

Self-Organized Interconnection Process Using Solderable ACA (Anisotropic Conductive Adhesive)

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In this paper, we discuss our design of a new class of low-melting-point alloy (LMPA)-filled anisotropically conductive adhesives (ACA) and a self-organized interconnection process for using these adhesives, and we demonstrate a good electrical conduction for the process. Flow, melting, coalescence, and wetting characteristics of LMPA fillers in the ACA facilitate this process. In order to exploit good coalescence and wetting characteristics of LMPA fillers, the polymer matrix has a sufficient fluxing capability against oxide films of both LMPA fillers and electrode materials. Furthermore, it is essential that the polymer have a low viscosity level around the melting point of the incorporated LMPA to achieve a good electrical conduction path.

In order to study coalescence and wetting characteristics, we formulated two types of ACA with different volume fractions of LMPA filler (10 vol% and 40 vol%). Our test board had an 18- μm thick Cu line-type pattern (10 mm \times 0.1 mm) and an area array-type pattern (square type: 0.1 mm \times 0.1 mm, circle type: φ , 0.1 mm) with five different pitches (50 μm to 250 μm). We measured thermal properties of the ACA by differential scanning calorimetry (DSC), and we determined a temperature profile for the interconnection process. We then monitored coalescence and wetting characteristics of LMPA fillers and morphology of conduction path in ACA by using a microfocusing X-ray inspection system and an optical microscope.

We determined that the developed LMPA-filled ACA have good coalescence and wetting characteristics regardless of pattern types. In addition, we were able to achieve a good electrical conduction path because of the coalescence and wetting characteristics of the LMPA fillers in the ACA. [doi:10.2320/matertrans.MF200918]

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1. Introduction

Lead-based solder alloys have been used widely to bond electronic parts onto printed circuit boards (PCB) in the electronics industry. However, because of the health hazard of lead toxicity from tin-lead (Sn/Pb) solders,¹⁾ a more environmentally friendly alternative has been actively investigated. Two principal groups of alternatives include lead-free solders²⁾ and polymer-based electrically conductive adhesives (ECAs).³⁾ Lead-free solders typically contain tin as a primary element, owing to its low melting point, low cost, and good wettability compared to other metals. However, typical lead-free solders, such as tin-silver (Sn/Ag) and tin-silver-copper (Sn/Ag/Cu), have a higher melting point than conventional tin-lead eutectic solder. Therefore, the reflow temperature of these lead-free solders is extremely high, and heat-sensitive components and low-cost organic PCB cannot be used with them. In addition, use of flux to improve their solderability causes a reduction in long-term reliability of the resulting solder joints, and also leads to environmental problems, such as destruction of the ozone layer, because of the volatile solvents used to clean the flux residue.

On the other hand, ECAs consist mainly of polymer matrices, which provide mechanical properties, and metal fillers, which provide electrical properties.⁴⁾ ECAs offer a large set of potential advantages over conventional solder, including processing temperature, high-resolution capability for fine pitch interconnection, and greater compatibility with

nonsolderable materials.⁵⁻⁷⁾ However, because electrical interconnection is achieved by physical and mechanical contact between metal fillers and the conduction pad, ECAs have several critical limitations, such as low conductivity and unstable contact resistance. Even though a new, improved class of ECA has been developed, low joint strength, silver migration, and difficulty in repairing these ECAs have also been reported.^{8,9)}

To overcome these drawbacks, our group has suggested a low-melting-point alloy (LMPA)-filled anisotropically conducting adhesive (ACA) that employs hybrid bonding technology of soldering and an adhesive bonding process. Fluxing capability of the polymer matrix with regard to oxide films of both the LMPA fillers and the electrode materials during the interconnection process appears to provide a critical advantage to achieve a good electrical conduction path using this technology.

In this study, we have designed and demonstrated a new class of LMPA-filled ACA and a self-organized interconnection process for using these ACA to achieve a good electrical conduction path. In addition, we have evaluated the coalescence and wetting characteristics of LMPA fillers and the morphology of the conduction path in ACA with different volume fractions of LMPA filler.

