Vol. **114** (2008) *ACTA PHYSICA POLONICA A* No. 6–A

Optical and Acoustical Methods in Science and Technology

Planar Optical Waveguides for Application in Optoelectronic Gas Sensors

K. Golaszewska[a,*], E. Kamińska[a], T. Pustelny[b], P. Struk[b], T. Piotrowski[a], A. Piotrowska[a], M. Ekielski[a], R. Kruszka[a], M. Wzorek[a], M. Borysiewicz[a], I. Pasternak[a] and K. Gut[b]

[a]Institute of Electron Technology, al. Lotników 32/46, 02-668 Warsaw, Poland

[b]Department of Optoelectronics at Faculty of Mathematics and Physics Silesian University of Technology, Krzywoustego 2, 44-100 Gliwice, Poland

In the paper, the results of technological investigations on planar optical waveguides based on high band gap oxide semiconductors were presented. Investigations concerned the technologies of depositing very thin layers of: zinc oxide ZnO, titanium dioxide TiO_2 and tin dioxide SnO_2 on substrates of quartz glass plates. There were investigated both morphological structures of the produced layers and their optical properties. The paper also presents investigations on the technology of input-output light systems in the Bragg grating structures.

PACS numbers: 42.82.Et, 07.07.Df, 42.79.Pw, 81.15.–z

1. Technology of thin layers for optical applications

The analysis of high band gap oxide semiconductors proved the potential possibility of applying very thin layers of zinc oxide ZnO, titanium dioxide TiO_2 and tin dioxide SnO_2 both as optical waveguides and as sensor layers to detect selected gases [1–3]. Literature information [4, 5] suggests that some oxide semiconductors are transparent for light from the visible spectrum. This information suggest also that the optical properties of layers made from these semiconductors vary in result of actions of selected gases presented in air atmosphere [6–10]. In order to explain the possibility of applying such layers, some hundreds nm thick of selected semiconductors, wide technological tests have been realized. The realized

*corresponding author; e-mail: krystyg@ite.waw.pl

investigations were focused on testing the morphology of surfaces of the obtained layers and on determining their refractive indices. The thin semiconductor layers were deposited on plates of the boronic-silicon glass type BK7 by means of the sputter-deposition method, applying the Leybold Z400 Sputtering System. In order to determine the refractive index values of these layers the Variable Angle Spectroscopic Ellipsometry VASE produced by the firm J.A. Woollam was applied. Ellipsometric measurements within the wavelength range $\lambda = 240$–1100 nm were carried out.

For each tested oxide semiconductor some technological conditions of the production of waveguide layers were applied. For each technological condition some samples were produced. The pictures of the obtained surfaces presented below are typical of the applied semiconductors. The pictures of morphological structures of the tested surfaces were obtained by using an atomic force microscopy (AFM) of the Digital Instruments Nanoscope IIIa type. The possibility of getting complete, entirely optical waveguide structures with input-output light systems performed in integrated optic technology was tested, too. In Figs 1–6 the morphology of surfaces of elaborated structures and their optical properties are presented.

1.1. Manufacturing of zinc oxide ZnO layers

The zinc oxide ZnO layers were obtained by using the sputter-deposition method under the following technological conditions:

— RF reactive sputtering;
— Zn (4N) target;
— processing gas: 30%O_2–70%Ar;
— total pressure: 1×10^{-2} mbar;
— power of magnetron: 100 W (cathode current: 140 mA);
— roughness of the obtained layers: 10 nm;
— thickness of the obtained layers: ≈ 260 nm.

