A Study on the Flexible Chip-on-Fabric Assemblies Using Anisotropic Conductive Films and Metal-Laminated Fabric Substrates

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Abstract—In this article, chip-on-fabric (COFa) assemblies using anisotropic conductive films (ACFs) and metal-laminated fabric substrates were investigated. To fabricate the metal-laminated fabric substrates, electrolss nickel-immersion gold (ENIG) metal-finished Cu circuits were fabricated on the B-stage nonconductive films (NCFs), followed by laminating onto the fabrics. Then, the 50-μm-thick Si chip was bonded onto the fabric substrates using ACFs with a thermocompression (T/C) bonding method. First, the ACFs’ joint properties, such as electrical resistances and adhesion strengths, were evaluated and compared with conventional chip-on-flex (COF) assembly. To enhance static bending flexibility without chip fracture, chip-in-fabric (CIFa) assemblies were developed after optimizing the thickness of a cover layer on the Si chip. Finally, mechanical and moisture-related reliability of the CIFa packages was evaluated through dynamic bending, 85 °C/85% relative humidity (RH), and washing reliability.

Index Terms—Anisotropic conductive film (ACF), bending test, chip on fabric (COFa), flexibility, metal-laminated fabric substrate, washability.

I. INTRODUCTION

ELECTRONIC textiles (e-textiles) combine electronic functionality with the fabric clothing for various applications, such as human activity monitoring, fashion, medical, or military applications [1], [2]. Simple sensing e-textiles have been already demonstrated by conductive threads or fabrics [3], [4]; however, complex electronic functionalities were realized using traditional electronic components, such as light-emitting diodes (LEDs), thin-film transistors (TFTs), and microcontrollers [5]–[9]. Normally, these modules using printed circuit boards (PCBs) or flexible printed circuits (FPCs) were first fabricated and then inserted [5], [6] or surface-mounted onto the fabrics [8], [9]. These modules were interconnected by mechanical connectors, such as rivets and buttons [4], [7], soldering [5], and conductive adhesives [8], [9]. However, these interconnection pitches are too

Material Technology Center (WMC) through the National Research Foundation of Korea (NRF) Grant of the Korean Government (MSIP) under Grant 2016R1A2B4010552. Recommended for publication by Associate Editor R. P. Panat upon evaluation of reviewers’ comments. (Corresponding author: Kyung-Wook Paik.)

Manuscript received August 12, 2019; revised October 23, 2019; accepted January 14, 2020. Date of publication January 21, 2020; date of current version March 10, 2020. This work was supported by the Wearable Platform Materials Technology Center (WMC) through the National Research Foundation of Korea (NRF) Grant of the Korean Government (MSIP) under Grant 2016R1A2B4010552. Recommended for publication by Associate Editor R. P. Panat upon evaluation of reviewers’ comments. (Corresponding author: Kyung-Wook Paik.)

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Digital Object Identifier 10.1109/TCMPT.2020.2968359

large to be used to assemble Si chips directly on these fabrics. If Si chips can be directly assembled onto the fabrics, highly functional e-textiles with various Si-based electronics, such as microcontroller, data storage, or signal processing units, can be realized without additional modules built on organic substrates, such as PCBs and FPCs. However, direct chip assembly using conventional wire bonding or solder-based flip-chip bonding methods were not feasible because fine-pitch electrical circuits were not feasible for thread-based fabric substrates and the lack of flexibility of conventional interconnection methods.

To solve this problem, conductive pastes were screen-printed onto the fabrics. However, these methods might still have issues on fine-pitch circuit capability due to the paste permeation through the fabrics [10], [11]. Recently, fine-pitch metal-pattern-laminated fabric substrates using B-stage adhesive films or nonconductive films (NCFs) had been introduced by our research group [12]. The NCFs are film-type adhesives which are solid at room temperature. Therefore, fine-pitch electrical circuits can be fabricated directly on the NCFs and then laminated onto the fabrics without any pattern displacement. Therefore, metal-laminated fabric substrates can provide fine-pitch metal interconnect suitable for direct chip assemblies compared with conventional fabric substrates using conductive threads and screen-printed conductors.

