Printed Flexible Temperature Sensor with NFC Interface

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Abstract – Integration of sensors with antennas is becoming popular for compact high-performance wireless sensing systems. In this direction, here we present a silver electrodes and Poly(3,4-ethylenedioxythiophene:polystyrene (PEDOT:PSS) based printed temperature sensor on a flexible PVC substrate. The temperature sensor was characterised using a digital multimeter for a temperature range from 25°C to 90°C. The sensor showed a 70% change in resistance for the tested temperature range. Further, the sensing part was integrated with a Near Field Communication (NFC) tag with the data obtained semi-quantitatively by means of the intensity of an Light Emittign Diode (LED) connected with the antenna system. In this case, the antenna works as an energy harvester to power an LED indicator connected in series to the resistive temperature sensor. The intensity of the LED, which varies with the increase of temperature, was measured using a lux-meter mobile application. The intensity at 70°C was ~42 lux whereas it decreased down to ~14 lux at room temperature (~25°C). The presented system showed potential use as a smart label in applications requiring temperature monitoring.

Key-words – Temperature Sensor, NFC Antenna, Flexible Electronics, Printed Sensors

I. Introduction

Smart sensors are essential parts of smart factories, serving as the interface between the digital and physical worlds. They are the drivers of Industry 4.0 and the Internet of Things (IoT) in factories and workplaces[1, 2]. The combination of sophisticated sensors, increased computational power and wireless connectivity, increasingly, by 5G networks, will enable new ways to analyze data and gain actionable insights to improve many areas of operations. As a result, significant progress has been made in the direction towards development of sensors for various applications such as environmental, biomedical, and security [3-5]. To this end, the advances in nanotechnology and printed electronics have unlocked interesting avenues for using various functional material to develop wearable and flexible sensors[6, 7]. As a result, several sensors such as sweat [8, 9], pressure[10, 11], temperature [12-14], pH [15], volatile organic compounds [16, 17] and biomarkers [18, 19] for environmental and healthcare monitoring [20, 21] have been reported in the literature.

Among various physical sensors, the temperature sensors have attracted much attention in healthcare and industrial applications. The conventional temperature sensors are made of semiconductors [22, 23], carbon derivatives [12, 24, 25] and temperature-sensitive materials. Conductive polymers have also attracted significant attention for temperature sensing, owing to their ease of processing and excellent electrical properties [26]. However, the polymers suffer from low stability at high temperature. PEDOT:PSS (Poly(3,4-ethylenedioxythiophene:polystyrene) is one of the most stable organic conductive polymers and it exhibits electrical properties similar to a metal or semiconductor [27, 28]. This material is suitable for fabricating temperature sensors on flexible substrates and with high-temperature range. The choice of flexible substrate depends on the specific application. For example, Polyvinyl Chloride (PVC) has been reported in literature due to its sufficient thermal stabilityfor applications such as food packaging.

Although several types of temperature sensors have been developed in recent years, the printed temperature sensors integrated with the wireless interface is attractive for wearable devices. Among various wireless technologies for the reading and transmission of sensor data, the radiofrequency identification (RFID) and near field communication (NFC) have been widely used as the technologies for the development of sensing tags [29-31]. In particular, NFC technology provides a safe and convenient communication method for end-users to check the quality of packed items simply by scanning printed smart labels with a smartphone (e.g. for food packaging applications). Herein, we report the development of printed temperature sensor integrated with a custom-designed NFC platform and an LED indicator to visually detect the temperature variations. Significant change of the LED's light intensity has been observed with temperature variations.

This paper is organized as follows: The design and fabrication of NFC and temperature sensor and their characterisation are described in Section II. The experimental results are presented in Section III and finally the results are summarized in Section IV.

II. Design And Fabrication

A. Materials

Commercial PVC sheet, used here as substrate, was purchased from the local vendor. Silver Conductive Paste was procured from RS Components, UK and the conductive polymer PEDOT:PSS was procured from Sigma Aldrich, UK.

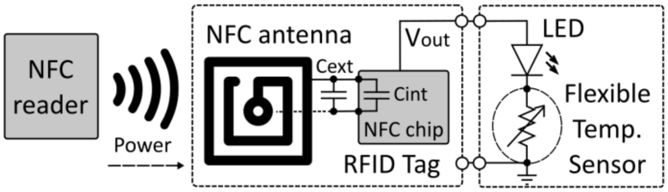

Fig. 1. Schematic diagram of the developed system for temperature detection including the NFC tag, reader and sensing module.

