Polymer-based Flexible Multiparameter Sensor with Smartphone Integration

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***Abstract*— Flexible sensors are highly coveted for their light and thin nature, robustness, pliability, and cost advantage in the manufacturing process. They are widely used in many research fields and industries. This work presents a PDMS-PEDOT: PSS-based pressure and temperature sensor, which works on the concept of change in capacitance for the former and change in resistance (with NTC characteristics) for the latter. Using existing techniques, a novel single-piece sensor has been developed that can detect the parameters simultaneously with a high sensitivity for low to medium pressure range (0-3 kPa) and over a temperature range of ~25-100 ºC with ~80% change in resistance. This has been integrated with a smartphone application to wirelessly transmit the data obtained over a Bluetooth connection. The device has an accuracy of 95.81% for temperature and 96.03% for pressure sensing, which is almost comparable to conventional sensors of the same nature. Its wireless capabilities will allow it to be used in many fields.**

Keywords—Flexible sensors, PDMS-based sensors, pressure, smartphone, temperature

I. INTRODUCTION

Flexible sensors have gained lots of hype in recent years for their ability to be used in any application in ways that make them a much better alternative to existing rigid sensors. In the creation of sensors including temperature sensors, humidity sensors, tactile sensors, and pressure sensors, more and more flexible substrates are being used [1]. The conventional CMOS techniques used to create pressure sensors are typically expensive and use stiff substrates [2-5]. However, these architectures are unable to give the good structural conformability, stability, and consistency needed for a variety of pressure sensing applications [6].

There have been numerous reports of temperature sensors in the past that used components, including semiconductors, metals, metal oxides, and ceramics [7-11]. A result of their quick response time, reliability, and accuracy, resistive temperature sensors are the most frequently reported [12,13]. A conductive organic polymer [14] serves as the temperature-sensitive layer in the resistive temperature sensor that is developed here. Poly (3,4-ethylenedioxythiophene): poly(styrenesulfonate)(PEDOT:PSS) with silver (Ag) conductive paste is employed as the temperature-sensitive layer. Capacitive and resistive sensors are the two that are most frequently employed. Capacitive pressure sensors outperform its resistive counterparts in terms of sensitivity, power consumption, and resilience to environmental changes. Flexible sensors frequently use the elastomer polydimethylsiloxane (PDMS), which has a low Young's modulus, mechanical flexibility, and transparency. The electrodes are also chosen to be flexible, in addition to the flexible substrate. Silver paste is among the materials that are most frequently used to make flexible electrodes [15] as it has a low melting point, excellent electrical conductivity, and is corrosion resistant.

By combining the manufacturing process of the pressure and temperature sensors, we have developed a novel single flexible multiparameter sensor that has been integrated with a Bluetooth module to wirelessly and continuously transmit data from the sensor to any smartphone. Prior work in this area has been done in terms of choosing the appropriate materials and designing the geometry such that sensitivity and accuracy are maximized and different materials [16,17] were tested for use as the detecting material. This work; however, focuses on the application of fabricated sensor and improving it in terms of user-friendliness by making it a wirelessly controlled sensor.

II. EXPERIMENTAL DETAILS

A. Materials

Both the temperature-sensitive substance PEDOT:PSS and the sensor's dielectric layer, PDMS (Sylgard 184), were bought from Sigma-Aldrich in India. PET sheet, which serves as the sensor's base, and Flexible Conductive Silver Paint (RS 186-3600), which is used to make the two capacitor electrodes, were both purchased from RS Components.

B. Fabrication of Sensor

The first layer (from bottom to top) is a PET sheet with conductive silver in contact with the PDMS microstructures. This is followed by a piece of PDMS which is flat on one side and has hemispherical microstructures [18] on the other and hollow microcavities within. The mold was 3D printed, and PDMS cured in it, in an oven at 65 ºC for 1 hour. These two together form the capacitive pressure sensor. On the flat side of PDMS, we put a layer of conductive silver which acts as the electrodes for the temperature sensor. This is 0.8 cm long and 0.2 cm wide. Lastly, PEDOT:PSS was drop casted on the top of PDMS layer [19], while being in contact with the silver electrodes. Two aluminum wires are attached to the silver electrode via epoxy to take readings from the temperature sensor. The fabricated sensor is very small, having dimensions 2 cm X 1.5 cm X 0.2 cm (L X W X H) (Fig. 1).

