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INKJET PRINTED RESISTIVE STRAIN GAGES ON FLEXIBLE SUBSTRATES

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Abstract. *In this paper, resistive strain gages designed and fabricated in inkjet printing technology with three different silver nanoparticle inks are presented. Inks have different Ag content (15, 20 or 25 wt%) and solvents (water type or organic type). Strain gages were printed on a 50 µm thick polyimide and 140 µm thick PET-based substrate with different printer types (professional and desktop). All printed sensors have the same size (17 mm × 5 mm). To determine the change of resistance due to bending of the steel beam, tensile tests were performed up to 1500 microstrains. Due to performed cycles of loading and unloading of the steel beam, gauge factor and stability of the response of the strain gages are measured. Resistance change was measured with Keithley SourceMeter 2410. For acquisition of measured data, in-house software tool was developed. Measured gauge factors of the sensors are in the range between 1.07 and 2.03 (depending on a used ink, substrate and printer). Results of this research indicate the strain gages with good GF can be produced even with low-cost equipment, such as desktop printer EPSON C88+ and PET-based substrate.*

Key words: *resistive strain gage, inkjet printing, silver nanoparticles, flexible substrate*

1. INTRODUCTION

Strain sensors are one of the most critical devices required for structural health monitoring, damage detection, condition-base maintenance and failure prevention. Although some promising technologies are emerging into the market, still about 50 % of all strain sensors rely on a strain gage principle. Strain gage provides benefits, like low price, simple measurement circuits and easy configuration etc.

Strain sensors can be fabricated in different technologies. In [1], Pt and NiCr strain sensors with Cu interconnection lines were fabricated on polyimide sheets using a DC magnetron sputtering system, and a base pressure in a 10^{-7} Torr range. Sensors and interconnections were photolithographically patterned, using either a lift-off process (with

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a negative photoresist) for Pt and NiCr, or by a chemical etching (and a positive photoresist) for Cu interconnection lines. These Pt thin film sensors have gauge factor *GF* ≈1.7. In [2], an aerosol-jet printing was applied to fabricate strain sensors. Using the maskless fine feature deposition characteristics of this printing technology and a pre-cure protocol, strain sensors were successfully printed onto carbon fiber prepregs, to enable fabricating composites with intrinsic sensing capabilities. Measured *GF* of these sensors was in the range 2.2 ± 0.06. Strain sensing architectures, such as smart flexible sensors adapted to textile structures, are able to measure their strain deformations. The optimization of the sensors, in terms of dimensions, geometry, preparation process, and filler concentration, has led to a sensitive, reliable strain gage, which can be easily deposited on any flexible substrate, such as a textile fabric [3].

The advantages of inkjet printing technology are high-speed of the process, the efficient use of ink materials, patterning capability, and the fact that thin films can be printed on flexible substrates, at low costs. Results obtained from the characterization survey showed coherence between the expected trend and the experimental behavior, and have encouraged future efforts towards the use of inkjet printing technology for the rapid prototyping of strain gages and other sensing architectures [4].

In our previous research, we fabricated and compared resistive and capacitive strain gage sensors [5]. Both were fabricated on polyimide substrate using inkjet printing technology. However, the capacitive sensors proved to be ineffective for measuring strain on metallic specimen, due to parasitic capacitance.

The aim of this work was to investigate the influence of three different nanoparticle inks and flexible substrates on the characteristics of single-element gages. Some improvements in design were introduced, in order to provide better stability of structures. The response was measured up to 30 minutes period.

Gages can be integrated into light-weight structures for purpose of monitoring. Focus of this investigation was on inkjet silver inks and flexible substrates for sensing tensile and compressive strain on the steel surface.

2. Strain Gages Fabrication

The printing of inks, especially those containing silver nanoparticles, has been found to be a crucial tool for direct patterning of electrically conductive interconnections in electronic devices [6-8]. A drawback for the widespread application of printing processes is the availability of suitable printable materials. A formulation of a suitable ink is a critical phase, as the performance or quality of the printing process strongly depends on the ink. A low tendency for sedimentation and properly adjusted behaviour of the liquid carrier matrix are essential for a reliable printing process [9].