B. NFC tag design and fabrication

The chosen NFC chip was the model RF430FRL154H from Texas Instruments (Dallas, Texas, USA), which operates in a High Frequency (HF) band (i.e. 13.56 MHz). With an adequate external RF electromagnetic field from an RFID reader, this chip can provide a regulated output voltage of ~2 V with an output current up to 500 µA. This harvested energy is enough to power a visual LED indicator. A TRF7970A from Texas Instruments was used as the reader. The custom antenna consists of a PCB planar coil whose inductance value was designed to achieve resonance at 13.56 MHz, considering the internal capacitor value (C_{int}) of the RF430FRL154H chip at that frequency. Since resonance is achieved at $\omega_0 = 1/\sqrt{LC}$ and C_{int}~35 pF at 13.56 MHz, the required inductance value is L~3.9 µH. However, to reduce the antenna dimensions, a 1.8 µH squared planar inductor was designed with N = 7 turns with 500 µm as conductor width as well as the interspacing between the lines and overall dimensions of 29 mm^2. To complete the resonant circuit, an external capacitor of C_{ext} = 40 pF was placed in parallel to C_{int}. The tag was fabricated on FR4 substrate using a mechanical milling machine model ProtoMat S103 (LPKF Laser & Electronics AG, Garbsen, Germany).

C. Sensor design and fabrication

The sensor was fabricated using the conductive silver paste/ink (RS 186-3600) on a commercial PVC substrate. Figure 2(a) shows the schematic diagram of the sensor fabrication steps on PVC substrate. The PVC was cut into 2 cm × 2 cm pieces and two electrodes were printed on the flexible PVC substrate using silver paste as illustrated in Figure 2(a). The samples were then dried in a hot-air oven at 50 ºC for 30 mins. A 2 mm gap was maintained in the middle of two electrodes. Further, a 10 µl of PEDOT:PSS was dispensed in the 2 mm gap using a micro-pipette. The samples were further dried at 50 ºC for 1 hr inside an air-oven. Thereafter, the samples were electrically characterised to evaluate their response. The sensor was then integrated with the NFC antenna as shown in Figure 2(b).

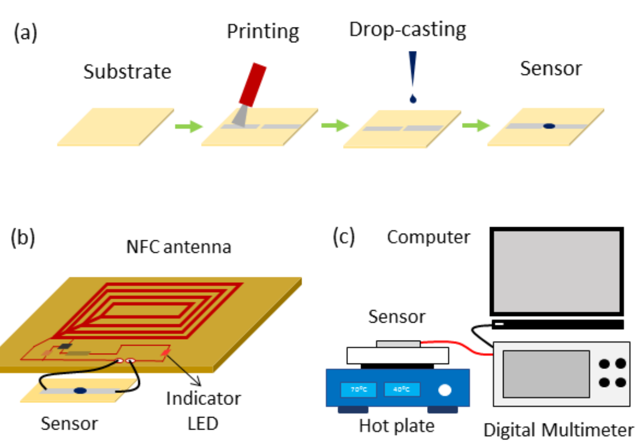

Fig. 2: (a) Fabrication steps; (b) schematics of sensor integrated with NFC antenna; and the (c) experimental set-up.

D. Characterization

The experiment was carried out using a temperature controllable hotplate (Stuart CD162). A high-precision IR thermometer (FLUKE 62 MAX) was used to monitor the temperature while performing the experiments. The sensor was placed above the hotplate and was connected to a digital multimeter (Agilent), as shown in Figure 2(c). The experiments were performed at ambient condition and the temperature of the probe was also monitored during the experiments. Thereafter the temperature of the hotplate was increased to the desired value and the resistance value corresponding to that temperature was recorded. The actual temperature on the sensor was recorded using the mentioned IR thermometer.

III. TEMPERATURE SENSING

PEDOT:PSS is sensitive to the temperature. The rise in temperature increases the rate of carrier mobility in the material and thus the resistance decreases [28]. The printed PEDOT:PSS element was tested for temperature sensing. A temperature sensing sample was prepared separately on PVC substrate with PEDOT:PSS having two silver electrodes. The sensing sample was then characterized using LabVIEW enabled digital multimeter and heating arrangement, i.e. a hotplate having digital display control as shown in Figure 2(c). The temperature-sensitive PEDOT:PSS with two Ag electrode was placed on the digital hotplate and the temperature was varied from 25 to 90º C. The resistance was found to be decreasing with the increase in temperature as illustrated in Figure 3. The sensor was given some time to saturate before the temperature of the underneath hotplate was increased to a higher value. The sensor was exposed to different temperature and the response (R/R_0) was recorded. Figure 3 shows the

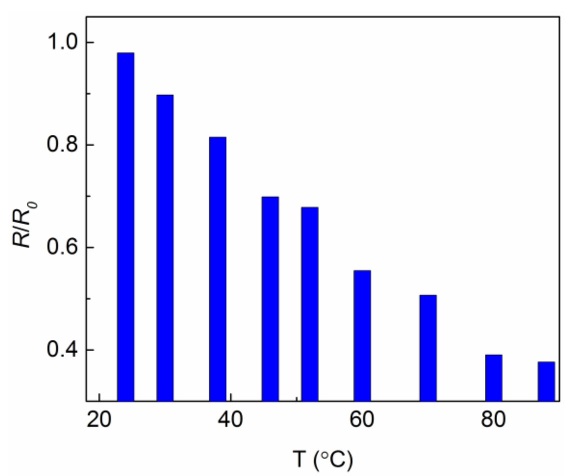

Fig. 3: Temperature sensor response.

change in R/R_0 with temperature.

