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Fabrication and implementation of printed sensors for taste sensing applications

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ABSTRACT

This paper presents the design, fabrication, and implementation of low-cost taste sensors. A single-step procedure was performed using commercial polymer films to develop laser-induced graphene which was used as electrodes in sensor patches for taste sensing purposes. The cost of these sensor patches is less than two dollars based on the requirement for low-cost polymer films and Kapton tapes for developing the sensor patches. Five different chemicals corresponding to the five fundamental tastes of sour, sweet, salty, bitter and umami were tested with the developed sensors. The electrical parameters of the circuitry formed between the electrode-electrolyte interfaces during the experimental procedure were obtained by using the complex non-linear least square curve fitting technique by fitting a simulation curve to the Cole–Cole curve obtained from the experimental results. The sensor patches operating on a capacitive principle, exhibited significant differences in terms of their impedimetric responses for the kinetic processes taking place during the experiments, with different concentrations for each chemical. Four different concentrations were tested for each chemical to analyze the performance of the sensor for that particular chemical. A comparison between the responses of the five chemicals for each concentration was done to inspect the differences between their responses. An analysis of the differences in the conductivity response by the sensor patch for the five chemicals at a specific concentration was also done. The sensor patches did not show any hysteresis in their output responses, while obtaining significant repeatability when testing the chemicals with them. The response time of the sensor patches was around two seconds with the recovery time is 10 min for the sensor being thoroughly washed and dried in between experiments The obtained experimental results from these sensor patches and their low cost, and easy fabrication process make them promising for their utilization in taste sensing purposes.

1. Introduction

Among the five different senses of sight, touch, smell, hearing, and taste, the work done on the taste sense is the least. Taste sensing does impart very significant information about the condition of a person. A human tongue has thousands of taste buds, each of which consists of hundreds of taste cells [1]. People having taste disorders [2] is one of the most significant problems happening in recent years. Each year, more than 200,000 people suffer from taste disorders, with one out of every ten children affected [3] in Australia. This is very alarming effect on taste disorder can lead to other disorders like obesity and high blood pressure. Even though a normal person starts losing his taste buds after the age of 50, there are other causes like respiratory infections, radiation therapy and surgeries near the head or neck region, which leads to the loss of taste buds. Even though otolaryngologists have been a common choice of medical assistance for the people suffering from taste disorders, researchers have been working to comprehend it scientifically [4,5].

An electronic tongue (e-tongue) has been the popular innovation for taste sensing during the last decade [6,7], where a complex system had been developing which replicates the functions of a human tongue. Even though the e-tongue does offer significant functioning as a regular tongue, there are certain disadvantages which are compelling researchers to five alternative options. Starting from the high-cost to develop the structure [8], the overall structure is complex [9] causing it to be difficult to afford for financially constrained patients [10]. Another major disadvantage related to the e-tongue is the dependence of its functionality on temperature and humidity [11]. Also, the adsorption of the analyte on the selective sensing surface limits the re-usability of the sensor [12]. Thus, it is desirable to develop alternative options that could

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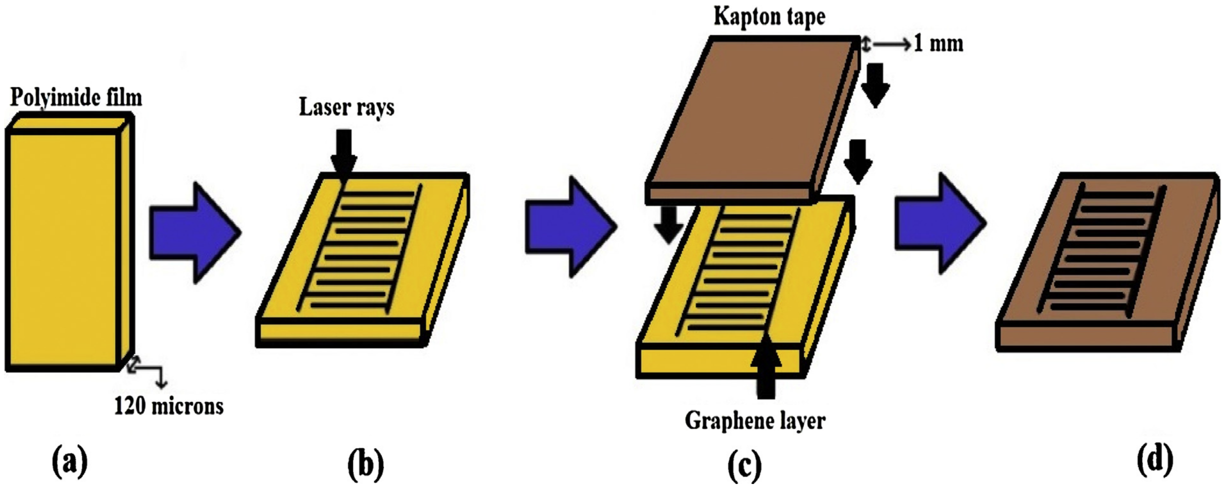

