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Piezoresistive properties of PEDOT:PSS

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ABSTRACT

Recent market studies mention the necessity to include sensors in the design of organic electronic devices in order to broaden the range of applications. It is therefore essential to identify potential organic mechanical sensor materials and to develop processes and methods to structure them and characterize their piezoresistive properties. Furthermore, it is also essential for organic electronic devices to know the change of resistance upon bending of flexible substrates. A material widely used in organic electronics is the complex of the intrinsically conductive polymer poly(3,4-ethylenedioxythiophene) and polystyrene sulfonate acid (PEDOT/PSS). In this paper first the fabrication of a polyimide (PI) membrane with integrated PEDOT/PSS strain gauges is presented. Upon a pressure difference the membrane is deflected and the resulting changes in resistance of the sensor elements are recorded. By applying a membrane mechanics model the resistance changes can be linked to the strain in the membrane and then the plane strain gauge factor k_{PS} for PEDOT/PSS of 0.48 ± 0.07 at $36.6 \pm 3\%$ rH can be determined.

1. Introduction

The most recent 2007 iNEMI (international electronics manufacturing initiative) roadmap [1] emphasizes the necessity to include sensors in the design of organic electronic devices. It is therefore essential to identify potential sensor materials and to develop processes and methods to structure and characterize their piezoresistive properties i.e. the strain gauge factor *k*. To the authors' knowledge there are only few examples in the literature on intrinsically conductive polymers used as mechanical sensors. Several publications deal with fabrics coated with polypyrrole (PPy) [2–5], PEDOT [2] or PEDOT/PSS [6]. In other experiments an epoxy pellet coated with PEDOT/PSS was exposed to a compressive load and the resulting changes of resistance were recorded [7]. These publications show that there is a change of resistance under mechanical load for intrinsically conductive polymers. But because the intrinsically conductive polymer is deposited on fibers or fabrics it is loaded in a very complex mechanical stress state and it is thus extremely difficult to deduce the "true" piezoresistive properties from these results. In a next step it is therefore necessary to develop experimental setups which allow for a defined mechanical loading of the intrinsically conductive polymers in order to be able to derive quantitative relationships between mechanical load and resistance i.e. the determination of the strain gauge factor *k*. That was presented in [8] for spin coated PEDOT with a four point bending setup. Another possible candidate material for mechanical transducers is PEDOT/PSS. It is readily commercially available as an aqueous dispersion under the tradename Clevios P from H.C. Starck GmbH (Leverkusen, Germany). So far it has been widely used in organic electronics e.g. as an electrode material in organic thin film transistors (OTFTs) or as a hole transport layer in organic light emitting diodes. A broad overview of these and other potential applications is given in [9]. In this study a reliable method to electromechanically characterize PEDOT:PSS is presented which might eventually pave the way to use it as a sensor material in organic mechanical transducers. In order to obtain defined mechanical deformations and to determine its piezoresistive properties a bulge test setup is chosen for these experiments. By applying a defined differential pressure it is possible to strain a membrane in a defined way. This method has therefore already been successfully used to determine mechanical properties of thin polymer layers [10–12]. As a substrate material PI is chosen as it has been widely used in micro machined membranes [13–15]. Based on recently published fabrication processes [16,17] PI membranes with integrated PEDOT/PSS strain sensors are produced. They consist of a stripe across a rectangular PI membrane. The specimens are then electro mechanically characterized in the bulge setup by applying a pressure difference and by a simultaneous two point recording of resistance. Based on a mechanical membrane model the piezoresistive properties of PEDOT/PSS characterized by the strain gauge factor *k* can then be derived from the experiments. This shows the potential of PEDOT/PSS as a mechanical sensor material and will also be of use for the reliable design of flexible organic electronics.

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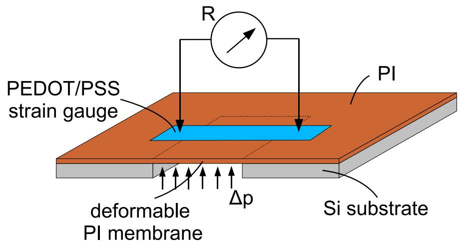

Fig. 1. Bulge test experiment: a differential pressure causes the membrane to deflect outwards. Corresponding changes in resistance are measured simultaneously.

