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Piezoresistive behaviour of flexible PEDOT:PSS based sensors

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ABSTRACT

In this work we developed a low cost flexible polymeric sensor. This sensor is realized using electrochemical synthesis of a conductive polymer (PEDOT:PSS) thin film deposited on a flexible substrate of polyimide using a peeling technique.

The sensor was characterized using two different setups able to evaluate the effects of microscopic and macroscopic deformation. Different ranges are considered to correctly define the behaviour and fields of application of the device, and to compare the performances with the data typically available in literature for strain sensors. Using the micro-bending setup we extracted a gauge factor of 17.8 ± 4, which is well above the typical value for commercially available flexible metallic strain gauges on polyimide substrates. A specific setup is also presented to analyze the behaviour of the sensor with respect to macroscopic bending. We evaluated the change of the resistance of the sample varying the bending angle in the range of 0–60° both in the inward and in the outward direction. We demonstrated in both cases a linear dependence of the resistance with respect to the bending angle, and furthermore a high reproducibility with low hysteresis. Finally we evaluated in the macroscopic regime of deformation also the response time of the sensor obtaining a very good dynamic response with amplitude fluctuations less than few percent with respect to a periodic deformation.

1. Introduction

In the last three decades, after the first discovery of conductive polymers made by Shirakawa et al. [1], a great deal of interest has been devoted to the use of those materials because of their flexibility, the low cost processability, the light weight, the easiness of tailoring their properties in order to obtain the needed characteristics.

Among those materials poly(3,4-ethylenedioxythiophene) gained an outstanding position due to its electrochemical and thermal stability, high conductivity, the large range of optical properties and transparency.

Usually this polymer that is insoluble, is available in its oxidized form in combination with a water soluble polymer, the polystyrene sulfonic acid (PSS).

The introduction of PSS in the polymerization process has two main benefits: on one side it balances the cationic charge of PEDOT, on the other side it allows the dispersion of the PEDOT in water generating a complex where the oligomeric PEDOT segments are attached to the long chains of the PSS [2].

The use of PEDOT:PSS ranges from antistatic coating applications (cathode ray tube screens, electronic packaging, photographic films, LCD polarizers), electronic and optoelectronic applications (all organic field effect transistors, organic light emitting diodes, capacitors, photovoltaic, photodetectors), sensors [3].

In particular, in the field of sensors, it has been demonstrated the use of this material in artificial noses [4], in humidity and glucose sensors [5] and in strain sensors realized with coated fibers and fabrics [6,7].

In this work, we focussed our attention on the realization of strain sensor based on PEDOT:PSS using a low cost technique [8] and on the characterization of its piezoresistive properties considering both a microscopic and a macroscopic bending behaviour. For the first case, we have been able to evaluate the GF, in the ppm range of the applied strain. A special attention has been paid to correctly calibrate the piezoresistive setup in terms of effective strain applied to the sensing device. For the second case, we evaluated the effect of bending both in a static regime and in a dynamic regime showing the time response of the sensor.

2. Sample preparation

Fig. 1 shows the fabrication process to realize the flexible piezoresistor sensor.

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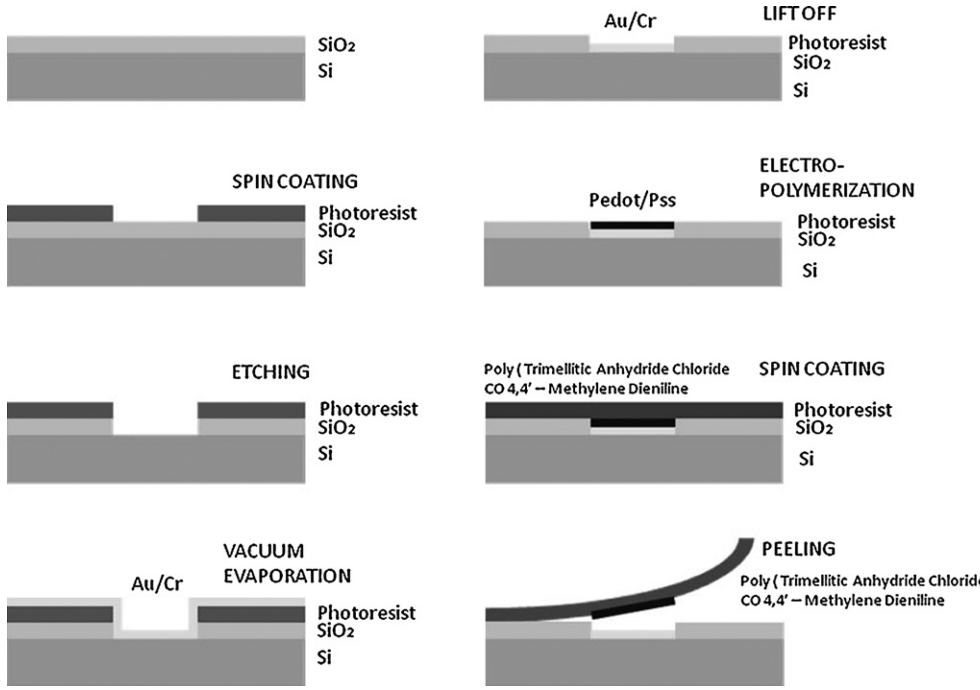

