A Study on the Conductive Particle Movements in Polyvinylidene Fluoride Anchoring Polymer Layer Anisotropic Conductive Films for 20-μm Fine-Pitch Interconnection


Abstract—Fine-pitch interconnection technology in electronic packaging has become very important because of electrical interconnection issues such as high contact resistance and open-/short-circuit failure. Nanofiber anisotropic conductive films (ACFs) and nanofiber sheet ACFs (NS ACFs) have been developed and reported by our research group to address the challenges for fine-pitch interconnection problems. However, they require complicated fabrication processes such as electrospinning, thermal compression, and plasma etching. In this paper, anchoring polymer layer (APL) ACFs and their fabrication process are introduced. The goal in employing the APL ACFs was to simplify the complex fabrication steps of nanofibers and NS ACFs by coating methods without compromising electrical performance. With the APL coating method, the electrospinning, thermal compression, and plasma etching steps can be reduced to a single process. Nonetheless, APL ACFs exhibit excellent electrical conduction at 20-μm fine-pitch interconnections by successfully suppressing the movement of conductive particles in the ACF. The capture rate of the APL ACFs was 78%, which was comparable to the value 81% of NS ACFs. APL ACFs open the possibility of cost-effective production of ACF interconnection materials for fine-pitch applications. Therefore, we use the word “anchoring” to suppress the movement of conductive particles during resin flow. In this paper, we discuss the fabrication process of APL structure and electrical properties of APL ACFs.

Index Terms—Anchoring polymer layer (APL), anisotropic conductive films (ACFs), fine-pitch interconnection, nanofiber ACFs, particle movement.

I. INTRODUCTION

The demand for higher resolution display devices such as smart phones, tablets, and televisions has risen dramatically over the past two decades. Large-screen televisions with ultra-high-definition (UHD) technology have rapidly replaced the high-definition (HD) display market after the development of 4K resolution technology. Furthermore, the virtual reality display industry, one of the most promising growth engines for near future industry, requires even higher resolution than the UHD resolution. Fine-pitch electronic packaging technology is a key element to realize high-resolution display products.

In display packaging and interconnection, chip-on-flex and chip-on-glass (COG) assemblies are the major interconnection methods for delivering an electrical signal from display driver chips to display panels. In order to provide electrical interconnections and mechanical attachment between chips and flexes or glasses, anisotropic conductive films (ACFs) have been widely used [1]. However, in fine-pitch interconnection, the pitch and the space between electrodes have become extremely finer, as the number of input/output pins has increased within the limited space. As a consequence, flip-chip bumps on a driver chip become longer in length and narrower in width. It has become more difficult to capture conductive particles in ACFs on the bumps, thus resulting in higher contact resistance or open-circuit failure. Moreover, the narrow space between bumps has caused the conductive particles to agglomerate between neighboring bumps, resulting in short-circuit failures [2], [3].

To resolve these challenges for fine-pitch interconnection, nanofiber ACFs and nanofiber-sheet (NS) ACFs were introduced by our research group [4], [5]. It was reported that the nanofiber ACFs and NS ACFs could solve the fine-pitch interconnection issues. By using the nanofiber and NS structures, the movement of conductive particles in ACFs could be successfully suppressed during the ACFs bonding process. Despite the advantages of the nanofiber and NS ACFs, the process of incorporating conductive particles into the nanofibers is complicated and difficult to apply to mass production. Moreover, NS ACFs require additional fabrication processes such as thermal compression and plasma etching.

In this paper, anchoring polymer layer (APL) ACFs have been introduced to overcome the production limit of the nanofiber and NS ACFs, and to address the problems for fine-pitch interconnections in COG assembly. One of the major advantages of the APL ACFs is the simplicity of the fabrication methods. For the APL fabrication, a polyvinylidene fluoride (PVDF) solution containing conductive particles was coated as a thin polymer film by using a comma-roll coater.
which is widely used for lamination and coating processes. The thickness of the APL is less than the diameter of the conductive particles, and consequently all conductive particles are located on the same level. To analyze the suppression effects of APL ACFs, final positions of conductive particles were traced and compared to their initial positions. Finally, APL ACFs were compared with the conventional and NS ACFs in terms of conductive particle capture rate, contact resistance, and insulation resistance using ten samples, respectively. They are expected to provide stable electrical properties in fine-pitch interconnections.

