Sensors & Transducers, Vol. 246, Issue 7, November 2020, pp. 23-31

www.sensorsportal.com

Sensors & Transducers

Published by IFSA Publishing, S. L., 2020
http://www.sensorsportal.com

Magnetron Sputtered ZnO Thin Films for Hydrogen Peroxide Vapor Detection

[1, *] Mikayel ALEKSANYAN, [1] Vladimir AROUTIOUNIAN, [1] Valeri ARAKELYAN, [1] Gohar SHAHNAZARYAN and [1] Gevorg SHAHKHATUNI

[1] Yerevan State University, Department of Physics of Semiconductors and Microelectronics, 1 A. Manoogian St., Yerevan, 0025, Republic of Armenia
[1] Tel.: + 37460710319, fax: + 37460710355
[*] E-mail: maleksanyan@ysu.am

Received: 24 October 2020 /Accepted: 25 November 2020 /Published: 30 November 2020

Abstract: In this study, we report the design and fabrication of a high-performance hydrogen peroxide vapor sensor based on La doped ZnO nanstructured film using the high-frequency magnetron sputtering method. The response (R_{gas}/R_{air}) of the sensor was measured at various operating temperature to different concentrations of hydrogen peroxide vapors. It was also studied the gas sensing properties of the sensor by impedance spectroscopy. Gas sensing tests indicate that La-doped ZnO sensor exhibit high sensitivity to low concentration of hydrogen peroxide vapor. We expect that in the future, La doped ZnO nanstructured sensitive thin films will be able to be utilized in highly sensitive, real-time hydrogen peroxide vapor sensors.

Keywords: Zinc oxide, Conductometric sensor, Magnetron sputtering, Hydrogen peroxide vapor, Thin film, Sensitivity.

1. Introduction

Hydrogen peroxide (H_2O_2) is an odorless and colorless liquid and it is more viscous than water. It is an important metabolic product in chemical and food industries. It is used as a fuel and has chemical applications, biological function, domestic uses, as well as therapeutic use, including use as an antimicrobial and oxidizing agent. Different concentrations of hydrogen peroxide with water solution are also used for industrial applications such as pulp- and paper-bleaching. It is available to consumers most commonly with a 3 % solution as a general disinfectant [1-4].

Due to such a wide range of applications the demand for developing hydrogen peroxide vapor detection methods is increasing year by year. Research on the detection and measurement of the concentration of H_2O_2 vapors received considerable attention in the last decade. Various methods such as gas chromatography, surface plasma resonance, fluorescence, Fourier-transform infrared spectroscopy, chemiluminescence detectors, mass spectrometry, colorimetry, electrochemistry and semiconductor gas sensors have been applied in hydrogen peroxide detection. Unlike other techniques, gas sensors based on metal oxide semiconductor (MOS) nanostructured materials have been widely used, having to the advantages of low cost, easy to miniaturize and production, high stability, selectivity, sensitivity, reliability and fast response [5-8].

In the manufacturing of conductomertric gas sensors several types of MOS materials have been explored, including SnO_2, ZnO, In_2O_3, TiO_2, WO_3, CuO and Fe_2O_3 with different dopants and morphologies.

1.1. The Properties of ZnO Material

Among the oxides, ZnO has some advantages such as its low cost, wide bandgap energy (3.4 eV), simple synthesis of nanostructures, high mobility of electron carriers, large exciton binding energy (60 meV) at room temperature and non-toxicity in nature that makes it eco-friendly. Zinc oxide is a group II–VI compound semiconductor and has promising catalytic, electrical, electronic, and optical properties. It has recently attracted great attention due to its physical properties and potential applications in solar cells, gas sensors and other electronic nanodevices. Zinc oxide is one of the most studied MOS materials due to its unique surface properties. ZnO has crystal structures of wurtzite, zinc blende and rock salt. The wurtzite is the most thermodynamically and chemically stable phase structure under ambient conditions. The wurtzite structure is a hexagonal close-packed structure (Fig. 1). Table 1 lists the main physical and chemical properties of ZnO material [9, 10].

Understanding the fundamental physical and chemical properties is the best way to the rational design of functional devices. In study of the properties of ZnO nanostructured material is essential for developing their potential as the building blocks for future nanoscale devices. The monocrystalline and polycrystalline (small grains with diameter of 15-30 nm) ZnO structures show a superior fatigue resistance, high isoelectric point and charge transfer properties, biocompatibility, and low impact on the environment at the end of life cycle. ZnO based nanomaterials are easy to fabricate, and raw materials and precursors are easily available [11].

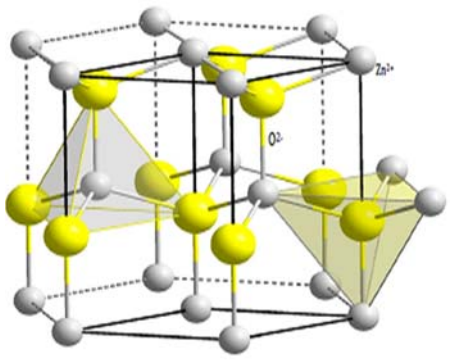


Fig. 1. The wurtzite structure of ZnO [12].

This material is also widely used in various gas sensors as a high-sensitive material with combination of 3 S parameters (Sensitivity, Selectivity and Stability). In particular, the polycrystalline structure of this material has quite promising parameters in terms of use in gas sensors. Due to its high chemical stability, catalytic activity and *large surface area to volume ratio*, ZnO polycrystalline material has become one of the main materials used in gas sensors [13].

Table 1. The physical and chemical properties of wurtzite ZnO.

Properties	**Value**
Lattice constants (T = 300 K)	
a_0	0.32469 nm
c_0	0.52069 nm
Density	5.606 g/cm^3
Melting point	2248 K
Relative dielectric constant	8.66
Gap Energy	3.4 eV, direct
Intrinsic carrier concentration	$<10^6$ cm^{-3}
Exciton binding energy	60 meV
Electron effective mass	0.24
Electron mobility (T = 300 K)	200 cm^2/Vs
Hole effective mass	0.59
Hole mobility (T = 300 K)	5–50 cm^2/Vs
Molar mass	81.406 g/mol
Heat capacity (C)	40.3 K^{-1}mol^{-1}
Gibbs free energy ($\Delta_f G^\circ$)	-320.5 kJ mol^{-1}

Although pure ZnO has not represented high sensing performance but conductometric sensors based on doped ZnO nanostructured material exhibit high sensitivity, selectivity and stability toward both oxidizing and reducing gases [14-18].

