SILVER NANOWIRE COATED POPLAR-PET CONDUCTIVE NONWOVEN FABRICS FOR PRESSURE SENSING APPLICATIONS

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Abstract

This study demonstrates the use of needle-punched nonwoven fabrics of poplar seed fiber and polyester fiber blends in sensor applications. For this purpose, the surfaces of the produced fabrics were functionalized by coating them with silver nanowires (AgNWs). AgNWs were synthesized according to the polyol method and then coated onto the nonwoven fabrics through dip coating process. Surface morphology is characterized by scanning electron microscopy (SEM), and the analysis revealed a uniform coating on the fabric surface. Measurement of electrical surface resistance of treated fabrics confirmed that the presence of silver nanowires significantly improved the electrical conductivity. The capacitor structure was fabricated as a sandwich via placing a stretchable sealing film (Parafilm®) between two conductive nonwoven samples. Variation in the relative capacitance as a result of loading and unloading was observed. Poplar blended nonwoven fabrics exhibited great potential to be used as capacitive sensors to measure variable weight pressures. By virtue of its biodegradability, availability and light-weight solution, bio-waste poplar fibers offer a novel application for developing wearable and flexible tactile sensors.

Keywords: Poplar, pressure sensing, conductive, silver nanowire, coating, wearable sensors

1. INTRODUCTION

The development of wearable pressure sensors utilising eco-friendly materials is of great interest in the application of flexible and stretchable physical sensing devices. These devices facilitate a wide range of applications, including electronic skin (e-skin), health monitoring, medical diagnostics, activity tracking, environmental monitoring, and more [1]. To date, four primary types of sensory models including capacitive, piezo-resistive, piezoelectric and optical type have been successfully developed for the production of flexible pressure sensors [2]. Among these, capacitive sensors are preferred due to their high sensitivity, low power consumption and simple fabrication process [3].

In general, a capacitive sensor has a sandwich structure in which an elastic dielectric layer is placed between two parallel plate electrodes. When external pressure is applied onto a sensor, it can deform the flexible electrodes and the elastomeric dielectric layer, altering the effective electrode area, thickness and permittivity of the dielectric layer. These changes result in variations in measured capacitance value, which can be monitored in real-time to record the applied pressure accurately. Typically, two flexible conductive fabrics serve as the electrode plates, separated by dielectric materials such as foams or soft polymers [1]. Various materials, including conductive polymers, carbon-based substances and metallic materials have been widely investigated in the literature for the fabrication of conductive textiles [4]. In recent years, silver nanowires (AgNWs) have gained significant attention for creating conductive networks in flexible capacitive materials due to their high electrical conductivity, ease of synthesis, antimicrobial activity and excellent stability against oxidation [5-7].

In the development of flexible electronics, the type of substrate, as well as conductive materials and fabrication approaches used in the design of flexible electronics, also has a significant impact. Hence, bio-based resources have gained considerable attention in recent years. As opposed to using non-biodegradable and non-renewable materials, many natural fibers offer promising potential to meet the demands of current consumer electronics, such as wool [6], cotton [2], kapok [8], cattail [9], poplar fibers [10]. Among them, poplar fiber, which is the seed hair of the populus genus of trees in the willow family (Salicaceae), is generally treated as waste material. Poplar fiber, a typical cellulose fiber, has a large hollow lumen and a very thin cell wall (average thickness of 1.2 μm) [11]. These air-filled lumens provide poplar fiber a fluffy texture, softness, extreme lightness and excellent thermal and sound insulation. Poplar, a renewable plant fiber, is abundant, biodegradable and has attracted growing attention by researchers [10]. Traditionally, poplar has been used as thermal and acoustic insulator due to its intrinsic hollow structure [12-13]. Furthermore, poplar fibers have been studied as oil sorbents for oily water cleanup [13-15] and to prepare aerogel materials [16]. Additionally, studies have explored poplar fiber as natural supports for wearable electronic applications [10].

In this study, pressure sensing was performed based on conductive and superhydrophobic pristine PET and poplar/ PET blend nonwoven fabrics. Three different sustainable nonwoven fabrics were produced by needle punching technique using biodegradable poplar fibers and hollow PET fibers at different mass ratios (0:100, 30:100, 60:100, w/w for poplar and PET fiber) and then coated with silver nanowires (AgNWs). The sensor exhibits notable attributes such as high sensitivity and rapid response time. These qualities enable thenonwoven fabric samples to effectively detect varying pressures from standard weights, making them highly suitable for applications in wearable devices such as flexible pressure-sensitive sensors. Furthermore, the use of eco-friendly materials in the production of sensors coincides with the increasing demand for sustainable and environmentally friendly technologies. Poplar fiber-based nonwovens have the potential to be an innovative product in the field of wearable electronics.

