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Design of flexible textronic temperature sensors

***Abstract**. The aim of this paper is to present design and simulation results of the novel flexible temperature sensor. Results of the compact analytical model were compared with the parameters of the obtained real structure. The carbon polymer composition with a SBS-modified polystyrene binder, characterized by a good Temperature Coefficient of Resistance (TCR), was used as a thermosensitive material. The complex electrical analysis of the typical resistive structure geometry was performed with the aid of the COMSOL Multiphysics® 4.4 environment.*

***Streszczenie.** Celem niniejszego artykułu jest zaprezentowanie wyników dotyczących projektowania i modelowania nowatorskich elastycznych czujników temperatury przy wykorzystaniu środowiska COMSOL Multiphysics® 4.4. Zastosowano kompozycję polimerowo-węglową ze spoiwem z modyfikowanego SBS polistyrenu, charakteryzującą się wysokim Temperaturowym Współczynnikiem Rezystancji (TWR). Wyniki analizy modelu analitycznego porównano z parametrami otrzymanych struktur rzeczywistych.*
*(**Projektowanie elastycznych tekstronicznych czujników temperatury**).*

Keywords: sensors modeling, flexible temperature sensors, textronics.
Słowa kluczowe: modelowanie czujników, elastyczne czujniki temperatury, tekstronika.

Introduction

Temperature is one of the most commonly monitored physiological parameter in smart clothing. Its too high or too low value can lead to hyperthermia or hypothermia, fainting and even death, so its current monitoring is very important, especially for certain occupational groups [1]. Modern, special textiles for medical, rescue and military are increasingly being retrofitted with temperature sensors that allow efficient lead action or convalescence. This work presents a novel construction of flexible textronic temperature sensors, designed to measure internal temperature. Sensors are made by screen printing technology using polymer composite with carbon black filler. These structures can be a cost-effective alternative to traditional, semiconductor, rigid sensors, especially in textronic and wearable electronics applications [2].

Examined sensor structure

Textronic sensors should meet a lot of special requirements, not only electronic ones but also textile ones. Apart from sufficient electrical parameters, such as a high temperature coefficient of resistance (*TCR*), accuracy and repetitiveness they should be flexible, light and easily integrated into the fabric [3]. The basic sensor structure consists of a flexible substrate – polyimide foil – Kapton® (75 μm), gold-plated copper contacts (35 μm) and thermoresistive layer, made of a carbon polymer composite with a SBS-modified polystyrene binder (42.9% of carbon filler by mass content). Layers were screen-printed, cured at the temperature equal of 120°C and afterwards protected with varnish from the negative impact of harmful external factors. The examined sensor structure is presented in Fig. 1 and major parameters of applied materials are described in Table 1, where ρ means resistivity.

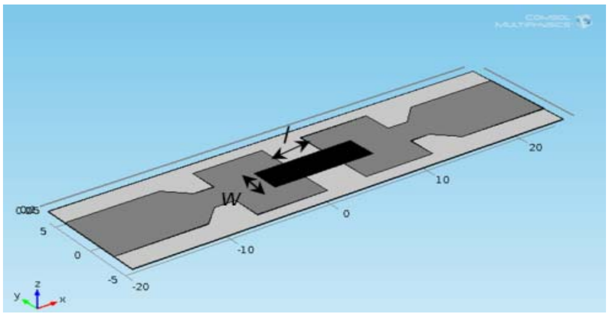

Fig.1. The examined sensor structure

Table 1. Parameters of applied materials [4,5]

Parameters	Value
Composition curing temperature [°C]	120
Composition curing time [h]	1/3
Composition *TCR* [ppm/°C]	70 000
ρ_{Au} [Ωm]	$2.19*10^{-8}$
ρ_{Cu} [Ωm]	$1.67*10^{-8}$
ρ_{Kapton} [Ωm]	$5.3*10^{14}$

Temperature sensor structure modeling

The complex numerical simulation was conducted with the aid of COMSOL Multiphysics® 4.4 environment, AC/DC module. Thermosensitive structure consists of three parts, the main rectangular one (1) and two connectors overlapping the contacts (2,3), presented in the cross section of the examined structure in Figure 2. The whole structure was placed in the air. The sensor model was powered from a DC source with a value of 0.1 mA, then voltage and sensor resistance were determined.

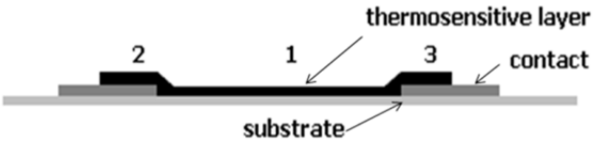

Fig. 2. The sensor cross section

Several versions of the sensor structure, shown in Fig. 1, were examined, differ from each other by thickness *d*, width *w* and length *l* of the layer – presented in Table 2.

