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## EVOLUTION OF STRUCTURAL, OPTICAL PROPERTIES AND ELECTRICAL TRANSPORT OF NiO<sub>x</sub> FILMS ANNEALED IN DIFFERENT ENVIRONMENT

The influence of the annealing medium of thin films of nickel oxide (NiO<sub>x</sub>) on structural, optical and electrical transport properties is studied in this paper. NiO<sub>x</sub> films were synthesized by sol-gel method and annealed at a temperature of 300 °C in air, inert nitrogen (N<sub>2</sub>), oxygen (O<sub>2</sub>) gases and vacuum. The values of the films thickness were determined from the transverse cleavage of the SEM image. The films thickness depends on the annealing medium. Measurements of the EDX spectra of NiO<sub>x</sub> films were carried out. Analysis of the quantitative O/Ni ratio showed that the film annealed in an air atmosphere is close to the stoichiometric parameters of NiO. Measurements of the EDX spectra of NiO<sub>x</sub> films were carried out. According to the Raman spectra, an increase in peak intensities is observed indicating an increase in the density of defects in the film by Ni vacancies depending on the annealing medium. Absorption spectra and Tauc plots of NiO<sub>x</sub> films were obtained. The optical density of the films depends on the annealing conditions of the films. Data analysis shows that the band gap width depends on the annealing medium and varies from  $E_g = 3.12$  eV to  $E_g = 3.45$  eV. The analysis of the impedance spectra allowed us to estimate the values of the resistances  $R_1$  and  $R_2$ . It is shown that an increase in the resistance of  $R_1$  is associated with a decrease in the density of defects in the NiO<sub>x</sub> film, decrease in the recombination resistance of  $R_2$ , and an increase in recombination processes at the interface.

**Key words:** nickel oxide, sol-gel technology, annealing environment, optical band gap, absorption coefficient, dispersion index, electrical transport characteristics.

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## Әртүрлі ортада күйдірілген NiO<sub>x</sub> қабықшаларының құрылымдық, оптикалық және электрлік тасымалдау қасиеттерінің эволюциясы

Бұл жұмыста никель оксидінің (NiO<sub>x</sub>) жұқа қабықшаларын құрылымдық, оптикалық және электр тасымалдау қасиеттері зерттелді. NiO<sub>x</sub> қабықшалары золь - гель әдісімен синтезделіп, 300 °C температурада ауада, инертті азот (N<sub>2</sub>), оттегі (O<sub>2</sub>) газдарында және вакуумда күйдірілді. Қабықшалар қалыңдығының мәндері СЭМ суреттеріндегі көлденең кескіндерінен анықталды. Қабықшалардың қалыңдығы күйдіру ортасына байланысты өзгереді. NiO<sub>x</sub> қабықшаларының EDX спектрлерін өлшеу жүргізілді. О/Ni сандық қатынасын талдау, ауа атмосферасында күйдірілген қабықша NiO стехиометриялық көрсеткіштеріне жақын екенін көрсетті. Комбинациялық шашырау спектрлері бойынша шыңдар қарқындылығының жоғарылауы байқалады, бұл күйдіру ортасына байланысты Ni бос орындарының қабықша ақауларының тығыздығының жоғарылауын көрсетеді. Жұтылу спектрлері алынды және NiO пленкаларының таук графиктері қабықшалардың оптикалық тығыздығы, қабықшаларды күйдіру жағдайларына байланысты. Деректерді талдау көрсеткендей, тыйым салынған аймақ ені күйдіру ортасына байланысты  $E_g = 3,12$  эВ-ден  $E_g = 3,45$  эВ-ге дейінгі аралықта. Кедергі спектрлерін талдау  $R_1$  және  $R_2$  кедергі мәндерін бағалауға мүмкіндік берді.  $R_1$  кедергісінің жоғарылауы

$\text{NiO}_x$  пленкасындағы ақаулардың тығыздығының төмендеуімен,  $R_2$  рекомбинациялық кедергісінің төмендеуімен және рекомбинациялық процестердің жоғарылауымен байланысты екендігі көрсетілген.

**Түйін сөздер:** никель оксиді, золь-гель технологиясы, күйдіру ортасы, оптикалық тыйым салынған аймақ, жұтылу коэффициенті, дисперсия индексі, электр тасымалдау сипаттамалары.

