**Michał Frydrysiak**

# Comparison of Textile Resistive Humidity Sensors Made by Sputtering, Printing and Embroidery Techniques

**DOI:** 10.5604/01.3001.0014.2391

**Lodz University of Technology, Faculty of Material Technologies and Textile Design,**
90-924 Lodz, Poland,
e-mail: michal.frydrysiak@p.lodz.pl

**Abstract**
*This paper presents various constructions of flexible textile humidity resistive sensor prototypes which can be used in textronic clothing applications and can be easily integrated with fabric. They can be also used as sensors applied to sheets in hospitals and nursing homes, as well as in special medical clothing, especially for protecting elderly people. The author describes a method of manufacturing such sensors by three different techniques, such as embroidery, printing and sputtering (PVD). Also presented are electrical properties of the textile sensors under various environmental conditions. The resistance of the sensors was studied in a wide range of humidity, from 30 to 90%, and at temperatures of 30 °C and 40 °C. The author then chose the right type of textile substrate on which the sensors should be made. A microscopic examination of the upper electroconductive layer of the prototype sensors was also conducted. These novel methods of sensor creation for humidity measurement on flexible textile substrates and their comparison could be used for clothing functionalisation.*

**Key words:** *textile, sensor, humidity, intelligent materials, PVD process, printing process, embroidery.*

## Introduction

Methods of relative humidity measurement can be generally divided into hygroscopic and condensation methods. In the first category of devices, which are classified as resistive or capacitive sensors, the electrical properties of materials change as a result of absorbing moisture from the environment. The humidity is indirectly determined by the measuring the dew point in the case of condensing hygrometers with the use of sensors with a chilled mirror [4]. The technology of sensors based on textile structures is one of the major developments in the field of textronics [1, 2, 5]. The resistance and capacitance changing in response to humidity can be detected by the sensors mentioned. Despite considerable research in the field of humidity sensors, only a few systems based on flexible substrates have been commercialised so far. This is caused by a few problems, the main ones being the nonlinear static characteristics of textile sensors and signal changes over time after repeated use [6, 8].

A resistive sensor (RTD) is of simple structure and small size. According to the nature of its use, it can also be placed on larger surfaces if two electrodes of a comb structure are placed in a flexible substrate sensitive to moisture. Moisture changes the volume and surface resistance of the material between the electrodes.

A typical resistive-type humidity sensor is usually created as an interdigital electrode structure printed onto an alumina substrate based on a stiff substrate and dip coating with a polyelectrolyte film [2]. Flexible sensors are typically made on flexible polymer foils used as substrates. The most common methods of producing elastic sensors are conventional photolithography [2, 4], ink jet printing [1, 4, 9] and screen printing [1, 14]. Sensors were also fabricated on a photosensitive fibre with a laser beam in [3]. The author also presented a flexible humidity sensor applied directly on a textile substrate with the use of the sputtering technique [15]. That kind of sensor can be easily integrated with clothes with the use of a typical sawing machine. The important features of such sensors are appropriate metrological parameters. Due to the heterogeneous nature of textiles, non-homogeneous metrological properties of textile sensors should also be expected.

## Materials and methods

In the first phase of the research, the author made examinations at an ambient (room) temperature. Under these conditions the value of humidity changed in the range from 30 to 90%. Basic parameters in the climatic chamber were: as follows (1) internal dimensions of the chamber: 600 x 500 x 500 mm (width x depth x height), (2) temperature range: -70 °C to 150 °C, (3) accuracy of temperature: 0.5 °C ± at ambient pressure, and (4) accuracy of relative humidity: ± 3.5%. The measurement was made with the use of a Motech TT4090 measuring bridge. The research was carried out for two ambient temperatures: 30 °C and 40 °C. These values were chosen as adequate for possible applications of the sensor, which could be placed between the textile layer packet in clothing for monitoring physiological parameters for elderly people. ***Figure 1*** presents a structure and qualitative measurement model of the humidity sensor. It consists of two electrodes made of electrically conductive material on a textile base material.

The author chose two types of textile substrates which could be applied for the production of textile humidity sensors: the Goretex membrane Fireblocker N2LY and Softshell FT 330 material. These materials have the ability to transport sweat from the skin surface. The basic parameters of these materials are shown in ***Table 1***.

