Studies on various chip-on-film (COF) packages using ultra fine pitch two-metal layer flexible printed circuits (two-metal layer FPCs)

Kyoung-Lim Suk a, Kyosung Choo b, Sung Jin Kim b, Jong-Soo Kim c, Kyung-Wook Paik a,⇑

a Department of Materials Science and Engineering, KAIST, 335 Gwahak-Ro Yuseong-Gu, Daejeon 305-701, Republic of Korea
b Department of Mechanical Engineering, KAIST, 335 Gwahak-Ro Yuseong-Gu, Daejeon 305-701, Republic of Korea
c STEMCO, Ochang Scientific Industrial Complex, 1111-4 Namchon-ri, Oksan-Myun, Cheongwon-gun, ChungCheng Buk-do 363-911, Republic of Korea

ABSTRACT

Various fine pitch chip-on-film (COF) packages assembled by (1) anisotropic conductive film (ACF), (2) nonconductive film (NCF), and (3) AuSn metallurgical bonding methods using fine pitch flexible printed circuits (FPCs) with two-metal layers were investigated in terms of electrical characteristics, flip chip joint properties, peel adhesion strength, heat dissipation capability, and reliability. Two-metal layer FPCs and display driver IC (DDI) chips with 35 µm, 25 µm, and 20 µm pitch were prepared. All the COF packages using two-metal layer FPCs assembled by three bonding methods showed stable flip chip joint shapes, stable bump contact resistances below 5 mΩ, good adhesion strength of more than 600 gf/cm, and enhanced heat dissipation capability compared to a conventional COF package using one-metal layer FPC. A high temperature/humidity test (85 °C/85% RH, 1000 h) and thermal cycling test (T/C test, –40 °C to + 125 °C, 1000 cycles) were conducted to verify the reliability of the various COF packages using two-metal layer FPCs. All the COF packages showed excellent high temperature/humidity and T/C reliability, however, electrically shorted joints were observed during reliability tests only at the ACF joints with 20 µm pitch. Therefore, for less than 20 µm pitch COF packages, NCF adhesive bonding and AuSn metallurgical bonding methods are recommended, while all the ACF and NCF adhesives bonding and AuSn metallurgical bonding methods can be applied for over 25 µm pitch COF applications. Furthermore, we were also able to demonstrate double-side COF using two-metal layer FPCs.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

As the demand for portable electronics increases, electronic packages having multi-functionality, higher density, and smaller size become necessary [1–5]. In particular, multi-functionality of the display driver IC (DDI) of handheld devices requires finer pitch chip-on-film (COF) packages. According to this trend, there have been some packaging technologies under development in terms of COF package design and process modification [6–10]. One of the new approaches to realize finer pitch COF packages is the modification of flexible printed circuits (FPCs) with ultra fine pitch as well as double-side electroplate layers (referred as two-metal layer FPCs) [11,12]. Two-metal layer FPCs having ultra fine pitch show excellent advantages, such as higher density, higher functionality due to finer pitch, and enhanced heat dissipation capability because of larger metal area compared with conventional FPCs (one-metal layer FPCs). Furthermore, two-metal layer FPCs can also solve the assembly yield problem of fine pitch FPCs with one-metal layer by locating some portion of circuits at the backside of FPCs. Therefore, two-metal layer FPCs with higher assembly yield and better heat dissipation capability can be applied to various electronic products such as cell phones, MP3, notebook computers, and so on.

The key technologies to fabricate fine pitch two-metal layer COF packages are manufacturing fine pitch FPCs with two-metal layers and achieving good alignment between the chip and substrate during the flip chip bonding process. When pattern pitches become finer below 30 µm, the manufacturability of FPCs becomes poor and some patterns are even short because of a poorly etched area [5,6]. To make two-metal layer FPCs having accurate pattern shape and pitch, a semi-additive process was adapted. In the semi-additive process, Cu is electro-plated after dry film lamination and development for pattern formation. The procedure is shown in Fig. 1. The manufactured two-metal layer FPCs had precise 20 µm patterns both on the top and bottom side of a polyimide and the via land size were 80 µm (Fig. 2). Bonding alignment accuracy was ± 3 µm at 20 µm pitch considering the coefficient of thermal expansion (CTE) of a two-metal FPC and a DDI chip. In this research, we demonstrate fine pitch COF packages with two-metal layers by ACF, NCF adhesive bonding and AuSn metallurgical bonding methods, and investigate the packages from the perspectives of assembly manufacturability, electrical properties, peel adhesion strength, heat dissipation capability, and reliability.

