



# Design and investigation of thin film nanocomposite electrodes for electrochemical sensors



Elena Medvedeva<sup>a</sup>, Alexander Baranov<sup>b</sup>, Andrey Somov<sup>c,\*</sup>

<sup>a</sup> FSUE SPA 'Analitpribor', Smolensk, Russia

<sup>b</sup> 'MATI'-Russian State Technological University, 121552 Moscow, Russia

<sup>c</sup> College of Engineering, Mathematics and Physical Sciences, University of Exeter, EX4 4QF Exeter, United Kingdom

## ARTICLE INFO

### Article history:

Received 28 November 2015

Received in revised form 30 January 2016

Accepted 21 February 2016

Available online 24 February 2016

### Keywords:

Electrochemical sensors  
Environmental monitoring  
Magnetron sputtering  
Nanocomposite electrode

## ABSTRACT

It is well known that even negligible continuous gas leaks at industrial plants may lead to serious occupational diseases. This fact – along with growing urbanization – impose more stringent requirements for ubiquitous gas leak monitoring and air quality control. To address this problem, sensitive, selective and stable sensors are required. The given work demonstrates the design and investigation of highly selective electrochemical sensors for continuous monitoring of carbon monoxide (CO) and hydrogen sulfide (H<sub>2</sub>S) gases. In particular, we present highly sensitive thin film nanocomposite electrodes for electrochemical sensors. The nanocomposite electrodes are obtained on the porous Polytetrafluoroethylene (PTFE) substrate by magnetron sputtering co-deposition of the graphite/platinum target. As a result, the thin film nanocomposite electrode consists of an amorphous carbon matrix which includes platinum metal nanoclusters (a-C/Pt). The electrochemical gas sensors with the developed electrodes are produced and tested in several gas atmospheres. The experimental results demonstrate that a-C/Pt has high sensitivity and stability as compared to traditional powder catalysts.

© 2016 Elsevier B.V. All rights reserved.

## 1. Introduction

Even though there has been a tremendous progress in gas monitoring equipment for industrial plants over the last decades, small and negligible gas leaks still occur. As a matter of fact, even negligible concentrations of continuous gas leaks may result in serious accidents and cause occupational diseases of factory workers. At the same time, global urbanization is projected to be around 66% by 2050 [1] that will lead to significant air pollution in urban areas and, as a result, will lead to respiratory infections. An improved control of air quality within metropolitan areas and at huge factories can be realized by the application of cheap, tiny and autonomous gas sensors which can ubiquitously and promptly detect hazardous gases as well as their overconcentration.

To address this problem, different sensing technologies have been used so far: semiconductor [2], catalytic [3], optical [4] and electrochemical [5].

A viable approach to guarantee secure detection of gas leak while ensuring the sensor performance and autonomous operation is the application of electrochemical sensors [5] which can detect

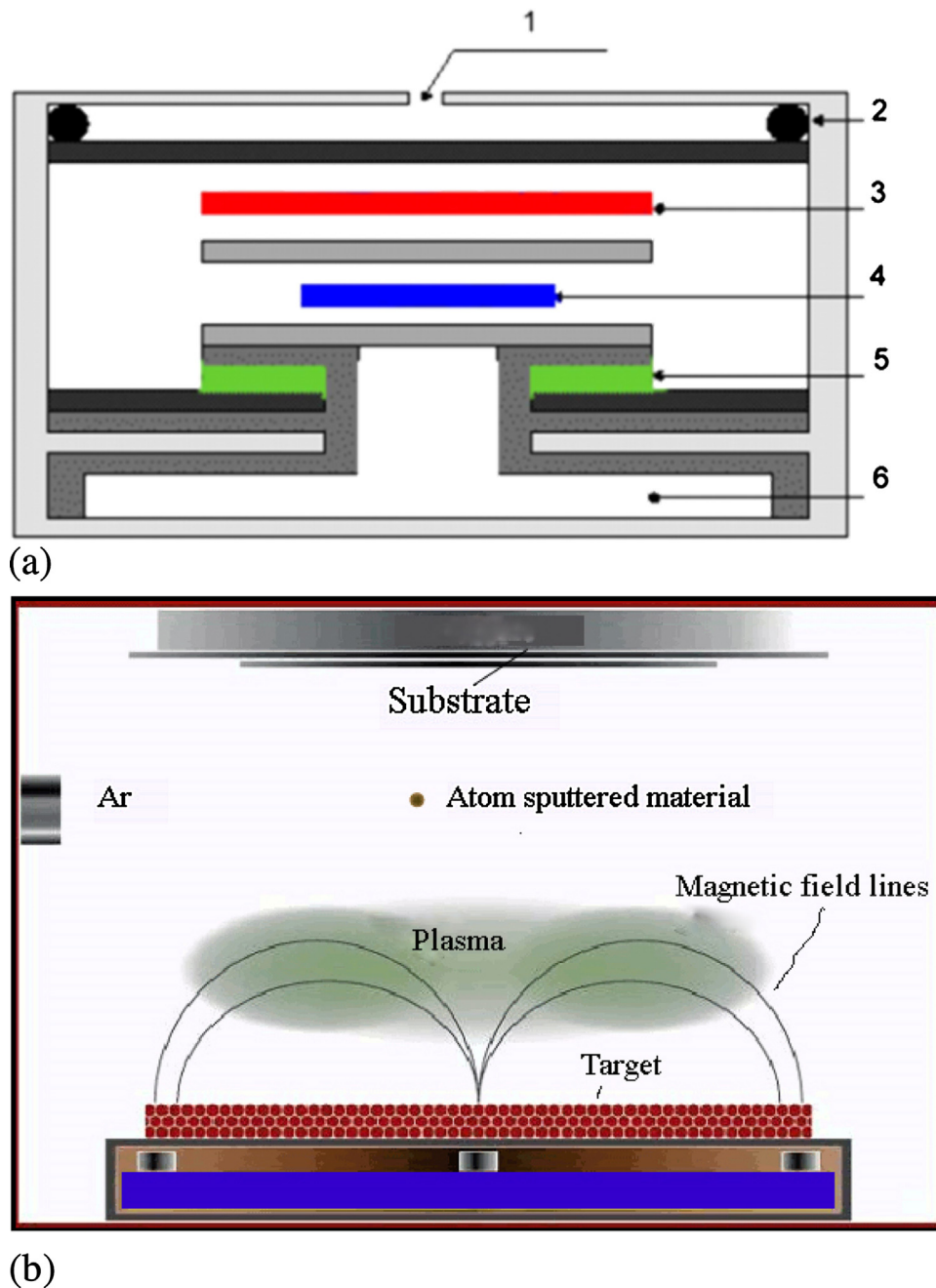
and quantify various gases, e.g., carbon monoxide (CO), hydrogen sulfide (H<sub>2</sub>S), nitrogen oxides (NO<sub>x</sub>). Sensitivity and selectivity of electrochemical sensors depend on a number of factors associated with a catalyst production, i.e., the catalyst morphology, size of nanoparticle, catalyst support, working electrode porosity and resistivity.