First two series of tested strain gages were fabricated in one layer. They were printed with the Dimatix DMP3000 printer using 10 pL nozzle volume cartridge. Printing was performed in a horizontal configuration instead of a vertical one. As printing head move along horizontal axis, ink drops onto substrate moving along the same axis, which leads to better printing results. Similar printing solution is presented in [10]. Samples were printed in 1016 dpi resolution, on 50 µm thick polyimide substrate, Apical GTS AV [11]. Key properties of this substrate are shown in Table 1.

The third series of strain gages were fabricated in one and two layer using Epson Stylus C88+ desktop printer with 180 nozzles and ink droplet size small as 3 pL. Gages were printed in 2000 dpi resolution on 140 µm thick PET-based substrate (Novacentrix Novele™ IJ-220) [12]. These series of strain gages present an example of low-cost sensor manufacturing process using low-cost equipment. Short developing time is additional advantage. PET-based substrate properties are shown in Table 2.

Table 1. Specifications of Apical 200 AV polyimide substrate.

Property	Value
Nominal thickness (µm)	50.8
Tensile Modulus (GPa)	2.8
Tensile Strength (MPa)	293
Elongation (%)	104
Coefficient of thermal expansion (ppm/ºC)	32
Yield (m^2/kg)	55

Table 2. Specifications of Novele™ IJ-220 PET-based substrate.

Property	Value
Basis weight (g/m^2)	175±10
Caliper (µm)	140±12
Smoothness Bekk (Sec.)	>1000
Stiffness (mN·m)	0.5±0.3

The first series of tested strain gages were printed in previously mentioned resolution, which corresponds to 25 µm drop spacing, and showed to be an optimal solution in terms of avoiding ink spillage and achieving uniform structures. Amplitude of the driving waveform was 23 V and the frequency was 2 kHz. The ink U5603 was made of silver nanoparticles (with 20 % wt of silver) and capped with a polymer coating that keeps the particles in a colloidal suspension, by Sun Chemical Corporation [13]. In the manufacturers' technical specifications, it is stated that the ink has a specific resistivity in the range of 5-30 µΩcm. To avoid rapid evaporation of the printed structures during sintering, they were firstly left to dry for 30 minutes at room temperature. After the printing process was finished, the samples were put in an oven and sintered for 45 minutes at 240°C.

The second series of tested strain gages were printed with water-based silver nanoparticle ink JS-B25HV, produced by Novacentrix with 25 % wt of silver [14]. This is an electrically conductive ink, with 2.8 µΩcm film resistivity, designed to produce circuits on porous and non-porous substrates including inkjet papers, PET, polyimide, and glass. JS-B25HV ink is specially formulated for compatibility and stability with Dimatix print heads. Drop spacing was kept the same (25 µm), but the amplitude of driving waveform was 30 V and the printing frequency was 1 kHz. The samples were sintered for 30 minutes on 270°C, as recommended by the manufacturer.

The third series of strain gages were printed with water-based silver nanoparticle ink JS-B15P, produced by Novacentrix with 15 % wt of silver [14]. Ink has 4.5 µΩcm film resistivity, and it is designed to produce circuits on porous substrates such as paper and Novele™ (a coated PET). Samples printed in one layer were sintered for 30 minutes on

100°C, while the samples printed in two layers were printed for 60 minutes also on 100°C. Detailed physical properties of used inks are shown in Table 3.

Design of printed strain gages in this paper is improved compared to the design presented in our previous research [15], by increasing the length of the end loop. Proposed length of strain gage end loop is five times longer than grid track width. Since the creep behavior depends on parameters such as gage material, adhesive thickness, cantilever material and design of strain gage, it is necessary to make additional measurements for our inkjet fabricated gages to determine which ratio of end loop length and track width is the most appropriate, so the creep behavior been reduced to a minimum. The contact pads design are also changed and placed inside the overall sensor area (Fig. 1). They have a taper section to adjust slowly the current density distribution. A photograph of sensor was taken with the 3.0 megapixels Moticam 2300 camera on a wafer probe station. Geometrical parameters of the strain sensors are presented in Table 4.

Table 3 Typical physical properties of silver inks [13], [14].

