic-scale mixture of two representative conductive metals, 60 wt% Ag (HAG150S, MK Corporation) and 40 wt% Cu (CUSP20, Join M) powders were mechanically milled at 300 rpm using a planetary mill. Figure 1 shows SEM images of the pure Ag and

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Cu particles used in this study. Both are spherically shaped with a rough surface. The average sizes of the Ag and Cu particles are 2.1 and 1.5  $\mu\text{m}$ , respectively. The total mass of balls inserted in an alumina vial was 200 g and the diameter of the zirconia balls used was 3 mm. After milling for 3 h, the appearance and microstructure of the collected particles were examined using field-emission scanning electron microscopy (FE-SEM; SU8010, Hitachi High-Technologies Corp.). Phases in the as-milled and heated particles were identified via X-ray diffraction (XRD; DE/D8 Advance, Bruker) analysis. The oxidation properties of the mechanically alloyed particles were analyzed using the degree of weight gain in thermogravimetry (TG; Q600, TA Instruments, installed at PH407, KBSI, Pusan) carried out in air.

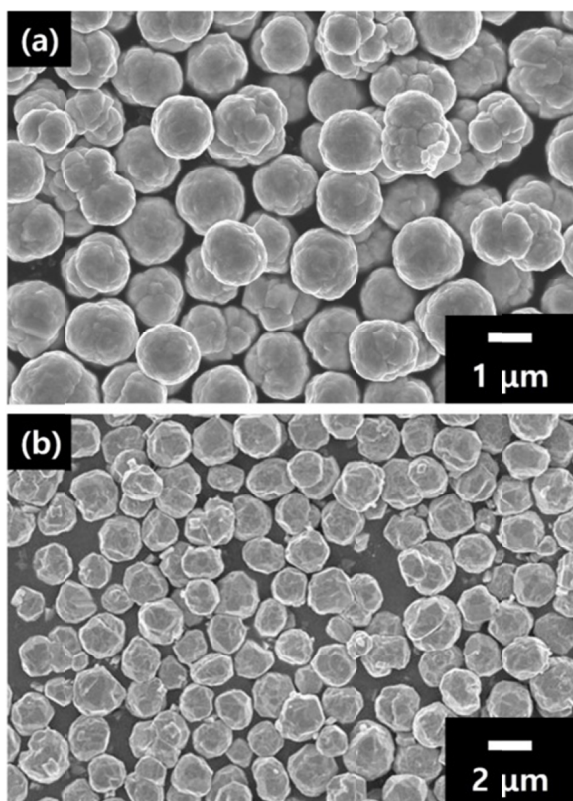


Fig. 1. SEM images of Ag and Cu particles used in this study

A paste containing the mechanically alloyed Ag-40Cu particles was prepared by mixing with  $\alpha$ -terpineol (98.5%, Samchun Chemical Co., Ltd.) as a vehicle, at a particle-to-vehicle weight ratio of 85:15. Dummy Si dies ( $3 \times 3 \times 0.525 \text{ mm}^3$ ) were attached on alumina-based direct bonded copper (DBC) substrates ( $10 \times 10 \times 1 \text{ mm}^3$ ) fully coated with 0.5  $\mu\text{m}$  Ag/5.0  $\mu\text{m}$  Ni. The Ag finish on the die was prepared by additional sputtering onto a Cu/Ti-metallized Si wafer, and the rear side of the die was coated with 0.1  $\mu\text{m}$  Ag/0.5  $\mu\text{m}$  Cu/0.1  $\mu\text{m}$  Ti layers. The prepared paste was printed onto the Ag-finished DBC substrate using a stencil mask with a slit volume of  $3 \times 3 \times 0.1 \text{ mm}^3$ . After printing, the die was placed on the printed pattern and the sandwich-structured sample was sinter-bonded at 225 or 250°C for 5 or 10 min. During the die-attach procedure in air, an external pressure of 5 or 10 MPa was applied throughout the bonding

time. Bonding strength of the fabricated bond-line was defined as the maximum stress measured during shear testing at 200  $\mu\text{m/s}$ . The microstructure of the bond-lines after the die-attach was observed using SEM and energy-dispersive X-ray spectroscopy (EDS; Noran System 7, Thermo Scientific).

