Sensors and Actuators A 184 (2012) 57–63

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Fabric pressure sensor array fabricated with die-coating and weaving techniques

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ARTICLE INFO

Article history:
Received 27 December 2010
Received in revised form 20 April 2012
Accepted 28 June 2012
Available online 6 July 2012

Keywords:
Pressure sensor
Electronic textile
PEDOT:PSS
Cytop
Die-coating

ABSTRACT

We report on the fabrication and characterization of a large area (handkerchief-size, i.e., >16 cm × 16 cm) of pressure sensor fabric. The sensor is constructed by weaving the fibers, which are coated with the organic conductive polymer poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) and a dielectric film of perfluoropolymer (Cytop), and the capacitances at the points of the crossed fibers vary with the applied force. The functional films are continuously coated with die-coating system with the thickness ranging from hundreds nm to several μm. The resultant fibers are loomed, forming the sensor fabric with an area of 16 cm × 16 cm. Its sensitivity ranged from 0.98 to 9.8 N/cm^2, which is within the range of human touch. Therefore, our fabric touch sensors could lead to applications from wearable keyboards to sensors embedded in beds for health care purposes.

1. Introduction

Recently, electronic textiles (e-textiles) [1–3] that integrate sensors, actuators and computers into fabrics have gained considerable attention [4–7]. Several types of fiber devices have been studied. For example, conductive polymer coated fibers and electrolyte form electrochemical transistors on silk fibers [8]. Highly soft capacitors in which dielectric films are sandwiched between conductive films have also been developed [9]. On the other hand, textile-based electrodes have been utilized for electrocardiogram in home healthcare because of their flexibility and conformability to human [10,11,4]. Micro-devices on plastic films that were fabricated through conventional microfabrication process were cut into ribbons and woven into fabrics. In this method, temperature sensors and LED display devices [12] were integrated into fabric while strain sensors [13] were also done. Electronic textile devices provide information to people easily because they can be worn or embedded in beds or floors to monitor the elderly and patients [1–3]. In these applications, touch sensors [7,14–17] have played a key role because they can detect a person's input, location and other information. In previous studies [1–3], many touch sensors have been developed by weaving copper wires as wefts and warps because of their simple structure and fabrication process. However, these touch sensors can detect only on–off states, not pressure, because these sensors monitor the electric connection between copper wefts and warps at the crossed points. To achieve more sophisticated interface devices, such as a wearable key board, or a joystick and large area-sensors to monitor human motion on beds or floors, pressure needs to be measured [4–7,14–17].

To construct pressure sensors with fabric, not simple copper wires but functional electronic films-coated fibers are required [17]. One of the pressure sensing methods with fabric is evaluating the capacitance between fibers, and the required structure consists of woven functional fibers with a coating of conductive film to create an electrode and dielectric film for insulation. However, in existing technologies for deposition, such as sputter and thermal evaporators, the length of fiber that can be processed is limited by the vacuum chamber size (several tens of centimeters), although tens of meters of fibers are required for weaving fabric [18]. In previous studies [12,17] with vacuum chamber-based coatings, only a small quantity of fabric (2 cm × 3 cm) could be woven from the fiber. Thus, a technology that can continuously coat electric functional films on meter-scale fibers is required. Moreover, because existing vacuum chamber-based machines can only coat films on flat surfaces, a mechanism for rotating fibers is also required [17]. Thus, meter-scale fibers are difficult to coat with functional films with existing technology.

To realize large-area fabric pressure sensors, we developed a technique to die-coat conductive and dielectric films continuously on meter-scale fibers and weave the resultant fibers. First, the textile construction of fabric pressure sensors with the size of a handkerchief (16 cm × 16 cm), which is the smallest area of wearable fabric, was designed, and the required fiber length was confirmed to be tens of meters. To fabricate tens-of-meter fibers with electrodes and dielectric film, we propose die-coating with a conductive polymer, poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate)

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0924-4247/$ – see front matter
http://dx.doi.org/10.1016/j.sna.2012.06.031

(PEDOT:PSS), and a dielectric polymer, perfluoropolymer (Cytop). In the system, polymers that can be processed in a solution of PEDOT:PSS and Cytop are continuously coated on long fibers with a nozzle of dies. Then, the wet films are dried with a heater. PEDOT:PSS is the most conductive polymer, and it can be used to coat a fiber using water dispersion and then drying the solvent of water [19–22]. Cytop can be used to coat fibers using organic solvent dispersion and then drying the solvent [22]. The thickness and traveling speed of die-coating of both polymers were evaluated. Then, tens-of-meter fibers were constructed, and sensor fabric was woven. The pressure sensitivity of the fabric was characterized. Finally the ability to sense touch input with woven pressure sensor fabric was demonstrated.

2. Design of textile system and required fiber length

A textile system to generate fabric with touch sensors was designed to produce 16 cm × 16 cm sensors. In the sensor structure, the fibers with PEDOT:PSS and Cytop were woven as wefts and warps, and the rest was filled with pristine nylon fibers (Fig. 1(a)). Capacitors formed at the points where fibers cross. Applied force at a cross point changes the capacitance by enlarging the area of contact with the fibers (Fig. 1(b)). The sensors at the fiber crossings are placed with a pitch of 2 cm, which is the same size as human fingers [23,24]. The diameter of the functional film-coated fibers is 485 μm, and that of the pristine nylon fiber is 250 μm. In this study, the sensors are fabricated in the pitch of finger [23,24], but smaller pitch fabric can be woven down to the fiber diameter (i.e., 485 μm) for achieving higher area density of the sensor.

