Int. J. Nanosci. Nanotechnol., Vol. 14, No. 2, June. 2018, pp. 101-109

A Short Review on Fabrication Methods of Micro-Cantilever for Ionic Electroactive Polymer Sensors/Actuators

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(Received: 16 September 2017 and Accepted: 14 November 2017)

Abstract

Micro-electroactive polymers have wide applications from industry to healthcare. Artificial muscles, microvalves, microswitches, haptic sensing, blood pressure and pulse monitoring are some potential applications for micro-electroactive polymers. The most advantage of micro-electroactive polymers as sensors and actuators is bio-compatibility and low power threshold for large deformations. In this short review, some applicable fabrication methods of micro-electroactive polymer cantilever are reviewed. Furthermore, a novel method based on standard micro fabrication techniques is designed and discussed in details which presents a conceptual design of a micro-electroactive polymer cantilever on a polymeric anchor located on a silicon substrate for future works.
Keywords: *Micro fabrication, Electroactive polymer, Cantilever.*

1. INTRODUCTION

Electroactive polymer (EAP) is a polymer composite that its shape and dimensions are changed in subject to an external electric field [1]. They exhibit a large amount of strain while sustaining large forces at low power [2]. This specific characteristic and capability leads EAPs to be utilized as actuators [1] and sensor [3, 4]. EAP actuators offer a mechanical response when stimulated by an external electric field, and conversely, EAP sensors induce an electrical current in presence of mechanical stimulation. Ionic electroactive polymer is an ionic-conductive membrane sandwiched between two electrodes in which the migration of the electrolyte ions into electrodes inside the membrane leads to bending deformation [5].

Integrated micro-electromechanical systems (MEMS) with micro-EAPs could be used as implants in human's body due to the flexibility and biological compatibility of micro-EAPs [6]. Artificial muscles for macro-/micro-robotics, nerve and cardiovascular tissue engineering, micro-valves, micro-switches, micro-shutters, micro-optical devices, and manipulation of living cells are some potential applications of integrated MEMS with micro-EAPs [7-11]. To incorporate micro-EAPs in MEMS, first fundamental primary step is to develop a method for fabrication of a micro-EAP cantilever. Then, the fabricated structures are integrated in MEMS or other devices for application of interest. Therefore, there is large demands for developing micro-EAP actuator technology.

There are some extensive reviews on application of micro-EAPs in micro-cantilever sensors [12-16] which indicates the fact that micro-EAPs are generally fabricated in cantilever formation. A micro-cantilever is a beam fixed from only one end whereas the other end is free to suspend to create a deformation [17].

Micro-cantilever sensors could be a potential candidate in physical [18], chemical [19], and biological sensors [20]. In comparison to other common sensors, the micro-cantilever sensors exhibit larger sensitivity [21]. Large aspect ratio, low production cost, several modes of operation, label free detection, feasibility for array fabrication, and ease of integration with on-chip electronic circuit are the distinct advantages of the micro-mechanical cantilever sensors [22]. Polymer-based micro-cantilevers are cheaper and highly sensitive than common silicon micro-cantilever due to lower stiffness of polymers [23].