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## Эволюция структурных, оптических и электротранспортных свойств пленок $\text{NiO}_x$ , отоженных в различных средах

В работе исследовано влияние среды отжига тонких пленок оксида никеля ( $\text{NiO}_x$ ) на структурные, оптические и электротранспортные свойства. Пленки  $\text{NiO}_x$  были синтезированы золь-гель методом и отожжены при температуре 300 °С на воздухе, инертных газах азота ( $\text{N}_2$ ), кислорода ( $\text{O}_2$ ) и в вакууме. Значения толщины пленок определяли по поперечному сколу СЭМ-изображения. Толщина пленок зависит от среды отжига. Проведены измерения EDX-спектров пленок  $\text{NiO}_x$ . Анализ количественного соотношения O/Ni показал, что пленка, отожженная в атмосфере воздуха, близка к стехиометрическим параметрам NiO. Проведены измерения EDX-спектров пленок  $\text{NiO}_x$ . По спектрам КР наблюдается увеличение интенсивности пиков, свидетельствующее об увеличении плотности дефектов пленки вакансиями Ni в зависимости от среды отжига. Получены спектры поглощения и таук-графики пленок  $\text{NiO}_x$ . Оптическая плотность пленок зависит от условий отжига пленок. Анализ данных показывает, что ширина запрещенной зоны зависит от среды отжига и варьируется от  $E_g = 3,12$  эВ до  $E_g = 3,45$  эВ. Анализ спектров импеданса позволил оценить значения сопротивлений  $R_1$  и  $R_2$ . Показано, что увеличение сопротивления  $R_1$  связано с уменьшением плотности дефектов в пленке  $\text{NiO}_x$ , уменьшением рекомбинационного сопротивления  $R_2$  и усилением рекомбинационных процессов на границе раздела.

**Ключевые слова:** оксид никеля, золь-гель технология, среда отжига, оптическая запрещенная зона, коэффициент поглощения, показатель дисперсии, характеристики электротранспорта.

### Introduction

Among many conductive oxide materials, nanostructured nickel oxide ( $\text{NiO}_x$ ) films attract considerable attention due to their unique structural, electrical and optical properties [1-2]. Numerous studies have made significant progress in the development and improvement of the properties of  $\text{NiO}_x$ , which has led to its widespread use in various electronic devices such as thin-film transistors, photovoltaic cells, LEDs, sensors, storage devices and catalysts [3]. Nickel oxide is an inorganic semiconductor with p-type transport properties that can be used as a hole-conduction layer (HTL) material in optoelectronic devices [4].  $\text{NiO}_x$  exhibits natural hole conductivity, as a rule, due to a large number of intrinsic defects, such as Ni vacancies and O vacancies. However, Ni vacancies are considered effective  $\text{NiO}_x$  acceptors, they also impair the transparency of the material in the visible area. It was found that the presence of a Ni vacancy in  $\text{NiO}_x$

grown in a medium with a high O content leads to significant absorption of subzones compared with an O vacancy in  $\text{NiO}_x$  grown in a medium with a high Ni content [5].

Various methods are used to improve the characteristics of  $\text{NiO}_x$  films, including changing the concentration of impurities, using various synthesis and post-treatment methods in UV ozone [6,7], oxygen plasma [8] and thermal annealing [9]. At the same time, the conditions of thermal annealing of the film are also of great importance. As a rule, in order to recrystallize the film and reduce the density of point defects, annealing is carried out in an oxygen-containing medium at a temperature of 200-500 °C and a duration of 10 to 60 minutes [10-13]. However, it is believed that atmospheric annealing does not allow the removal of  $\text{NiOOH}$  phases on the surface of an oxide semiconductor [14]. It is assumed that there is a high probability of the formation of  $\text{NiOOH}$  phases after heat treatment as a result of

reaction with moisture from the atmosphere. The use of vacuum annealing can contribute to the thermal decomposition of the NiOOH phase. In addition, since the NiO<sub>x</sub> phase is more stable than the Ni<sub>2</sub>O<sub>3</sub> phase, at low oxygen partial pressure [15], vacuum heat treatment should reduce the content of this phase on the surface.

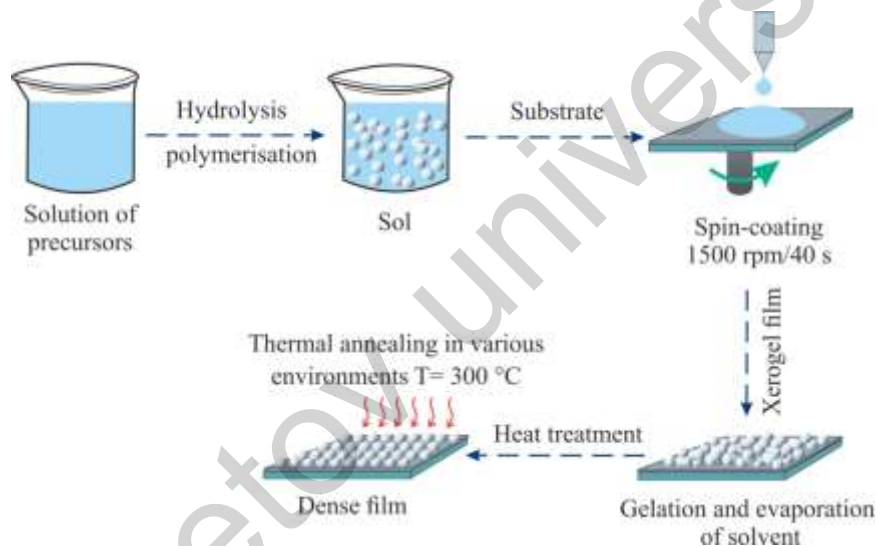
Thus, it is necessary to study technological methods for optimizing internal defects in NiO<sub>x</sub> to simultaneously increase the conductivity and transparency of films, for the application of transparent optoelectronic devices.