	Ink U5603	Ink JS-B25HV	Ink JS-B15P
Silver content (wt %)	20	25	15
Resistivity (μΩcm)	5-30	2.8	4.5
Viscosity (cP)	10-13	8	4
Surface tension (dynes/cm)	27-31	30-32	30

Table 4 Geometrical parameters of the strain gages.

	Dimensions
End track width	0.677 mm
End loop width	0.979 mm
Track width	0.205 mm
Track spacing	0.217 mm
Track length	9.574 mm
Number of turns	N=8

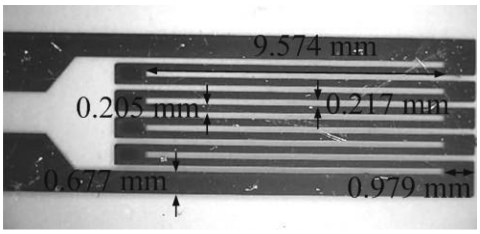

Fig. 1 Representative sample of strain gages with geometrical dimensions

3. MEASURING PRINCIPLE

The terms stress and strain ε (1 $\mu\varepsilon = 10^{-6}$ m/m) are used to describe deformations of solid materials. When the strain is not too large, most of the solid materials behave like linear springs, and the displacement is proportional to the applied force. If the same force is applied to a thicker peace of solid material, the spring is stiffer and the displacement is smaller. This leads to a relation between force and displacement that depends on the dimensions of the material [16].

The resistive strain gage is a physically simple device, which can be easily applied in a straightforward manner for elementary measurements of surface strains [17]. These devices provide a suitable way to test new materials for their strain sensitivity by bonding the gages to a beam with a known strain behavior. The strain of the beam increases with the distance from the point of the applied force. Maximal deflection δ_{max} for elastic deformations of the used steel beam 67SiCr5 [18] is approximately 50 mm (which is greater than the maximal deflection of 15 mm applied in this research).

Tested strain gages were mounted close to the fixed end, where the strain ε has the greatest value and equals to:

$$\varepsilon = \frac{6 \cdot (L_{beam} - z) \cdot \delta \cdot h}{4 \cdot L_{beam}{}^{3}}, \tag{1}$$

where δ is the deflection, h is the cantilever thickness, z is the distance from the fixed end of the cantilever to the middle of the strain gage, and L_{beam} is the length of the cantilever, as shown in Fig. 2. Deflection was controlled with screw mechanism at the free end of the cantilever, where two turns bend the cantilever for exactly 1 mm. Deflection is measured with digital sliding caliper Kern IP54. The relative resistance change is equal to:

$$\Delta R / R \approx GF \cdot \varepsilon, \tag{2}$$

where GF is the gauge factor of the material and R is the initial resistance of gage.

The gages were bonded on the top side of the steel beam, for measuring tensile strain (denoted with “1”), and on bottom side of the steel beam, for measuring compressive strain, denoted with “2”, by two-component epoxy adhesive (Fig. 2).

In order to quickly and simply test strain gage, Source Meter Keithley 2410 was used for measurement and as a current source (with excitation current of 1 mA). Control software tool “KSM 2410 RC” was developed for acquisition of measured data. It was written using National Instruments LabVIEW software. The measuring principle is shown in Fig. 3.

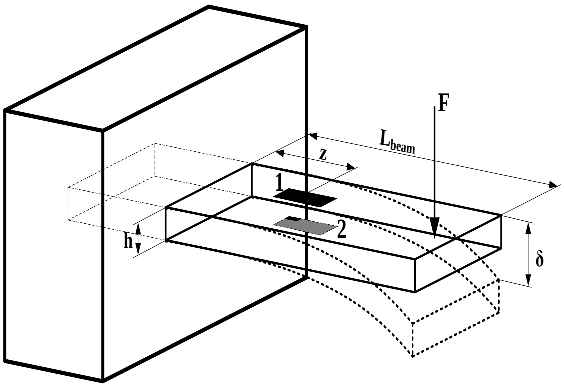

Fig. 2 Gages placement for measuring tensile (gage denoted with “1”) and compressive (gage denoted with “2”) strain.