The novelty of this work is in designing of highly selective electrochemical sensors for continuous monitoring of carbon monoxide (CO) and hydrogen sulfide (H<sub>2</sub>S) in the gaseous environment. The selectivity of the sensor is provided by the thin film carbon-platinum working electrode which enables the oxidation reaction at predefined potential. This solution prevents other oxidation-reduction reactions happen on the working electrode in aqua system.

This paper is organized as follows: in Section 2 we overview the state-of-the-art in terms of catalyst deposition and magnetron sputtering to introduce the reader to these technologies. Section 3 describes the sensor fabrication process followed by the extensive experimental results presentation and discussion in Section 4. In Section 5 we provide our concluding remarks and plans for future work.

\* Corresponding author.

E-mail address: [and-somov@yandex.ru](mailto:and-somov@yandex.ru) (A. Somov).



**Fig. 1.** (a) Electrochemical sensor where “1” –diffusion barrier, “2” –locking ring, “3”–working electrode, “4”–reference electrode, “5” –auxiliary electrode, “6”–electrolyte, (b) Installation diagram of magnetron sputtering.

## 2. State-of-the-art

### 2.1. Catalyst deposition

The traditional technology of catalyst production includes the mechanical deposition (or pasting) [5], screen-printing [6] and chemical reduction processes [7]. These deposition technologies are not always suitable for mass production due to their high cost associated mainly with labor expenses and noble metal consumption (platinum, palladium and etc.). At the moment, there is an ongoing research aiming at decrease of Pt used in the technological process while ensuring high electrocatalytic activity. As a result, the technology *catalyst support* was actively investigated last time [8]. Different carbonaceous materials, e.g., graphene, carbon fibers

and carbon nanotubes, have been studied as catalyst support [9–11] and demonstrated excellent catalytic activity [12].

A number of deposition techniques including electrodeposition and vacuum deposition (sputtering) have been widely employed to apply the catalyst layers to working electrode. It should be noted that sensitivity and selectivity of nanocomposite materials can be further increased by reducing the size of the noble metal nano-inclusions [13]. As the size of a particle is progressively reduced, the particle volume properties become altered by its surface characteristics. As a matter of fact, the reduction of geometrical dimensions leads to the volume reduction of the surface area ratio which makes the properties of the substance dependent on the particle size [14,15]. It is quite natural that the surface properties dominate over the bulk properties when the particle size decreases below a certain limit (5–10 nm). This allows one to change the properties of the

nanocomposite structure by changing the size of the nanoparticles in a wide range. As a result, nanocomposite materials with defined combinations of properties (electrical, chemical, and optical) can be produced. In contrast, the production of bulk materials typically fails in this respect.

## 2.2. Magnetron sputtering

In our work we use the technology of magnetron sputtering for the catalyst production on the inert porous support for application to electrochemical gas sensors. Even though the magnetron sputtering technology is well known [16], in this work we present the results of magnetron sputtering co-deposition of graphite/platinum catalyst on the porous substrate. The deposited catalyst consists of an amorphous carbon matrix (*a-C*) which includes metal nanoclusters [17], platinum in our case.

