PEDOT:PSS based Disposable Humidity Sensor for Skin Moisture Monitoring

Ajay Beniwal[1], Dina Anna John[1], and Ravinder Dahiya[2]*

[1]James Watt School of Engineering, University of Glasgow, G12 8QQ, Glasgow, UK

[2]Bendable Electronics and Sustainable Technologies (BEST) Group, Northeastern University, Boston, MA 02115, USA

* *Fellow, IEEE*

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Abstract—This paper presents a flexible and disposable humidity sensor based on Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS). The sensing layer is developed by drop casting PEDOT:PSS on screen printed graphene-carbon (G-C) ink based interdigitated electrodes (IDEs) on paper substrate. The humidity sensing properties are investigated in a wide humidity range (25 %RH - 90 %RH) at room temperature (RT; 27 ºC ± 2 ºC). The sensor exhibits substantial % response (118.5 % at 90 %RH) in the considered range with response/recovery time as 70/30 seconds (sec). The applicability of the sensor has been demonstrated for skin moisture/humidity monitoring under normal and moist conditions. A read-out circuit is designed for demonstrating the real-time monitoring of skin moisture level. The obtained results indicate the suitability of the developed sensor for applications such as skin moisture monitoring, environmental humidity monitoring, non-contact switching, agriculture, and healthcare industries.

Index Terms—Disposable humidity sensor; eco-friendly; PEDOT:PSS; printed electronics; skin moisture monitoring.

I. INTRODUCTION

The Flexible, and printed electronics on disposable or degradable substrates is gaining considerable attention for various applications such as e-Skin, wearable health monitoring, food packaging and robotics, etc. [1-5]. As a result, several sensors such as humidity, temperature, pressure, pH etc. with flexible form factor have been reported in literature [2, 4, 6-9]. Among these, humidity sensor is of great importance considering its wide applicability in various areas such as environment monitoring, agriculture, skin moisture analysis, industry, healthcare and non-contact switching [10, 11]. Considering the frequent occurrence of skin related ailments, the use of these sensors is particularly important for skin moisture/humidity analysis