Table 2. Temperature sensor parameters

R	*w* [mm]	*l* [mm]	*d* [μm]	R_{30} [Ω]
R_1	3	4	10	2 650
			20	1 330
			30	8 80
R_2	3	3	10	1 990
			20	1 000
			30	670
R_3	6	3	10	990
			20	500
			30	330
R_4	10	1	10	200
			20	100
			30	70

In modeling the thermosensitive layer geometry (Table 2) and parameters of substrate and electrode materials (Table 1) were taken into account, the R_{30} means the resistance at the temperature of 30°C. Resistance can be determined from the following formula.

$$R = \left(\frac{\rho}{d}\right)\left(\frac{l}{w}\right) = R_S N_S \qquad (1)$$

where: ρ – resistivity [Ωm], R_S – sheet resistance [Ω/sq], N_S – number of squares. In the study the following basic equations were used (2, 3, 4):

$$\nabla J = Q_j \qquad (2)$$

$$J = \sigma E + J_e \qquad (3)$$

$$E = -\nabla V \qquad (4)$$

where: J – current density, Q_j – charge density, E – electric field density, J_e – externally generated current density, V – electric scalar potential.

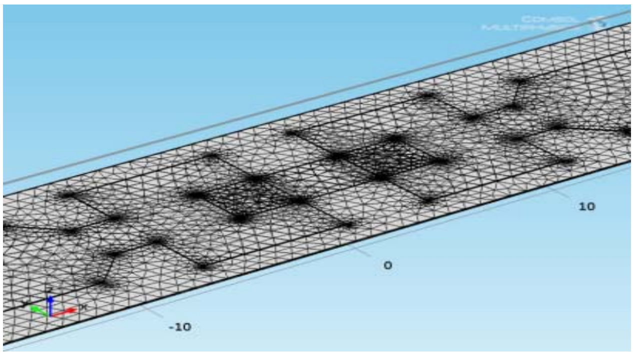

Fig. 3. Mapped mesh for the sensor structure

Figure 4 shows the spatial distribution of the DC potential and Figure 5 the electric potential distribution along the *x* coordinate.

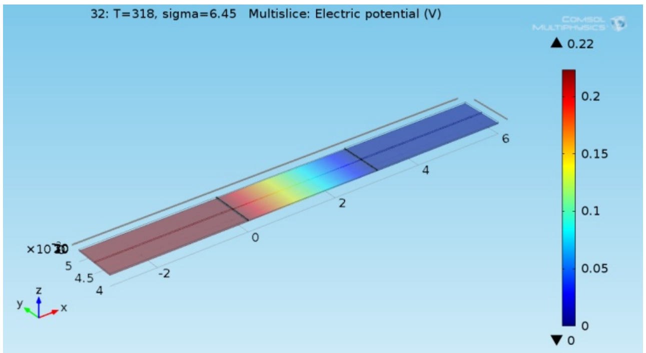

Fig. 4. The spatial distribution of the DC potential

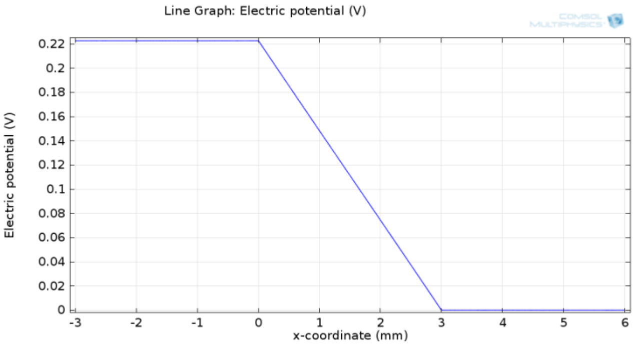

Fig. 5. The distribution of the DC potential along x-coordinate

Due to the low power dissipated in the thermosensitive layer (for *R* = 2.65 kΩ, *I* = 0.1 mA the power is equal to *P* = 26.5 µW) the phenomenon of self-heating of the sensor has been omitted. Another important issue, which has to be taken into account in flexible electronics modeling, is the impact of mechanical stresses on the sensor. In our case thanks to the high *TCR* the influence of bending, which is unfavourable feature of the examined layers, may be omitted [6].

Figure 3 shows the exemplary predefined tetrahedral mesh of examined structure, number of tetrahedral and triangular elements was about 350 000.

The above characteristics show a linear distribution of the potential along electrodes and thermosensitive layer.

Examined sensor structure

Modeling results were compared with the experimental data of the real structures with thickness about 20 µm. Comparative results are presented in Figure 6 – Figure 8. Temperature sensors were tested by the help of measurement setup consists of calorimeter, thermocouple, digital multimeter coupled with registration computer. Sensor resistance was measured at the range of 30-45°C with temperature stabilization of 0.3°C. For each temperature the measurement series of 15 structures were carried out. The standard deviation for a series of measurements did not exceed 3%, related to the maximum value of the measuring range. The following figures contain the average values of measurement series and simulation results with the linear approximation characteristics. The exemplary results for the structures of varying thickness are shown below.

