Printed Wheatstone bridge with embedded polymer based piezoresistive sensors for strain sensing applications

H. F. Castro ^a, V. Correia ^{a,b}, N. Pereira ^a, P. Costa^{b,c}, J. Oliveira^{a,b}, S. Lanceros-Méndez ^{c,d*}

^a Algoritmi Research Center, University of Minho, 4800-058 Guimarães, Portugal

^b Department/Center of Physics, University of Minho, 4710 - 057 Braga, Portugal

^c Basque Center for Materials, Applications and Nanostructures (BCMaterials), Parque Tecnológico de Bizkaia, 48160-Derio, Spain.

^d IKERBASQUE, Basque Foundation for Science, 48013-Bilbao, Spain

* Corresponding author: senentxu.lanceros@bcmaterials.net

Abstract

Printed sensors find an increasing interest essentially due to their characteristics of flexibility and low cost per unit area. In this work a screen printed Wheatstone bridge is presented, suitable for strain sensing applications. A piezoresistive ink composite based on biocompatible thermoplastic elastomer styrene-ethylene/butylene-styrene (SEBS) as matrix and multi-walled carbon nanotubes (MWCNT) as nanofillers was used as a piezoresistive sensing material. Different deposition techniques, such as, screen printing, spray painting and drop casting were evaluated in order to optimize the resistance variation related to the piezoresistive effect. Several Wheatstone bridges with one and two sensors were designed to obtain an output sensitivity as a function of the strain submitted to the sensors. Further, different sensor geometries were evaluated to maximize the strain output sensitivity. Electro-mechanical bending tests showed a good linearity and a sensitivity up to 18 mV/V in the all screen printed half Wheatstone bridge output with two MWCNT/SEBS sensors.

Keywords: signal acquisition, Wheatstone bridge, printed electronics, screen-printing.

1. Introduction

Printed electronics is proven to be a suitable technology for large area and flexible applications due to its low-cost manufacturing and to enable cost-effective ways to implement smart and functional materials at temperatures compatible with polymer substrates. Thus, printed electronics is particularly suitable for application needs characterized by a conjugation of low-cost processes and large-area, i.e. applications that require low-cost per surface area, such as wearable electronics [1,2], interactive surfaces [3] and artificial skin [4], among others.

Sensors are increasingly applied in the determination of multiple physical and chemical quantities in a wide variety of applications in industry, medicine and engineering. Despite their robust features, conventional sensors shows some cost and scalability limitations, as well as difficulties to be embedded in material structures [5].

Flexible sensors are continuously gaining applicability and interest, together with the large area capability, based on a wide range of flexible substrates and innovative materials [6,7] providing scalability and integration solutions otherwise difficult for conventional sensors.

Being the stress/strain sensors, among the most widely used ones due to their wide applicability, new solutions are increasingly explored for flexible applications, to improve integration, and implementation in large areas, highlighting the investigations and solutions related to the fabrication of sensors by additive manufacturing and, in particular, by printing technologies [6–8].

In this scope, this work is devoted to the development of a printed signal acquisition circuit based on the Wheatstone bridge with embedded piezoresistive sensors, which can be applied in touch and interactive applications. Thus, it is possible to obtain an fully embedded circuit that

incorporates the sensor, enabling an all-printed *on-site* solution consisting of sensors, signal acquisition circuit and filtering [9], minimizing the signal degradation by means of electromagnetic noise due to circuit-sensor delocalization.

Several piezoresistive sensor configurations are presented using all screen printed electrodes in a Wheatstone bridge configuration of one and two sensors. The Wheatstone bridge tracks and sensor electrodes were screen printed and the strain piezoresistive material was deposited through different techniques, including screen printing, spray painting and drop casting, in one or two sensors configuration and with different sensor channel geometries.