2. Self-Organized Interconnection Process Using Solderable ACA

We have designed a self-organized interconnection process, shown in Fig. 1, that uses a new solderable ACA with a

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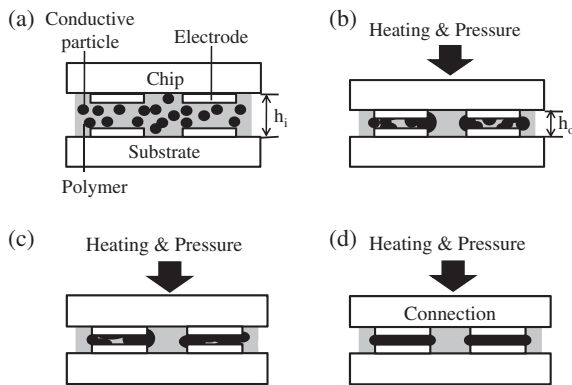


Fig. 1 Schematic of new self-organized interconnection process using solderable ACA. (a) Initial condition, (b) coalescence of LMPA fillers, (c) wetting behavior of LMPA fillers, and (d) completion of self-organized interconnection.

polymer-based matrix and a LMPA filler, which generally has a lower melting point than the peak curing temperature of the polymer. Before reflow, the solderable ACA with a LMPA is applied on the substrate, and the component is mounted on the ACA. Then, as the assembly is reflowed with a predetermined curing temperature profile, the ACA is liquefied and its viscosity decreases with increasing temperature. At this stage, when the curing temperature reaches the melting point of the LMPA, the LMPA start to melt and flow into the ACA.

In order to obtain coalescence and wetting characteristics most effectively for LMPA fillers on conduction pads, we lower initial stand-off-height (SOH) h_i was to final SOH h_o by applying bonding pressure. Coalescence and wetting characteristics are accelerated, and, finally, a metallurgical interconnection is accomplished between molten LMPA fillers, as well as between the molten LMPA fillers and conduction pads of the chip and substrate.

Previous studies¹⁰⁻¹²⁾ have shown that using fluxing capability to remove oxides of both LMPA fillers and conduction pads helps to promote wetting characteristics. The polymer should not be cured too much before it reaches the melting point of the LMPA filler in order to achieve a good electrical conduction path. Thus, melted LMPA fillers flow more easily, coalesce with each other, and are wetted on the conduction pads during the interconnection process. Excessive curing of the polymer hinders the flow-coalescence-wetting characteristics of LMPA fillers and will ultimately inhibit achieving the appropriate electrical conduction path.

3. Experimental

3.1 Materials

LMPA filler was obtained from Senju Metal Industry Company. Sn-58Bi ($T_m = 412$ K), with a diameter of $45\ \mu\text{m}$, was used as a LMPA filler material. Two kinds of ACA with different volume fractions (10 and 40 vol%) were formulated. Diglycidylether bisphenol A (DGEBA) was used as a binder. Diaminodiphenylsulfone (DDS) was used as a curing agent, and an amine-type catalyst was also employed. To remove

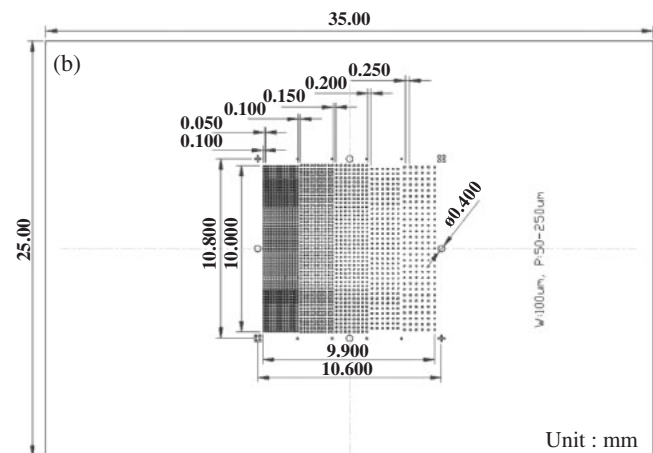
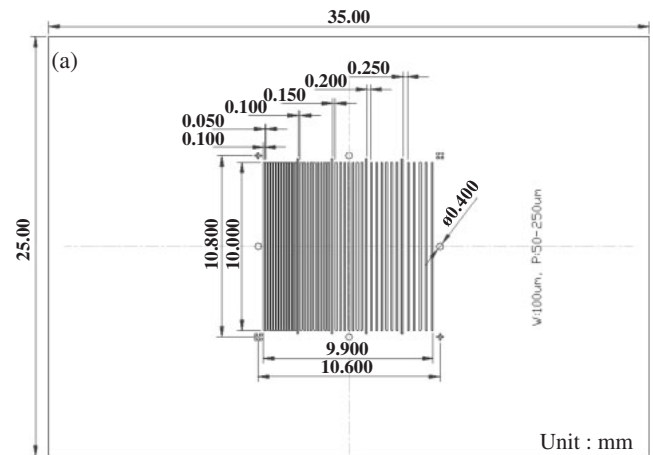


Fig. 2 Configuration of (a) line-type pattern, and (b) area array-type pattern.

oxide films on LMPA fillers and conduction pads of components and the PCB, we used carboxylic acid as a reductant.

