PEDOT: PSS Polymer Aerosol Jet-printing for Robotic Skin Sensors

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***Abstract*—Robot skin sensors are being developed to improve the tactile perception that comes with physical touch. This is desired as it enhances the interaction between robots and humans. In this publication, we present a process for improving the deposition of PEDOT: PSS using Aerosol jet printing technology. Previously, we deposited PEDOT: PSS with the MEMS fabrication techniques in the cleanroom. The PEDOT: PSS, an organic polymer that gives the robot skin sensors their piezoresistive ability, is deposited on the designated microfabricated sensor electrodes, significantly cutting down the manufacturing time. Testing of the robot skin sensors is done on an automated testing station having a force plunger and an integrated circuit. The results display the resistance values measured across the sensors and their tactile responses to applied strain.**

Keywords—Aerosol jet Printing, Tactile Sensor, Microfabrication, PEDOT: PSS

I. Introduction

Artificial haptic response to physical touch for robotic applications imitating human skins has been desired for a few decades. The concept of robots equipped with tactile microstructure replicating similar responses as human skin has been investigated to make available sensory data. This is needed for human-guided behavioral learning for improving safety, human motion intent, and navigation along clustered regions. Pressure, force, torque, and temperature are some of the physical variables that can be captured by several sensing modalities integrated within a sensitive robotic skin [1].

It is expedient that further research into the applicability, safety, and reliability of tactile sensors continues for improved performance within domestic and industrial applications. Skin sensor designs, fabrication techniques, multi-modal sensor integration, and circuitry are some of the varying aspects examined toward achieving optimum feedback response in comparison to natural human skin. For the scope of this work, the application of the PEDOT: PSS, Poly (3,4-ethylene dioxythiophene)-poly(styrene sulfonate), through inkjet printing rather than the previous deposition process carried in the cleanroom was explored [2, 3]. In previous fabrication processes, using the conventional deposition methods, the formulation of the organic polymer PEDOT: PSS inks considers parameters of viscosity, conductivity, and voltage requirements for EHD (Electro Hydro Dynamic) which makes the realization of serial high-density manufacturing rather cumbersome [1]. In methods involving the wet lift-off photolithography, the subsequent steps required for the isolation of sensor areas deposited with the organic polymer PEDOT: PSS, takes a lot of time and high precision eliminating human errors to achieve reasonable sensor yield and optimum sensitivity of robot skin sensors. Aerosol jet printing was explored as an alternative to the cleanroom techniques in formation of the thin films, particularly for fabrication of the flexible circuits [4] In this paper, the method of inkjet printing the PEDOT: PSS using the OPTOMEC® Aerosol Jet printer in the fabrication of robot skin sensors on Kapton® substrate is described with the feedback response when strain is applied.

II. Materials and Methods

The working principle of robot skin sensors is based on the piezoresistive characteristics of the PEDOT: PSS deposited on the sensor structures, which determines the sensitivity of the flexible skin sensors coupled with the sensor geometry of the fabricated sensor electrodes [5]. These microfabricated structures with an aerosol jet-printed organic polymer act as strain gauges varying resistances with respect to pressures applied on the surface of the skin sensors.

A. Fabrication of Sensor Electrodes

The sensor electrodes were fabricated in the cleanroom, and these microfabricated structures consist of 300nm Gold sputtered using Lesker PVD75®. This was done for a 75min period onto a Kapton® sheet that was cleaned and cut in the shape of a 4-inch carrier silicon wafer onto which it adhered. The Gold, which serves as metallic electrical contacts with the PEDOT: PSS, was patterned to desired sensor geometries using a photolithography process that utilized a photomask under ultraviolet light to transfer the sensor design onto a gold surface coated in the photoresist. Then a wet etching technique was employed for the etching of gold particles from unwanted regions. Fig 1 details the sensor structure fabrication process.

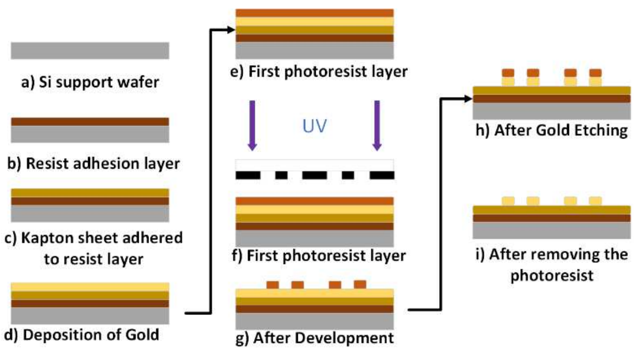

Fig 1. The fabrication process is involved in the patterning of robot skin sensor structures in the cleanroom [5].