Magnetron sputtering provides nanocomposite materials with free combination of components, in particular, C and Pt. This feature is highly important when a component saturation concentration in a matrix of another one is small. Catalyst injection into the carbon matrix at vacuum sputtering helps to avoid agglomerating of Pt particles that improves catalyticity of catalyst.

Another important feature of magnetron sputtering co-deposition (with respect to the electrochemical sensors with a liquid electrolyte) is the ability to form the metal clusters inside a highly irregular carbon matrix. It happens during the process of nanocomposite *a-C/Pt* formation and is in contrast with the typical approaches [18,19] when a metal is injected in previously formed structure of main metal or when clusters are deposited on a support.

The basic components of an electrochemical sensor are a working (sensing), a counter (auxiliary) and a reference electrode. These electrodes are enclosed in the sensor housing and contact with a liquid electrolyte. The above mentioned feature of the magnetron sputtering co-deposition is highly relevant to the processes running on the working electrode. In our case the working electrode is a Teflon membrane (that is porous to gas but impermeable to the electrolyte) with the deposited catalyst layer on its inner face. The gas diffuses into the sensor through the membrane and the catalyst layer. On the inner side of the working electrode electrolyte permeates into the catalyst layer. As a result, a three-phase boundary appears (gas–electrolyte–catalyst) inside the catalyst at which the electrochemical reaction occurs. For that reason, it is crucial to regularly distribute the catalyst (Pt) around the catalytic layer to improve the effective contact area with Pt.

Also, the magnetron sputtering technology for thin film nanocomposites is characterized by the improved sensor reproducibility, while keeping the production costs low [20,21]. It is achieved by the application of a single technological process producing a whole array of electrodes.

## 3. Sensor design

### 3.1. Electrochemical sensor

Fig. 1 presents schematic of the electrochemical sensor used in this work. It is a three-electrode cell which enables investigating of electric current intensity depending on voltage on the working electrode. This cell is designed for detecting and controlling of hazardous gases concentration in the environment.

### 3.2. Synthesis of electrodes

In this work, we use the technology of magnetron sputtering for the production of thin *a-C/Pt* thin film electrodes of electrochemical

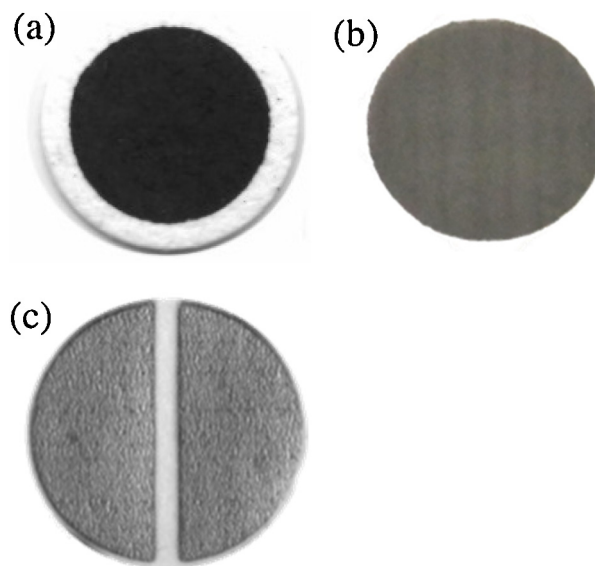


Fig. 2. (a) Pasted electrode and synthesized electrodes: (b) working, (c) reference and auxiliary.

sensors. The choice of *a-C* and Pt combination is due to unique physical, chemical and electrochemical properties which depend on the relationship among  $sp$ -,  $sp^2$ - and  $sp^3$ - hybridized conditions of carbon atom [22,23]. Injection of nanoclusters of metals (noble [24], rare earth [25], ferromagnetic [26]) into *a-C* expands their physical and chemical properties, e.g., makes them catalytically active [27].

The amorphous matrix provides a reasonable electrical conductivity and the necessary permeability to gas diffusion, while the noble metal nano particles provide higher electrochemical activity. As a result, thin film catalysts with the required combination of properties can be produced.

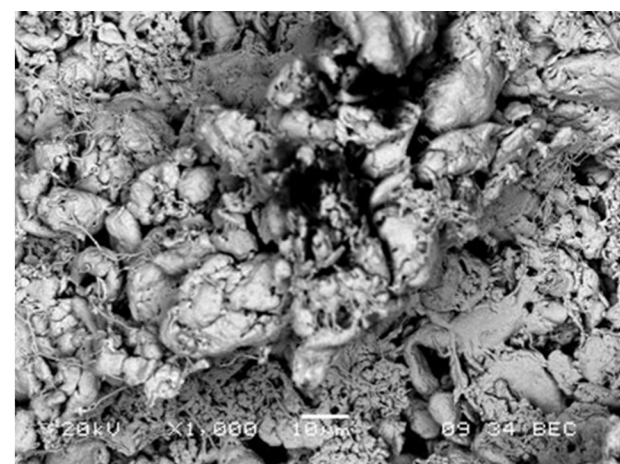
The *a-C/Pt* thin films are deposited by magnetron co-sputtering of carbon–platinum target in argon. We note here that the platinum target was inserted in the carbon one. The synthesis of *a-C/Pt* catalyst is conducted on a magnetron facility equipped with the magnetron of constant current and system ensuring the carrier rotation (see Fig. 1b). The films are deposited on a porous PTFE FM-400 substrate with 15 mm diameter and porous size  $1\ \mu\text{m}$  at room temperature. The argon pressure is  $10^{-1}$ – $10^{-2}$  Pa and the magnetron operating conditions are  $U = 500\ \text{V}$ ,  $I = 200\ \text{mA}$ . The thickness of the thin film electrodes was changing and is around  $0.4\ \mu\text{m}$ .

