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NFC based Polymer Strain Sensor for Smart Packaging

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Abstract

This paper presents a polymer strain sensor integrated with an NFC tag to detect strain semi-quantitatively. The strain sensor is fabricated using flexible and transparent polymer Polydimethylsiloxane (PDMS) microchannel having conductive polymer poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) as an active material. The sensor was tested with different bending conditions and it was found that the resistance increases with higher bending. A maximum of 3 order change in resistance was observed for ~100° bending. The sensor was finally tested using a custom-developed passive NFC tag having an LED connected in series with the strain sensor and powered from the reader via the NFC antenna in the tag.

1 Introduction

The mobile telephony and smartphones with rich functions have created new opportunities for high standard, secure and efficient delivery systems. The safety of goods during transportation is a key step particularly for food packages, as even slight damage could raise health and safety concerns [1]. For this reason, several types of sensors such as pH [2, 3], biomolecules [4-6], humidity [7], VOCs [8, 9] etc. have been explored with self-powered or power storage means such as supercapacitor and battery. Likewise, the smart labels with physical sensors such as strain [10, 11] and temperature sensors [12-15] with radiofrequency identification (RFID) and near field communication (NFC) could offer new possibility for monitoring the packages. In this regard, few examples of RFID tags have also been presented to recognize mishandling of packages during storage [16] and for meat traceability [17]. Flexible RFID tag datalogger attached to the bottles have also been reported to collect environmental data [18]. There are several other examples in the literature where RFID has been implemented in packages for sensing applications [19-21].

Both RFID and NFC could enable battery-less powering and data backscatter communication. However, in NFC the tag just interacts with a reader or NFC-enabled device (e.g. smartphone) held in close proximity of 1-3 cm for safe data transmission. NFC technology has been used, for instance, to develop a multi-gas sensing platform to control the gas concentration in food packages [22, 23]. Another example consists of an NFC sensing tag for continuous object-level monitoring of relative humidity, light and temperature [24]. Most of these previous studies have focused on the wireless chemical sensors for detection of specific gases. This work aims to wirelessly monitor the dynamic strain to detect potential damage to packages during transit or storage.

Strain sensors are classified as piezoelectric, piezoresistive and piezocapacitive [25]. In piezoresistive strain sensors, the variation in the length, due to mechanical strain, causes a change in the electrical resistance of the device [26]. High flexibility plays an essential role in the durability and long-term stability of the strain sensor. In the literature, several polymer-based strain sensors have been reported [27-29]. In [30] carbon nanotube (CNT) based strain sensor was fabricated by dielectrophoresis (DEP) method. Apart from CNT, poly(3,4-ethylenedioxythiophene) (PEDOT: PSS) has come to wider attention due to good electrical properties. This paper presents an NFC-based strain sensor. The dynamic strain sensor has been developed and reported in [31]. Extending that work further, herein the NFC platform has been designed and integrated with an LED to visually detect the strain variations, as significant change has been observed in the of the light intensity of LED's.

2 Materials and Methods

A. Sensor design and fabrication: The strain sensor was fabricated using flexible and transparent polymer PDMS. PDMS and PEDOT:PSS were procured from Sigma Aldrich. The other necessary consumables were procured from local vendors. The polymer PDMS and crosslinker were mixed at 10:1 ratio and poured into a circular mold (dia 5.5 cm) and then the mixture was degassed for 1 hr using desiccator. Then the mold was cured at convection oven for 2 hrs at 70°C. A detailed fabrication of microchannel is available at one of our previous works [31] After the microchannel fabrication, conductive polymer PEDOT:PSS was injected into the channel followed by drying and electrodes were fixed using metal wires. The schematic diagram and the optical image of the fabricated sensor are shown in Figure 1(a) and 1(b), respectively.