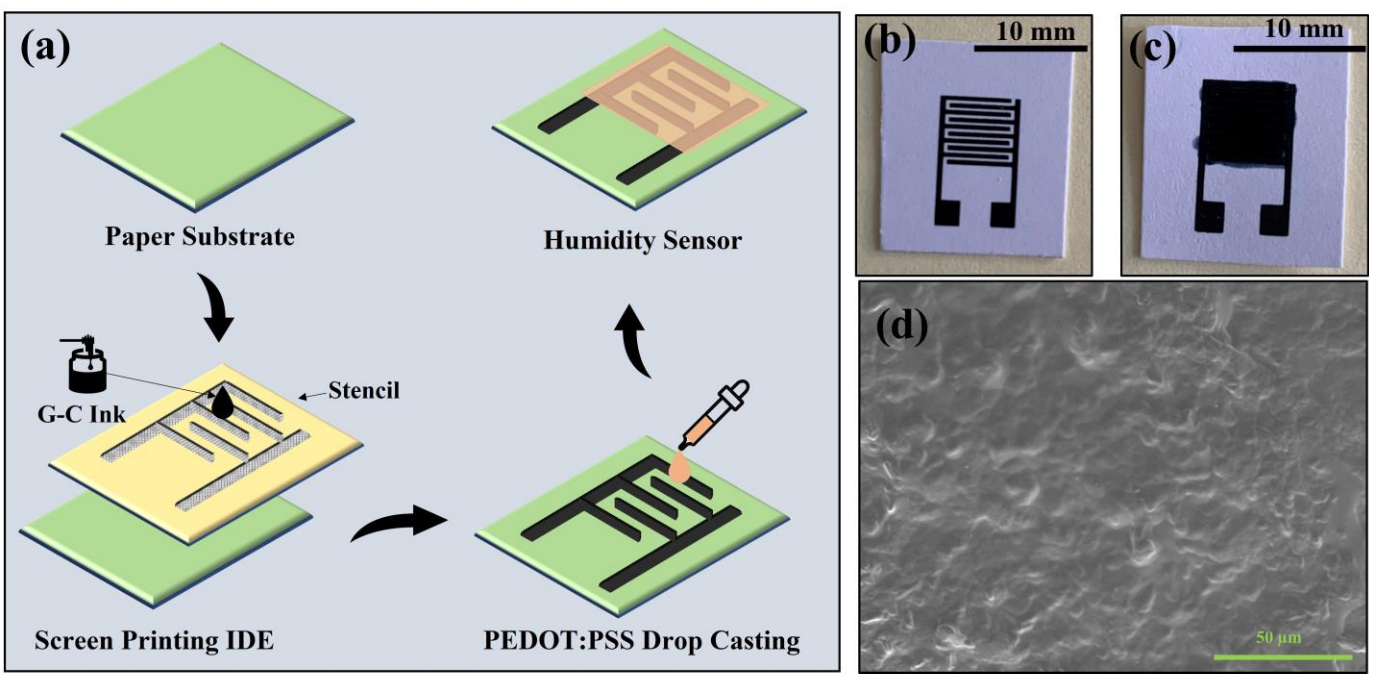

Fig. 1 (a) Schematic representation of the fabrication process for PEDOT:PSS based humidity sensor. (b) Screen-printed graphene-carbon ink based interdigitated electrodes on paper substrate. (c) PEDOT:PSS based flexible and disposable humidity sensor. (d) SEM images of the deposited PEDOT:PSS layer at 50 µm scale.

Corresponding author: Ravinder Dahiya (r.dahiya@northeastern.edu). Digital Object Identifier: 10.1109/LSEN.XXXX.XXXXXXX (inserted by IEEE).

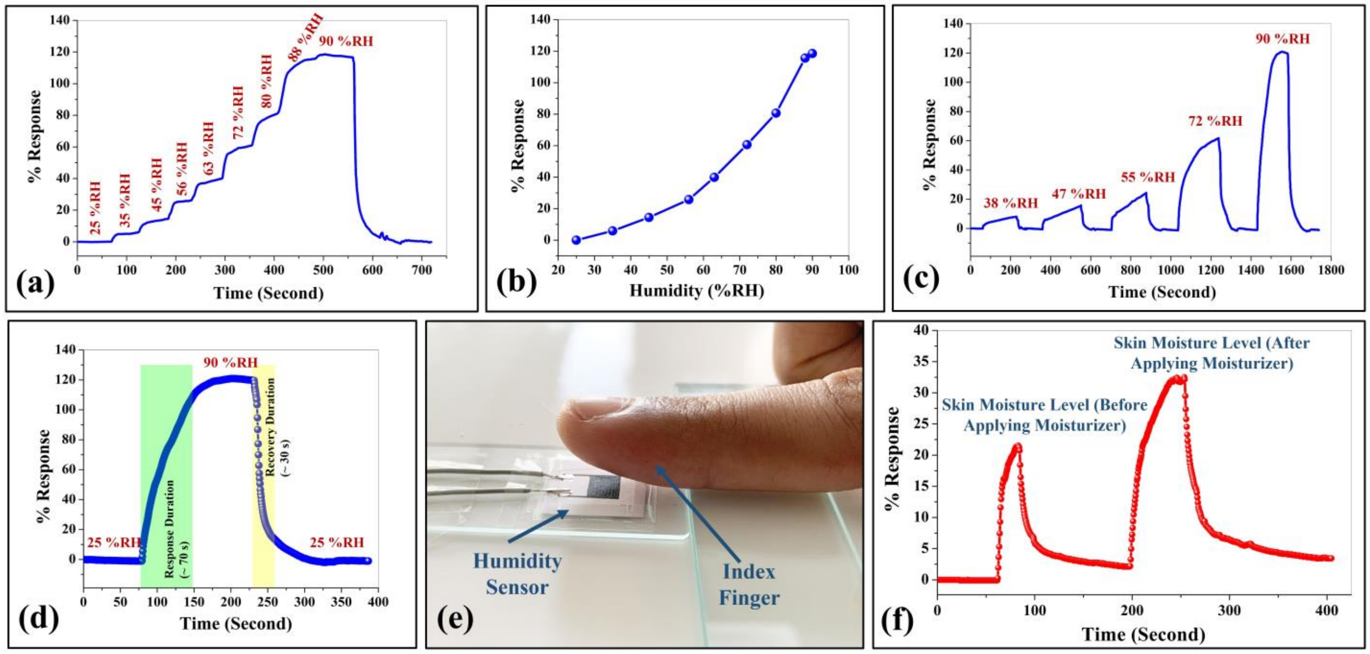

Fig. 2 (a) Humidity sensing characteristics of the sensor for 25 %RH to 90 %RH at room temperature (27 ºC ± 2 ºC). (b) % Response analysis within considered range. (c) Response at 38 %RH, 47 %RH, 55 %RH, 72 %RH and 90 %RH. (d) Response and recovery time graph (e) Skin moisture analysis using index finger. (f) Sensor response towards skin moisture level before and after applying moisturizer.