⇑ Corresponding author. Tel.: +82 42 350 3375; fax: +82 42 350 8124. E-mail address: kwpai@kaist.ac.kr (K.-W. Paik).
2. Experiments

2.1. Test vehicles

For this study, fine pitch DDI chip, two-metal layer FPC, ACF, and NCF adhesives were prepared. The DDI chip size is 16 mm × 1.5 mm with 700 μm thickness, and the chip has 1163 peripheral I/O of electroplated Au bumps with dimensions of 12 μm width, 80 μm length, and 10 μm height. The chips have various bump pitches, 35 μm, 25 μm and 20 μm (Fig. 3). Two-metal layer FPCs contain top and bottom Cu electrodes connected to each other by via and they also include various pad pitches matched with DDI chips (Fig. 4). The specifications of test samples are listed in Table 1. The chip and substrate have four-point structures for bump contact resistance measurements and four insulation patterns for insulation resistance measurements between nearby bumps, as shown in Fig. 5. Thirty-six μm thick NCF and 35 μm thick ACF having conductive particles of 3.5 μm diameter coated with an insulation layer were used as interconnecting adhesives.

2.2. Characterization of ACF and NCF materials

Characterization of adhesives is important to determine the optimal bonding temperature and time and also to understand the reliability of the packages. Curing behavior was measured by a differential scanning calorimeter (DSC, Perkin Elmer DSC 7) from 30 °C to 250 °C at a heating rate of 10 °C/min and thermo-mechanical properties were measured by thermo-mechanical analyzer (TMA, Seiko EXSTAR 6000). The coefficients of thermal expansion (CTEs) were calculated from the dimensional changes of cured adhesives versus temperature from 30 °C to 250 °C with a heating...
2.3. Demonstration of fine pitch two-metal layer COF packages using various bonding methods

Fine pitch two-metal layer COF packages were demonstrated using three kinds of bonding methods: ACF and NCF adhesives bonding, and AuSn metallurgical bonding. ACF bonding was performed using a flip chip bonder. In the ACF bonding process, polymer resin flows and is subsequently cured, while conductive particles are captured between chip bumps and FPC electrodes. NCF bonding is similar to the ACF bonding procedure except that there are no conductive particles in adhesive resin. Considering the curing characteristics of ACF and NCF, bonding parameters were optimized. The actual ACF and NCF bonding temperature measured by a thermo-meter was 200 °C when the tool temperature was 255 °C and stage temperature was 65 °C. At this temperature, the curing times of ACF and NCF were 11.5 s and 11 s, respectively (Table 2). To obtain fully cured adhesives, the bonding process was conducted for 15 s at 200 °C. The curing ratio of adhesives was calculated through FT-IR (IFS66v/s & Hyperion3000, Bruker) measurement comparing the epoxy peak area around 910–1700 cm⁻¹. The absorbance spectra were normalized by the peak of the benzene ring around 1507 cm⁻¹. The optimal bonding pressure was determined as 60 MPa in terms of stable joint shapes and bump contact resistances. The metallurgical bonding method is different from adhesive bonding from the perspective of metal-lurgy formation in flip chip joints. During AuSn bonding process, AuSn phases are made. The fine pitch COF packages with two-metal layers manufactured by three kinds of bonding methods were electrically tested (using Keithley 236 source-measurement equipment), and cross-sectional flip chip joints were observed (using field emission SEM, Hitachi S-4800). Optimized bonding conditions are summarized in Table 3.