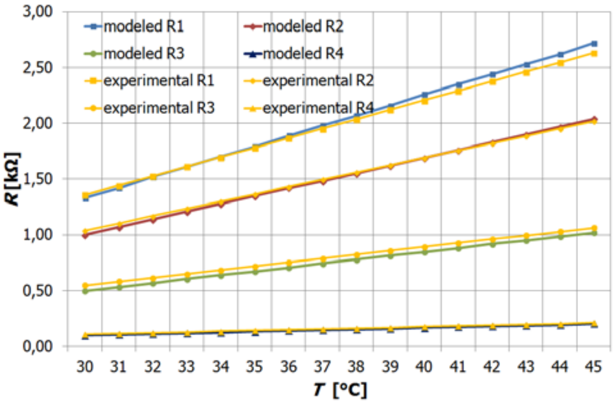

Fig. 6. The sensor resistance vs. temperature for *d* = 20 µm

Depending on the sensor geometry the different resistance values could be observed. There is a good agreement between the experimental and modeled results. By modifying the geometry of the sensor structure it is possible to easily change the value of its resistance. Further work of the team include the use of another thermosensitive material – the poly (methyl methacrylate) (PMMA) filled with different concentration of multiwalled carbon nanotubes (MWCNT). It is characterized by a lower *TCR* but it is more stable during mechanical stresses [7].

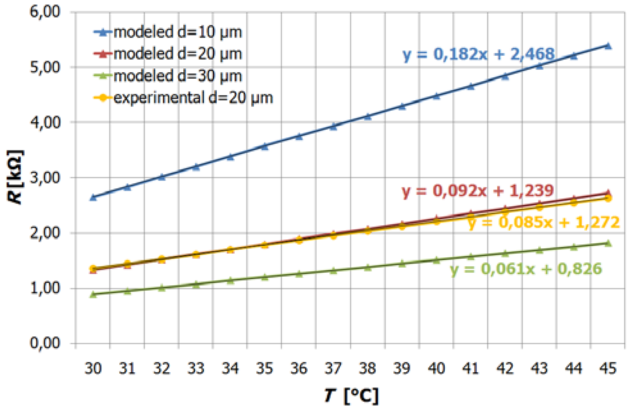

Fig. 7. The R_1 sensor resistance vs. temperature for different layer thicknesses

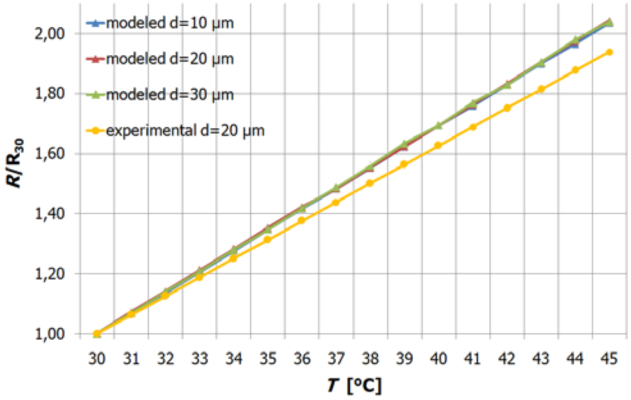

Fig. 8. The normalized *R* resistance vs. temperature

As it could be observed modeling results are comparable with the real values. Currently our team is working on a new model, taking into account moreover mechanical stresses and their influence on the sensor resistance.

Conclusions

The modeling of the textronic flexible temperature sensor construction (Figure 1) was analyzed by the help of Comsol Multiphysics® 4.4 environment. A series of a real samples was performed using a screen-printing technology, afterwards manufactured sensors were examined. Results of modeling and measurements, shown in Fig. 6 – Fig. 8, confirm the compatibility and repetitiveness of obtained structures. Discrepancy between these characteristics for the same sensor did not exceed 5% of the maximum value of the range (Fig. 6). Sensors with layers characterized by a higher value of resistance R_{30} are more sensitive and allow to achieve greater changes of the measured voltages (for I = const.). Higher resistance reduces also the influence of wires. The use of wires made of silver plated copper of 32 AWG (0.2 mm diameter), characterized by a DC resistance per 1 meter equal to 0.557 Ω/m, leads to the increase of the sensor resistance with 2 m wire less than 1.2 Ω [8]. This value is less than 0.2% of the maximum value of the sensor resistance. In case of the application of 316L 2 ply stainless steel thread (0.2 mm diameter), which is frequently used in textronics, the resistance of 2 m wire is higher than in case of silver plated copper one and is about 102 Ω. In our case the application of stainless steel wires is possible only for a modified construction of R_1 sensor with lower w or a different sensor geometry - the meander layer structure. For the technological reasons the thinnest obtained layer was with the thickness of 20 µm. In real operating conditions flexible sensor is subjected to mechanical stress, therefore the correct choice of sensor geometry is so important. Mechanical stresses can affect on the sensor resistance, reducing the length of the layers along the force direction should limit the impact of these stresses. The increase of the sensor resistance changes vs. temperature could be obtained by reducing the width or thickness. The best sensor geometry for flexible electronics application is a meander structure, that geometry will be taken into account in further investigations. Finally it is worth noting that obtained results confirm their compatibility with simulation.

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