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# PEDOT:PSS: a Conductive and Flexible Polymer for Sensor Integration in Organ-on-Chip Platforms

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**Abstract**

Sensing and stimulating microstructures are necessary to develop more specialized and highly accurate Organ-on-Chip (OOC) platforms. In this paper, we present the integration of a conductive polymer, poly (3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS), on a stretchable membrane, core element of an Heart-on-Chip. The electrical conductivity along with its biocompatibility, high transparency (≈88 %) and mechanical elasticity (≈1.2 GPa) make this material a candidate to develop novel microstructures for electrical monitoring and stimulation of cells in flexible-substrate based OOCs. Microstructures with different shapes and geometries of PEDOT:PSS embedded in a 9 μm-thick Polydimethylsiloxane (PDMS) membrane are developed following a wafer-level fabrication approach. PEDOT:PSS layers between 120 nm and 300 nm are obtained by varying the deposition conditions. The layers are successfully patterned and microstructures with lateral dimensions down to 2 μm. The obtained results indicate that this polymer is a suitable material for microfabrication of sensing and stimulating elements in OOC platforms.

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*Keywords:* Organ-on-Chip; Sensing;PDMS; Membrane; Cell;Microenvironment, Heart-on-Chip.

## 1. Introduction

Organ-on-Chip (OOC) aims at creating specialized dynamic cell cultures that mimic physiological conditions of functional units of human organs. These conditions can be achieved by using microstructures that enable to physically and chemically stimulate a cell culture microenvironment [1,2]. Growth, proliferation, differentiation,

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maturation and controlled interactions between different cell types in the model are facilitated in the controlled environment of an OOC chip [2]. Recently, research has focused on developing platforms able to simulate the activity of multiple organs such as lung [3], kidney [4], gut [5] and heart [6].

In particular, for a heart-on-chip platform involving human induced pluripotent cells (hiPSCs), it is imperative to apply continuously a mechanical stimulation to induce the functional and structural maturation of derived cardiomyocytes. An heart-on-chip platform consists on a PDMS-based flexible membrane functioning as the culture medium [7]. The mechanical stimulus is transmitted to the cell culture by stretching the membrane.

However, for a deep understanding of the biological processes within the microenvironment, the development of an in situ monitoring system is necessary. Developing electrical sensing structures without affecting the mechanical functionality of the membrane is highly challenging. In particular, it is necessary to employ a material with low stiffness and good electrical performance. Most of the metals used in microfabrication are characterized by high stiffness (Young Modulus E of 70-200 GPa) [8], which makes them inadequate candidates for stretchable structures. On the other hand, 'soft' materials are not always easily integrated using IC and MEMS fabrication compatible processes. These materials are normally patterned using alternative methods that limit the minimum feature size and lack of compatibility with high-scale fabrication. Therefore, it is essential to identify alternative materials and define processes suitable to fabricate electrical sensing and stimulating devices for flexible OOC with higher mechanical stability and IC compatibility. In this paper we present the successful integration of PEDOT:PSS–based microstructures at wafer scale on a 9 μm-thick PDMS membrane. Moreover, insights about PEDOT:PSS deposition and achieved feature sizes are given.

## 2. Processing PEDOT:PSS to develop sensing and stimulating devices for OOC

An interesting alternative material to develop microstructures, meant to monitor and stimulate the cell microenvironment in OOC, is the conductive polymer PEDOT:PSS. PEDOT is a polymer derived from ethylene dioxythiophene monomer. The electrical conductivity is caused by the delocalized π-electrons within its chemical structure and the presence of sulfonated polystyrene (PSS). It offers benefits due to its electronic and ionic conduction, as well as for its mechanical ($E \approx 1.2$ GPa) and optical properties ($T > 90$ %) [9]. Microstructures were successfully realized by patterning the polymer on a silicon (Si) substrate, following a wafer-level fabrication approach. In Fig. 1(a) the main steps of the patterning process are depicted. Firstly, a 1 μm-thick plasma enhanced chemical vapor deposition (PECVD) silicon oxide ($SiO_2$) is deposited on a 100 mm-Si wafer. Then a layer of 100 nm of Titanium (Ti) is sputtered and subsequently patterned to create the electrical contacts. The PEDOT:PSS layers is deposited by spin coating and cured on a hotplate at 150ºC for 5 minutes. The achieved layer thicknesses versus the spinning conditions are reported in Fig 1(b). The electrical resistivity of a 300 nm thick PEDOT:PSS layer is 41 μΩm. On top of the PEDOT:PSS an Aluminum (Al) layer is sputtered and patterned. The Al layer is used as hard mask during the reactive-ion etching (RIE: $O_2$, 20 mTorr, 50 W) of the PEDOT:PSS. The PEDOT-based microstructures are now defined and the metal contacts are exposed. As last step, the Al hard mask is removed by wet etching using a solution of acetic acid, nitric acid and hydrofluoric acid (PES).