[12]. Too low or too high humidity levels can cause problems such as dry skin, eczema, fungal infections, allergies etc. Along with this, the skin humidity can also be used to monitor the wound healing, physiological state and diseases attributed to dehydration (specially for athletes) [13, 14]. Therefore, skin moisture monitoring sensor can allow precautionary measures towards maintaining the appropriate humidity level.

Although, a wide variety of humidity sensors (with different sensing mechanisms) have been reported using various materials (*e.g.* In–SnO_2 [15], SnO_2/RGO [16], MoS_2/Ag [17] PANI/PEDOT:PSS [18], silver nanoparticle ink and PEDOT:PSS [19], Graphene-PEDOT:PSS [20] etc.) including sensors for skin humidity/moisture detection or monitoring water evaporation from skin [12, 21-23]. However, many of these sensors are developed using non-environmental friendly sensitive materials, electrodes and/or substrates, which raises concerns through growing electronic waste (e-waste) issue [24]. Their cumbersome synthesis, limited sensing performance, complex and/or wasteful fabrication processes also adds to the challenges for sensor development. Therefore, there is a need to develop simple, cost-effective, and resource-efficient method for high performance flexible and eco-friendly humidity sensors, with disposability as a viable option.

In this work, a PEDOT:PSS based humidity sensor is developed on a G-C ink based interdigitated electrodes screen printed on a paper substrate. The PEDOT:PSS is selected as sensing material considering its excellent humidity sensing properties, biocompatible nature, good thermal stability and compatibility towards solution based processes [25]. The choice of PEDOT:PSS sensing layer in combination with G-C IDEs is encouraged from our previous work [26]. Further, paper is selected as a substrate because it is recyclable, disposable, and easily available. The humidity sensing characteristics of the developed PEDOT:PSS based sensor are investigated in a wide humidity range (25 %RH - 90 %RH). The sensor displays good sensing performance in the considered range. The potential applicability of the sensor has been demonstrated for skin moisture monitoring application. Skin humidity is monitored under normal and moist conditions, and cyclic repeatability of the sensor is also presented.

This paper is organised as follows: Section II explains the materials and methods used for sensor fabrication. The obtained results towards humidity sensing are given in Section III and conclusions are described in Section IV.

II. MATERIALS AND METHODS

A. Materials

PEDOT:PSS (PH 1000, *Ossila*), graphene-carbon ink (C2171023D1: Graphene Carbon Ink:BG04, *Sun Chemical*), silver conductive (*RS 186-3600, RS Components*) and paper/substrate (matt double sided photopaper) are used.

B. Sensor Fabrication

The humidity sensor was fabricated by screen printing graphene-carbon ink-based IDEs on paper substrate followed by drop casting PEDOT:PSS on IDEs. The schematic illustration of the fabrication steps is shown in Fig. 1(a). The G-C ink-based IDEs patterns were printed on paper substrate using Screen-Stencil Printer C920 (*Aurel Automation*). The printed IDEs were placed in oven for an hour at 60 ºC. After this, PEDOT:PSS layer was deposited using drop casting over the G-C printed IDEs and left overnight for drying in oven at 40 ºC. The silver conductive paste was used for realising wire connections for 2-wire resistance measurements. The screen-printed IDEs and PEDOT:PSS based humidity sensor are shown in Fig. 1(b-c). The scanning electron microscopic (SEM) of the deposited PEDOT:PSS layer at 50 µm scale is shown in Fig. 1(d).

C. Set-up for Humidity Sensing

The humidity sensing characteristics were obtained in a sensing chamber (size: 50 cm x 40 cm x 45 cm), made up of acrylic sheet,

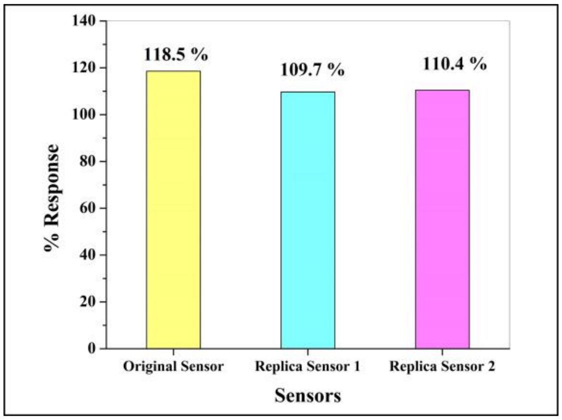

Fig. 3 Reproducibility analysis: comparative analysis among the % responses of the original sensor with the replica sensors.

