Biodegradable Temperature Sensor enabled using Printed Electronics

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Abstract— **Printed electronics are considered the future of manufacturing electronic devices due to their cost-effectiveness, speed, and customizability compared to traditional methods using silicon. As medical electronics usage increases, there's a growing concern about safely disposing of electronic waste without harming the environment, especially since many of these devices are single-use. Researchers are focusing on developing conductive materials that are non-toxic and biodegradable. In this study we demonstrate the effectiveness of a fully-biodegradable temperature sensor patch. The patch was made using a biodegradable, water-soluble substrate consisting of 3% PVA films. Ink deposition is achieved using the inkjet method. The resulting sensor is flexible, bendable, and suitable for use as an e-skin patch. Here, two different conductive materials such as poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) and silver have been used as an active layer. The resultant sensor performance and their corresponding biodegradability studies have been studied and compared thoroughly. The fully-biodegradable PEDOT:PSS sensor exhibited good linearity in resistance measurements between 30-110 °C, with a temperature coefficient of resistance (TCR) value of 13.2×10^{-4} C^{-1} and a sensitivity of 85.85 Ω/°C.**

Keywords—printed electronics; flexible electronics; temperature sensor; biodegradable;

I. Introduction

The motivation of this research stems from the pressing need to address the environmental impact of electronic waste. Traditional electronics often contain non-biodegradable materials that can persist in landfills for centuries, posing significant threats to ecosystems and human health. By developing electronics that are designed to degrade safely and naturally at the end of their lifecycle, researchers aim to minimize the environmental footprint of electronic devices. Biodegradable electronics offer the potential for sustainable solutions in various applications, including medical devices, wearable technology, and disposable electronics, ultimately contributing to a cleaner and more sustainable future.[1]

As a first step towards minimizing the e-waste, researchers have focused on using biodegradable polymer substrates which offers a sustainable solution in various industries, ranging from packaging to biomedical applications. The commonly available degradable substrates includes polyglycolic acid (PGA), polyethylene glycol (PEG), poly(vinylalcohol) (PVA), and potentially derived from renewable resources like corn starch, cellulose, or polylactic acid (PLA).[2] These substrates can break down naturally into harmless byproducts thereby reducing environmental impact. Among these, we choose PVA as a substrate in our study owing to their biodegradability, high water-solubility and the ease of production.[3] By using these biodegradable polymer substrates, we can mitigate the adverse effects of traditional plastics on ecosystems, marine life, and human health. Additionally, they offer versatility in applications while maintaining functionality and durability.

A biodegradable temperature sensor represents a significant advancement in the field of sustainable technology. These sensors are typically made from biocompatible and biodegradable materials. They function similarly to the traditional temperature sensors, detecting changes in temperature and providing valuable data for various applications including environmental monitoring, food safety, and healthcare.[4] Additionally, in fields like healthcare, biodegradable temperature sensors offer a safe and environmentally friendly option for monitoring patient vitals without the need for invasive procedures or subsequent waste management. These sensors are being utilized for real-time temperature monitoring in wound healing, drug delivery systems, agricultural monitoring, and environmental sensing. The biodegradable temperature sensors are typically made up of materials such as silicon nanomembrane, silk fibroin, cellulose derivatives, and bio-based polymers.[5] The research work until now on this area, lacks with respect to sensitivity, limited temperature range and demonstrating them with a low cost highly scalable techniques.

In this regard, here we show a highly scalable low cost inkjet printing technique demonstrating a completely bio-degradable temperature sensor on a PVA substrate. We used biodegradable PEDOT:PSS and non-biodegradable silver inks to fabricate temperature sensors and simultaneously compared their performance. The fully-biodegradable sensor based on PEDOT:PSS exhibited good linearity in resistance measurements between 30-110 °C, with a temperature coefficient of resistance (TCR) value of -13.2×10^{-4} C^{-1} and a sensitivity of 85.85 Ω/°C.

II. Experimental details

A. Preparation of biodegradable PVA substrate

The PVA film was used as a biodegradable substrate to build the sensor on top of it. The as bought PVA powder from Sigma Aldrich was used to make the PVA sheets. Firstly, a 3% PVA solution was prepared and stirred at 130 °C for around 45 minutes. The obtained solution was poured on a ceramic petri-dish with dimensions of 21 x 29.7 cm (comparable to the size of an A4 paper sheet) and dried in oven at 50 °C for about 12 h. The dried sheet was peeled out and found to have a thickness of around 100 µm

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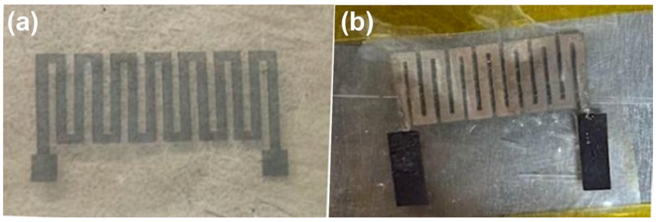

Figure 1: (a) Inkjet printed PEDOT:PSS temperature sensor on PVA substrate (b) Fabricated silver temperature sensor on PVA substrate.