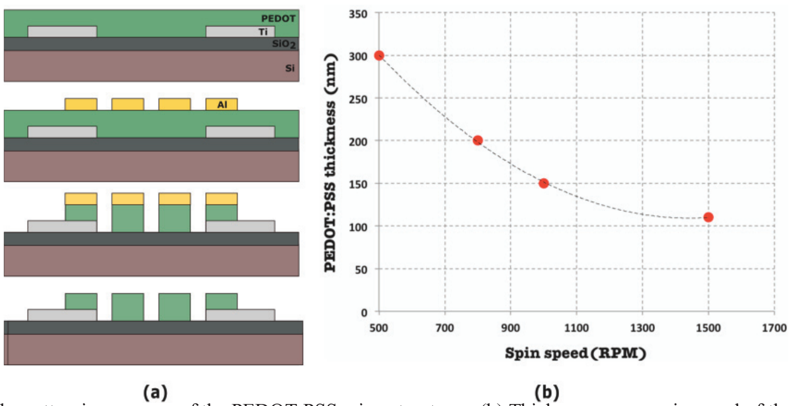



Fig. 1. (a) Main steps of the patterning process of the PEDOT:PSS microstructures. (b) Thickness versus spin speed of the deposited layers.

Customized features are obtained by lithographically defining the hard-mask patterning. The resulting PEDOT:PSS microstructures, that can be used as microelectrodes as well as strain gauges are shown in Fig. 2(a-c) and Fig. 2(b-d), respectively. In particular, Fig 2(c) shows a close up of the microelectrodes demonstrating that lateral dimensions down to 2 µm were successfully patterned with our process.

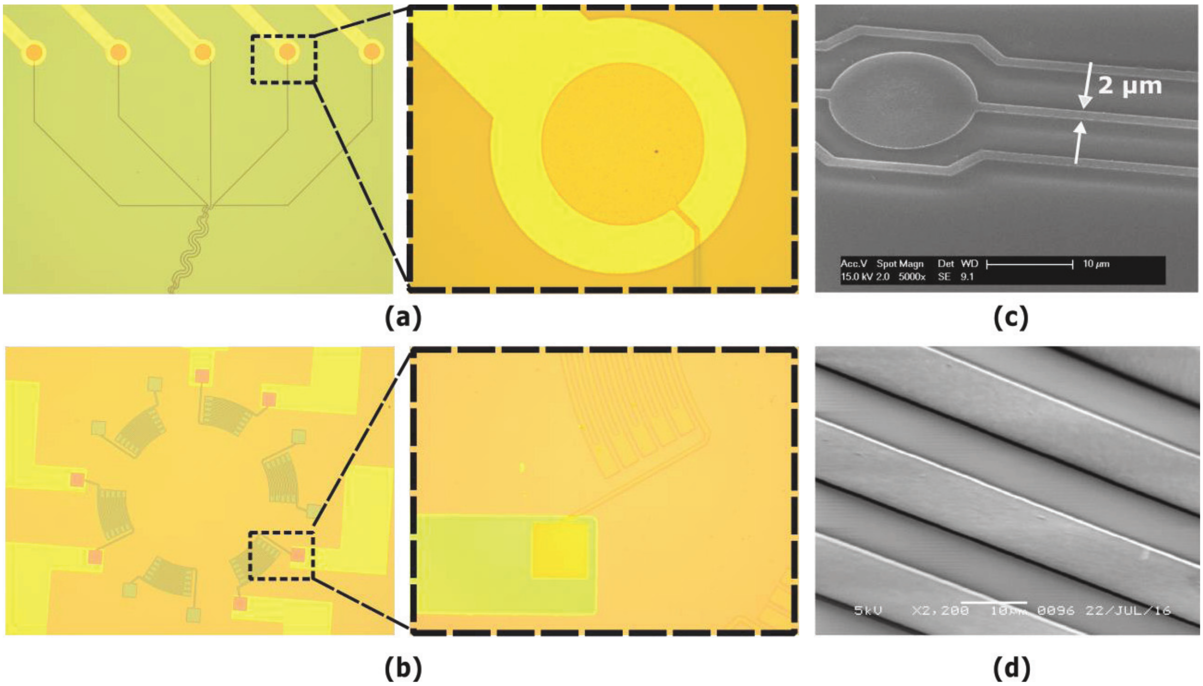
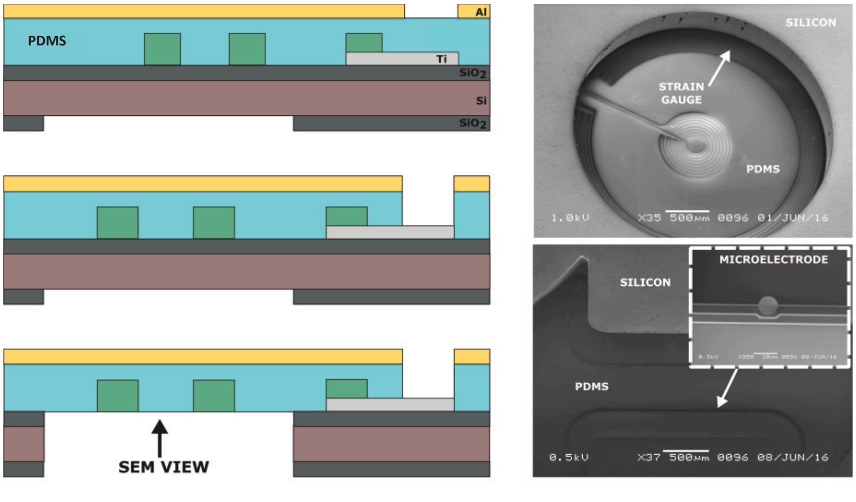



