Reliability Analysis of Screen-printed Tags with Low-power Electronics on Flexible Substrates

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***Abstract*— The additive manufacturing of RFID smart tags typically involves printing of antennas using electrically conductive materials along with the hybrid integration of the off-the-shelf low-power electronic components. In this case, the conductivity of printed material could significantly influence the reliable working of electronics as the electromagnetic performance of the antenna depends on it. In this research, we demonstrate the effect of conductive materials for printed antenna and show how their reliable operation could be attained by using suitable number of coatings. The printed antenna with its low-power electronics circuit is also compared with the conventional copper etched rigid and flexible tags to show the challenges regarding the electromagnetic performance. The printed tags are further subjected to different bending cycles to investigate their mechanical stability under varying strain conditions.**

***Keywords*— Flexible electronics; Printed electronics; Smart RFID Tag; Conductive ink; Mechanical reliability**

I. Introduction

The development of customizable, inexpensive, and mass-producible smart radio frequency identification (RFID) tags or labels is in high demand as they have the power to enhance the visibility and efficiency across the supply chain in several areas ranging from health and beauty to apparel, pharmaceuticals and beyond [1-5]. Such smart labels could also improve the food monitoring and prevent food spoilage [6], and their battery-free identification with low-power electronics is a huge advantage [7-10]. Near field communication (NFC), the subset of high-frequency RFID, is more advanced in this battery-free sensing of the environmental parameters and provides an extra degree of freedom in safety and quality measurement.

Typically, the conductive antenna in a smart tag is produced by the etching of copper in a rigid circuit board (e.g., FR4). Whilst, etching is an efficient process for antenna production, the waste chemicals generated from this process have a harmful impact on the environment [11]. The copper lost due to etching and the use of toxic substrate material such as FR4 also have a detrimental impact on environmental sustainability. Further, the cost of production of such tags is high and they are not available in flexible form-factors. As a result, different additive manufacturing (AM) based printed electronics technologies such as screen printing, ink-jet printing, roll-to-roll printing, nanoimprint, etc. have been explored [12-15], mainly for realizing passive components such as conductive tracks. This is complemented by the hybrid integration of low-power electronic chips on the same substrate with the antenna.

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Despite the added advantage of simple fabrication and low fabrication cost, the printed technology has several limitations, which vary with the printing technique adopted for fabrication [16]. In the event of printed RFID tags, the electrical conductivity of the antenna traces, and the substrate on which the antenna is printed, are important parameters to be considered [17, 18]. The integration challenges related to the substrates are analysed in detail in our previous work [19]. From that analysis, we noted that the photopaper is an attractive green solution. The motivation of this work is to understand the challenges related to the conductive material in printing antennas and investigate the possible solutions to overcome the challenges. In particular, we have analysed the influence of printed layers on the resistance of antenna traces and hence on the electromagnetic performance. Further, the printed tags were subjected to different bending cycles to investigate the mechanical stability under varying strain conditions.

This paper is organised as follows: Section II discusses the fabrication of printed NFC tags and their electrical schematic; Section III discusses the challenges in the electromagnetic performance of the antenna and the solution through the change in conductive material and thickness of the printing layer. Section IV shows the mechanical reliability testing of the printed antenna with the number of bending cycles. The key outcomes are summarised in Section V.

II. Fabrication of The Tag

The NFC-based smart tags were fabricated in three different ways: (a) etching conductive copper on FR-4 substrate, (b) etching copper on Polyimide substrate, and (c) printing

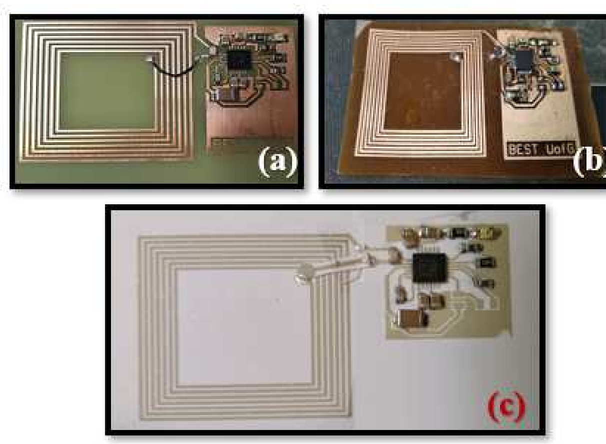

Fig. **1.** Smart tags fabricated by (a) etching copper on FR-4, (b) etching copper of flexible polyimide, and (c) screen printing of silver on photopaper.