2.4. Characterization of fine pitch two-metal layer COF packages

The fine pitch two-metal layer COF packages were characterized in terms of electrical, mechanical, and thermal properties as well as reliability. Electrical properties were investigated by the measurements of bump contact resistance and insulation resistance due to their importance in fine pitch packages since several μm mis-align-ment or agglomerated conductive particles between patterns in the case of ACF bonding can result in an electrical short. The short criterion was set as 10⁸ Ω. If the measured insulation resistance was below 10⁸ Ω, it was determined as electrical short. The 90°C peel adhesion test at a speed of 30 mm/min was performed to measure adhesion strength between chip and two-metal layer FPCs, and then the failure site was observed by optical microscope. The thermal property was characterized by measuring the flip chip joint temperature to find out how effective the two-metal layer COF package was for dissipating heat compared to a one-metal layer COF package. Then, the heat transfer was simulated using the ICEPAK program. For reliability evaluation, a high tempera-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Specifications of test DDI chip and 2-metal layer FPC.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DDI chip</strong></td>
<td><strong>Chip size</strong></td>
</tr>
<tr>
<td>I/O configuration</td>
<td>Peripheral array</td>
</tr>
<tr>
<td>Bump materials</td>
<td>Electroplated Au</td>
</tr>
<tr>
<td>Bump size</td>
<td>12 μm (w) × 80 μm (l) × 10 μm (h)</td>
</tr>
<tr>
<td>Bump pitch</td>
<td>35 μm, 25 μm, and 20 μm</td>
</tr>
<tr>
<td>Gap between bumps</td>
<td>22 μm, 12 μm, and 7 μm</td>
</tr>
<tr>
<td><strong>2-Metal layer FPC</strong></td>
<td><strong>FPC size</strong></td>
</tr>
<tr>
<td>Cu electrode with Sn</td>
<td>Top: 7 ± 0.3 μm</td>
</tr>
<tr>
<td>finish</td>
<td>Bottom: 9 ± 0.3 μm</td>
</tr>
<tr>
<td>Inner lead pitch</td>
<td>35 μm, 25 μm, and 20 μm</td>
</tr>
<tr>
<td>Hole/land size of via (μ)</td>
<td>25/80 μm</td>
</tr>
</tbody>
</table>

rate of 5 °C/min under a 100 mN uniaxial tensile load. The modulus and the glass transition temperature ($T_g$) were obtained using dynamic mechanical analyzer (DMA) by measuring the storage modulus and the loss tangent (tan $\delta$) of adhesives under sinusoidal force of 100 mN at 0.02 Hz from 30 °C to 250 °C at a heating rate of 5 °C/min.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Curing behavior of ACF and NCF by DSC measurement.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td><strong>Onset temperature (°C)</strong></td>
</tr>
<tr>
<td>ACF</td>
<td>80.5</td>
</tr>
<tr>
<td>NCF</td>
<td>79.9</td>
</tr>
</tbody>
</table>

Fig. 5. Electrical test patterns (a) four-point structure for a bump contact resistance measurement and (b) an insulation pattern for an insulation resistance measurement.

Table 3

| Optimized bonding conditions for fine pitch 2-metal layer COF packages. |
| --- | --- | --- | --- |
| **Bonding conditions** | **ACF bonding** | **NCF bonding** | **AuSn metallurgical bonding** |
| Tool temperature (°C) | 255 | 255 | None |
| Stage temperature (°C) | 65 | 65 | |
| Pressure (MPa) | 60 | 60 | |
| Time (sec) | 15 | 15 | |
| Underfill curing/Sn diffusion | None | None | 120 °C, >40 min/150 °C, >120 min |
ture/humidity test (85 °C/85% RH, 1000 h) and thermal cycling test (T/C test, −40 to 125 °C, 1000 cycles) were performed.

3. Results and discussion

3.1. Material properties of ACF and NCF

The curing behavior of ACF and NCF were listed in Table 2. The adhesives start to cure from the onset temperature and the complete curing times of adhesives at 200 °C are 11.5 s and 11 s, respectively. Therefore, the bonding conditions were set up at 200 °C for 15 s (a tool temperature of 255 °C and a stage temperature of 65 °C for a flip chip bonder). The Tgs of ACF and NCF are 127.7 °C and 121.1 °C, respectively, as shown in Table 4. Above Tg, adhesives become rubbery, therefore, a higher Tg of adhesives is required to have better reliability of COF packages.