2. Experimental

2.1 Materials and printing methods

The conducting material for the conductive tracks and finger electrodes, silver nanoparticle ink Metalon® HPS-021LV from Novacentrix [10], was screen printed using a polyester screen mesh size of 158×158 threads per square inch, with gaps of $64 \mu\text{m}$. The squeegee orientation angle was set to 45° relative to the printing substrate and the tension on the mesh was 20 N. The mesh was placed at a $100 \mu\text{m}$ distance of the substrate. After the printing of the electrodes, the layer was heated at 120°C for 30 minutes in an oven (Binder, ED23) under atmospheric environment to sinter the silver particles and remove organic residues.

For the deposition of the strain sensible material, a piezoresistive ink composite based on the biocompatible thermoplastic elastomer Calprene CH-6120, a SEBS copolymer with a ratio of Ethylene-Butylene/Styrene of 68/32 supplied by Dynasol. Multiwall carbon nanotubes, MWCNT, were supplied by Nanocyl: reference NC7000, purity of 90%, length of $1.5 \mu\text{m}$ and outer mean diameter of 9.5 nm . This composite exhibits excellent mechanical and piezoresistive properties from a wide range of deformations, featuring suitable piezoresistive response up to 80% deformation with a piezoresistive sensitivity near 2.7 [11]. A composite MWCNT/SEBS composite with 5 weight percent (wt%) MWCNT content was prepared by dispersing the MWCNT in cyclopentyl methyl ether (CPME, supplied from Carlo Erba with a density of 0.86 g/cm^3 at 20°C) within an ultrasound bath, and further adding SEBS, as reported by Gonçalves *et al.* [11], with properly adjusted inks viscosity for the different deposition techniques.

The MWCNT/SEBS piezoresistive ink was deposited on top of the silver screen printed electrodes by screen printing, spray painting and drop casting with viscosities around 2000 cps, 200 cps and 1500 cps, using a polymer/solvent (SEBS/CPME) ratio of 1:6 (g:mL), 1:8 and 1:5 for screen, spray and drop casting, respectively. The screen-printed mesh for the piezoresistive layer deposition was the same used for the printing of the conductive tracks and sensor electrodes. The obtained screen printed films shows an average thickness of 30 μm . The spray technique was achieved with a commercial airbrush from VEKIT DUO, serie APOLO 0.35. To obtain printed films with 3 μm the used pressure was between 2 and 4 bars and using an 80–100 mm distance between pistol and substrate. The films deposited by drop casting (doctor blade coating) shows an average thickness of around 50 μm . After the addition of the MWCNT/SEBS ink through the several deposition techniques, the piezoresistive layer was cured for 60 minutes under ambient conditions (relative humidity of $35 \pm 3\%$; room temperature $20 \pm 3\text{ }^{\circ}\text{C}$).

The silver nanoparticles conductive tracks and finger electrode configuration were screen printed on a, PET substrate MELINEX® ST-MX505-0100 from DuPont Teijin Films with a thickness of 100 μm , optically clear and printable in both sides. This substrate is pretreated on both sides for improved adhesion of the printed materials and heat stabilized for improved dimensional stability [12].

The morphological cross-sectional images of the sensors were obtained by scanning electron microscopy (SEM) with a Nova NanoSEM™ from FEI equipment.

2.2 Wheatstone bridge

An electrical circuit consisting of a Wheatstone bridge was used to obtain an output signal (V_G), in volts, proportional to the resistance variation of the sensors. Fig. 1a and 1b shows the electrical circuit of the Wheatstone bridge with one and two sensors used in the present work. Fig. 1c and 1d shows the printed result with R_1 and R_2 , R_3 as the piezoresistive strain sensors for the one and two sensors geometry, respectively. Interdigitated conductive layer layouts of the strain sensors

were designed with different channel length (L) and width (W), in order to maximize channel width over length (W/L) ratio across the piezoresistive sensor area of 1 cm^2 . The finger conductive width (d_f) was also adjusted accordingly. Fig. 1e illustrates the three different screen printed conductive layer layouts of the piezoresistive sensor used in this work, namely: i) $L = 0.5 \text{ mm}$ and $W/L = 170$; ii) $L = 0.7 \text{ mm}$ and $W/L = 80$; and iii) $L = 1.0 \text{ mm}$ and $W/L = 40$.