In order to investigate coalescence and wetting characteristics of LMPA fillers and the morphology of the conduction path in ACA, we used two types of test boards; one had a line-type pattern and the other had an area array-type pattern with Cu plated on the FR-4 board. Test board size was $35\ \text{mm} \times 25\ \text{mm}$, copper line size was $10\ \text{mm} \times 0.1\ \text{mm}$, and spaces between patterns were at 50, 100, 150, 200 and $250\ \mu\text{m}$. For the areaarray-type pattern, a $100\ \mu\text{m} \times 100\ \mu\text{m}$ square-type pattern was formed at the upper and lower sides of pattern, and a circle-type pattern with diameter of $100\ \mu\text{m}$ was formed at the middle of the pattern. Configurations of the metal patterns are shown in Fig. 2. For the SOH adjustment, the same Sn-58Bi solder ball with a diameter of $300\ \mu\text{m}$ and copper wire with a diameter of $100\ \mu\text{m}$ were used.

3.2 Differential scanning calorimetry (DSC) and viscosity test

In order to observe the curing behavior of the polymer and the melting behavior of the LMPA filler, a differential scanning calorimeter (DSC) was used to carry out thermodynamic analysis. The mixed ACA was placed into the DSC pan and heated from room temperature to $573\ \text{K}$ at a ramped heating rate of $10\ \text{K}/\text{min}$. Nitrogen was used as a purging gas.

A torsional parallel rheometer with a diameter of 20 mm and a frequency of 1 Hz was used to observe the temperature-dependent viscosity characteristics of the polymer matrix. Mixed ACA was heated from room temperature to 523 K and a ramped heating rate of 10 K/min. The temperature profile for the self-organized interconnection process was determined by using the results from the DSC analysis and the viscosity test.

3.3 Self-organized interconnection process test

Before beginning the self-organized interconnection process test, copper-patterned test boards were rinsed with acetone for 1 min, washed in DI water, and dried by air-jet. Then, an ACA with a different volume fraction of filler was dispensed onto the test board. Next, the lower test board was mounted on the flip-chip bonder (LAMDA: FINETECH Co.). For SOH adjustment, a Sn-58Bi solder ball with a diameter of 300 μm and a copper wire with a diameter of 100 μm were placed on the fixed lower test board. After the upper test board was mounted on the lower test board and reflowed at the temperature profile described in Section 3.2 above, applying a bonding force of 20 N. SOH was maintained at 300 μm by the solder ball, which melted at the melting point of the LMPA. Finally, SOH was fixed to at 100 μm by the copper wire during the interconnection process.

After the interconnection process, a microfocus X-ray inspection system (SMX-160, Shimadzu) and an optical microscope (VHX-100, Keyence Co.) were used to observe coalescence and wetting characteristics of the LMPA fillers and morphology of conduction path in the ACA.

4. Results and Discussion

4.1 ACA formulations

As a LMPA filler material, Sn-58Bi eutectic alloy was selected from a group of candidates that included Cu, Zn, Ag, In, Sn, Au, and Bi, because of its relatively low eutectic temperature of 412 K and its ultimate tensile strength and shear strength that are higher than those of Sn-37Pb eutectic alloy.¹³⁾ Depending upon the specific application, a binary system, such as Sn-58Bi (T_m : 412 K), In-48Sn (T_m : 390 K), In-3Ag (T_m : 414 K), or Sn-3.5Ag (T_m : 494 K), or a ternary system, such as Bi-41.7Sn-1.3Zn (T_m : 400 K), Bi-45Sn-0.33Ag (T_m : 413–418 K), Sn-3Ag-0.5Cu (T_m : 493 K), etc., can be substituted.

