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TEMPERATURE MEASUREMENT PERFORMANCE OF SILICON PIEZORESISTIVE MEMS PRESSURE SENSORS FOR INDUSTRIAL APPLICATIONS

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Abstract. *Temperature and pressure are the most common parameters to be measured and monitored not only in industrial processes but in many other fields from vehicles and healthcare to household appliances. Silicon microelectromechanical (MEMS) piezoresistive pressure sensors are the first and the most successful MEMS sensors, offering high sensitivity, solid-state reliability and small dimensions at a low cost achieved by mass production. The inherent temperature dependence of the output signal of such sensors adversely affects their pressure measurement performance, necessitating the use of correction methods in a majority of cases. However, the same effect can be utilized for temperature measurement, thus enabling new sensor applications. In this paper we perform characterization of MEMS piezoresistive pressure sensors for temperature measurement, propose a sensor correction method, and demonstrate that the measurement error as low as ± 0.3 °C can be achieved.*

Key words: MEMS sensor, temperature measurement, sensor correction

1. INTRODUCTION

The most commonly used temperature sensors for contact temperature measurement in industrial processes are those based on Seebeck effect (thermocouples), and those based on the temperature dependent resistance of platinum (Resistance Temperature Detectors – RTDs). The former do not offer high accuracy (worse than ± 0.5 °C), but have the widest temperature range, while the latter can be of very high performance (better than ± 0.05 °C for Standard Platinum Resistance Thermometers – SPRTs).

In a typical industrial plant both temperature and pressure measurements are required at various points of the process, often at remote locations, while monitoring and control functions are centralized. Industrial telemetry relies on the use of a special kind of

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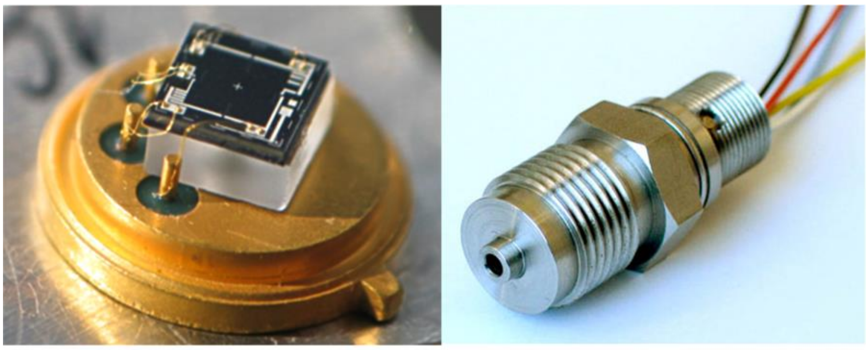
industrial-grade instruments able to transmit their measurement indication in the form of an electrical signal from the measurement site to the control room, and therefore called industrial transmitters.

During the past three decades, industrial pressure transmitters evolved from simple electronic devices that perform analog signal processing and generate an analog output signal to much more complex computerized instruments with two-way digital communication. Contemporary intelligent pressure transmitters owe their high measurement performance to sensor correction techniques based on digital signal processing. In this paper we investigate the possibility of using silicon piezoresistive MEMS pressure sensors for temperature measurement, utilizing hardware resources already existing in contemporary intelligent pressure transmitters. Some early results of our work were presented in Ref. [1], while this paper contains more comprehensive information based on measurement data obtained for a new set of sensors.

Research of silicon MEMS piezoresistive pressure sensors, including their design, fabrication and correction techniques, has been performed at the Center of Microelectronic Technologies (CMT) for more than 25 years [2]-[11]. One of the successful types of pressure sensing elements developed and fabricated at CMT is the SP-9, which was chosen for this work. It is intended for measurement of absolute or relative pressure in the range from 0.5 bar to 50 bar. The base material used for its fabrication is a double sided polished single crystal n-type silicon wafer (specific resistivity from 3 Ωcm to 5 Ωcm). Four p-type piezoresistors are formed by boron diffusion on the surface of the silicon substrate, constituting a Wheatstone bridge. Two piezoresistors are in the radial direction and the remaining two in the transversal direction relative to the edges of a micromachined diaphragm. The diaphragm is square, 2×2 mm^2 in size, fabricated by anisotropic etching of silicon on the bottom side of the wafer. The thickness of the diaphragm is from 43 μm to 160 μm, depending on the nominal pressure range of the sensing element. Positions of the piezoresistors are optimized for each diaphragm thickness in order to achieve the highest linearity of the output signal. The overall size of the sensing element die is $3.2\times3.2\times0.38$ mm^3. After the fabrication of the die, it is anodically bonded to a 1.7 mm thick glass support. If a sensing element is intended for relative pressure measurement, there must be a channel through the glass support in order for the fluid at the reference pressure to reach the bottom side of the sensing element diaphragm. A photograph of the sensing element mounted on a TO-5 housing is shown in Fig. 1a.