III. APPLICATION

The fabricated flexible sensor is integrated with an Arduino and HC-05 Bluetooth module so that we can wirelessly interact with it and collect data using a smartphone. By placing the sensor on any part of the body, we can obtain a temperature reading which is due to the change in resistance of the PEDOT:PSS. By applying pressure on the top surface, stress builds up in the sensor structure, which results in deformations and a change in capacitance which corresponds to the applied pressure. There are certain conversions employed to interpret the resistance and capacitance changes to temperature and pressure readings in the phone application via Arduino-Bluetooth setup.

We compute the Temperature Coefficient of Resistance (TCR), which is the proportional change in resistance per degree of temperature change, in order to obtain data from the temperature sensor. It is quantified as shown in equation (1):

$$TCR = \Delta R/(R_{ref} \times \Delta T) \quad (1)$$

where ΔR is the change in resistance and ΔT is the corresponding change in temperature. *TCR* is theoretically determined when ΔT gets indefinitely tiny ($\Delta T \rightarrow 0$), in order to define the rate of change in resistance at any temperature on that curve as in (2):

$$TCR_{(\Delta T \rightarrow 0)} = (dR/R)/dT \quad (2)$$

It is generally known that the relationship between resistance change, and temperature is not linear but rather parabolic. This function's mathematical description is $Y = aX^2 + bX + c$, where $Y = \Delta R/R$ (in ppm) and $X = T$ (temperature in ºC). In this instance, *Y* will specify the resistance change from the nominal value (at +25 ºC) in ppm for any temperature T. In other words, the derivative function *Y'* will be used to represent this for the function Y. The slope (TCR) of a line tangent to the parabola is defined by this function, which also shows how *TCR* is changing. This is represented as $Y' = 2aX + b$, where *Y'* is expressed in ppm/ºC. Using the equation for *Y'*, standard values of *a* and *b* of PEDOT:PSS in the range of ~25-100 ºC (from Steinhart-Hart equation) as 1.01×10^{-3} and 2.38×10^{-4} respectively, and a *TCR* value of 0.48%/ºC for PEDOT:PSS from literature [20], we can calculate the temperature by substituting the resistance values in the equation which we get from the Arduino. This formula gave the temperature values with an error of only 4.19%.

For the pressure sensor we first performed linear fitting [21,22] of the pressure and capacitance values obtained in a control experiment (Fig. 2). Since the trend is almost linear, we obtain an equation of line, $C = mP + b$, where C is capacitance, m is slope of value 0.549, P is pressure in kPa, and b is the y-intercept of value 4.003. This equation was used to provide the readings from the Arduino set-up which calculates the capacitance values and outputs the equivalent pressure. This method gave us the pressure readings with an error of 3.97%

IV. RESULT

The developed sensor with Arduino set-up (Fig. 3) has a very high accuracy and sensitivity, but after making conversions so that resistance and capacitance values can be translated to pressure and temperature readings, respectively, we get a slightly lower but still very effective sensor (due to approximations made). The temperature sensor reports an accuracy of 95.81% in the temperature range of ~25-100 ºC, and the pressure sensor reports an accuracy of 96.03% in a pressure range of 0-3 kPa where it shows an almost linear characteristic (Fig. 4), w.r.t direct measurement from the sensor. The controlled experiment was done used using an IM3536 Hioki LCR meter. To provide the pressure stimulus, load was systemically applied in steps of 10gf on the sensor surface. We obtained the linear characteristics for data conversion of pressure using this method. This is summarized in Table 1.