having holes/openings for sensor cable (for 2-wire resistance measurement), tip of commercial humidity meter (used for calibration purpose) and power cable of humidifier unit. The humidifier (*PureMate PM 908 Digital Ultrasonic Cool Mist Humidifier*) was placed inside the chamber for regulating the humidity. Commercial humidity meter (*ATP - Humidity & Temperature Meter DT-625*) was used for calibration purpose. Digital multimeter (*Agilent 34461A 6½ Digit Multimeter*) interfaced with LabVIEW was used for change in resistance measurements. Further, dehumidification process was achieved by purging the chamber and exposing the developed sensor to air.

III. RESULTS AND DISCUSSION

A. Humidity Sensing Analysis

The sensing characteristics of the fabricated PEDOT:PSS based humidity sensor, examined in humidity range 25 %RH to 90 %RH at RT, are presented in Fig. 2. The stepwise responses of the sensor at intermediate humidity levels (within the considered range) are shown in Fig. 2(a). The stepwise responses evaluated at 35 %RH, 45 %RH, 56 %RH, 63 %RH, 72 %RH, 80 %RH, 88 %RH and 90 %RH are observed to be 5.9 %, 14.4 %, 25.8 %, 39.9 %, 60.6 %, 80.7 %, 115.6 % and 118.5 %, respectively, are displayed in Fig. 2(b). The % response is evaluated considering baseline resistance at 25 %RH. Further, sensor is also analysed at different humid conditions, to examine its ability to return to initial state post exposure. The response, analysed at 38 %RH, 47 %RH, 55 %RH, 72 %RH and 90 %RH (as shown in Fig. 2(c)) is found to be consistent with the intermediate response shown in Fig. 2(a). The response and recovery times of the

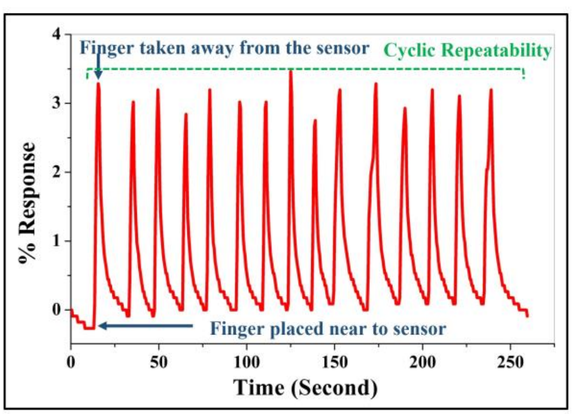

Fig. 4 Cyclic repeatability analysis for skin moisture monitoring.

sensor (time to attain ~90 % of maximum resistance change) are obtained by exposing it to humidity and dehumidification, respectively. The response and recovery times (for considered humidity range i.e., 25 %RH to 90 %RH) are observed as 70 sec and 30 sec, respectively, as shown in Fig. 2(d). Furthermore, to examine the sensor-to-sensor performance variability or reproducibility, the response of the original sensor (118.5 %) is compared with the replica sensors (replica sensor 1: 109.7 % and replica sensor 2: 110.4 %) at 90 %RH as shown in the Fig. 3. The obtained results indicates that the performance of the reproduced/replica sensors is found well in accordance with the original sensor with minor variations in % response. The obtained sensing performance indicates suitability of the sensor for multiple application areas such as healthcare, environmental, agriculture, industrial etc.

B. Sensor Application

The sensor application is demonstrated for skin moisture monitoring (using index finger) as shown in Fig. 2(e). The skin moisture/humidity is monitored under normal (found to be ~50 %RH before applying moisturizer) and moist (found to be ~60 %RH after applying moisturizer) conditions as displayed in Fig. 2(f). The obtained results clearly distinguish the % responses between normal and moist skin (finger) moisture levels, which are 21.5 % and 32.5 %, respectively. The moist skin leads to greater variation in resistance due to enhanced humidity level. The obtained results indicate that the developed humidity sensor has potential application towards monitoring skin moisture level and could also be used for evaluating the moisturizing properties of commercial skin moisturizers. Furthermore, the cyclic repeatability of the sensor is examined by placing finger near to the sensor and then taken away as shown in Fig. 4. The decreased cyclic % response (as compared to response observed in Fig. 2(f)) is attributed to reduced exposure time (~ 2 - 3 sec) of the sensor due to rapid switching of finger placed or moved away cycles. The obtained results indicate the repeatable behaviour of the sensor.