In this study, we prepared La doped ZnO based sensor for detection of hydrogen peroxide vapor and confirmed its high sensitivity by means of gas sensing studies. In Section 1, the introductory part and the properties of ZnO material are presented. In Section 2, the fabrication steps of Zn<La> sensor are presented. In Section 3, the studies of sensing properties of hydrogen peroxide sensor are presented. The hydrogen peroxide sensing mechanisms are discussed in Section 4. The conclusions are outlined in Section 5. Fabricated sensors have also sufficient selectivity and stability over time.

2. Experimental

The sensitive layers were deposited by magnetron sputtering method. First, sputtering targets (5 targets) based on ZnO (wurtzite) doped 0.5; 1; 1.5; 2; 2.5 at.% La_2O_3 were fabricated using solid-phase reaction method. The process used to prepare the magnetron sputtering targets may be found in our previous reports [19, 20]. The synthesized ZnO<La> compositions were subjected to mechanical processing in order to eliminate surface defects having smooth, parallel tablets with the diameter of 50 mm and the thickness of 2 mm (see Fig. 2).

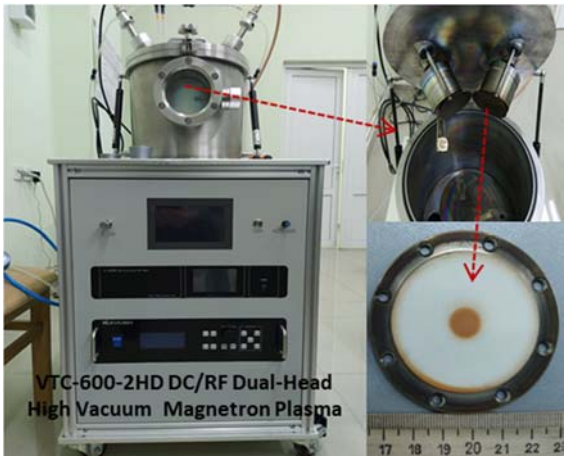


Fig. 2. The photos of the VTC-600-2HD DC/RF Dual-Head High Vacuum Magnetron Plasma System and the ZnO<La> sputtering target.

2.1. Magnetron Sputtered ZnO Layer

Magnetron sputtering is one of the best methods for obtaining thin films from very wide range of materials including metals, dielectrics, ceramics, polymers and so on [21].

Magnetron sputtering is a process whereby atoms of a solid target material are ejected (or vaporized) due to the momentum transfer from an atomic-sized energetic bombarding particle impinging on the target surface. Then these vaporized particles are condensed on the substrate material. The sputtering is carried out using gaseous ions from plasma that are then accelerated and directed toward the target. The plasma used during the sputtering is created and controlled by magnetron guns [22].

The ZnO<La> sensitive layers were deposited by the VTC-600-2HD DC/RF Dual-Head High Vacuum Magnetron Plasma System (see Fig. 2). As known, plasma is weakly ionized quasi-neutral gas made up of ions and electrons to be a good electrical conductor. Generally, processes that depend on the use of the plasma are referred to as plasma processing. The plasma processing has plasma densities between 10^8~10^{13}/cm^3 and during the sputtering of the ZnO<La> layer the plasma density was 10^{10}/cm^3. The gas atoms may not be fully ionized and there are not only electrons and ions but also neutrals. The electron velocities are much higher than that of ions and neutrals. The plasma properties are heavily dependent on the excitation and ionization energies of the gas. The most suitable gas is argon (Ar) because it is an 'inert' or 'noble' gas, thus not explosive when subjected to the RF (13.56 MHz) magnetic field or spark and it has low ionization energy (15.7 eV). High purity argon (99.99 %) was used as a plasma sustaining gas during the sputtering of ZnO<La> targets obtaining nanostructured gas-sensitive film with enhanced parameters. The krypton gas is also a good candidate for this application, but it's expensive. Ar is relatively cheap to manufacture since it is extracted directly from the atmosphere [23].

Generally, plasma can be used for different purposes depending on the type of the PVD process. It can be used as a source of ions or as a source of electrons. For applying power sources for discharge there are two sources: DC (continuous DC, Pulsed DC) and AC (LF (~100 Hz), MF (~100 Hz - ~1 MHz) and RF (> ~1 MHz)). The RF magnetic field with 13.56 MHz was used by us as a power source. For magnetron DC and AC sputtering processes plasma is used as a source of ions for the sputtering from a target material if the plasma ions are directed toward it. The uniformity of plasma is very important concern for more tunable deposition process environment. Plasma uniformity is mainly dependent on sputtering system geometry and the means by which the plasma was produced. The plasma produced by DC diode is not ideal for sputtering because the electrons ejected from the cathode are accelerated away from the cathode and are not efficiently used for sustaining the discharge [24].

Ceramic substrates with the interdigitated electrodes, the temperature sensor (Pt 1000) and the heater were used as sensor substrate (Multi-Sensor-Platform) (see Fig. 3).

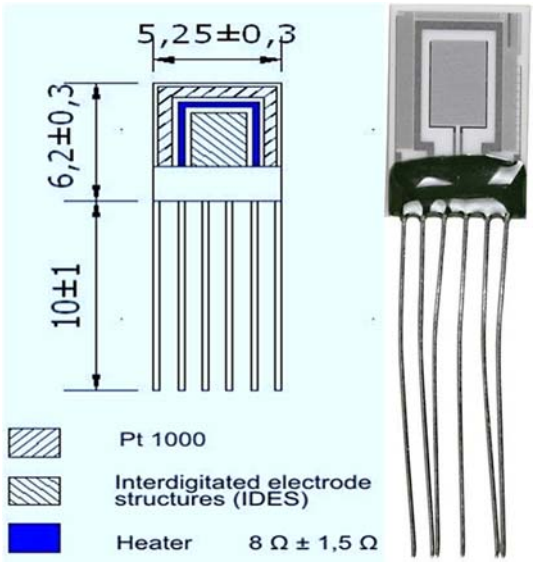


Fig. 3. The schematic diagram of the Multi-Sensor-Platform (with mm unit) and the photo of Multi-Sensor-Platform based sensor.