Goretex Fireblocker N2LY is a protective layer against water, with a surface mass of 150 g/m$^2$. This material consists of a polyester fabric with Teflon coating covered with nanofibres. FT 330 material is a type of soft shell fabric. It is the product layer and has a water resist-

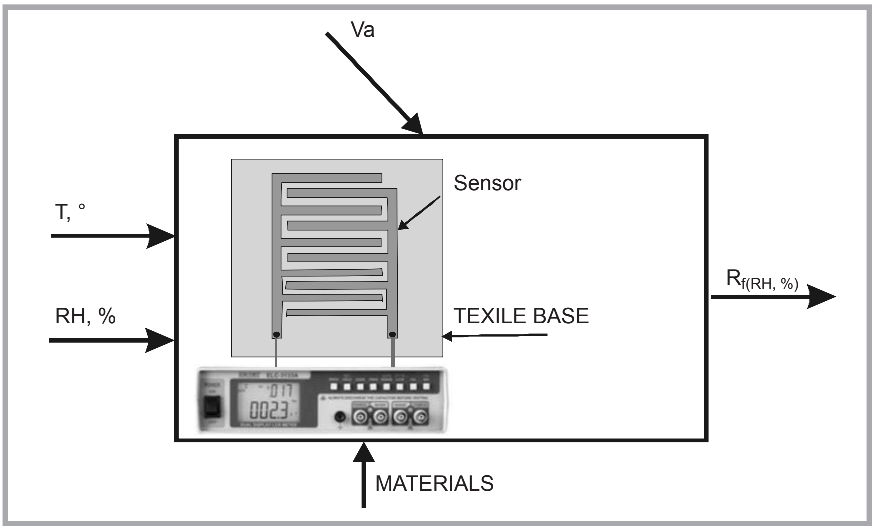



***Figure 1.*** *Quality model of textile sensor measurement.*

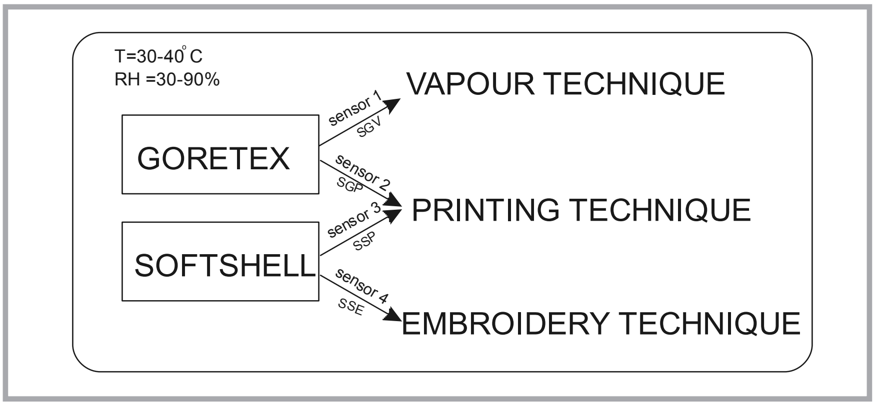



***Figure 2.*** *Methods used on appropriate substrate for producing textile humidity sensors.*

ance of 10000 mm and breathability of 10000 g/m$^2$ during 24 h. From the smart textiles point of view, attention should be paid to sweat monitoring. It is one of the directions in the approach to the health care monitoring system in various applications. These systems can be used in clothing applications for children, the elderly, patients and athletes. Very interesting applications are those which increase work safety in occupations with a high thermal load, e.g. metallurgist. It should be remembered that a common feature of all applications is the measurement of moisture in clothing layers next to human skin. Hence, it is possible to measure the dehydration of the human body, thus improving health.

Two textile substrates and three different electrically conductive materials for electrodes were used to manufacture textile sensors. Silver modifier particles were used in all cases. Multifilament yarn coated with a silver layer, micro- inclusion paint with silver, and silver material were used during the research. Each of these modifiers was applied to the textile substrate by various technologies. For this purpose, techniques of embroidery, printing and resistance sputtering were used. ***Table 2*** presents the use of the three types of additives and their basic parameters.