Fig. 1. Electrical circuit of the Wheatstone bridge with (a) one and (b) two sensors, and the equivalent screen printed result, (c) and (d), respectively. (e) Geometry and dimensions of the sensors used in this work.

In order to obtain a resistance in the same order of the piezoresistive sensors, all other resistors in the Wheatstone bridge were built in the same way, but outside of the designated deformation sensing area.

2.3 Electrical characterization

The electrical characterization of the piezoresistive sensor elements was realized by measuring the resistance at room temperature for the different deposition techniques and sensor geometries. The measurement of the electrical resistance was performed with a QuadTech 1920 Precision LCR Meter. For the measuring of the sensor electrical resistance, 20 samples for each different channel W/L ratio and deposition technique were used, so that the reproducibility of the printing materials and methods was assured. For the electrical characterization of the Wheatstone bridge, a Keithley 2400 SourceMeter was used to apply a bias voltage of 5 V to the source voltage (V_S) and to measure the output voltage V_G . For the Wheatstone bridge characterization, 5 samples were used for each different channel W/L ratio and deposition technique. The temperature sweeps between 20 °C and 90 °C were performed in 10 °C steps and the output voltage of the Wheatstone bridge, V_G , was measured at each step.

2.4 Electro-mechanical characterization

For the sensitivity to deformation of the printed Wheatstone bridge, electro-mechanical bending tests were performed. The V_G is measured using Agilent 34401A Digital Multimeter when applied a bias voltage of 5 V to V_S , at the same time that the sensor is submitted to mechanical stress. Unless otherwise stated, all V_G measurements are showed subtracted of the bias voltage resulting of the unbalance condition due to differences in the resistances of the Wheatstone bridge elements. All output sensitivity measurements related to deformations are identified by ΔV_G and calculated from Eq. 1:

$$\Delta V_G = V_G|_{Z=2.5 \text{ mm}} - V_G|_{Z=0 \text{ mm}}, \quad (1)$$

where $V_G|_{Z=2.5 \text{ mm}}$ is the output voltage when the sensors are in bended state with $Z = 2.05 \text{ mm}$, and $V_G|_{Z=0 \text{ mm}}$ is the output voltage in the resting state with $Z = 0 \text{ mm}$.

Fig. 2. (a) Graphical representation of the printed Wheatstone bridge sensing area with one and two piezoresistive sensors. Schematics views of the mechanical geometry used for vertical displacement of the sensing area (Z) in (b) perspective and (c) transversal plane.

For the electro-mechanical characterization of the Wheatstone bridge, a sensing area was designated both for the one and two piezoresistive strain sensors geometry. Fig. 2a illustrates the adopted sensing area. All electro-mechanical characterization experiments were performed using a three-point bending mechanical mode with a universal testing machine Shimadzu-AG-IS. Fig. 2b and 2c illustrates the used three-point bending mechanical mode, where two fixed points are located in the extremities of the piezoresistive sensor, while the third point is located in the middle of the sensor and a vertical displacement (Z) is applied in relation to the two extremity points. The electro-mechanical tests consisted in several loading-unloading cycles with Z ranging between 0 mm and 2.05 mm, while recording the V_G .

3. Results and discussion

Fig. 3 shows optical images of the printed sensors with a channel geometry of $W/L=170$. Fig. 3a displays the screen printed sensor electrodes without the deposition of the piezoresistive ink. From this picture it can be observed that it is possible to obtain a fine screen printed pattern of Ag electrodes, with the selected screen mesh properties, allowing to obtain L and d_f down to 0.5 mm. On the other hand, Fig. 3b, 3c and 3d show the same sensor structure, as depicted in Fig. 3a, with

the addition of the MWCNT/SEBS piezoresistive ink using screen printing, spray painting and drop casting as the deposition method, respectively. In these pictures, it is noticeable the resulting difference in the thickness of the MWCNT/SEBS ink as a function of the different deposition techniques.

