ROLL-TO-ROLL GRAVURE PRINTED SMART FOOD PACKAGE TO REPLACE THE "USE-BY" DATE SYSTEM OF FOODS

By

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ABSTRACT

The implementation of internet of things (IoT) to the food industry offers a great deal, accompanying each functional unit from production to the consumption to ensure the quality of a particular food item. Among several factors, the fluctuation in temperature through the cold chain are prone to the propagation of foodborne pathogens and is considered as a leading factor to reduce the shelf life. Therefore, a smart food package, which dynamically monitors the time-temperature history (TTH) throughout the food logistics will be very crucial to access meaningful data regarding the quality and safety of a food package. This smart packaging system utilizing NFC function of the smartphone to access quality information of a food item not only prevents from the blind disposal of consumable items if the quality is good enough to consume but also prohibits the consumers from its usage if the quality is bad, which at present is heavily relied upon the due date. However, the cost issue associated with the manufacturing of radio frequency identification (RFID) prohibits these systems from implementing to a smart packaging system for everyday consumable food products. To resolve this, we incorporated fully scalable, high throughput, and flexible roll-to-roll (R2R) gravure printing system to realize the NFC antenna, flexible printed circuit board (FPCB), a thermistor, and a battery. We successfully demonstrate the printing of NFC antenna as well as the thermistor continuously from the two printing units at a practical printing speed of more than 6 m/min on a polyimide (PI) substrate. The printing conditions such as nip-roll pressure, blade angle was optimized to 6 kgf and 9°, respectively to ensure the quality printing of both antenna and the thermistor, whereas the viscosity of the silver nanoparticle ink for realizing antenna was 1000 cP. The Si-chip transponder was embedded to the printed NFC tag, by using a daughter board, to record the temperature at custom-defined time instants throughout the cold chain.

INTRODUCTION

The United Nations' Food and Agriculture Organization (FAO) estimated one-third of the food supply was wasted worldwide which accounts for about 1.4 billion tons, whereas 25 percent people from developing countries are lacking nourished food. This causes an alarming issue towards food management not only for mankind but also for the environmental safety. One of the major factors for food loss is the existing date system as a reference to examine the validity of a food item, which is not very reliable leading to misinterpretation and is static toward examining the quality standards. The fluctuation in temperature as a function of time corroborate heavily towards the growth of foodborne pathogens along the cold chain. Therefore, monitoring time-temperature history (TTH) of the food packages play vital role in examining the quality of each food product in all associated units during production, distribution, and consumption. A smart package thus comprises a sensing unit to monitor the temperature with respect to time, a memory unit to store the measured temperature values, and a communication unit to retrieve the stored temperature information and post-process to compute the development of foodborne pathogens by connecting to the item-specific algorithm stored in the manufacturer server system.

Several research works demonstrated the feasibility of utilizing TTH history in for smart packaging [1]. However, the cost of those smart packages is very high prohibiting them to apply for low-cost food products. On the other hand, despite showing a promising result in modern electronics market readying for wearable and flexible devices, printing electronics yet cannot meet all the aforementioned standards for realizing smart packaging unit. Roll-to-Roll (R2R) printing on film substrates has the potential for high throughput, low-cost organic electronic devices. However, in the sharp cutting-edge technology of IOT and smartphone, low cost R2R printed devices are not sufficient for practical application. The major limitation of printing electronics at present is in the realization of memory chips due to the issues associated with high operating power, size, and yield. The use of Si chip together with the low cost R2R electronic device allows the printing technology to be able to bring the real-world application out of such hybrid integrated devices.[Hybrid integration of current Si-based memory devices would therefore provide the best compromise to attain the cost benefit at the same time maintaining the reliability of the overall sensing device. Additionally, the Si-chips can be vigorously assembled to the flexible substrates using conducting glues and bonding techniques. In this work, we propose a hybrid smart packaging system to monitor the TTH of a food package along the cold chain utilizing roll-to-roll (R2R) printed NFC antenna and a temperature sensor (Figure 1) embedded with Si-chip based transponder with microcontroller and a flexible printed battery. We successfully demonstrate the dynamic monitoring of TTH by using custom-developed Android app which detects the recorded temperature by utilizing the NFC function of the smartphone operating at 13.56 MHz.