3.2. Fine pitch two-metal layer COF packages using various bonding methods

Fig. 6 shows the demonstrated fine pitch two-metal layer COF package using optimized bonding conditions, as summarized in Table 3. The curing percent of ACF and NCF was more than 90% at the bonding conditions. More than 90% curing percent is needed to guarantee good package performances [13]. The bump contact resistances of ACF and NCF bonding generally decrease and stabilize as the bonding pressure increases, but bonding pressures that are too high can deteriorate the bump contact resistances and packages’ reliability [14,15]. In this experiment, 60 MPa produced stable bump contact resistance values. The contact resistances of the fine pitch two-metal layer COF packages using ACF, NCF, and AuSn metallurgical bonding methods are 3.3 ± 1.2 mΩ, 2.7 ± 1.1 mΩ, and 3.6 ± 0.4 mΩ, respectively, regardless of bump pitches (35 μm, 25 μm, and 20 μm). Fig. 7 shows the joint shapes of 20 μm pitch of COF packages using ACF, NCF, and AuSn metallurgical bonding methods. In ACF and NCF bonding, bump contact with electrode through conductive particles and direct bump con-

<table>
<thead>
<tr>
<th>Thermo-mechanical properties</th>
<th>ACF</th>
<th>NCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTE change above Tg</td>
<td>1500 ppm/°C</td>
<td>3700 ppm/°C</td>
</tr>
<tr>
<td>Tg (°C)</td>
<td>127.7</td>
<td>121.1</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>0.86</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Fig. 6. The demonstrated fine pitch two-metal layer COF packages.

Fig. 7. Cross-sectional SEM images of 20 μm pitch two-metal layer COF packages using (a) ACF, (b) NCF, and (c) AuSn metallurgical bonding methods.

Fig. 8. The bump contact resistances of fine pitch two-metal layer COF packages using (a) ACF, (b) NCF, and (c) AuSn metallurgical bonding methods.
tact with electrode were obtained. In AuSn metallurgical bonding, 
AuSn alloy joint was observed. It is concluded that the fine pitch 
two-metal layer COF packages were successfully demonstrated 
using ACF, NCF, and AuSn metallurgical bonding methods.

3.3. Characteristics of fine pitch two-metal layer COF packages

3.3.1. Electrical properties

The bump contact resistances and insulation resistances of two-
metal layer COF packages were measured. Fig. 8 shows the results 
of the bump contact resistance of COF packages using ACF, NCF, 
and AuSn metallurgical bonding methods. The resistances of the 
ACF bonding method were below 5 mΩ at all three of the bump 
pitches, 35 μm, 25 μm, and 20 μm. NCF and AuSn metallurgical 
bonding methods also showed similar values regardless of bump 
pitches. These results match well with the flip chip joint observa-
tions shown in Fig. 7. To determine the fine pitch capability of 
COF packages depending on various bonding methods, insulation 
resistances were measured with the criterion of 10⁸ Ω. As the 
bump pitches become finer, a few μms of mis-alignment can cause 
an electrical short between bumps [16,17]. Fig. 9a shows the 
acceptable insulated rate of various bump pitches, which means 
the percent of insulated bumps whose values were over 10⁸ Ω. 
COF packages by the ACF bonding method had a 100% acceptable 

![Fig. 9. Bump insulation properties of fine pitch two-metal layer COF packages using 
ACF bonding method (a) at various bump pitches and (b) the optical image of 
agglomerated conductive particles between 20 μm pitch bumps resulting in bump 
shortage.](image)

![Fig. 10. The peel adhesion strength of fine pitch two-metal layer COF packages 
using various bonding methods.](image)

![Fig. 11. Flip chip joint temperature of two-metal layer COF vs. one-metal layer COF 
packages.](image)

![Fig. 12. The simulated temperature distribution of (a) two-metal layer COF and (b) 
one-metal layer COF, and flip chip joint temperature of (c) two-metal layer COF and 
(d) one-metal layer COF.](image)
insulated rate at both 35 µm and 25 µm pitches. However, about 5% were shorted at 20 µm pitch due to the agglomerated conductive particles between bumps, as shown in Fig. 9b. These results are well matched with existing reports about fine pitch limitation of using ACF bonding [16,17]. Therefore, the ACF bonding method can be applicable to above 20 µm pitch. NCF and AuSn bonding methods showed stable insulation, even at 20 µm pitch.

