Sensors and Actuators A 236 (2015) 73–81

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Highly stable flex sensors fabricated through mass production roll-to-roll micro-gravure printing system

Memoon Sajid[a], Hyun Woo Dang[a], Kyoung-Hoan Na[b,*], Kyung Hyun Choi[c,*]

[a] Department of Mechatronics Engineering, Jeju National University, Jeju, Republic of Korea
[b] College of Engineering, Dankook University, Republic of Korea
[c] Department of Mechatronics Engineering, Jeju National University, Jeju, Republic of Korea

ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 6 October 2015
Accepted 21 October 2015
Available online 28 October 2015

Keywords:
Carbon
PVDF
PVAc
Flex
Micro-gravure
Protective coating

ABSTRACT

A highly stable low cost flex sensor has been fabricated in this research work using micro-gravure mass production roll-to-roll printing system. The active layer was fabricated on PET substrate using composite of Activated Carbon with PVDF. PVDF has been added as a binding agent to improve the mechanical stability of the active layer. Protective coating of PVAc was deposited on top of active layer using the same system. The sensors' electrical and morphological characterizations were performed to find out the surface characteristics and response of the sensors towards various bending angles. Results show promising response of both the protected and un-protected sensors towards positive and negative bending. Sensors with different lengths and widths were tested for both types and the best recorded response for protected sensors was 2.3 MΩ to 3 MΩ to 3.6 MΩ for −120° to 0° to 120° bend while for non-protected sensors was 0.25 MΩ to 0.4 MΩ to 0.55 MΩ for −120° to 0° to 120° bend. Protective coating caused increase in the overall sensor resistance thus reducing the operating power of the device. Also, increasing the sensor width decreases the resistance and so does reducing the length. The sensors were mounted on a glove and the results indicate stable and accurate operation.

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1. Introduction

Flex sensors are widely used in human machine interface (HMI) devices to control their operation using gestures [1–5]. Flex sensors are also used to interpret sign language by mounting them on gloves and interfacing with signal processing circuits [6–8]. Strain and flex sensors have been applied in health monitoring to measure the muscle joint angle and movement [9–11]. Flex or flex sensors are simpler form of strain sensors that can only measure bending in contrast to strain sensors that are also able to measure elongation or strain in addition to bending. This simplicity makes the flex sensors easier and cheaper to fabricate as compared to strain sensors [2]. Mostly, the working principle of cheap flex sensors is based on resistive active layers whose resistance changes upon the change in bending angle with respect to their resistance while at straight position [12]. The second most common type of flex sensors is optical sensors in which a fiber optic cable acts as the sensing unit and the changes in refractive index and power output are observed upon bending [13]. MOSFET based two dimensional stress and flex sensors have been fabricated with percentage change of only 12% and an error of 8% in output [14]. The mechanical model of flex sensors based on PEDOT:PSS thin film on polyimide substrate to sense finger movement has been studied and parameters optimization has been performed to achieve more stable, predictable, and reliable output [12]. A multi-fiber optical flex sensor has been fabricated to track the probe posture inside the body and tested for colonoscopy that is an endoscopic medical procedure [13]. Optical flex sensors based on periodically tapered soft glass fibers have been fabricated and characterized displaying good results but the fabrication and testing procedures are complicated and expensive [15]. Electrical resistance profiling of flex sensors adopted to measure spatial arrangement of the human body has been studied using the commercially available flex sensors [16,17]. A displacement flex sensor using conductive paste filler has been fabricated to measure very small displacements but it cannot be employed for larger displacements [18]. Micro-strain sensors based on long-period grating optical fibers have been fabricated and characterized but the characterization methods are too complex to be used in small applications [19]. A transparent self-sensing deformable surface flex sensor based on PEDOT:PSS plus carbon electrodes and P(VDF-TrFE) Ferro-electric active composite has been fabricated and studied [20]. A micro-

* Corresponding authors.
E-mail addresses: memoonsajid@gmail.com (M. Sajid), khna@dankook.ac.kr (K.-H. Na), amm@jejunu.ac.kr (K.H. Choi).

http://dx.doi.org/10.1016/j.sna.2015.10.037
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cantilever/nanotube based highly sensitive flexible micro strain sensors based on SWCNTs has been fabricated and discussed with limited size and displacement measurement range [21]. Polyimide fibers coated with PEDOT:PSS for strain and humidity sensing have been fabricated showing acceptable results [22] but the fabrication procedure for these strain sensors is also complex, expensive, and limited scale as mentioned above. Carbon based flex sensor on polyester has been fabricated but the percentage change is quite low and it can only be used for one direction bending [23]. A cotton fabric-based MEMS proprioceptive sensor was fabricated using AgNP's with good response to different finger flexion states [24]. Transparent conductive-polymer micro strain sensors based on PEDOT:PSS on PET substrate for touch input sheets of flexible displays have been fabricated [25]. Micro-strain sensors are actually small scale flex sensors and can only measure very minor displacements. A low cost novel flex sensor (strain gauge) has been fabricated based on traces drawn on paper by the conventional bendable carbon pencils [26]. The sensors are quite sensitive but the repetitive response is not remarkable due to mechanical defects produced in the active layer.