TABLE I. ERROR ANALYSIS IN SMARTPPHONE INTEGRATION

Sensor Parameter	*Avg. reading from smartphone*	*Avg. reading directly from sensor*	*Equipment used to take measurement from sensor directly*	*Error in smartphone reading w.r.t direct reading*
Pressure	21.8 kPa	22.7 kPa	Digital Multimeter	3.97%
Temp.	23.9 ºC	24.9 ºC	LCR meter	4.19%

V. CONCLUSION

This study demonstrates the construction and application of a wireless, single-piece flexible piezocapacitive pressure and piezoresistive temperature sensor. The current method has the benefits of being simple, affordable, scalable, compatible with large-area flexible substrates, and, most crucially, wireless applications. The performance of the constructed sensor showed to be consistent and reproducible. In the future, we intend to add-on to the flexible sensor the ability to detect few more parameters such that it can be deployed in areas such as agriculture and healthcare.

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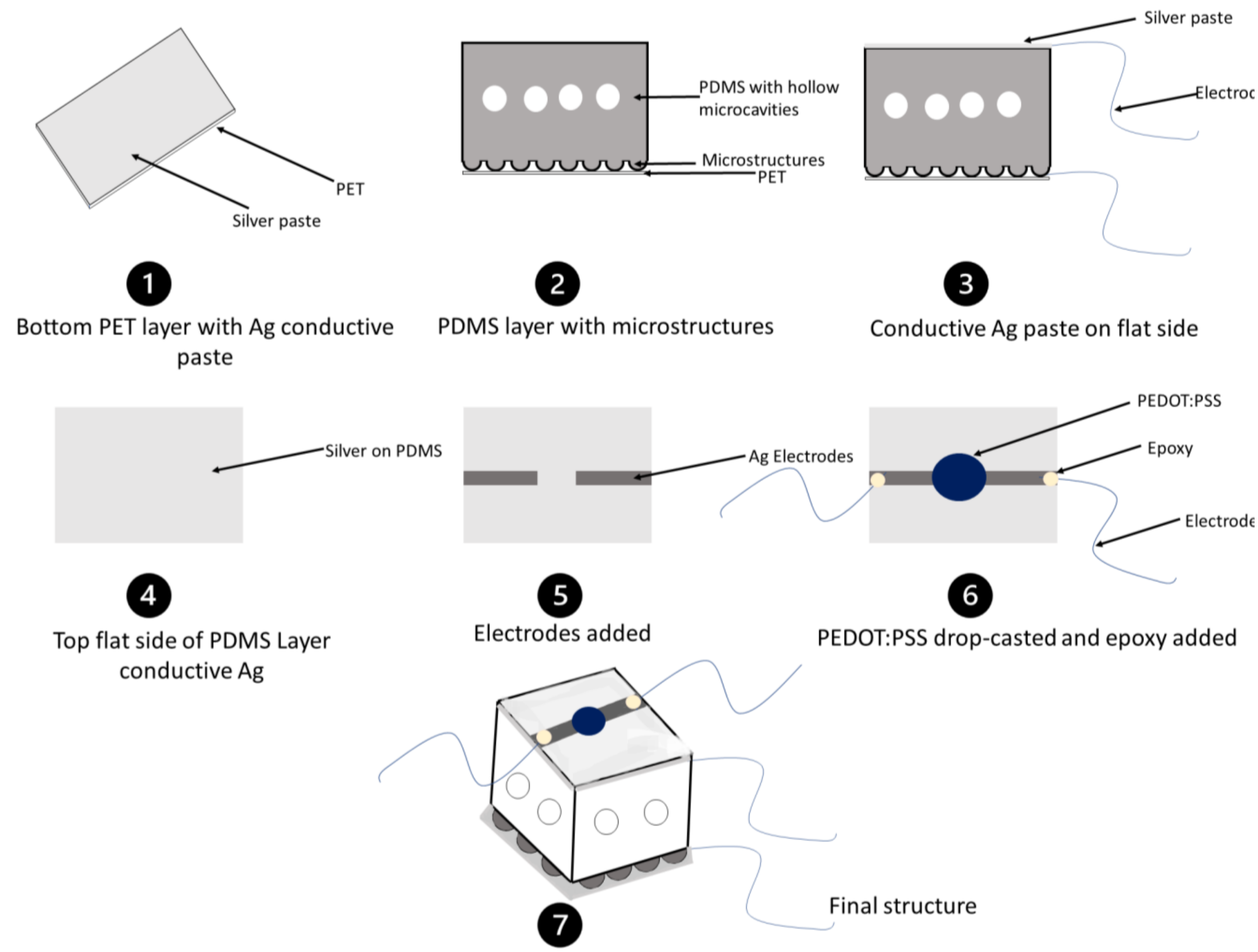

