Optical and Acoustical Methods in Science and Technology

Planar Optical Waveguides Based on Thin ZnO Layers

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The paper quotes the results of investigations concerning planar optical waveguides with a high value of the refractive index, achieved basing on a broad-band gap semiconductor ZnO, deposited on glass or quartz substrates. The investigations were focused on the properties of the waveguides, determining the modal characteristics, the attenuation coefficient and the structure of the surface.

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1. Introduction

Zinc oxide ZnO is a semiconductor material with a wide broad-band gap of 3.4 eV. It displays attractive properties permitting to apply it in sensor techniques as well as in systems of integrated optics. Data quoted in literature indicate that it is transparent in a visible range. It is characterized by a high value of the refractive index ($n \approx 2$) [1–6], which is a favorable feature of the waveguide in systems of integrated optics [3]. The primary aim of the investigations is to develop in future a photonic sensor structure attained in compliance with the techniques of integrated optics applied as sensors of selected gases, e.g. NH_3, NO_x, … Gas sensors constructed on the basis of integrated optics are particularly desirable in environments liable to considerable hazards of explosion, i.e. in industry [1]. An innovation of the solution suggested by us is the construction of a sensor structure in compliance with the techniques of integrated optics, comprising a waveguide layer, a sensor layer and input-output elements, viz. Bragg's gratings, all mounted on common substrate. The subject matter of the present paper is to investigate the optical waveguide properties of ZnO layers depending on the applied deposition technology and their thermal treatments [7–18].

2. Planar optical waveguide

The fundamental property of planar waveguide structures is the relation between the number of the waveguide modes in the function of the layer thickness propagating in the structure and its refractive index. It had been assumed that single-mode structures would permit to propagate only the modes TE0 and TM0 and also multimode structures for TE0, TM0, as well as TE1 and TM1. Comprehensive numerical investigations of waveguide structures were carried out. The calculations were realized applying the software OptivaveMode 2D Solver.

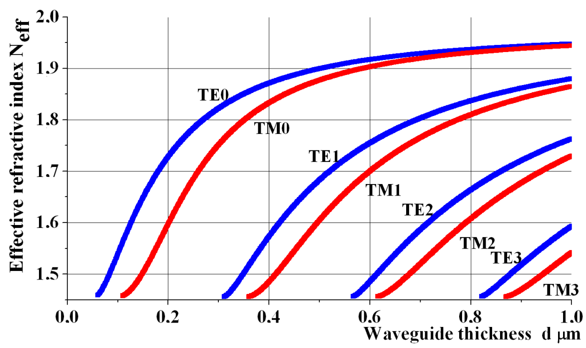

Fig. 1. Effective refractive index $N_{\rm eff}$ in the function of the thickness of the waveguide layer d.

In order to find the required thickness of the layer, the dependence of the effective refractive index in the function of the layer thickness for an electromagnetic wave with a wavelength of $\lambda = 677$ nm, was determined, assuming that the waveguide structure consists of ZnO with a refractive index value $n_{\rm w} = 1.975$, deposited on a quartz substrate with a refractive index $n_{\rm s} = 1.456$. The refractive index of the environment amounted to $n_{\rm c} = 1.000$ (Fig. 1). In result of the analysis of the characteristics quoted above, single-mode waveguide layers were produced with a thickness of $d = 300$ nm, as well as multimode waveguides with a thickness of $d = 500$ nm.