Four types of sensors using two types of textile substrates were made. It was not possible to use all application technique modifiers for each textile substrate because in some cases the textile substrate was damaged or conductive paths did not conduct current. For example, the Goretex membrane was destroyed during the embroidery process, because the machine's needle caused damage to its structure.

PVD technology did not allow to obtain electroconductivity of the tracks on knitted softshell materials. Only the printing technique was suitable for the two textile substrates. ***Figure 2*** shows schematic executions of the sensors according to the relevant technology.

Initial research of the surface resistance measurements was conducted for the prototype sensors. The direct measurement method was used, as well as a recorder – a Agillent 6,5 Digits Millimeter with a resistance accuracy of 0.010 + 0.001 (% of reading + % of range).

**Embroidery sensor**

This type of sensor was made on a knitted softshell base. A computerised embroidery machine (Janome) was used for this purpose. Due to technological and material properties as well as the settings of the yarn tensioner, the average embroidered paths were of 1.57 mm width. The embroidered paths and their cross-sections are shown in ***Table 3, no. 1***. The average value of surface sensor resistance on the knitted substrates was 1.1 Ω/cm.

**Printing sensor**

A continuous ink-jet multiple-deflection system with a nozzle of 0.2 mm diameter was used for the printing sensor. The paint used during the printing process was based on silver. These methods are widely used in industrial cod-

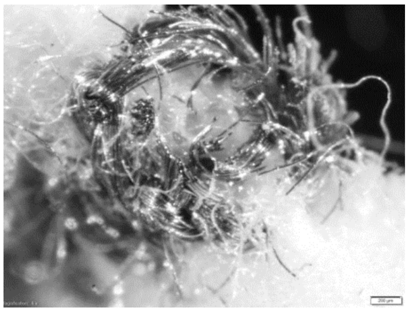
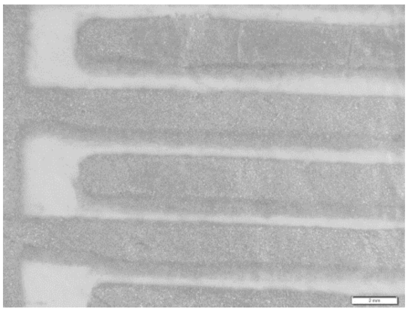
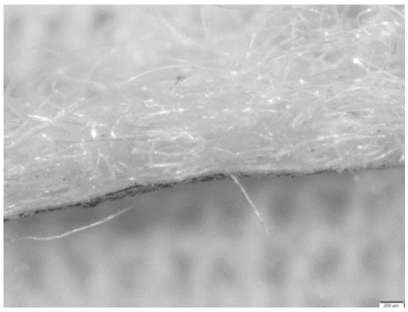
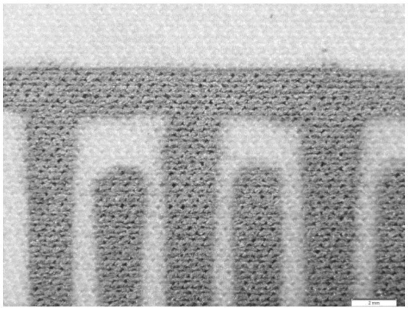
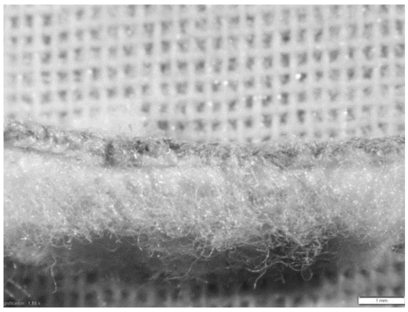
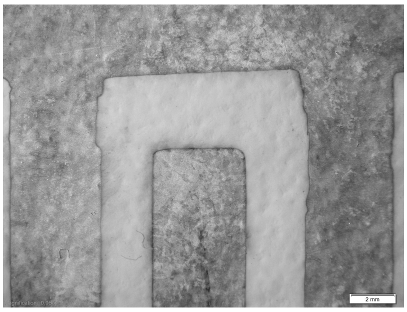
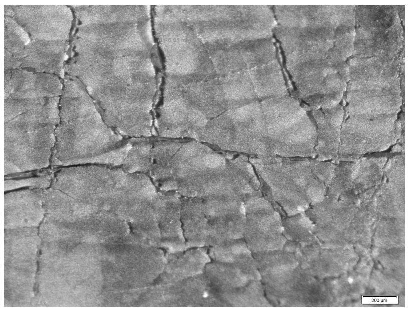
***Table 1.*** *Parameters of base textile materials.*