Table 1 shows the principal components of an ACA formulation. In this study, our ACA formulation included a diglycidylether bisphenol A (DGEBA) epoxy resin as the base resin, diaminodiphenylsulfone (DDS) as the curing

agent, and amine-type catalyst, BF_3MEA . Further, we added a carboxylic acid to the ACA formulation to remove oxide films of LMPA filler surfaces and conduction pad surfaces during the interconnection process.

4.2 Curing behavior and viscosity characteristics of the ACA

For the ideal self-organized interconnection, LMPA fillers should be melted, flowed, coalesced, and wetted on conduction pads of the components and PCB before curing the ACA. Otherwise, flow-coalescence-wetting behavior is hindered because of curing progress of the ACA. Therefore, curing behavior should be matched to flow-coalescence-wetting characteristics of LMPA fillers. It is desirable that peak curing temperature be higher than the melting point of LMPA fillers in order to enhance flow-coalescence-wetting characteristics of LMPA fillers in an ACA formulation.

Curing behavior of the resin, melting behavior of the LMPA filler, and viscosity test results are shown in Fig. 3. Curing peak temperature of the resin was about 427 K, and the melting point of the LMPA filler was about 414 K; therefore, the resin was not sufficiently cured.

Viscosity test results show a very low viscosity level (about 100 cPs) at the melting point of the LMPA filler. Viscosity is one of the critical properties associated with achieving a good metallurgical conduction path because of flow-coalescence-wetting characteristics of LMPA fillers in ACA formulations during the interconnection process.

The resulting temperature profile for the self-organized interconnection process that we designed is shown in Fig. 4. It consists of stages; first there is a melting stage that encompasses melting, flow, coalescence, and wetting of the LMPA fillers, next is the curing stage of the resin. In the melting stage, we heated the test vehicle at a ramped heating rate of 120 K/min from ambient temperature to a temperature 20 K higher (maintained for 20 s) than the melting point of the LMPA filler (433 K) in order to ensure complete melting of the LMPA fillers. In the curing stage, we heated the test vehicle at a ramped heating rate of 120 K/min up to

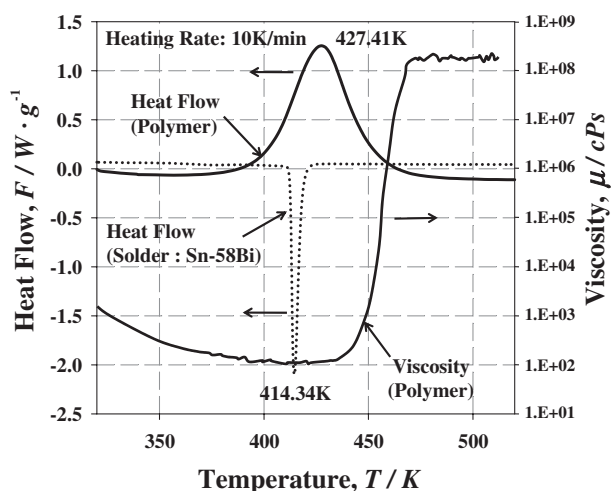


Fig. 3 Dynamic DSC and DMA scan with 10 K/min for ACA.

Table 1 Components of new ACA formulation.

	Components
Epoxy	DGEBA
Curing Agent	DDS
Catalyst	BF_3MEA
Reductant	Carboxylic Acid
LMPA Filler	Sn-58Bi(ϕ , 45 μm)

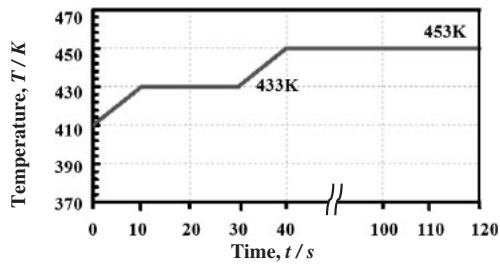


Fig. 4 Temperature profile for self-organized interconnection process.

453 K until the resin was finally cured. Based on the previous work,¹⁴⁾ curing temperature and time were set at 453 K and 80 s in order ensure that polymer was sufficiently cured.