2. EXPERIMENTAL

2.1 Materials

Poplar fibers were harvested during the blooming period in mid-May in Türkiye. Hollow polyethylene terephthalate fiber (PET, length: ~64 mm) was kindly supported by SASA Polyester Sanayi A.Ş., Türkiye. Silver nitrate ($AgNO_3$, ≥99.8%, Sigma-Aldrich), polyvinylpyrrolidone (PVP40, average mol. wt. 40.000) (Sigma-Aldrich), ethylene glycol (EG) (Merck), ethanol (Merck), acetone (99.5% pur.) (TEKKİM) were procured from Labor-Teknik Laboratuvar Malzemeleri Sanayi Ve Ticaret A.Ş., Türkiye. All chemical reagents were used as received.

2.2 Methods

Mechanical cleaning of poplar fibers was carried out with steel tweezers to remove contamination such as dust, seeds, leaves etc. on the surface. Subsequently, the cleaned poplar fibers were blended with PET fibers in three different ratios (0:100, 30:100 and 60:100, w/w) without the need for chemical pre-treatment processes. The produced nonwoven fabrics were labeled as PET, P-Po30 and P-Po60 with blend ratios of 0/100, 30/100 and 60/100 (w/w) for the amount of poplar and PET fibers, respectively (as shown in **Table 1**).

In this study, nonwoven fabrics were produced in two stages, the first is carding, where webs were formed by blending fibers in the specified ratios, and the other is needle-punching, where the carded webs were bonded to produce nonwoven fabrics. The thickness and density of nonwoven fabrics were given in **Table 1**.

Table 1 Properties of produced nonwovens

Sample	Blend Ratios (Poplar/PET) (in g mass, w/w)	Thickness (mm)	Mass per Unit Area (g/m^2)
PET	0/100	2.9 ± 0.008	243 ± 2.59
P-Po30	30/100	3.0 ± 0.010	263 ± 2.95
P-Po60	60/100	3.1 ± 0.011	279 ± 3.01

Preparation of Silver Nanowire (AgNW) Solution

Initially, a silver nitrate solution was prepared by dissolving silver nitrate in ethylene glycol in a glass flask for 45 minutes. Simultaneously, a PVP solution was prepared by dissolving PVP40 in ethylene glycol in a three-necked glass flask, placed in an oil bath, and stirred on a hot plate at 180°C for 45 minutes. Following this, a 1 M NaCl- EG solution was added to the PVP solution, and the mixture was allowed to react for an additional 10 minutes. The silver nitrate solution was gradually introduced into the PVP solution at a rate of 1 mL/min using a syringe pump. The combined solution was stirred at 180℃ for another 20 minutes before being cooled to room temperature. Once cooled, acetone was added to dilute the mixture, and the silver nanowires (AgNWs) were precipitated via centrifugation. Finally, the precipitated AgNWs were diluted in ethanol (EtOH) at a concentration ratio of 1 g/ 20 ml for application onto the nonwoven fabric.

Fabrication of nonwoven fabrics coated with AgNWs

The nonwoven fabrics were submerged in 15 mL of AgNW suspension for 10 s as a cycle of dip-coating (**Figure 1**). After drying at 60℃ for 30 minutes, silver nanowire-functionalized nonwoven fabrics were obtained. The number of dip-coating cycles was increased by 5 to decrease the electrical resistance of the fabrics to about 15 Ohm.

