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INDIVIDUALLY CONTROLLED CONDUCTING POLYMER TRI-LAYER MICROACTUATORS

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ABSTRACT

We are currently developing a range of microdevices based on polypyrrole (PPy) tri-layer microactuators that function in air. Here, we present recently developed microfabrication and patterning methods using photolithography for both thick, membrane and thin film poly(vinylidene difluoride) (PVDF) based PPy tri-layer actuators. We fabricated monolithically integrated, articulated actuator devices, *i.e.* comprising individually controllable actuators. We also introduce an interface for such PPy actuators based on a flexible printed circuit board, comprising the electrical contacts, into which the actuator device was inserted.

Comparative evaluations showed that the microfabricated tri-layer actuators functioned as good as the normally fabricated actuators. The new interface seemed to actually improve the actuator performance.

KEYWORDS

Polypyrrole, poly(vinylidene difluoride) (PVDF), microactuators, patterning, interface.

INTRODUCTION

There is a need for soft and flexible manipulators for handling biological objects, such as single cells and tissues. Polypyrrole (PPy) actuators are an attractive option since they use low power and are soft and compliant. PPy can be electrochemically oxidized and reduced. This reversible redox reaction is accompanied by a volume change of the material caused by the ingress and egress of ions from the electrolyte as illustrated in Figure 1. This volume change has been used to fabricate PPy/Au bending bilayer microactuators [1, 2] that, for instance, were employed as joints in a microrobot [3].

Recently, PPy tri-layer bending type microactuators have been demonstrated to operate in air without the need of an external liquid electrolyte [4-6]. Figure 2 illustrates a typical PPy tri-layer actuator. It is made of three main layers laminated together: two outer layers of PPy and a middle, insulating layer of PVDF to separate the two electrodes and to contain the electrolyte. In addition, a thin Au layer is sputtered on both sides of the PVDF to increase the conductivity and function as a seed layer for PPy electrosynthesis.

Figure 1: (a) Illustration of the electrochemical oxidation and reduction of PPy doped with TFSI anions.

Figure 2: Schematic representation of the bending principle of a PPy tri-layer actuator. At the positive electrode, PPy is oxidized and anions from the electrolyte contained inside the pores of the PVDF membrane move into the PPy causing a volume expansion. At the negative electrode, the PPy is reduced causing expulsion of anions and thus volume reduction. The process is fully reversible causing a rocking motion.

To date, only simple, single PPy tri-layer bending type microactuators have been fabricated and characterized, but they lack individual control and had problems with short circuiting due to electrical connections. For the above mentioned applications, there is a need to also fabricate complex structures, comprising individually addressable microactuators, for instance, in the form of multi-degree of freedom grippers or legs for microrobotics. We are currently developing a range of novel microdevices based on individually addressable PPy tri-layer microactuators that function in air [7, 8].

For this, we have developed different

microfabrication and patterning methods using photolithography for both thick PVDF-membrane and thin film PVDF-based PPy tri-layer actuators, which require different processing steps. These new microfabrication methods extend our processing capabilities as well as generate novel designs for PPy microactuator based devices.

In addition, the lack of a proper interface is still a major obstacle for further development of PPy microactuator based devices. Often alligator clips or Kelvin clips (alligator clips with separately addressable sides) have been used to apply a mechanical force in order to establish an electrical connection, but they are bulky and the mechanical pressure may damage the relatively fragile microactuators or cause short-circuiting. Here, we present an interface based on a flexible printed circuit board comprising the electronic circuit into which the actuator unit was embedded.

EXPERIMENTAL

Patterning

The PPy tri-layer actuators were patterned using an adapted microfabrication technology based on photolithography [8]. Figure 3 illustrates the processing steps of the fabrication of the thick PVDF membrane actuator unit.

Figure 3: Process steps for microfabricating the thick PVDF membrane actuator unit (top view and cross section along the dashed line). 1. Sputtering 200-300 Å Au on both sides. 2. Wet chemical etching of the Au electrodes and conducting frame. 3. Electrochemical synthesis of PPy(TFSI). 4. The final actuator unit is manually cut out from the membrane and conducting frame.

(1) A 200-300 Å layer of Au was sputtered on both sides of a piece of PVDF membrane (5 x 5 cm²) from Millipore, Immobilon-P, 0.45 μm pore size, thickness 110 μm. (2) The Au electrode pattern was fabricated by employing either lift-off or wet chemical etching, using the thick film photoresist Ma -P1275. (3) PPy was

electrochemically synthesized on both sides of the patterned Au membrane at a constant current of 0.1 mA/cm² for 12 h either at -18 °C or room temperature in a propylene carbonate (PC) solution containing 0.1 M pyrrole monomers and 0.1 M LiTFSI (bis(trifluoromethanesulfonyl)imide lithium salt) with 1% DI water. (4) After the PPy(TFSI) synthesis, the actuator unit comprising three individual actuators (2 x 10 mm²) was manually cut-out. Figure 4a shows a photograph of a finished actuator unit.

The bending curvature of the tri-layer actuator is determined by the total thickness of the actuator. In order to reduce the bending curvature of the tri-layer microactuators the thickness of the PVDF was reduced by using a spincoatable PVDF [9]. Recently we have also succeeded to pattern these thin film tri-layer actuators [7].