The electrodes fabricated using the pasted powder catalyst (Fig. 2a) and magnetron deposition (Fig. 2b and Fig. 2c) are shown in Fig. 2. The second option is performed in this work. It ensures higher selectivity, increased long-term stability, reduced leakage current and reduced dependency on temperature and pressure.

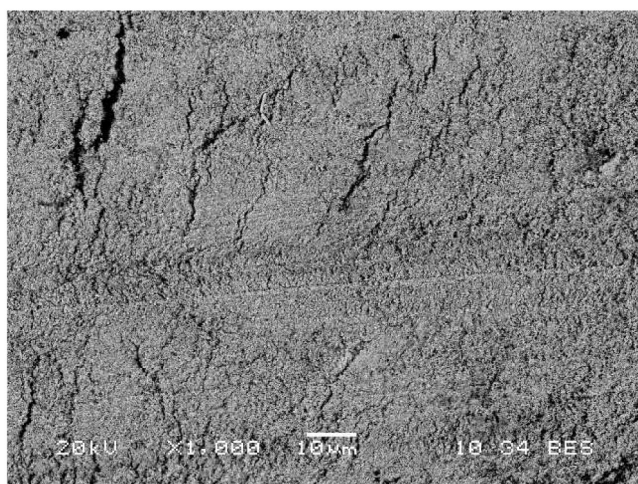
Fig. 3 depicts electronic photograph showing the surfaces of evaporated and pasted electrodes. It is clearly seen that the surface roughness of evaporated electrode is much higher compare to pasted electrode. It results in a larger active surface.

## 4. Experimental results

In this section we evaluate the sensor performance in terms of sensitivity, selectivity and response. In fact, we conduct all the experiments for CO and  $\text{H}_2\text{S}$  sensors. The experiments are conducted on ten sensors of each type and, therefore, present average results. The developed thin film electrodes are embedded in the sensor nodes with a liquid electrolyte and tested in the presence of CO and  $\text{H}_2\text{S}$ .



(a)



(b)

Fig. 3. Electronic photograph of (a) evaporated electrode and (b) pasted electrode.

Table 1  
Sensitivity of electrochemical cell.

Gas	Sensitivity of electrochemical cell	
	Background current, $\mu\text{A}$	Sensitivity, $\mu\text{A}$
CO	0.05	48.6 (100 ppm)
H <sub>2</sub> S	0.01	30.1 (30 ppm)

#### 4.1. Sensitivity

The sensitivity of the electrochemical sensor,  $K$ , is characterized by a linear dependence of the sensor output signal on the gas concentration fluctuation and is given by:

$$\kappa = \frac{I_1 - I_0}{C_1 - C_0} \times 100 \quad (1)$$

where  $I_0$  and  $I_1$  are the initial and final output sensor signals, respectively, measured during the change of gas concentration, while  $C_0$  and  $C_1$  are the initial and final measurements of gas concentration in the atmosphere.

Table 1 demonstrates the sensor sensitivity (response) in the presence of two gases CO and H<sub>2</sub>S in the environment. In the absolute numbers the sensors improve the results of commercial sensors by Nemoto (NAP-505 for CO and Ne4 for H<sub>2</sub>S) [28] while guarantying low background current which is lower than 1%. A thorough analysis of sensitivity is detailed in Fig. 4.

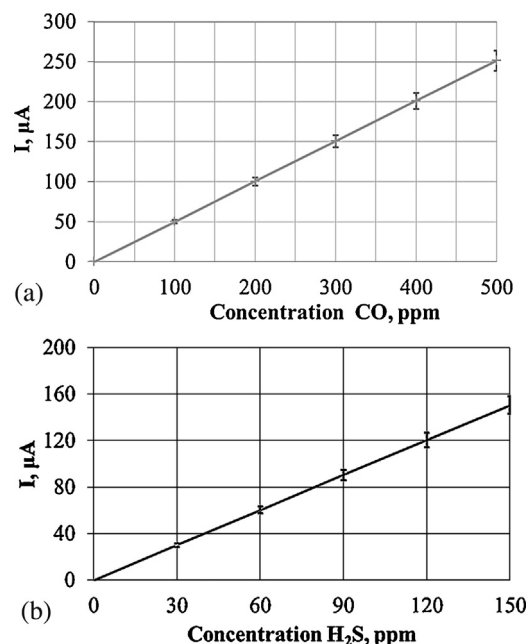


Fig. 4. Electrochemical sensor sensitivity dependence on the concentration of (a) CO and (b) H<sub>2</sub>S.