(a)

(b) (c)

Figure 1 – (a) Roll to roll (R2R gravure printing showing printing of 1st and 2nd layers, (b) PI roll with printed antenna and temperature sensor patterns, and (c) printed single flexible tag

OVERVIEW OF PRINTING TECHNOLOGY

Printed electronics involves the use of printing equipment to transfer various conducting, dielectric, and semiconducting inks to the flexible substrate like plastic or paper for obtaining flexible devices. Different printing technologies such as screen printing, ink jet printing, offset printing, flexographic printing, gravure printing is used in realizing these flexible devices [2]. Unlike other printing techniques, roll-to-roll printing technology is capable of continuous printing suitable for large scale and is commercially viable high-throughput technology [3,4]. Roll-to-Roll (R2R) Gravure printing beats other printing technologies in terms of high throughput and resolution. Gravure printing uses the engraved cells in the gravure roll where the ink is filled, wiped by doctor blade, transferred, and finally spread to the substrate. [5]. Basic working principle of Gravure printing is demonstrated in Figure 2.

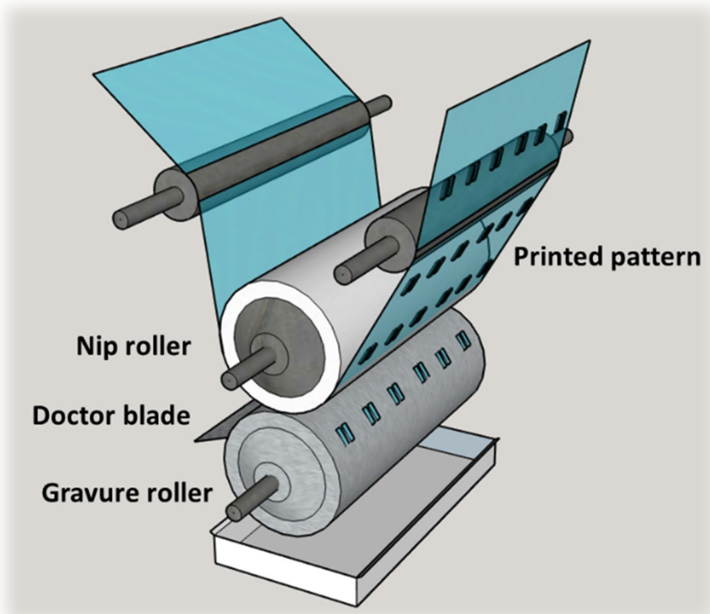


Figure 2 – Schematic image of roll to roll gravure printing unit

DESIGN CONSIDERATION

The dimension of antenna was designed considering the inductance and resonance frequency for the NFC transponder chip. A total of eight tags comprising three different rectangular antenna patterns were designed with varied width, gap, and the number of turns. Furthermore, as many numbers of sensor patterns were designed considering the suitable resistance temperature sensor for the ADC of the chip. The width and gap of antenna patterns and sensor are tabulated in Table 1. During printing, antenna design engraved roll was implemented in the 1st roll whereas the sensor pattern engraved roll was implemented in 2nd roll because of the utility of different kind of inks.

Compared to the designed dimension (Figure 3) of width and gap of antenna (Table 1(a)), the actual printed antenna has slightly different width and gap dimensions as shown in an optical image (Figure 4). The width of antenna in the cross-printing direction (perpendicular to printing direction) is greater than the designed one resulting the reduced gap whereas the width and gap of antenna in printing direction is close to the designed width and gap dimensions. This spreading effect has caused the Antenna B to have short problem in the cross-printing direction.

This spreading of the ink in the cross-printing direction is also seen in the sensor patterns (Figure 5). Lesser viscosity of the sensor patterns resulted the spreading effect in both printing and cross printing direction. However, spreading is more in the cross-printing direction compared to the printing direction.

Considering this issue, the sensor patterns which has higher resolution were designed such that they are all oriented in printing direction and overcome the possible short problem. As a result, none of the sensor had the short issue even the gap between adjacent lines were less. Unlike sensor patterns, antenna design needs to be done in both printing and cross printing direction. Therefore, it is recommended to minimize the width of the antenna patterns in cross printing direction to maintain the required gap between the lines during the roll design so that in final printing, both the printing direction and cross printing direction lines will have similar width and gap, which will be considered in our future works.

