proceedings

Proceedings

The Study of the Structure Based on the Array of ZnO-Nanorods as a Sensor of the Gas Flow Rate †

Victor Petrov *, Alexandra Starnikova

Southern Federal University, Research and Education and Centre "Microsystem Technics and Multisensor Monitoring Systems", 2, Chekhov St., 347922 Taganrog, Russia; vvpetrov@sfedu.ru

* Correspondence: vvpetrov@sfedu.ru; Tel.: +7-(8634)-37-16-24

† Presented at the 6th International Electronic Conference on Sensors and Applications, 15–30 November 2019; Available online:https://ecsa-6.sciforum.net/.

Published: 14 November 2019

Abstract: This work shows the possibility of using arrays of ZnO nanorods grown on a glass substrate as a sensitive element for measuring air flow velocity. Since oxide semiconductors have a temperature dependence of resistance, a theoretical and experimental assessment was made of the influence of air velocity on the increase in resistance of a sensitive element. It has been theoretically shown that when air is blown through, the temperature of the free end of the ZnO nanorod can decrease by several degrees. An experimental evaluation showed that when gas is blown at a speed of 12.5 cm/s, the resistance of the sensing element increases by about 20%, which is equivalent to a temperature increase of about 4 degrees. In addition, it was found that the dependence of the increase in the resistance of the sensitive element when exposed to an air flow from 0 to 12.5 cm / s is close to linear.

Keywords: Zinc oxide nanorods; electrical resistance; sensing element; gas flow rate

1. Introduction

Currently, the urgent task is to measure low air flow rates in flow metering systems, environmental monitoring, as well as in industrial ventilation systems [1]. The air flow has a three-dimensional structure, which depends on the regime of fluid flow (laminar or turbulent) [2]. The measurement of flow velocities in the range of 0.4–2 m/s is performed by vane anemometers or hot-wire anemometers [3]. However, for measuring air flow rates below 0.3–0.4 m/s, practically no instruments are proposed.

It is known that wide-gap oxide semiconductors (zinc, tin, titanium oxide, etc.) have a temperature dependence of resistance, which, when these materials are used in a number of functional elements of electronics, reduces their operational characteristics [4,5]. However, the positive side of this effect can be used to measure air flow rates. When airflow is applied to thin films of metal oxides heated to a certain temperature, their resistance will decrease due to heat transfer. As a result, it will be possible to obtain the dependence of the sample resistance on the air flow rate. In addition, metal oxides can be obtained in the form of nanostructures (nanotubes, nanorods, nanowires, etc.) [6–10]. Their use in measuring the speed of small air flows should be more effective.

2. Materials and Methods

Arrays of ZnO nanorods were synthesized on silica glass using the hydrothermal method [11,12], which was carried out in an aqueous solution of zinc nitrate and hexamethylenetetramine (C6H12N4). Hydrothermal treatment was carried out in the temperature range 90–97 °C for 1–3 h with vigorous stirring. The resulting ZnO nanorods had a predominantly vertical orientation with a height of 590–660 nm and an average transverse size of about 30–40 nm. Contact metallization of

V-Cu-Ni with a thickness of 0.2–0.3 µm was deposited on top of the nanorods. The nanorods were in contact with each other so that they provided ohmic contact when transmitting current from one electrode to another [13]. The resistance of the obtained sensitive elements varied within hundreds—units of MΩ depending on the temperature of their heating. Figure 1 schematically shows the design of the sensing element.

Figure 1. Schematically of the sensing element. Contact metallization V-Cu-Ni (1), array of ZnO nanorods (2), glass substrate (3).

It was suggested that, when a stream of ZnO nanorods is exposed to a stream of air at a certain speed, the temperature of their free ends will decrease. This should lead to an increase in the electrical resistance of the sensing element. To confirm the proposed mechanism, we evaluated the effect of air flow on the temperature distribution along the length of the ZnO nanorod, which is fixed at one end to a substrate heated to a certain temperature. The assessment was carried out according to the formula [14]:

$$T_2 = T_1 \frac{k \cdot a}{\mu \cdot sh(a \cdot l) + k \cdot a \cdot ch(a \cdot l)} \quad (1)$$

where $a = \sqrt{\frac{\mu \cdot p}{k \cdot \sigma}}$, T_1, T_2—temperature of the fixed end and temperature of the free end of the ZnO nanorod, respectively; l, σ, p—the length, area and perimeter of the cross section of the ZnO nanorod, respectively; k—the coefficient of thermal conductivity of the rod; μ—coefficient of heat transfer from the rod to the environment.

Theoretical calculations carried out using the expression (1) showed that the temperature of the free end of the nanorod when it is blown with air can decrease from hundredths to several degrees, depending on the values k and μ.