Fig. 1. Fabrication process.

The fabrication starts with a 2 in. highly doped p^+ silicon wafer (500 μm thick) covered with a 250 nm of thermal grown silicon oxide. A pattern with lines of 2 cm × 1 cm dimension is defined on top of the oxide using a standard lithography process. Afterwards, a wet etching in a buffered hydrofluoric acid solution ($HF + NH_4$ + water) is performed in order to remove the oxide and expose the contact areas. In the next step, a 10 nm layer of chromium and 90 nm gold are evaporated and subsequently lifted-off. The resulting patterned electrode represents the template that can be used for the realization of the piezoresistive sensors.

The PEDOT:PSS polymer matrix is deposited on the patterned electrode by electrochemical polymerization. The solution was realized using the monomer EDOT as received from Bayer AG and poly(sodium 4-styrene sulfonate) (NaPSS, average Mw 1,000,000); a mixture of acetonitrile and distilled water (solution 1:1 v/v%) was used as a solvent.

The deposition of the PEDOT:PSS was carried out using the chronoamperometry; the concentration of EDOT was 0.1 M and the NaPSS concentration was 0.02 M [9]. Platinum is used as the counter electrode. The electropolymerization is carried out at a constant potential of 3 V (versus Ag/AgCl reference electrode).

The polymer grows only in the conductive areas where the metallic films were deposited; this gives the possibility of realizing sensors of different shapes and aspect ratio in order to optimize their piezoresistive response.

The patterned electrodes are finally transferred to a polyimide support. This support can be obtained depositing a solution of a poly(trimellitic-anhydride-chloride copolymerized with 4,4-methylenedianiline) in *N*-methylpyrrolidone onto the anode. It is possible to use both a casting technique that allows us to obtain substrates with a thickness of about 500 μm and a spin coating technique that allows us to obtain a substrate ranging from 100 μm to 300 μm. In our case we spin coated the solution at 1000 rpm. After curing at 130 °C for 90 min, a flexible and tough polyamide film with 100 μm thickness is peeled off from the anode surface. The spin coating process can be tailored to obtain the desired thickness of the flexible substrate. Different thicknesses can be used for specific ranges of sample elongation.

The obtained flexible sensor is shown in Fig. 2, the PEDOT:PSS film is represented by the black pattern.

The two electrodes are contacted with two copper wires using silver paste and an epoxy-based glue that guarantees a stable adhesion of the wires.

3. Experimental results: piezoresistive behaviour in microscopic deformations

The piezoresistive sensors were characterized using two different setups for the measurement: one for micrometric and one for the macroscopic deformations.

The first setup is shown in Fig. 3. The DUT (device under test) is deformed by an insulating tip. It is possible to apply both a static and a dynamic deformation controlled by a piezoelectric actuator (Physyk Instrument) acting on the sample [10]. The piezo actuator through an insulating rigid tip applies a vertical force at the

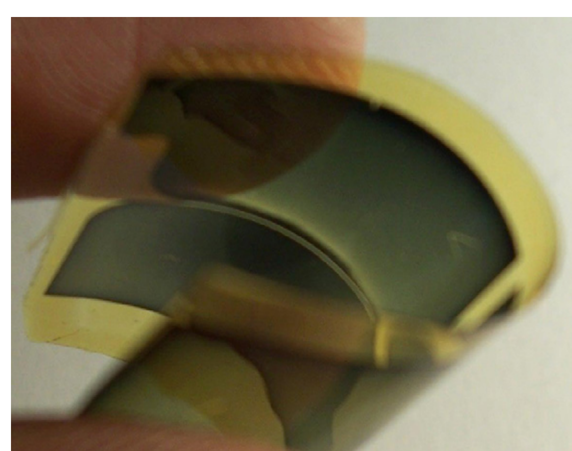

Fig. 2. The PEDOT:PSS patterned layer on a flexible substrate.