| Material | Thickness, mm | Mass, g/m$^2$ |
|---|---|---|
| Goretex Fireblocker N2LY | 0.96 | 150 |
| Softshell FT 330 | 2.98 | 400 |

***Table 2.*** *Different additives used during the production of the textile humidity sensors.*

| Sensorial material | Technique | Material resistance | Characterisation |
|---|---|---|---|
| Silver yarns | Embroidery | 14 Ω/m | 156.0 tex multifilament |
| Silver paint | Printing | $3 \times 10^{-2}$ Ω/m (measured on glass) | Fast dry to handle (at low temp.) 15 min. at 20°C |
| Silver | PVD | $1.59 \times 10^{-3}$ Ω/m | Very pure content of Ag – 99.9% |

*Table 3. Embroidered paths and their corss-sections.*

| No | Type of sensor | Image of a part of the sensor | Cross-section |
|---|---|---|---|
| 1 | Embroidery sensor, Silver yarn |  |  |
| 2 | Printing sensor, Goretex membrane |  |  |
| 3 | Printing sensor, Softshell membrane |  |  |
| 4 | Sensor sputtered with silver magnification 1500x. |  |  |

ing, marking, and labeling. The printing system was chosen due to the relatively large particles of silver, which allowed to obtain electroconductive layers on the textile substrates at a small temperature (25 °C). The average value of the resistance of the partial sensors produced on a knitted base was 0.9 Ω/cm and on a Goretex substrate – 1.1 Ω/cm. Results for the printing sensor on the Goretex membrane are presented in ***Table 3, no. 2***. Results for the printing sensors on the Softshell membrane are presented in ***Table 3, no. 3***.

**Sensor manufactured by the (PVD) sputtering method**

Physical vapour deposition technology involves the evaporation of metal or cathode sputtering in a vacuum while ionising gases and metal vapour or their phases from the plasma [6, 9].

In this research textile substrates modified by PVD (resistance evaporation), which is a classic technique called puttering. Before the PVD process, the specimens were preconditioned at 22 °C and 55% relative humidity. The process of applying metal was made in a vacuum chamber. The conditions for this process were the following: initial vacuum – 0.0005 Pa, time of metal deposition – 5 minutes, and metal deposited – Ag of 99.99% purity. Thermal metal evaporation was performed from the resistive boat installed inside the chamber.

All samples were mechanically washed before application of the metal layer to eliminate additional contaminants from the substrate surface, which allowed to achieve good adhesion to the substrate

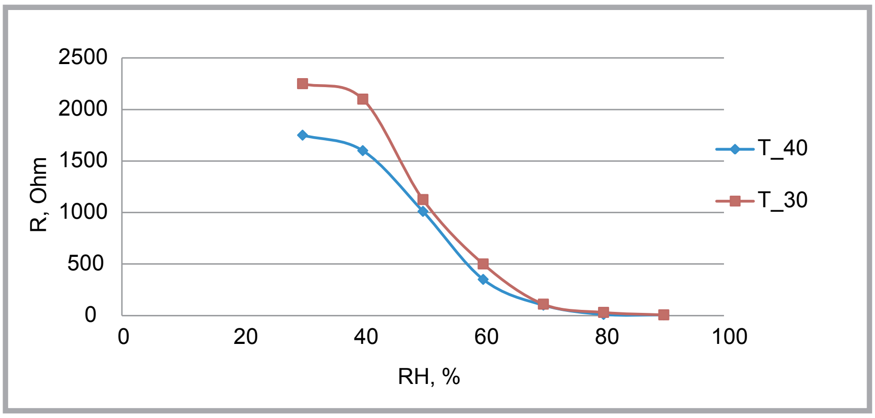



***Figure 3.*** *Average characteristics of resistance changes under the influence of relative humidity changes for the embroidery sensor (SSE).*