3.3.2. Peel adhesion strength

Fig. 10 represents the peel adhesion strength of the packages using various bonding methods. The adhesion strength of the ACF bonding method was slightly higher than those of NCF and AuSn metallurgical bonding methods because ACF more bled out around bonding area during the bonding process. The failure sites of all the packages were the electrode itself, the inner adhesive, the interface of the chip/adhesive, and the interface of the FPC/adhesive. The adhesion strengths of all COF packages were higher than 600 gf/cm, which is the typical industrial standard.

3.3.3. Heat dissipation capability

To analyze the heat transfer characteristics of the two-metal layer COF packages, the heat dissipation capability of the COF packages were compared with one-metal layer COF packages. A heater was attached to the chip surface of the COF packages. The top surface of the heater was in a free convection condition and Al block was attached at the bottom surface of the packages. A K-type thermocouple with a diameter of 20 µm was inserted at the flip chip joint to measure the joint temperature. Fig. 11 shows the flip chip joint temperature of both COF packages under various applied powers. The joint temperature of one-metal and two-metal layer COFs increased to 126.2 °C and 101.1 °C, respectively, at a fixed applied power of 40 W. The two-metal layer COF showed a flip chip joint temperature 25 °C lower than that of the one-metal layer COF due to higher heat dissipation through thermal via and bottom electrodes. For academic understanding, the experimental results were correlated with the simulation by ICEPAK 4.4.8, provided by FLUENT, Inc. ICEPAK is a well-known program for analyzing the heat transfer phenomena within an electronics package system. As schematized in Fig. 12, in addition to lower flip chip joint temperature, two-metal layer COF showed lower surface temperature as well, 99.3 °C compared to 126.9 °C. The experimental and simulated flip chip joint temperatures were similar to each other. Therefore, two-metal layer COF packages had significantly enhanced heat dissipation capability.

3.3.4. Reliability evaluation

Fig. 13 shows the contact resistance change of two-metal layer COF packages during a high temperature/humidity test (85 °C/85% RH, 1000 h). The contact resistances of COF packages by ACF, NCF, and AuSn metallurgical bonding methods were stable during the test. In addition, the packages showed excellent thermal cycling reliability (T/C test, -40 to 125 °C, 1000 cycles), as represented in Fig. 14.

3.3.5. Double-side COF package demonstration

In addition to these characteristics of single chip COF packages, good electrical, mechanical, thermal properties, and excellent reliability, higher density packages could be also demonstrated by double-side chips assembly. Fig. 15 shows flip chip joints of double-side COF assembly by a NCF bonding method. Both upper and bottom patterns were well aligned, even at 20 µm pitch, as well as at pitches of 25 µm and 35 µm.
4. Conclusion

Fine pitch two-metal layer COF packages were demonstrated by various bonding methods, ACF and NCF adhesives bonding, and AuSn metallurgical bonding. All of the COF packages showed stable flip chip joint properties and secure contact between bumps and electrodes at 35 μm, 25 μm, and 20 μm pitch. However, about 5% of the insulation resistance patterns of 20 μm pitch in ACF joints were lower than 10^8 Ω, which was defined as an electrical short due to agglomerated conductive particles between nearby 20 μm pitch bumps. Therefore, ACF bonding method can only be applicable above 20 μm pitch, and NCF and AuSn bonding methods can be applied to less than 20 μm pitch COF packages. The COF packages had good adhesion strength (>600 gf/cm) regardless of bonding methods, and significantly enhanced heat dissipation capability compared to one-metal layer COF. The measured flip chip joint temperature of two-metal layer COF was lower by 25°C at a fixed applied power condition. In addition, higher density COF packages can be also demonstrated by double side chips assembly.

Acknowledgments

The authors gratefully acknowledge the financial support as well as sample preparations from STEMCO and experimental support from STECO.

References