Further, the sensor was connected to the designed NFC antenna system. Figure 4 shows the circuit and the system associated with the semi-quantitative temperature measuring set-up. The set-up consists of the custom-made NFC tag, the temperature sensor, and an NFC reader. In this case, the NFC tag was used to power the LED indicator which is connected in series with the temperature sensor. The temperature sensor, in this case, is resistive and thus the resistance of the same decreases with the increase in temperature value. Therefore, in the presence of the NFC reader, the LED glows with different intensities based on the resistance of the temperature sensor, as shown in Figure 4(a). Currently a rigid NFC tag is used, although we plan to extend this work further to develop a flexible version. Figure 4(b) shows a schematic illustration of the sensing tag using a lux-meter mobile application, while Figure 4(c) shows the intensity of indicator at different temperatures. The intensity at 70ºC was ~42 lux whereas the intensity decreased down to was ~14 lux at room temperature (~25ºC).

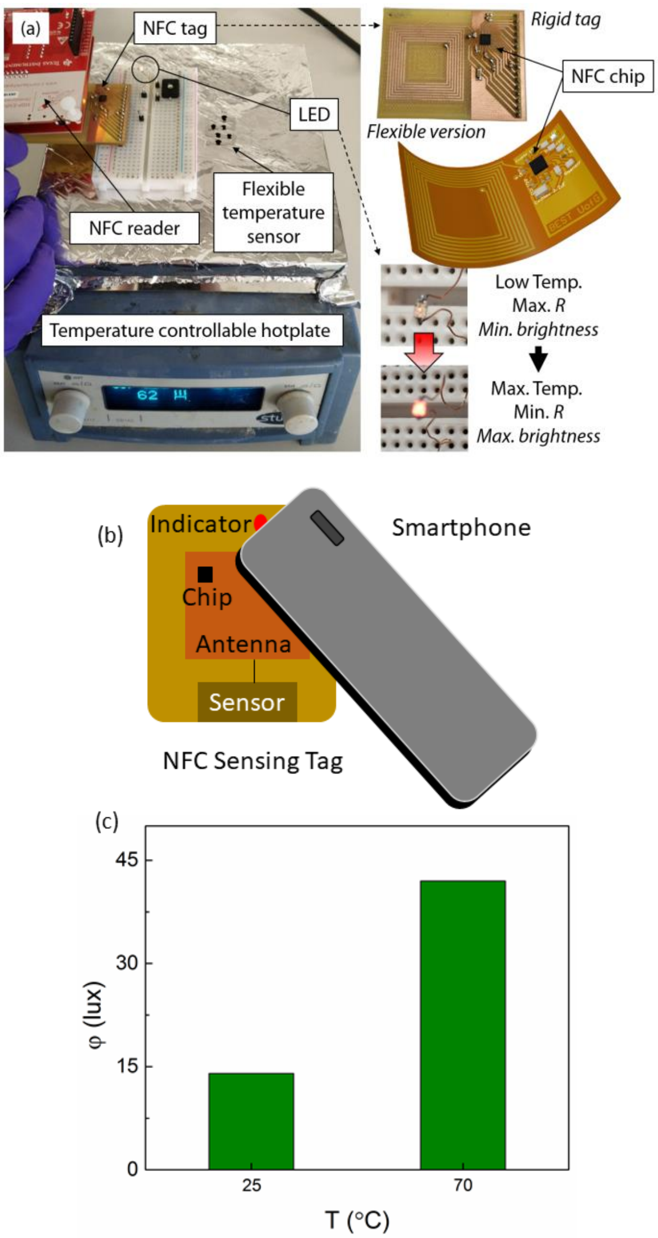

Fig. 4: (a) Photograph of NFC tag system along with reader, including the optical images of the LED for extreme temperature conditions. The rigid tag version and the schematic of the flexible are also shown; (b) schematic illustration of sensing tag using a lux-meter mobile application; and (c) the intensity of indicator at different temperatures.

IV. Conclusions

In this paper, PEDOT:PSS based temperature sensor integrated with an NFC system is presented. The temperature sensor was characterized using digital multimeter for a temperature range from 25ºC to 90ºC. The sensor showed a 70% change in resistance for a temperature change of ~60ºC. The sensing part was further integrated with an NFC antenna and the temperature was obtained semi-quantitatively by means of the intensity of LED connected with the antenna system. The NFC antenna resonates at ~13.56 MHz and can be operated using any NFC enabled smartphone. This wireless-enabled temperature sensor can be used as a smart label in packaging applications. This work can further be extended to develop a fully flexible smart label with detailed analysis.

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Note: *Corresponding author, † Equal contributions

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