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Fabrication and electrical and humidity-sensing properties of a flexible and stretchable textile humidity sensor

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ABSTRACT

A novel flexible and stretchable textile impedance-type humidity sensor was fabricated by weaving white cotton fabric to form a substrate with a pair of parallel electrodes that were made of conductive yarns, and then spray-coating the as-woven textile substrate with a copolymer of methyl methacrylate (MMA) and [3-(methacrylamino)propyl] trimethyl ammonium chloride (MAPTAC) (poly-MMA/MAPTAC) to form a humidity-sensing film. The effects of the concentration of poly-MMA-MAPTAC on the sensitivity, flexibility and stretchability of the textile impedance-type humidity sensor were studied. The 10 vol.% poly-MMA/MAPTAC-coated textile impedance-type humidity sensor had very high stretchability, high flexibility, wide working range, high sensitivity, acceptable linearity, low hysteresis, fast response/recovery time and long-term stability over a relative humidity (RH) range of 20–90% RH. The humidity-sensing mechanism of the textile impedance-type humidity sensor was explained using complex impedance spectra. The fast Fourier transform (FFT) was used to discriminate between a textile impedance-type humidity sensor under bending and human breath monitoring.

1. Introduction

Electronic textiles are currently attracting interest because they can be integrated into smart clothing and wearing Internet of Things (IoT) applications to improve quality of life. An electronic textile system comprises flexible sensors that are embedded into textile yarns and can sense valuable information about the wearer [1,2]. Most currently available commercial electronic textile systems are hybrids, meaning that classical rigid electronic sensors such as silicon chips are embedded into textile structures [3]. A challenge that arises from the use of these electronic textile systems is the integration of classical rigid sensors into the textile yarns mainly because bending and stretching the textile yarns produces strain. This strain can cause sensors failure especially in breakable inorganic sensing materials. Therefore, the directly weaving of flexible and stretchable sensors into textiles remains an important challenge associated with wearable electronics applications [4–6].

Humidity sensors have become increasingly important and are widely used to improve quality of life and industrial processes. Many materials have been coated on rigid substrates to form classical humidity sensors; these materials include polymers [7–9], ceramics [10,11], graphene oxide-based [12,13] and composites [14–16]. Polymer-based sensing materials have been regarded as promising for fabricating textile humidity sensors because they are light-weight, flexible, low cost and simply fabricated [17,18]. Various materials and methods have been used to fabricate textile humidity sensors [19–23]. Tröster et al. [19] fabricated a flexible humidity sensor that was based on poly(3,4-ethylenedioxythiophene)–poly(styrene sulfonate) (PEDOT–PSS) on a polyimide (PI) substrate, and this as-prepared flexible humidity sensor was woven into a textile using a commercial band weaving machine. Jang and Han [20] fabricated a wearable resistive-type humidity sensor that was based on a polyvinyl alcohol (PVA) on polyethylene terephthalate (PET) substrate using the dip-coating method. The electrodes of the humidity sensor were formed from a thin copper film by RF magnetron sputtering. Rosace et al. [21] fabricated a wearable resistive-type humidity sensor that was based on multi-walled carbon nanotubes (MWCNTs) coated on conducting cotton fabric. Recently, Weremeczuk et al. [22] and Kindeldei et al. [23] fabricated humidity sensors that were directly printed electrodes and sensing-materials on textile using the ink-jet printing technique. However, these textile humidity sensors required either complex fabrication processes or they were not very sensitive. Therefore, the need remains to develop a complete textile humidity sensing system with high reliability, high sensitivity, low cost and simple fabrication.

The process that is described herein for fabricating textile impedance-type humidity sensors sensor is somewhat

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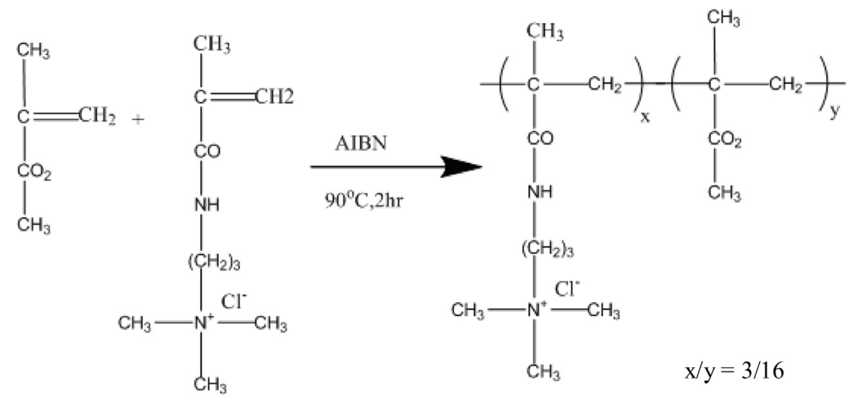