II. EXPERIMENTS

A. Fabrication and Optimization of PVDF APL ACFs for COG Interconnection

For the fine-pitch COG test vehicles, silicon chips with 12-μm-height Au bumps having 20-μm pitch and a 7-μm bump gap were used. For glass substrates, 0.13-μm Ti/Au electrodes with 20-μm pitch and a 7-μm electrode gap were used. The COG test vehicles were designed to measure the contact resistance of the bump joints by Kelvin four-point probe patterns. For this pattern, current and voltage were applied to each electrode, and the contact resistance was measured at the joint where they meet. They were also designed to detect short-circuit failures by the insulation resistance patterns between 24 nearby joints [6].

For the APL ACFs, PVDF with a melting point of 168 °C was dissolved in a mixture of dimethylacetamide (DMAC) and acetone by following a conductive particles with a diameter of 3.25 (±0.5) μm for the polymer core shell, coated by 0.25 (±0.15)-μm Ni/Au metal coating layers. The mixture of solvent DMAC and nonsolvent acetone was used because it could help increase the tensile strength of the APL by softening the porous surface of the APL [7], [8]. The APL solution was then coated on a release film by a roll laminator at a temperature of 75 °C to evaporate the solvents and produce APL containing conductive particles in a film form. Finally, nonconductive films (NCFs) were laminated on the top and bottom of the APL to fabricate APL ACFs as shown in Fig. 1. The APL containing conductive particles was analyzed by focused ion beam (FIB) to measure its thickness around the conductive particles.

The fabricated APL ACFs were used to assemble a fine-pitch COG interconnection, as shown in Fig. 2. The APL ACFs were laminated on a glass substrate, and a chip was mounted on top of the glass substrate. Heat and pressure were then applied assembled by the thermo-compression bonding method at 160 °C and 70 MPa for 8 s. The chip and the glass substrate were electrically conducted by the captured conductive particles in the vertical direction, while they were electrically insulated in the horizontal direction by the APL.

B. Effects of PVDF APL on Conductive Particle Movement in APL ACFs

The tensile strength of the APL was the major factor to determine the effects of the APL on conductive particle movement in APL ACFs. A material with high tensile strength was expected to suppress the movement of the conductive particle effectively. Therefore, by doing an APL tensile strength test, we could predict the performance of APL ACFs. A tensile strength test was conducted to determine the ultimate tensile strength (UTS) of the APL by using an Instron 5583 machine in the D638 condition of American Society for Testing and Materials (ASTM) before and after surface modifications. The dimensions of the specimen neck were 3.18 mm × 9.51 mm × 0.004 mm, and the test speed was 10 mm/min at room temperature. The UTS of the APL was the major factor to determine the effects of the APL on conductive particle movement in APL ACFs, and they were also compared with the NS in the previous research.

After the thickness and the surface of the APL were optimized, an NCF lamination process was followed to fabricate APL ACFs. The movement of the conductive particles in the APL ACFs was compared before and after bonding by an optical microscope. Unlike the unpredictable movement of the conductive particles in conventional ACFs, it was expected that the actual moving path of the conductive particles in the APL ACFs could be observed. This was because the APL structure was expected to remain after the bonding process since the bonding temperature was lower than the melting temperature of the APL. The actual movement of the conductive particles in the APL ACFs was observed. Finally, four conductive particles were selected, the area of the quadrangle formed by these points was calculated, and the results were compared before and after the bonding process.

C. Characterization of the PVDF APL ACFs Joint Electrical Properties

After the 20-μm fine-pitch COG package was assembled by using the APL ACFs, a cross-sectional analysis of the APL ACFs joints was conducted to observe the remaining APL between the conductive particles and the bumps or electrodes. The electrical contact resistance of the single bump joints was...
the measured to detect any high contact resistance problem caused by the remaining APL. In addition, the insulation resistance between 24 neighboring joints was measured to search for any short-circuit failure at the 20-μm fine-pitch interconnection caused by agglomerated conductive particles between the bumps.