In this work, NiO<sub>x</sub> films were obtained by sol-gel method and the effect of thermal annealing in various media on the morphology, optical and electrical properties of NiO<sub>x</sub> films was studied [16].

## Materials and methods

### Thin films preparation

Nickel oxide films were obtained on the surface of a solid substrate as follows: nickel nitrate hexahydrate [Ni(NO<sub>3</sub>)<sub>2</sub> · 6H<sub>2</sub>O] weighing  $m = 145$  mg (Sigma-Aldrich) was dissolved in a volume of ethyleneglycol ( $V = 1$  ml). Monoethanolamine (5  $\mu$ l) was added to the resulting solution. The solution was stirred at room temperature for 16 hours and then kept for 24 hours at room temperature. It was applied to the surface of a solid substrate using a pipetted dispenser by centrifugation (SPIN150i, Semiconductor Production System) at a rotational speed of 1500 rpm. The obtained films were pre-annealed at a temperature of 100 °C for 15 minutes. After that, the films were annealed in different media at a temperature of 300 °C for 45 minutes (Fig. 1).



**Figure 1** – Schematic representation of NiO<sub>x</sub> thin films deposition from a sol by a spin-coating technique

The surface of NiO<sub>x</sub> thin films was studied using scanning electron microscopy (SEM), MIRA 3 LMU (TESCAN). Energy dispersive X-ray radiation (EDX) is measured in an INCA PentaFET-x3 analyzer (Oxford Instruments, England) to assess the quality of thin films.

Scanning probe microscopy is used to study the surface roughness of NiO<sub>x</sub> thin films using an atomic force microscope JSPM-5400 (AFM, JEOL). The AFM images were processed using a modular program for analyzing data from scanning probe microscopy (Win SPMII Data-Processing Software). The average grain size distribution of NiO<sub>x</sub> was obtained from topographic images using ImageJ software.

The Raman spectra were measured using the Gurzil Raman Microscope TORMS-532/TORMS-785 (Thunder Optics, France). To excite the spectra,

radiation from a semiconductor laser (ThunderOptics, France) with a wavelength of 523 nm and a line width of 0.3nm was applied.

The absorption and transmission spectra of the studied samples were measured on AvaSpec-ULS2048CL-EVO spectrometer (Avantes). A combined deuterium-halogen light source AvaLight-DHc (Avantes) with an operating range of 200-2500 nm was used as probing radiation.

The impedance spectra were measured on a P45X potentiostat-galvanostat in the impedance mode with an additionally installed FRA-24M frequency analyzer module. The error in determining the parameters of charge carrier transport did not exceed 5% and was predominantly 1-1.5%. Fitting and analysis of the spectral parameters were performed using the EIS-analyzer software according to the procedure described in [17].