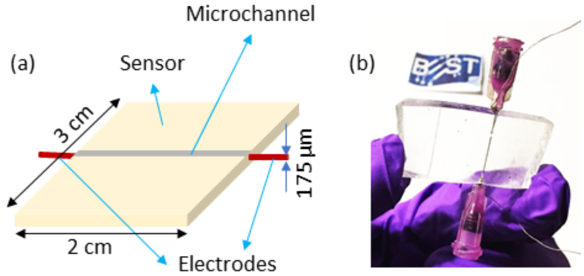

Figure 1: (a) Schematic illustration of microchannel based strain sensor; (b) optical image of the fabricated sensor.

B. NFC tag design and fabrication: The NFC transponder chip RF430FRL154H (Texas Instruments, Dallas, Texas, USA) was used along with a custom-designed RFID antenna. This chip operates in High Frequency (HF) band (i.e. 13.56 MHz) and is able to provide a regulated voltage of ~2 V with an output current up to 500 µA given that an adequate external RF electromagnetic field from the RFID reader is provided. This harvested energy is enough to power the LED. A TRF7970A from Texas Instruments was used as the reader. Tag antenna consists of a PCB custom-designed planar coil and the internal capacitor of the RF430FRL154H chip. Resonance is achieved at $\omega_0 = \sqrt{LC}$, with C~35 pF being the input capacitance of the RFID chip at the frequency of interest, 13.56 MHz. Therefore, 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 seven turns and dimensions of 29 mm^2, being 500 µm the width of the conductor and the interspacing between the lines. To achieve resonance, an external capacitor of 40 pF was placed in parallel to the internal chip capacitor. The tag was fabricated on FR4 substrate using a mechanical milling machine model ProtoMat S103 (LPKF Laser & Electronics AG, Garbsen, Germany).

C. Characterization: The microchannel based strain sensor was characterized using a digital multimeter (Agilent 34461A) connected to a LabVIEW application. Further, the semi-quantitative measurements were taken directly from the developed NFC tag. In this case, the variation in the intensity of the LED was used as the measure of strain.

3 Results and Discussion

Figure 2 shows the circuit and the system associated with the semi-quantitative strain measuring set-up. The set-up consists of a custom-made NFC antenna, RFID chip, strain sensor, and an NFC reader. In this case, the NFC tag was used to power an LED which is connected in series with the strain sensor.

In the presence of the NFC reader, the LED glows with different intensities based on the resistance of the strain sensor. The strain sensor, in this case, is resistive and thus the resistance of the same increases with the increase in strain value. Figure 3(a) shows the temporal normalized resistance (R_N) response of the strain sensor. The response, in this case, was measured by bending the sensor to different angles. The response was calculated using normalized resistance of the sensor where the maximum strain, in this case, was correlated to the maximum change in the resistance.

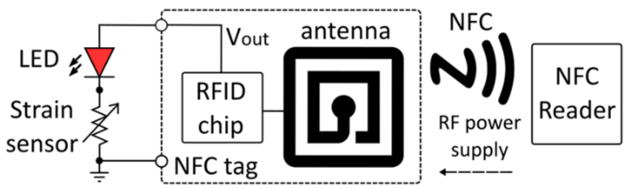

Figure 2: The system developed for the detection of strain.