### 3. Results and discussion

SEM images and an XRD pattern observed after 3 h of mechanical alloying of the 60(wt%)Ag/40Cu powder mixture are shown in Fig. 2. The shape of the alloyed particles is irregular, and the sizes range from a few microns to 20  $\mu\text{m}$ . The average size of the milled particles was 9.5 ( $\pm 3.3$ )  $\mu\text{m}$ , which is much

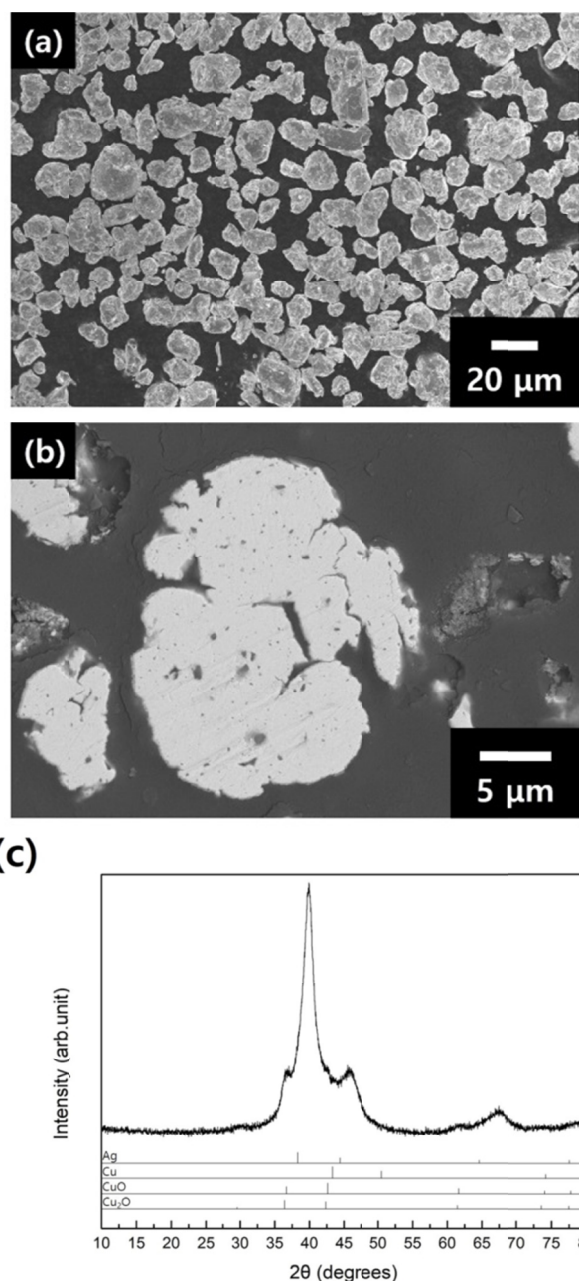


Fig. 2. SEM image showing (a) appearance of 60Ag/40Cu powder mixture mechanically alloyed for 3 h and (b) BSE image showing cross-section of the alloyed particle. (c) XRD pattern of the alloyed powder

