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Biomedical Prospect of IPMC (Ionic Polymer Metal Composite) Based Sensors

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Abstract

Bio-inspired devices are becoming increasingly important in face of the complexity of today's demanding applications. In this context studies exploring usability of Ionic-Polymer-Metal-Composites (IPMCs) in design and development of low-cost and easy-to-handle sensors is gaining momentum owing to flexible structure as well as bio-compatible attributes of IPMCs. The advancement of IPMC based devices is reviewed herein highlighting the author's own investigations.

Keywords: Ionic-Polymer-Metal-Composite; Actuation; Sensing; Biomedical Application

Introduction

The engineering importance of IPMCs (Ionic-Polymer Metal Composites), owing to their coupled actuation and sensing capabilities is well documented in the literature [1-5]. However, the most challenging domain of IPMCs based applications lay in the realization of its actuation [6-9] and especially sensing functionalities [10,11] relevant to post-silicon smart systems. For the past few years the author of this article has been engaged in studying the dual actuation-sensing capabilities of IPMCs exploring its bio-medical significance [12-16]. The discussion in this mini review will focus on the development of IPMC based sensors that are prospective in biomedical application highlighting the author's own work.

Background

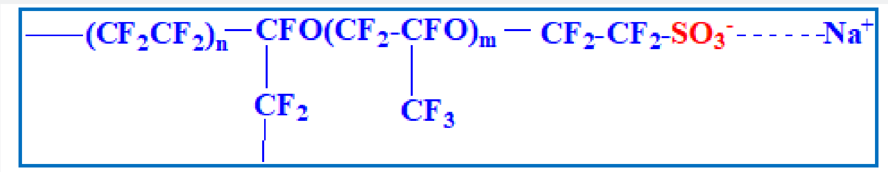
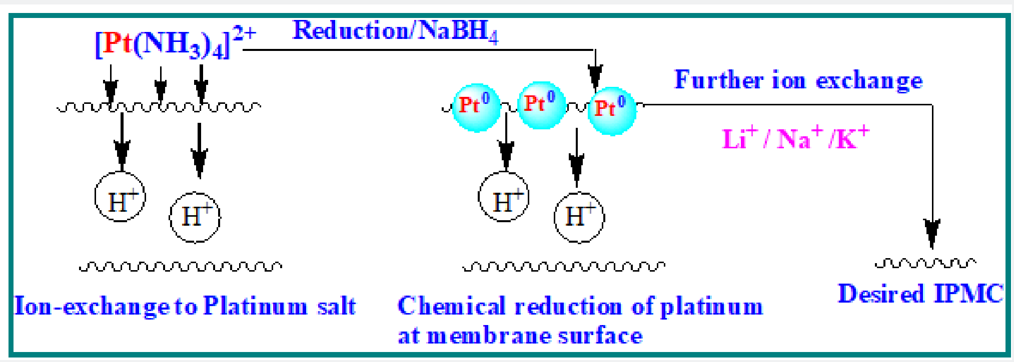


Figure 1: Pictorial representation of Nafion polymer.



Scheme 1: Schematic representation of IPMC preparation.

An IPMC (Ionic Polymer Metal Composites) strip is composed of a poly-electrolyte substrate primarily derived from Nafion or Flemion. Nafion, is an Ion-Exchange fluorocarbon polymer (Figure 1) with linear backbone with no cross linking, and attached with few fixed ionic groups, -SO_3- or –COO^- for cations, and -NH_4+ for anions. The preparation of IPMC requires surface electroding of the polymer. Method of deposition of noble metals on the surface of the polymer film (surface electroding) governs the efficiency of a particular application. The polymer backbone is usually soaked with depositions of a noble metal, M (where, M = Pt, Au and Ag) based by chemical reduction in which the ionic polymer is subjected to ion-exchange process with the cationic salt of a noble metal followed by the reduction of surface anchored metal ions by reducing agent like $NaBH_4$ (Scheme 1). For exchange of noble met al ions, $[Pt(NH_3)_4]Cl_2$ has generally been employed [1]. However, this $[Pt(NH_3)_4]Cl_2$ complex is very expensive. Furthermore, preparation of $[Pt(NH_3)_4]Cl_2$ form chloroplatinum salt involves number of steps, and time consuming. We have recently explored a novel method of surface electroding of Nafion film using $[Pt(H_2O)_4]^{2+}$ complex [12]. Preparation of $[Pt(H_2O)_4](ClO_4)_2$ is comparatively simpler which uses a relatively cheaper starting material K_2PtCl_4. AFM studies revealed the granular appearance of platinum metal onto the surface of the IPMC with a peak/valley depth of approximately 50 nm [12]. During the AFM study, it was also observed that platinum particles are dense and, somewhat, possess coagulated shapes [12]. The Nafion based polymer strip possesses as its ionic termination group at the side-branches of the polymeric backbone, thereby leaving only the cations and solvent molecules to traverse along the membrane while the anions remain fixed. The essential mechanism for both actuation and sensing abilities of IPMCs [16] is the migration of cations (Na^+, Li^+, K^+) inside the polymer matrices, towards the cathode electrode and away from the anode electrode due to either an imposed electric field (actuation) or an imposed deformation field (sensing). The actuation and sensing mechanisms in IPMC strip is typically demonstrated in (Figure 2).