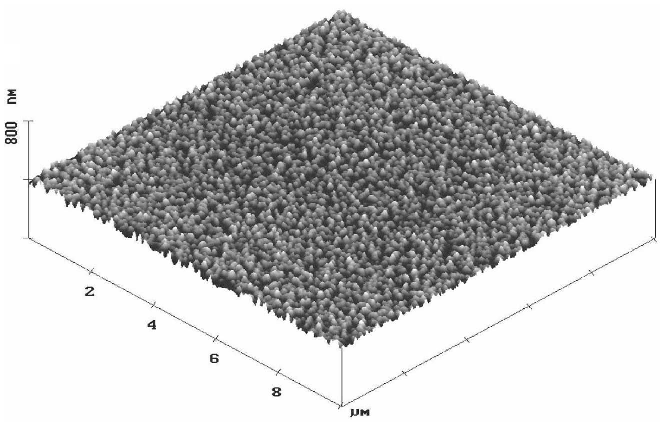

Fig. 1. Surface morphology of a ZnO film, determined by means of the AFM method.

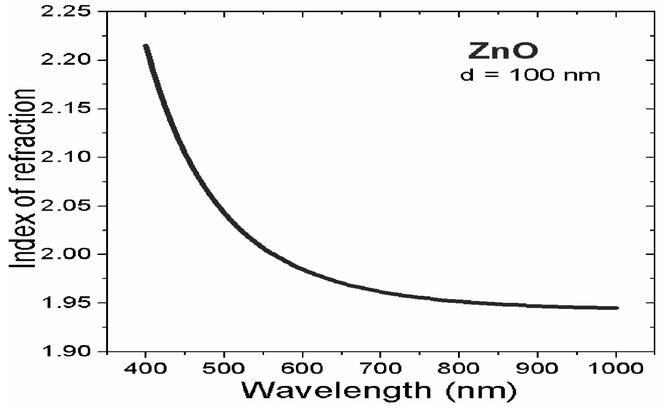

Fig. 2. The refractive index of ZnO layer.

1.2. Manufacturing of titanium oxide TiO_2 layers

The titanium oxide TiO_2 layers were obtained by using the sputter--deposition method under the following technological conditions:

— DC reactive sputtering;
— Ti (4N) target;
— processing gas: 10%O_2–90%Ar;
— total pressure: 5×10^{-3} mbar;
— power of magnetron: 100 W;
— roughness of the obtained layers: 4 nm;
— thickness of the obtained layers: $\approx$ 270 nm.

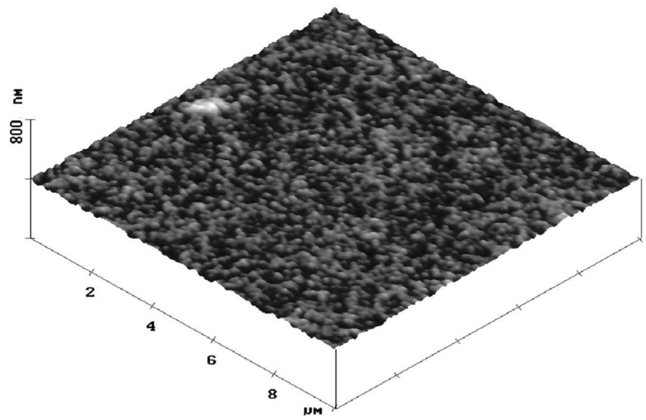

Fig. 3. Surface morphology of a TiO_2 film, determined by means of the AFM method.

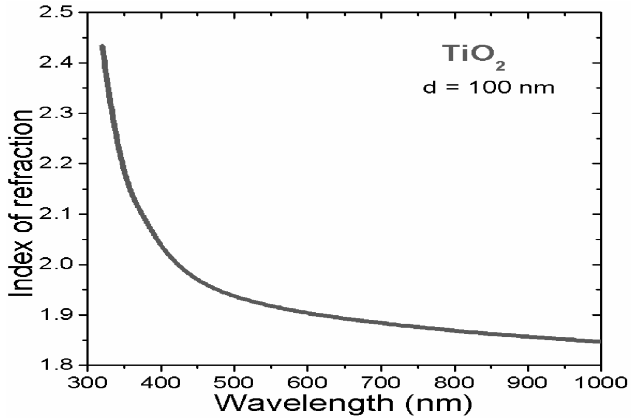

Fig. 4. The refractive index of TiO_2 layer.