(comparable to the thickness of a sheet of paper) – later cut to smaller patches as needed. The obtained PVA sheets are really thin, bendable, and transparent. The films are durable to some extent of force, but can also be torn easy with bare hands, similarly to a sheet of paper.

B. Fabrication of temperature sensors via inkjet printing

Two conductive material inks were used for the creation of the temperature sensor samples. The inkjet printable water based thermally curable nanosilver ink was purchased from Novacentrix Metalon JS-A191s and the biodegradable PEDOT:PSS ink was purchased from Sigma Aldrich. Both the inks were used as received and printed at room temperature with a drop spacing of 25 µm alongside the cartridge voltage of 25 V. The printed temperature sensors using PEDOT:PSS and silver inks on the PVA substrates are shown in Fig.1 (a-b).

III. Results and Discussion

The fabricated temperature sensors have been studied for their sensing performance with respect to different temperature ranges. To determine the effectiveness of the produced sensor, a resistance measurement has been taken during continuous temperature change. The experimental setup consisted of two measurement probes. For the resistance measurements, the substrate was placed on a hot plate in order to accurately manipulate the temperature around the sensor, and effectively of the conductive material itself. The viable range of the temperatures that could be achieved with this setup was between 30 to 150 °C. The resistance change has been recorded with the temperature increment of 10 °C.

A. Temperature sensor measurement

At first both the samples have been subjected to the temperature-dependant resistance measurement to test and analyse the performance of the sample as a temperature sensor. As a general principle, a large difference between the low and high temperature measurement should be calculated in order to properly calibrate the sensor. A good linear trend of the measured values is a crucial aspect of a properly functioning device, as it allows one to accurately map the resistance value to the temperature. The temperature coefficient resistance (TCR = $((R_H - R_L)/R_L)/(\Delta T)$) of the sensor can be calculated by this formula, where R_H and R_L denote the resistance value measured at highest and lowest temperatures, respectively, and ΔT is the change in temperature between those two measurements. The TCR is a vital parameter for many practical applications of temperature sensors which refers to the relative change in

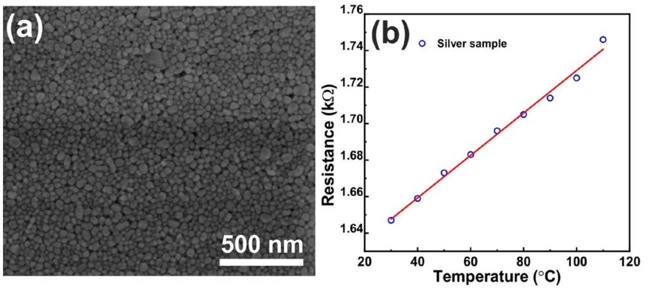

Figure 2: (a) Scanning electron micrograph of the printed silver droplet showing good film formation with reduced porosity. (b) Inkjet printed silver based temperature sensor performance with respect to different temperature range fabricated on PVA substrate.

resistance when the temperature increases by 1 °C. The lower the TCR value, the better the sensor's stability and accuracy. A lower TCR implies that the resistance changes less for a given change in temperature, making the sensor more reliable and precise in measuring temperature fluctuations. Besides, another important parameter in temperature sensor is sensitivity which is defined as $S = (R_H - R_L)/\Delta T$. Higher the sensitivity, better the sensor performance.

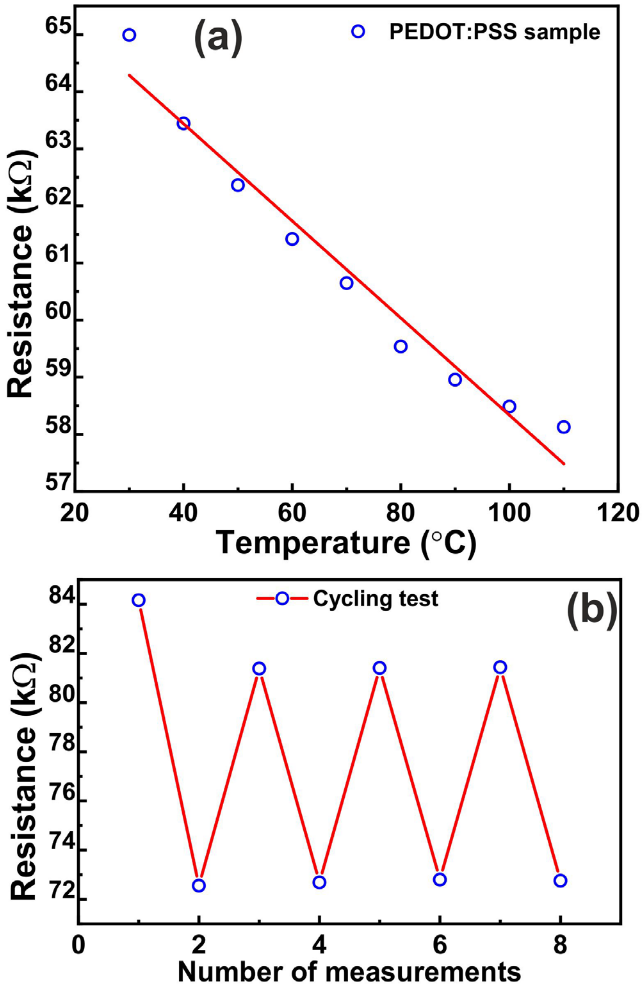

Figure 3: (a) Inkjet printed PEDOT:PSS temperature sensor performance with respect to different temperature range fabricated on PVA substrate showing a linear fit. (b) Cycling test of the same sample measured between 30 and 100 °C.