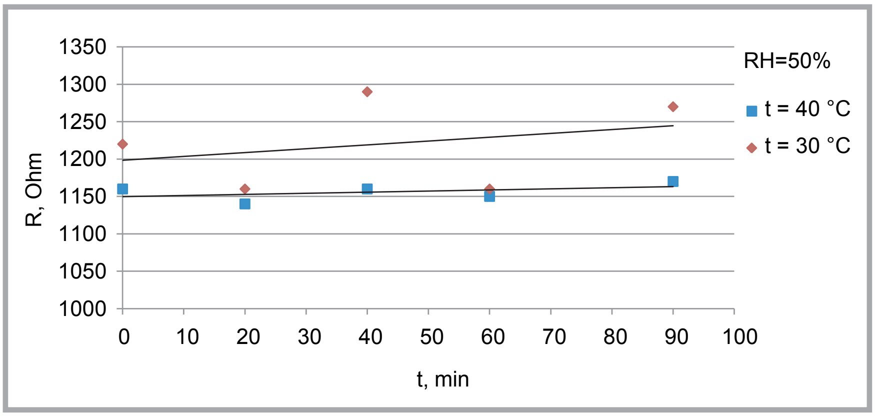



***Figure 4.*** *Analysis of the embroidery sensor's stability at RH = 50%.*

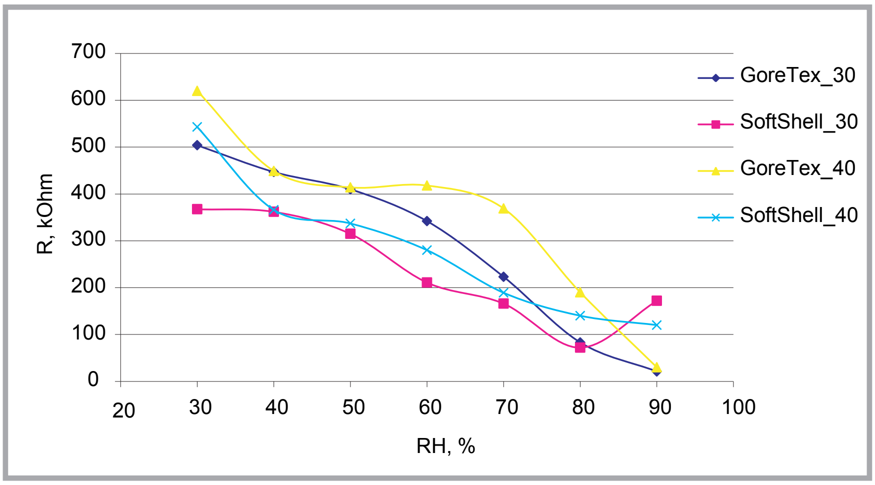



***Figure 5.*** *Average characteristics of resistance changes under the influence of relative humidity changes for the printing sensors (SGP, SSP).*

***Table 4.*** *Statistical analysis of results obtained for textile sensors for such parameters as $R_{av}$ – average sensor resistance at RH – 50%; $e_{max}$ – largest correction value; U – measurement uncertainty.*

| Sensor | $R_{av}$ | $e_{max}$ | U |
|---|---|---|---|
| SGV | 369.27 Ohm | 10.52% | 11.37% |
| SGP | 297.65 kOhm | 7.89% | 5.93% |
| SSP | 1217.25 kOhm | 9.12% | 6.74% |
| SSE | 2.72 MOhm | 16.2% | 13.23% |

[15]. Microscopic images of the humidity sensor produced are presented in ***Table 3, no. 4***.

## Research

Five replications were carried out for each temperature (30 °C, 40 °C). The diagrams in ***Figures 3, 5*** and ***7*** present the average characteristics of resistance changes as a function of the relative humidity changes. Stability parameters of the sensors at both temperatures (30 °C, 40 °C) and at the humidity point (RH = 50%) were also studied, average results for which are presented in ***Figures 4, 6*** and ***8***.