4.3 Coalescence and wetting characteristics of LMPA fillers

In order to observe coalescence and wetting characteristics of LMPA fillers in ACA, two kinds of ACA were formulated by mixing with LMPA fillers at 10 and 40 vol%. Figure 5 shows X-ray photographs of the assembly with a copper line pattern test vehicle. The dotted line shows the original copper line patterns, and the dark gray region indicates coalesced and wetted LMPA fillers. Fig. 6 shows that formulated ACA display good coalescence and wetting on the copper line pattern at both LMPA volume fractions of 10% and 40%. However, using ACA with 10 vol% LMPA fillers, we can see in Fig. 5(a) that wetted LMPA fillers were not connected on

line patterns at the left side of the assembly. Apparently, the LMPA fillers were insufficient to wet the line pattern entirely. On the other hand, when the volume fraction of LMPA fillers in ACA was 40%, the LMPA fillers were neither coalesced nor wetted; in fact, they were nearly imperceptible, even though the bridge phenomenon occurred because of the excessive volume fraction of the LMPA fillers, as shown in Fig. 5(b).

Figure 6 shows X-ray photographs of the assembly with the copper area array pattern test vehicle. In Fig. 6, it is apparent that the formulated ACA had good coalescence and wetting on copper area array patterns of the square and circle-type at both LMPA volume fractions of 10% and 40%, as with the copper line-type pattern assembly. In this copper area array pattern test, although noncoalesced and wetted LMPA fillers were nearly imperceptible, the bridge phenomenon was increased with decreasing space between the patterns. Using an ACA with 10 vol% LMPA fillers, bridge phenomena were observed in the area array-type pattern, as compared to the line-type pattern, because the total pattern area to wet and interconnect in the area array-type pattern was smaller than that in the line-type pattern. Therefore, we conclude that LMPA volume fraction in the ACA does not appear to play a role in the bridge phenomena, according to conduction pad geometry.

We have determined, as a result of two types of pattern tests, that the formulated ACA showed a good fluxing effect against oxide films of LMPA filler surfaces and conduction pad surfaces during the interconnection process. In addition, the ACA had good flow-coalescence-wetting

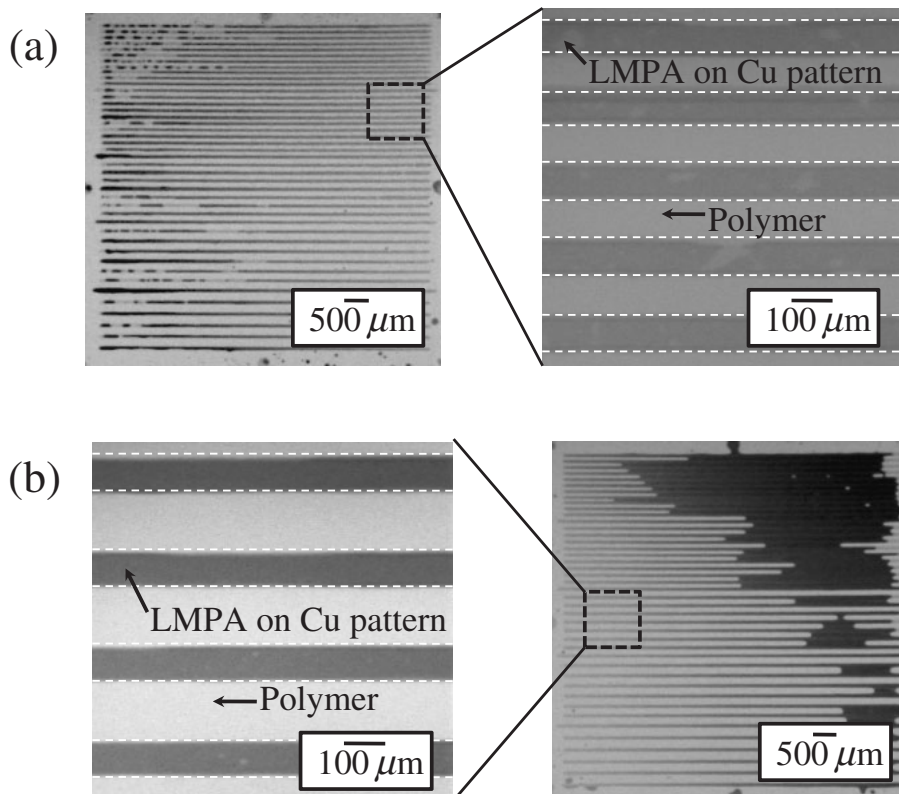


Fig. 5 X-ray photographs of line-type pattern assembly with (a) volume fraction of 10% and space of 100 μm and (b) volume fraction of 40% and space of 150 μm .