In the design of the textile system, both warps and wefts of PEDOT:PSS and Cytop-coated fibers are required. For the warp, the long fabric length and additional warping length are required because warps are tied to parts of the looming machines. The additional warping length ($L_{machine}$) is at least 1 m for small looming machines and at least 20 m for conventional automatic machines. In this study, small hand looming machines were used with an additional warping length of 1 m. The width of the fabric (W_{warp}) and its height (W_{weft}) are 16 cm and 16 cm, respectively. The warp yarn density of the fabric (C_{warp}) is 0.5 yarns/cm because the functional film-coated fibers are placed with a pitch of 2 cm. Thus, the required warp length (L_{warp}) is expressed as follows.

$$L_{warp} = C_{warp} \times W_{warp} \times (L_{machine} + W_{weft})$$
$$= 0.5 \times 16 \times (100 + 16) = 928\,\text{cm}$$

For the weft, the width of the fabric plus an additional 0.5% is required. The width of the fabric (W_{warp}) was 16 cm, and the weft

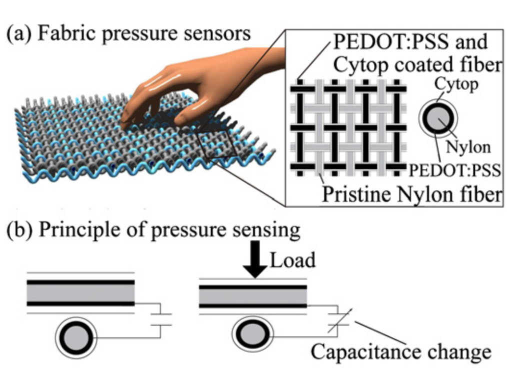

Fig. 1. Concept of fabric pressure sensor array. (a) In the structure of the sensor, conductive polymer and dielectric film-coated fibers are woven as wefts and warps, forming capacitive type of pressure sensors. (b) In the sensing mechanism, applied pressure induces capacitance change.

yarn density of the fabric (C_{weft}) was 0.5 yarns/cm. Thus, the weft length (L_{weft}) is expressed as follows.

$$L_{weft} = C_{weft} \times W_{weft} \times W_{warp} \times 1.05$$
$$= 0.5 \times 16 \times 16 \times 1.05 = 504\,\text{cm}$$

Therefore, the required fiber length (L) is

$$L = L_{warp} + L_{weft} = 1432\,\text{cm} = 14.32\,\text{m}$$

As a result, existing sputters or other thin film deposition system cannot form functional films on a fiber that is 14.32 m long. In other words, it is confirmed that a continuous thin film coating technique for tens-of-meter fibers is indispensable.

3. Die-coating of PEDOT:PSS and Cytop

3.1. *Configuration of die-coating*

Tens-of-meter fibers are processed with a die-coating technique. The system that we developed consists of a winding machine to continuously transfer fibers, a dies to coat PEDOT:PSS and Cytop, and a heater to dry the solvent, and is shown in Fig. 2(a). The machine on both sides is a winding machine (Factory-Automation Electronics Inc.) that moves fibers from left to right. To prevent the fibers from hanging loosely, they were transferred under a certain amount of tension using bobbins with pressure sensors. The machine was operational up to 50 m/min. The machine in the middle of the photograph contained a dies and a heater. As shown in Fig. 2(b), the dies consisted of reservoirs of PEDOT:PSS and Cytop and a nozzle for coating PEDOT:PSS onto the fibers. Because the dies surrounded the fibers with a gap, the wet film coated all surfaces of the fiber. A heater evaporated the solvent to dry the film.

The thickness of the PEDOT:PSS and Cytop in die-coating was defined by the gap between the diameter of fiber and that of

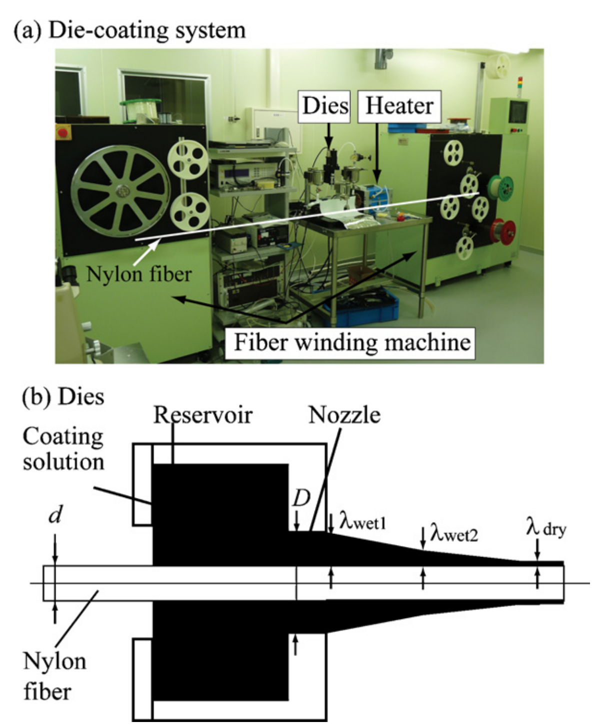

Fig. 2. Die-coating system for forming PEDOT:PSS and Cytop film on fibers. (a) A developed die-coating system consists of winding machines, a dies and a heater. (b) The dies is composed of a reservoir of solution and a coating nozzle. The coating parameters consist of gap between the fiber and dies and wet thickness and dry thickness of PEDOT:PSS and Cytop films.