Nano-composite of activated carbon with MWNT's and PVDF/PVA binders has been used to fabricate the electrode of high performance flexible super capacitor [27]. Investigation of the properties of the film fabricated in above mentioned research showed promising properties of the composite to imply it for fabrication of flex/strain sensors. In this paper, a film of composite of activated carbon with PVDF acting as binder has been used as the active layer on PET substrate for bend sensing in both directions. Effect of the dimensions of sensors, and PVAc protective coating, on the sensors' performance has been investigated. The final sensors with protective coating exhibit excellent response for bend angles of -120° to 0° to 120° with ~40% reduction in normal state resistance (at 0°) for a bend of -120°, and ~60% increase for a bend of 120°.

2. Experimental

2.1. Materials

Activated Carbon with 100 mesh particle size in powder form, PVDF (Polyvinylidene fluoride), Toluene, and NMP (*N*-Methyl-2-pyrrolidone) were purchased from Sigma–Aldrich. PVAc (Polyvinyl Acetate) beads by GPC with average Mw ~100,000 were used. 0.2 mm thick PET (Polyethylene Terephthalate) roll was used as substrate.

Ink for active layer was synthesized by mixing activated carbon with PVDF in 9:1 by weight. The contents were dissolved by 15 wt% in NMP solvent. The solution was placed on mechanical shaker at room temperature for 10 h and was then kept on magnetic stirrer for 1 h. The synthesized ink for micro-gravure printer had a viscosity of 20 cps and density of 1120 kg/m^3.

The ink for protective coating was synthesized by dissolving 10% weight/volume PVAc in toluene solvent. The mixture was placed on magnetic stirrer at 50 °C for 3 h to get a uniform homogenous solution and after that the inks were ready to be used for sensor fabrication.

2.2. Sensor fabrication

The sensors were fabricated by solely utilizing the mass production micro-gravure roll-to-roll printing system [28]. The system photograph, and schematic of operation and working principle are presented in Fig. 1. PET roll with a thickness of 0.2 mm and a width of 140 mm was used as large scale substrate for sensors. The web tension has a voltage controlled open-loop passive controller with a maximum torque output of 3 Nm at 100% output. The tension controller output was set at 15% and the temperature of the in-situ curing chamber was fixed at 130 °C.

For the fabrication of the active layer, the web velocity was fixed at 3 mm/s and the gravure roll velocity was kept at 5 mm/s. This implies that the thickness of the coated film will be approximately 1.66 times higher than the minimum achievable thickness for the specific ink as there is a linear relationship between the ratios of gravure roll speed to web speed in range of 100–200% [29]. The thickness depends on the ink properties as well as the velocities of the moving web and the gravure roll. If the velocity of the web and the gravure roll are equal, the thickness is the minimum achievable for a uniform and continuous thin film. If the velocity of the gravure roll is higher than that of the web, the thickness will increase as the number of passes will increase. The gravure roll used for the active carbon layer deposition was 150 mm in width with 45° line patterns and coated the whole PET substrate.

After the active layer deposition, the sensors were protected with a coating of PVAc deposited through the same fabrication system. The gravure roll used this time had the same line patterns but a width of 70 mm. This made it possible to deposit the protective coating in the center of the roll while leaving the sides for making electrical contacts. The gravure roll speed was kept equal to the web speed and both were fixed at 3 mm/s. This made it possible to achieve the minimum thickness of the film and in the

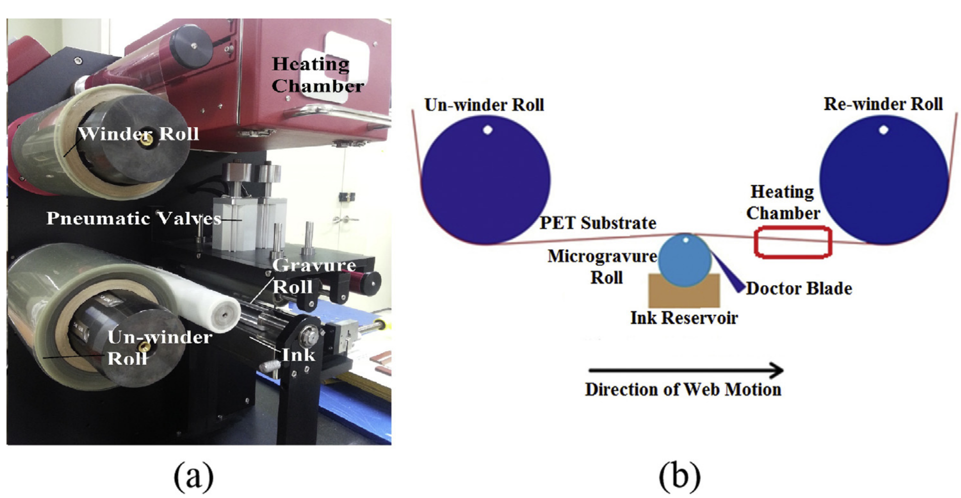

Fig. 1. Photograph of the micro-gravure roll-to-roll printing system (a), schematic and working principle of the micro-gravure roll-to-roll printing system (b).

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