larger than that of the initial particles. The milling was carried out under dry conditions, and the result was different from that observed in a similar experiment under wet conditions, with the size consistently decreasing with an increase in milling time [13]. In the backscattered electron (BSE) image showing a cross-section of alloyed particles (Fig. 2(b)), the domains of Ag and Cu phases are not distinguishable, and a lamellar structure was not observed. Moreover, in the XRD pattern, there are no peaks corresponding to pure Ag and Cu phases. Hence, all the new peaks measured for the milled particles are attributable to Ag-40Cu mechanical alloy and Cu oxide [11,12,14,15]. The absence of peaks corresponding to pure Ag and Cu indicates the formation of a non-equilibrium supersaturated face-centered-cubic (FCC) solid solution phase that cannot be achieved by a normal casting process [11,12,14,15]. The lattice parameter of the synthesized FCC phase was estimated to be around 3.90 Å, using Vegard's law [11]. These results imply that the added Ag and Cu are mixed homogeneously at atomic scale in the particles. Hence, the completely alloyed Ag-40Cu powder can be used as a filler material for the die-attach process. Although peaks for pure Ag and Cu were clearly observed after incomplete alloying following milling for 3 h in a similar experiment [12], peaks for the pure metals were not observed after 3 h in this experiment due to higher milling energy. The amount of Cu oxide phase formed seems to be low because the milling was conducted using a closed vial.

To confirm the functional benefit of mechanically alloyed Ag-40Cu powder, weight gain by oxidation was measured while heating in air. Figure 3 shows the TG results obtained using three types of powders (Ag, Cu, and mechanically alloyed Ag-40Cu) during dynamic heating. The heating rate was 10°C/min. Although Cu powder is continuously oxidized at a temperature above 150°C, the oxidation of Ag does not occur. The Ag-40Cu powder is slightly oxidized at a temperature above 200°C, which is delayed compared with the behavior of Cu. The extent of weight gain is also lower than that estimated from the composition of Ag-40Cu. These results suggest that the oxidation sensitivity of mechanically alloyed Ag-40Cu powder is

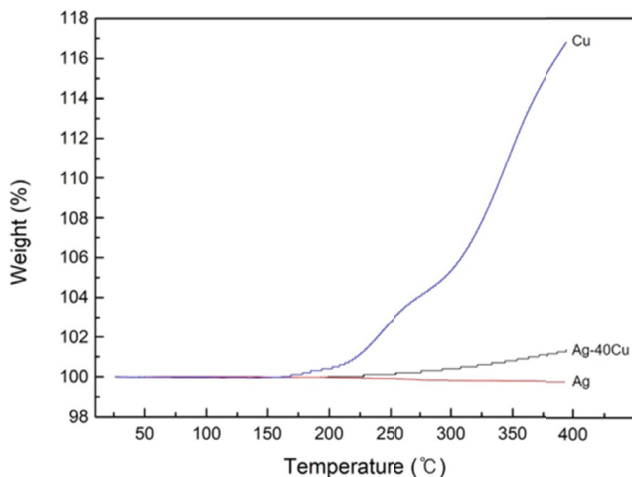


Fig. 3. TG results of Ag, Cu, and mechanically alloyed Ag-40Cu powders during dynamic heating in air

not significant, and that the powder is a suitable material for the bonding process at 225°C. The anti-oxidation characteristics of the Ag-40Cu powder might be due to both a blocking effect by Ag, preventing contact between oxygen and Cu, and the slight oxidation of Cu during the milling. Ag atoms in the Ag-40Cu particle and the surface render the Cu oxidation difficult [16].

Figure 4 shows the shear strength of chips bonded using the paste containing the alloyed Ag-40Cu powder under different bonding conditions. Note that the conditions indicated on the X-axis include two different external pressures and two different bonding times. After sintering at a pressure of 5 MPa for 5 min, the chips were very slightly bonded on the DBC substrate, irrespective of the bonding temperature. These incomplete bonding results are not included in the results shown in Fig. 4. The chips sinter-bonded at a pressure of 5 MPa for 10 min exhibited relatively low shear strength (not exceeding 8 MPa) regardless of the temperature. However, at a temperature of 225°C, the strength was enhanced significantly by an increase in pressure to 10 MPa. The value increased to 15.3 ( $\pm 1.4$ ) MPa after sinter bonding for 10 min. This strength value is similar to that measured for the sample sinter-bonded at 220°C and 0.07 MPa for 60 min using a paste containing micron-sized Ag particles or at 275°C and 1 MPa for 20 min using nanoscale Ag paste [3,4]. Furthermore, after bonding at 250°C, the strength was similar or slightly enhanced for a higher pressure of 10 MPa. As a result, the strength after sinter-bonding for 10 min was just 9.0 ( $\pm 0.9$ ) MPa, indicating that the higher bonding temperature was less effective in enhancing the bonding strength.

