The Effect of Fillers in Nonconductive Adhesive on the Reliability of Chip-on-Glass Bonding with Sn/Cu Bumps

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The effect of a nonconductive adhesive (NCA) on the reliability of chip-on-glass (COG) bonding was studied. Double layer bumps consisting of dome-shaped Sn on Cu columns were formed by electroplating and a reflow process, and were used for this study. COG bonding was performed between the reflowed Sn/Cu bumps on the oxidized Si wafer and an indium tin oxide/Au/Cu/Ti/glass substrate using a thermo-compression bonder. Three types of NCAs were applied during COG bonding: NCA-A with no fillers, NCA-B with fluoropolymer fillers, and NCA-C with silica fillers. Thermal cycling from −25°C to 125°C for 2000 cycles was performed to evaluate the effect of NCA type on the reliability of COG joints. The initial contact resistance values of the COG joints ranged from 32.2 mΩ to 39.3 mΩ. The contact resistance increased during the thermal cycling and the trend of contact resistance increment was different among three NCA types. The failure rate was the highest in NCA-C, followed by NCA-B and NCA-A in descending order. After the thermal cycling, the cross-sections of COG joints were observed with scanning electron microscopy to analyze the failure mechanism. The failures occurred primarily due to trapped fillers and NCAs at the interface between Sn/Cu bumps and the ITO substrate. [doi:10.2320/matertrans.M2011207]

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1. Introduction

Chip-on-glass (COG) bonding is widely used for driver integrated circuit (IC) packaging in flat panel displays.1–7) In this COG technology, the driver IC is directly mounted on the liquid crystal display module by the flip chip method. COG technology offers both the thinnest packaging options and the smallest packaging area. The most common COG technology currently used in display applications is based on anisotropic conductive film.6–10) The principle of COG bonding using anisotropic conductive film is that the electrical connections are established through conductive particles and the mechanical interconnections are maintained by the adhesive.6) Recently, COG bonding using a nonconductive adhesive (NCA) has been reported.11–14) This technology realizes the direct electrical contact between bumps on a chip and pads of the substrate. COG bonding using NCA has several advantages, including facilitation of fine pitch bonding, reduced materials cost, and superior electrical performance. However, failure may occur from thermal strain due to thermal expansion mismatch between the chip and glass during thermal cycling.5,12) In general, silica filler is added to NCA to release thermal strain by reducing the coefficient of thermal expansion (CTE) of NCA.5,15) Effects of silica filler addition to nonconductive paste (NCP), anisotropic conductive adhesive, and underfill materials have been reported.15–17) Jang et al.15) improved thermomechanical properties of NCPs, such as CTE, modulus, and glass transformation temperature ($T_g$), by controlling the silica filler content. Yim et al.16) also reported that the incorporation of silica nonconductive fillers into the anisotropic conductive adhesive improves the material property, resulting in better reliability of anisotropic conductive adhesive flip chip assembly on an organic substrate. Chan et al.17) also reported that the CTE of underfill materials was decreased by adding silica filler to increase device reliability performance. However, as silica filler content increases, NCA has a poor dispensability due to an increase in the viscosity.15) Additionally, as hard silica filler is easily trapped in a soft bump during bonding, trapped fillers may induce an increase in the contact resistance.18) Therefore, it is very important to clarify the effect of filler addition in NCA in COG bonding technology.

We recently developed an ultra fine pitch COG bonding technology using Sn/Cu bumps and NCA. Our previous study reported that the hemispherical Sn/Cu bumps were very effective to compensated the bump height non-uniformity, to control the excessive deformation of Sn bumps that caused the bridging between neighboring bumps, and to reduce the NCA trapping.5) However, the effects of silica or polymer filler addition on the reliability were unclear since the reliability test condition was not severe. In this study, we evaluated the effect of NCA type using a severe reliability test. The thermal cycling test from −25°C to 125°C for 2000 cycles was performed in the COG joints, and the variation in contact resistance during thermal cycling was monitored.

2. Experimental Procedure

Figure 1 shows the process flow of the experiment. COG joints were formed between the Si chip and glass substrate to investigate the effects of NCAs during thermal cycling. To form under bump metallization (UBM) and interconnection lines, we deposited the thin films onto the oxidized Si wafer by DC magnetron sputtering in this order, Ti (50 nm), Cu (1 μm), Au (100 nm) and Ti (50 nm). Additionally, we deposited the thin films onto a glass substrate (Corning® 1737 glass) by DC magnetron sputtering in this order, Ti (50 nm), Cu (1 μm), Au (50 nm) and indium tin oxide (ITO) (100 nm). The metal patterns for UBM and the interconnections were fabricated through a photolito-
The bumps used in this experiment were Sn (4 μm)/Cu (12 μm) double-layer bumps. The Sn/Cu bumps were formed by electroplating, and dome-shaped Sn bumps were formed on Cu columns by reflow. The reflow process was performed at 275°C for 10 s using a rapid thermal annealing (RTA) system with no flux. COG bonding was performed between the reflowed Sn/Cu bumps on the oxidized Si wafer and the ITO/Au/Cu/Ti/glass substrate at 90 MPa using a thermo-compression bonder after the NCA was dispensed. To investigate the effect of NCA type, three different NCAs were used in this experiment, as shown in Table 1. NCA-A contained no fillers, NCA-B contained fluoropolymer fillers and NCA-C contained silica fillers. The bonding was performed at 110°C for 10 s for NCA-A and at 150°C for 90 s for NCA-B and NCA-C.