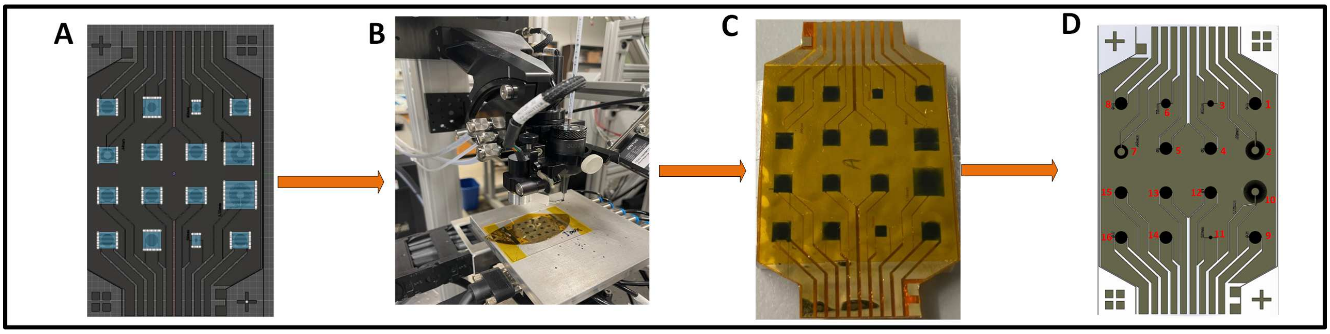

Fig 2. Illustration of the aerosol jet printing process of PEDOT: PSS unto a robot skin sensor. (A) shows Autodesk Fusion 360 interface for generating the G-code for the PEDOT: PSS deposition. (B) shows the Aerosol Inkjet printer used to deposit the organic polymer. (C) shows the PEDOT: PSS printed on the skin sensors. (D) shows the geometries of the different sensors numbered in order of their connections

B. Plasma Treatment of Sensor Structures

After the fabrication of sensor structures in the cleanroom, the resistance of each skin sensor on the sensor patch is inspected to determine the yield ensuring there is no short circuit occurrence within its links. After satisfying this requirement, the sensor is ready for PEDOT: PSS deposition process. This step begins with a plasma treatment of the substrate to improve the adhesion of the PEDOT: PSS ink to the surface. In previous studies, we have used PEDOT: PSS stock from Sigma Aldrich, but because of its high viscosity, it had to be mixed with other solvents to make it suitable for deposition [3]**.** In this study, we used the PEDOT: PSS stock from Heraeus (CleviosTM®) and it has the following properties: 15-60mPa.s viscosity, the conductivity of 850S/cm, and solid content of 1.0%-1.3%. This ink has low viscosity allowing for direct application with an Aerosol Inkjet printer without the need to adjust its admissibility with other compounds. However, this type of PEDOT: PSS ink wouldn't adhere to the Kapton's surface, hence the need to introduce a plasma treatment of the substrate's surface to improve its wettability. The plasma treatment was carried out in a Harrick® Plasmer Cleaner device. The substrate was inserted into the chamber, and after evacuation and reaching low vacuum, the substrate was exposed to air RF plasma at 30W for a 2min period. With an effective period of 30mins, the skin sensor patterned substrate is ready for inkjet printing of the PEDOT: PSS organic polymer using the Aerosol jet printer.

C. G-code Generation

Before commencing deposition of the PEDOT: PSS after zplasma treatment of the substrate, it is important to feed the instructions in the form of precise coordinates to the aerosol jet print system. This enables precise displacement of the substrate during deposition of the ink onto the skin sensor patch. This was realized by generating G-code command lines, imported into the Inkjet print system. The Autodesk® Fusion 360 manufacturing workspace software was used to create printing patterns in DXF format based on the design of the imported CAD model. The Autodesk® Fusion 360 provides a library and capabilities that allow simulation of the printing process based on the designed pattern of trajectory. Once the design trajectory was confirmed through simulation in the software environment, the custom post-processor was activated to generate the G-code parsed in X and Y coordinates that also indicated the feed rate, which also represents the print speed. Fig. 2a shows the Autodesk® Fusion 360 interface indicating the DXF contoured line drawings of regions over the skin sensor surface where the G-code should be generated [6].