Anisotropic conductive films (ACFs) have been proven as one of the most promising interconnection materials’ candidates for flexible chip packaging for e-textile applications. The ACFs are film-type adhesive materials consisted of thermosetting polymer resin and conductive particles and widely used in display packaging applications. The ACFs have several advantages over conventional connector or solder interconnection, such as fine-pitch capability, low assembly temperature, and flexibility. Especially in terms of flexibility, the conventional solder interconnection had limitations due to the brittle nature of the intermetallic compounds (IMCs) formed between solder and metal bumps [13], [14]. On the other hand, ACFs’ joint can be stable against bending deformation [13]–[17]. Using ACFs’ interconnection, highly flexible chip-on-fabric (COFa) assemblies can be realized. Using the ACFs’ interconnection, highly flexible COFa assemblies can be realized. In addition, recent studies on conventional chip on flex (COF) found out that the flexibility of the COF was significantly improved when the cover layer structure consisting of polyimide (PI) and adhesive films was applied on top of the chip. By using the chip-in-flex (CIF) structure, the stress applied on the chip surface can be reduced, and chip crack can be enhanced.
under static and dynamic bending environments [13], [17].
Therefore, the effects of the same cover layer application on the static bending flexibility of chip in fabric (CIFa) should also be investigated.

In this article, chip-on-fabric (COFa) assemblies using fabric substrates and ACFs will be demonstrated. Fabric substrates were fabricated by the metal pattern lamination method using two types of NCFs, and COFa was fabricated by a thermocompression (T/C) bonding method. First, the ACFs’ joint properties of COFa were investigated and compared with the conventional COF. To improve the bending flexibility, the cover layer structure was applied on the COFa to fabricate CIFa similar to the CIF [13], [16]. The effects of the cover layer structure on the static bending flexibility were also investigated by a four-point bending test. Finally, the dynamic bending test, 85 °C/85% relative humidity (RH) test, and washing test were conducted to evaluate the reliability of CIFa.

II. EXPERIMENTS

A. Materials and Test Vehicles

In this article, 50-μm-thin Si chips were used. The Si chip had I/O pads in the peripheral array having a daisy chain structure to measure the electrical continuity of all the ACFs’ joints. On the I/O pads, 12-μm-thick Cu/Ni/Au square bumps were plated having 500-μm pitch. Fabric substrates design had the matching daisy chain test pattern and total eight four-point Kelvin structure patterns to measure the daisy chain resistances and ACFs’ single joint contact resistances after the test chip was assembled. Fig. 1 shows the design layouts of the test vehicles.

For the fabric substrates’ fabrication, 12-μm-thick Cu foil, polyester/rayon woven fabrics, and 40-μm-thick NCFs were used. The fabrics were not pretreated prior to the substrate fabrication. In the previous study, the NCFs showed no resin precuring after the Cu patterning process before lamination, no pattern displacement after lamination, and excellent bending fatigue properties of the Cu electrodes [12]. The materials properties of the NCFs were summarized in Table I.

The ACFs consisted of epoxy-based resin and Au-/Ni-coated polymer balls as conductive particles. The diameter of the polymer balls was 20 μm and the contents were 20 wt%. In cover layer materials, 135-μm-thick PI film and epoxy-based cover adhesive films were used. Thickness of the adhesive films was varied from 15 to 60 μm.

B. Fabrication of the Fabric Substrates and COFa Assemblies

Fabric substrates were fabricated by metal pattern lamination methods, as shown in Fig. 2 [12]. First, the Cu foil was attached to the NCFs, and then, Cu circuits were fabricated by conventional patterning processes. Then, electroless nickel–immersion gold (ENIG) metal finish was performed on the Cu/NCFs at 80 °C. Finally, carrier releasing film was removed, and ENIG/Cu circuits were laminated onto the fabrics using a pressure lamination method. The pressure lamination method used the nitrogen pressure of 25 psi and the temperature was 160 °C for 60 min. Metal patterns were laminated through the NCFs’ resin permeation into the fabrics because the NCFs resin viscosity gradually decreased with the temperature [12].

To fabricate COFa, ACFs were laminated on the Si chip and assembled onto the fabric substrates using a T/C bonding method. The bonding condition was 1 MPa, 210 °C, and 10 s. After COFa was assembled, CIFa was fabricated by applying the cover layer structure on top of the COFa using a vacuum lamination method at 110 °C for 5 min and 25-psi
N\textsubscript{2} pressure. To prevent any lamination defects such as voids or delamination, the cover layer film was prelaminated on the COFa using a roll laminator at 40 \textdegree C.

C. ACFs’ Joint Characterization

Scanning electron microscope (SEM) was used to observe the ACFs’ joint morphology of COFa (SE mode). Daisy chain resistance was measured by a two-wire method, and the ACFs’ joint contact resistances were measured by a four-wire method using a four-point probe; and 90\degree peel test was also conducted to evaluate the adhesion strength of the COFa without the cover layer structure.

D. Bending Flexibility Evaluation of CIFa

Static four-point bending test and dynamic bending test were conducted to evaluate the bending flexibility of CIFa. Fig. 3(a) shows the experimental setup of the four-point static bending test. All the tips were placed inside the Si chip and the test speed was 10 \textmu m/s, and the minimum bending radius was measured where Si chip fractured.

