$RuO_2/Bi_2Ru_2O_7$ THICK-FILM STRAIN SENSOR WITH LOW-TEMPERATURE SENSITIVITY

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Structural health monitoring that gathers information about performance and conditions of civil engineering structures requires implementation of sensor networks that include strain sensing devices. This paper introduces $RuO_2/Bi_2Ru_2O_7$ thick-film strain sensor with low-temperature sensitivity. Under strain, $RuO_2/Bi_2Ru_2O_7$ thick resistive film experiences reversible deformation that can be registered as a change in film resistivity. Based on that effect, a prototype of the strain sensor is being realized and evaluated. Evaluation included measurements of the resistance change under applied strain, determination of the gage factor and investigations of sensor's temperature coefficient of resistance and thermal stability.

Keywords: structural health monitoring, strain sensor, $RuO_2/Bi_2Ru_2O_7$ thick resistive film, temperature coefficient of resistance, thermal stability.

1. Introduction

Structural health monitoring (SHM) refers to provision of accurate and semi-real-time information about performance and conditions of various civil engineering structures, such as buildings, bridges, roads, etc., in order to prevent the potential dangers by detecting them in time. SHM systems are based on sensor networks that collect information about the degree of strain in estimating risks of structural damage and collapse.

In recent years, thick-film strain sensors are often being used for these purposes because of their good strain sensitivity, stability, reliability and low manufacturing costs [1, 2]. Since strain sensors for structural health monitoring are usually deployed on primary locations, such as columns, walls and ceilings of a building, there is a number of factors that have negative effect on their performance. A major problem for strain sensors for SHM applications is the cross-sensitivity of temperature and strain because of day-night and seasonal temperature variations. This problem can be eliminated by employing materials that are less sensitive to temperature instead of using temperature compensation. For these reasons, a prototype of $RuO_2/Bi_2Ru_2O_7$ thick-film strain sensor with low-temperature sensitivity has been realized. Obtained results are presented in this paper.

2. Experimental results

Thick-film strain sensor (Fig. 1, *a*) was realized using 10 kΩ/sq $RuO_2/Bi_2Ru_2O_7$ resistive thick-film composition in combination with Pd/Ag conductive composition. Devices were formed on 96% Al_2O_3 substrates using conventional thick-film screen printing techniques. Resistive film was 21 mm long and 3 mm wide, with six pads that divided resistor into 7 identical sequences (3×3 mm).

After screen-printing, leveling and drying in an infrared conveyer belt drier, 25 μm thick dry samples were fired in a thick-film firing conveyor belt furnace in 30 min cycle with 10 min dwelling time at peak temperature of 850°C.

Prototype samples were realized and all measurements were performed at the Institute for electronics and telecommunications IRITEL a.d. Belgrade, Serbia.

Resistances of the thick-film strain sensor were measured using an HP34401A instrument. The straining was simulated using a custom-made device that allowed substrate deflection of up to 300 μm —

maximum reliably obtainable deflection for the substrate material in question (Fig. 1, *b*). The resistive film was centrally positioned on a substrate that was fixed on both ends providing maximum straining.

Gage factor *GF* of the strain sensor as a measure of the strain sensitivity was calculated using [3]

$$GF = \frac{\Delta R}{R\varepsilon_{\max}} = \frac{\Delta Rl}{R\Delta l} = \frac{\Delta RL^2}{6Rdt}, \tag{1}$$

where $\Delta l/l$ designates the relative change of the film length due to substrate deflection d, t is the substrate thickness, and L is the distance between fixed substrate ends.

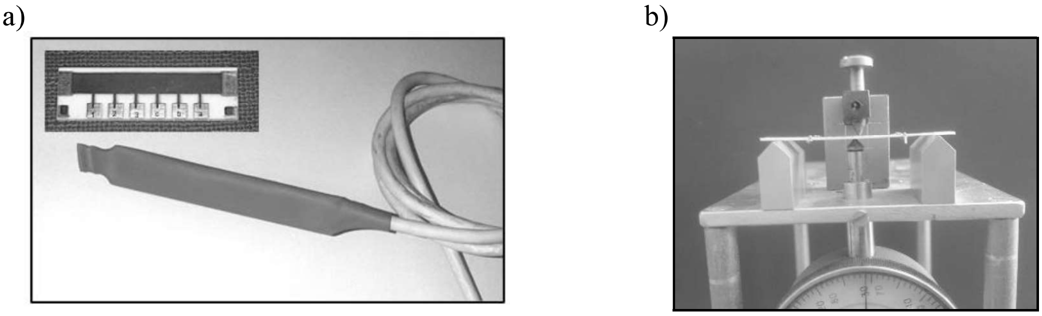

Fig. 1. Thick-film strain sensor (*a*) and sensor straining simulation (*b*)

All strain sensitive materials and processing parameters were carefully evaluated and selected to obtain optimum sensing performances. Gage factor of the device is sensitive to the conducting phase choice, maximum temperature and dwelling time of the firing process. Interface of the conducting and resistive film can also affect strain sensitivity of the device due to the doping effect.