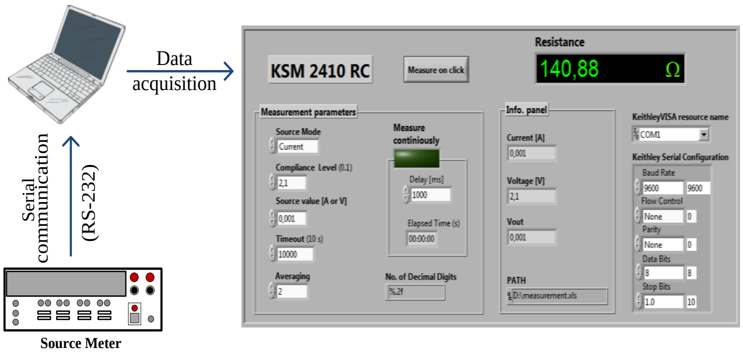

Fig. 3 Principle of data acquisition using Keithley Source Meter 2410 and control software tool.

In our previous work [8], we have presented a bridge as an alternative for measuring small resistance changes accurately. The sensor placement, as shown in Fig. 5, enables the best response when the load is applied and its temperature compensation [19]. The testing gages were connected in a full-bridge Wheatstone circuit, where the differential output voltage can be approximated as

$$V_{out} \approx GF \cdot \varepsilon \cdot R \cdot I_{SET}\,, \tag{3}$$

where I_{SET} is the set excitation current and R is the initial resistance, ideally the same for all the resistors. Since the output of the full Wheatstone bridge is a differential voltage, an instrumentation amplifier is used. For a low noise signal acquisition, it was used INA122PA instrumentation amplifier due to its high amplification and low offset voltage [20]. To suppress the supply ripple and high frequency interference, it was used low-pass active filters made with LM224 quad operational amplifier, as shown in Fig. 6.

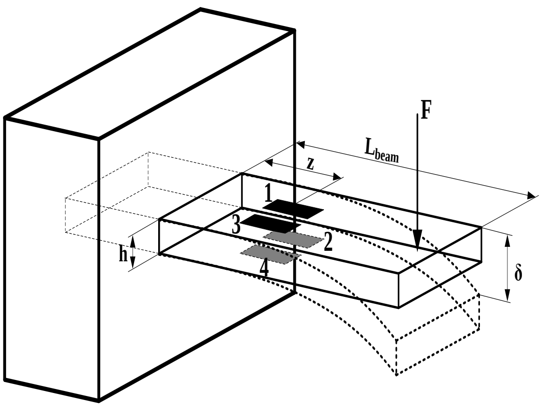

Fig. 5 Cantilever with four placed strain gages (1, 2, 3 and 4) connected in a full-bridge Wheatstone circuit.

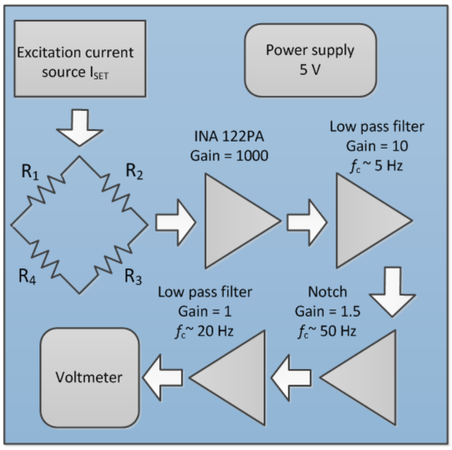

Fig. 6 Block diagram of the developed signal conditioning circuit.

4. Results and Discussion

Measurements were performed on twelve gage samples. Presented results of *GF* are average values of the tested strain gages. Shown microstrain ranges represent ranges where the gages have approximately linear characteristic.

4.1. First series of printed strain gages (Ink U5603, polyimide substrate, Dimatix printer)

Measured Δ*R*/*R* resistance values of first series of printed strain gages are obtained using Keithley Source Meter controlled by developed software tool, are shown in Fig. 7. Average resistance of tested strain gages was 140 Ω. As it can be seen, average *GF*, when the beam is loaded, is 1.07. When the beam is unloaded, average *GF* = 1.03. Results are in accordance with our previous measurements presented in [5], where the measurements were performed with Wheatstone bridge (*GF* was 1.09 when the beam was loaded, and when the beam was unloaded, *GF* was 1.01). In [10], Sunchemical ink was also used for sensor fabrication, and obtained *GF* was around 0.35.