Antenna Designs	Width(µm)	Gap(µm)
Antenna design A	1200	550
Antenna design B	1000	400
Antenna design C	1500	200

(a) Antenna design

Sensor pattern	Width(µm)	Gap(µm)
Pattern 1	100	150
Pattern 2	150	200
Pattern 3	200	200
Pattern 4	800	400
Pattern 5	400	400
Pattern 6	500	500
Pattern 7	400	200
Pattern 8	200	200

(b) Temperature sensor pattern designs

Table 1 – Width and gap of designed antenna and thermistor patterns

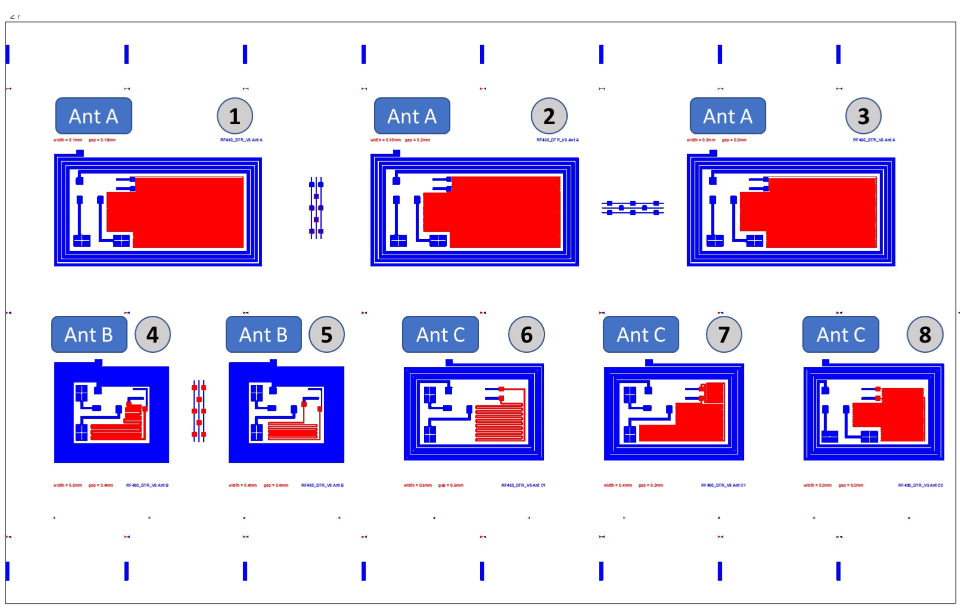
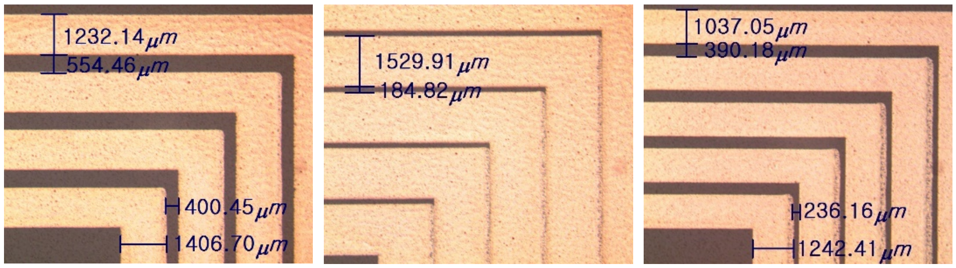
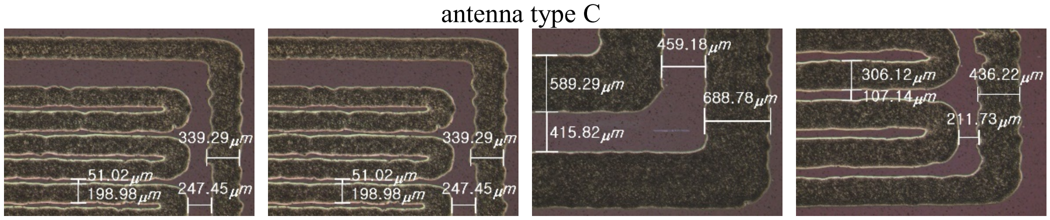


Figure 3 – CAD design of the antenna and temperature sensor pattern



(a) (b) (c)

Figure 4 – Optical images showing the width and gap in printing direction and cross printing direction of three antenna designs (a) antenna type A, (b) antenna type B, and (c antenna type C



(a) (b) (c) (d)

Figure 5 – Optical images showing the width and gap in printing direction and cross printing direction of sensor patterns (a) pattern 1, (b) pattern 2, (c) pattern 5, and (d) pattern 8.