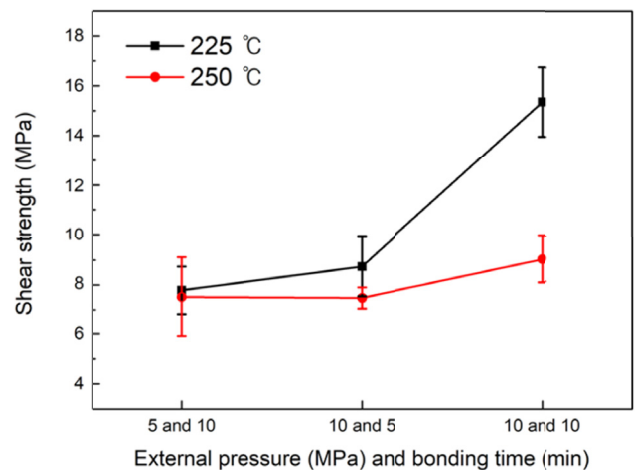


Fig. 4. Shear strength of chips bonded using the mechanically alloyed Ag-40Cu powder with different bonding temperatures, external pressures, and bonding times

Cross-sectional BSE images of bond-lines formed with different external pressures and bonding times at 225°C using the mechanically alloyed Ag-40Cu powder are displayed in Fig. 5. The upper, middle, and lower images indicate low-magnification bond-line images, images showing the sinter-bonding between Ag-40Cu particles in the magnified bond-line, and images showing the sinter-bonding between the Ag finish and Ag-40Cu particles, respectively. In the sample bonded at 5 MPa for 5 min,