Table 2  
Cross sensitivity of carbon monoxide and hydrogen sulfide sensors.

Tested gas	Concentration (ppm)	Sensors' readings (ppm)	
		CO	H <sub>2</sub> S
Chlorine (Cl)	100	0	0
Carbon monoxide (CO)	100	100	0
Hydrogen sulfide (H <sub>2</sub> S)	30	0.5	30
Nitrogen dioxide (NO <sub>2</sub> )	30	0.3	0
Hydrogen chloride (HCl)	100	0	0
Sulfur dioxide (SO <sub>2</sub> )	25	0	0
Formaldehyde (CH <sub>2</sub> O)	10	0	0
Ethylene oxide (C <sub>2</sub> H <sub>4</sub> O)	100	0	0
Ammonia (NH <sub>3</sub> )	200	0	0

Fig. 4a and b shows that sensitivity of the sensor to CO and H<sub>2</sub>S in the range 0–500 ppm and 0–150 ppm, respectively. These curves have linear dependence on gas concentration in the environment that simplifies the sensors' calibration. The figures are the average values obtained from ten sensors. The sensitivity thresholds are 1 and 2 ppm for H<sub>2</sub>S and CO, respectively.

#### 4.1.1. Cross sensitivity

The evaluation of the electrochemical sensor cross sensitivity to different acid gases is highly important when considering the long-term operation of the cell. The results of this evaluation are presented in Table 2.

As a matter of fact, H<sub>2</sub>S sensor has no sensitivity to other gases listed in the column 'Tested Gas' in Table 2. In contrast, Nemoto's NE4 sensor for H<sub>2</sub>S has significant response to SO<sub>2</sub> and NO<sub>2</sub> [28]. As for the CO sensor fabricated in this work, it has negligible sensitivity (at the level of an error rate) to H<sub>2</sub>S and NO<sub>2</sub>.

#### 4.2. Sensor response

The response time of the electrochemical sensor is set by the material properties of a diffusion membrane, i.e., by the coefficient of gas penetration to a certain material, membrane structure and its geometry inside packaging. In this section, we evaluate the sensors' response time with respect to the measured gas concentration

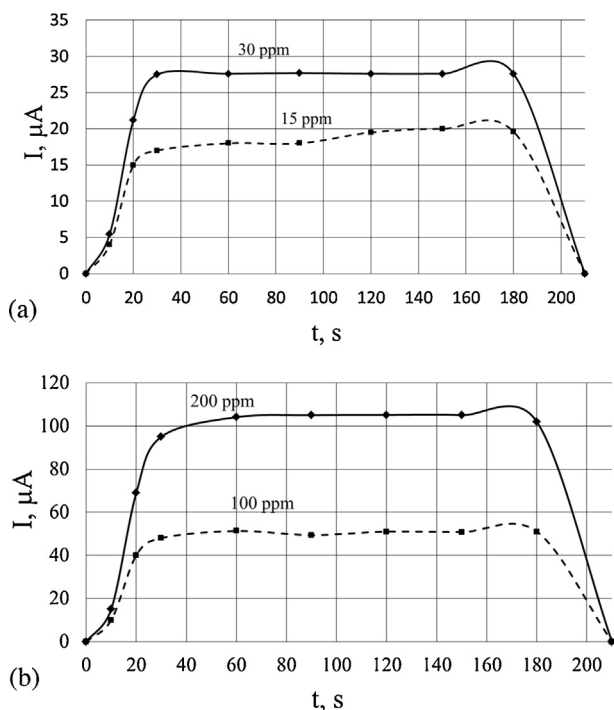


Fig. 5. Typical response and recovery characteristics to (a) H<sub>2</sub>S, (b) CO.

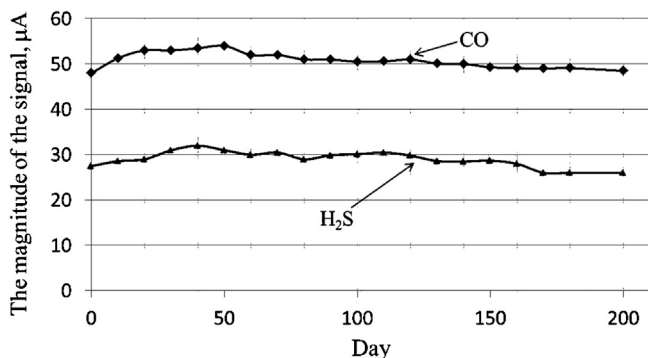


Fig. 6. Stability of electrochemical sensor sensitivity over time (6 months).

change. The special focus is made on the time when the readings of a gas analyzer are set and stable in time.

Fig. 5a and b shows the sensor response with respect to 15 and 30 ppm H<sub>2</sub>S concentrations, as well as 100 and 200 ppm CO. To conduct this experiment, the sensors are placed in a chamber with clean air for measuring their background current. Then the proper gas concentration is supplied to the chamber to measure the sensor response. The required gas concentration in the chamber sets within 2–3 s. The gases were supplied for three minutes in each experiment. After three minutes the tested gas is changed for clean air. We note that  $T_{0.9}$  (time required to achieve 90% of maximal signal response) does not exceed 30 s for all the cases.