Gas sensitive ZnO<La> layers were deposited onto Multi-Sensor-Platform by the VTC-600-2HD DC/RF Dual-Head High Vacuum Magnetron Plasma System under the following conditions: 60 W input power, 150 °C deposition temperature, 70 mm distance between the target and substrate, 2×10^4 Pa base pressure, 6×10^{-1} Pa deposition pressure, and 20 minutes duration of sputtering. Then, the sensors were sensitized by deposition of palladium catalytic particles on the surface of the sensing layers by the ion-beam sputtering method (the deposition time was 3 seconds, the cathode current and the anode voltage

were equal to 65 A and 25 V, respectively). Finally, the samples were annealed at 350 °C during 3 hours for stabilization of sensing parameters. Five different sensors (from targets of ZnO doped 0.5; 1; 1.5; 2; 2.5 at.% La) were made with the same technological modes described above.

It is known that the gas sensitivity of resistive sensors is greatly influenced by the thickness of the sensing film. In the case of the thick films (> 300 nm) the sensitivity decreases and the response and recovery times increase. In the case of very thin films (< 50 nm) the sensor parameters are quite promising, but the stability of the film is quite low and the sensor may lose its gas sensing properties in a short time. It is necessary to find the optimal thickness of the film, in which case we have a trade off the key parameters of the sensor [25, 26].

The thicknesses of the ZnO<La> thin films were measured by the Alpha-Step D-300 (KLA Tencor) profiler. The result of the study of the film-substrate transition profile is shown in Fig. 4. The thickness of the ZnO<La> film was equal to 80 nm and this was the optimal thickness for our sensors.

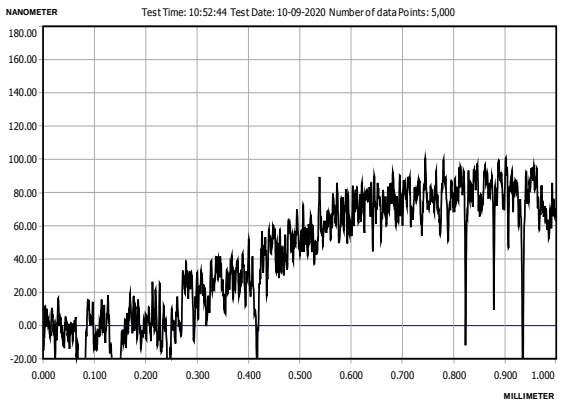


Fig. 4. The thickness measurement result for the La-doped ZnO film.

It should be noted that the deposition rate of RF magnetron sputtering was almost unaffected by the percentage of dopant in the ZnO material. The films deposited in the same technological modes from all 5 targets had almost the same thicknesses (80 nm).

3. Results and Discussion

At first, the gas sensing properties of the ZnO<1at.% La> thin layer were studied in the presence of hydrogen peroxide vapours using a home-made computer-controlled gas testing system [1]. To have the necessary concentration of H_2O_2 in the chamber, the liquid hydrogen peroxide was introduced into the chamber on the special hot plate designed for the quick conversion of the liquid H_2O_2 to the gas phase. The response of the fabricated sensors is calculated as, $R=R_{gas}/R_{air}$, where R_{air} is the resistance of the sensor in the presence of air and R_{gas} is the resistance in the presence of the target gas.

Initially, the ZnO<1at.% La> sensor's responses were measured at different operating temperatures in the presence of 100 ppm hydrogen peroxide vapours. Fig. 5 shows the dependence of the sensor's response on the operating temperature. The maximum response value was observed at 200 °C operating temperature, but from the temperature of 150 °C the sensor showed quite promising sensing results (at 50 and 100 °C operating temperatures the ZnO<1at.% La> sensor showed response to hydrogen peroxide vapours, but did not recover after eliminating the gas effect).

The changes in the sensor's resistance in the presence of 100 ppm hydrogen peroxide vapours at different operating temperatures were also measured (see Fig. 6). At both temperatures (200 and 250 °C), the response times of the sensor are a few seconds, but the recovery times are longer. It is noteworthy that at 250 °C operating temperature the sensor's resistance changed about 25 times in the presence of 100 ppm hydrogen peroxide vapours.

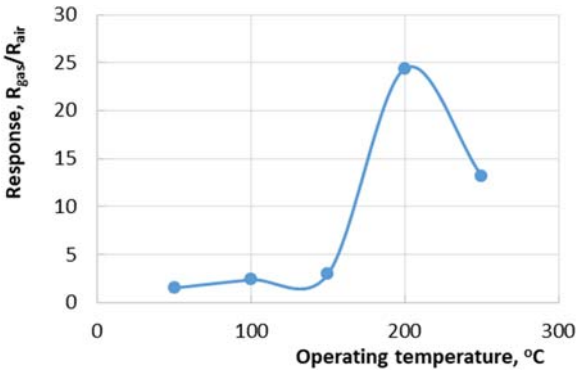


Fig. 5. The dependence of the ZnO<1at.% La> sensor's response on the operating temperature in the presence of 100 ppm hydrogen peroxide vapors.

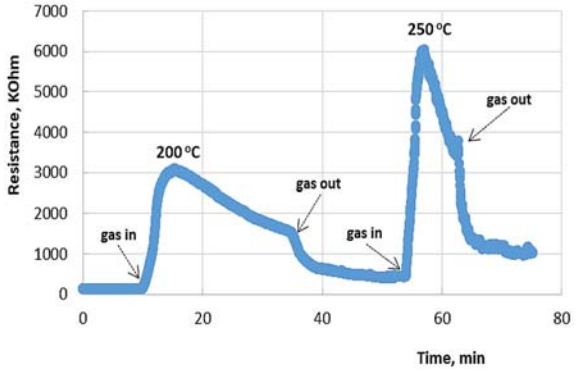


Fig. 6. The resistance variation of the ZnO<1at.% La> sensor in the presence of 100 ppm hydrogen peroxide vapors at 200 and 250 °C operating temperatures.