1.3. Manufacturing of tin dioxide SnO_2 layers

The tin dioxide SnO_2 layers were obtained by using the sputter-deposition method under the following technological conditions:

— DC reactive sputtering;
— Sn (4N) target;
— processing gas: 20%O_2–80%Ar;
— total pressure: 1×10^{-2} mbar;
— power of magnetron: 75 W;
— roughness of the obtained layers: 25 nm;
— thickness of the obtained layers: ≈ 300 nm.

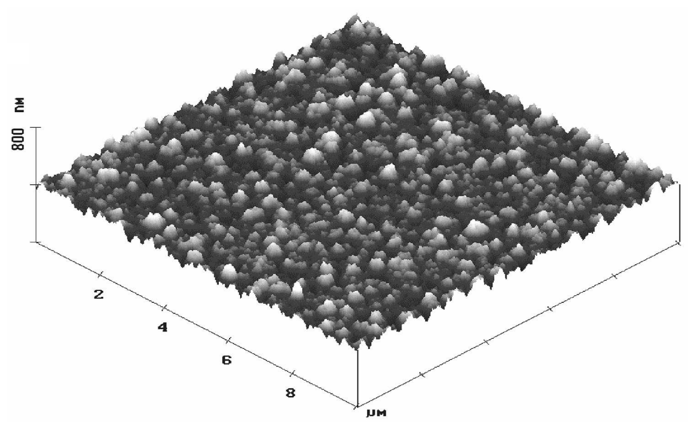

Fig. 5. Surface morphology of a SnO_2 film, determined by means of the AFM method.

Investigations have shown that among the tested oxide semiconductors the best optical and morphological properties were possessed by TiO_2 layers. The

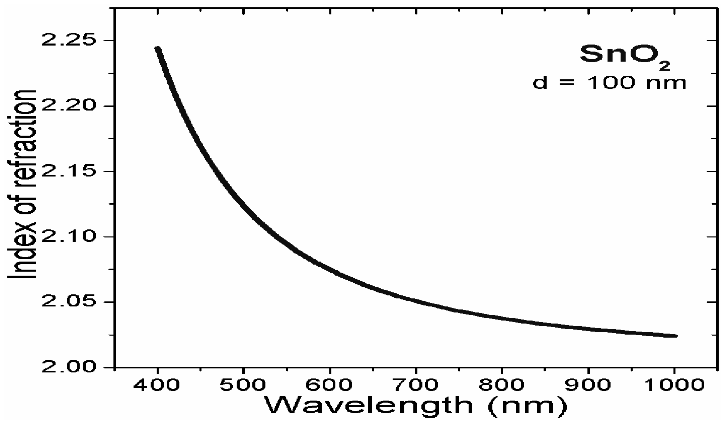

Fig. 6. The refractive index of SnO_2 layer.

roughness of TiO_2 layers was twice smaller than in the case of ZnO layers and nearly 7 times than in SnO_2. The roughness of waveguide layers decides about the scattering of the propagated light. Therefore two Bragg's grating couplers as the input-output system on TiO_2 waveguide layers have been produced and tested. The Bragg grating couplers were produced by means of the photolithographic method. All the obtained Bragg grating couplers displayed very bad morphological and optical properties, non permitting the introduction of light into the TiO_2 waveguides. (Investigations concerning of Bragg's grating couplers on TiO_2 waveguides are being continued.) Preliminary tests have also shown that the attenuation of light in SnO_2 waveguide layers at the present state of technology is very high, making it impossible to use them as optical waveguide structures. Therefore, no decision has been taken to use SnO_2 layers for the purpose of obtaining optical grating couplers.

The tests of manufacturing optical Bragg grating couples have been undertaken on ZnO layers.