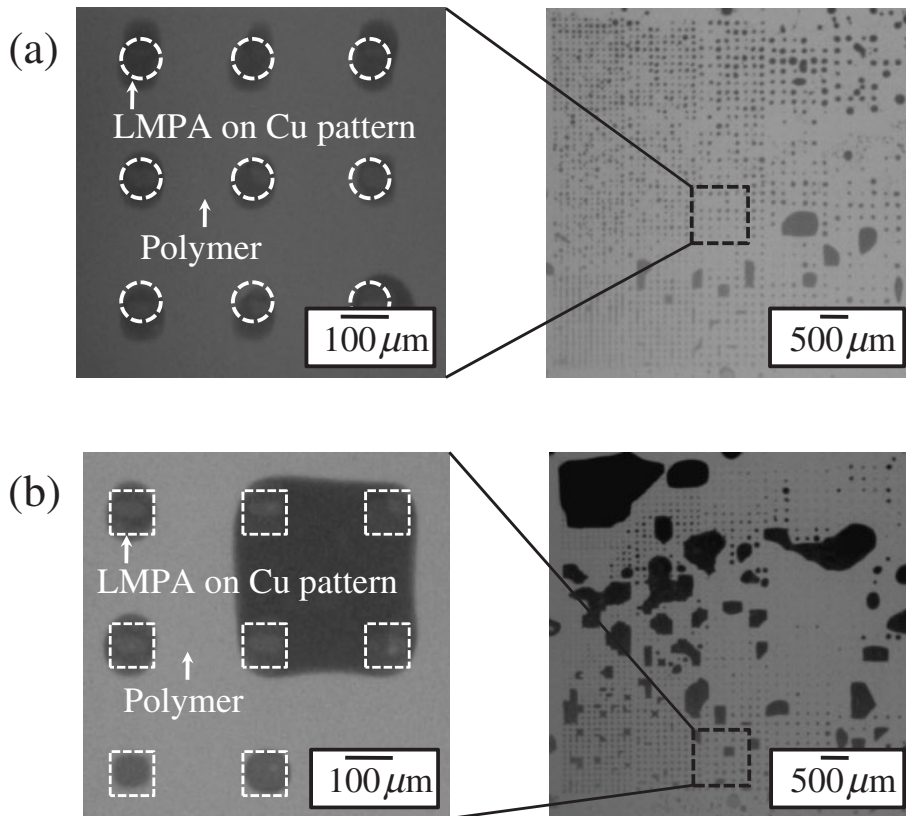


Fig. 6 X-ray photographs of area array-type pattern assembly with (a) volume fraction of 10% and circle pads and (b) volume fraction of 40% and square pads. Space was 150 μm .

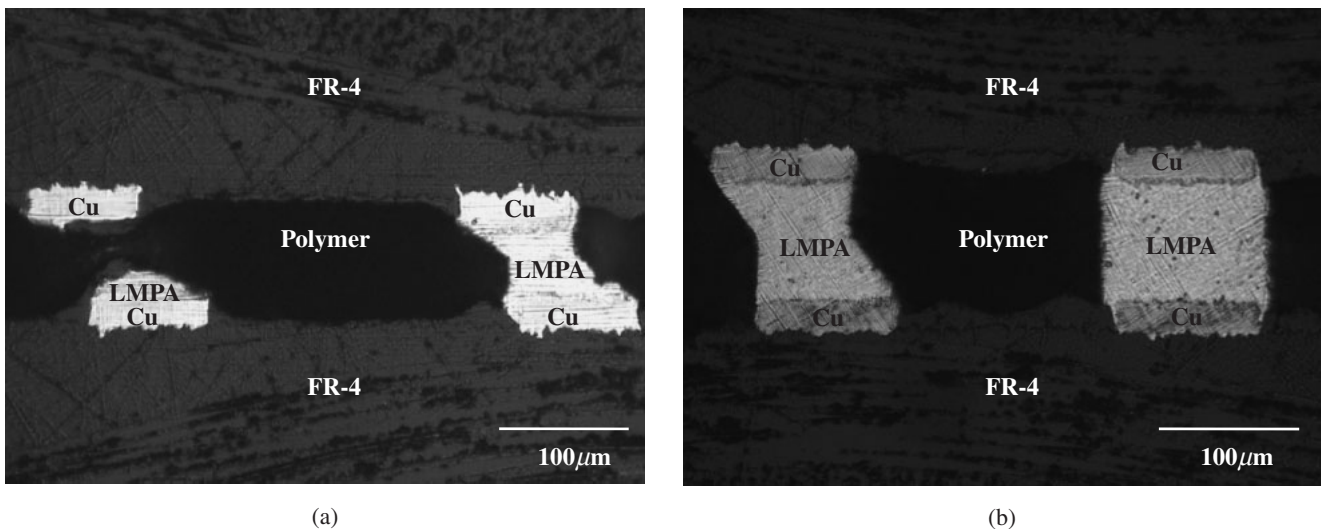


Fig. 7 Morphology of conduction path between upper and lower line-type pattern assembly with (a) volume fraction of 10% and space of 250 μm and (b) volume fraction of 40% and space of 200 μm .