#### 4.3. Sensor stability

The sensor output signal degrades over time due to an ageing process. It influences the electrical, mechanical, chemical and thermal properties of the sensor materials. Fig. 6 shows the stability of the electrochemical sensor sensitivity over six months. This experiment is performed as follows. The sensors are placed in the chamber with constant concentration of CO (100 ppm) or H<sub>2</sub>S (30 ppm) for

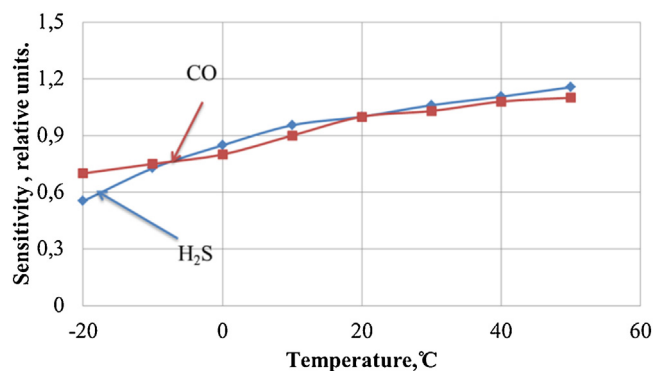


Fig. 7. Relative sensitivity dependence of the electrochemical sensor on the ambient temperature in the range from -20 °C up to +50 °C.

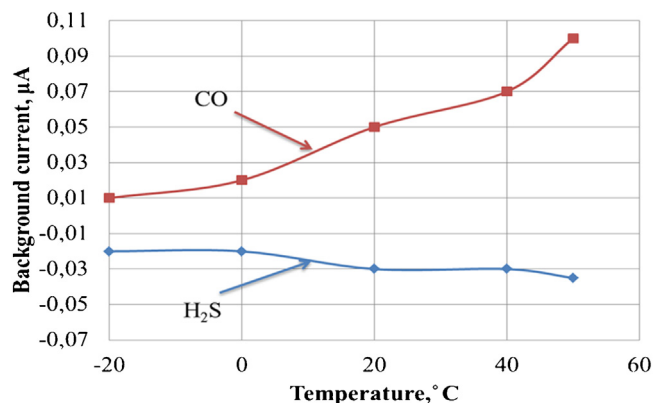


Fig. 8. Background current dependence of the electrochemical sensor on the ambient temperature in the range from -20 °C up to +50 °C.

six months. At the same time the sensors were conducting the gas measurement once a week.

Fig. 6 demonstrates that the sensitivity of the CO and H<sub>2</sub>S cells are stable enough within six months. There is a slight increase in sensitivity at around '50' days tick. This increase happens due to the set of three-phase system mode.

#### 4.4. Temperature effect

Environmental temperature influences a high number of sensor properties such as response time, sensitivity, deterioration. Fig. 7 and Fig. 8 show the sensor sensitivity and its background current with respect to the change of the ambient temperature in the range from -20 °C up to 50 °C, respectively.

This experiment is conducted in a climate chamber. First, we place the sensor in the chamber and set up the temperature. As soon as the required temperature is set up, the sensor must be in the chamber within fifteen minutes prior to starting the measurements. After that we measure the background current of the sensor. Then a tested gas is supplied to the chamber to measure the sensor sensitivity. Gas concentrations for CO and H<sub>2</sub>S during the sensor sensitivity measurement are 100 ppm and 30 ppm, respectively.

To ensure that the background current is stable at this temperature, we repeat the background current measurement with clean air.

Afterwards we change the temperature and repeat the measurement of the background current and sensitivity for the required temperature levels. The rate of the temperature change must not be higher than 1 °C/min.

The effect of the ambient temperature on the electrochemical sensor sensitivity  $K$  is normalized by  $K_T$  and is defined in Eq. (2).

$$K_T = \frac{I_{1,Tc} - I_{0,Tc}}{I_{1,T20} - I_{0,T20}} \times 100 \quad (2)$$

where  $I_{0,T20}$  and  $I_{1,T20}$  are the initial and final output signals of the sensor at  $20 \pm 2^\circ\text{C}$  temperature, and  $I_{0,Tc}$  and  $I_{1,Tc}$  are the initial and final output signals of the sensor at the current ambient temperature.

The effect of temperature on sensitivity is negligible and both sensors react on its change almost equally (see Fig. 7).

Fig. 8 demonstrates that the background current of the electrochemical sensor starts to change drastically at  $40^\circ\text{C}$ . This change is connected with the sensor side effects, e.g., chemical reactions, which are not well investigated at the moment. However, the background currents for both cases are negligible within the tested temperature range.

