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An invisible bend sensor based on porous crosslinked polyelectrolyte film

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ABSTRACT

This paper reports the fabrication and electromechanical characterization of a thin porous polyelectrolyte film and its application in an invisible bending transducer. The porous film consists of 10 bilayers of polycation and polyanion that are adsorbed using electrostatic self-assembly (ESA). Such porous film can be thermally crosslinked. The size of the pores on top surface is adjustable and can be covered up by a type of Na^+-montmorillonite nanosheet whose size is comparable to those of the pores. As a result, the sealed top surface can be coated by metal for an electrode. After such polymeric film is integrated into a sandwich structure that was designed for a bend sensor, it can perform as an ultrathin piece of elastomer. It is found that the bending of the substrate resulted in the increasing of the current. It is hypothesized that the tunneling current through the thin polymeric film changes when the film is compressed by bending. Finite element simulation corroborates the existence of strain concentration especially near two ends of the polymer film and the shoulder of the bottom electrode.

1. Introduction

The bend sensor is used to detect the position and orientation of an object, thus having wide applications in interactive computer games, the automotive industry and manufacturing control [1–5]. The commercial bend sensors are mainly dependent on a conductive thin film whose resistivity changes with the curvature [1,4–7]. In the usual case, such sensors have to occupy a considerable area in order to contain the long polymer resistive wire. At the continuous monitoring mode, the resistive wire keeps consuming electric power when the sensor is in an idle situation (flat position). Capacitive type sensors detect the variation of the capacitance of a dielectric layer between two parallel electrodes. The permittivity variation of the dielectric layer as a response to flexion exhibited limited sensitivity, thus requiring addition amplifying circuit [8]. The change in dimension (thickness and area) of the dielectric layer also results in the variation of the capacitance. However, extra efforts are necessary to fabricate this type of sensor with high nominal capacitance in order to reduce the loss due to parasitic capacitance [2,9–11]. Moreover, the capacitive sensors may also have current response to strain, resulting in power consumption. This paper presents a bend sensor that possesses a capacitor-like structure, which dramatically reduces the occupied area, thus making pixel sensing feasible. The current between the two electrodes vary with the flexion. When the sensor is in the flat position, it hardly consumes power. Another unique feature is the sensor is transparent in the visible light spectrum. This see-through structure enables the sensors to fit special applications where the presence of the hidden electronic surveillance is required not to be revealed. They can be placed on large window panels or contact lens to detect deformation. Installed outdoors, they have higher tolerance to sunshine and temperature variation because of reduced absorption. As a result, less photo- and thermal-degradation are anticipated, leading to a longer field life and more stable operation [12]. They allow an easy registration onto other objects because the features underneath are visible through the sensor. They not only sense the flexion but also allow for diagnosis of other symptoms such as cracks developing on the surface under the sensor. Fig. 1a illustrates the visual effect of the invisible bend sensors fabricated on a piece of plastic transparency.

Such sensors have a vertical structure with two transparent indium-tin-oxide (ITO) electrodes and a thin porous dielectric layer (nanospring) in between as shown in Fig. 3h. In particular, the top electrode is wider than the bottom one so that the dielectric layer is confined between two electrodes. The dielectric layer is a multilayer of polycation, poly(allylamine hydrochloride) (PAH), and polyanion, poly(acrylic acid) (PAA), which are generated by electrostatic self-assembly (ESA). The porous structure is generated by a process which was demonstrated by M. F. Rubner co-workers [13]. The self-assembled polyions are integrated mainly by electrostatic interaction. The post-annealing turns the electrostatic interaction into covalent bond [14]. It is speculated that the porous structure makes the dielectric layer compressible and the covalent bonds

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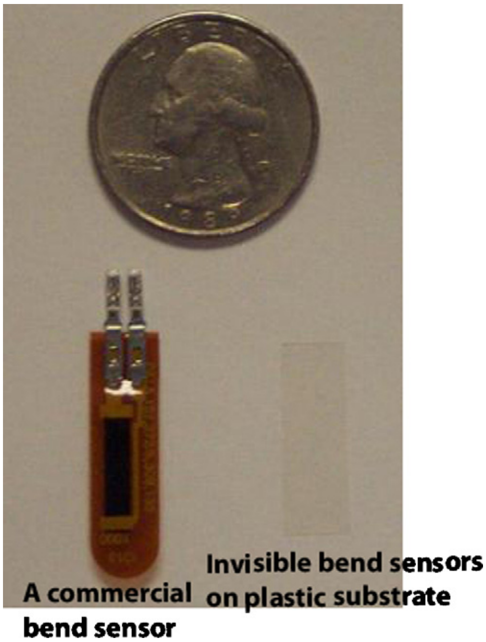

Fig. 1. Visual effect of the invisible bend sensors fabricated on plastic transparency. More than 10 sensors are allowed to be constructed on this area. The left is a typical opaque commercial bend sensor.

enable it to respond quickly to cyclic flexion and relief. In other words, the PAA/PAH multilayer performs like a thin piece of elastomer. When the sensor is flat, there is hardly any conductive electric current between two electrodes. When being bent, the soft dielectric layer is compressed and the gap between the two electrodes decreases. As a result, the flexion leads to the decreasing of dielectric thickness and increasing of the current.