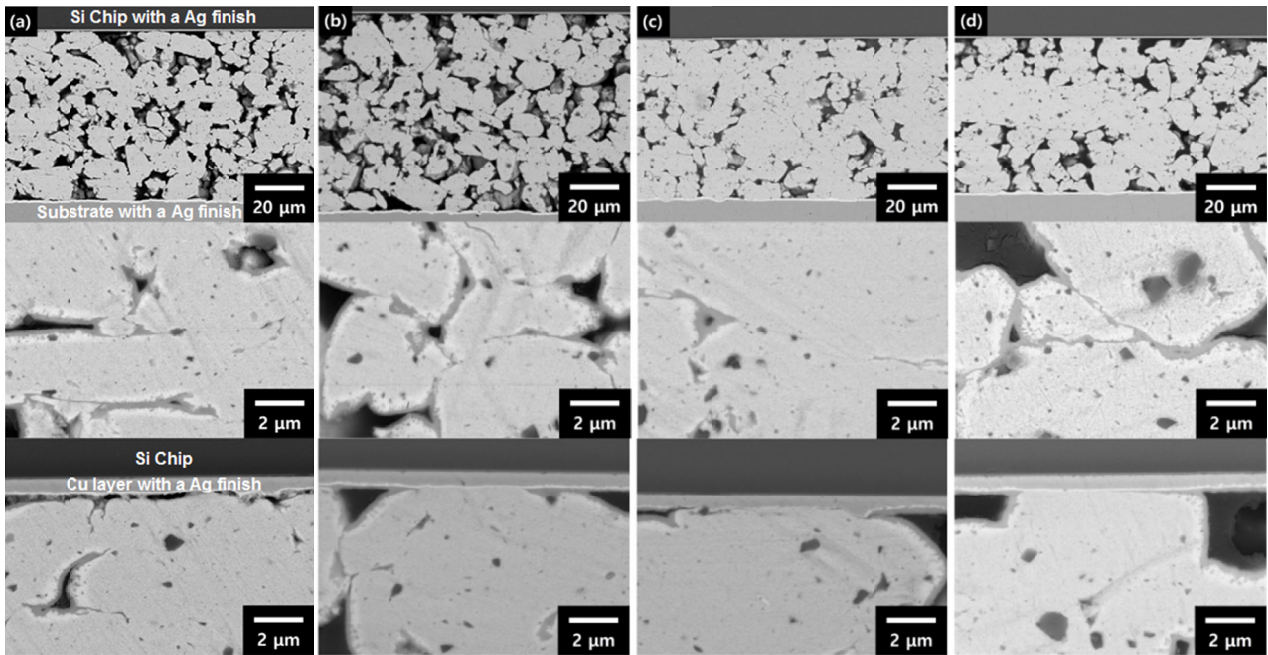


Fig. 5. Cross-section BSE images of bond-lines formed with different conditions (external pressure/bonding time) at 225°C using mechanically alloyed Ag-40Cu powder: (a) 5 MPa/5 min (b) 5 MPa/10 min, (c) 10 MPa/5 min, and (d) 10 MPa/10 min

the interface between Ag finish and particles split after the epoxy used for mounting the sample was cured, owing to weak adhesion between them, although sinter-bonding between particles was clearly observed (Fig. 5(a)). However, when the bonding time was increased to 10 min at this pressure, a bonded interface was observed due to the reinforcement of the adhesion at the interface, as shown in Fig. 5(b). When the pressure was increased to 10 MPa, the voids between particles diminished, resulting in a decrease in bond-line thickness (Fig. 5(c, d)). The degree of sinter-bonding between particles at this pressure was not very

different with respect to bonding time. As the representative fracture surface was the interface between the Ag finish on a chip and the Ag-40Cu particles, the enhanced shear strength due to an extended bonding time of 10 min can be attributed to improvement in adhesion between the Ag finish and the particles.

Cross-sectional BSE images of bond-lines formed with different external pressures and bonding times at a higher bonding temperature of 250°C are presented in Fig. 6. The increase in bonding temperature induced a slight change in the bond-line region. The Ag finish/particles interface formed at 5 MPa for