Fig. 1. Schematic diagram of the fabrication of graphene sensors. After the PI films of 120 microns were taken as the raw material (a), laser writing was done on the film (b) to generate (c) and transfer graphene (d) to the Kapton tapes.

be used as taste sensors. Even though some research groups have developed systems for taste assessment [13], there are certain limitations associated with their work. The systems were solely based on the identification of one [14] or two [15] taste types. The idea behind our work is to have a sensor which can clearly classify the five fundamental taste types. This could help us to develop a system that can be used to identify and monitor the concentration of a particular type of taste in a food material.

Flexible sensors, due to their advantages of low cost and high mechanical flexibility, have been a favorite choice for some time for a lot of health-related applications like physiological parameter monitoring [16], tactile sensing [17] and monitoring of the other four external senses [18]. Different kinds of materials like carbon [19], silver [20], copper [21], etc. have been used to develop the electrodes of the flexible sensor. Among the polymers, polydimethylsiloxane (PDMS) [22], polyethylene terephthalate (PET) [23], and polyimide (PI) [24] have been common choices to build the substrate of the sensors. The choice of the material depends mainly on the application of the sensor. Similarly, different techniques [25–27] have been employed to develop the flexible sensors. The use of a particular technique for fabrication depends on the resolution of the sensor prototypes. In our work, a laser cutting technique [28,29] was used to develop the laser-induced graphene (LIG) sensors. Less sample preparation time, low-cost and smooth cuts are some of the advantages of using a laser cutting technology to develop the flexible systems [30]. The detailed fabrication procedure for our LIG sensors has been reported in our previous paper [31]. This paper reports a brief description of the fabrication with the main focus on the implementation of these sensors as taste sensors.

The taste buds of a normal human being can be divided into five categories: sour, salty, bitter, sweet, and umami. Even though there are millions of food materials that can be categorized in one of these sectors, researchers have established [32] the following chemicals for experimental purposes that can be exactly replicated to these fives tastes:

- Sour: Citric acid
- Salty: Sodium chloride
- Bitter: L-tryptophan
- Sweet: Sucrose
- Umami: Guanosine monophosphate (GMP)

After the sensor was fabricated, the above-mentioned chemicals were tested at four fixed concentrations. The concentrations were based on the minimum amount [14,33] of that chemical present in the food. Then a comparison was done on each of the four concentrations of the five taste types to verify the differences in their outputs.

The paper is split into five sections. After the introduction given in Section one, the fabrication process of the sensor patches and their operating principle are described in Sections two and three respectively. Experimental set-up results along with a discussion are shown in the fourth and fifth Sections of the paper respectively. The conclusions of the paper are given in the final section of the paper.

2. Fabrication of graphene sensors

Low-cost commercial PI films (Zibo Zhongnan Plastics Co., Ltd.) were taken for laser-writing purposes. Low-cost, high flexibility and high resistance to wear and tear are some of the reasons for choosing PI as the raw material. Fig. 1 shows a schematic diagram of the overall fabrication process followed to generate the graphene sensors. The PI films, of around 120 μm of thickness, were used for the laser writing process. After the laser-induced graphene was formed, Kapton tapes, of around 1 mm of thickness, were used transfer the graphene use it as a sensor patch. Even though the tapes used as the substrate for the final sensor patch were of the same material as the raw material, it was not suitable to be directly used as the raw material for two reasons. Firstly, since the thickness of the Kapton tapes were much higher than that of the PI films, a photo-thermal induction process would not have been possible with such a high thickness of the raw material. Secondly, the stickiness of the Kapton tapes would have damaged the specified design of the electrodes during the laser induction process.

Initially, the polymer film was attached to the glass substrate by biocompatible tapes (3 M 810D Ruban Magique^{MC}) before taking it to the laser platform. The reason for choosing glass as the template was because of its non-reactive nature towards the laser cutting process. The laser writing process caused photo-thermal induction of graphene, where the sp^3 hybridized carbon atoms of the polymer were converted to sp^2 hybridized carbon atoms of graphene. The induced graphene was then transferred to commercial Kapton tapes by carefully placing the tapes over the generated graphene and applying manual pressure over it. This transfer was done to use the generated graphene as electrodes in a sensor patch. The