## 5. Conclusion

In this work, we have demonstrated electrochemical sensors based on thin film nanocomposite electrodes which are manufactured using magnetron sputtering. Experimental results have shown high potential of magnetron sputtering approach for fabricating the electrodes sensitive to CO and  $\text{H}_2\text{S}$  gases. In particular, the developed sensors have no cross sensitivity to other hazardous gases apart from negligible cross sensitivity of CO sensor. In terms of stability, the sensors' sensitivity does not degrade much over time (200 days) and at the temperature variation conditions (from  $-20^\circ\text{C}$  up to  $+50^\circ\text{C}$ ) are selective to toxic gases and have good sensitivity in terms of the response signal.

The experimental results lead to a conclusion that the developed sensors could be a good option for application in the autonomous monitoring systems, such as wireless sensor networks, in difficult-to-access areas and used for developing actions to prevent dangerous situations, e.g., gas leaks, fire, and poisoning of the staff.

Our future plans include the development and evaluation of wireless gas sensor nodes with the sensors presented in this work and their deployment in field conditions.

## Acknowledgement

This work was supported by the grant No. RFMEFI57714X0133 from the Ministry of Education and Science of Russian Federation.

## References

- [1] United Nations, World Urbanization Prospects, Report, New York, 2014, ISBN 978-92-1-151517-6.
- [2] N.N. Samotaev, A.A. Vasiliev, B.I. Podlepetsky, A.V. Sokolov, A.V. Pisiakov, The mechanism of the formation of selective response of semiconductor gas sensor in mixture of  $\text{CH}_4/\text{H}_2/\text{CO}$  with air, *Sens. Actuators B: Chem.* 127 (2007) 242–247.
- [3] E.E. Karpov, E.F. Karpov, A. Suchkov, S. Mironov, A. Baranov, V. Sleptsov, L. Calliari, Energy efficient planar catalytic sensor for methane measurement, *Sens. Actuators A: Phys.* 194 (2013) 176–180.
- [4] A. Makeenkov, I. Lapitskiy, A. Somov, A. Baranov, Flammable gases and vapors of flammable liquids: monitoring with infrared sensor node, *Sens. Actuators B: Chem.* 209 (2015) 1102–1107.
- [5] R. Eggins Brian, *Chemical Sensors and Biosensors*, John Wiley & Sons Ltd., London, 2002.
- [6] J. Hart, A. Crew, E. Crouch, K. Honeychurch, R.M. Pemberton, Some recent designs and developments of screen-printed carbon electrochemical sensors/biosensors for biomedical environmental, and industrial analyses, *Anal. Lett.* 37 (2004) 789–830.
- [7] F. Vork, L. Janssen, E. Barendrecht, Oxidation of hydrogen at platinum-polyppyrrrole electrodes, *Electrochim. Acta* 31 (1986) 1569–1575.
- [8] Tingting Yang, Mingliang Du, Han Zhu, Ming Zhang, Meiling Zou, Immobilization of Pt nanoparticles in carbon nanofibers: bifunctional catalyst