The sensing responses of the ZnO<1at.% La> film at 150 °C operating temperature towards ppm level of H_2O_2 were tested and the results are shown in Fig. 7.

The results indicated that the sensor exhibited clear and reversible gas responses to ppm levels of the gas. The absolute sensor responses to H_2O_2 vapors at the concentrations of 100 and 200 ppm, were about 3 and 14 respectively.

The gas-sensitive properties of the sensor are excellent at 200 and 250 °C operating temperatures, but at 150 °C the power consumption of the sensor is quite low. From this point of view, it is quite difficult to choose a specific operating temperature. On the other hand, the impedance properties of the sensor are fairly promising at 150 °C.

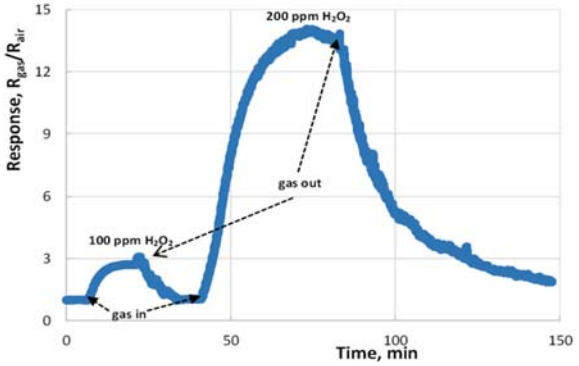


Fig. 7. The response-recovery curves of ZnO<1at.% La> sensor observed at different concentration of H_2O_2 vapors at 150 °C operating temperature.

There were also studied the gas sensing properties of the sensor by impedance spectroscopy using the ZIVE-SP1 Potentiostat and the Keithley 4200-SCS (Semiconductor Characterization System).

The Nyquist plot is commonly depicted as a semicircle at high frequency. The Nyquist plots of ZnO<1at.% La> sensor were observed in the air and in the presence of 200, 300 and 400 ppm hydrogen peroxide vapors at 150 °C operating temperature. Fig. 8 and Fig. 9 show the significant deviations of Nyquist plots at the presence of H_2O_2 vapors and in the air.

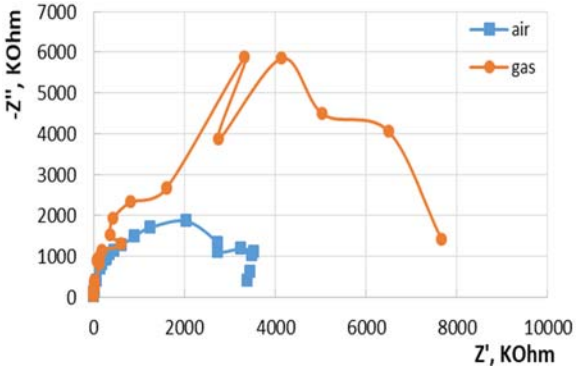


Fig. 8. The Nyquist plots of ZnO<1at.% La> sensor observed in the air and in the presence of 200 ppm H_2O_2 vapors at 150 °C operating temperature.

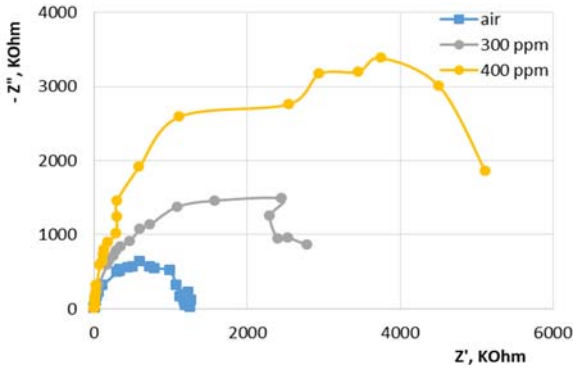


Fig. 9. The Nyquist plots of ZnO<1at.% La> sensor observed in the air and in the presence of 300 and 400 ppm H_2O_2 vapors at 150 °C operating temperature.

Future researches will focus not only on the study of the deviations of Nyquist plots at the presence of H_2O_2, but also on the build of the sensor equivalent circuit, obtaining more comprehensive information about the gas-sensitive element.

It was extracted the response vs. concentration curve for the ZnO doped 1 at.% La film. Fig. 10 shows the dependence of response on the hydrogen peroxide vapor concentration at 150 °C operating temperature. Here, similar to the resistive response, we consider an impedance response with the following definition: $R=Z''_{gas}/Z''_{air}$ (at 460 Hz frequency). It's clear, that the dependence has a linear characteristic, which will allow not only to detect of hydrogen peroxide vapors but also to accurately measure the low concentrations of this gas.

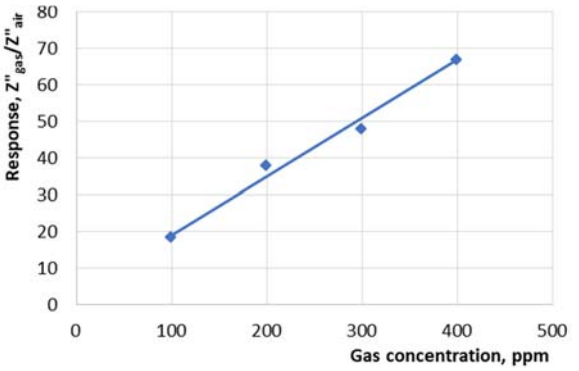


Fig. 10. The dependence of the ZnO<1at.% La> sensor's response on the H_2O_2 vapor concentration at 150 °C operating temperature.