III. RESULTS AND DISCUSSION

A. Fabrication and Optimization of PVDF APL ACFs for COG Interconnection

The surface and thickness of the fabricated APL were analyzed and measured by a scanning electron microscope (SEM). Cross-sectional SEM images of each APL layer with 30, 25, and 20 wt% PVDF concentrations in the mixture of DMAC and acetone are shown in Fig. 3. Although the APL thickness of the 30 wt% PVDF was 4.5 μm, very thin polymer layers remained on the top and bottom of the conductive particles. As the concentration of the PVDF polymer decreased, the thickness of the APL also decreased. For the 25 wt% PVDF, the average thickness of the APL was decreased to 3.2 μm, which was almost the same as the diameter of the conductive particles. Finally, when the polymer concentration was decreased to 20 wt%, the average thickness of the APL was 2.2 μm, which was even smaller than the diameter of the conductive particles as shown in Fig. 4. As a result, all the conductive particles were located in the monolayer APL structure, and their metal surfaces were partially exposed by a coating method as shown in Fig. 4(a) and (b), without the plasma-etching process required for the NS layer. Also, the bottom of the conductive particles was exposed after the APL coating process. This was because the conductive particles made direct contact with the releasing film during the APL coating process.

The top surface of the conductive particles incorporated in the APL structure was analyzed by an FIB analysis. The maximum thickness of the APL on the top surface of the conductive particles was less than 150 nm as shown in Fig. 5. Although polymer layers were still remaining on the top surface of the conductive particles after the coating process, measurements indicate that this 150-nm-thick PVDF layer was removed during the ACFs bonding process. In summary, the APL structure was successfully fabricated by a simple roll-to-roll coating process. The concentration of PVDF in the mixture of DMAC and acetone was optimized at 20 wt%, where the thickness of the APL was 2.2 μm and the polymer layer around the conductive particles was less than 150 nm thick.

B. Effects of PVDF APL on Conductive Particle Movement in APL ACFs

The tensile strength test of the PVDF APL was conducted based on ASTM standards to determine the mechanical properties of the APL. The UTS of the APL was 57.8 MPa, which was similar to that of NS reported in previous research. Therefore, a high suppression effect of conductive particle movement by the APL was expected.

Unlike the conventional ACFs, the moving path of the conductive particles in APL ACFs can be observed by comparing their displacement before and after ACFs bonding, as shown in Fig. 6. It was clearly observed that every conductive particle...
including the whole APL structure moved certain distances and directions from the center of chip as a neutral point. This behavior cannot be observed in case of the conventional ACFs because of random movement of the conductive particles. This result could be explained by the bonding temperature, which was lower than the melting temperature of the APL. The APL still remained after ACFs bonding and rigidly incorporated the conductive particles together as shown in Fig. 7. The APL could endure the applied ACFs resin flow during the ACFs bonding process, and it could prevent the conductive particles from flowing out with the resin flow.

To calculate the capture rate of the APL ACFs, a number of conductive particles per a bump area 1040 μm² was counted and compared with the actual number of the conductive particles on the bump after bonding. Then, the result was compared with the conventional ACFs and the NS ACFs. For the conventional ACFs, about 40 conductive particles were needed to capture 12 particles on a bump after the ACFs bonding process, as shown in Fig. 8. For both NS ACFs and APL ACFs, about 15 conductive particles were needed to capture 12 particles on a bump, respectively. Both NS ACFs and APL ACFs showed about an 80% conductive particle capture rate. It was found that the APL ACFs significantly suppress the movement of the conductive particles and improve the conductive particle capture rate such that is on per with that of the NS ACFs.