- for hydrogen evolution and electrochemical sensor, *Electrochim. Acta* 167 (2015) 48–54.
- [9] Y. Wang, C.X. Guo, X. Wang, C. Guan, H.B. Yang, K. Wang, C.M. Li, Hydrogen storage in a Ni-B nanoalloy-doped three-dimensional graphene material, *Energy Environ. Sci.* 4 (2011) 195–200.
- [10] X.W. Mao, X.Q. Yang, G.C. Rutledge, T.A. Hatton, Ultra-wide-range electrochemical sensing using continuous electrospun carbon nanofibers with high densities of states, *ACS Appl. Mater. Interfaces* 6 (2014) 3394–3405.
- [11] B.H. Wu, D. Hu, Y.J. Kuang, B. Liu, X.H. Zhang, J.H. Chen, Functionalization of carbon nanotubes by an ionic-liquid polymer: dispersion of Pt and PtRu nanoparticles on carbon nanotubes and their electrocatalytic oxidation of methanol, *Angew. Chem. Int. Ed.* 48 (2009) 4751–4754.
- [12] A.L. Dicks, The role of carbon in fuel cells, *J. Power Sources* 156 (2006) 128–141.
- [13] T.S. Ahmadi, Z.L. Wang, T.C. Green, A. Henglein, M.A. El-Sayed, Shapecontrolled synthesis of colloidal platinum nanoparticles, *Science* 272 (1996) 1924–1925.
- [14] I.N. Leontyev, S.V. Belenov, V.E. Guterman, P. Haghi-Ashtiani, A.P. Shaganov, B. Dkhil, Catalytic activity of carbon supported Pt/C nano-electrocatalysts, *J. Phys. Chem.* 115 (2011) 5429–5434.
- [15] Jianshuai Mu, Li Zhang, Min Zhao, Yan Wang,  $\text{CO}_3\text{O}_4$  nanoparticles as an efficient catalase mimic: Properties, mechanism and its electrocatalytic sensing application for hydrogen peroxide, *J. Mol. Catalysis A: Chem.* 378 (2013) 30–37.
- [16] M.C. Simmonds, M.L. Hitchman, H. Kheyrandish, J.S. Colligon, N.J. Cadec, P.J. Iredale, Thin sputtered platinum films on porous membranes as working electrodes in gas sensors, *Electrochim. Acta* 43 (1998) 3285–3291.
- [17] L. Calliari, L. Minati, G. Speranza, A. Paris, A. Baranov, S. Fanchenko, Core-level photoemission from nanocluster–matrix composites: Au clusters in amorphous carbon, *Appl. Surf. Sci.* 314 (2014) 800–806.
- [18] M. Penza, R. Rossi, M. Alvisi, G. Cassano, M.A. Signore, E. Serra, R. Giorgi, Pt- and Pd-nanoclusters functionalized carbon nanotubes networked films for sub-ppm gas sensors, *Sens. Actuators B: Chem.* 135 (2008) 289–297.
- [19] N. Patel, B. Patton, C. Zanchetta, R. Fernandes, G. Guella, A. Kale, A. Miotello, Pd-C powder and thin film catalysts for hydrogen production by hydrolysis of sodium borohydride, *Int. J. Hydrogen Energy* 33 (2008) 287–292.
- [20] U. Yogeswaran, Shen-Ming Chen, A review on the electrochemical sensors and biosensors composed of nanowires as sensing material, *J. Sensors* 8 (2008) 290–313.
- [21] J.R. Stetter, Amperometric gas sensors, *J. Am. Chem. Rev.* 108 (2008) 352–366.
- [22] J. Robertson, E.P. O'Reilly, *Phys. Rev. B* 35 (1987) 2946.
- [23] V.V. Sleptsov, A.A. Kuzin, G.F. Ivanovsky, V.M. Elinson, S.S. Gerasimovich, P.E. Kondrashov, A.M. Baranov, Optical properties and phase composition of  $\alpha\text{-C}$ : H films, *J. Non-Cryst. Solids* 136 (1991) 53–59.
- [24] A.D. Remenyuk, T.K. Zvonareva, I.B. Zaharova, V.A. Tolmachev, L.V. Belyakov, T.S. Perova, Optical study of platinum-modified amorphous carbon, *Semiconductors* 43 (2009) 915–920.
- [25] G. Speranza, L. Calliari, M. Ferrari, K. Tran Ngoc, A. Chiasera, A.M. Baranov, V.V. Sleptsov, A.A. Nefedov, A.E. Varfolomeev, S.S. Fanchenko, Erbium-doped thin amorphous carbon films prepared by mixed CVD sputtering, *Appl. Surf. Sci.* 238 (2004) 117–120.
- [26] S.G. Yastrebov, V.I. Ivanov-Omskii, V. Pop, C. Morosanu, A. Slav, J. Volron, Magnetic properties of amorphous carbon modified with iron, *Phys. Eng. Semiconductors* 39 (2005) 874–879.
- [27] Y.V. Pleskov, Y.E. Evstefeeva, A.M. Baranov, Threshold effect of admixtures of platinum on the electrochemical activity of amorphous diamond-like carbon thin films, *Diam. Relat. Mater.* 11 (2002) 1518–1522.
- [28] Nemoto Sensor Engineering Company Ltd.—Nemoto Gas Sensors Overview, 2015 (accessed November 2015) <http://www.nemoto.eu/products.html>.

## Biographies

**Elena Medvedeva** is a physics engineer at FSUE SPA “Analitpribor”, Russia, and a PhD candidate at Moscow Aviation Institute (National Research University). She graduated from National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), faculty of theoretical and experimental physics, in 2001. Her research interests include design and investigation of catalysts for the electrochemical sensors.

**Alexander Baranov** is a Professor at “MATI”—Russian State Technological University. He graduated from Moscow Institute of Electronic Machinery in 1987. He received a PhD in Phys. and Math. in 1994 from Moscow Institute of Electronics and Mathematics (Technical University) and the Doctor of Technical Science degree in 2003 from “MATI”—Russian State Technological University. Prof. Baranov is the project leader on several National and International research projects. His current research interests include the energy efficient wireless gas sensors, gas sensors development and characterization, wireless sensor networks, energy harvesting technology for wireless application and thin film nanocomposite catalysts.

**Andrey Somov** is a Research Fellow with the College of Engineering, Mathematics and Physical Sciences, University of Exeter, UK. Before joining the University of Exeter in 2016, for nearly six years, he had worked as a Senior Researcher for CREATE-NET Research Center, Italy. Andrey graduated from “MATI”—Russian State Technological University, Russia (2004) and holds the diploma of Electronics Engineer from the same institution (2006). He received his PhD (2009) from the University of Trento,

Italy, for work in the field of power management in wireless sensor networks. Before starting his PhD, Andrey worked as an electronics engineer in space technology at VNIEM corporation, Russia. In the fall 2008 he was a visiting researcher at the University of California, Berkeley, USA, where he conducted research in energy efficient sensor networks. Dr. Somov has published more than 40 papers in peer-reviewed

international journals and conferences. He has been General Chair of the 6th International Conference on Sensor Systems and Software (S-Cube'15) and the 'IoT360' Summer School on the Internet of Things in 2014 and 2015. His current research interests include power management for the wireless sensor nodes and associated proof-of-concept implementation.