The contact resistance of each COG joint was measured using the four-point probe method after each time interval. A joint with a contact resistance greater than 200 mΩ was regarded as a failed bump. To analyze the failure mechanism, the cross-sections of the COG joints were characterized by scanning electron microscopy (SEM).

### 3. Results

#### 3.1 Formation of Sn/Cu bumps and COG joints using a 30 μm pitch size

Figure 2 shows the electroplated Sn/Cu bumps successfully electroplated on a metal line and in an area array pattern. The thickness of the Cu bumps was approximately 12 μm, while that of the Sn bumps was approximately 4 μm. After reflow, the Cu columns remained unchanged, and Sn capping layers changed to dome-shaped bumps, as shown in Fig. 3. Reflowed Sn/Cu bumps were well aligned, and no bridging between neighboring bumps was observed. The surfaces of the Sn/Cu bumps became smoother after the reflow process. These Sn/Cu bumps were shaped similar to those in our previous study.

Figure 4 represents a typical 30 μm pitch COG joint bonded at 90 MPa. After bonding, the deformation of reflowed Sn/Cu bumps was observed, and contact was successfully achieved between the Sn/Cu bump and the ITO/Au/Cu/Ti/glass substrate. A portion of the Sn bump was removed from the ITO/Sn interface due to the heavy deformation; however, no bridging was observed between neighboring bumps. NCA trapping was not observed at the COG joints with NCA-A (no filler), as shown in Fig. 4. The trapping of NCA and filler was observed at the interfaces of COG joints with NCA which contained fillers. NCA and filler were trapped more in the COG joints with NCA-C which contained silica fillers. The initial average contact
resistances of the COG joints are shown in Table 2. The initial contact resistance values of all COG joints were measured between 32.2 m\(\Omega\) and 39.3 m\(\Omega\), and none of the COG joints experienced electrical failure. These initial contact resistance values were slightly greater than our previous values. Nevertheless, all joints had a very low contact resistance value, regardless of the NCA type.

### 3.2 The reliability test of COG joints during thermal cycling

Thermal cycling was performed up to 2000 cycles to evaluate the effect of NCA type. The variations in contact resistance of the COG joints during thermal cycling up to 2000 cycles are shown in Fig. 5. The contact resistance increased during thermal cycling, regardless of NCA type. However, the incremental changes in contact resistance were different for the three NCA types. The contact resistance of the COG joints bonded with NCA-A increased to approximately 111.7 m\(\Omega\) after 2000 cycles, and no failure was observed. The contact resistance of the COG joints bonded with NCA-B increased to approximately 172.7 m\(\Omega\) after 2000 cycles, and failures were observed after 1500 cycles. The contact resistance of the COG joints bonded with the NCA-C increased to approximately 595.6 m\(\Omega\) after 2000 cycles, and failure was observed after 500 cycles. The failure rates of the COG joints are shown in Fig. 6. The failure rate of the COG joints increased with thermal cycling and reached 35.1% after 2000 cycles for NCA-B, while that for NCA-C was 77%. However, the COG joint with NCA-A, which did not contain fillers, survived up to 2000 cycles without failure.

### 3.3 Microstructural characterization after thermal cycling

When bumps were viewed from the top, the shapes of the bumps were rectangular (14 \(\mu\)m \(\times\) 32 \(\mu\)m). The cross-sectional images of the COG joints bonded with three NCAs after thermal cycling are shown in Fig. 7. Figures 7(a1), (b1) and (c1) illustrate the cross-sectional images viewed from the narrow side of the bump, and Figs. 7(a2), (b2) and (c2) are the cross-sectional images viewed from the wide side of the bump. Figures 7(a3), (b3) and (c3) are the magnified images of Fig. 7(a1), (b1) and (c1), respectively. In all COG joints, thick Cu\(_3\)Sn and Cu\(_6\)Sn\(_5\) layers were observed between Sn and Cu bumps. The Sn phase remained, even though Sn reacted with Cu to form intermetallic compounds during thermal cycling. Trapped NCA and fillers were not observed in the COG joints bonded with NCA-A (Fig. 7(a)), while they were clearly observed in Sn/ITO interfaces of the COG joints bonded with NCA-B and NCA-C, as shown in Figs. 7(b) and (c). In the COG joints bonded using NCA-C, delamination was also observed near the trapped NCA and fillers in Sn/ITO interfaces after thermal cycling.