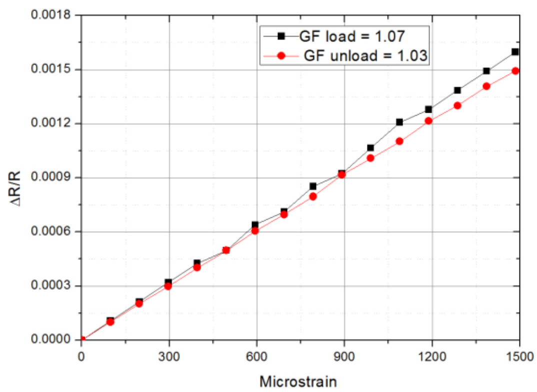

Fig. 7 Relative resistance change *ΔR/R* as a function of the applied microstrain for first series of printed strain gages for the loading (black line) and unloading (red line) of the beam.

4.2. Second series of printed strain gages (Ink JS-B25HV, polyimide substrate, Dimatix printer)

The measurement results of tensile (positive) strain for second series of tested strain gages when the beam is loaded and unloaded are shown in Fig. 8. The measurement results show that when the beam is loaded, average *GF* is 2.03, and when the beam is unloaded, average *GF* is 1.96. As it can be seen, there is a significant increase of gauge factor as compared to the first series of tested strain gages, with a presence of small values of hysteresis. Possible reason for that is because the ratio of strain induced changes in atomic structure of silver nanoparticles ink JS-B25HV to the strain producing them is better than it is for the first ink. Average resistance value of tested sensors was 142 Ω.

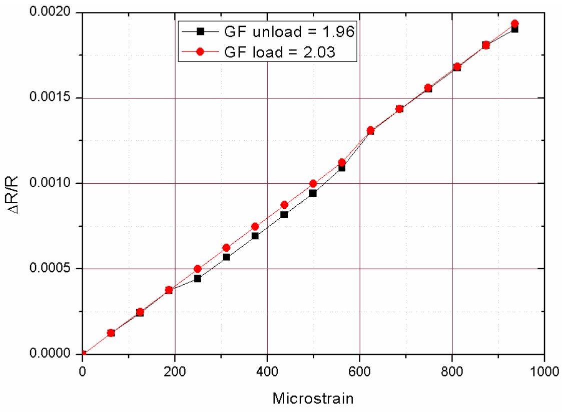

Fig. 8 Relative resistance change *ΔR/R* as a function of the applied microstrain for second series of printed strain gages for the loading (red line) and unloading (black line) of the beam.

In order to investigate compressive (negative) strain, measuring cables were connected to the Cu wires of gage, which was bonded at the bottom side of steel beam. Steel beam was upturned so that the compressive strain was measured also with the upper gage. As it can be seen in Fig. 9, average gauge factor is lower than when measuring tensile strain, and it is *GF* = 1.59. Tested gages have linear characteristics up to approximately 1400 microstrains.

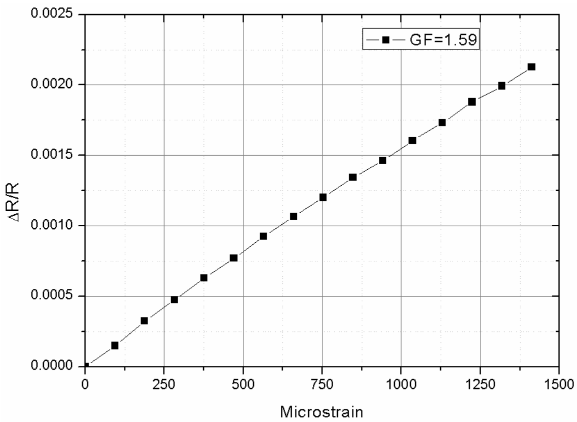

Fig. 9 Relative resistance change *ΔR/R* as a function of the applied microstrain for compressive strain for second series of tested strain gages.