For experimental confirmation of the calculations, we measured the dependence of the resistance of the ZnO array of nanorods on temperature and air flow rate. The measurements were carried out on an automated bench for calibration of gas sensors of the center for collective use "Microsystem technique and integrated sensorics" of the Southern Federal University—Figure 2 [15]. To measure the dependence of the resistance of the ZnO array of nanorods, the sample was placed in a measuring chamber (7) on a heater. Heating was carried out using the power supply unit (11), synthetic air supply was controlled using the control unit for the gas distribution system (1) together with the elements of the stand (2–6). The resistance of the samples was measured using a Keithly 2450 multimeter (10), displayed on a computer screen (9) and stored in its memory. The sample heating temperature (T) was controlled by a thermocouple; the measurement error was ±0.5 °C.

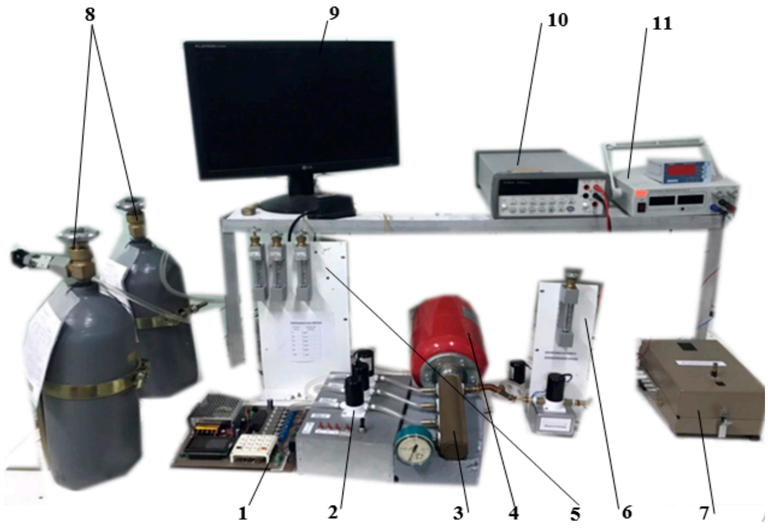

Figure 2. An automated stand for calibrating gas sensors: an electronic control unit for the gas distribution system (1), solenoid valves (2), a mixing chamber (3), a container for a mixture of gases (4), a flow control unit for the source gas components (5), a control unit a gas mixture stream (6); measuring chamber (7); cylinders with original gas components (8), personal computer (9), multimeter (10), power supply (11).

In [16], the temperature dependence of the resistance (R) of a sensitive element based on ZnO nanorods was measured. The dependence has the form characteristic of semiconductors [17]. In the temperature range of 100–250 °C, it is well approximated by a power-law dependence with a correlation coefficient of 0.95:

$$R = 2.19 \cdot 10^{10} \cdot T^{-4.21}, \quad (2)$$

The dependence of the resistance of the ZnO array of nanorods on the air supply rate was also measured at the stand shown in Figure 2. For this, the temperature of the sample was maintained at 200 + 0.5 °C, and air was supplied at a speed of 0 to 12.5 cm/s. The resistance of the sensor increased by approximately 20%—Figure 3.

The dependence shown in Figure 3 is well approximated by an expression with a correlation coefficient of 0.986:

$$R = 0.0346 \cdot V + R_0, \quad (3)$$

where V is the air flow rate (cm/s); R_0 is the resistance of the sensor structure at zero air flow rate.

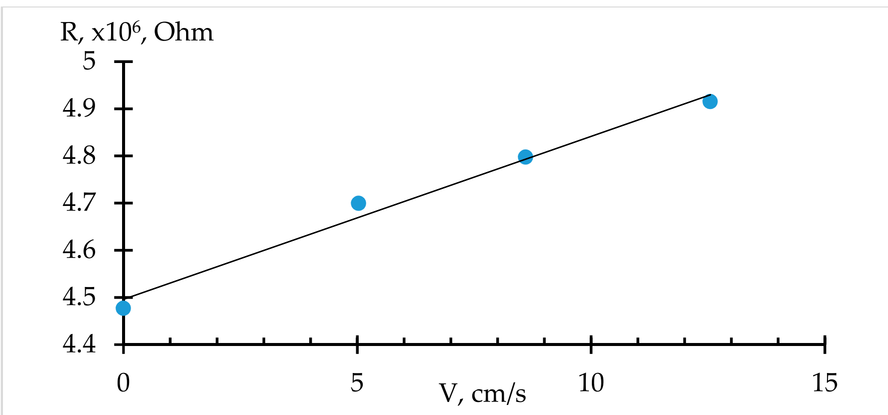

Figure 3. The dependence of the resistance of the sensor structure on the speed of air flow (points—experiment; line—approximation).

The calculation performed using expression (3) shows that the temperature of the sensor element based on ZnO nanorods should decrease by about 4 degrees.

Thus, it was confirmed that with an increase in the air flow rate while blowing the sensor element, its resistance increases due to cooling of the free ends of the preheated ZnO nanorods.

In addition, it can be noted that, in contrast to the known designs of hot-wire anemometers [18], the manufacturing technology of the sensitive element proposed in this paper seems simpler, and the measured gas flow rates are lower.