The gas-sensitive properties of the sensors based on ZnO doped 0.5; 1.5; 2; and 2.5 at.% La were also studied. A change in the concentration of the dopant in the ZnO material changes its resistance, but the dependence has no pattern (Fig. 11). It is assumed, that such behavior is associated with stoichiometric disorders of the thin film ZnO. The minimum resistance (0.07 MOhm) is observed in the case of 0.5 at.% concentration of La and the maximum (25.6 MOhm) in the case of 2.5 at.% La.

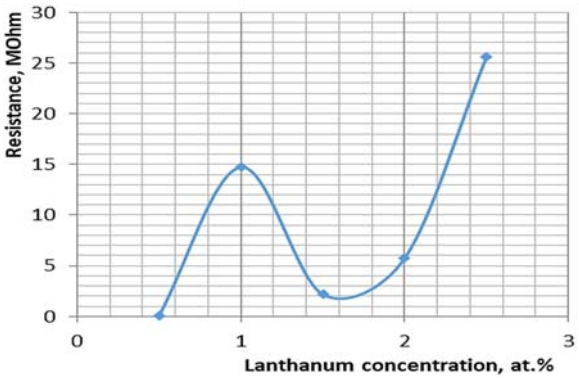


Fig. 11. The dependence of the ZnO<La> sensor's resistance on the Lanthanum concentration at 150 °C operating temperature in the air.

The response-recovery curves of ZnO<La> sensor with different percentage of La observed at 100 ppm of H_2O_2 vapors at 150 ^{0}C operating temperature are presented in Fig. 12. The maximum sensitivity was observed at 2 at.% La concentration in ZnO material and increased concentration of the dopant has led to a sharp drop in the response (Fig. 13).

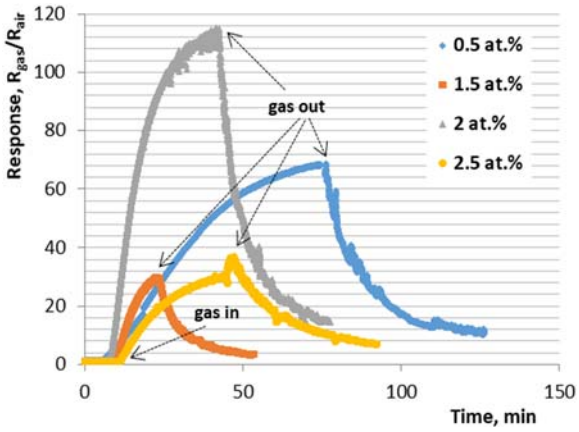


Fig. 12. The response-recovery curves of ZnO<La> sensor with different percentage of dopant (La) observed at 100 ppm of H_2O_2 vapors at 150 ^{0}C operating temperature.

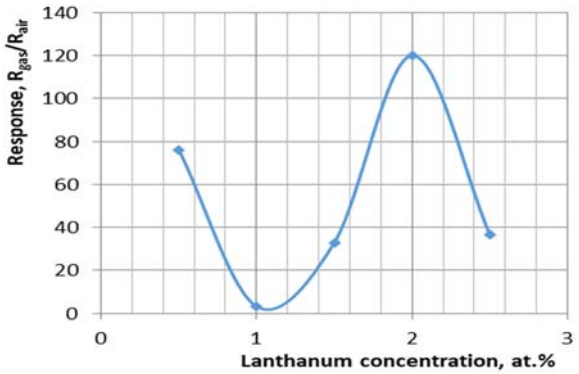


Fig. 13. The dependence of the ZnO<La> sensor's response on the Lanthanum concentration in the presence of 100 ppm H_2O_2 vapors at 150 °C operating temperature.

This ZnO<2 at.% La> based sensor showed extremely high sensitivity to very low concentrations of hydrogen peroxide vapors at relatively low operating temperatures. The resistance variation of the ZnO<2 at.% La> sensor in the presence of 100 ppm hydrogen peroxide vapors at 150 °C operating temperature is presented in Fig. 14. At this concentration of H_2O_2, the resistance of the film changes more than 120 times and after eliminating the effect of target gas, the resistance is almost completely recovered.

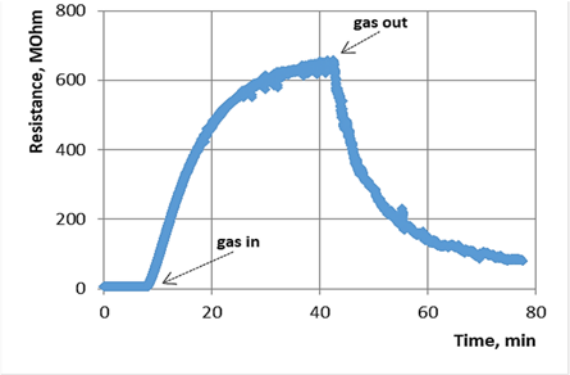


Fig. 14. The resistance variation of the ZnO<2 at.% La> sensor in the presence of 100 ppm hydrogen peroxide vapors at 150 °C operating temperature.

There were also studied the gas sensing properties of the ZnO doped 0.5; 1.5; 2; and 2.5 at.% La sensors by impedance spectroscopy. The best sensing results were demonstrated by ZnO<2 at.% La> and ZnO<0.5 at.% La> sensors.

The Nyquist plots of the sensors were observed in the air and in the presence of 100 ppm hydrogen peroxide vapors at 150 °C operating temperature (see Fig. 15 and Fig. 16). In the presence of target gas the larger deviation of Nyquist plot was observed for ZnO<0.5 at.% La> sensor and the curves observed both in the air and in the target gas have almost semicircle appearance.

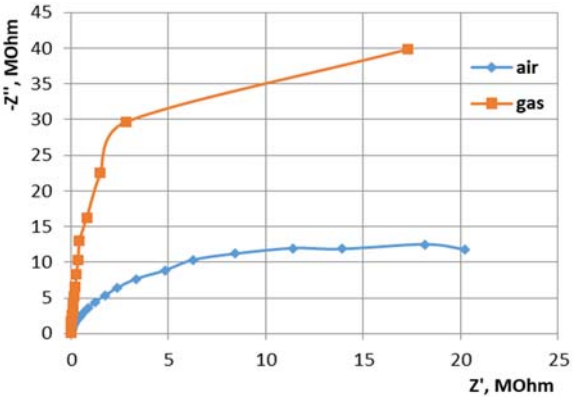


Fig. 15. The Nyquist plots of ZnO<2at.% La> sensor observed in the air and in the presence of 100 ppm H_2O_2 vapors at 150 °C operating temperature.