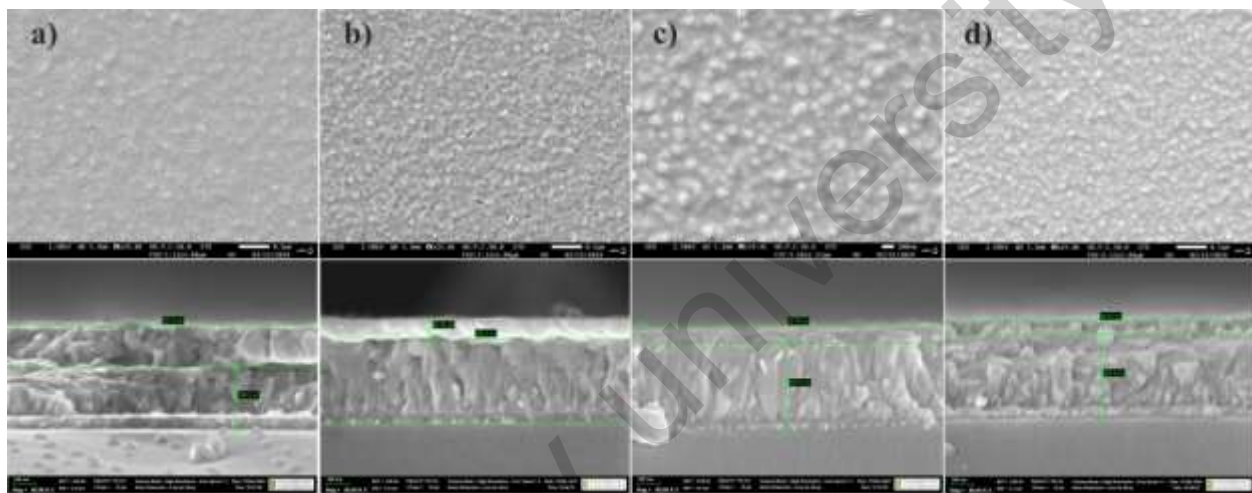
## Results and discussion

### Surface morphology

Fig. 2 shows SEM images of the surface of nanostructured NiO<sub>x</sub> films annealed at 300 °C in air, inert nitrogen (N<sub>2</sub>), oxygen (O<sub>2</sub>) and vacuum. As can be seen from the SEM image, the morphology of the NiO<sub>x</sub> film in the annealed air atmosphere has a smoother surface structure. For films annealed in an inert N<sub>2</sub> atmosphere and in a vacuum, the surface morphology has a fine-grained structure. The film annealed in an O<sub>2</sub> atmosphere has a morphology with larger grains. The thicknesses of NiO<sub>x</sub> films were determined from the SEM images of the transverse

cleavage. It can be seen from the SEM image that the film annealed on an air atmosphere has the greatest thickness value of ~ 187 nm. For NiO<sub>x</sub> films annealed in N<sub>2</sub>, the thickness is ~ 89 nm. During annealing in O<sub>2</sub>, a decrease in film thickness to ~ 76 nm is observed, the smallest film thickness of ~ 58 nm is obtained by annealing in vacuum.

Table 1 shows the results of EDX analysis of NiO<sub>x</sub> films annealed at 300 °C in various media. For the EDX analysis, the NiO<sub>x</sub> film was applied to Si substrates. According to the EDX spectra, a change in the quantitative ratio of the elemental composition of O/Ni is observed. Thus, when annealed in an air atmosphere, the NiO<sub>x</sub> film becomes closer to the stoichiometric index (O/Ni ~ 0.8).



**Figure 2** – Change in ambient temperature up to 300 °C in (a) air, (b) nitrogen, (c) oxygen and (d) vacuum

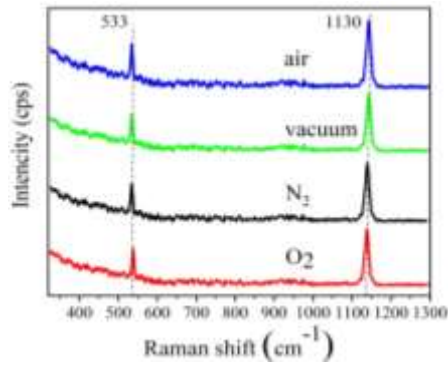
**Table 1** – Morphology parameters and EDX analysis (Atomic percentages) of the surface of NiO<sub>x</sub> films

Annealing ambient	Film thickness, Nm	Ni, %	O, %	Ni/Oratio
Air	187	44.5	55.5	0.80
Nitrogen	89	33.4	66.6	0.50
Oxygen	76	18.0	82.0	0.21
Vacuum	58	42.3	64.4	0.65

Annealing of films in an inert atmosphere of N<sub>2</sub> and vacuum leads to a decrease in the stoichiometric index to 0.5. Annealing of films in pure O<sub>2</sub> gas leads to a significant decrease in the atomic nickel content to 18% and the stoichiometric index by 0.21. Thus, quantitative EDX analysis of films annealed in inert N<sub>2</sub>, O<sub>2</sub> gas and in vacuum indicates insufficient stoichiometry between Ni and O atoms.

### Raman spectra of light in NiO<sub>x</sub> films

Fig. 3 shows the Raman spectra of NiO<sub>x</sub> films annealed in various media. The Raman spectra were measured in the range of 300 cm<sup>-1</sup>–1500 cm<sup>-1</sup>. In the Raman light scattering spectra of NiO<sub>x</sub> films, bands with a scattering maximum of 533 cm<sup>-1</sup> corresponding to Ni-O oscillations belonging to a single-phonon longitudinal optical mode of the first order (1P) LO and a strong band with a scattering maximum of 1130 cm<sup>-1</sup> relating to a two-phonon longitudinal optical mode of the second order (2P) 2LO are observed [18]. As can be seen from the Fig.3, the intensity of the bands depends on the annealing medium of the NiO<sub>x</sub> films. The maximum scattering intensity is observed for NiO<sub>x</sub> films deposited on the air atmosphere. The lowest scattering intensity has a NiO<sub>x</sub> film pressed on an oxygen atmosphere. The observed increase in peak intensities in the scattering spectrum of films indicates an increase in the density of defects in the film formed by Ni vacancies depending on the annealing medium.