The static characteristic of the sensor is given by the relationship $y = f(x)$, where, $x$ – the input quantity (ambient humidity), $y$ – the measurand (resistance of sensor). If $y \in [0, Y_m]$, then the measuring nominal range of the sensor is equal to the range of the nominal indication interval, given as $Y_m$.

In order to identify the mean real characteristic, it was necessary to set standard values $n$ of the measurand $x_{wi}$ $(i = 1, ..., n)$, which would be ordered in an increasing series, thus $x_{wi+1} > x_{wi}$. By measuring a value corresponding to the standard value, it was possible to find the successive values of $y(x_{wi})$ from $i = 1$ to $i = 7$, to obtain the relationship $y_g(x_w)$. Then, in the range of $i = n - 1$ to $i = 1$ and for $y_d(x_w)$, $y_g(x_w) \neq y_d(x_w)$ was obtained, which was caused by the occurrence of the hysteresis phenomenon. That operation should be repeated not less than $k = 3$ times. In research presented it was $k = 5$, as a result of which the mean real characteristic was obtained. Next was determination of the measurement uncertainty at the point of the largest correction value ($e_{max}$). At the point of the static characteristic, $(x_{wm}, y(x_{wm}))$, corresponding to the largest absolute value of the correction, a series of measurements of the standard value, $x_{wm}$, were made under repeatable and reproducible conditions. Statistical analysis of the results obtained is presented in ***Table 4***.

Based on the results presented, the sensor chosen was the one with the smallest uncertainty, which was the (SGP) Goretex printing sensor.

In further research, tests were carried out for that sensor under laboratory conditions close to real. The author conducted tests with a group of volunteers at the age of 20-35. During the study, volunteers tested clothing with humidity sensors placed on the back. The study was performed on stationary bikes. A schematic of the research stand is presented in ***Figure 9***. The parameters measured were the frequency of the pulse respiratory rhythm, and the underclothing humidity and temperature. The research volunteers maintained a constant level of effort (pulse = 110) over a period of 30 minutes. As a reference sensor, an HMP50-L probe and Keithley 6517A electrometer were used. A computer was also used as a recording device. Examples of test results are presented in ***Figure 10*** ( RH changes during the rest period) and ***Figure 11*** (RH changes during the active period).

In the initial test phase (for the rest condition), at a low humidity (RH < 50%), the difference between measurement results of the textile sensor and reference sensor was 15% ± 6%. In the increased effort phase the difference was 4.5% ± 6%.

## Discussion and conclusions

During this work, four kinds of humidity sensors were prepared with the use of two variants of textile base materials and electrical silver modifiers. Three different methods of manufacturing were considered for constructing the humidity sensors: embroidery, printing and sputtering (PVD). These prototype sensors were of the resistive kind. The humidity sensors produced were characterised by a surface resistance per unit area of several ohms. The sensors created by the different techniques varied in their electrical parameters (resistance) depending on the humidity changes for the two research temperature points (30 °C, 40 °C). These temperature points were selected according to the sensor's working temperature, similar to that of the human body.

In the results presented, the sputtering sensor had the most linear static characteristic, but in a narrow range of humidity measured (30%-70%). The printed and embroidery sensors' characteristic was not monotonic and was nonlinear. In all cases the stability of electrical properties of the textile sensors depended on the substrate (membranes) and working temperature conditions. Another difficulty

