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Flexible Circuits Based on Aluminum Conductor and Nonwoven Substrate

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Abstract— Electronic textiles, integrating functional electronics circuits into fabric materials, are emerging as an important branch of flexible circuits. In this paper, we introduce a novel material combination for electronic textiles that can be used in implementing hybrid electronics. This type of circuits is fabricated by laminating patterned aluminum foils onto a nonwoven substrate in a high-speed roll-to-roll method. An isotropic conductive adhesive and an anisotropic conductive adhesive are used to assemble standard surface mount device components onto the fabricated circuits. The surface mount techniques are characterized by means of contact resistance measurements, component bonding strength tests, circuit bending tests, and scanning electron microscopy. An NFC tag with relative humidity sensing functionality is fabricated to evaluate the fabricated circuits to an electronic system level.

I. INTRODUCTION

Electronic textiles, also known as e-textiles, are textile products that can interact with environments or users and are commonly achieved by realizing functions found in conventional rigid printed circuit boards (PCBs) [1]. E-textiles are becoming one important area in The Internet of Things. A typical configuration of e-textiles comprises a flexible textile/fabric substrate and conductive tracks [2]. The conductive tracks can be made from various conductive inks, e.g. silver (Ag) particle inks, conductive fabrics, containing metal or conductive polymer filaments, and fibers that are coated with conductive materials [1,3].

E-textiles are low-cost and innovative when implementing wearable sensors [4] and input/output devices, such as lightning sources [5], keyboards [6], and antennas [7] etc. However, when implementing complicated electronics systems, such as microcontrollers and associated peripheral devices, conventional rigid PCBs are commonly used [1]. One popular approach is to mount standard surface mount device (SMD) components onto rigid PCBs, which are subsequently interposed onto e-textiles [8-10]. This approach in turn results in a bulky structure and discomforts in wearable applications.

To reduce the bulky structures and discomforts, one solution would be to have SMD components mounted directly onto conductive tracks. Several approaches have been presented, including wire-bonding (sewing) component terminals onto corresponding land pads [11], metal-to-metal direct contact with the assistance of non-conductive adhesive [12], and using low-temperature solder paste [13]. Although satisfactory

contact resistance were achieved, these surface mounting techniques require a tremendous amount of human efforts and lack the possibility to apply the surface mounting techniques (SMTs) that have been well-developed for conventional rigid PCBs.

In this paper, we present a new material combination that uses patterned aluminum (Al) foils as conductors and nonwoven fabric as substrate (hereafter denoted as Al-nonwoven circuits). Instead of sewing and printing, this type of Al-nonwoven circuits is manufactured in a high-speed roll-to-roll method. Two SMTs, using an isotropic conductive adhesive (ICA) and an anisotropic conductive adhesive (ACA), are evaluated to assemble standard SMD components on to the fabricated circuits. The SMTs are characterized by means of contact resistance measurements, component bonding strength tests, circuit bending tests, and scanning electron microscopy (SEM). As a demonstration on a system level, an NFC tag with relative humidity (RH) sensing functionality is also fabricated.

II. EXPERIMENTAL DETAILS

A. Flexible circuit fabrication

Fig. 1 shows a simplified circuit fabrication process and post processing of the Al-nonwoven circuits. The Al foil is laminated on a plastic carrier using the adhesive film A in advance. A chemical etching process is performed to pattern the Al foil. With the help of the adhesive film B, the patterned Al foil is laminated onto the nonwoven substrate, which sandwiches the Al foil between the nonwoven substrate and the plastic carrier. The plastic carrier is subsequently removed, where the Al foil is still laminated with the nonwoven substrate. In order to avoid delamination between the Al foil and the nonwoven substrate, the adhesive film A has a less adhesion than the adhesive film B. An organic solvent, Methyl Ethyl Ketone (MEK), is used to manually clean the adhesive films in order to expose the Al conductor, where SMD components are mounted onto. A fabricated Al-nonwoven circuit sheet is presented in Fig. 1(b). It needs to point out that the chemical etching process results in a mirrored pattern of the designed circuit layouts on the plastic carrier. When removing the plastic carrier from the back side of the Al foil, the patterns that remains on top of the nonwoven substrate are no longer mirrored.

Fig. 1. (a) Circuit fabrication process. (b) A fabricated Al-nonwoven circuit sheet.

B. Surface mounting techniques

Four different SMD component packages are chosen to be evaluated for mounting onto the Al-nonwoven circuits: two-terminal leadless components with packages 1206, 0805, 0603, and a gull-wing leads component with small outline integrated circuit (SOIC) 16.