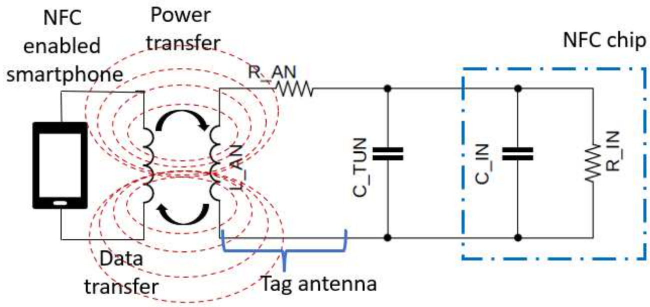

Fig. **2.** Electrical schematic of the NFC tag.

TABLE I: SERIES RESISTANCE AND THE MEASURED QUALITY FACTOR OF THREE DIFFERENTLY FABRICATED TAGS.

Tag fabrication methods	**Measured dc resistance (Ω)**
(a) Copper etched tag on FR-4 (rigid)	2
(b) Copper etched tag on Polyimide (flexible)	6
(c) Silver lines printed on photopaper (printed)	50-120

conductive silver ink on the paper substrate, as shown in Fig. 1. The antenna and circuit design for these tags are described in our previous work [8]. Tags fabricated in (a) and (b), follow the conventional method of copper etching which increases the manufacturing time, fabrication cost and leads to electronic waste. The tag in (c) is fabricated by the screen-printing method, and optimised parameters for printing are discussed below.

A. Parameter optimisation of the screen printing

The screen printer from Aurel Automation (C920) is used to print the tag pattern with silver conductor paste PE828 from Dupont, UK. The squeezing pressure of the print head is optimised at 1.8 Kg, where the front and back speeds of the printing are kept at 100 mm/s. The gap between the screen and the printing substrate is maintained at approximately 1 mm. After printing, the silver pattern is annealed at the temperature of 60 ºC in an oven for 2 hours.

B. Electrical model of the NFC tag

In the radio frequency mode, the chip on tag is powered by the NFC reader on an NFC-enabled commercial smartphone. The designed tag includes a programmable microcontroller-based (16-bit MSP430) low-power integrated circuit (IC) RF430FRL152H from Texas Instruments (Dallas, Texas, USA) which is used as the NFC transponder. The chip requires 1.45V to 1.65V supply from the magnetic field of the smartphone (NFC reader). For the identification and sensing of the external parameters, no battery is required as the chip draws its required power from the mutual coupling of the magnetic fields between the reader and tag antenna, as shown in Fig. 2. The NFC tags are usually designed at 13.56 MHz resonance frequency, which is the required frequency for any NFC application. The internal resistance and capacitance of the NFC chip are modeled as R_IN and C_IN, where the value of C_IN is found around 35pF. The tag antenna is designed as a square inductor L_AN of 1.8 µH with a dimension of 29 mm^2, width, and spacing of 500 µm. This antenna dimension was optimized in our previous work [8]. To