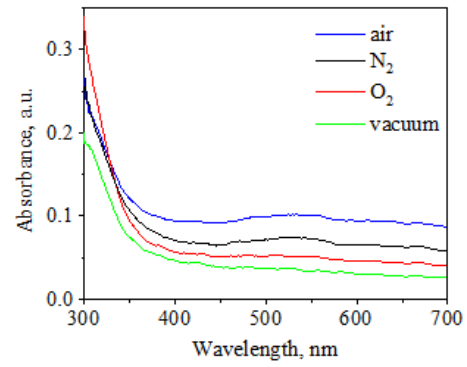
**Figure 3** – Raman spectra for NiO<sub>x</sub> films

### Optical properties

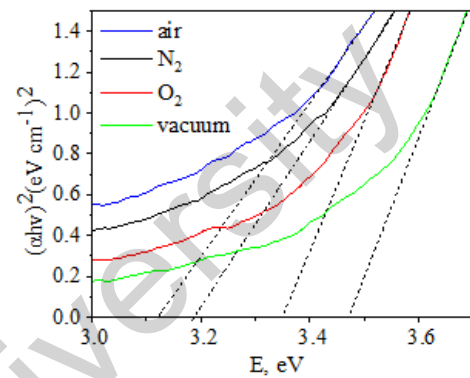
Fig. 4 shows the absorption of NiO<sub>x</sub> films obtained under various annealing conditions. It can be seen from Fig. 4a that the absorption spectrum of NiO<sub>x</sub> has a maximum at a wavelength equal to  $\lambda = 300$  nm. The absorption spectra of annealed films in air has an optical density of 0.25. During annealing in N<sub>2</sub>, an increase in optical density to 0.26 is observed. The films annealed in O<sub>2</sub> have an increase in optical density up to 0.33. The optical density reduces to 0.19 for films annealing in vacuum. The absence of correlations between the thicknesses of films annealed in different media and the values of optical densities in the absorption spectra is associated with the compaction of the structure of NiO<sub>x</sub> films, as shown in [19].

The observed good absorption of films in the short-wavelength region of the spectrum corresponds to the interband transition from the valence band to the bottom of the conduction band. This region corresponds to transitions from the final states of the valence band to the expanded states of the conduction band. A band in the long-wavelength part of the absorption spectrum of NiO<sub>x</sub> films at  $\lambda > 360$  nm is observed. The band may be associated with light scattering on grains in the NiO<sub>x</sub> film. Fig. 4b shows the Tauc graphs for NiO<sub>x</sub> films. The optical band gap was calculated by plotting the dependence  $(\alpha h\nu)^2$  from photon energy  $E$  in eV ( $\alpha$  is the absorption coefficient,  $h\nu$  is the photon energy) and extrapolation of the rectilinear part of this graph to the energy axis.

Data analysis shows that the band gap width depends on the annealing medium and varies from  $E_g = 3.12$  eV to  $E_g = 3.45$  eV. This can be caused by both the high density of film defects and the high density of oxygen vacancies responsible for the high conductivity of films [20]. Interstitial oxygen in NiO<sub>x</sub> films act as lattice defects and can reduce the optical band gap. In addition, interstitial oxygen atoms diffuse from NiO<sub>x</sub> films during the thermal annealing process, as a result, the optical band gap  $E_g$  of NiO<sub>x</sub> films increases.



a)



b)

**Figure 4** – Absorption spectra (a) and Tauc plots (b) of NiO<sub>x</sub> films obtained under various annealing conditions

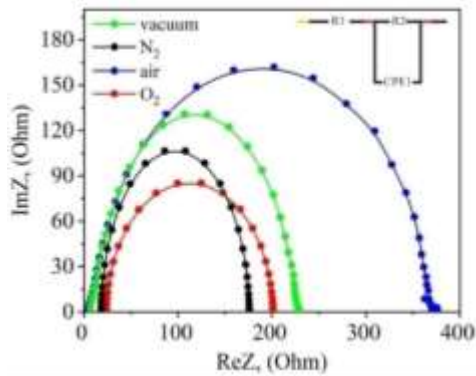
**Table 2** – Parameters of optical characteristics of NiO<sub>x</sub> films under various annealing conditions

Annealing ambient	$D$ , ( $\lambda = 305$ nm)	Optical band gap (eV)
Air	0.20	3.12
Nitrogen	0.26	3.18
Oxygen	0.32	3.34
Vacuum	0.23	3.45

### Photoelectrical characterizations

The influence of the annealing medium of NiO<sub>x</sub> films will obviously affect the hole transport in NiO<sub>x</sub> films. To study in detail the effect of the annealing medium on the transport of charge carriers in the NiO<sub>x</sub> film, the electrical impedance spectra were measured.

Fig. 5 shows the impedance spectra of FTO/NiO<sub>x</sub>/Al cells annealed in different media obtained using a hodograph fitting. The model was analyzed according to an equivalent electrical circuit using the EIS-analyzer software package (in Fig. 5). Table 3 shows the electrical transport parameters of the cells calculated, where  $R_1$  is the total resistance of the external electrodes adjacent to NiO<sub>x</sub> (total resistance of the film),  $R_2$  is the recombination resistance at the NiO<sub>x</sub>/electrode boundary.