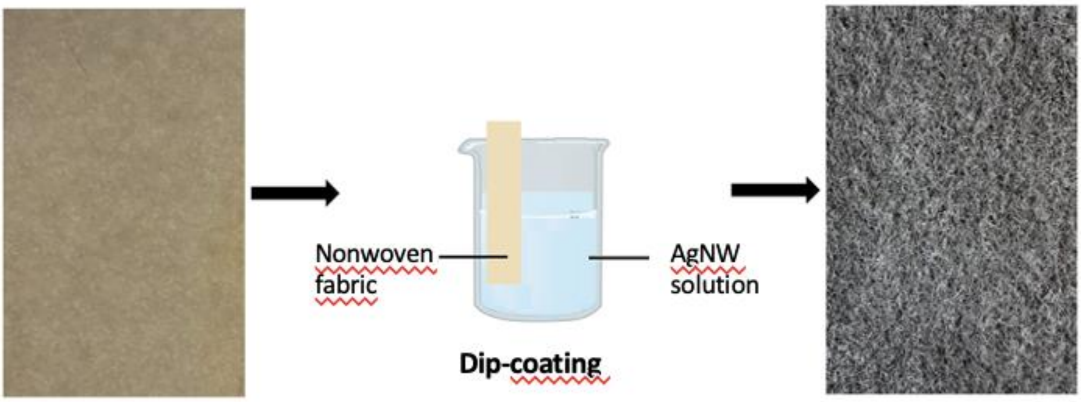

Figure 1 The preparation process of AgNW-coated nonwoven fabric

Fabrication of capacitance using the conductive nonwoven fabrics

A capacitive type fiber-based pressure sensor was constructed by placing a 0.01-mm thick Parafilm® between two AgNW coated same nonwoven fabrics. **Figure 1** illustrates the resulting sandwich structure. All three fabrications were performed on conductive nonwoven fabrics consisting of pure PET and poplar/PET blend fibers under the same environment. This capacitance is used as a pressure sensor. The relationship between capacitance, material properties, and dimensions can be expressed as capacitance (C) being directly proportional to the product of emissivity (ε) and surface area (A), and inversely proportional to the material thickness (d).

Characterization and measurements

The surface morphology of the conductive nonwovens were examined using scanning electron microscopy (SEM, TESCAN VEGA3). The surface electrical resistance of the conductive nonwovens was measured using a Digital Multimeter (FLUKE 17B+) which has ± 0.5% accuracy with wide measurement range. Besides, measurements to detect the capacitance change have been performed using the same multimeter. Pressure is generated by placing standard weights (10- 20- 50- 100- 200-500 g) on the fabric-based capacitor and the response of the sensor to loadings at different weights was recorded.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology of PET and Poplar/PET Blend Nonwovens Decorated with AgNWs

In this work, a simple method to fabricate highly flexible, sensitive and environmentally friendly textile-based pressure sensor was presented. Pristine PET and poplar/PET blend nonwoven fabrics, P-Po30 and P-Po60, were utilized as substrates, while AgNW conductive networks -synthesized using the polyol method- were deposited onto the fabric surfaces via a dip-coating process. This scalable dip-coating technique facilitates practical applications for flexible pressure sensors [2]. Upon complete impregnation of the nonwoven fabrics with an ethanol suspension of AgNWs, the color of the fabrics changed from the original white (for pristine PET fabric) and yellowish (for poplar blends) to grey, indicating successful AgNW coating, as shown in **Figure 1**.

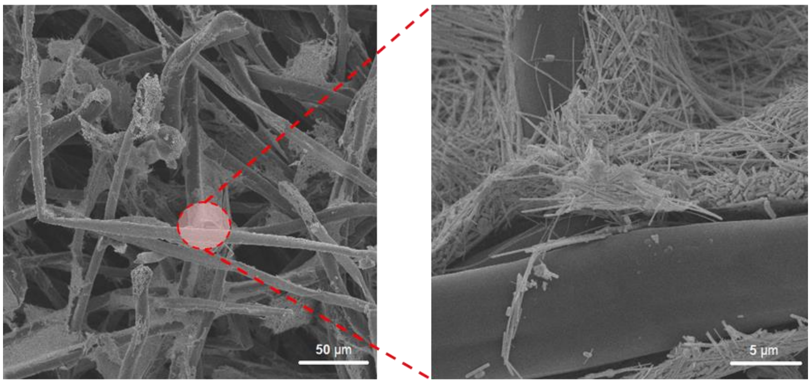

Figure 2 SEM image of the surface morphology of blend nonwoven after AgNW coating. AgNWs formed on the fiber surface ensure an effective interconnection that facilitates electrical conductivity. The inset provides a magnified view of the coating, highlighting AgNW clusters.

The SEM images of the nonwovens clearly illustrate that the surface was completely covered by AgNW conductive networks after 5 dip-coating cycles (**Figure 2**).