$$J = -D[\nabla C + \frac{zF}{RmT} C.\nabla V] \quad (1)$$

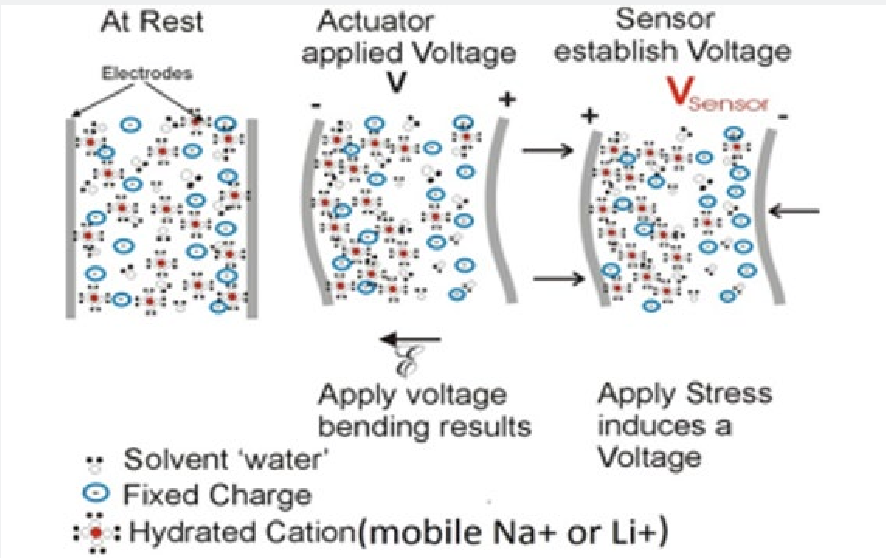


Figure 2: Mechanism of actuation and sensing in IPMCs.

During actuation the cations migrate towards the cathode when an electric field is applied across the IPMC strip and bending occurs towards the anode due to depletion of cations along with the strain at cathode side due to influx of cations. The ion movement phenomena under potential gradient could be mathematically represented by the following Nernst-Planck (NP) equations: Where, J = flux of ionic species, D = diffusion coefficient, C = concentration of ionic species, V = electric potential field, z = valence of ionic species, F = Faraday's constant, R = universal gas constant and T = temperature. The first term in the right-hand side of the Eq. 1 is the diffusion effect and the second term is the migration term due to electrophoresis potential. Using the Nernst-Planck equation the sensing and actuation mechanism can be described as follows;

Discussion

IPMC Actuators

When an external voltage is applied at both sides of the IPMC membrane strip, an electric field gradient across the strip is induced. In accordance to Eq 1, the second term on the right-hand side acts as an external force which prompts the movement of ions and thus causes the difference in ion concentration across the membrane. Difference in ion concentration results in expansion and contraction of polymer which consequently applies a mechanical pressure due to ion diffusion at two sides of membrane which results in the bending of membrane. Performance of an IPMC based actuator reportedly prepared by using of $[Pt(H_2O)_4](ClO_4)_2$ [12,13] is typically shown in (Figure 3). In (Figure 4), successively shown are the photographs of a five fingered IPMC

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micro-hand (5 mm length, 400 µm width at a pitch of 600 µm) displaying significant actuation at the applied voltage of 2.5V. The results of reported studies [13] necessarily suggests that the IPMC actuator prepared by using $[Pt(H_2O)_4]^{2+}$ exhibits very regular and quite comparable electrical, electrochemical, and actuation properties to that of reportedly exhibited by the IPMC actuator prepared by standard method using $[Pt(NH_3)_4]Cl_2$ [1] .

Figure 3: Successive photographs of IPMC strip actuating under application of voltage +2.5V to -2.5V.

Figure 4: Successive photographs of the five fingered IPMC mini hand showing high actuation under application of voltage +2.5V to -2.5V.