Finally, we tried to identify the reasons for conductive particle movement after bonding despite the existence of the APL structure. The particle movement behaviors in the APL were divided into two different sections as shown in Fig. 9. Section 1 is the participative section, and section 2 is the nonparticipative section. Section 1 was defined as the area where the conductive particles were actually captured between bumps, while the section 2 area did not participate in the bump joint bonding. The change in the area of each section was measured and calculated to determine the difference between two sections. To do so, the area of a quadrangle created by four conductive particles and arrangement around those particles were traced. After bonding, we could find the same particle...
array around the first four particles we selected. The area in section 1 was increased by 28.8% as indicated in Table I, whereas the area in section 2 was not changed. This could be explained by the elastic modulus equation and the relationship between stress and strain

$$E = \frac{\sigma(\varepsilon)}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{F}{A_0} \cdot \frac{L_0}{\Delta L}.$$  

When force is applied to an object, there is a ratio of extension to the original length called strain $\varepsilon$. $A_0$ and $L_0$ are the initial area and $x$-axis length of quadrangle area, respectively, and $L$ is the amount of change of the $x$-axis length after bonding process. For section 1, pressure and heat were applied due to the bumps after bonding, and compressive force was exerted on the APL in section 1, which eventually elongated the length of the APL and increased the area. However, for section 2, there was no change in area since there was no pressure applied by the bumps. This observation could be supported by additional experiments at different bonding temperature. The Young’s modulus of a polymer varies depending on the temperature, in that it decreases as the temperature increases. If the polymer is exposed to the temperature close to the melting temperature, the modulus significantly drops, as does the tensile strength. Table I shows the change in area depending on the bonding temperatures: 120 °C, 160 °C, and 200 °C. At 120 °C bonding temperature, the area changes $\Delta A$ in section 1 area was only 11.4%. As the bonding temperature was increased to 160 °C, $\Delta A$ increased to 28.8%, and finally, $\Delta A$ increased to 53.2% at 200 °C. However, there was only a minor $\Delta A$ for section 2 for all three bonding temperatures. Only 200 °C showed over 10% of $\Delta A$ because the temperature was over the melting temperature of APL and minor viscous force of the resin flow could elongate the APL. As the temperature increases, the modulus of elasticity decreases sharply and the elongation increases, resulting in increase in the APL area. As a result, the particle density in section 1 decreased and eventually the capture rate decreased as shown in Table II.

### Table I

<table>
<thead>
<tr>
<th>Bonding T</th>
<th>Change in PVDF APL area</th>
<th>Change in particle density of section 1</th>
<th>Capture rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 °C</td>
<td>11 %</td>
<td>-9.90 %</td>
<td>92 %</td>
</tr>
<tr>
<td>160 °C</td>
<td>29 %</td>
<td>-22.50 %</td>
<td>84 %</td>
</tr>
<tr>
<td>200 °C</td>
<td>53 %</td>
<td>-34.60 %</td>
<td>67 %</td>
</tr>
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#### C. Characterization of the PVDF APL ACFs Joints

**Electrical Properties**

The contact resistances of 20-μm fine-pitch COG assemblies using the APL ACFs were measured and compared with those of the conventional ACFs and the NS ACFs. At 160 °C bonding temperature, the average contact resistance of the conventional ACFs was 254 mΩ, while those of the NS ACFs and the APL ACFs were 244 and 222 mΩ, respectively. The contact resistances of all three ACFs were stable contact resistance under 500 mΩ. It was found that the roughly 150-nm-thick PVDF layer remaining on the top of the conductive particles of APL did not affect the electrical conduction between conductive particles and bumps as shown in Fig. 10. The anticipated 150 nm film over the particles gave fairly uniform and low resistance. Fig. 10 shows cross sections from measured bonds. This implies that the Ni/Au metal coating layer of the conductive particles in the APL ACFs directly contacted the bump and the electrode, as in the conventional ACFs, NS ACFs, and APL ACFs.

Electrical insulation resistances were then measured to detect any short-circuit failure in the 20-μm fine-pitch COG assembly using the conventional ACFs, NS ACFs, and APL ACFs. A total of 120 insulated circuits were measured for each ACF type, and the short-circuit rate was defined as the ratio of the short circuits to the total number of the insulated circuits after ACFs bonding. As a result, the conventional ACFs showed an 8.3% short-circuit rate, while the NS ACFs and the APL ACFs showed no short-circuit failure. Conventional ACF joints likely to be short circuits were observed as shown in Fig. 11. The conventional ACFs required very high conductive particle density of 45 K pcs/mm² to achieve stable...
Fig. 10. Cross-sectional SEM images of conductive particle joints by using (a) conventional ACFs, (b) NS ACFs, and (c) PVDF APL ACFs.