**Figure 5** – Impedance spectra of FTO/NiO<sub>x</sub>/Al, cells annealed in different environment

**Table 3** – The value of the electrophysical parameters of the films

Annealing temperature, °C	$R_1$ , (Ohm)	$R_2$ , (Ohm)
Air	5.19	371.45
Vacuum	8.75	282.65
N <sub>2</sub>	23.98	224.26
O <sub>2</sub>	26.72	202.18

The analysis of the impedance spectra allowed us to estimate the values of the resistances  $R_1$  and  $R_2$ . It is important to note that  $R_1$  and  $R_2$  depend on the bias voltage and cell configuration, however, if these parameters do not change, then changes in the values of  $R_1$  and  $R_2$  will be associated with changes in the structural properties of NiO<sub>x</sub> during annealing in different media.

$R_1$  represents the total resistance of the outer adjacent layers (FTO/Al). In our case, all functional layers except NiO<sub>x</sub> were obtained under the same conditions, then it is obvious that changes to  $R_1$  will be associated with a change in the resistance of NiO<sub>x</sub> films. As can be seen from Table 3, the value of  $R_1$  has the lowest value for a cell with NiO<sub>x</sub> annealed on an air atmosphere. The maximum resistance value  $R_1$  has a NiO<sub>x</sub> film annealed in an inert atmosphere N<sub>2</sub>. An increase in the resistance value  $R_1$  depending on the annealing medium is associated with a decrease in the density of defects formed by Ni vacancies depending on the annealing medium responsible for high conductivity [21].

The  $R_2$  resistances characterizing charge recombination at the NiO<sub>x</sub>/electrode interface also vary depending on the annealing medium of the NiO<sub>x</sub>

film. It should be noted that the higher the value of  $R_2$ , the lower the charge recombination rate at the NiO<sub>x</sub>/electrode interface will be [22-25]. As can be seen from Table 3, cells with film annealed in the air atmosphere have the highest resistance value  $R_2$ , which indicates a low recombination rate of holes at the NiO<sub>x</sub>/electrode interface. Annealing of NiO<sub>x</sub> films in the O<sub>2</sub> atmosphere leads to a decrease in recombination resistance, which means an increase in recombination processes.

## Conclusion

The structural, optical and electrical transport properties of NiO<sub>x</sub> films produced by sol-gel technology were investigated. It was found from SEM images the surface of NiO<sub>x</sub> films have a granular structure, the sizes of which depend on the annealing medium. According to EDX analysis of films, it was shown that films annealed in inert N<sub>2</sub>, O<sub>2</sub> and in vacuum have insufficient stoichiometry between Ni and O atoms. The results of measuring the Raman spectra showed that the observed increase in peak intensities in the scattering spectrum of films is associated with an increase in the density of Ni defects depending on the annealing medium. It is shown that the band gap width depends on the annealing medium and is explained by the presence of interstitial oxygen in NiO<sub>x</sub> films, which act as lattice defects, this leads to an increase in the optical band gap  $E_g$ . The values of the resistances  $R_1$  and  $R_2$  of NiO<sub>x</sub> films annealed in different media estimated from the impedance spectra. It is shown that an increase in  $R_1$  resistance depending on the annealing medium. It is associated with a decrease in the density of defects in the NiO<sub>x</sub> film. Decrease in the recombination resistance ( $R_2$ ) indicates an increase in recombination processes at the NiO<sub>x</sub>/electrode interface. The results obtained will find applications of NiO<sub>x</sub> thin films on electronic devices such as solar cells, gas sensors and catalysts cells.

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## References

- 1 Imran M., Coskun H., Khan A.N. and Ouyang J. Role of annealing temperature of nickel oxide (NiOx) as hole transport layer in work function alignment with perovskite // Applied Physics A. – 2021. – Vol.127. – Art.No.117.
- 2 Aimukhanov A.K., Zeinidenov A.K., Omarbekova G.I. and Plotnikova I.V. Investigation of optical and electrophysical characteristics of composite films nio/pedot: pss // Eurasian Phys. Tech. J. – 2020. – Vol.17. – P.55-60.