A silver (Ag) particle based ICA (Henkel Loctite 3880) is used, which is deposited on the land pads of components through stainless steel stencils. The parameters of the stencils are package-dependent and are given in TABLE I. The components are manually placed onto the Al-nonwoven circuits and the curing procedure is performed in a convection oven at 125°C for 10 min.

Package	Thickness (mm)	Aperture (mm × mm)
1206	0.2	0.9 × 0.8
0805		0.6 × 0.6
0603		0.5 × 0.4
SOIC16		1.5 × 0.7

A nickel-gold (Ni-Au) particle based ACA (Delo Monopox AC265) is used for an automatic component mounting, performed in an automatic chip bonder (Datacon 2200 evo). The following procedures are carried out in sequence for every component: ACA dispensing, components placement, and ACA curing. The ACA is cured by applying a 2.0 kg load on top of placed components together with a 200 °C heat for 10 s.

C. Characterization methods

The contact resistance of ICA and ACA mount joints are measured with the 4-wire (Kelvin) method incorporated with a Rohde & Schwarz HMC8012 multimeter. The component terminals that show no electrical connections or whose contact resistance is unreasonably high are considered as failures.

Component bonding strength tests are performed in accordance with international standards [14,15], with setups and procedures described in our previous work [16]. A shear force parallel to the nonwoven substrate is applied to components with 1206-0603 packages, while a pulling force 45° to the nonwoven substrate is applied to the leads of SOIC16 components. The failure modes occurred during the bonding strength tests are also recorded and compared to the failure modes given in [14,15].

Circuit bending tests are carried out in order to determine the flexibility of the assembled circuits. Two-terminal leadless SMD components, 0603, 0805, and 1206, are assembled and taped onto a cylinder with the directions of components parallel to the cylinder circumference. Different bending diameters, from 5.0 down to 1.0 cm with a step of 1.0 cm are used. During bending the resistance is measured from the ICA and ACA mount joints. The diameter that the multimeter reads open circuit, i.e. the mount joints are broken, is considered to be the limit. The values one step above this is reported as the largest bending diameter that the circuits can withstand.

The cross-sections of the mounting joints are inspected using a SEM (MAIA3 GMU 2016), which sample preparations and operation details were described in [16]. In order to show full system functionality, an NFC tag with RH sensing functionality is implemented, which design details is also given in [16].

III. RESULTS AND DISCUSSIONS

A. Contact resistance

TABLE II shows the measured contact resistance and component bonding strength. Except the 1206 sized components mounted using the ACA, all contact resistance are in $> 1 \Omega$ level (soldering on rigid PCBs is less than 0.1Ω [16]). They are also accompanied with unneglectable failure rates ranged from 10 to 50%. The standard deviations also suggests that the contact resistances are unstable.

Technique	Package	Contact resistance (Ω)	Failure rate (%)
ICA	1206	1.41 ± 1.07	30
	0805	2.67 ± 1.35	20
	0603	3.65 ± 2.72	20
	SOIC16	4.06 ± 3.02	30
ACA ^a	1206	0.64 ± 0.22	10
	0805	1.47 ± 0.91	50

^a The ACA is not used for 0603 or SOIC16 components.

B. Component bonding strength

The measured component bonding strengths are presented in Fig. 2, which shows that the ACA-mounted components withstands a shear force ~4 times higher than the corresponding ICA-mounted components (20.96 N to 5.07 N from 1206-sized components and 11.94 N to 2.53 N for 0805-sized components). The phenomenon could be caused by that the ACA is dispensed on all the area under the components, which does not only bonds a component onto its land pads, but also onto the substrates under it. Compared to the ACA, the ICA only bonds a component onto its land pads. It also shows that components with larger packages achieve a higher bonding strength, e.g. comparing 1206-sized components to 0805-sized components.

This is due to a larger amount of conductive adhesives deposited for larger packages (see TABLE I). In order to improve the environmental endurance of assembled circuits, i.e. improving component bonding strengths, components with relatively large packages are recommended, e.g. 1206-sized or larger. In addition, the ACA has achieved ~25% component bonding strength to soldering on conventional rigid PCBs (data provided in [16]).

Failure modes are summarized and presented in TABLE III, with the failure modes explained in the footnotes. Mode 3-5 are observed from ICA-mounted components, where Mode 5 is dominant. It indicates that the lamination between the land pads and the nonwoven substrates is often weaker than the adhesion provided by the ICA. Substrate failures are observed from ACA-mounted components. Thus, in this case, the component bonding strengths depend on the tensile strength of the nonwoven substrate.

Fig. 2. Measured component bonding strength.