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3. Experiment

The waveguide layers of ZnO were made by means of the method of reactive cathode magnetron sputtering in the system Leybold Z-400 on quartz substrates. The deposition processes were run in the RF mode. ZnO powder of 99.99% purity was vaporized from the ceramic target in an atmosphere which was a mixture of oxygen O_2 (70%) and argon Ar (30%), at a total pressure $p_{\mathrm{Ar+O}} = 1 \times 10^{-2}$ mbar and a partial pressure of the oxygen $p_{\mathrm{O}} = 3 \times 10^{-3}$ mbar for the intensity of electric current flowing through the cathode with a value of $I_{\mathrm{c}} = 140$ mA. The rate of deposition amounted to < 20 nm/min. The thickness of the obtained layers was $d \approx 300$ nm or $d \approx 500$ nm. During the depositing processes of waveguide layers the substrates were not additionally heated. After their deposition the layers were subjected to a two-stage process of soaking, making use of the rapid thermal annealing (RTA) technique, first for ten minutes in a nitrogen atmosphere at 400°C in order to eliminate mechanical strain, and then in oxygen at a temperature of 500°C or 600°C.

The metrological stage consisted in the determination of: (i) the morphology of the surface of ZnO layers by applying the AFM technique (using Nanoscope IIIa type), (ii) the refractive index and thickness of the layers by means of the ellipsometer (SENTECH SE400) at a 632.8 nm wavelength; (iii) the modal characteristics and (iv) the attenuation coefficient. The modal characteristics were determined on the measurement stand presented in Fig. 2a.

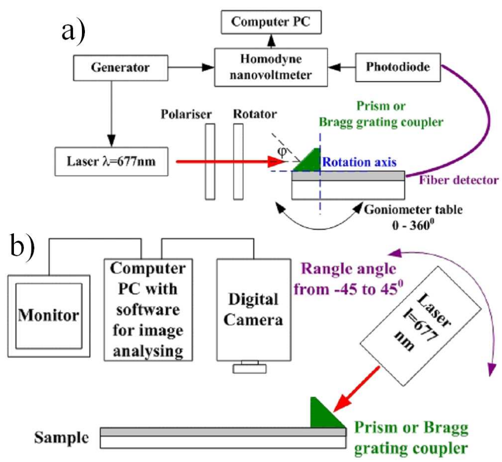

Fig. 2. Measurement stand for measuring: the modal spectrum (a), the attenuation coefficient (b).

The fundamental data of this measurement stand were following. Semiconductor laser emitted light with a wavelength $\lambda = 677$ nm. The laser beam passes through a polarizer, and next through a rotator, fixing the state of polarization for TE or TM modes. The tested samples were placed on a rotating goniometric table. As an optical coupler a (BGO) $Bi_{12}GeO_{20}$ crystal prism was used with a refractive index of $n_{\mathrm{p}} = 2.5407$. The optical signal from the tested sample was then passed by means of a detective fibre to the photodiode. In order to restrict the effect of optical and electrical noise and disturbances a homodyne nanovoltmeter was used. The signal from the homodyne is recorded in a PC computer.

The test stand for the determination of the attenuation coefficient (Fig. 2b) comprises a semiconductor laser $\lambda = 677$ nm. The light from the laser is passed through the prismatic coupler to the waveguide layer, where the light is attenuated and scattered. The image of the optical beam propagating in the planar waveguide is recorded by a digital camera and next subjected to digital processing making use of the software LabView [10].

4. Results

The first stage of the investigation consisted in the determination of the effect of RTA soaking on the morphology of the ZnO layers.

Layers of ZnO deposited on quartz or semiconducting substrates are, depending on the technology of their production, characterized by a structure with a considerably developed topography of the surface (Fig. 3). The observed irregularities of the ZnO surfaces amount in the case of their production by means of cathode magnetron sputtering to rms > 20 nm [11]. The process of soaking influences the quality of the surface of ZnO layers (their roughness). When ZnO layers are soaked at a temperature of 600°C, the roughness reaches rms ≈ 4 nm. After soaking of the ZnO layers at a temperature of 700°C the roughness of the surfaces increased to rms ≈ 6 nm. This comparison leads to the conclusion that the process of soaking ought to be run at temperature not exceeding 600°C. Table I quotes information about the thicknesses of the respective ZnO layers as well as their refractive indices. The refractive index of layers with a thickness of ≈ 300 nm amounts to $n = 2.08$. In the case of layers whose thickness exceeds 500 nm the value of the refractive index is $n \approx 1.9$.