An industrial-grade pressure sensor consists of a pressure sensing element (e.g. the SP-9) and a metallic sensor body that ensures optimal operating conditions for the sensing element, protects it from damage, and provides for a standardized process connection. A photograph of an industrial pressure sensor based on the SP-9 sensing element is shown in Fig. 1b. A separation membrane, located inside the metallic body, eliminates a direct contact between the sensing element and a possibly electrically conductive, chemically aggressive or dirty fluid whose pressure is measured. The sensing element is surrounded by chemically inert silicone oil which is also a good dielectric.



a) b)

Fig. 1 Photographs of a) SP-9 sensing element mounted on a TO-5 housing, b) industrial pressure sensor based on the SP-9 sensing element

A simplified electrical circuit diagram of a piezoresistive sensor with current excitation is shown in Fig. 2. For a typical sensing element made by CMT, the resistances R_1, R_2, R_3, and R_4 are approximately equal in the absence of the applied pressure. Their value is within the range from 2 kΩ to 3 kΩ, and the temperature coefficient of the resistance is in the range from 0.13 %/°C to 0.15 %/°C.

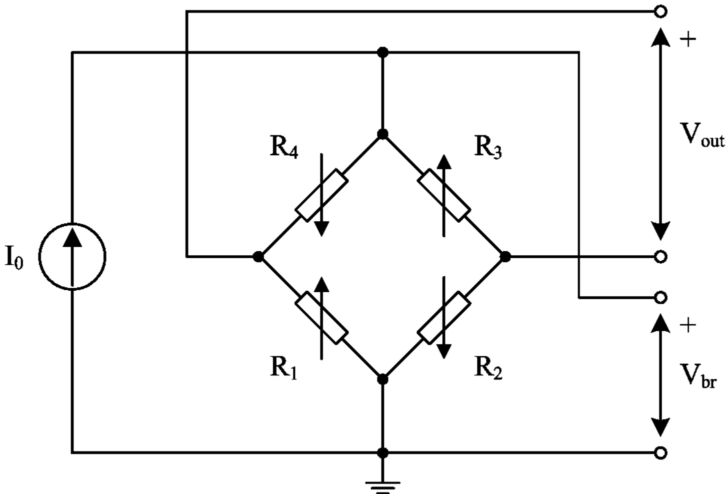


Fig. 2 Simplified electrical circuit diagram of a piezoresistive pressure sensor with current excitation

2. METHOD

2.1. Sensor characterization

In order to devise a temperature measurement method based on the resistance of the sensor's Wheatstone bridge, three gauge pressure sensors based on the SP-9 sensing element are characterized in terms of their temperature response. The mechanical construction of all the sensors is the same, featuring a separation membrane and silicone oil filling.

The experimental setup used for the characterization of the sensors was similar to the one described in our previous work [11], except for the relative pressure that was set to zero by leaving the sensors' pressure ports at the normal atmospheric pressure throughout the experiment. Acquisition of the signals from the pressure sensors was performed using a custom designed signal acquisition unit connected to a personal computer. A simplified block diagram of the unit is shown in Fig. 3.