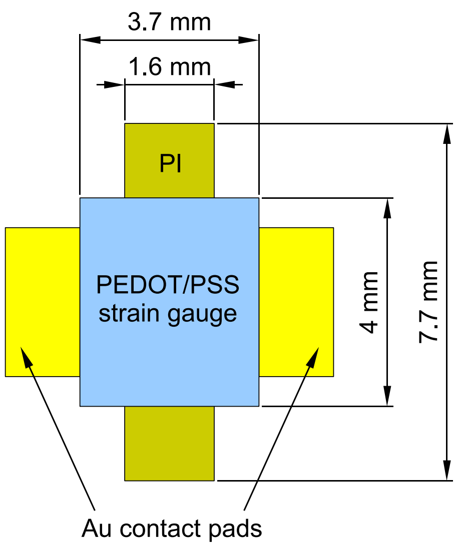

Fig. 2. Layout for stripe configuration. The PEDOT/PSS strain gauge is deposited on top of the PI membrane. The Au contacts are added by e-beam evaporation for reliable contacts to the strain gauge.

2. Experimental

2.1. Layout

The functional principle of the setup is shown in Fig. 1. A deflection of the membrane causes a corresponding change in resistance due to mechanical strain. The resistance is directly measured by an electrometer (Keithley 6517A). The actual layout was accordingly straightforward with two gold pads added to ensure low contact resistance to the electrometer (see Fig. 2).

2.2. Fabrication process

The fabrication process was published in detail elsewhere [16,17]. For this reason only a very brief summary with the most important steps is given here (see Fig. 3). The final samples consisted of a 500 μm thick Si wafer with 3 μm thick PI membranes. The PEDOT/PSS strain gauges with a thickness of 150 nm were deposited on top of these membranes (see Fig. 4).

2.3. Bulge test setup

The basic principle of a bulge test is to apply a defined pressure difference and record the resulting membrane deflection. The actual bulge test setup used in this research was applied in previous experiments [18] for the determination of creep in glassy polymer membranes and was described in detail there. Here, only a very brief overview of the setup is therefore given (see Fig. 5). The pressure is adjusted by a flow controller (Bronkhorst) which is connected to a PC with a LabVIEW control and measurement program. The resulting deflections are measured by a white light interferometer (WLI) (Zygo New View 5000) and then processed by the measurement software MetroPro (Zygo). For the stripe configuration in this research the changes of resistance during deflection were determined at a testing voltage of 40 V by two point measurements with an electrometer (Keithley 6517 A). The

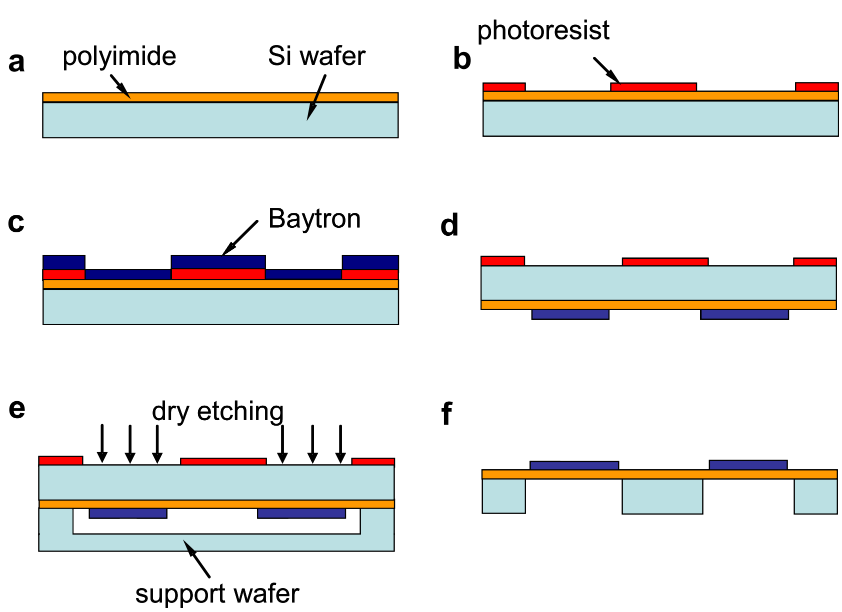

Fig. 3. Process flow for the fabrication of the samples: (a) a 3 μm thick layer of the polyimide PI 2723 (HD Microsystems GmbH, Bad Homburg, Germany) is spun on a silicon wafer and imidized at 350 °C for 10 min, (b) a 10 μm thick layer of the photoresist AZ 4562 (Microresist GmbH, Ulm, Germany) is patterned by standard photolithography, (c) Clevios P (H.C. Starck GmbH, Leverkusen, Germany) is spin coated and then dried at 60 °C for one minute which results in a solid layer. By manually agitating the wafer in acetone the photoresist and PEDOT/PSS layers on top of it are dissolved leaving the patterned PEDOT/PSS film behind, (d) standard photolithography with a 10 μm thick layer of the photoresist AZ 4562 on the backside of the wafer, (e) glueing of the wafer to a support wafer for protection of the specimen and subsequent dry etching from the backside, (f) by removal of the support wafer the samples can be obtained.