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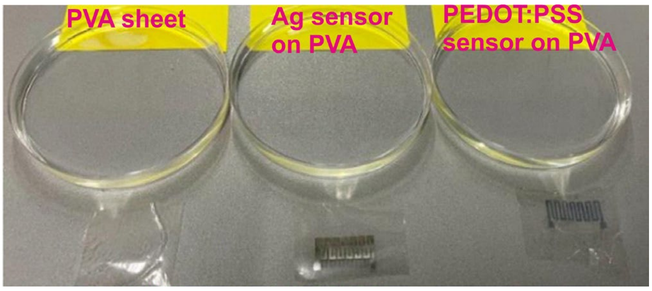

Figure 4: Water solubility/degradability test of PVA sheet, fabricated Ag sensor, and PEDOT:PSS sensor.

Fig. 2a shows SEM micrograph of the printed silver droplet demonstrating smooth film formation. Next, the printed silver temperature sensor has been measured with different temperature range starting from 30-130 °C, as shown in Fig. 2b. It has been observed that the resistance increases until 110 ºC and starts to decrease after that. The linear fit up to 110 °C shows a good linear fit with the R^2 value of 0.992. Here, the calculated average TCR turned out to be $9,0229\times10^{-4}$ C^{-1} and the average sensitivity equals to 1,331 Ω/°C.
Similarly, the fabricated PEDOT:PSS sample has been tested for the sensing performance. As the PEDOT:PSS is a *p*-type material, a reverse trend in resistance (Fig. 3a) has been noted in comparison with silver samples. PEDOT:PSS sensors demonstrates good linearity with a R^2 value of 0.9678. To further test its cyclability, the PEDOT:PSS sensor has been altered between 30 °C and 100 °C over 8 measurements. The less change here indicates the good stability of the PEDOT:PSS sensors. Finally, the calculated TCR value equal to $9,8\times10^{-4}$ C^{-1} with the average sensitivity equal to 61,34 Ω/°C.

B. Biodegradability results of temperature sensors

The degradability test is carried out by submerging the PVA substrate, printed silver and PEDOT:PSS temperature sensors in DI water over a range of different number of hours such as 2 hours, 24 hours, 48 hours and 7 days (Fig. 4). As visible, the dissolution of the sheets are gradual, and the conductive material can be seen separated from the substrate and floating in water. After 24 hours, the PEDOT:PSS sensor has been noted to dissolve very fast, while silver sensor needed 7 days to complete the degradation. By day 7, the PVA substrate and PEDOT:PSS sensors have found to dissolve completely. However, at the end of 7 days, still there remains a bit of PVA which could be due to the heat treatment (130 °C) given to the sheet preparation which is expected to reduce the solubility rates, often shrinking and becoming more firm and brittle after a week of submerging in distilled water, as shown in Fig. 5. It is theorized that the exposure to high temperatures changes internal structure of the material, resulting in non-solvable product.
With respect to the sensor performance, the silver sample has exhibited higher sensitivity than the PEDOT:PSS samples. While, PEDOT:PSS is a biodegradable polymer and therefore exhibits a faster degradation when compared to the silver samples. Altogether, we observed a trade-off between the sensor performance and degradability and thus depends on the requirement of the parameters, both the sensor can be exploited for the commercial applications

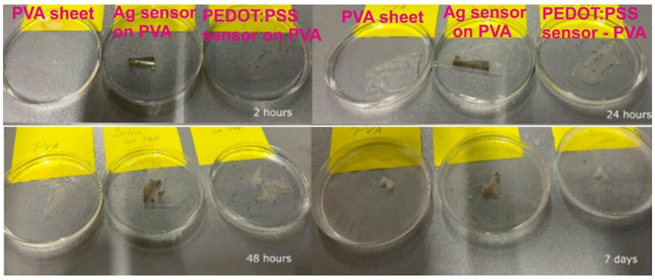

Figure 5: The degradability test is carried out for 3 different samples over a range of time starting with 2 h, 24 h, 48 h and 7 days.

CONCLUSION

In summary, we develop a fully-biodegradable temperature sensor patches presenting a significant step towards mitigating the environmental impact associated with electronic waste. By utilizing biodegradable PVA substrates and non-toxic conductive materials, such as PEDOT:PSS and silver inks, we demonstrate not only the feasibility but also the effectiveness of eco-friendly alternatives in electronic manufacturing. The fabricated sensor are highly flexible, bendable, and importantly suitable for e-skin applications and thereby leaving a potential for various medical and wearable technology applications. Finally, both the fabricated temperature sensors performance have been studied and compared in this work along with their detailed bio-degradability studies.

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