- 3 Timoshnev S., Kazakin A., Shubina K., Andreeva V., Fedorenko E., Koroleva A., Zhizhin E., Koval O., Kurinnaya A., Shalin A., Bobrovs V. and Enns Y. Annealing temperature effect on the physical properties of NiO thin films grown by DC magnetron sputtering // *Advanced Materials*. – 2024. – Vol.11. – Art.No.2300815.
- 4 Irwin M.D., Buchholz D.B., Hains A.W., Chang R.P. and Marks J.T. p-Type semiconducting nickel oxide as an efficiency-enhancing anode interfacial layer in polymer bulk-heterojunction solar cells // *PNAS*. – 2008. – Vol.105. – 2783-2787.
- 5 Arunodaya J. and Sahoo T. Effect of Li doping on conductivity and band gap of nickel oxide thin film deposited by spin coating technique // *Mater. Res. Express*. – 2019. – Vol.7. – Art.No.016405.
- 6 Alkarsifi R., Ackermann J. and Margeat O. Hole transport layers in organic solar cells: A review, *Journal of Metals // Materials and Minerals*. – 2022. – Vol.32 (4). – P.1-22.
- 7 Lian Q., Wang P-l., Wang G., Zhang X., Huang Y., Li D., Mi G., Shi R., Amini A., Zhang L. and Chun C. Doping Free and Amorphous NiO x Film via UV Irradiation for Efficient Inverted Perovskite Solar Cells // *Advanced science*. – 2022. – Vol.9. – Art.No.2201543.
- 8 Nishihara Y., Chikamatsu M., Kazaoui S., Miyadera T. and Yoshida Y. Influence of O<sub>2</sub> plasma treatment on NiO x layer in perovskite solar cells // *Japanese Journal of Applied Physics*. – 2018. – Vol.57. – Art.No.04FS07.
- 9 Porqueras I. and Bertran E. Electrochromic behaviour of nickel oxide thin films deposited by thermal evaporation // *Thin Solid Films*. – 2001. – Vol.398-399. – P.41-44.
- 10 Huang F., Chu C., Wang Z., Zhang Y., Ye J., Lv Y., Gong H., Li Y., Zhang Z-H. and Gu S. GaN-based quasi-vertical Schottky barrier diode hybridized with p-NiO layer to achieve 1.1 kV breakdown voltage and enhance the current spreading effect // *Applied Physics Express*. – 2022. – Vol.15 (8). – Art.No.084001.
- 11 Kazakin A.N., Komarevtsevm I.M., Vyacheslavova E.A., Kondrateva A.S., Mishin M.V., and Enns Ya.B., Modification of the optical and electrical properties of NiO films by thermal annealing // *SPbPU Journal – Physics and Mathematics*. – 2022. – Vol.15 (3.3).
- 12 Karsthof R., Frodason Y.K., Galeckas A., Weiser P.M., Zviagin V. and Grundmann M. Light Absorption and Emission by Defects in Doped Nickel Oxide // *Advanced Photonics Research published by Wiley-VCH GmbH*. – 2022. – Vol.3. – Art.No 2200138.
- 13 Lany S, Osorio-Guillén J. and Zunger A. Origins of the doping asymmetry in oxides: Hole doping in NiO versus electron doping in ZnO // *Phys. Rev. B*. – 2007. – Vol. 75. – Art.No 241203(R).
- 14 Martínez-Gil M., Pintor-Monroy M.I., Cota-Leal M., Cabrera-German D., Garzon- Fontecha A., Quevedo-L'opez M.A. and Sotelo-Lerma M. Influence of annealing temperature on nickel oxide thin films grown by chemical bath deposition // *Mater. Sci. Semicond. Process*. – 2017. – Vol.72. – P.37-45.
- 15 Wang M., Thimont Y., Presmanes L., Diao X. and Barnabe A. The effect of the oxygen ratio control of DC reactive magnetron sputtering on as-deposited non stoichiometric NiO thin films // *Appl. Surf. Sci*. – 2017. – Vol.419. – P.795-801.
- 16 Jiménez-González A.E., and Cambay J.G. Deposition of NiO<sub>x</sub> thin films by sol-gel technique. *Surface //Engineering*. – 2000. – Vol.16(1). – P.73-76.
- 17 Bisquert J., Mora-Sero I. and Fabregat-Santiago F. Diffusion-recombination impedance model for solar cells with disorder and nonlinear recombination // *Chemelectrochem*. – 2013. – Vol.1 (1). – P.289-296.
- 18 Cazzanelli E., Kuzmin A., Mariotto G., Mironova-Ulmane N., Study of vibrational and magnetic excitations in NiMg<sub>1-x</sub>Co<sub>x</sub> solid solutions by Raman spectroscopy // *J. Phys.: Condens. Matter*. – 2003. – Vol.15. – Art.No 2045.
- 19 Beisembekov M.K., Omarbekova G.I., Tazhibayev S.K., Aimukhanov A.K., Baltabekov A.S., Ziyat A.Z. and Zeinidenov A.K. The role of annealing temperature on the optical and electrical transport properties of NiO<sub>x</sub> films // *Optical Materials*. – 2024. – Vol.151. – Art.No 115398.
- 20 Ivanova T., Harizanova A., Shipochka M. and Vitanov P., Nickel oxide films deposited by sol-gel method: effect of annealing temperature on structural, Optical, and Electrical Properties // *Materials*. – 2022. – Vol.15 (5). – Art.No 1742.
- 21 Murphy A.R. and Fréchet M.J. Organic semiconducting oligomers for use in thin film transistors // *Chem. Rev*. – 2007. – Vol.107 (4). – P.1066-1096.
- 22 Yang P., Li L., Yu S., Zheng H. and Peng W. The annealing temperature and films thickness effect on the surface morphology, preferential orientation and dielectric property of NiO films // *Appl. Surf. Sci*. – 2019. -Vol.493. - P.396-403.
- 23 Sharma P.K., Singh M.K., Sharma G.D. and Agrawal A. NiO nanoparticles: facile route synthesis, characterization and potential towards third generation solar cell // *Mater. Today Proc*. – 2021. – Vol.43. – P.3061-3065.
- 24 Kumar V. and Agarwal S.K. *Physics of Semiconductor Devices*. – Narosa Publishing House, 1998. – 1358 p.
- 25 Shkir M., Ganesh V., AlFaify S., Yahia I.S. and Zahran H.Y. Tailoring the linear and nonlinear optical properties of NiO thin films through Cr<sup>3+</sup> doping // *J. Mater. Sci. Mater. Electron*. – 2018. – Vol.29. – P.6446-6457.