It should be mentioned that gage factors lower than 2.5 are due to geometrical change in resistive film volume induced by elongation [4]. Since thick resistive film has a gage factor greater than 2.5, elongation affects its microstructure, and thus the conduction processes taking place in the resistive film. Strain sensitivity of the ongoing conducting processes (metallic conduction and tunneling processes [5, 6]) depend on the stiffness of the insulating and conducting phases. The bulk modulus of the conducting phase of the film has significantly higher values than bulk modulus of the glass phase [7]. Therefore, metallic conduction has lower strain sensitivity than the tunneling process, and performance of the sensor is governed by the strain sensitivity of the tunneling process.

Chosen for its specific conductive and insulating phase ratio, elongated custom-made 10 kΩ/sq resistive film exhibits reversible resistance change, as shown in Fig. 2. Straining of 300 μm caused relative resistance change of approximately 0.32% in the operating temperature range. Gage factor of the device was ≈5.

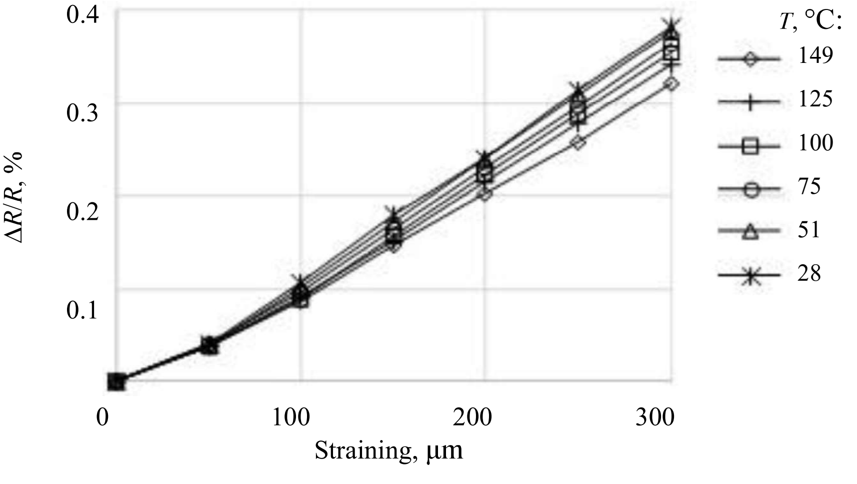

Fig. 2. Relative resistance changes vs. resistive film straining for full length sensing film at various temperatures

In order to explore how the film length affects the sensing performance of the strain sensor, relative resistance change of the device was measured between the following conducting pads: 1-a, 2-b and 3-c (Fig. 1, *a*) for three segments designated R_1, R_2 and R_3 respectively. The obtained results are shown in Fig. 3.

Resistance change was within the 0.26—4% range. It was observed that the segment with the highest initial resistance experienced the smallest relative resistance change. The observed behavior was due to a presence of thin resistive film lines (0.3 mm thick) perpendicular to the body of the element whose width increased with the applied strain.

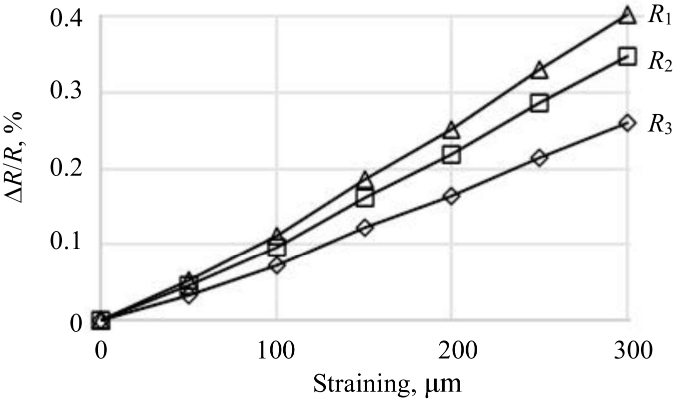

Fig. 3. Relative resistance changes vs. resistive film straining
for three different resistive film segments

In order to further explore whether resistance of the thick resistive film changes with variations in temperature, temperature coefficient of resistance was calculated using the following equation:

$$TCR = \frac{R(T_2) - R(T_1)}{R(T_1)\,(T_2 - T_1)} . 10^6 \text{ ppm/°C}, \quad (2)$$

where $R(T_i)$ is the film resistance R at specific temperature T_i. *TCR* values for strained devices are shown in Fig. 4 for temperatures of 25 and 125°C. It can be seen that cold *TCR* does not depend on the applied load and that *TCR* values of the thick-film are close to constant.