INK RHEOLOGICAL PARAMETERS

For printing antenna layer, hydrophilic silver nanoparticle-based ink with viscosity of 1000cP and surface tension of 43mN/m was used. In order to obtain better ink transfer and print quality, the nip roll pressure of 6 kgf, printing speed of 6m/min, and blade angle of 9° was maintained. Similarly, for printing thermistor layer, hydrophobic nanoparticle-based ink with viscosity of 400cP, surface tension of 32mN/m was used. The optimized printing condition was 6kgf printing pressure at nip roll and printing speed of 8m/min.

Figure 6 shows the how the viscosity of ink changes with the varying shear rate. It shows how the ink viscosity is reduced while printing thus showing the effect of printing speed, pressure in ink transfer.

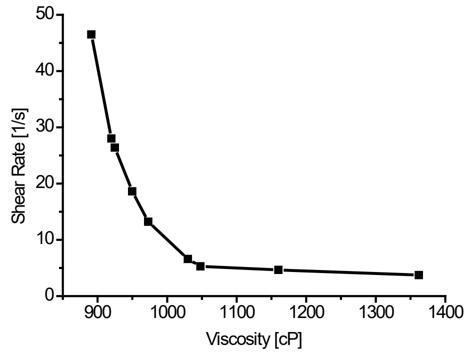


Figure 6 – Viscosity vs shear rate of silver ink to print antenna

PI (polyethylene imine) film as substrate was used for printing antenna and temperature sensor as it can withstand high curing temperature. High temperature curing is required as the printed antenna are required to have high Q factor (Figure 7b) to be detectable by smartphone for NFC reading of time temperature log. Figure 7a shows how the resistance of the antenna reduces over the curing time at 240°C. It shows that the antenna resistance is already saturated at 10 to 20 min and further curing isn't necessary. However, considering the temperature sensor pattern, which have very fine width and is easily broken at higher annealing temperature curing, optimized curing temperature of 240°C for 20 minutes is done using pattern 8 with antenna C.

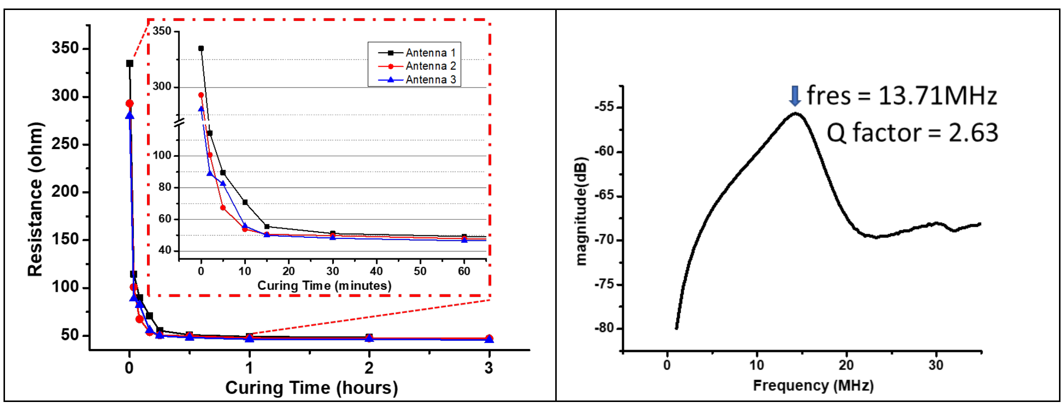


Figure 7 – (a) Antenna resistance with curing time (b) Q factor of the antenna

TEMPERATURE SENSOR CHARACTERIZATION

In order to characterize R2R printed temperature sensor, temperature-controlled chamber was custom-designed in which the desired temperature with 1°C could be controlled. The R2R printed hydrophobic silver-based temperature sensor showed PTC (positive temperature coefficient) behavior with excellent repeatability and no noticeable hysteresis over 6 cycles of 33°C to -15°C (Figure 8a). Resolution of at least 1°C was obtained (Figure 8b) when tested over 30 to -15°C. Figure 8c shows an excellent response time of the sensor from ambient room temperature to set temperature in the chamber. Slight variation in the ambient temperature is due to varying ambient temperature over long experiment as the ambient room temperature cannot be controlled. Noticeably, all measured R2R printed temperature sensor shows the same slope (Figure 8d) and the base resistance are in similar range thus enabling the possibility of single point calibration during mass production.