Several efforts have been made for the fabrication of micro-EAP cantilevers in different ways including photolithography, laser machining, mechanical milling [24], and plasma etching [25]. Kikuchi et al. [26] developed a novel fabrication method for miniaturized EAPs with electroless gold plating using selective plasma treatment of Nafion. Melbsurne et al. [27] made a bimorph-type thermal detector by deposition of polystyrene film on a commercial silicon cantilever via plasma enhanced chemical vapor deposition (PECVD). Fabrication of tri-layered micro-cantilever have also been reported by Lin et al. [28] by coating an Au/Si3N4 cantilever with poly acrylonitrile/single-walled carbon nanotubes composite. Shang et al. [29] introduced a method to fabricate polymer/metal bimorph micro-EAP system. In this method, a polyvinyl chloride (PVC) film was spin-coated on a substrate followed by sputtering of an aluminum layer and some common microfabrication process. Last, reactive ion etching process was used to etch the PVC. Ultrathin conducting interpenetrating polymer networks patterned by using reactive ion etching to fabricate a suspended polymeric micro-cantilever by Maziz et al. [30]. Fabrication of a dielectric elastomer actuator reported by Gerratt et al. [31]. Firstly, deep reactive ion etching process was utilized to fabricate a silicon mold. After that, the mold is refilled with polydimethylsiloxane and carbon mixture, followed by a low modulus silicon elastomer. After curing treatment, dry isotropic silicon etch process was performed to remove the mold. In 2012, a micro-fabrication approach was introduced to create an array of standing Nafion structures on a substrate by using molding method [32]. In this method, the electrodes were formed on desired sides of standing structures by selective approach. Akbari and Shea [33] was also presented a micro-fabrication method for an array of dielectric elastomer actuators by using channel concept to create a sufficient space for the membrane to expand in-plane. The proposed micro-actuator was fixed from all sides and therefore its deformation was like a dome shape. Stassi et al. [34] used 3D polymeric printing technology to fabricate functional micro-cantilever for bio-sensing applications. Choi et al. [35] designed a thin film piezoelectric and high-aspect ratio polymer leg mechanisms for millimeter scale robotics. In this design, several models were used to create the out-of-plane and in-plane rotations using piezoelectric cantilevers and high aspect ratio polymer beams, respectively, which is out of scope of this review. Taaber et al. [36] formed a micro-cantilever from polymerized ionic liquid by using electron beam irradiation on an AFM tip.

Due to the crucial role of micro-EAPs in the variety of modern technologies e.g. biotechnology, the presented work reviews and compares four different methods of fabrication of micro-EAPs cantilever; first, laser ablation method where a thin film of an EAP will be fabricated and cut into micro-sized cantilevers. Second, fabrication of micro-EAP cantilever on a silicon substrate by etching silicon to produce sufficient workspace. Third method includes a process in which the device layers will be formed diversely (top to down) one by one on a sacrificial layer; and by removing the sacrificial layer, the structure would be released. Last, fabrication of the micro-cantilever on the silicon substrate by using a polymeric anchor approach is discussed.

2. METHODS

Herein, three different methods of micro-fabrication of an EAP including laser cut [37], silicon etch [38], and released structure methods [22] are reviewed, and then in continuous, a novel method in the micro-cantilever EAP fabrication is proposed by utilizing a "polymeric anchor". The aim of this short review is to present conceptual designs and general approaches of reported methods including their advantages and disadvantages. The quantitative data and fabrication parameters such as spin-coating angular velocity, time and temperature of curing photoresist are varied depending on materials and geometrical parameters of desired designs and application of interest. Therefore, in this section, the methods are reviewed generally and qualitatively without discussing details. Challenges, advantages, and disadvantages of the presented methods are discussed in the next section.

2.1. Laser Ablation

In this method, which is inspired from the Gaihre et al. [37] work, firstly, a thin layer of an electrolyte layer is fabricated by spin-coating method. After that, the electrode layers are coated on both sides of thin electrolyte layer. Sputtering could be used for metal electrodes deposition and spin-coating for conductive polymers. Finally, the whole actuator is cut to small cantilevers by laser ablation technique as shown schematically in Figure 1.

2.2. Silicon Etch

In this method, a standard micro-fabrication technique which was used by Hilt et al. [38] is employed to make a micro-EAP cantilever.