2. Finite element simulation

Simulation was performed using Abaqus software to visualize strain among the multilayer. The dimensions are consistent with the real device. Fig. 2 illustrates qualitatively the simulation of the strain distribution in the sensor and most importantly the location of the peak strain. The peak occurs at two ends of the dielectric layer, as well as in the vicinity of the two shoulders of the bottom electrode. It is found that the strain is increased as the sensor is bent. The contours in this figure represent the minimal in-plane principal strain field which reflects the deformation of multilayers thin film. The seven vectors illustrated in the inset represent the magnitude and orientation of two points (illustrated in the figure with two white dots) across the dielectric layer in the shoulder region, which vary with the flexion of the sensor. The top vector (the longest) corresponds to the distance between the two points in the flat situation while the bottom vector (the shortest) denotes the reduced distance in the most flexed situation.

3. Experimental details

3.1. Materials and equipment

The polyelectrolytes used for the self-assembly process were PAH (aqueous solution, MW 70,000, 3 mg/mL) and PAA (aqueous solution, MW 50,000, 3 mg/mL), both of which were obtained from Aldrich–Sigma. The Na^+-montmorillonite nanosheet was obtained from the clay minerals society. It was diluted to 7 mg/mL by DI water. After sonification for 30 min, only the top layer of the clear

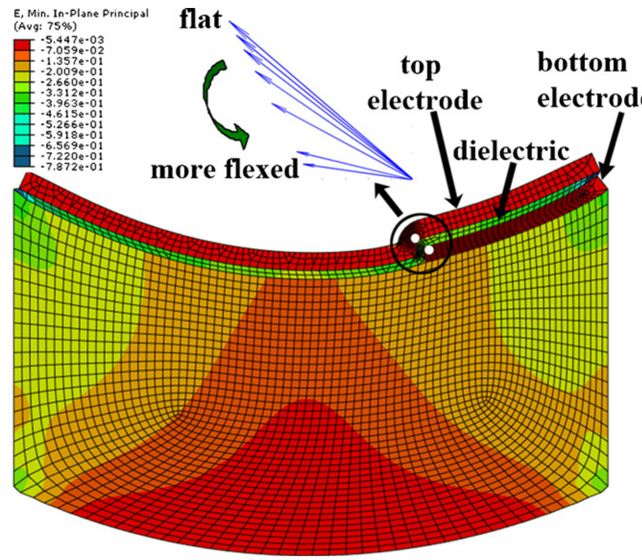

Fig. 2. The simulation result by Abaqus qualitatively illustrates the strain distribution in the dielectric layer. It shows that the dielectric layer which is sandwiched between top and bottom electrodes is compressed when the sensor is bent. The inset shows seven vectors rotating from top to bottom. The vectors represent both magnitude and orientation of two points (illustrated by two white dots) across the shoulder of the dielectric layer with the curvature of the sensor. The top vector is the longest, representing the distance between two points in the flat position. The bottom one is the shortest, representing the reduced dielectric thickness in the most flexed situation.

solution was extracted for use. The plastic transparency was coated with an ITO layer with a thickness of about 250 nm and sheet resistivity of 8–12 Ω/square and it was obtained from Delta Technologies. A transparent UV-curable polymer (NOA 73) used for encapsulating the sensor was from Norland Products. The electrical characterization was conducted by an HP 4156A semiconductor parameter analyzer.

3.2. Fabrication of the sensor

The fabrication started from the ITO-coated plastic transparency (Fig. 3a). The ITO layer was patterned to form the bottom electrode (1 mm wide) using photolithography (Fig. 3b). The next lithography step patterned out a 3 mm wide window on the photoresist over the bottom electrode (Fig. 3b). Then 10 bilayers of polycation and polyanion, PAH/PAA, were alternately adsorbed on the surface using ESA assembly (Fig. 3c). In detail, the plastic substrate was alternately dipped in each polyion solution for 10 min until 10 bilayers were achieved. Between every two dipping, an intermediate rinsing in DI water and drying by nitrogen were necessary in order to remove weakly attached components, thus preparing the surface for the subsequent adsorption [16]. After that, the resulting dense polyion film was dipped in an acidic solution (pH 2.4) for 1 min to generate the porous structure (Fig. 3d). The sample was further soaked in DI water for 10 h in order to shrink the pores on the top electrode (Fig. 3e). Then, the pores were covered by three layers of Na^+-montmorillonite nanosheet with comparable size still using ESA assembly (Fig. 3f). Next, a 300 nm thick ITO layer was sputter deposited for the top electrode (Fig. 3g). The lift-off was implemented by dissolving photoresist, leaving the transparent sensor structure on plastic substrate (Fig. 3h). The sample was annealed at 180 °C for 2 h to crosslink the PAH/PAA polymer multilayer [14]. Finally, the sensor was encapsulated in order to be isolated from the atmosphere by a thin transparent film of polymer, NOA 73, which was cured by the irradiation of UV light.