C. Readout Circuit and Application Demonstration

A read-out is designed for demonstrating the real-time monitoring of skin moisture/humidity level. The change in resistance behavior is converted to a voltage value by connecting the sensor to a resistor in a voltage divider circuit. This voltage is inputted to the analog pin of the microcontroller. The circuit employs ATMEGA 328 microcontroller. The resistor in the voltage divider can be adjusted to get a voltage value corresponding to % responses. Arduino program is written to glow the LEDs according to different states of % responses which represents % RH values. Three LEDs (red, green, and yellow) are connected to the digital pins of the microcontroller. To turn on the LED, HIGH signal is provided to these pins. There are three conditions corresponding to %RH values which are implemented with the readout, given as: case(i) humidity level < 40 %RH; red LED will turn on, case(ii) 40 %RH ≤ humidity level ≤ 60 %RH; green LED glows and case(iii) humidity level > 60 %RH; makes the yellow LED on. The circuit made on the printed circuit board (PCB) with its connection to the sensor is shown in the Fig. 5(a) and schematic diagram of the readout is displayed in the Fig. 5(b). For

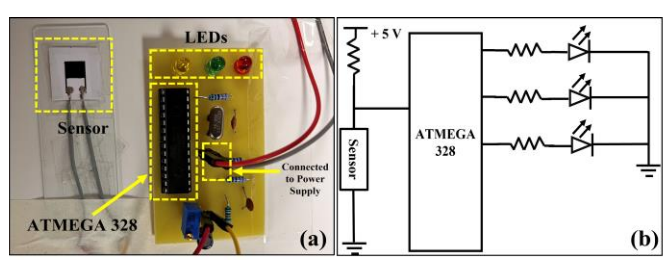

Fig. 5 (a) Fabricated printed circuit board connected to the sensor. (b) Schematic circuit diagram.

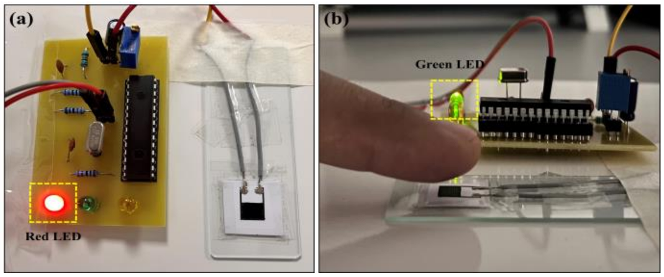

Fig. 6. Working of the readout; (a) Red LED on under humidity level < 40 %RH i.e., case(i), (b) Green LED on under 40 %RH ≤ humidity level ≤ 60 %RH i.e., case(ii).

demonstrating the functioning of the readout circuit with the humidity sensor, two different %RH conditions are tested. In the first case, the sensor is examined under humidity level < 40 %RH i.e., case(i), which turns the red LED on as shown in Fig. 6(a). In the second case, the sensor is exposed to moist skin (finger) with moisture levels within 40 %RH ≤ humidity level ≤ 60 %RH i.e., case(ii), which activates the green LED, as represented in Fig. 6(b).

IV. CONCLUSION

In this work, a PEDOT:PSS based flexible and disposable humidity sensor is presented. The graphene-carbon interdigitated electrodes-based sensor was printed on a paper substrate. The humidity sensing properties are investigated in a wide humidity range (25 %RH - 90 %RH) at RT. The sensor displays ample % response (118.5 % at 90 %RH) in the considered humidity range having response and recovery times as 70 sec and 30 sec, respectively. The reproducibility or sensor-to-sensor performance variability is also examined by comparing the sensing performance of the original sensor with the replica sensors, which is found to be well in accordance with having only minor variations in % response. Further, the sensor application is demonstrated for skin moisture monitoring (using index finger). The skin moisture/humidity is monitored under normal and moist conditions and the obtained results suggests that sensor has the ability to clearly distinguish the % responses of normal and moist skin (index finger) moisture levels. Further, the real-time monitoring of skin moisture/humidity level is also demonstrated via using designed readout circuit. The obtained results suggest sensor's suitability for multiple application areas such as skin moisture analysis, environmental monitoring, agriculture, healthcare, non-contact switching and industrial applications.

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