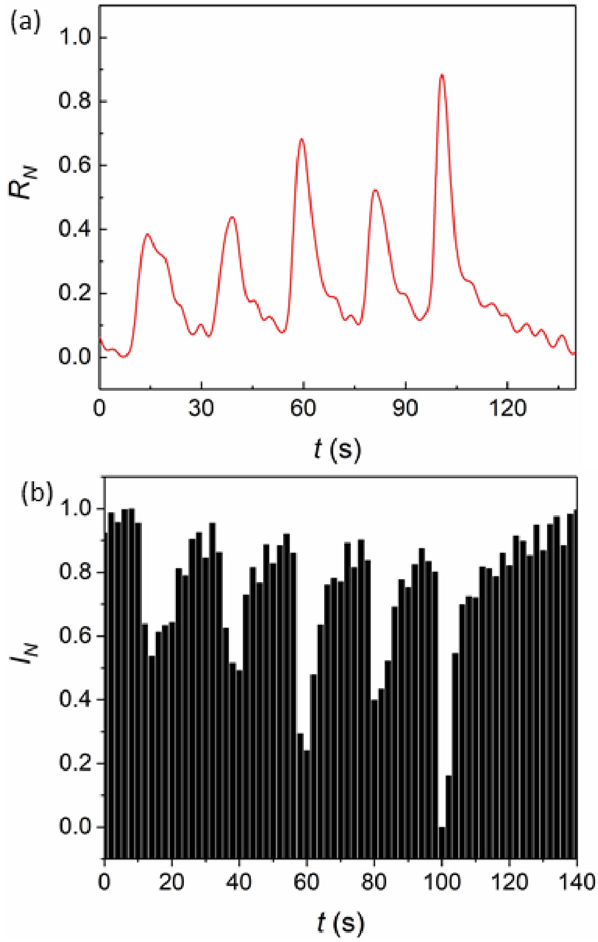

Figure 3: (a) Normalised resistance (R_N) response of the sensor with time; (b) the normalised current (I_N) response of the sensor due to strain.

Further, the corresponding current values were also calculated for the bending cycles. Figure 3(b) shows the normalised current response (I_N) of the sensor. The system was then tested with the intensity of the LED connected to the sensor in series as illustrated in Figure 2. The intensity of the LED decreased significantly once the sensor underwent bending. For the maximum strain condition, the LED was found to be almost OFF whereas the LED intensity was highest for relaxed or no strain condition. Figure 4(a) shows the optical image of the system with different parts whereas Figures (b-d) show the decrease in the intensity of the LED with the increase in strain.

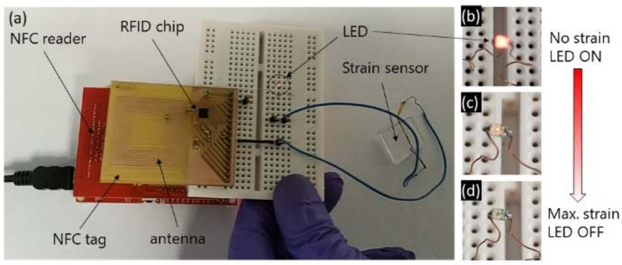

Figure 4: (a) The optical image of the NFC tag system along with the reader; (b-d) the optical images of the LED for no strain to maximum strain condition.

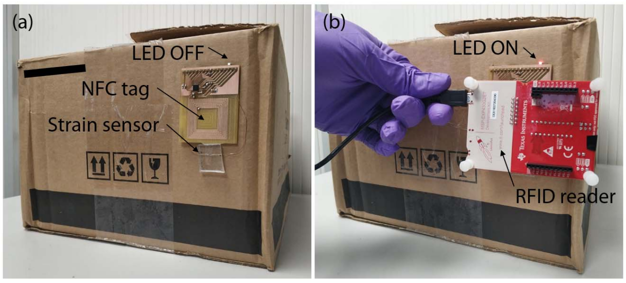

Figure 5: (a) Optical images of the NFC tag system attached to a carboard package for smart packaging application; (b) optical image of the LED ON when the RFID reader gets close to the tag.

As a proof of concept, Figure 5 shows the NFC-based strain sensor system attached to a cardboard package for smart packaging applications. When the RFID reader is approached to the tag, the light intensity of the LED will reveal the potential damage that the package is exposed to due to bending or crushing.

4 Conclusions

This paper presents a conductive polymer PEDOT:PSS and PDMS based strain sensor with an NFC tag to detect the strain semi-quantitatively. The strain sensor is based on microchannel which is fabricated using flexible and transparent polymer Polydimethylsiloxane (PDMS) microchannel and conductive polymer PEDOT:PSS was injected into the channel as the active material. The sensor showed higher resistance for higher strain. A maximum of 3 order change in resistance was observed for ~100□ bending. Electrical discontinuities upon bending lead to the change in the response. The sensor was then connected to a custom-developed NFC tag system which contains an LED indicator for measuring the strain in a semi-quantitatively way. This work can be further extended as a smart label for food-packaging monitoring, which is kept as future scope of this work.

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Note: *Corresponding author; †Equal contribution.

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