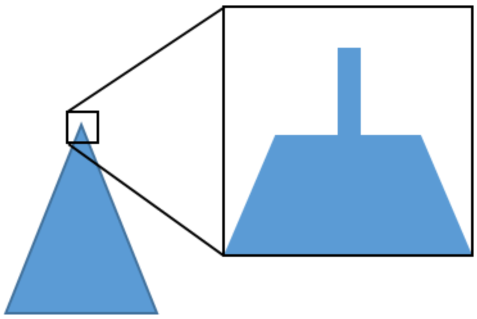

Figure 1. *Micro-EAP fabricated by laser ablation technique*

Firstly, a metallic micro-cantilever is fabricated using common microfabrication method. For this purpose, a metallic layer is deposited on the SiO_2/Si substrate followed by capping with a thin layer of silicon dioxide (Figure 2b). In the next step, a photoresist mask is used to etch the patterned area anisotropically until it reaches the wafer surface (Figure 2d). Then, a thin layer of silicon dioxide is grown on the whole chip including the side walls. In this manner, all surfaces of metallic layer is covered by silicon dioxide. By anisotropic reactive ion etching process, silicon dioxide located in the bottom of patterned area is removed while the metallic layer is still covered by silicon dioxide (Figure 2e). The exposed silicon surface is deeply etched using tetramethylammonium hydroxide which creates a suspension area for the cantilever (Figure 2f). By immersing the wafer in buffered hydrofluoric acid, all silicon dioxide is removed and the metallic cantilever is achieved (Figure 2g). To make a micro-EAP cantilever, secondly, after fabrication of a metallic cantilever as bottom electrode, a small area of the metallic surface is covered by a tape to create a contact pad (Figure 2h). The electrolyte layer is spin-coated followed by coating of the upper electrode, which could be carried out by employing spin-casting for polymeric electrodes or sputtering for metallic electrodes (Figure 2i). Finally, the

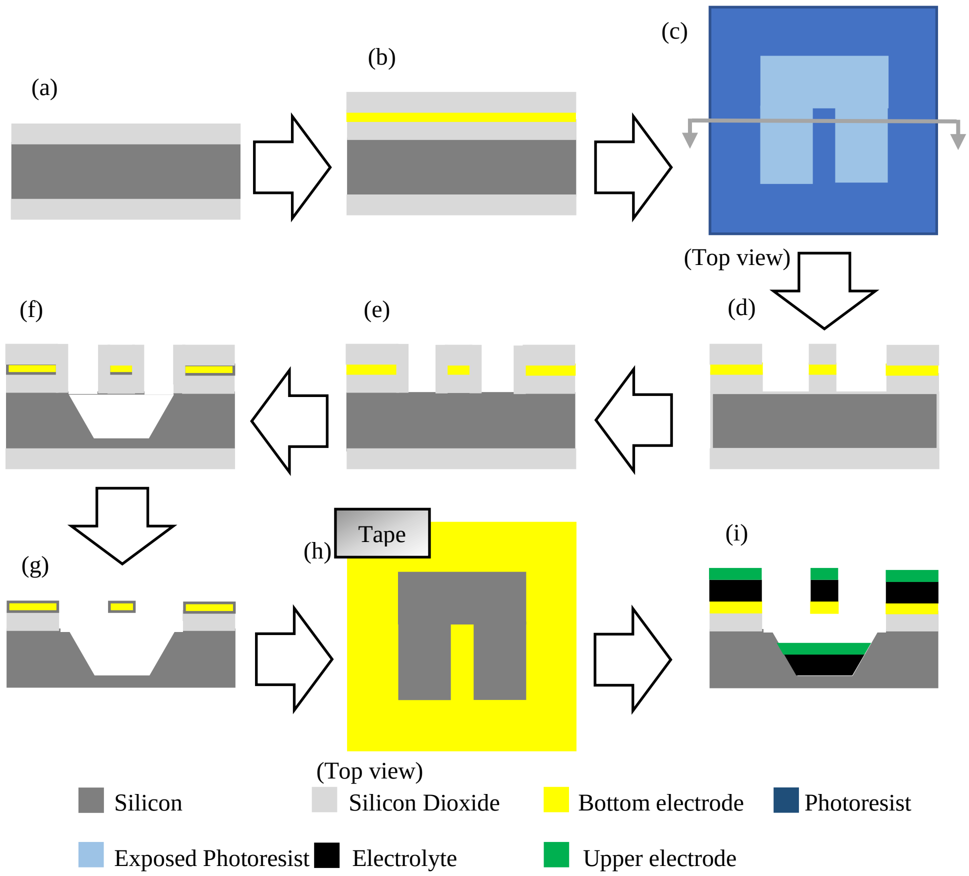

***Figure 2**. Silicon etch method in micro-EAP fabrication.*

micro-EAP is obtained by removing the tape and its residual using acetone. Figure 2 shows schematic diagram of micro-EAP cantilever fabrication using silicon etch method.