D. Optomec Aerosol Jet Printing System

The OPTOMEC® Aerosol Inkjet print system is part of a custom-built NeXus micromanufacturing platform [7] consisting of the following components: An Aerosol printer head equipped with a 300μm diameter nozzle, a process control cabinet, KEWA process control software, a 6DOF positioner for carrying sample and height adjustment and a NI LabVIEW® interface for synchronizing ink deposition process and motion control of the stages. The aerosol jet printing process works using aerodynamic principles to realize PEDOT: PSS ink deposition on the substrate [8]. The ink placed into the ultrasonic atomizer is formed into a dense mist of aerosol droplets that are carried along the deposition path and focused with compressed nitrogen gas through the nozzle tip. The viscosity of the ink and the process recipe determining the atomizer flow rate, and morphology of the deposited PEDOT: PSS ink on the substrate are important criteria for achieving successful printing of the skin sensors. Fig 3A shows the printed lines at 100μm based on the inputted process recipe in Table 1. Fig 3B, shows the Dektak profilometer measurement of PEDOT: PSS indicating the thickness of about 100nm of the deposited ink.

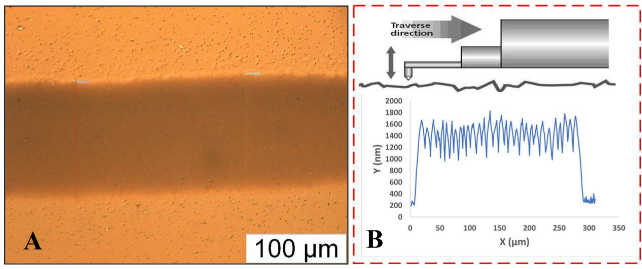

Fig 3. (A) shows the width of the line is 60 microns. (B) illustrates profilometry measurement of the PEDOT: PSS film composed of ten layers which thickness is around 1.4 μm.

TABLE I. PARAMETERS FOR PRINTING

Sheath Flow Rate	***50 sccm***	Print Speed	***10mm/s***
Atomizer Flow Rate	***20 sccm***	Atomizer Bath Temperature	***27°C***
Atomizer Current	***500mA***	Stand-off Distance	***3mm***

E. Skin Sensor Lamination

Once the aerosol jet printing of the organic polymer is realized, resistance testing of each skin sensor is carried out, identifying its resistance range to determine closely similar skin sensor patches it could be paired with. The skin sensors on the robot skin sensor patches are then laminated with Kapton® tape, paired, and then adhered back-to-back with the sensing area facing outward. The lamination of the sensor patches is necessary to allow for ease of handling, preventing the skin sensors from being exposed to atmospheric moisture, and most importantly, eliminating temperature drift achieved by the doubling of the skin sensor patches [3].

F. *Testing Station and Electronic Circuit*

The testing of the sensors is realized with the help of an automated testbench designed for testing PEDOT inkjet-printed sensors in our previous study [3]. A force actuator is controlled using a PD (proportional and derivative) loop to follow the desired load on each sensor. All motor control is done with robotics instead of human labor to create repeatable tests. The response of the sensor is read through an ADC (analog to digital converter) and then logged using a python script. Graphs are generated after post-processing to compare the response to the force applied.