In addition to the static bending flexibility, dynamic bending properties were also evaluated using a cyclic bending test machine, as shown in Fig. 3(b). The test speed was 60 cycles/min up to 100 000 cycles, which were similar to our previous studies on the CIF [13]. Repeated bending deformation was performed on the CIFa from the flat state to 12-mm bending radius. During the dynamic bending test, \textit{in situ} daisy chain resistances were measured by connecting pads on CIFa to the electrical resistance measuring system.

E. Reliability of CIFa

The 85 \textdegree C/85% RH test (85/85 test) was conducted to evaluate the moisture-related reliability of CIFa [18]. During the test, electrical contact resistances were measured after every 250 h up to 1000 h, and a total of three samples were tested. In addition, a washing test was conducted to evaluate the effects of water immersion on the CIFa. To duplicate the actual laundry washing conditions, CIFa samples were immersed into detergent-added tap water and stirred at 200 r/min using a magnetic stir bar. Detergent concentration was 1 g/L. Test temperature was 40 \textdegree C and samples were immersed for 20 min/cycle. A total of five cycles were tested using two samples.

III. RESULTS AND DISCUSSION

A. Fabrication of the Fine Metal-Pattern Fabric Substrates

Fig. 4 shows the fabric substrates with ENIG metal-finished Cu electrodes. After Cu patterning and ENIG metal finish plating, the fabric substrates’ circuits were successfully fabricated on the NCFs and successfully transferred to the fabrics without any pattern displacement or fabric damages. The previous study showed that the NCFs might be thermally precured during the Cu patterning processes, and this problem was solved by optimizing the curing onset temperature at 150 \textdegree C [12]. In this article, an additional ENIG plating process was performed on the NCFs at 80 \textdegree C; therefore, the NCFs’ precuring was further evaluated through the Fourier transform infrared (FT-IR) analysis.

Fig. 5 shows the FT-IR spectra of the epoxy-based NCFs before and after Cu patterning and ENIG finish plating. The absorbance peaks around 912 cm\textsuperscript{-1}, assigned as an epoxide group, did not decrease after Cu patterning and the subsequent...
ENIG metal finish plating. This FT-IR result showed that the NCFs were not precured even after ENIG metal finish plating, which means that the stable lamination properties can be achieved.

B. ACFs’ Joint Properties of COFa

Fig. 6 shows the photographic and cross-sectional SEM images of COFa after T/C bonding. Si chip was successfully bonded onto the fabric substrates without any chip crack. In addition, cross-sectional SEM images showed that fabric substrates under Si chip were compressed by high temperature and pressure due to the mechanically compliant behavior of fabrics [see Fig. 6(b)]. As shown in Fig. 6(c), stable ACFs’ joint was formed between the bumps of the chip and electrodes of the fabric substrate, and the average gap height of the ACFs’ joint was 10.3 μm, which was higher than 7-μm gap height of conventional COF at the same bonding pressure of 1 MPa [13], [15]. Normally, ACFs’ resin flow occurred to fill the space between Si chips and rigid substrates, and some ACFs’ resin flowed out of the Si chip bonding area. However, in the case of the COFa, the compressed fabric probably reduced ACFs’ resin bleeding out, resulting in higher gap heights compared with COF.

Fig. 7 compares the ACFs’ joint properties of COFa and conventional COF [13]. Due to the well-captured conductive
balls, 5.54 $\Omega$ of daisy chain resistance and 12.6-m$\Omega$ contact resistance were obtained. The contact resistance of the single ACFs’ joint in COFa was lower than that in COF, as shown in Fig. 7(b). Due to the reduced ACFs’ resin flow out of the bonding area, more conductive particles might be captured between fabric substrates and Si chip, resulting in lower contact resistances despite of the larger gap height.

COFa using fabric substrates showed higher peel adhesion strength than COF using FPCs, as shown in Fig. 7(c). While COF failed at the interface between ACFs’ resin and FPCs [16], COFa showed cohesive failure at the fabric substrate (Fig. 8). Therefore, the number of the captured conductive particles could not be counted after a peel test. This failure mode difference might be due to the difference in the surface of the substrates: PI for FPCs and NCFs for fabric substrates.

C. Static Bending Flexibility of CIFa: Effects of the Cover Layer Thickness

Previous studies on the COF have reported that the static bending flexibility was significantly improved when the cover layer structure was applied on a COF, which was called CIF. The improved flexibility of the CIF was due to the shifted neutral axis toward the chip center and reduced stress concentration from the defects of the grinded chip edge. In addition, better bending flexibility was also achieved as the cover layer structure becomes thicker. However, too thick cover layer led to very stiff CIF packages [13], [17]. Based on the previous studies about the CIF, the cover layer structure was also applied to the COF, and the static bending flexibility was evaluated for both convex and concave bending directions.