2.3. Released Structure

Creating an anchor or support for a micro-cantilever EAP is the most challenging part in its fabrication process. In silicon etch method, an anchor from silicon wafer was fabricated via silicon etching. However, it is possible to use a polymeric material to fabricate anchor for the micro-cantilever. Among all existence polymers, SU-8 can be used in photolithography process for creating structures with a large range of thickness from a few micrometers to hundreds of micrometers with high aspect ratio [22].

The first step of inspired method from Seena et al. [22] study is that the silicon wafer is covered by a thin sacrificial layer (Figure 3a). Then the top electrode (metallic or polymeric) is patterned using coating and lift off process (Figure 3b). In the next step, the electrolyte layer is patterned similar to polymeric electrode using lift off process and spin-coating (Figure 3c). After that, the bottom electrode is coated same as the top electrode which can be metallic or polymeric (Figure 3d). Then, a thick polymeric layer is grown as an anchor to create the suspension environment (Figure 3e). Finally, the whole structure is released by removing the sacrificial layer using lift-off process (Figure 3f). Schematic diagram of micro-EAP cantilever fabrication using released structure method is illustrated in Figure 3.

2.4. Polymer Support

To fabricate a micro-EAP cantilever using polymeric support method, firstly, a silicon wafer is covered by a thick layer of SU-8 photoresist, followed by UV exposure of the anchor pattern (Figure 4a).

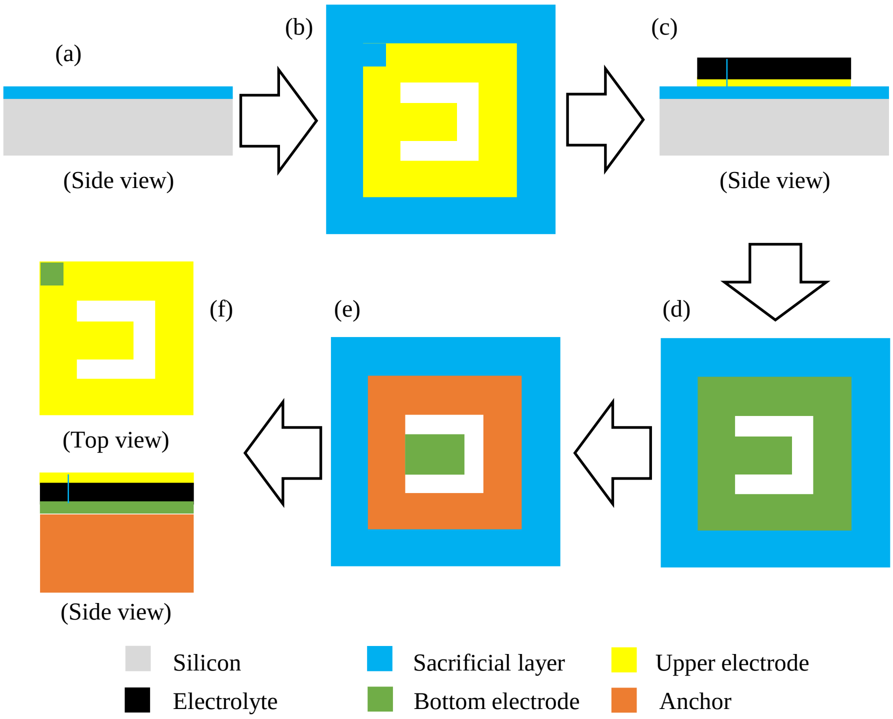

***Figure 3**. Released structure method for micro-EAP fabrication.*

Adherence between SU-8 and substrate is an important parameter in micro-fabrication and hence, spin-coating should be carried out precisely according to the provider's recommended procedures or by the use of a primer [39]. In the next step, a positive photoresist (e.g. AZ 3312) is spin-coated, exposed, followed by developing process (Figure 4b-c). A metal electrode is deposited as the bottom electrode and, lift off process is executed by acetone to remove both exposed positive photoresist and unexposed SU-8 (Figure 4d-f). In conclusion, a metallic cantilever on top of a polymeric anchor is acquired. The next steps are similar to silicon etch method. A small area is covered by a tape to form a contact pad (Figure 4g). The electrolyte layer is grown followed by deposition of top electrode (Figure 4h). Last, by removing the tape and washing the residuals with acetone the final structure is acquired. Figure 4 demonstrates micro-EAP cantilever fabrication using polymer support method schematically.