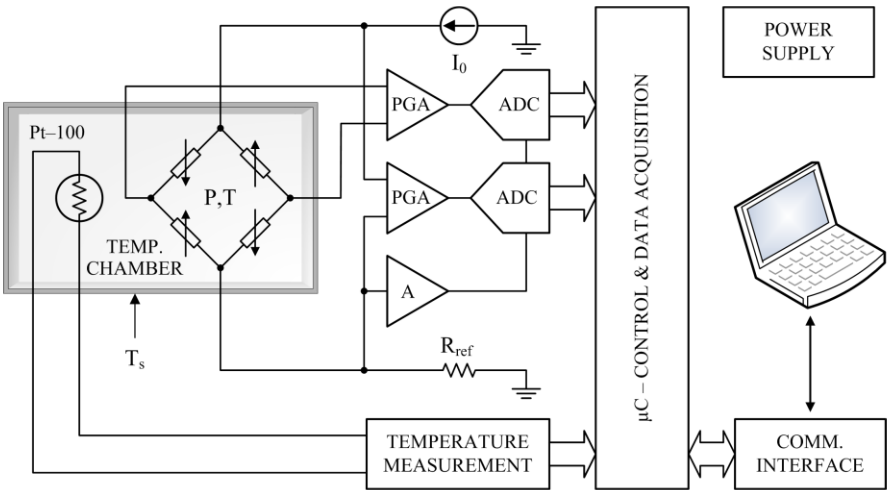


Fig. 3 Simplified block diagram of the signal acquisition unit

The input circuitry connected to the sensor under test consists of a constant current source for sensor excitation (I_0=420 μA), two 24-bit delta-sigma analog-to-digital converters (ADC), two zero-drift programmable gain instrumentation amplifiers (PGA), one zero-drift buffer amplifier and one high-performance resistor (R_{ref}=5 kΩ with ±0.01% tolerance, temperature coefficient of resistance ≤ 2 ppm/°C). The amplifiers are necessary when low level signals are measured and also because of the high impedance of the sensor used as the signal source. Measurements are ratiometric, with the ADC reference voltage proportional to the sensor excitation current ($V_{ref}=I_0 \cdot R_{ref}$), in order to eliminate the error introduced by variations of the excitation current. The resistance of the sensor, seen at its excitation port, is calculated as $R_{br}=(R_{ref}/(A \cdot 2^{n-1})) \cdot N$, where A is the amplifier gain, n is the resolution of the ADC, and N is the numeric value at the ADC's output (in this case A=1 and n=24). In this experiment the voltage between the remaining ends of the Wheatstone bridge was not measured. For the reference measurement of the pressure sensor's temperature a high performance Pt-100 sensor was used. The temperature measurement block shown in the diagram is realized using the same circuitry as the one used for the pressure sensor, thus enabling the inputs of the signal acquisition unit to be interchangeable. The Control & data acquisition block is based on a MSP430F169 microcontroller. It controls all the unit's functions, including the communication with the PC computer via the RS-232 interface (the Comm. interface block). The Power supply block contains low-noise voltage regulators. The power consumption of the signal acquisition unit is low, so it is powered by 4 AAA batteries. The temperature of the sensor under test is controlled using a climatic test chamber, in the range from -20 °C to 70 °C. During the sensor characterization experiment the operator sets the temperature value, waits for the sensor temperature to settle and then initiates the measurement. The process is repeated for each temperature value in a sequence. The personal computer receives the measurement data from the signal acquisition unit, displays the measurement indications and saves the data to a file.

A diagram showing the experimentally obtained dependences of R_{br} on the temperature T for the three tested sensors is shown in Fig. 4. In order to evaluate the temperature measurement performance of the tested sensors without any sensor correction method applied, a linear calibration function is used. Its parameters are calculated by fitting it to the obtained characterization data of each of the sensors, using the least squares method [12]. The temperature measurement error is calculated as the difference between the obtained temperature indication and the temperature value measured using the Pt-100 sensor, at all the set temperatures. The results are shown graphically in Fig. 5. It can be concluded from the diagram that the temperature measurement error exhibited by the tested sensors is within ± 4 °C.

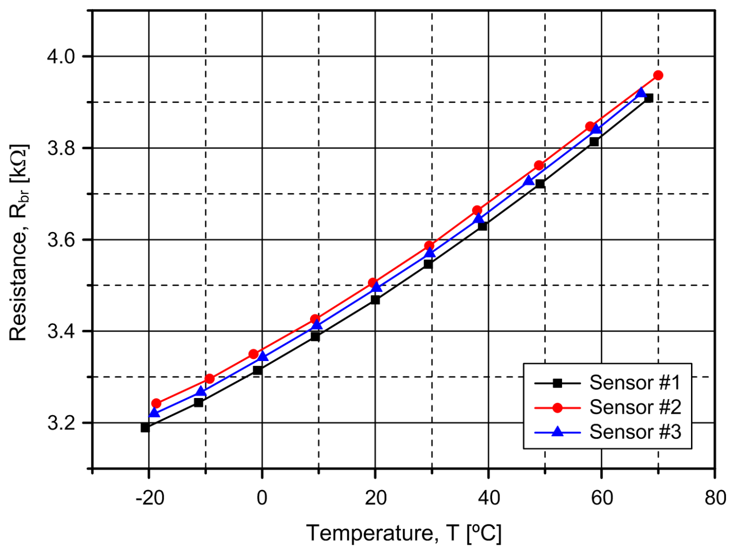


Fig. 4 Experimentally obtained dependences of the resistance R_{br} on temperature T for three tested sensors