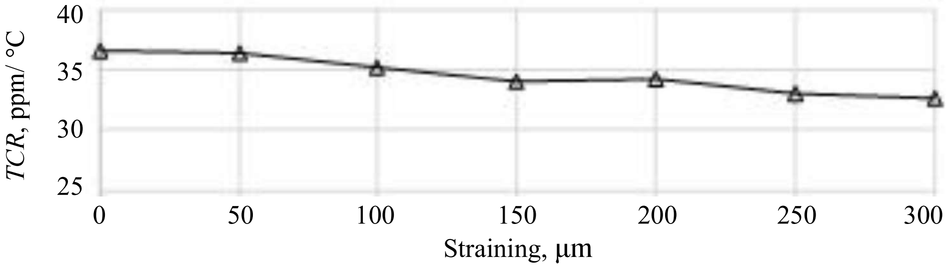

Fig. 4. TCR vs. thick resistive film straining for temperatures from 25 to 125°C

As for temperature stability, the thick-film devices were subjected to operating temperatures in the range from 25 to 150°C. Results presented in Fig. 5 show that an increased operational temperature does not interfere with the sensing performance of the device. Temperature dependence of the resistance depends on the nature of the insulating phase and additives used in the production process. Higher temperatures cannot affect operation of the device since softening of the glass phase requires temperatures close to 500°C. It should be pointed out that strain sensors for SHM operate at ambient temperatures and, as an example, road temperatures in dry hot areas do not exceed 70°C [8].

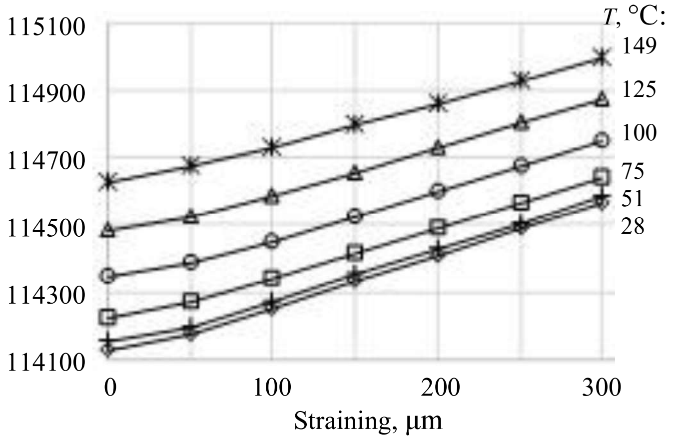

Fig. 5. Resistance change vs. temperature for strain sensor subjected to straining at various temperatures

3. Conclusion

Structural health monitoring requires employing strain sensors with low-temperature sensitivity. For this purpose, a prototype of thick-film strain sensor with low-temperature sensitivity has been realized. The device is based on $RuO_2/Bi_2Ru_2O_7$ resistive thick-film composition screen-printed on 96% Al_2O_3 substrate. Under strain resistive film experienced reversible deformation that was registered as a change in film resistivity. An analogue signal that was being created was proportional to the pressure applied to the device. Gage factor of the device was ≈5 due to geometrical change in resistive film volume induced by elongation. Sensing device was thermally stable and its TCR did not depend on the applied load. Further investigations will include the in-situ testing, where the sensors will be deployed on civil engineering structures in two ways — either embedded in the material or glued to the material surface with forces applied parallel and perpendicular to the surface of the sensor.

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Товстоплівковий датчик на основі $RuO_2/Bi_2Ru_2O_7$ з низькою температурною чутливістю

Моніторинг стану будівель для отримання інформації про експлуатаційні характеристики та їхній стан потребує використання сенсорних мереж, до складу яких входять датчики напруги. У цій роботі представлено товстоплівковий датчик напруги на основі $RuO_2/Bi_2Ru_2O_7$ з низькою температурною чутливістю. Через напруження товста плівка на основі $RuO_2/Bi_2Ru_2O_7$ зазнає зворотної деформації, яка проявляється як зміна опору плівки. На основі цього ефекту було реалізовано прототип датчика напруги. Дослідження датчика полягало у вимірюванні зміни опору внаслідок прикладення напруги, визначення стресових факторів та перевірку температурного коефіцієнта опору датчика та його температурної стабільності.

Ключові слова: моніторинг стану конструкцій, датчик напруження, товста резистивна плівка $RuO_2/Bi_2Ru_2O_7$, температурний коефіцієнт опору, температурна стабільність.