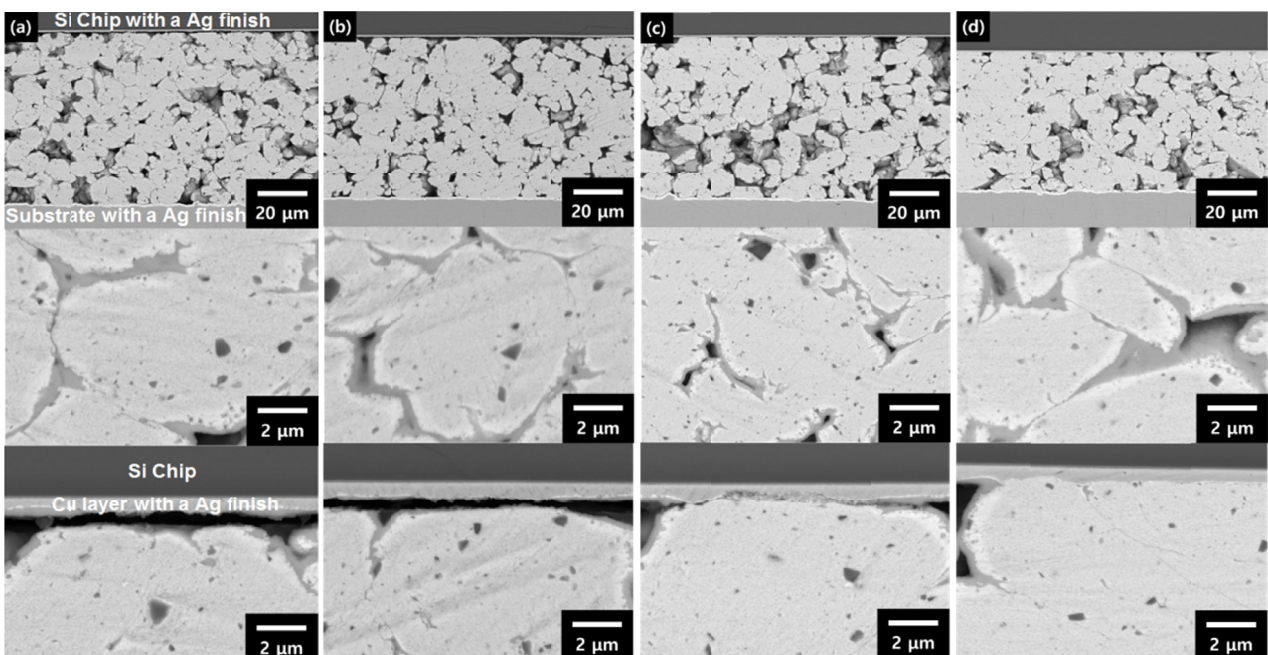


Fig. 6. Cross-section BSE images of bond-lines formed with different conditions at 250°C using mechanically alloyed Ag-40Cu powder: (a) 5 MPa/5 min (b) 5 MPa/10 min, (c) 10 MPa/5 min, and (d) 10 MPa/10 min

5 min was still observed to split (Fig. 6(a)), and a weak interface was maintained, with the images showing fractured or a slightly bonded interface after an increase in just one parameter value (Fig. 6(b, c)). A clear enhancement in bonding was observed only in the sample fabricated by applying 10 MPa for 10 min (Fig. 6(d)). These images confirm that an increase in the bonding temperature to 250°C is detrimental to the bonding, which is similar to the trend seen in Fig. 4.

To determine the effect of die-attach heating on phase change in the mechanically alloyed Ag-40Cu, XRD patterns were recorded after heating the powder at various temperatures. These are presented in Fig. 7. The peaks observed for the initial mechanically alloyed powder shift to lower angles as the temperature increases. As a result, the peaks of the alloyed Ag-40Cu after heating at 225°C decompose into Ag and Cu peaks. The decomposition becomes intense, with the formation of sharper peaks, after heating at 250°C. For heating in air, the oxidation of Cu also seemed more intense with an increase in temperature.

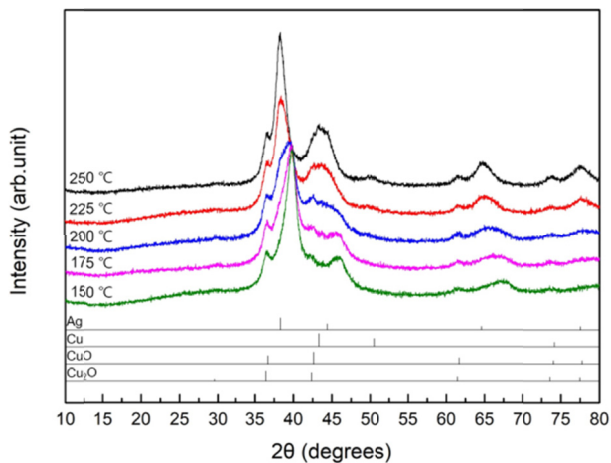


Fig. 7. XRD patterns after heating of mechanically alloyed Ag-40Cu powders at different temperatures

To determine the reasons for the detrimental effect of an increase in bonding temperature on the bonding as well as degree of oxidation, EDS mapping was conducted after the mechanically alloyed Ag-40Cu particles were sintered at 10 MPa for 10 min at 225 and 250°C. The results are displayed in Fig. 8. Although phase decomposition into Ag and Cu phases occurred at these temperatures, domains of pure Ag and Cu are not defined in the mapping images, which implies that the Ag and Cu phases exist only at the nanoscale. Moreover, the mapping intensity for oxygen increases, in general, as the temperature increases, confirming the TG result that the extent of Cu oxidation increases with an increase in temperature. The intensity of oxygen is maximum at the edges of the particles that are not sinter-bonded with a neighboring particle. Therefore, we conclude from the results of lower shear strength at higher temperature shown in Fig. 4, and from the higher oxygen content at higher temperature shown in Fig. 8, that an increase in Cu oxidation severely hinders sinter-bonding with neighboring particles and the Ag finish in the metallization of chips and substrates.