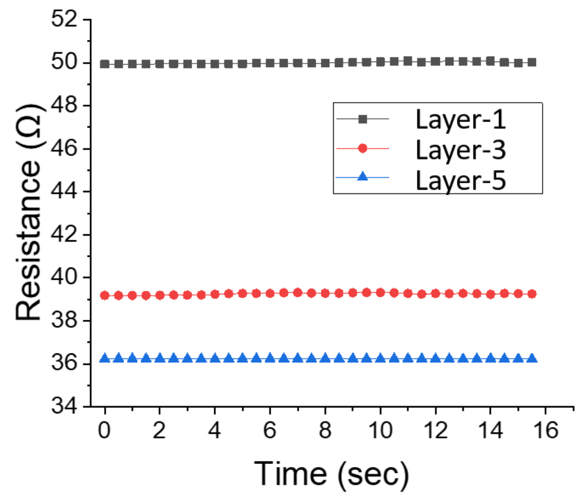

Fig. **3.** Resistance versus time for first, third, and fifth coating layers of silver paste.

achieve the resonance frequency, a tuning capacitance C_TUN of 39 pF is added in parallel to the antenna and the NFC chip. The system is identical to the voltage transformer where the mobile phone acts as the primary winding and the tag antenna as the secondary winding.

III. CHALLENGES AND SOLUTIONS

A. Challenge: Electromagnetic performance of the antenna

The power transfer from the phone to the NFC chip depends on the carrier frequency of 13.56 MHz and the distance between the phone and the tag antenna. However, after maintaining these parameters, challenges can also be seen in the power transfer capability of printed traces, which decreases the reliability of the tags. This is due to the use of conductive materials in the printed antenna. Table I shows the measured dc resistance (R_AN in Fig. 2) for three types of fabricated tags. The dc resistance offered by the printed antenna is around 40-60 times higher than the copper etched antennas, and because of this the quality factor of the antenna (Q_{AN}) gets degraded. The Q_{AN} is defined as:

$$Q_{AN} = \frac{X_{L\_AN}}{R_{L\_AN}} = \frac{Energy\ stored\ in\ antenna}{Energy\ Loss\ due\ to\ the\ resistance}$$

The energy loss due to the resistance of the antenna is the ohmic loss [18, 20] and it is inversely proportional to the quality factor. Due to this ohmic loss, the NFC chip does not get sufficient power needed its reliable operation. As a result, the printed tags have higher defects compared to the conventional tags. Few solutions are discussed below to address this challenge.

B. Solution 1: Changing of conductive paste materials

To minimize the ohmic loss, the antenna can be printed with materials having high conductivity. Different conductive pastes such as commercial carbon, Graphene-carbon paste, custom doped PEDOT:PSS with AgNW (silver nanowire), and CuNw (copper nanowire) particles have been used. However, the resistance of the antenna is around 700 Ω for carbon and graphene paste, which is far beyond the resistance value of the silver-printed antenna. The viscosity of the custom PEDOT:PSS paste was less than the commercial paste and the sheet resistance

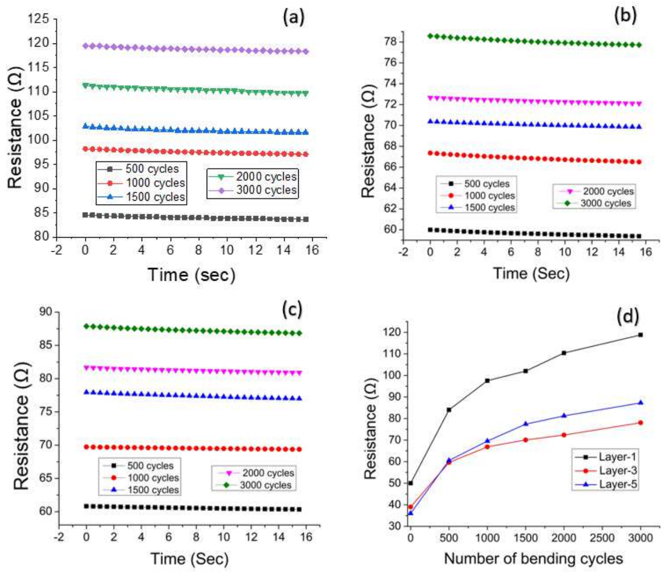

Fig. **4.** Resistance versus time plot for five different bending cycles with (a) layer-1 antenna, (b) layer-3 antenna, and (c) layer-5 antenna. (d) Non-linear response of the measured resistance with respect to the number of bending cycles for three-layer coatings.

with Ag/CuNw is found 15-20 times higher than the silver paste. This custom paste needs a different study to increase the conductivity as well the viscosity which is not included in this work. Therefore, compared to the other conductive materials, we have chosen silver paste for further study.