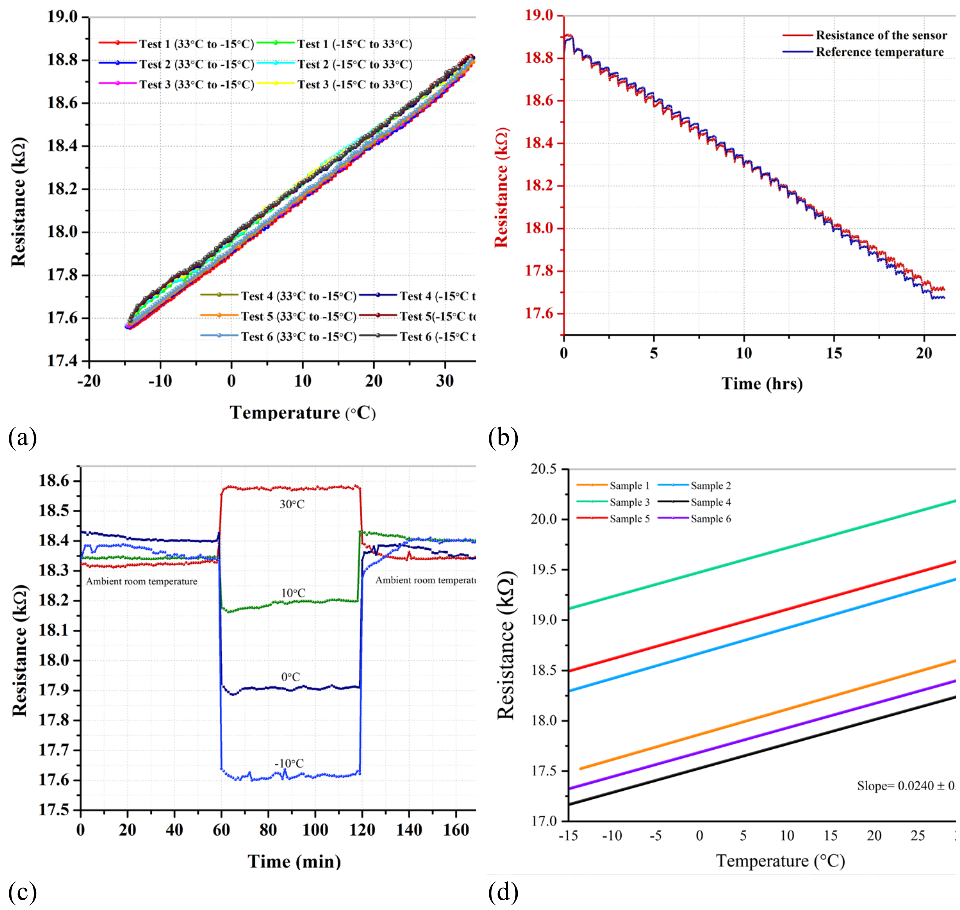


Figure 8 – Temperature sensor characterization showing (a) linearity, repeatability without hysteresis, (b) resolution, (c) response time and (d) reliable slope

NFC TAG INTEGRATION

The change in resistance of the sensor over varying temperature is detected by the ADC of the NFC transponder chip RF430FRL152H which has inbuilt MSP430 microcontroller. Constant current is generated at ADC pins of the microcontroller. Voltage drop at temperature sensor connected at this point is measured and sent to smartphone via NFC. The conversion of voltage to resistance and then to temperature is done in the android app where all the temperature history stored in the chip is displayed in user friendly graphical view in the smartphone (Figure 9). This temperature time history (TTH) log is sent for further processing in the server to show the spoilage of the food.

Figure 9 – Image of smartphone reading the temperature time history stored in the label

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