Fig. 11. Conductive particle movement of 20-μm-pitch COG assembly by using various ACFs.

electrical conduction in the fine-pitch interconnection. As a result, many conductive particles flew out during the bonding process, and agglomerated between two neighboring bumps resulting in a short-circuit failure. On the other hand, the APL ACFs required only 18 K pcs/mm² of conductive particle density due to the suppression effect of conductive particle movement and a higher capture rate. Moreover, the remaining APL prevented contact between the conductive particles and electrical shortage. Therefore, by using the APL ACFs, it was possible to significantly reduce the amount of conductive particles required for stable electrical conduction and excellent electrical insulation in the fine-pitch interconnection.

IV. CONCLUSION

A monolayer APL structure containing conductive particles was successfully fabricated by the comma-roll coating method. The thickness of the APL was around 1.5–2 μm, which was even smaller than the diameter of the conductive particles, and consequently the conductive particles could be located in a single level. The bottom surface of the conductive particles was mostly exposed, and a roughly 150-nm-thick PVDF layer was coated on the top of the conductive particles. The APL ACFs created excellent electrical conduction paths between bumps and electrodes, and stable contact resistance could be achieved without an additional plasma-etching process, especially required for the NS ACFs. In addition, the APL reduced the loss of particles during bonding which maintains the number of conductive particles required for stable contact resistance. By using the APL ACFs, the capture rate of conductive particles was dramatically increased from 31% to 78%. The remaining APL effectively suppressed the conductive particles movement and prevented the conductive particles from flowing out and agglomerating between bumps. As a result, the APL ACFs could prevent short-circuit failure in the 20-μm fine-pitch COG interconnections. The APL ACFs reduce the complicated fabrication processes of NS ACFs by employing a simple comma-roll coating method.

REFERENCES

Sang-Hoon Lee received the B.S. degree in mechanical engineering from Pennsylvania State University, University Park, PA, USA, in 2010, and the M.S. and Ph.D. degrees from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 2012 and 2017, respectively.

He is currently a Senior Engineer with the Package Development Team, Semiconductor R&D Center, Samsung Electronics, Hwasung, South Korea. His current research interests include the development of advanced anisotropic conductive films combined with nanofiber and anchoring polymer layer technologies for fine-pitch interconnection in electronic devices, thermal compression bonding, laser-assisted bonding, fan-out wafer-level package, and fan-out panel-level package.

Dal-Jin Yoon received the B.S. degree in materials science and engineering from the Sejong University, Seoul, South Korea, in 2014, and the M.S. degree from the Korea Advanced Institute of Science and Technology, Daejeon, South Korea, in 2016, where he is currently pursuing the Ph.D. degree with the Nano-Packaging and Interconnect Laboratory.

His current research interests include ultrafine-pitch interconnection technologies using anchoring polymer layer anisotropic conductive films for electronics application.

Kyung-Wook Paik received the B.S. degree in metallurgical engineering from Seoul National University, Seoul, South Korea, in 1979, the M.S. degree from the Korea Advanced Institute of Science and Technology (KAIST), Daejeon, South Korea, in 1981, and the Ph.D. degree in materials science and engineering from Cornell University, Ithaca, NY, USA, in 1989.

From 1982 to 1985, he was a Research Scientist with KAIST, where he was involved in the development of gold bonding wires. He was a Senior Technical Staff Member with the Interconnect Multichip Module Technology and Power IC Packaging, General Electric Corporate Research and Development, Brookline, MA, USA, from 1989 to 1995. In 1995, he joined the Department of Materials Science and Engineering, KAIST, as a Professor, where he is currently with the Nano-Packaging and Interconnect Laboratory and involved in flip-chip bumping and assembly, adhesive flip chips, embedded capacitors, and display packaging technologies.