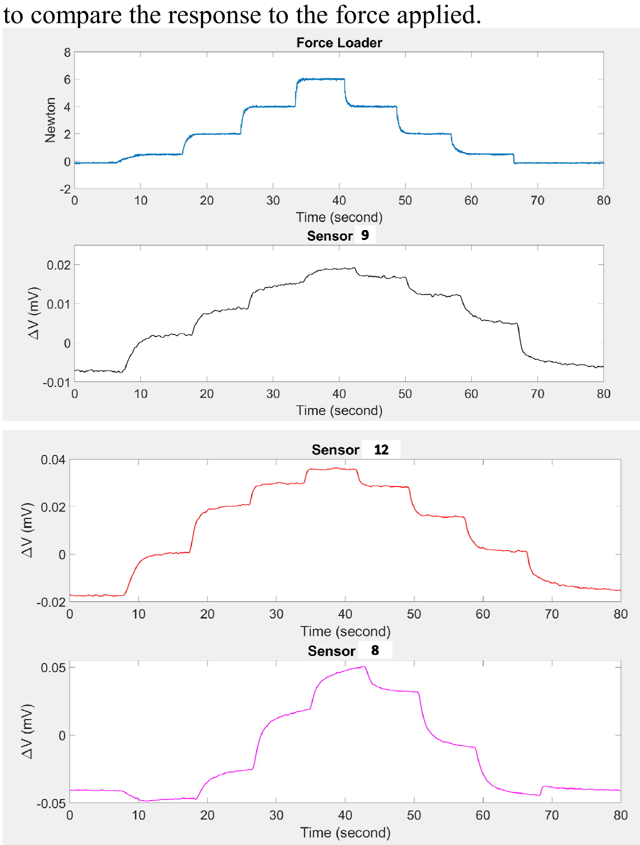

Fig 4. Response graphs of aerosol jet printed PEDOT: PSS skin sensors for sensors #: 9, 12 & 8.

III. Results and Discussion

Resistance measurement of the fabricated skin sensor patches is taken and documented, determining the pairing of patches with similar readings to be laminated together. Tables 2 and 3 show the resistance values of two skin sensor patches laminated together. The resistance of the skin sensor patches is within the range of 40Ω to 5kΩ. The sensitivity of the sensors was determined based on the electrical response measurements conducted with the help of our automated testing bench. To this purpose, controlled deformation of the PEDOT structures was realized by applying strain with indenter at the specific location of each sensor on the sensor patch. This deformation, with respect to varying force load profiles, induces corresponding varied voltage responses of each skin sensor. Different electrode geometries of sensors (Fig.2, [5]) are responsible for varying resistance measurements - Tables II and III. Each of the sensor responses shown in Fig. 4 corresponds to the skin sensor's resistance values in Tables 2 and 3. Fig. 4, shows the response of the three skin sensors, sensors 9, 12 and 8 from the newly fabricated skin sensor patch representing skin sensors within the low, mid, and high-performance range respectively for each force profile from 1N-6N in step ladder form. It evaluates the sensitivity of the PEDOT: PSS skin sensors by recording voltage changes across the given sensor in response to the applied force. The results show the newly fabricated skin sensor patches sensitivity is in range of 1.8–16.2 µV/N, while sensors fabricated through cleanroom techniques have a sensitivity of 0.4µV/N and 5.1µV/N as stated by Saadatzi et al and Wei et al respectively [2, 4]. The majority of sensors can be grouped in two sets with respect to the range of sensitivity values:

- 2 – 6 µV/N for sensors with numbers 3 – 6 and 9 – 13.
- 6 – 11 µV/N for sensors # 1, 2, 7, 8 14 – 16.
- exception - sensor 8 (patch 1) with sensitivity 16.2 µV/N.

Observed distribution of sensitivity values is most likely due to the different geometries of the sensors.

TABLE II. Skin sensors resistance and sensitivity values – top sensor array.

Sensor Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Resistance value (Ω)	4.9k	450	105	143	40	137	538	3.0k
Ave. Sensitivity (µV/N)	8.6	10.1	3.6	3.5	3.8	6	10.3	**16.2**
Sensor Number	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Resistance value (Ω)	92.0	80	103	108	189	273	413	96
Ave. Sensitivity (µV/N)	4.5	4.8	4.6	8.9	**1.8**	10.9	7.8	9.4

TABLE III. Skin sensors resistance and sensitivity values - bottom sensor array.

Sensor Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Resistance value (Ω)	4.4k	886	105	166	47	157	845	5.8k
Ave. Sensitivity (µV/N)	**9.5**	8.5	3.8	4.2	**2.6**	5.0	6.4	8.6
Sensor Number	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Resistance value (Ω)	104	724	111	237	126	337	367	158
Ave. Sensitivity (µV/N)	5.2	3.6	3.8	3.7	3.3	7.5	6.3	3.0

IV. Conclusion

In this paper, we investigated a new method of depositing PEDOT: PSS through aerosol jet printing, replacing the technically challenging and time-consuming techniques applied in the cleanroom. Aerosol jet printing reduces the number of steps and time required to realize the robot skin sensor fabrication process, reducing the process time from about 5 hours to 26 mins for a laminated paired skin sensor patch. It also diminishes the likelihood of human error in the patterning of the PEDOT: PSS on the skin sensor structures, as indicated in its characterized sensitivity of 6.2µV/N as compared to 0.4µV/N and 5.1µV/N of cleanroom fabricated ones. In future, we plan to apply aerosol jet printing for the fabrication of the sensor's electrodes and conducting structures.

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