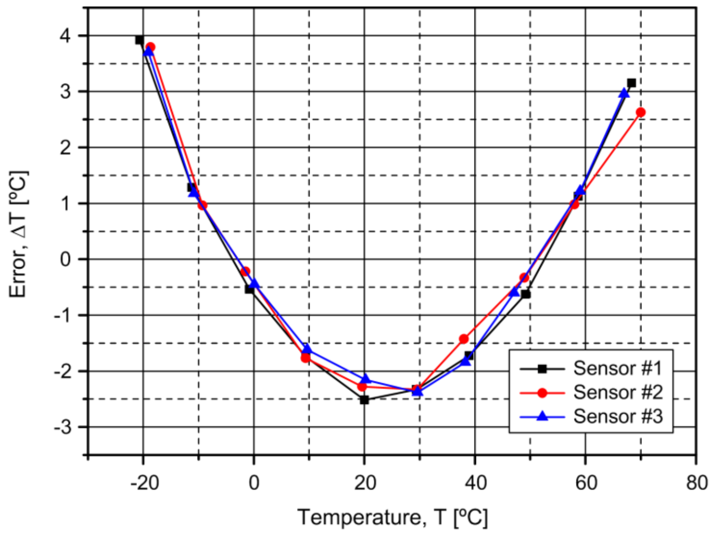


Fig. 5 Temperature measurement error ΔT as a function of temperature T for three tested sensors, without sensor correction

2.2. Sensor correction method

In order to improve the measurement performance, a suitable sensor correction method must be applied. In this case a third order polynomial has been chosen for the sensor calibration function. Its parameters were determined by fitting it to the sensor characterization data, using the least squares method [12]. A diagram showing the calibration functions obtained in this way for the three tested sensors is given in Fig. 6.

3. Results & Discussion

Temperature measurement error with the described correction method applied can be estimated by calculations performed using the characterization data obtained in 2.1. Such a calculation indicates that the temperature measurement error is within ± 0.3 °C for the three tested sensors.

In order to experimentally verify that the performance expected based on calculations can be achieved in real applications, a series of temperature measurements was performed using the same sensors with the described correction method applied. The time interval between the sensor characterization and the new series of measurements was approximately six months. An offset correction was subsequently performed at 20 °C. A diagram showing the temperature measurement error as a function of temperature for the three tested sensors is shown in Fig. 7. It can be seen from the diagram that the measurement error exhibited by the tested sensors is indeed within ± 0.3 °C. This result represents a great improvement achieved by using the proposed sensor correction method, since the temperature measurement error is reduced by at least 10 times compared to the results obtained without the correction method applied.

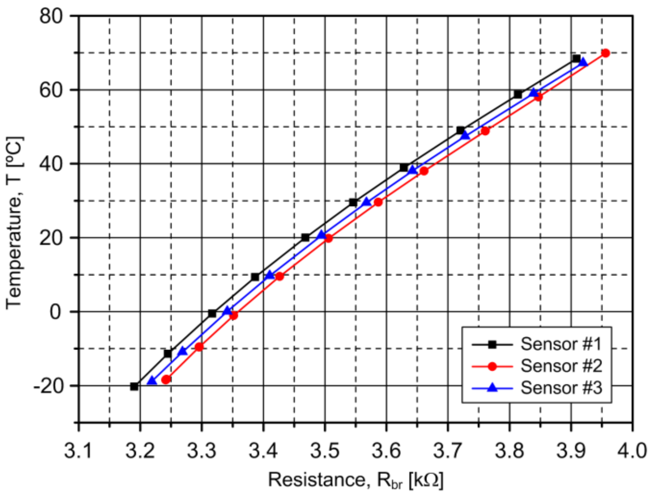


Fig. 6 Calibration functions of three tested sensors

The achieved measurement accuracy is better than that of thermocouples and also surpasses a majority of dedicated semiconductor-based temperature sensors. However, typical industrial pressure sensors are neither designed nor optimized for temperature measurement, so there are some disadvantages and limitations that must be considered in practical applications. The temperature range, size and shape, and dynamic behavior of the sensors are the most important limitations, and therefore will be discussed here.