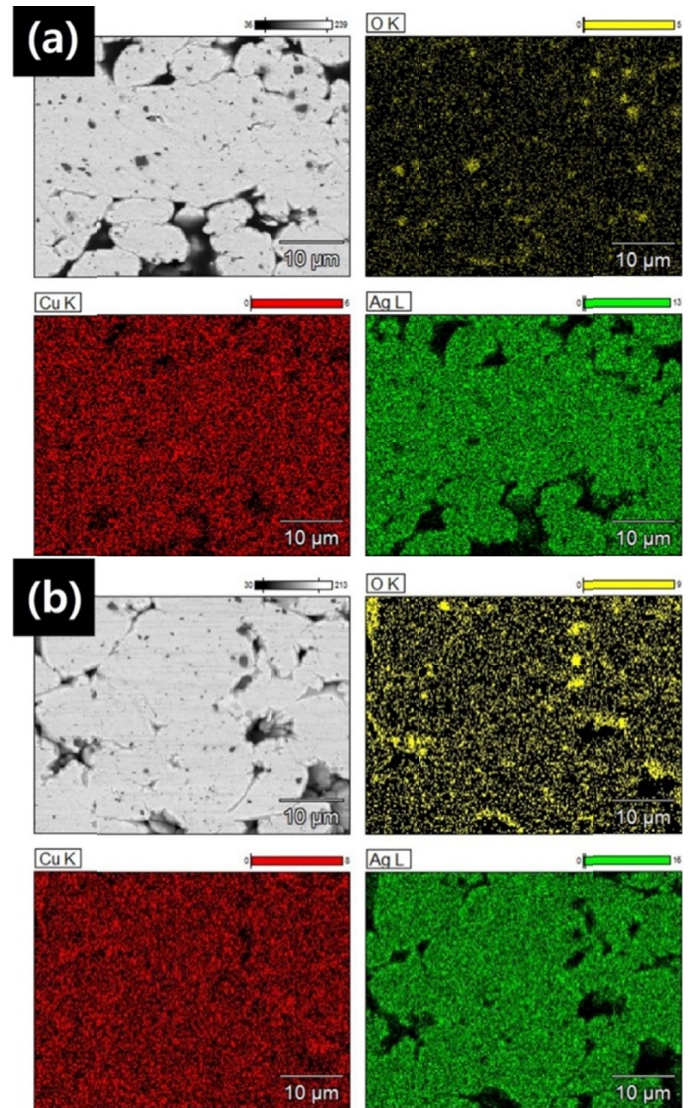


Fig. 8. EDS mapping results of mechanically alloyed Ag-40Cu particles sintered at 10 MPa for 10 min at different temperatures: (a) 225°C and (b) 250°C

#### 4. Conclusions

The 60Ag/40Cu powder mixture was completely mechanically alloyed by dry high-energy milling for 3 h. Ag and Cu were completely dispersed in the cross-section of the alloyed particles because the Ag and Cu were mixed at atomic scale. The XRD peaks of the alloyed powder are those of a non-equilibrium phase that cannot be realized by casting. Furthermore, the antioxidation properties of the alloyed powder are higher than that estimated from the composition, mainly due to a shielding effect of Ag against contact between Cu and oxygen. In the die-attach at 225°C in air, a high pressure and long bonding time increased the shear strength of the bonded die. The combination of 10 MPa and 10 min induced a sufficient strength of 15.3 MPa. However, an increase in temperature to 250°C was detrimental to the bonding strength, due to excessive oxidation of the alloyed particles. The alloy clearly begins to decompose into nanoscale Ag and Cu phases above 225°C during the heating process.

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