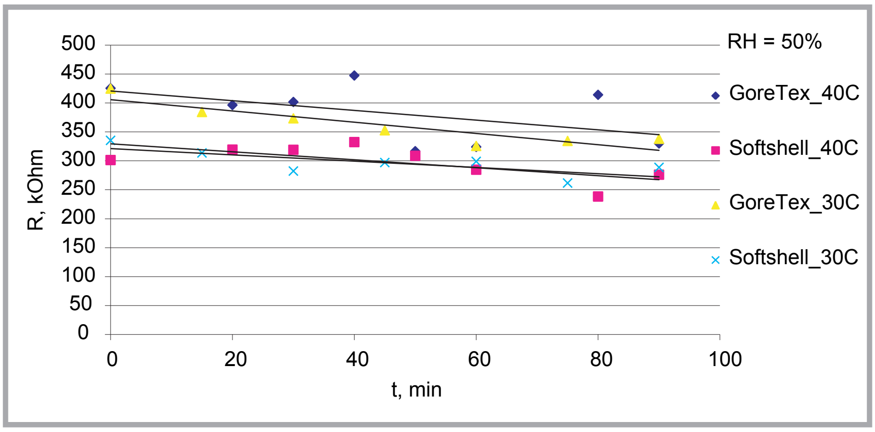



***Figure 6.*** *Analysis of the printing sensor's stability at RH = 50%.*

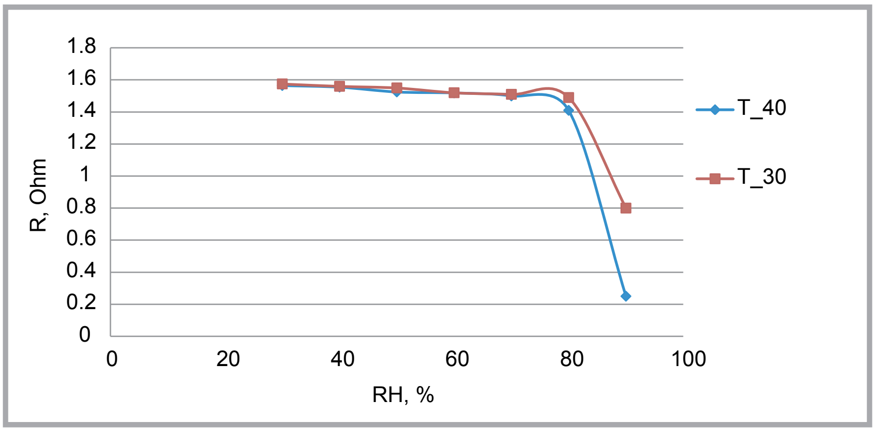



***Figure 7.*** *Average characteristics of resistance changes under the influence of relative humidity changes for the sputtering sensor (SGV).*