Interface

The developed interface was based on a flexible printed circuit board (FPCB). Standard commercial FPCB from DuPont, Pyralux LF copper clad LF9110R (provided by DuPont de Nemours, Luxembourg) was used as the starting material. Using standard photolithography, an etched Cu pattern, forming the electronic circuit including contact pads, was patterned using wet chemical etching in a HCl and H₂O₂ solution (2:1). Fine metal wires for external control were soldered to the contact pads, see Figure 4b. The interface was then folded, thus automatically aligning the top and bottom contacts for the actuators. The microactuator unit was inserted in the folded interface and the assembled unit was pressed together to obtain a good electrical contact between the Cu lines and PPy actuators (Figure 4c).

Figure 4: A photographs showing the assembly process. The microfabricated PPy actuator unit (a) is inserted in the FPCB interface (b) that is folded around the patterned PPy actuator unit as indicated by the arrows. (c) Shows the assembled device. The actuator unit comprised 3 individually addressable actuators 10 mm long and 2 mm wide.

RESULTS

The microfabricated PPy tri-layer actuators appeared similar to normally “macro-”fabricated tri-layer actuators. Next, we investigated the effect of the microfabrication processing steps on the performance by comparing single

microfabricated actuators with normally fabricated tri-layer actuators, *i.e.* manufactured as a large sheet and cut out by hand in the same shape as the microfabricated actuators. We applied an alternating voltage of ± 1.5 V at 0.05 Hz between the 2 PPy electrodes. Both the current response and the tip displacement of the normal and microfabricated actuator showed to be almost identical indicating that the microfabrication process has no negative effect on the functioning of the device.

Thereafter, we assessed the functioning of the interface method. The current and tip displacement of a single tri-layer actuator were assessed using both a Kelvin clip and the FPCB interface. Figure 5a shows the displacement as a function of the applied potential. Figure 5b shows the current response of the PPy tri-layer actuator using a driving voltage of ± 1.5 V. As can be seen, the developed FPCB interface resulted in a better actuator performance than contacting using the Kelvin clip.

Figure 5: Displacement (a) and current (b) response of a PPy tri-layer actuator contacted using either a Kelvin clip or the developed FPCB interface. In (b) the driving voltage was ± 1.5 V.

Finally, we assembled a complete actuator unit as shown in Figure 4c. Unfortunately, the fold in the FPCB fold was too flexible so we needed to apply an external force (two alligator clips, see Figure 6) to receive a good mechanical and thus good electrical contact.

Each PPy actuator in the actuator unit was connected to one pair of wires (top and bottom contact) via the PVDF interface and addressed using one channel of the multiplexing unit of the potentiostat (Iviumstat) that drives the actuators. The three multiplex channels can

only be addressed sequentially, so therefore, only one actuator could be addressed at the time. The actuators were actuated at ± 2 V, but with different pulse lengths. The first actuator was addressed with 1 s pulses for 5 cycles, directly thereafter the second at 2 s pulses for 5 cycles and finally the third at 5 s pulses for 5 cycles. Figure 6 shows frame grabs of the stimulation of actuator 1 and 3. As can be seen each actuator moves individually without cross-talk to the other actuators. We did not optimize the PPy synthesis process, so deflection range was only a few mm.

Figure 6: Overlay images of two frame grabs showing individual actuation of “Leg 1” and “Leg 3”. In each image only the addressed leg moves, while other legs do not. The actuator unit was not optimized so the deflection was only a few mm.

Having developed both the interface connection to individual PPy actuators and a patterning method using the PVDF membrane, we are now continuing to downscale the PPy tri-layer actuators. The first step is to reduce the PVDF thickness by employing a spin coatable PVDF. Figure 7 shows recent results of such patterned, *thin film* PVDF tri-layer actuator devices designed as “fingers” with two individually controllable actuators. The present devices have individual actuators that are 5×10 mm² and 2×4 mm². We are currently reducing also the lateral size of the PPy actuators to micrometer dimensions in order to employ these in small micromanipulation tools.

Figure 7: Thin film PVDF PPy tri-layer actuator devices. (a) A “finger, with individually controllable joints of patterned 5×10 mm² PPy tri-layer actuators. (b) A finger with two 2×4 mm² actuators and separated top and bottom contact pads to minimize short circuiting.

DISCUSSION AND CONCLUSION

The development of soft microactuators for microrobotics and micromanipulation of biological objects based on electroactive polymers is currently

hampered by the lack of good interfacing methods. Also, they cannot be individually controlled. Here, we present a novel patterning method for the fabrication of individually controllable PPy tri-layer (micro-)actuators. We also have developed an interface that is light-weight and allows for easy assembly. Using the interface, we demonstrated successfully the individual control of PPy tri-layer actuators that were monolithically integrated on a single PVDF unit. It showed that the microfabricated tri-layer actuators functioned as good as the normally fabricated actuators. The new interface seemed to actually improve the actuator performance.

We are currently working on downscaling the process even further with the goal of microfabricating PPy trilayer *microactuators* that function in air and can be individually addressed. We also continue to improve the interface, amongst others to reduce flexibility of the fold and make a self-contained unit eliminating the need for external pressure. Finally, we intend to achieve parallel addressing of the actuators, by replacing the potentiostat multiplexing.

The developed interfacing method could also be applied to other electroactive polymer devices such as ion polymer metal composites (IPMC) and dielectric elastomers (DE).

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