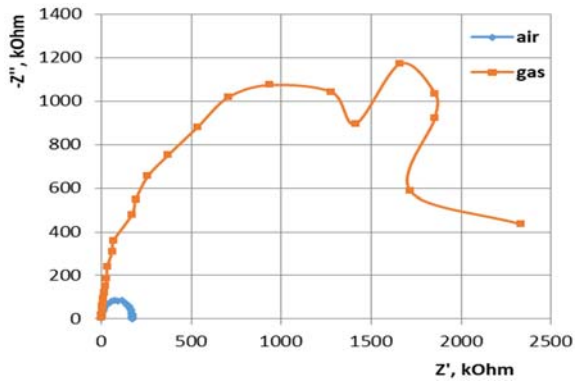


Fig. 16. The Nyquist plots of ZnO<0.5 at.% La> sensor observed in the air and in the presence of 100 ppm H_2O_2 vapors at 150 °C operating temperature.

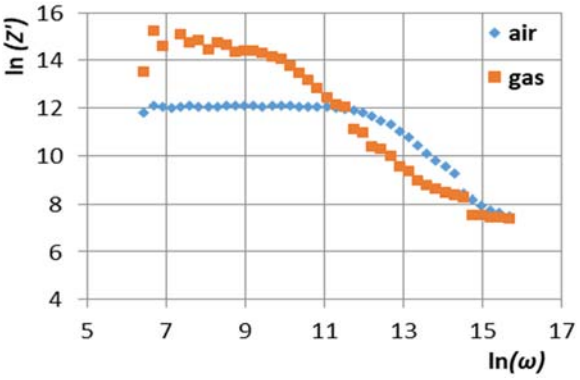


Fig. 17. Frequency dependencies for the real component of the impedance for the ZnO<0.5 at.% La> sensor in the air and in the presence of 100 ppm H_2O_2 vapors at 150 °C operating temperature.

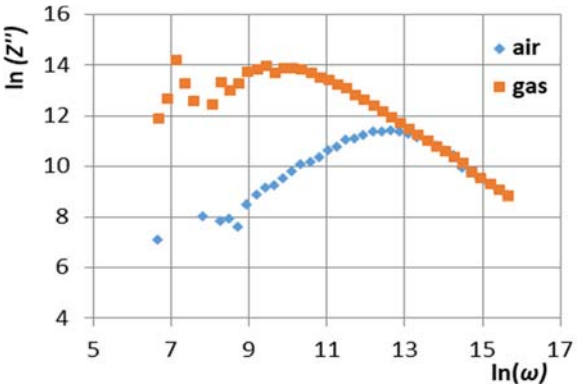


Fig. 18. Frequency dependencies for the imaginary component of the impedance for the ZnO<0.5 at.% La> sensor in the air and in the presence of 100 ppm H_2O_2 vapors at 150 °C operating temperature.

The frequency dependencies for the real and imaginary components of the impedance for the ZnO<0.5 at.% La> sensor were also extracted. At low frequencies the deflection of the curves due to target gas is incomparably large, which is due to the fact that at high frequencies the capacitive properties of the sensitive film are revealed.

4. Hydrogen Peroxide Sensing Mechanism

The basis of the operation of conductometric MOS based sensors is the change in resistance under the effect of reactions taking place on the surface of the sensing layer. The change of the sensor resistance is related to an ionosorption phenomenon and can be explained by a transfer of free charge carriers from the sensing layer to adsorbed surface species (or vice versa). The initial exposure to air results in oxygen adsorption on the surface through transferring electrons from the conduction band to the adsorbed oxygen. Depending on the working temperatures various oxygen species (O_2^-, O^-, O^{2-}), water, and carbon dioxide-related species are present at the active surface of the MOS. Oxygen species play an important role in the sensing mechanism of MOS based gas sensors. The oxygen chemisorption means the formation of O^{2-}, O^- and O_2^- species on the surface. They originate due to electrons which are captured by adsorbed neutral oxygen species on the surface of the oxide. These types of sensors operate mainly at higher temperatures than room temperature. The working temperature of metal oxide gas sensors is in the range of 25-500 °C. In this temperature range, the formation of chemisorbed oxygen ion species mainly depends on the variation of the temperature during gas-sensing measurements. For n-type semiconductor the majority charge carriers are electrons and upon interaction with a reducing gas an increase in conductivity occurs. In the case of oxidizing gases, an increase in resistance is observed. It is known that the outbreak and intensity of chemical reactions are highly dependent on temperature. The formation of chemisorbed oxygen ion species, such as O_2^-, O^-, and O^{2-}, mainly depends on the variation of the temperature during gas-sensing measurements. The related reactions are shown in the following equations [27, 28]:

$$O_{2(gas)} \leftrightarrow O_{2(adsorbed)} \quad (1)$$

$$O_{2(adsorbed)} + e^- \leftrightarrow O^-_{2(adsorbed)} \ (<100\ ^0C) \quad (2)$$

$$O^-_{2(adsorbed)} + e^- \leftrightarrow 2O^-_{(adsorbed)} \ (100\text{-}300\ ^0C) \quad (3)$$

$$O^-_{(adsorbed)} + e^- \leftrightarrow O^{2-}_{(adsorbed)} \ (>300\ ^0C) \quad (4)$$

Depending on the type of target gas and the morphology of the sensitive material, the optimal operating temperature varies. At low operating temperatures, the response of MOS based sensor is restricted by the rates of the chemical reactions, and at high temperatures, it is limited by the diffusion rate of gas molecules [29].