2. Manufacturing of optical Bragg grating couples on ZnO waveguide layers

The grating couples of Bragg's type were produced on waveguide ZnO layers by means of the photolithography method [2, 3, 5]. Figure 7 presents a picture of the used negative photomask, where a shape of the coupler is a very thin chromium--aluminum layer, deposited on a glass plate. The shapes of the grating couplers were obtained by exposing the photoresist to light of ≈ 250 nm wavelength for ≈ 5 s.

Figure 8 shows the propagation of light at $\lambda = 650$ nm, into the ZnO planar waveguide. The light in the structure is excited by a grating coupler of Bragg's type. In Fig. 9 one can admit distinctly the attenuation of a light beam during its propagation. The value of the light attenuation coefficient in the presented

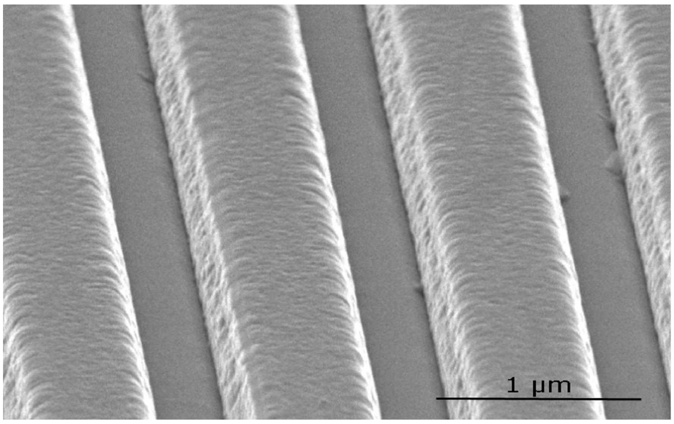

Fig. 7. Negative photomask of the light grating coupler.

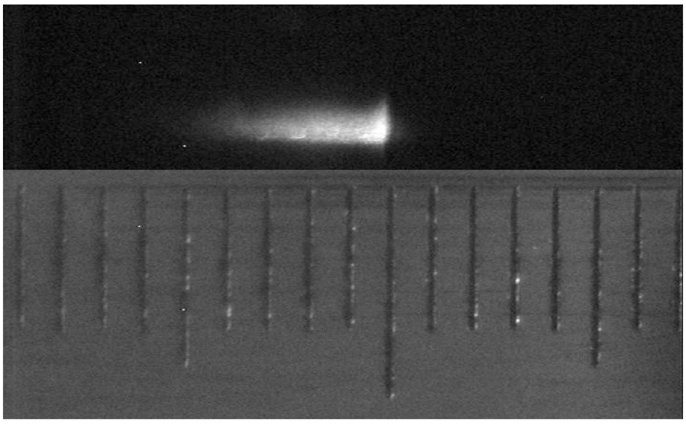

Fig. 8. Propagation of light in a ZnO waveguide with Bragg's grating coupler.

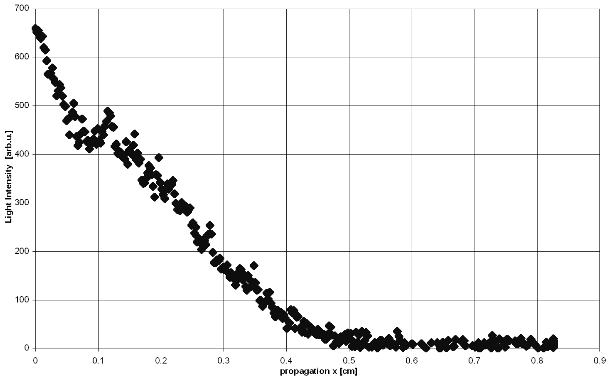

Fig. 9. Decay of the intensity of light during its propagation in the ZnO waveguide.

structure is equal to $\alpha = 21 \pm 2$ dB/cm. The α coefficient was determined in the analysis of the intensity of light in the image, using the proper numerical program. The results of this analysis are presented in Fig. 9. Such a high value of the light attenuation coefficient α testifies on the intensive scattering effects in ZnO waveguides. The α coefficient of the presented structure is comparable to the values presented in literature and even lower [2, 6].