In Fig. 10, it is presented a comparison between stability of the response of one representative sample strain gage (from second series of tested gages) and commercial sensor

CEA-06-125UN-350 produced by Micro-Measurements (Vishay Precision Group) [21] under constant deflection of the beam for 30 minutes. Measurements were performed for four deflection steps (0 mm, 5 mm, 10 mm and 15 mm). As expected, the lowest ripple of strain sensors has been recorded for deflection of 0 mm. As it can be seen in Fig. 10, commercial strain sensor has better resistance stability under different beam deflection, because commercial sensors have excellent encapsulation and sensitive grid is made of Constantan.

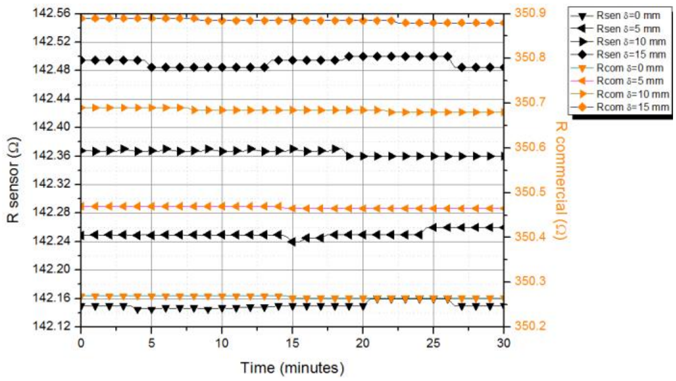

Fig. 10 Time response of one sample strain gage from second series of tested gages (denoted *R sensor*) and commercial sensor CEA-06-125UN-350 by Micro-Measurements (denoted *R commercial*) under constant deflection of the steel beam.

4.3. Third series of printed strain gages (Ink JS-B15P, PET-based substrate, Epson printer)

In Fig. 11, it is shown sensitivity of gages fabricated in one layer, on PET-based substrate with Epson Stylus C88+ printer using JS-B15P nanoparticle silver ink. The average electrical resistance of tested strain gages was 104 Ω. *GF* is slightly higher when beam is loading (~1.94) than for unloading the beam (~1.85). It is expected that, in cycling between a loaded and unloaded condition, there is a some degree of hysteresis.

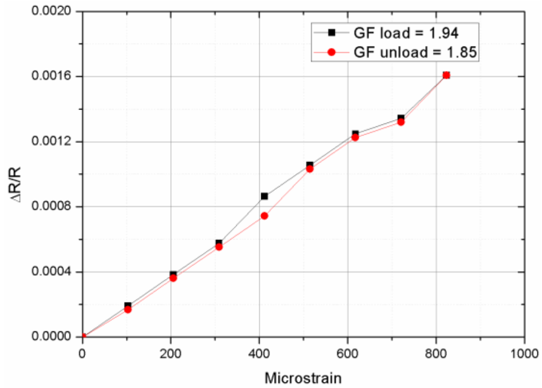

Fig. 11 Relative resistance change *ΔR/R* as a function of the applied mechanical deformation for third series of tested strain gages (one printed layer).

In [4], the realization process uses the Epson desktop printer, “Metalon JS-B15P” ink and PET substrate as printing base. Sensors have estimated *GF* of 1.6 for one printing layer, which is smaller than *GF* obtained with strain gages shown in this work.

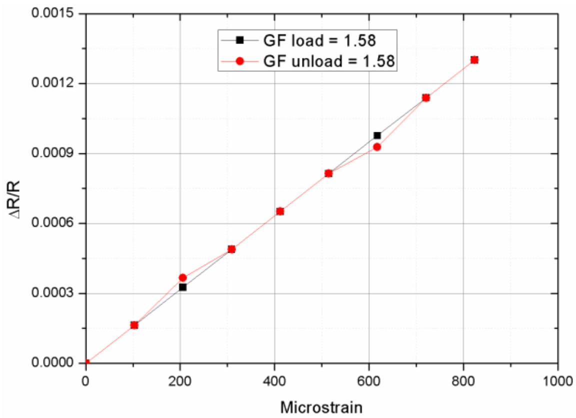

Fig. 12 Relative resistance change *ΔR/R* as a function of the applied mechanical deformation for third series of tested strain gages (two printed layers).