Hydrogen peroxide is an oxidizing gas and in the case of n-type semiconductor it increases the resistance of the film. Upon exposure to hydrogen peroxide vapors, the gas molecules splits and created O_2 molecules react with semiconductor surface and take electrons from the lattice, forming oxygen ions

which result in a decrease of electrical conductance of the n-type semiconductor (La-doped ZnO sensitive film). The corresponding reactions are as follows [30]:

$$2H_2O_2 \rightarrow 2H_2O + O_2 \quad (5)$$

$$O_2 + e^- \rightarrow O_2^- \quad (6)$$

In the absence of the target gas, the localized oxygen ions are intensively desorbed from the semiconductor surface, returning the previously taken electrons back to the lattice. As a result, the resistance of the semiconductor decreases [31].

5. Conclusions

We have successfully prepared the La doped ZnO sensitive thin films and demonstrated hydrogen peroxide vapor sensors at low operating temperature. The excellent gas sensing performance can be attributed to the following aspects: the sensor provides not only high response to ppm level of H_2O_2 vapors at low operating temperature but also significant deviation of Nyquist plots at the presence of hydrogen peroxide vapor. To introduce optimum amount of La_2O_3 dopant into the ZnO base material can be maximized and present best sensing properties.

References

[1]. G. Shahkhatuni, V. Aroutiounian, V. Arakelyan, M. Aleksanyan, G. Shahnazaryan, Investigation of Sensor Made of ZnO:La for Detection of Hydrogen Peroxide Vapours by Impedance Spectroscopy Method, *Journal of Contemporary Physics (Armenian Academy of Sciences)*, Vol. 54, Issue 2, 2019, pp. 188-195.

[2]. L. Chen, X. Xua, F. Cui, Q. Qiu, X. Chena, J. Xu, Au nanoparticles-ZnO composite nanotubes using natural silk fibroin fiber as template for electrochemical non-enzymatic sensing of hydrogen peroxide, *Analytical Biochemistry*, Vol. 554, 2018, pp. 1-8.

[3]. S. Parthasarathy, V. Nandhini, B. G. Jeyaprakash, Improved sensing response of photo activated ZnO thin film for hydrogen peroxide detection, *Journal of Colloid and Interface Science*, Vol. 482, 2016, pp. 81-88.

[4]. M. S. Aleksanyan, A. G. Sayunts, H. A. Zakaryan, V. M. Aroutiounian, V. M. Arakelyan, G. E. Shakhnazaryan, Influence of UV Rays on the Volt-Capacity Characteristic of SnO_2:Co Sensor of Vapors of Hydrogen Peroxide, *Journal of Contemporary Physics (Armenian Academy of Sciences)*, Vol. 55, Issue 2, 2020, pp. 151-156.

[5]. H. Tian, H. Fan, J. Ma, L. Ma, G. Dong, Noble metal-free modified electrode of exfoliated graphitic carbon nitride/ZnO nanosheets for highly efficient hydrogen peroxide sensing, *Electrochimica Acta*, Vol. 247, 2017, pp. 787-794.

[6]. B. P. Garreffi, M. Guo, N. Tokranova, N. C. Cadyb, J. Castracane, I. A. Levitsky, Highly sensitive and selective fluorescence sensor based on nanoporous silicon-quinoline composite for trace detection of hydrogen peroxide vapors, *Sensors & Actuators: B. Chemical*, Vol. 276, 2018, pp. 466-471.

[7]. J. S. Lee, D. W. Jeong, Y. T. Byunc, Porphyrin nanofiber/single-walled carbon nanotube nanocomposite-based sensors for monitoring hydrogen peroxide vapor, *Sensors & Actuators: B. Chemical*, Vol. 306, 2020, p. 127518.

[8]. V. Aroutiounian, V. Arakelyan, M. Aleksanyan, A. Sayunts, G. Shahnazaryan, P. Kacer, P. Picha, J. A. Kovarik, J. Pekarek, B. Joost, Nanostructured sensors for detection of hydrogen peroxide vapours, *Sensors & Transducers*, Vol. 213, Issue 6, June 2017, pp. 46-53.

[9]. Z. Fan, J. G. Lu, Zinc Oxide Nanostructures: Synthesis and Properties, *Journal of Nanoscience and Nanotechnology*, Vol. 5, Issue 10, 2005, pp. 1561-1573.

[10]. C. R. Wuethrich, C. A. Muller, G. R. Fox, H. G. Limberger, All-fibre acousto-optic modulator using ZnO piezoelectric actuators, *Sensors and Actuators A: Physical*, Vol. 66, Issue 1-3, 1998, pp. 114-117.

[11]. J. Gomez, O. Tigli, Zinc oxide nanostructures: from growth to application, *Journal of Materials Science*, Vol. 48, 2013, pp. 612-624.

[12]. K. W. Guo, Property of Zinc Oxide (ZnO) Nanostructures Potential for Biomedical System and Its Common Growth Mechanism, *Journal of Applied Biotechnology & Bioengineering*, Vol. 2, 2017, 00046.

[13]. V. M. Aroutiounian, M. S. Aleksanyan, V. M. Arakelyan, G. E. Shahnazaryan, G. H. Shahkhatuni, Hydrogen Peroxide Vapor Sensor Based on Zinc Oxide, in *Proceedings of the 6th International Conference on Sensors Engineering and Electronics Instrumentation Advances (SEIA' 2020)*, Porto, Portugal, 23-25 September 2020, pp. 13-17.

[14]. V. S. Bhati, M. Hojamberdiev, M. Kumar, Enhanced sensing performance of ZnO nanostructures-based gas sensors: A review, *Energy Reports*, Vol. 6, 2020, pp. 46-62.

[15]. A. Ferreira, N. Martin, S. L. Méndez, F. Vaz, Tuning electrical resistivity anisotropy of ZnO thin films for resistive sensor applications, *Thin Solid Films*, Vol. 654, 2018, pp. 93-99.

[16]. H. Ding, L. Zhang, Z. Tang, Y. Dong, X. Chu, Black phosphorus quantum dots doped ZnO nanoparticles as efficient electrode materials for sensitive hydrogen peroxide detection, *Journal of Electroanalytical Chemistry*, Vol. 824, 2018, pp. 161-168.

