ELECTRICALLY DRIVEN PAPER ACTUATORS USING CONDUCTING POLYMERS

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Cooperation between the electrical conductivity and hygroscopic nature of conducting polymers can provide an insight into the development of a new class of electro-active polymers (EAPs) or artificial muscles working in ambient air. Since the first observation of a curious phenomenon whereby an electrochemically synthesized polypyrrole film undergoes rapid bending due to water vapor sorption [1], we have devised polymer motors capable of transducing chemical free energy change of sorption directly into continuous rotation [2]. Furthermore, we have found the polypyrrole film contracts in air under application of an electric field [3]. The principle lies in the desorption of water vapor caused by Joule heating, where the electric field controls the sorption equilibrium and the film sorbs and desorbs water vapor reversibly in response to the electric field [4]. Unlike conducting polymer actuators driven by electrochemical doping and dedoping, this system operates in air without using an electrolyte solution, counter and reference electrodes. This paper deals with a study on origami actuators fabricated by folding a sheet of conducting 'paper'. The mechanism is based on the electrically induced changes in the elastic modulus of a humido-sensitive conducting polymer film through reversible sorption and desorption of water vapor molecules, which is responsible for amplifying a contraction of the film (~ 1%) to more than a 100-fold expansion (> 100%) of the origami actuator.

Differing from 1D fiber and 2D film actuators, the origami actuator has its 3D structure constructed by folding a conducting polymer film. An *L*-shape film made from electrochemically synthesized polypyrrole doped with tetrafluoroborate is folded into the figure of an accordion shape. It is found that the origami actuator exhibits rapid and significant expansion upon application of the electric field. The maximum strain increases as the applied voltage is increased with the value reaching 147% at 2 V, which is two orders of magnitude larger than the film contraction (0.8%) caused by desorption of water vapor due to Joule heating. Here, the unfolding of the creases causes a significant expansion of the origami actuator. At the creases formed by folding the polypyrrole film, the force to fold balances with that to unfold, thereby exhibiting spring characteristics. This balancing of forces also determines the length of the origami actuator. The application of the electric field causes desorption of water vapor and contraction of the film, leading to an increase in the elastic modulus making the film more difficult to be deformed. Therefore, a force to unfold the creases allows the angles to be extended, thereby expanding the origami actuator. However, a further application of the electric field brings about contraction of the actuator. This can be explained by refolding the creases where a force to hold overcomes that to unfold due to further film contractions. On the other hand, when the electric field is turned off, resorption of water vapor lowers the modulus allowing the creases to be folded, leading to the slight contraction of the origami actuator. Finally, further sorption of water vapor restores the actuator to its original size.

In conclusion, the origami actuator exhibits strains two orders of magnitude larger (> 100%) than that induced by the electrochemical or chemical doping of conducting polymers, driven at voltages two orders of magnitude lower (< 3 V) than that of piezoelectric and electrostatic actuators or dielectric elastomers.

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