The strain gage printed in two layers has smaller *GF* than gage printed in one layer, but hysteresis is manifestly smaller. Measured *GF* is approximately equal for tensile and compressive strain (~1.58). Average strain gages resistance printed on PET-based substrate in one layer was 104 Ω, while for two layers strain gages was 61 Ω.

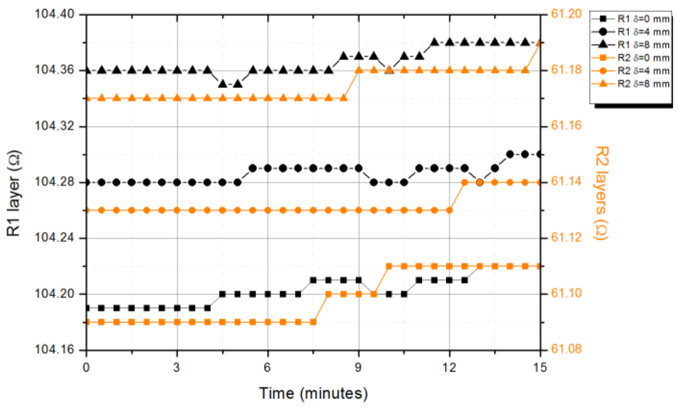

Fig. 13 Time response under constant deflection of the steel beam for one printed layer (*R1 layer*) and two printed layers (*R2 layers*) strain gages.

As it can be seen in Fig. 13, strain gages printed with Epson printer on PET-based substrate are not stable as strain gages fabricated in combination with Dimatix printer on polyimide substrate. Stability measurements were performed for 15 minutes, since after that time readings of gages became unstable. It means that strain gage starts to display resistance values which corresponds to higher beam strains. Strain gage with two printed layers are more stable than gage with one layer, due to thicker and more uniform lines structure.

Beside presented measurements, it was also measured resistance change of printed gages in two month interval in laboratory conditions. It is observed that, at 25-26°C and 55 % of relative humidity, after one month, sensor resistance values decrease from its initial value for 1-1.5 %, after two months, for 2-2.5 % and after three months for 10 %.

Future improvements of the presented resistive strain sensor will be focused on encapsulation and investigation of possible wireless applications with the *LC* circuit.

5. Conclusion

Substrate material choice playing important role in the fabrication of strain gages, since the strain of measuring object is transmitting through the substrate. Strain gages were developed on polyimide and PET-based substrates.

Strain gages mounted on the surface of a metallic test specimen respond only to the strains that occur at the surface of the test specimen. As such, the results from strain gauge measurements must be analyzed to determine the state of stress occurring at the strain gauge locations. *GF* of resistive strain gages printed with three different silver nanoparticle inks onto polyimide and PET-based substrate have been successfully measured and compared. Based on measured results for strain sensitivity, the second series of tested resistive strain gages have the highest strain sensitivity, with average *GF* ~ 2.03, while the corresponding value of *GF* for the first series was around 1.07, and for the third series of strain gages *GF* ~ 1.94 (for one layer) and *GF* ~ 1.58 (for two layers).

The first series of tested gages (printed with ink U5603 based on concentrated dispersion of silver nanoparticles in organic solvent ethanol-ethylene glycol mixture, on polyimide substrate with Dimatix printer) have smaller *GF* than the commercial strain gages, probably because of that the silver nanoparticles exhibit some negative piezoresistive behavior, which is damping the positive resistance change.

The second series of tested gages (printed with water-based ink JS-B25HV on polyimide substrate with Dimatix printer) have much better strain sensitivity, but their stability of the resistance response under constant deflection of the steel beam isn't good as commercial sensors, as it is shown.

The third series of tested gages (printed with water-based ink JS-B15P on PET-based substrate with Epson desktop printer) also have higher *GF* than the first series of tested gages. The most linear strain sensitivity function is achieved for two printed layers on PET-based substrate.

Results of this research indicate the strain gages with good *GF* can be produced even with low-cost equipment, such as desktop printer EPSON C88+, and PET-based substrate. Also, it can be concluded that inkjet printing technology (with various inks, substrates and printers) is suitable for prototyping and development of strain and force sensors, and could be expanded for other sensor types through development of new nanoparticle inks, geometrical printing design and encapsulation of fabricated sensors.