3- DISCUSSION

Laser ablation technique is a straight forward and low-cost method for fabrication of micro-EAP cantilevers. However, handling a thin layer of electrolyte is challenging and there is a high probability of tearing or folding of electrolyte layer during process. Two solutions are suggested to overcome this challenge; first, utilizing 50 μm thick layer of electrolyte layer which could be handle easily. Although this kind of high thickness of electrolyte layer leads actuator to lose some of its aspects, it worth due to its simplicity. Second, using a sacrificial layer as a support. This support offers stability and electrolyte layer could be handle with confidence not to be damaged. In this solution, firstly, one side of electrolyte layer is coated by electrode layer. Then, the sacrificial layer is removed and the structure is transferred to another substrate to execute coating of the other side of the electrolyte layer with electrode layer. Next, the fabricated EAP is cut to small sizes, and finally, individual micro-EAP could be handled for the purpose of interest without any tearing or folding.

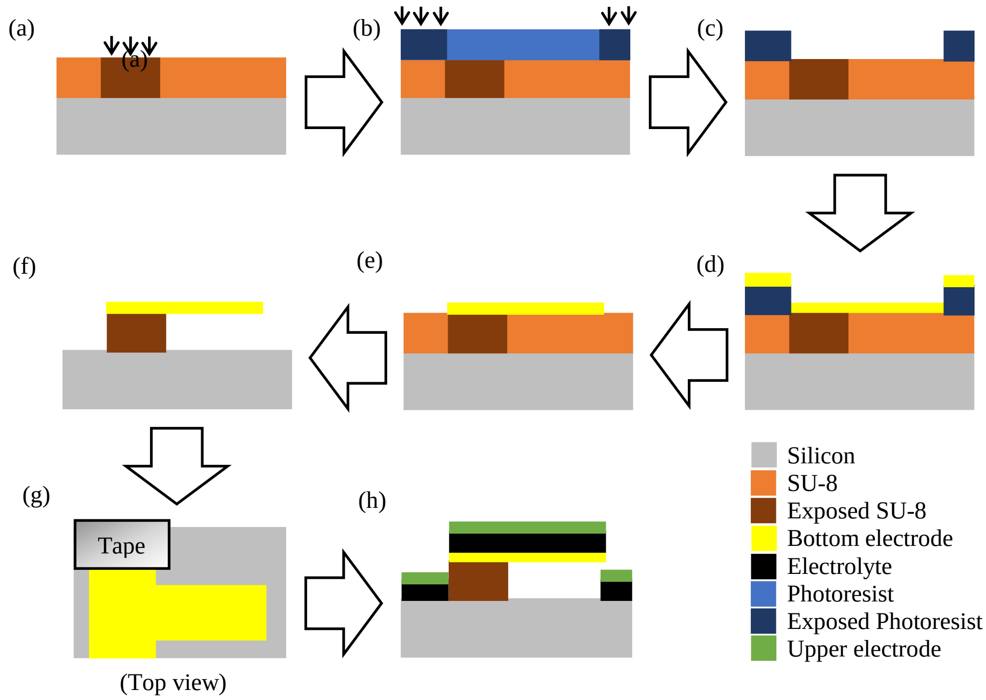

Figure 4. *Polymer support method for micro-EAP fabrication*

Using standard micro fabrication technique is an advantage of silicon etch method in fabrication of a micro-EAP. Furthermore, by using this method, the micro-EAP is placed on a support (silicon wafer) that creates some convenience for handling the actuator. Fabricating an array of micro-EAPs is another advantage of this method. In contrast, fabrication of a micro-metal cantilever is a challenge and needs some micro-fabrication expertise. The bottom electrode in fabricated micro-EAP by silicon etching method should be metallic which can be consider as a drawback.