3. Results

Studies have shown that sensor elements based on ZnO nanorods can be used as a sensitive element for measuring low air velocities. The parameter sensitive to the flow velocity is the resistance of the sensor element, which linearly increases in the range of flow velocities 0–12.5 cm/s.

Funding: The reported study was partially funded by RFBR, project number 20-07-00653.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ash, J. *Sensors of measuring systems*: In 2 book. Book 2; Mir: Moscow, Russia, 1992; 480p, ISBN 5-03-001641-4. (In Russian)
2. Bradshaw, P. *Introduction to Turbulence and its Measurement*; Mir: Moscow, Russia, 1974; 278p.
3. Kuznetsov, D.N.; Zori, A.A.; Kochin, A.E. *Measuring Microprocessor Systems for the Speed and Temperature of Gas and Liquid Flows*; DonNTU: Donetsk Oblast, Ukraine, 2012, 226p.
4. Myasnikov, I.A.; Sukharev, V.Y.; Kupriyanov, L.Y.; Zavyalov, S.A. *Semiconductor Sensors for Physico-Chemical Research*; Science: Moscow, Russia, 1991; 327p, ISBN 5-02-001542-3.
5. Samsonov, G.V.; Borisova, A.L.; Zhidkova, T.G. *Physical and Chemical Properties of Oxides*; Directory. Metallurgy: Moscow, Russia, 1978; 472p. (In Russian)
6. Pan, Z.; Dai, Z.R.; Wang, Z.L. Nanobelts of Semiconducting Oxides. *Science* **2001**, *291*, 1947–1949, doi:10.1126/science.1058120.
7. Kołodziejczak-Radzimska, A.; Jesionowski, T. Zinc Oxide—From synthesis to application: A review *Materials* **2014**, *7*, 2833–2881, doi:10.3390/ma7042833.
8. Wang, Z.L. Piezoelectric Nanogenerators Based on Zinc Oxide Nanowire Arrays. *Science* **2006**, *312*, 242–246, doi:10.1126/science.1124005.
9. Kumar, R.; Al-Dossary, O.; Kumar, G.; Umar, A. Zinc Oxide Nanostructures for NO_2 Gas–Sensor Applications: A Review *Nano-Micro Lett.* **2015**, *7*, 97–120, doi:10.1007/s40820-014-0023-3.
10. Nikolaev, A.L.; Kamencev, A.S.; Lyanguzov, N.V.; Petrov, V.V.; Kaidashev, E.M. Design and Study of a High Performance CO Sensor Based on ZnO Nanowires. In *Proceedings of the International Conference on Physics, Mechanics of New Materials and Their Applications*; Parinov, I.A., Chang, S.-H., Gupta, V.K., Eds.; Nova Science Publishers, Inc.: Hapac, NK, USA, 2017; pp. 441–446, ISBN 978-1-53614-083-5.
11. Abdullin, K.A.; Bakranov, N.B.; Ismailov, D.; Kalkozova, J.K.; Kumekov, S.E.; Podrezova, L.V.; Cicero, G. Composite materials based on nanostructured zinc oxide. *Semiconductors* **2014**, *48*, 471–475, doi:10.1134/S1063782614040022.
12. Gritsenko, L.; Abdullin, K.; Gabdullin, M.; Kalkozova, Z.; Kumekov, S.; Mukash, Z.; Sazonov, A.; Terukov, E. Effect of thermal annealing on properties of polycrystalline ZnO thin films. *J. Cryst. Growth* **2017**, *457*, 164–170, doi:10.1016/j.jcrysgro.2016.07.026.
13. Petrov, V.; Starnikova, A.; Abdullin, K.; Makarenko, D. Features of the mechanism of gas sensitivity of the zinc oxide nanorods arrays to carbon monoxide. *J. Phys. Conf. Ser.* **2018**, *1124*, 022017, doi:10.1088/1742-6596/1124/2/022017.
14. Yanpolsky, A.R. *Hyperbolic Functions*; FIZMATGIZ: Moscow, Russia, 1960; 195p.
15. Petrov, V.V.; Kamentsev, A.S.; Chetverikov, S.E. Automated Stand for Gas Mixture Formed and Gas Sensors Calibration In Proceedings of the Abstracts & Schedule 2018 International Conference on "Physics and Mechanics of New Materials and Their Applications" (PHENMA 2017), Busan, Republic of Korea, 9–11 August 2018; pp. 183–184.

16. Petrov, V.V.; Varzarev, Y.N.; Abdullin, K.A. Temperature Dependence of Electrical Properties of ZnO Nanorods Array. In Proceedings of the 2nd International Conference on Informatics, Technology, and Engineering 2019 (InCITE 2019), Bali, Indonesia, 22–23 August 2019; Universitas Surabaya: Surabaya, India, 2019; pp. C37–C40.
17. Shalimova, K.V. *Semiconductor Physics*; Energy: Moscow, Russia, 1976; 416p.
18. Chen, J.; Liu, C. Development and characterization of surface micromachined, out-of-plane hot-wire anemometer. *J. Microelectromech. Syst.* **2003**, *12*, 979–988, doi:10.1109/jmems.2003.820261.