Fig. 3. Screen printed sensor electrodes ($W/L=170$) (a) and sensors with the MWCNT/SEBS piezoresistive ink using screen printing (b), spray painting (c) and drop casting (d) as the deposition method on top of the electrodes.

SEM images were obtained in order to evaluate the resulting thickness of the piezoresistive layer obtained by the different deposition techniques (Fig. 4).

Fig. 4. Cross-sectional SEM images of the sensors prepared by screen printing (a), spray painting (b) and drop casting (c) as the deposition technique of the MWCNT/SEBS piezoresistive ink.

Fig. 4a shows a screen printed piezoresistive layer thickness of around $\sim 2.5 \mu\text{m}$. As expected, the screen printed MWCNT/SEBS layer shows the lower thickness when compared with the other deposition techniques used in this work. On the other hand, in Fig. 4b is shown a piezoresistive layer thickness of $\sim 23 \mu\text{m}$ deposited by spray painting. In this technique it was observed a smoother sensing layer but also a larger thickness variation along of the several samples, reaching up to 20% when compared to variations up to 10% for the screen printed samples. Finally, Fig. 4c displays the obtained thickness of $\sim 41 \mu\text{m}$ in the drop casted MWCNT/SEBS layer (with a variation of 10%).

Fig. 5a presents the sensor resistance as a function of the deposition technique of the MWCNT/SEBS piezoresistive ink with W/L ratio equal to 170. It is observed that the screen printing deposition technique shows the larger resistance range, from $32 \text{ k}\Omega$ to $3.5 \text{ M}\Omega$, with an average of $2.05 \text{ M}\Omega$, that corresponds to a sheet resistance range between 0.08 and $8.75 \text{ k}\Omega\text{-per-square}$ when normalized by the thickness of the material. As the screen printed MWCNT/SEBS composite presents the lowest thickness of all three deposition techniques studied, it is expected to show the higher resistance value. Furthermore, with a smaller thickness, the existence of imperfections and impurities at the screen printed piezoresistive or electrode patterns results in more significant effect in the sensor resistance when compared with the others deposition techniques studied in this work. On the other hand, the spray painting technique shows an average sensor resistance of $31 \text{ k}\Omega$ and a range from $6.7 \text{ k}\Omega$ to $80 \text{ k}\Omega$, which represents a sheet resistance range from 0.17 to $1.84 \text{ k}\Omega\text{-per-square}$ after normalization by the thickness. With this deposition technique, a lower resistance was obtained due to the deposition of more piezoresistive material on the sensor structure than those verified by screen printing. Finally, the drop casting technique leads to a sensor resistance range between $42 \text{ k}\Omega$ and $59 \text{ k}\Omega$ (sheet resistance between 1.97 to $2.42 \text{ k}\Omega\text{-per-square}$ after normalization by the thickness), with an average of $48 \text{ k}\Omega$. . This deposition technique shows a narrower range in the sensor resistance values than the other printing techniques. This effect can be explained by the properly adjusted ink viscosity and

electro-mechanical properties for drop casting that result in a thicker piezoresistive layer, minimizing the effect of pattern irregularities on the sensor resistance.

In Fig. 5b it is shown the screen printed sensor resistance as a function of the channel geometry. As expected, it is observed a decrease in the sensor resistance with increasing channel W/L ratio. Additionally, it is noticeable a larger increase in the sensor resistance at lower W/L ratios. Once again, this behavior is explained by the presence of irregularities in the screen printed MWCNT/SEBS layer that has a higher probability to exist over a larger L.

Fig. 5. Sensor resistance as a function of the (a) deposition technique (with W/L=170) and (b) the W/L ratio of the interdigitated fingers when the piezoresistive material is deposited by screen printing.