However released structure method is a standard technique for fabrication of polymer MEMS, it suffers from a lot of challenges, for example, choosing a proper material as the sacrificial layer preventing damaging of other layers during structure releasing process. In addition, during patterning each layer, there is a high probability of damaging of the previous layers. Therefore, it is necessary to choose proper materials as photoresist, electrodes, electrolyte, and anchor layers. Another disadvantage of this method is reduction of the amount of ions exist in the electrolyte layer during the fabrication process due to immersing in the photoresist solvent. In other words, ions can move freely inside the electrolyte layer as well as solvent, and hence, they will disperse all over the solvent in addition to electrolyte layer, which means the amount of ions inside the device is reduced; However, the absence of acids or bases in etching process is an advantage of this method.

Although polymeric support method is similar to silicon etch method, fabricating a metallic cantilever by polymeric support method is much easier than the later. The most advantages of the proposed method are firstly, being free etching process, and secondly the amount of ions inside electrolyte is remaining constant. In this method, there is no reduction for the number of ions due to the absence of developing process after spin-coating the electrolyte layer. However, one of the disadvantages of the method is that the bottom electrode should be metallic and not polymeric. Since in this method, a standard micro-fabrication process is utilized to fabricate a micro-cantilever with a polymeric anchor on a silicone substrate, it could be integrated in MEMS devices

Table 1. Advantages and disadvantages of fabrication methods of micro-cantilever ionic EAP

Method	Advantage	Disadvantages
Laser Ablation	Straight forward Low cost	No substrate Not a standard micro-fabrication Miniaturizing limitation
Silicon Etch	Standard micro-fabrication Placed on a silicone substrate Capable of array patterning	Deep silicon etching Bottom electrode should be metallic
Released Structure	Standard micro-fabrication for polymers Free etching Capable of array patterning	Alignment Lots of developing and removing process Ion reduction
Polymer Support	Standard micro-fabrication Placed on a silicone substrate Free etching Capable of array patterning	Bottom electrode should be metallic

such as microvalves, and microswitches. In designing a MEMS device fabrication process including ionic EAPs, it should be considered that ionic liquid could be removed during etching or developing processes.

The fabricated micro-EAP which is biocompatible and integratable in MEMS can be utilized for several applications such as biological devices. Keshavarzi et al. [40] suggested a setup for measuring blood pressure, pulse rate, and rhythm. By taking advantage of micro sized EAP cantilever sensors, the proposed setup could be miniaturized and located in smart phones or watches. When the device is located next to the skin, the micro-cantilever senses the pressure and pulses generated by vessels.

Summary of advantages and disadvantages of proposed methods for fabrication of micro-cantilever ionic EAP are presented in Table 1.

4- CONCLUSION

In this paper, three different methods of fabrication of a micro-EAP cantilever with potential application in micro-sensor/actuator is reviewed and a novel method based on standard micro fabrication techniques is developed. In laser ablation method, an EAP using typical fabrication process is produced and then it is cut to micro-cantilever shapes. It is a straight forward method with limitation in miniaturization. In silicon etch method, firstly a metallic micro-cantilever is fabricated in which the suspension environment is created by deep etching of silicon. And secondly, the electrolyte and electrode layers are coated respectively on top of the fabricated metallic micro-cantilever. Deep etching of silicon in this method is challenging however the fabrication procedure is designed according to the standard micro-fabrication. In released structure method, micro-cantilever EAP is fabricated by spin-coating or deposition of the top electrode layer, following by electrolyte, bottom electrode, and anchor layers on a sacrificial layer. After that, the structure will be released by removing the sacrificial layer. Although this method is offered for the polymeric micro-cantilever fabrication in the literature, it deals with some challenges in fabrication of micro-EAP cantilevers due to the probability of reduction of free moving ions inside the electrolyte layer in developing and demasking steps. Polymeric support method is a novel method that presented for the first time in this paper and it covers most advantages of three previous methods. In this method, firstly, a metallic micro-cantilever is fabricated on a polymeric support without any need to wet etching, and secondly, electrolyte and top electrode layer is spin-coated or sputtered. Polymeric support is relatively straight forward with less limitation for miniaturizing, it is according to standard micro-fabrication process, it benefits from polymeric anchor, and there is no concern about the performance reduction due to absence of chemical developing process, demasking, or even etching treatment after coating of the electrolyte layer. The presented methods could be examined and compared to each other quantitatively, and utilized for different applications for future works.

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