[17]. J. Wanga, S. Fana, Y. Xia, C. Yang, S. Komarnenic, Room-temperature gas sensors based on ZnO nanorod/Au hybrids: Visiblelight-modulated dual selectivity to NO_2 and NH_3, *Journal of Hazardous Materials*, Vol. 381, 2020, 120919.

[18]. V. Aroutiounian, V. Arakelyan, M. Aleksanyan, G. Shahnazaryan, P. Kacer, P. Picha, J. Kovarik, J. Pekarek, B. Joost, Thin-film SnO_2 and ZnO detectors of hydrogen peroxide vapors, *Journal of Sensors and Sensor Systems*, Vol. 7, Issue 1, 2018, pp. 281-288.

[19]. V. M. Aroutiounian, V. M. Arakelyan, M. S. Aleksanyan, G. E. Shahnazaryan, A. G. Sayunts, B. Joost, Study of Hydrogen Peroxide Vapors Sensor Made of Nanostructured Co-doped SnO_2 Film, *Sensors & Transducers*, Vol. 229, Issue 1, 2019, pp. 24-31.

[20]. G. H. Shahkhatuni, V. M. Aroutiounian, V. M. Arakelyan, M. S. Aleksanyan, G. E. Shahnazaryan, Conductometric sensor for hydrogen peroxide vapors detection, *Armenian Journal of Physics*, Vol. 11, Issue 3, 2018, pp. 153-159.

[21]. M. S. Aleksanyan, Magnetron Sputtering Techniques and Their Applications at Gas Sensors Manufacturing, *Armenian Journal of Physics*, Vol. 12, Issue 1, 2019, pp. 62-77.

[22]. S. H. Salman, A. A. Shihab, A. K. Elttayef, Design and Construction of Nanostructure TiO_2 Thin Film Gas Sensor Prepared by R.F. Magnetron Sputtering Technique, *Energy Procedia*, Vol. 157, 2019, pp. 283-289.

[23]. F. Papa, H. Gerdes, R. Bandorf, A. P. Ehiasarian, I. Kolev, G. Braeuer, R. Tietema, T. Krug, Deposition rate characteristics for steady state high power impulse magnetron sputtering (HIPIMS) discharges generated with a modulated pulsed power (MPP) generator, *Thin Solid Films*, Vol. 520, Issue 5, 2011, pp. 1559-1563.

[24]. A. Bogaerts, E. Neyts, R. Gijbels, J. Mullen, Gas discharge plasmas and their applications, *Spectrochimica Acta Part B: Atomic Spectroscopy*, Vol. 57, Issue 4, 2002, pp. 609-658.

[25]. R. L. Wilson, C. E. Simion, C. S. Blackman, C. J. Carmalt, A. Stanoiu, F. D. Maggio, J. A. Covington, The Effect of Film Thickness on the Gas Sensing Properties of Ultra-Thin TiO_2 Films Deposited by Atomic Layer Deposition, *Sensors*, Vol. 18, Issue 3, 2018, pp. 735-748.

[26]. X. Du, S. M. George, Thickness dependence of sensor response for CO gas sensing by tin oxide films grown using atomic layer deposition, *Sensors & Actuators: B. Chemical*, Vol. 135, Issue 1, 2008, pp. 152-160.

[27]. R. Ahmad, S. M. Majhi, X. Zhang, T. M. Swager, K. N. Salama, Recent progress and perspectives of gas sensors based on vertically oriented ZnO nanomaterials, *Advances in Colloid and Interface Science*, Vol. 270, 2019, pp. 1-27.

[28]. X. Liu, S. Cheng, H. Liu, S. Hu, D. Zhang, H. Ning, A Survey on Gas Sensing Technology, *Sensors*, Vol. 12, Issue 7, 2012, pp. 9635-9665.

[29]. A. B. Gadkari, T. J. Shinde, P. N. Vasambekar, Ferrite gas sensors, *IEEE Sensors Journal*, Vol. 11, Issue 4, 2011, pp. 849-861.

[30]. F. Xu, H. P. Ho, Light-Activated Metal Oxide Gas Sensors: A Review, *Micromachines*, Vol. 8, Issue 11, 2017, pp. 333-386.

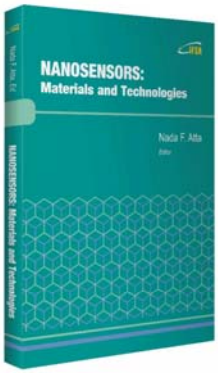
[31]. M. J. Martin, G. B. Brieva, J. L. Fierro, Hydrogen Peroxide Synthesis: An Outlook beyond the Anthraquinone Process, *Angewandte Chemie International Edition*, Vol. 45, Issue 42, 2006, pp. 6962-6984.

Published by International Frequency Sensor Association (IFSA) Publishing, S. L., 2020 (http://www.sensorsportal.com).

NANOSENSORS:
Materials and Technologies

Hardcover: ISBN 978-84-616-5378-2
e-Book: ISBN 978-84-616-5422-2

Nada F. Atta, Ed.



Nanosensors: Materials and Technologies aims to provide the readers with some of the most recent development of new and advanced materials such as carbon nanotubes, graphene, sol-gel films, self-assembly layers in presence of surface active agents, nano-particles, and conducting polymers in the surface structuring for sensing applications. The emphasis of the presentations is devoted to the difference in properties and its relation to the mechanism of detection and specificity. Miniaturization on the other hand, is of unique importance for sensors applications. The chapters of this book present the usage of robust, small, sensitive and reliable sensors that take advantage of the growing interest in nano-structures. Different chemical species are taken as good example of the determination of different chemical substances industrially, medically and environmentally. A separate chapter in this book will be devoted to molecular recognition using surface templating.

The present book will find a large audience of specialists and scientists or engineers working in the area of sensors and its technological applications. The *Nanosensors: Materials and Technologies* will also be useful for researchers working in the field of electrochemical and biosensors since it presents a collection of achievements in different areas of sensors applications.

Order: http://www.sensorsportal.com/HTML/BOOKSTORE/Nanosensors_IFSA.htm