TABLE III

SUMMARY OF FAILURE MODES

Technique	Package	Failure mode
ICA	1206	10% Mode 4 ^b , 90% Mode 5 ^c
	0805	10% Mode 4, 90% Mode 5
	0603	10% Mode 3, 5% Mode 4, 80% Mode 5
	SOIC16	50% Mode 3 ^a , 50% Mode 5
ACA	1206	100% substrate failure ^d
	0805	40% Mode 5, 60% substrate failure

^a Mode 3: Cured adhesive joints fail due to external forces.

^b Mode 4: Components and cured adhesive joints are removed from corresponding land pads, while the joints are intact and still attached to the components.

^c Mode 5: The land pads of components are removed from the substrate together with the components.

^d Substrate failure: The substrate around the mounted components are torn apart while land pads, adhesive joints, and components are still intact.

C. Circuit bending test

The circuit bending tests show that ICA-mounted components can withstand a bending diameter of 3.0 cm while ACA-mounted components can withstand the smallest bending diameter used, 1.0 cm, without open circuit. The results of circuit bending tests also confirm that the ACA can achieve a better component bonding strength than the ICA.

D. SEM

The cross-sections of an ICA joint and an ACA joint are inspected under the secondary electron (SE) mode and presented in Fig. 3 (a) and (b) respectively. Despite the high contact resistance, the ICA and ACA fill the space between the component electrodes and corresponding land pads continuously without obvious voids. Fig. 3 (c) and (d) show higher

magnifications of the ICA and ACA joints under backscattered electron (BSE) mode. The Ag and Ni-Au particles, confirmed by energy-dispersive X-ray spectroscopy, are visible and appear bright, which are responsible for electrical connectivity. The contents that appear dark under BSE mode are epoxy resin, which are responsible for component bonding strength.

Fig. 3. SEM cross-sectional overviews under SE mode of (a) an ICA joint and (b) an ACA joint. (c) and (d) are corresponding magnifications for (a) and (b) using the BSE mode. (a)-(d) are taken at an accelerating voltage of 15 kV and working distance of 8.0 mm.

Fig. 4. SEM top views for one land pad of 1206-sized resistors. The SE mode is used with accelerating voltage of 1.5 kV and working distance of 3.0 mm. (a) overview of the land pad. (b) Magnification of the land pad, where an example of contamination is marked by the dotted circle.

The surface of an Al land pad is inspected under SE mode and presented in Fig. 4(a), where contaminations are seen on top of the land pad. The contaminations are likely to be the adhesive film A (shown in Fig. 1) remained after the circuit cleaning process. Fig. 4(b) shows a magnification of the land pad, which reveals that the Al land pad has a rough surface together with a great number of notches. In addition, some μm -sized contaminations also exists in the notches. The residue and surface roughness together lead to reducing electrical contact points per area that the Al land pad can provide. Thus, it results in a high contact resistance and a high failure rate. However, it

does not rule out that other cleaning methods or instrument would achieve a better result.

It can be seen from Fig. 4(a) that the nonwoven substrate shows a net-shaped microstructure, where voids are observed. Thus, the adhesion between the Al land pad and the nonwoven substrate is not continuous, which further leads to the Mode 5 often occurs during the component bonding strength tests.

E. NFC tag with RH sensing functionality

An NFC-equipped smartphone, HUAWEI P20 Pro, is used to interact with the assembled NFC sensor tag as shown in Fig. 3(d). This experiment shows that the smartphone can interact with the NFC chip of the tag. However, due to the failure rate previously described, the smartphone does not display the measured RH value. The leads of the used microcontroller, Atmel ATtiny 48, are not totally connected to their corresponding land pads.

Fig. 5. A fabricated NFC tag with RH sensing functionality.

IV. CONCLUSIONS

In this paper, we have shown a novel material combination for e-textiles, using Al as conductor and nonwoven as substrate, which is fabricated in a high-efficiency roll-to-roll method. The Al-nonwoven circuits can be used in constructing hybrid electronics without any additional rigid PCB interposers. Furthermore, it enables applying SMTs that are developed for conventional rigid PCBs.

Two SMTs, using an ICA and ACA, have been evaluated in order to form functional electronics systems. The results show that the best component bonding strength is achieved through ACA where 20.96 N and 11.94 N are achieved for 1206- and 0805-sized components. In comparison, the ICA has achieved ~25% component bonding strength as compared to the ACA. A drawback of this material combination is that the Al conductor has a rough surface, which in turn results a high and unstable contact resistance. An NFC tag with RH sensing functionality was fabricated to demonstrate that the Al-nonwoven circuits can be used in construction functional electronics systems.

The Al-nonwoven circuits have showed potentials to be used in semi- or fully-automatic component mounting process. Although the SMT using ICA was performed manually, it can be upgraded to a semi-automatic process if the ICA deposition and the component placement were performed by machines. Together with the roll-to-roll fabrication method, this type of circuits has provided one solution towards low-cost and high-performance e-textiles.

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