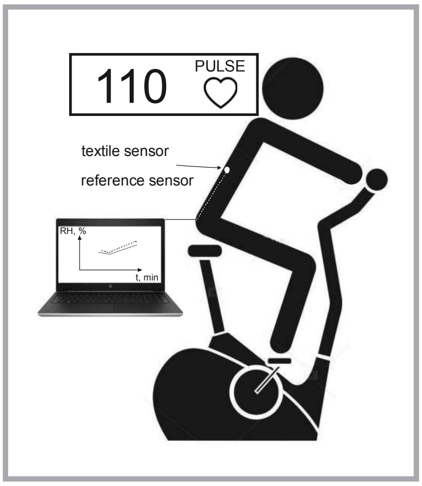



***Figure 9.*** *Stand for active tests of humidity sensors.*

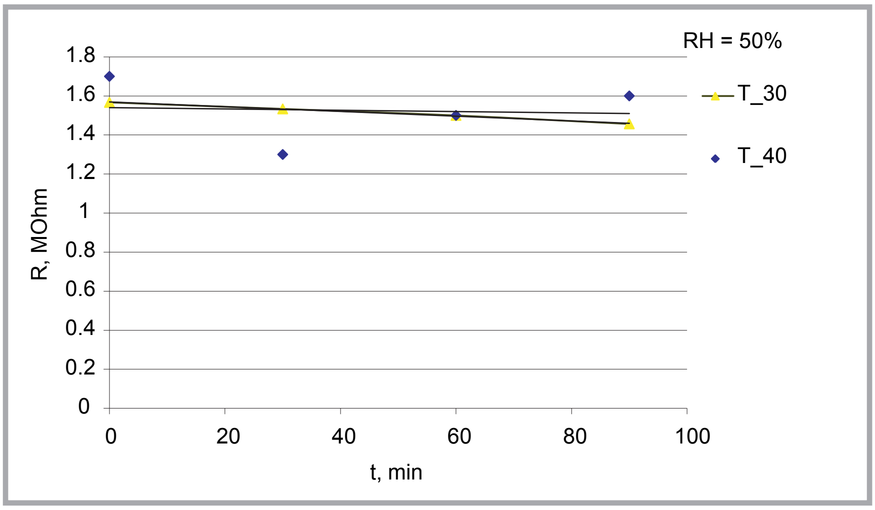



***Figure 8.*** *Analysis of the sputtering sensor's stability at RH = 50%.*

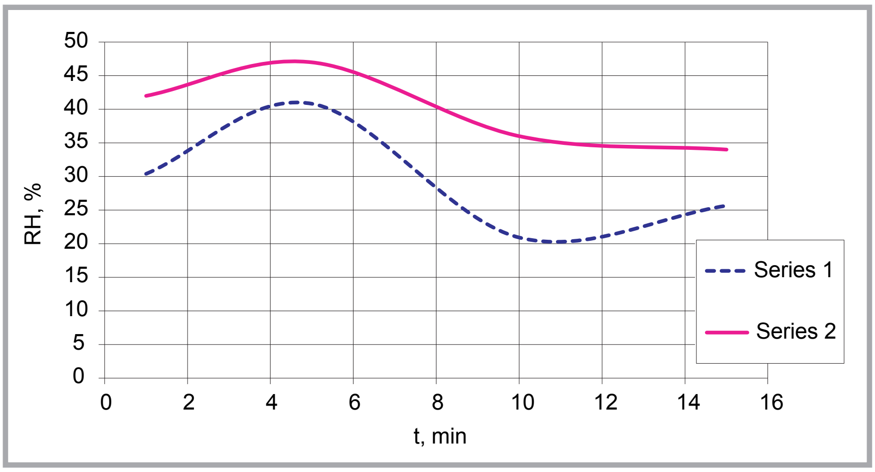



*Figure 10. RH changes during the rest period. Series – 1 SGP textile sensor; series – 2 reference sensor.*

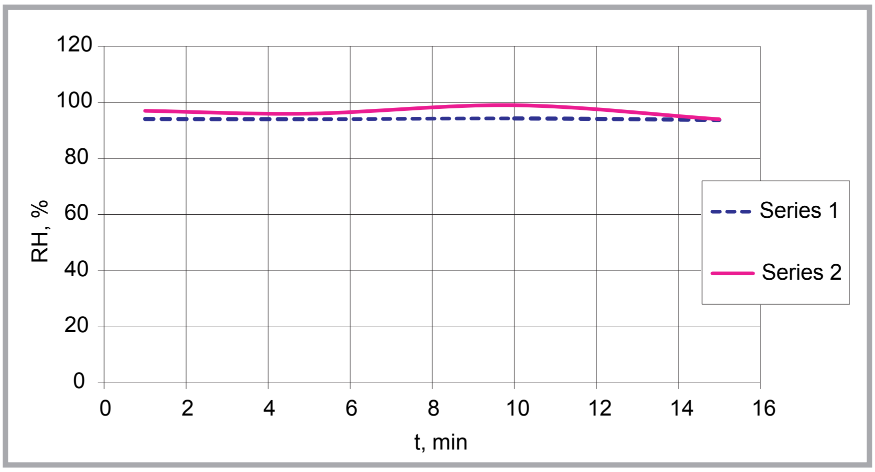



*Figure 11. RH changes during the active period (Cycling, pulse: 110) Series – 1 SGP sensor; series – 2 reference sensor.*

was adjusting the technology depending on the textile substrate. PVD technology did not allow to obtain electroconductivity of the tracks on knitted soft-shell materials. Only the printing technique was suitable for the two textile substrates. From statistical analysis presented, the author chose the sensor with the smallest uncertainty (5.93%) and correction value (7.89%), which were obtained for the Goretex printing sensor (SGP).

The functional tests demonstrated the suitability of the selected SGP sensor for smart clothing applications. The tests showed the usefulness of the textile sensor in sportswear. Especially, in the phase of increased effort, the difference between measurement results of the textile sensor and the reference sensor was 4.5% ± 6%, which is a satisfactory value. This type of sensor can be used, for example, for a hydration monitoring system.


## Acknowledgements

*This work was supported by funds within the framework of the LIDER IV project: "Textronics system for protecting elderly people", financed by The National Centre for Research and Development.*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***Received 13.02.2019 Reviewed 03.12.2019***