Fig. 1. Chemical reaction and chemical structure of poly-MMA/MAPTAC.

novel: a copolymer of methyl methacrylate (MMA) and [3-(methacrylamino)propyl] trimethyl ammonium chloride (MAPTAC) (poly-MMA/MAPTAC) was synthesized and was directly coated using spray-coating on a handmade woven textile substrate to form a sensing film; this method reduces the cost of labor. The as-prepared poly-MMA/MAPTAC films were characterized by scanning electron microscopy (SEM) and infrared spectrometry. The effects of the concentration of the poly-MMA/MAPTAC on the sensitivity, flexibility and stretchability of the textile impedance-type humidity sensor were investigated. The humidity sensing characteristics were subsequently studied. The textile impedance-type humidity sensor was used for human breath monitoring application. The time-impedance spectra of the textile impedance-type humidity sensor upon bending and human breath monitoring were computed by fast Fourier transform (FFT) for differentiating whether this textile humidity sensor is under bending or human breath monitoring. The humidity-sensing mechanism of the textile impedance-type humidity sensor that was made of poly-MMA/MAPTAC was studied by complex impedance spectra obtained under varying RH.

2. Experimental

2.1. Fabrication of textile impedance-type humidity sensor

The copolymer poly-MMA/MAPTAC was prepared using a method similar to that in our previous investigation [24]. The copolymer poly-MMA/MAPTAC was prepared as follows. MMA (2 ml, 99%, Merck), MAPTAC (0.3 ml, 50% solution, Aldrich), 1.2 ml ethanol and azobisisobutyronitrile (AIBN, 0.01 g) were homogeneously mixed with vigorous stirring; the mixture was placed in an oven at 90 °C for 2.5 h to yield the copolymer poly-MMA/MAPTAC. Fig. 1 shows the reaction and the chemical structure of poly-MMA/MAPTAC. The as-prepared poly-MMA/MAPTAC was dissolved in methanol to yield 5, 10 and 20 vol.% poly-MMA/MAPTAC solutions.

Fig. 2(a) presents the manufacturing process of the textile impedance-type humidity sensor. Firstly, a 1 cm-wide and 1 cm-long piece of woven textile substrate that was made of white cotton and a pair of parallel electrodes that was made of conducting yarns (hybrid of stainless steel wire/cotton) were handwoven (steps 1 and 2). Then, the as-prepared copolymer poly-MMA/MAPTAC solution was directly spray-coated (step 3) on the woven textile substrate to form a sensing film. Finally, a semipermeable nonwoven fabric was attached to the surface of the sensor (step 4) to improve its washability, yielding a textile impedance-type humidity sensor. Fig. 2(b) schematically depicts the pattern of a woven textile-type humidity sensor. The thickness of the sensing film was 216 nm. The diameter of the electrode and white cotton were 350 and 200 nm, respectively. The gap between electrode and cotton was 700 nm.

2.2. Instruments and analysis

The surface microstructure of the copolymer poly-MMA/MAPTAC that was directly coated on the woven textile substrate was observed using a scanning electron microscope (SEM). An infrared spectrometry (Nicolet 380) was used to obtain the IR spectra of the copolymer poly-MMA/MAPTAC. Fig. 3 presents the humidity-sensing measurement system. A divided flow humidity generator was used as the principal means of for generating the humidity in the test. The complex impedance of the textile humidity sensors was measured as a function of relative humidity (RH) using an LCR meter (Philips PM6304) in a temperature-controlled chamber, in which the testing humidity (RH values) was controlled by mixing dry and wet air using mass flow controllers (Hastings). The required testing humidity (RH values) was adjusted by reading a standard humidity hygrometer (accuracy of ±0.1% RH, Rotronic). Flexibility and stretchability experiments were conducted in which the sensors were bent through various angles and stretched to various displacements, respectively, and their impedance deviations were monitored as functions of the period of exposure to humidity. The bending angle was measured using a goniometer. The sensor was first fixed in the flat state and then gradually changed the required bending degree of the sensor.

2.3. Statistical analysis

FFT is a well feature extraction method to extract information in time domain at different frequency bands into the frequency domain. The measured signal features in the frequency domain generally showed as the signal energy and the amplitude of the dominant spectral peaks in specific frequency ranges. Thus, FFT analyses were then computed on time–impedance signals of the textile impedance-type humidity sensor upon bending and human breath monitoring to determine the frequency spectra.

3. Results and discussion

3.1. IR spectra

Fig. 4 presents the FT-IR results of the poly-MMA, poly-MAPATC and as-prepared copolymer poly-MMA/MAPTAC. The characteristic vibrations of poly-MMA (Fig. 4(a)) appear at 1740 and 1140 cm^{-1} for C = O stretching band and C–O stretching band, respectively. The characteristic vibrations of poly-MAPTAC (Fig. 4(b)) appear at 1670 and 1540 cm^{-1} for C=O stretching band and N–H bending