#### References

- 1 M. Imran, H. Coskun, A.N. Khan, and J. Ouyang, *Appl. Phys. A* 127, 117 (2021).
- 2 A.K. Aimukhanov, A.K. Zeinidenov, G.I. Omarbekova, and I.V. Plotnikova, *Eurasian Phys. Tech. J.* 17, 55-60 (2020).
- 3 S. Timoshnev, A. Kazakin, K. Shubina, V. Andreeva, and et al., *Adv. Mater.* 11, 2300815 (2024).
- 4 M.D. Irwin, D.B. Buchholz, and et al., *Proc. Natl. Acad. Sci. U.S.A.* 105, 2783-2787 (2008).

- 5 J. Arunodaya, and T. Sahoo, Mater. Res. Express 7, 016405 (2019).
- 6 R. Alkarsifi, J. Ackermann, and O. Margeat, J. Met. Mater. Miner. 32(4), 1-22 (2022).
- 7 Q. Lian, P.-L. Wang, G. Wang, X. Zhang, Y. Huang, and et al., Adv. Sci. 9, 2201543 (2022).
- 8 Y. Nishihara, M. Chikamatsu, S. Kazaoui, T. Miyadera, and Y. Yoshida, Jpn. J. Appl. Phys. 57, 04FS07 (2018).
- 9 I. Porqueras, and E. Bertran, Thin Solid Films 398-399, 41-44 (2001).
- 10 F. Huang, C. Chu, Z. Wang, Y. Zhang, and et al., Appl. Phys. Express 15(8), 084001 (2022).
- 11 A.N. Kazakin, I.M. Komarevtsevm, E.A. Vyacheslavova, and et al., SPbPU J. Phys. Math. 15(3.3) (2022).
- 12 R. Karsthof, Y.K. Frodason, and et al., Adv. Photon. Res. 3, 2200138 (2022).
- 13 S. Lany, J. Osorio-Guillén, and A. Zunger, Phys. Rev. B 75, 241203(R) (2007).
- 14 M. Martínez-Gil, M.I. Pintor-Monroy, and et al., Mater. Sci. Semicond. Process. 72, 37-45 (2017).
- 15 M. Wang, Y. Thimont, L. Presmanes, X. Diao, and A. Barnabe, Appl. Surf. Sci. 419, 795-801 (2017).
- 16 A.E. Jiménez-González, and J.G. Cambrey, Surf. Eng. 16(1), 73–76 (2000).
- 17 J. Bisquert, I. Mora-Sero, and F. Fabregat-Santiago, Chemelectrochem 1(1), 289–296 (2013).
- 18 E. Cazzanelli, A. Kuzmin, G. Mariotto, and N. Mironova-Ulmane, J. Phys. Condens. Matter 15, 2045 (2003).
- 19 M.K. Beisembekov, G.I. Omarbekova, and et.al., Opt. Mater. 151, 115398 (2024).
- 20 T. Ivanova, A. Harizanova, M. Shipochka, and P. Vitanov, Mater. 15(5), 1742 (2022).
- 21 A.R. Murphy, and M.J. Fréchet, Chem. Rev. 107(4), 1066–1096 (2007).
- 22 P. Yang, L. Li, S. Yu, H. Zheng, and W. Peng, Appl. Surf. Sci. 493, 396–403 (2019).
- 23 P.K. Sharma, M.K. Singh, G.D. Sharma, and A. Agrawal, Mater. Today Proc. 43, 3061–3065 (2021).
- 24 V. Kumar, and S.K. Agarwal, Physics of Semiconductor Devices (Narosa Publishing House, 1998), 1358 p.
- 25 M. Shkir, V. Ganesh, S. AlFaify, et al. J. Mater. Sci. Mater. Electron. 29, 6446–6457 (2018).

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