Fig. 1. Layer by layer making of the flexible piezocapacitive /piezoresistive sensor for pressure and temperature detection

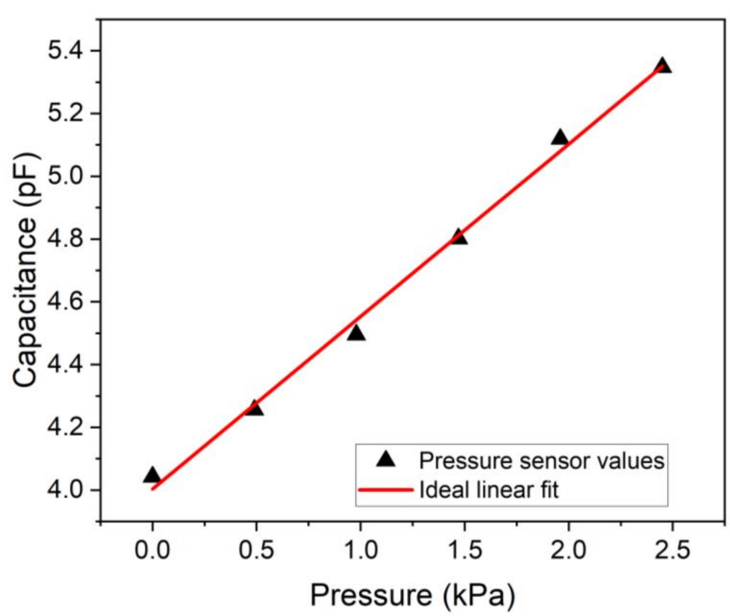

Fig. 2. Linear fitting of experimentally obtained values from pressure sensor

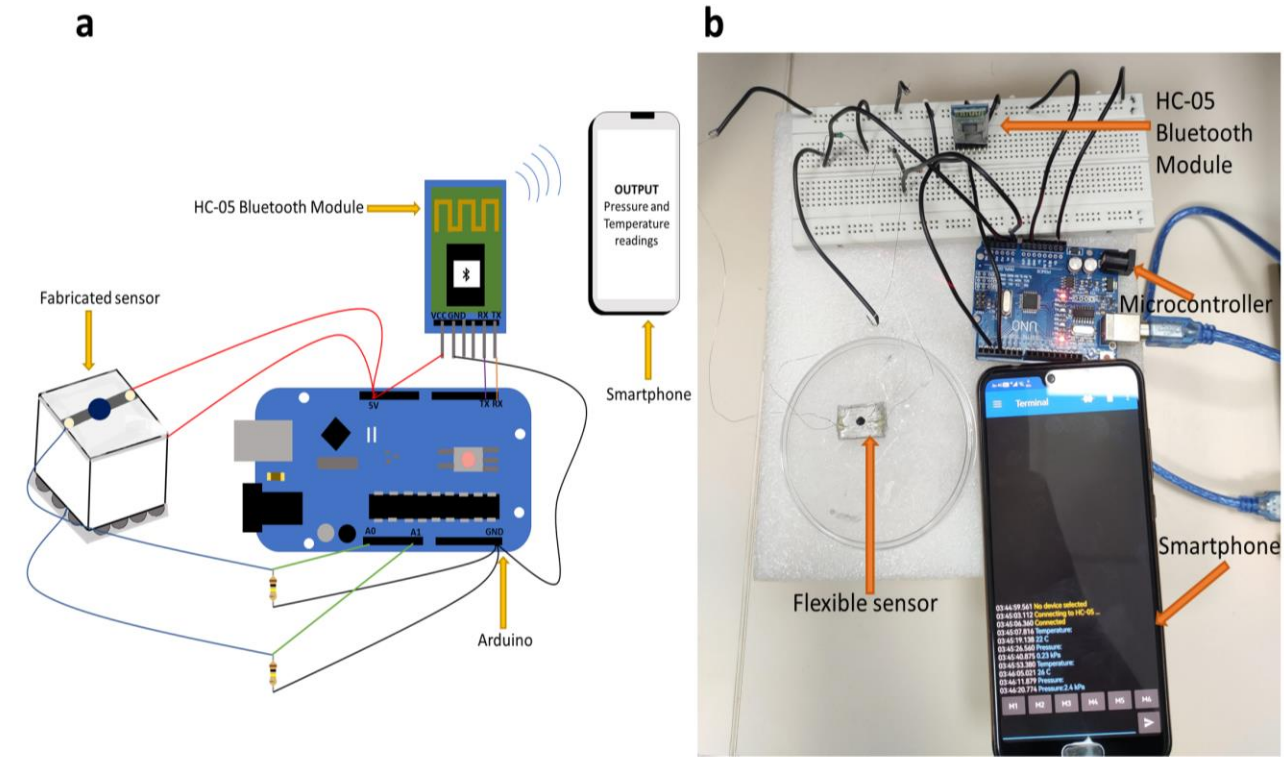

Fig. 3. (a) Schematic illustration showing the usability and circuit diagram. (b) Real-life experimental output depicted on the right