C. Solution 2: Changing the layer thickness of the silver paste

The thickness of printed silver paste is varied with one, three, and five layers, and the corresponding resistances for a period of 15 sec and at the interval of 0.5 sec were measured with digital multimeter (Agilent $6\frac{1}{2}$ digit, 34461A) with a LabVIEW program. Fig. 3 shows the resistance versus time plot for three different layers and the values are given in Table II. It is observed that the resistance value decreases with the increase in the number of layer and this eventually translates into lesser ohmic losses in the antenna. The change in resistance from layer-1 to layer-3 is 22% whereas the change from layer-3 to layer-5 is 7%. Therefore, the variability of the resistance decreases with the number of layers. However, with more layer coatings, the printed antenna gets smudged, and no inducting effect can be seen. Therefore, the number of layers should be optimised depending on the structure of the antenna. Here, we have seen that the layer-5 is optimum for the designed antenna.

IV. Mechanical reliability testing

The printed conductive tag antennas with different number of coatings were subjected to up to 3000 bending cycles to investigate their electro-mechanical reliability. Resistances were measured after every 500 bending cycles. A bending and twisting endurance setup (Yuasa DMLHP) is used for the measurement. Fig. 4(a), (b), and (c) show the resistance versus time plot of the antenna for layer 1, layer 3, and layer 5 respectively. It is observed that, in each layer, resistance increases with the number of bending cycles. Table III shows the percent change in the resistance with the increased number of bending cycles for all three samples. From the table, a rapid change can be observed in the first bending test of 500 cycles from the initial no-bending state. This can be explained by the small cracks on the printed pattern with the applied bending stress. It is one of the reasons for the degradation in the performance of the printed tags after the application of mechanical stress. This also means that a working printed tag may stop working (due to increasing resistance) if it is subjected to longer bending cycles. Fig. 4(d) shows the measured resistance with number of bending cycles. It can be observed that for layer-5, the change in resistance as well as the final resistance after 3000 cycles are higher than the layer-3. With a greater number of coatings, and hence higher thickness, the printed pattern cannot sustain for long bending cycles, and this could be one of the reasons for higher resistance in layer-5 after 3000 bending cycles. An optimum thickness can reduce the resistance without making it susceptible to the degradation due to mechanical stresses.

TABLE II: Average and percent standard deviation of the antenna-resistance with three coating layers

Layer coating	**Measured dc resistance (Ω)**
Layer-1	50±0.08
Layer-3	39.25±0.06
Layer-5	36.235±0.005

TABLE III: Percent change in resistance with increased number of bending cycles for three coating layers

Layer coating	**% Change in resistance with the number of bending cycles**				
	500 cycles	**1000 cycles**	**1500 cycles**	**2000 cycles**	**3000 cycles**
Layer-1	68	16.1	4.5	8.2	7.6
Layer-3	51.9	12.1	4.8	3.2	7.9
Layer-5	67.1	14.8	11.3	4.9	7.4

V. Conclusion

In summary, we have compared the electromagnetic performance of the printed antenna with the ones obtained using conventional copper etching in rigid and flexible substrates. The resistance of printed antenna is found to be higher than the conventional tags which leads to the ohmic loss of the printed antenna. Different commercially available and custom-made materials were also used for the printed antenna, however silver was used here as it shows higher conductivity. Number of coating layer of the silver printed antenna were increased from 1 to 5 and it is found that the resistance decreases with number of layers. The mechanical reliability test shows an initial rapid increase in resistance with the applied strain which limits the flexibility of the printed tag. In conclusion, 3 layer of silver coating is found optimum as it has lower resistance but is relatively less susceptible than 5 layers. Appropriate coating or the plasma treatment of the substrate can be the future research in this direction to further improve the tag performance.

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