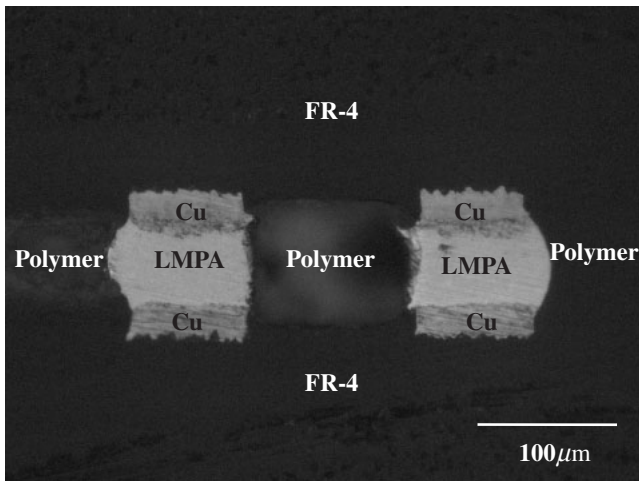
characteristics on both line and area array patterns, regardless of volume fractions of LMPA fillers in the ACA formulation.

4.4 Conduction path formation

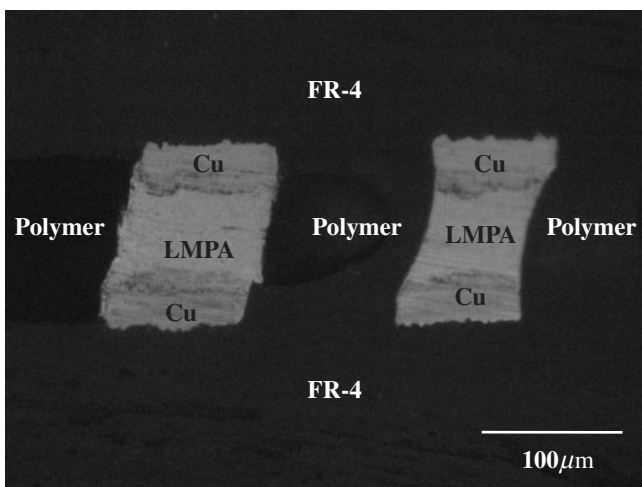
Figure 7 shows the morphology of the conduction path, which was formed by coalesced and wetted LMPA fillers between the upper and lower line-type conduction pads. Figure 7(a) indicates that the conduction paths were only

partially formed, even though coalescence and wetting of the LMPA fillers was sufficient. On the other hand, the assembly with 40 vol% ACA had a good conduction path, as shown clearly in Fig. 7(b).

Figure 8 shows the morphology of the conduction path between upper and lower area array-type conduction pads. From Fig. 8, we can see that the LMPA fillers were wetted on the copper conduction pads and formed a good metallurgical interconnection.



(a)



(b)

Fig. 8 Morphology of conduction path between upper and lower area array-type pattern assembly with (a) volume fraction of 10% and (b) volume fraction of 40%. Space is 100µm.

5. Conclusion

In this study, we have designed and demonstrated a new class of LMPA-filled ACA and a self-organized interconnection process for using these ACA to achieve a good electrical conduction path. The ACA that we developed had a

good fluxing effect with regard to the oxide films of LMPA filler surfaces and conduction pad surfaces during the interconnection process. In addition, the resin material has a sufficiently low viscosity level to enhance the flow-coalescence-wetting characteristics of the LMPA fillers in the ACA formulation at the melting point of the LMPA fillers. Our results showed good coalescence and wetting characteristics. Furthermore, good metallurgical interconnections were formed between the LMPA fillers and the conduction pads. This new ACA formulation can be used for a variety of applications, by adjusting the various kinds of LMPA filler material, the level of filler loading, and the resin characteristics.

Acknowledgements

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