Fig. 2. Optical and SEM images of successfully patterned PEDOT:PSS microstructures: a) and c) Microelectrodes; b) and d) A serpentine-like geometry proposed as a strain gauge to sense the stress on the culture cell medium in a heart-on-chip platform.

## 3. Integrating PEDOT:PSS microstructures in a PDMS membrane based OOC platform

The designed microstructures were successfully integrated in a PDMS membrane proving the compatibility of the material with an heart-on-chip platform presented in [6,7]. Although PEDOT:PSS has already been applied in related devices for neuron cell study, either rigid materials were used as the supporting substrate or the complexity of fabrication methods lack of compatibility with high scale manufacturing schemes [10,11]. The microstructures were embedded in 9 µm-thick PDMS membranes, while maintaining a wafer-level fabrication approach (Fig. 3 (a)). Once the conductive polymer is patterned as described in previous section, a PDMS layer was deposited by two-step spin coating process, the first at 300 rpm and the second performed at 6000 rpm. The PDMS is cured at 100°C for 30 minutes. To open the contact pads, the PDMS is etched by RIE ($SF_6/CF_4$), using an Al hard mask.

The last process phase consists on the membranes releasing by deep reactive-ion etching (DRIE) using a 6 µm-thick PECVD $SiO_2$ as masking layer on the wafer backside. The landing layer made of 1 µm PECVD $SiO_2$ is then removed by wet etching. In Fig. 3(b) a SEM image shows the microstructures corresponding to the strain gauges and the microelectrodes embedded in two PDMS membranes with different sizes and shapes.




(a) (b)

Fig. 3. (a) Wafer-level fabrication process of the PEDOT: PSS microstructures embedded on a 9 μm-thick PDMS membrane.; (b) SEM images of the microstructures corresponding to the strain gauges and microelectrodes embedded in the PDMS membranes.

## 4. Conclusion

We developed a process to obtain thin PEDOT:PSS microstructures, with a good electrical conductivity and in a variety of features and sizes, while following a wafer-level fabrication approach. A detailed description of the PEDOT:PSS patterning is reported. Subsequently, we demonstrated the integration of the obtained conductive polymer microstructures into a 9 μm-thick PDMS membranes that represents the flexible substrate of an heart-on-chip platform. The achieved results clearly indicate that this material can be effectively used in the microfabrication of electrical conductive structures for OOC applications. Further electrical and mechanical investigations on the strain gauges and microelectrodes are required.

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