IPMC Sensors

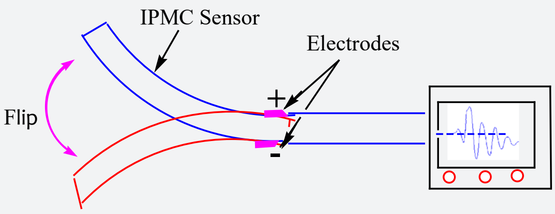

Figure 5: Sensing features of IPMC strip.

Ion diffusion in the IPMC membrane could also take place upon application of a mechanical pressure which results in an electric current for a fleeting period of time along with an electric potential at both sides electrodes of IPMC which persist for few seconds. The general scheme of cationic transfers is schematically depicted in (Figure 2) resulting in a measurable voltage yield. Movement of cations to one side of the membrane generates an electric signal vis-a-vis creates a difference in ion concentration which causes ion diffusion at the reverse side and ions tend to distribute evenly across the membrane to maintain a more stable condition. This causes the induced electric potential to disappear after a few seconds. Typical sensing signals obtained from IPMC strips are depicted in (Figures 4). In his pioneering work Sadeghipour developed a novel IPMC vibration sensor/damper [18]. Subsequently, the use of IPMC as cantilevered vibrating sensors [1], pressure transducer [19], velocity sensor [20] and tactile sensor [21] were developed. IPMCs can be used for both static and dynamic mechanical sensing. Such sensors reportedly demonstrated the potential in sensing curvature variation for engineering structures [22], fluidic flows [23], force [24] and even the inclination (angle change) of a body [25] (Figure 5).

IPMC Sensors in Biomedical Application

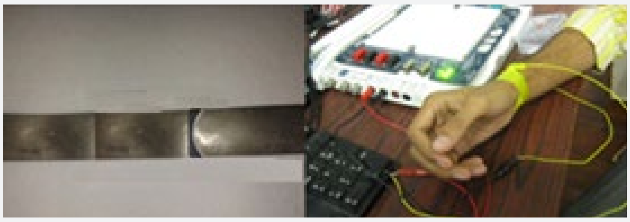

Figure 6: (a) IPMC sensor strip and (b) schematic representation of experimental set up.

IPMCs being soft and hydrophilic materials are also highly prospective for biomedical applications that include multifunctional tactile sensors [26], muscle movement detectors [10], pressure sensors in human spines [19] and hand prosthetic applications [27]. Most intriguing one is the sensing of 'pulse rhythms' by using IPMCs in [28]. Pulse rate is very important in health monitoring as well as diagnosis of many diseases. The methods used for pulse rate monitoring are mostly based on ECG (electrocardiography) [29] and PPG (photoplethysmography) [30]. However, these techniques are not suitable for routine use. Reports on the use of polymer based piezoelectric sensors in monitoring cardiac signals with a varied degree of success are available in the recent literature [31,32]. The possibility of using IPMC in measuring human pulse bit has been reported in recent past [14]. In the reported work [14] a wrist band (12.5 × 5 × 0.2 mm) made of Nafion based IPMC is developed (Figure 6a) for sensing the rhythm of human pulse bits, and the each pulse bit produces dynamic de-

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formation of IPMC band, and thus signals (voltage) generated due to endo-ionic mobility inside the IPMC strip wrapped around the wrist were acquired and processed with a PC based data acquisition program (Figure 6b). This work introduces the concept of a novel pulse bits rhythm sensing device. explores the domain of bio-potential sensing using electro-active polymer composites by placing them over a subject's wrist arteries. The sensor strip when fastened against the hand is poised to generate a potential difference across the metal-plate electrodes while being subjected to mechanical impact loading due to pulsating blood flow. module. In subsequent studies [16] possibility of using IPMCs as soft wearable sensors for monitoring human pulse rates was further confirmed. The sensor-strip has been placed over the wrist artery, and the electrical potential generated because of thrusted mechanical stimuli (due to pulsating blood flow) is passed through a pulse rate extraction scheme which yields the number of beats generated per minute. The configuration is validated on ten healthy individuals presiding in diverse physiological states. The polymer-sensor registers a steady recovery of the human pulse rates, while encountering error percentages of 4-15% when evaluated against standard plethysmographic measure.

Conclusion

In this mini review, following a brief introduction on IPMCs and background of IPMC fabrication, the prospective of IPMC as actuators and sensors is reviewed referencing the advancement of studies. The results of the studies with regard to the biomedical application of IPMC discussed herein may provide pointers for further advancement of the reported system leading to a mature technology.

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