### 4. Discussion

The 30 \(\mu\)m pitch COG joints were successfully fabricated using the Sn/Cu bumps and three different NCAs. The plastic
deformation of soft Sn compensates for the bump height non-uniformity. Since Sn is softer than Cu, only the Sn bump was deformed, and Cu columns remained unchanged during bonding. Therefore, Sn/Cu bumps can effectively prevent electrical short due to excessive deformation of Sn bumps. In COG bonding with NCAs or NCPs, the bumps are in direct contact with the pads on the glass substrate, and this mechanical contact is maintained through tight contact with NCA or NCP. During thermal cycling, the glass substrate expanded more than the Si wafer chip, and thermal stress was generated by the thermal expansion mismatch between the Si and glass. This thermal stress caused the contact pressure to decrease, and the contact resistance of COG joints increased during thermal cycling (Fig. 5).

The adhesive redistributes the stress and strains from the CTE mismatch by tightly adhering to the chip, bumps, and substrate. This role of NCA is similar to that of the underfill material. Additionally, various fillers were added to NCAs or NCPs to improve the thermal and electrical properties of NCAs or NCPs materials. Silica fillers were also added to NCAs or NCPs to reduce the CTE of NCAs or NCPs. In our study, NCA-C, which contained silica filler, had the lowest CTE, as shown in Table 1. Silica fillers with various sizes from 1 μm to 3 μm were distributed in whole NCA-C. It was previously reported that, when the CTE of the adhesive layer is relatively low, the strain in the adhesive layer can be lowered due to the smaller CTE mismatch between the adhesive layer and chip/substrate. As the induced shear strain in the adhesive layer was reduced, thermal cycling reliability improved. It was reported that a flip-chip assembly with an NCP with a lower CTE and higher modulus due to silica filler addition has good reliability performance in thermal cycling. Polymer fillers have also been added to NCAs or NCPs to reduce the dielectric constant (low-k). It was reported that a low dielectric constant polymer adhesive was fabricated by the incorporation of low-k filler in anisotropic conductive film for high-frequency interconnection material. However, polymer filler does not affect the CTE. The NCA-B, which contained polymer filler, had a similar CTE to that of NCA-A that has no fillers (Table 1). As shown in Fig. 5 and Fig. 6, the COG joints with NCA-A and NCA-B had different reliability performances, although their CTEs are similar. Additionally, although the CTE of NCA-C was the lowest, the reliability performance of COG joints with NCA-C was the poorest. Therefore, other effects of fillers on the reliability of COG joints are implicated in the present experiment.

When the bonding process was performed, NCAs were trapped between bumps and pads. As the amount of trapped NCAs increased, the contact resistance slightly increased because the contact area decreased. If hard fillers were added to the NCA, it was easily embedded in the soft Sn during bonding because the Sn has a low hardness and the high plastic deformation capability. Once the filler was trapped between Sn bumps and ITO pads, the NCA was also trapped near the filler because a gap between the fillers and Sn bump was formed, into which NCA easily flowed. Additionally, as the filler was harder, more NCA and filler were trapped because harder filler was easily embedded in the soft Sn bump. As a result, NCA and
fillers were trapped to a lesser degree in the COG joints using NCA-B compared to those using NCA-C because the silica with NCA-C is harder than the fluoropolymer with NCA-B. Since the thermal expansion of NCA is greater than that of Sn bumps, the trapped NCA expanded when it was heated. Finally, the trapped NCA and fillers generated cracks and delamination, causing an increase in contact resistance during thermal cycling.18) In the previous paper where the silica filler addition improved the reliability, Au stud bumps were used for bonding with NCP.15) Due to the geometry of Au stud bump, NCA and filler were not trapped between the ITO pads and the bumps. Therefore, NCA and filler trap was not important. In our experiment, COG joints treated with NCA-A that did not contain fillers had the lowest amount of trapped NCAs and the best performance (Figs. 5 and 6). Although filler addition can reduce the thermal expansion of NCA, it increased the amount of trapped NCAs between the bump and pad interfaces. Trapped NCAs caused an increase in contact resistance and decreased thermal cycling reliability. These results suggest that the disadvantages of filler addition are much greater than the advantages.

5. Conclusions

We investigated the effect of fillers in NCA on COG joints formed using Sn/Cu bumps and three NCA types during thermal cycling up to 2000 cycles. Contact resistance increased during thermal cycling. The increase of contact resistance differed from NCA types during thermal cycling. After 2000 cycles, the COG joints using NCA-A, which did not contain fillers, had the lowest contact resistance and no failed bumps among the COG joints using NCAs. If filler were included in NCA, NCA was easily trapped between the Sn bumps and the pads because the hard filler was easily embedded in the soft Sn bumps. Delamination and cracks were generated because the trapped NCA expanded during thermal cycling. Finally, the contact resistance increased, and failed bumps were generated. As a result, the trapping of fillers and NCA at the interfaces between Sn/Cu bumps and the ITO substrate was the main reason for failures.

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