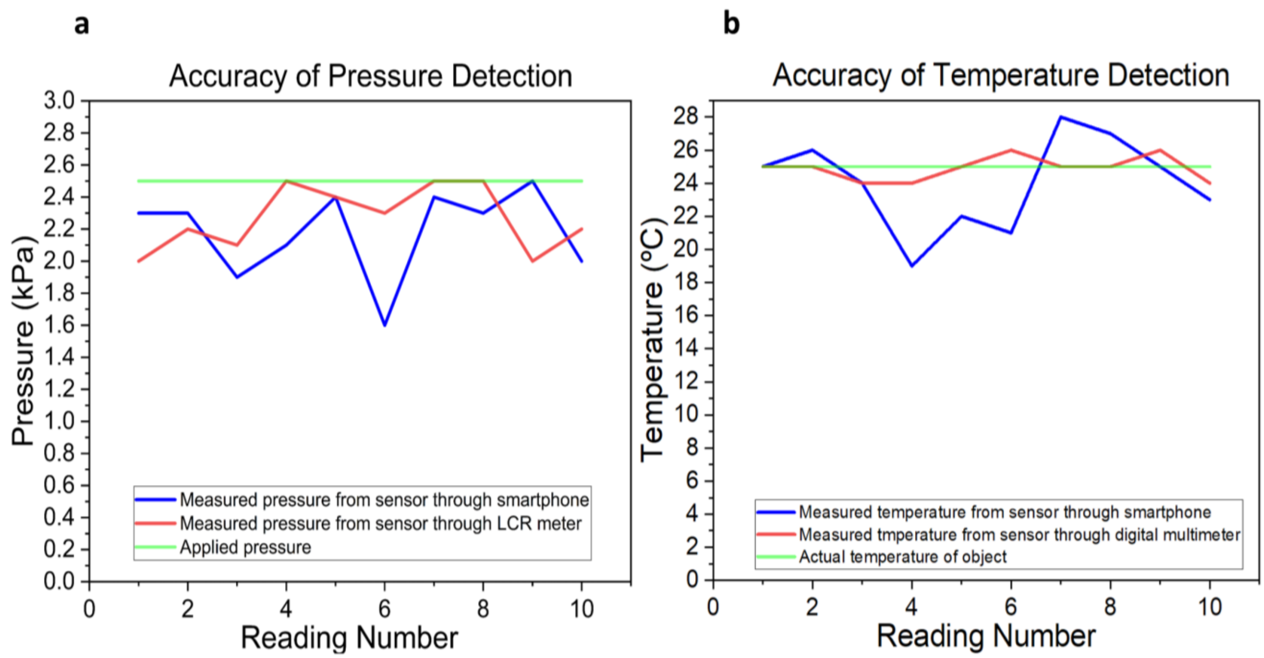

Fig. 4. Comparison of accuracy when readings are taken directly from sensor vs when they are taken via a smartphone. The increased error in the latter case can be observed. (a) shows the variation in reading for pressure and (b) shows the variation in reading for temperature