In order to analyze the electrical response of the Wheatstone bridge for mechanical deformations, electro-mechanical tests were carried out on the printed sensor, using the setup illustrated by Fig. 2. Fig. 6 presents the electro-mechanical measurements, consisting of 4 loading-unloading mechanical cycles, on the all screen printed Wheatstone bridges with MWCNT/SEBS

piezoresistive ink on the interdigitated electrodes with a channel geometry of $W/L=170$. The experiments were performed in circuits with the following screen printed resistances (see Fig. 1 for reference): R1 - 14.47 kOhm; R2 - 11.75kOhm (sensor); R3 - 1.42 kOhm; R4 - 11.25 kOhm in Fig. 6a and R1 - 10.97 kOhm; R2 - 15.47 kOhm (sensor); R3 - 18.77 kOhm (sensor) and R4 - 12.71 kOhm in Fig. 6b.

It is observed that the output voltage of the Wheatstone bridge follows the mechanical deformation applied to the samples, i.e. V_G increases with increasing deformation and decreases with decreasing deformation. Furthermore, the electrical response of the all screen printed samples with one and two sensor configuration (Fig. 6) displayed a sensitivity of 5 mV/V and 12 mV/V, respectively, which represents an output sensitivity increase of 2.4 times for the two sensor configuration.

(c)

Fig. 6. Electrical output of the all screen printed Wheatstone bridge (W/L=170) when a cyclic vertical displacement is applied to the sensing area with (a) 1 sensor and (b) 2 sensors. Piezoresistive measurements for 500 cycles using 5% of deformation at 5 mm/min (c).

Further, Fig. 6 shows a decrease of the maximum value of V_G with increasing number of cycles, which is attributed to mechanical relaxation of the MWCNT/SEBS piezoresistive material of the sensors. In fact, it has been reported that the minimum and maximum resistance decrease and stabilize after ~60 cycles as presented in Fig 6 C, due to irreversible modifications of the MWCNT network [11] and mechanical hysteresis of the material [13], while maintaining the gauge factor in all cycles. The maximum decrease for the one and two sensors configuration is 20% and 15% between the first and fourth cycle, respectively, while the minimum values remains stable between cycles. This result show that the configuration with two sensors leads to a less dependent output response of V_G to this effect when compared with the one sensor configuration.

The electro-mechanical measurements also showed a non-linear V_G reaction when the vertical displacement is lower than 0.5 mm. It is reported [14] that this effect occurs due to the electrical resistance conditioning of hard domains in the tri-block SEBS thermoplastic elastomer copolymer.

Further electro-mechanical measurements were carried out to analyze the output sensitivity of the sensors deposited by the different deposition techniques and sensor geometries of the Wheatstone bridge studied in this work. Fig. 7a shows the output response ΔV_G of the Wheatstone bridge as a function of the deposition technique of the MWCNT/SEBS piezoresistive layer including all sensor geometries developed in this work. In the screen printed two sensor configuration V_G increases 2.5 times from an average of 4.8 mV/V to 12 mV/V, when compared with the one sensor configuration. This piezoresistive deposition technique shows the widest output sensitivity range with the two sensors configuration between a minimum of 8.1 mV/V to a maximum of 18 mV/V and the one sensor between a minimum of 2.1 mV/V to a maximum of 7.7 mV/V. On the other

hand, the spray printed piezoresistive ink samples show an average sensitivity of 1.2 mV/V and 2.4 mV/V for the one and two sensors configuration, respectively, representing an increase of 2 times between configurations within a range of 0.7 mV/V and 2.5 mV/V, respectively. Finally, the drop casted piezoresistive ink samples exhibits an average output sensitivity of 0.9 mV/V and 1.5 mV/V for the one and two sensors configuration. This result represents an increase of 1.7 times between the two piezoresistive drop casted configurations. In this technique it is observed the lower output sensitivity variation between samples with 0.3 mV/V and 0.9 mV/V. With respect to the three different W/L ratio of the channels, Fig. 7a shows that the deposition of the piezoresistive layer through screen printing is more dependent on the channel W/L ratio due to the wider variation of the output sensitivity. In the same way, it is also possible to conclude that the drop casted piezoresistive layer is the less dependent of the sensor channel geometry.