The temperature range of a silicon piezoresistive sensing element is predominantly determined by the physical properties of silicon as a semiconductor material. It extends from cryogenic temperatures to 130 °C, whereas platinum resistance thermometers can measure temperatures up to 600 °C, and certain types of thermocouples beyond 1000 °C. There is, however, a multitude of applications where the temperature is below 130 °C, including liquid fuel or water tanks and pipelines, heating, ventilating, and air conditioning (HVAC) systems etc.

The size and shape of pressure sensors, as well as their mass and other properties, can differ significantly depending on intended applications. In some cases the sensing element can be surrounded by the fluid whose pressure or temperature is measured, with only a minimal mechanical support, whereas in many industrial applications a relatively large metallic body with a protective oil filling is required (as described in the Introduction). Since the thermal time constant of the sensing element in the air is of the order of 10 s, the time constant of the whole sensor is predominantly determined by other sensor elements, especially the sensor body. Furthermore, dynamic properties of all contact temperature measurements inevitably depend on parameters and conditions external to the sensor, which contribute to the overall thermal inertia of the system. Many industrial processes involve large amounts of fluids and/or large metallic objects whose heat capacity causes the thermal response time of the system to be much greater than that of a typical industrial pressure sensor. Some preliminary results indicate that the thermal time constant of the described industrial pressure sensor is approximately 400 s in still air, which will be further investigated in our future work.

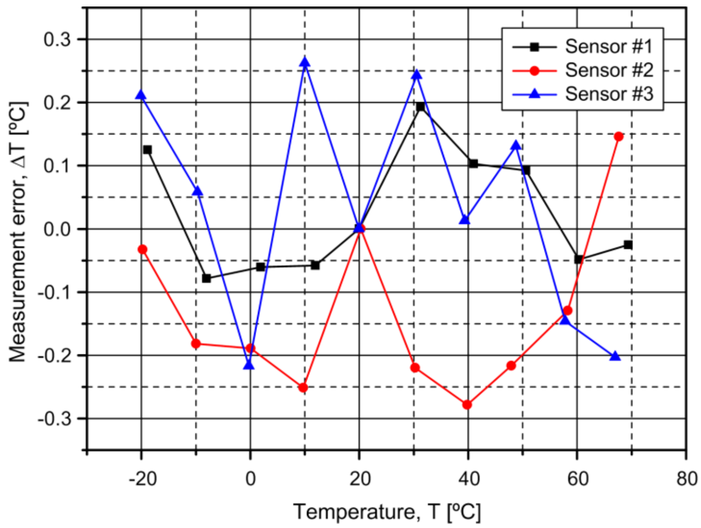


Fig. 7 Temperature measurement error ΔT as a function of temperature T for three tested sensors, with sensor correction

4. Conclusion

In this paper we presented a method for temperature measurement using MEMS piezoresistive pressure sensors. Three such sensors made by CMT were tested and characterized for temperature measurement. The measurement error, which was within ± 0.3 °C in the observed temperature range (from -20 °C to 70 °C), can be considered as a good result, knowing that many dedicated semiconductor-based temperature sensors, as well as thermocouples, exhibit greater measurement errors.

The use of piezoresistive pressure sensors instead of dedicated temperature sensors for temperature measurements has some disadvantages and limitations. Being a silicon-based semiconductor device, the pressure sensing element has a very limited temperature range (less than 130 °C) compared to some dedicated temperature sensors such as platinum resistance thermometers, and especially thermocouples. Another limitation is the thermal response time of a typical industrial-grade pressure sensor. In spite of these limitations, many applications exist where the described temperature measurement method can be useful. Some interesting new applications are possible. For example, in industrial processes with many pressure sensors installed there is often a need for an additional temperature measurement. The presented method enables a simple on-site conversion of a pressure transmitter into a temperature transmitter, as well as sensor validation and various multisensor configurations.