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REFERENCES

[1] D. Lichtenwalner, A. Hydrick, A. Kingon, "Flexible thin film temperature and strain sensor array utilizing a novel sensing concept." *Sensors and Actuators A: Physical*, vol. 135, no. 2, pp. 593-597, 2007.

[2] D. Zhao, T. Liu, M. Zhang, R. Liang, B. Wang, "Fabrication and characterization of aerosol-jet printed strain sensors for multifunctional composite structures", *Smart Materials and Structures*, vol. 21, no. 11, pp. 115008, 2012.

[3] C. Cochrane, V. Koncar, M. Lewandowski, C. Dufour, "Design and development of a flexible strain sensor for textile structures based on a conductive polymer composite." *Sensors* vol. 7, no. 4, pp. 473-492, April 2007.

[4] B. Ando, S. Baglio, "All-inkjet printed strain sensors", *IEEE Sensors Journal*, vol. 13, pp. 4874-4879, December 2013.

[5] C. Zlebic, N. Ivanisevic, M. Kisic, N. Blaz, A. Menicanin, Lj. Zivanov, M. Damnjanovic, "Comparison of resistive and capacitive strain gauge sensors printed on polyimide substrate using ink-jet printing technology", Proc. of 29th IEEE International Conference-MIEL, Belgrade, Serbia, 2014, pp. 141-144.

[6] V. Osch, T. HJ, J. Perelaer, A. de Laat, U. Schubert, "Inkjet printing of narrow conductive tracks on untreated polymeric substrates", *Adv. Mater.*, vol. 20, pp. 343-345, January 2008.

[7] K. J. Lee, B. H. Jun, T. H. Kim, J. Joung, "Direct synthesis and inkjetting of silver nanocrystals toward printed electronics", *Nanotechnology*, vol. 17, no. 9, pp. 2424-2428, April 2006.

[8] D. Kim, S. Jeong, B. K. Park and J. Moon, "Direct writing of silver conductive patterns: Improvement of film morphology and conductance by controlling solvent compositions", *Appl. Phys. Lett.*, vol. 89, pp. 264101-264101-3, December 2006.

[9] M. Maiwald, C. Werner, V. Zöllmer, M. Busse, "INKtelligent printing< UP>®</UP> for sensorial applications", *Sensor Review*, vol. 30, pp. 19-23, 2010.

[10] V. Correia, C. Caparros, C. Casellas, L. Francesch, J. Rocha, S. Lanceros-Mendez. "Development of inkjet printed strain sensors." *Smart Materials and Structures*, vol. 22, no. 10, pp. 105028, 2013.

[11] GTS Flexible Materials, [Online]: http://www.gts-flexible.com/about-gts/apical/

[12] Novacentrix Novele IJ-220, [Online]: http://store.novacentrix.com/Novele_IJ_220_p/910-0070-02.htm

[13] Sun Chemical, [Online] Available: http://www.sunchemical.com

[14] Novacentrix, [Online] Available: http://www.novacentrix.com/products/metalon-inks/silver

[15] C. Zlebic, M. Kisic, N. Blaz, A. Menicanin, S. Kojic, Lj. Zivanov, M. Damnjanovic, "Ink-jet Printed Strain Sensor on Polyimide Substrate", 36th International Spring Seminar on Electronics Technology, Alba Iulia, Romania, 2013, pp. 409-414.

[16] Webster J. G., *The Measurement, Instrumentation, and Sensors: Handbook*, CRC Press, 1999, Chapter 22, pp. 571-589.

[17] Hannah R. L., Reed S. E., *Strain gage user's handbook*, Springer, Cambridge University Press, 1992, Chapter 1, pp. 1-79.

[18] Matbase, [Online] Available: http://www.matbase.com/

[19] R. S. Figliola, D. E. Beasley, *Theory and Design for Mechanical Measurements*, John Wiley and Sons; 5th edition, 2010, Chapter 11, pp. 466-503.

[20] Burr-Brown Corp., "Single supply instrumentation amplifier INA122", 1997, [Online] Available: http://www.datasheetcatalog.org .

[21] Micro-Measurements (Vishay Precision Group), [Online] Available: http://www.vishaypg.com/docs/11224/125un.pdf.