Fig. 7. Output sensitivity of the Wheatstone bridge as a function of the) deposition technique of the piezoresistive layer (a); and the channel geometry of the interdigitated sensor fingers (b).

Fig. 7b shows the relation between the output sensitivity and the sensor channel geometry, indicating an increase of the output sensitivity with the channel W/L ratio.

These results show that the piezoresistive layer output sensitivity is more significant for the screen printed sensors than for the ones prepared by spray printing or drop casting, which reflects a larger electrical resistance variation of the screen printed sensors when submitted to the applied stress, It is to stress that screen printing is a manufacturing method with a high reproducibility in terms of printing patterns, commonly used in the manufacturing industry. Further, it allows the fabrication of thin layers, which leads to improved sensor sensitivity. The main issue to take care about is related to the use of composite inks, as particle agglomeration or failure in the proper dispersion of the fillers will lead to variations in the sensitivity and performance of the different sensors.

Additionally, it is observed a further increase in the output sensitivity with for higher sensor channel W/L ratios. Thus, the use of an all screen printed Wheatstone bridge with higher sensor channel W/L ratios brings more advantages in the development of integrated systems, consisting of printed strain sensors and acquisition circuit, due to the highest sensitivity and the added benefits inherent to all screen printed systems. Furthermore, with this technique and a sensor geometry with W/L of 170 it is possible to maximize the output sensitivity gain between the two sensors over one sensor configuration, as well as in relation to the other deposition techniques, reaching up to a maximum value of 18 mV/V.

Finally, to evaluate the effect of temperature variations in the ΔV_G response, electro-mechanical tests were performed under different temperature conditions, as shown in Fig. 8, for the sensors prepared by screen and spray printing, as they shown higher ΔV_G . Fig.8 shows that a stable response of ΔV_G is obtained up to 70 °C both for one and two sensors, screen and spray printed sensors. At temperatures higher than 70 °C, it is noticeable a decrease in ΔV_G with increasing temperature. Furthermore, this effect is independent of the piezoresistive layer deposition method, as can be observed both for screen printed (Fig. 8a) and spray printed (Fig. 8b) sensors, and it is also independent of the one or two sensors configurations. Thus, this behavior is fully attributed to thermally induced variations of the MWCNT/SEBS piezoresistive material, once the glass transition of polystyrene is around 70 °C [15].

Fig. 8. Output sensitivity of the Wheatstone bridge as a function of temperature using screen printing (a) and spray printing (b) as the deposition technique of the piezoresistive layer.

The results obtained in this work demonstrate the applicability of all screen printed Wheatstone bridges with MWCNT/SEBS piezoresistive sensors for the development of signal acquisition and filtering systems.

4. Conclusions

Several signal acquisition circuits with embedded strain sensors based on MWCNT/SEBS piezoresistive sensors were developed. Three different techniques were used for the deposition of the piezoresistive sensors, and results show that screen printing was the technique with higher output sensitivity to strain. Additionally, a two sensors configuration shows an average gain of 2.5 times when compared with the one sensor configuration. Hence, the screen printed Wheatstone bridge with two sensors has the best electro-mechanical output sensitivity, with values up to 18 mV/V, and good linearity. The Wheatstone bridges with screen printed and spray printed piezoresistive layer show stable electro-mechanical output sensitivity values when submitted to temperatures up to 70 °C, decreasing for higher temperatures.

The results obtained in this work demonstrate the promising applicability of all screen printed Wheatstone bridges with MWCNT/SEBS piezoresistive sensors for the development of fully embedded systems for signal treatment, consisting of signal acquisition and filtering.

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