Fig. 9 shows the minimum bending radius of CIFa (COFa with cover layers) depending on the total cover layer thickness and bending directions. For a convex bending direction, Si chip without the cover layer structure was easily fractured at 25-mm bending radius due to the high tensile stress on the chip. However, as the thickness of the cover layer on chip increased, the minimum bending radius drastically decreased and 7.4-mm bending radius was obtained when a total of 195-$\mu$m-thick cover layer was laminated on the Si chip.

On the other hand, concave bending caused compressive stress on the chip, and therefore, the minimum bending radius
Fig. 12. (a) 85/85 test results of the optimized CIFa and cross-sectional SEM images of ACFs’ joint and fabric substrates (b) before and (c) after 1000-h 85/85 test.

slightly decreased. Based on the results, the CIFa structure was optimized as a 60-μm-thick cover adhesive layer and 135-μm-thick cover PI film on top of the Si chip. Again, total cover layer thickness larger than 195 μm could not be used due to poor bendability and plastic deformation of the polymeric layers. The minimum bending radius of CIFa was 7.4 mm for convex and 9.5 mm for concave bending, as shown in Fig. 10.

D. Reliability of the Optimized CIFa

The dynamic bending test, 85/85 test, and washing test were performed on the optimized CIFa to evaluate the reliability. Fig. 11 shows the dynamic bending test results of the optimized CIFa. After 100 000-cycle dynamic bending at 12 mm radius, the daisy chain resistance of the CIFa was stable. Since the ACFs had resilience against bending deformation, there was no ACFs’ joint morphology change for both bending directions.

Fig. 12 shows the 85/85 test results of the optimized CIFa. Contact resistance gradually increased; however, no open failure was observed after 1000-h 85/85 test. Cross-sectional SEM images showed that ACFs’ resin and fabric substrates were swollen after the 85/85 test. Especially, for fabric substrates, NCFs’ resin swelling caused interfacial delamination between electrodes and fabrics. Studies on the various polymer-fabric composites under high temperature and humidity environment have reported that the moisture was absorbed either to the fibers or polymer resin, and moisture-induced plasticization caused composites damages and degraded mechanical properties [19]–[22]. In CIFa, weight gain by moisture absorption was observed for both ACFs and NCFs resin; however, fabrics did not absorb moisture under the 85/85 environment, as shown in Fig. 13(b). Since the backside of the fabrics was
not filled with the NCFs’ resin, moisture penetration might be easier through the backside of the fabrics than the cover layer structure [see Fig. 13(a)]. As a result, NCFs’ resin in the fabrics substrates might be easily affected by the penetrated moisture. This caused fabric substrates damages, and the ACFs’ resin was also affected by the hygroscopic swelling, which might be presumably due to the moisture penetration along the damaged interfaces of the fabric substrates, as shown in Fig. 13(a).

Fig. 14 shows the washing test results of the optimized CIFa. Contact resistances of ACFs’ joint were stable after five cycles or total 100-min washing. Similar to moisture, liquid water can also induce interfacial damages of polymer-reinforced fabric composites [23]–[25]. However, cross-sectional SEM images showed that the ACFs’ joint and fabric substrates remained stable without any delamination or swelling compared with 85/85 test, which might be presumably due to the lower temperature at 40 °C.

IV. CONCLUSION

In this article, 500-μm-pitch CIFa assemblies were successfully demonstrated using ACFs and metal-laminated fabric substrates. The fine metal-pattern fabric substrates were successfully fabricated by laminating ENIG/Cu circuit patterns on the fabrics using NCFs. After T/C bonding, stable ACFs’ joints were obtained without any chip crack or fabric substrates damages. Compared with conventional COF, lower joint resistances and higher peel adhesion strength were obtained.

CIFa was fabricated by applying the 195-μm-thick cover layer structure on top of the flip-chip COFa, and static bending flexibility of CIFa in the convex bending direction was significantly improved from 25- to 7.4-mm minimum bending radius without chip crack. The optimized CIFa packages showed stable ACFs’ joints after 100 000-cycle dynamic bending at 12 mm radius and five-cycle washing test. Although no open failure was obtained after 1000 h of the 85/85 test, the increase in resistance was observed, which might be due to the moisture penetration through the fabric substrates. To prevent this, NCFs’ resin property should be further optimized to reduce the moisture effects on the NCFs’ resin and ACFs’ joint.

Highly functional e-textiles can be realized by fine metal-pattern-laminated fabric substrates, ACFs’ interconnection, and CIFa with the cover layer structure. Using the CIFa structure, flexible Si chips, such as microcontroller, wireless communication, and data storage devices, can be successfully integrated into fabrics with flexibility. Finally, CIFa assembly can provide an excellent method for future fabric-based flexible electronics.

REFERENCES


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