3. Investigations of TiO_2 optical waveguides

On the actual stage of technology one can produce completely photonic waveguide structures with input-output systems on the base of TiO_2 nanothin layers. The grating couplers obtained on TiO_2 have very low qualities, practically excluding their applications. For checking the possibility of light propagation in elaborated TiO_2 waveguides the prism method of light inserting was used. The tests were realized in the measurement setup presented in [8]. The exemplary result for the TE mode polarization is presented in Fig. 10. The tested waveguide is two-modes one.

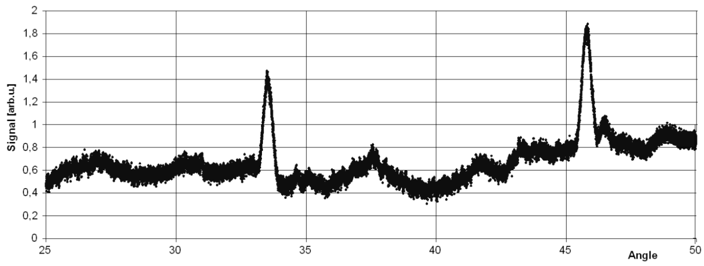

Fig. 10. Modal characteristics of the TiO_2 waveguide concerning its excitation by means of the prism method.

Unfortunately, the obtained characteristics do not permit to determine the attenuation of light in TiO_2 waveguides. It does not permit either to specify the state of efficiency of light energy transformation from a laser beam to the waveguide.

4. Remarks

Investigations concerning the technology of ZnO waveguides are continued, and actually in some ZnO waveguides the attenuations are below 10 dB/cm.

The results attained in the technology of TiO_2 waveguide structures show that in near future it will be possible to manufacture complete optoelectronic structures consisting of waveguides, a sensing layer for the detection of selected gases and with input-output structures using the Bragg grating couplers. The obtained results will be published.

Acknowledgments

The work was sponsored by the Ministry of Science and Higher Education within the grant N515 025 32/1887.

References

[1] T. Pustelny, *Physical and Technical Aspects of Optoelectronic Sensors*, SUT, Gliwice 2005, p. 86.

[2] P. Lambeck, *Meas. Sci. Technol.* **17**, R93 (2006).

[3] E. Maciak, Z. Opilski, T. Pustelny, *Mol. Quant. Acoust.* **26**, 205 (2005).

[4] G.J. Valdhuis, P. Lambeck, *Appl. Phys. Lett.* **71**, 2895 (1999).

[5] W. Jakubik, E. Maciak, T. Pustelny, A. Stolarczyk, M. Urbanczyk, *Mol. Quant. Acoust.* **28**, 125 (2007).

[6] A. Piotrowska, E. Papis, E. Kaminska, K. Golaszewska, T. Pustelny, E. Maciak, Z. Opilski, *Europ. Phys. J. Special Topics* **154**, 143 (2008).

[7] J. Ignac-Nowicka, T. Pustelny, E. Maciak, W. Jakubik, M. Urbanczyk, *Opt. Eng.* **42**, 2978 (2003).

[8] T. Pustelny, I. Zielonka, C. Tyszkiewicz, B. Pustelny, J. Jurusik, *Mol. Quant. Acoust.* **26**, 217 (2005).

[9] M. Matsuguchi, A. Okamoto, Y. Sakai, *Sensors Actuators B* **94**, 46 (2003).

[10] T. Pustelny, E. Maciak, Z. Opilski, A. Piotrowska, E. Papis, K. Golaszewska, *Europ. Phys. J. Special Topics* **154**, 155 (2008).