3.2 Electrical Resistance

Most textiles are inherently non-conductive, serving as an insulator with high electrical resistance. To utilize textiles in wearable e-textile components, it is essential to convert the substrate into a conductive platform for specific functional processes. In this study, AgNW coating effectively reduced the surface electrical resistance of non-conductive PET, P-Po30 and P-Po60 nonwovens. Increasing the number of dip-coating cycles to five led to a notable reduction in electrical resistance, reaching approximately 15 Ω/cm, as each cycle deposited more metal particles onto the fabric surface. However, addition of more cycles increases the cost and may lead to excessive release during washing, which negatively impacts the environment. In addition, the electrical resistance varied based on the distance between the two multimeter probes; shorter distances resulted in lower resistance, with 15 Ω measured at 1 cm [10]. Hence, five dip-coating cycles and measurement distance of 1 cm were selected for further analysis.

3.3 Pressure Sensing

The capacitance formed by the sandwiched structure of two conductive nonwovens is effectively changed when increasing forces are applied, leading to deformation in thickness [4]. As external pressure compresses the fabric layers, the distance between the electrode fabrics decreases, the contact area between the electrodes increases, which results in increase in capacitance according to Eq.(1). Study of the working mechanism revealed that the layers of conductive nonwoven fabrics have a great influence on the performance of pressure sensors.

The pressure sensitivity of PET and poplar/PET blend nonwoven fabrics was assessed using a setup where a 1 cm long section of the material surface was connected to a digital multimeter (**Figure 3a**) to measure real-time responses to different applied pressures (**Figure 3b**). When a light force was applied, the electrical resistance of the material increased slightly and returned to its original state when the force was removed. When pressed with varying weights (ranging from 10 g to 500 g), the capacitance showed a periodic change following a consistent and repetitive pattern (**Figure 3c**). The observed capacitance changes were more noticeable with heavier weights due to the increased pressure applied to the substrate. However, when the weights were removed, the resistance consistently returned to its baseline value, demonstrating the potential of the substrate to sense a wide range of pressures.

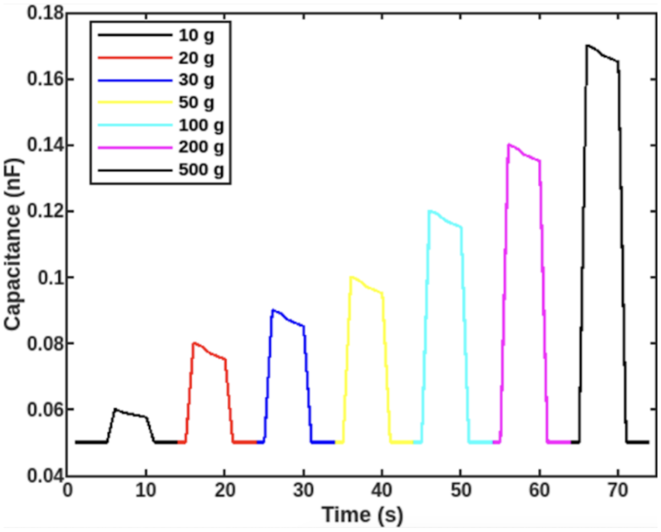

Figure 3 Record the relative capacitance over time while weights were loaded and unloaded

Pressures from different standard weights caused a notable increase in the capacitance value of the nonwoven fabrics and also the increase in the capacitance value was quite similar for all three nonwoven fabrics, so only one graph was presented. As illustrated in **Figure 3**, the capacitance increased from 0.05 nF to 0.06 nF at the lowest weight of 10 g, while it increased much higher to 0.17 nF at the highest weight of 500 g. This is related to the decrease in thickness with the increase in the weight pressure. This result suggested that the needle-punched poplar blended nonwoven fabric–based capacitor can be used as a pressure-sensitive sensor.

4. CONCLUSION

In summary, pure PET and poplar/ PET blend nonwoven fabrics were fabricated using needle-punching technique and subsequently coated with AgNWs. Owing to the high affinity for AgNWs, the nonwoven fabrics achieved high conductivity of about 15 Ohm/cm after five dip-coating cycles. The conductive nonwoven fabrics were then transformed into flexible and wearable capacitors to serve as a pressure-sensitive sensor. The fabrics revealed excellent potential in sensing a wide range of pressures under counterweight pressing, indicating that the capacitor made of poplar/ PET blend fabric can detect weights ranging from 10 g to 500 g. Based on the outstanding performance and cost-effective production process, the poplar fiber-based tactile sensor paves the way to promote new opportunities in the development of next-generation wearable electronics.

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