In our future work in this research field we intend to improve the sensor measurement performance and to overcome the limitations by using more advanced sensor designs, materials and fabrication techniques. For example, the mentioned temperature range limitation can be overcome by fabricating sensing elements on SOI (Silicon-On-Insulator) substrates [13]. Combined pressure and temperature influences as well as dynamic properties of the sensors will be investigated. The development of sensor correction methods will be continued and expanded to other types of MEMS sensors.

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REFERENCES

[1] M. Frantlović, I. Jokić, Ž. Lazić, B. Vukelić, M. Obradov, D. Vasiljević-Radović, S. Stanković, "Temperature measurement using silicon piezoresistive MEMS pressure sensors", in *Proc. 29th International Conference on Microelectronics - MIEL 2014*, 2014, pp. 159 - 161 (DOI: 10.1109/MIEL.2014.6842110).

[2] Z. Djurić, J. Matović, M. Matić, N. Mišović (Simičić), R. Petrović, M. A. Smiljanić, and Ž. Lazić, "Pressure Sensor with Silicon Diaphragm", in *Proc. XIV Yugoslav Conference on Microelectronics MIEL*, Beograd, 1986, pp. 88-100.

[3] J. Matović, Z. Djurić, N. Simičić, M. Matić, and R. Petrović, "A Nonlinear Simulation of Pressure Sensors", in *Proc. 19th Yugoslav Conference on Microelectronics MIEL '91*, Beograd, 1991.

[4] D. Tanasković, N. Simičić, Z. Djurić, Ž. Lazić, R. Petrović, J. Matović, M. Popović, and M. Matić, "Temperature Characterics of Silicon Pressure Sensor: The Effect of Impurity Profile Variation", in *Proc. 2nd Serbian Conference on Microelectronics and Optoelectronics MIOPEL 93*, 1993, pp. 297-302.

[5] Z. Đurić, "Rezultati istraživanja i razvoja Si senzora i transmitera pritiska u IHTM – Centru za mikroelektronske tehnologije i monokristale", in *Proc. 20th International Conference on Microelectronics MIEL*, 1995 (Serbian).

[6] M. M. Smiljanić, Z. Djurić, Ž. Lazić, M. Popović, and K. Radulović, "Piezootporni senzori pritiska na SOI pločicama namenjeni funkcionisanju na visokim temperaturama", in *Proc. 49th Conference for Electronics, Telecommunications, Computers, Automation and Nuclear Engineering ETRAN*, Budva, 2005,vol. 4, pp. 185-188 (Serbian).

[7] M. M. Smiljanić, Ž. Lazić, Z. Djurić, and K. Radulović, "Dizajn i modelovanje modifikovanog senzora niskih pritisaka SP-6 IHTM-CMTM", in *Proc. 51st Conference for Electronics, Telecommunications, Computers, Automation and Nuclear Engineering ETRAN*, Herceg Novi - Igalo, 2007, pp. MO3.2-1-4 (Serbian).

[8] M. M. Smiljanić, Z. Djurić, Ž. Lazić, and B. Popović, "SOI piezootporni senzor pritiska za opseg radnih temperatura od 600C do 3000C", in *Proc. 52nd Conference for Electronics, Telecommunications, Computers, Automation and Nuclear Engineering ETRAN*, Palić, 2008, pp. MO2.6-1-4 (Serbian).

[9] M. M. Smiljanić, V. Jović, and Ž. Lazić, "Maskless convex corner compensation technique on a (1 0 0) silicon substrate in a 25 wt% TMAH water solution", *J. Micromech. Microeng.* 22 115011, 1-11, 2012, doi:10.1088/0960-1317/22/11/115011

[10] M. Frantlović, I. Jokić, and D. Nešić, "A Wireless System for Liquid Level Measurement", in *Proc. 8th International Conference on Telecommunication in Modern Satellite, Cable and Broadcasting Services TELSIKS*, 2007, pp. 475-8.

[11] M. Frantlović, V. Jovanov, and B. Miljković, "Intelligent Industrial Transmitters of Pressure and Other Process Parameters", *Telfor Journal*, 2009, Vol. 1, No. 2, pp. 65-8.

[12] J. Wolberg, Data Analysis Using the Method of Least Squares, Berlin, Heidelberg: Springer-Verlag, 2006.

[13] S. S. Kumar, B. D. Pant, "Design principles and considerations for the 'ideal' silicon piezoresistive pressure sensor: a focused review", *Microsyst. Technol.*, vol. 20, pp. 1213–1247, 2014.