The next stage of investigations was the determination of the optical waveguide properties of the produced ZnO layers. An analysis of the determined modal characteristics permitted to verify the structure with respect to the number of propagating modes. The modal spectra of single-mode layers can be seen in Fig. 4, Fig. 5 and Fig. 6, and those of multi-mode layers in Fig. 7, Fig. 8 and Fig. 9. The effective refractive indices of the respective modes, determined basing on these spectra, were compared with numerically determined values presented in Fig. 1.

4.1. Single-mode waveguide layers

An analysis of the intensity of scattered light of the propagating mode as a function of the path of propagation in the waveguide permits to determine the attenuation coefficient of the mode [10]. This method was applied to determine the attenuation coefficients α in ZnO layers. The soaking of waveguide ZnO layers influenced

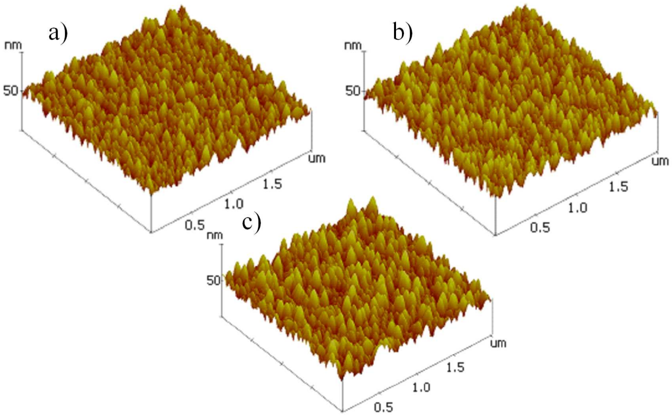

Fig. 3. Morphology of the ZnO layers: (a) without soaking, rms = 4.3 nm; (b) $T_{max} = 600°C$, $t = 10$ min, O_2, rms = 4.2 nm; (c) $T_{max} = 700°C$, $t = 10$ min, O_2, rms = 6.3 nm.

TABLE I

The thickness and refractive index of ZnO layers.

Layer	RTA soaking	Thickness [nm]	Refractive index
#1	without soaking	303	2.086
#2	O_2–500°C/10 min	294	2.042
#3	O_2–500°C/10 min, O_2–600°C/10 min	306	2.084
#5	O_2–500°C/10 min	548	1.947
#6	O_2–500°C/10 min, O_2–500°C/10 min	584	1.875

the value of the attenuation coefficient α. In the case of unsoaked layers #1 the whole path of light propagation amounted to about $d \approx 3$ mm, which converted to the value of the attenuation coefficients, corresponding to $\alpha_{TE0} \approx 35$ dB/cm (Fig. 4). The ZnO waveguide layer #1 was obtained without its soaking.

The ZnO waveguide layer #2 was soaked in an O_2 atmosphere for about 10 min at a temperature 500°C. It could be observed that the total distance of light propagation in it increased for the TE0 mode to about 4 mm, which corresponds to the attenuation coefficients equal to: $\alpha_{TE0} = 30$ dB/cm for TE0 mode and $\alpha_{TM0} = 31$ dB/cm in the case of the TM0 mode (Fig. 5).

The most favourable results were obtained in the case of the ZnO layer #3, soaked for 10 min in an N_2 atmosphere at a temperature of 400°C, and next for 10 min in an O_2 atmosphere, followed by soaking for 10 min at a temperature of 600°C, also in an O_2 atmosphere. In this case the distance of light propagation inside the ZnO waveguide layer amounts for the TE0 mode to $d \approx 7$ mm (corresponding to an attenuation coefficient of $\alpha_{TE0} = 14$ dB/cm, $\alpha_{TM0} = 18$ dB/cm (Fig. 6)). The process of soaking results in a considerable drop of the optical attenuation in the layer, and thus to an increased

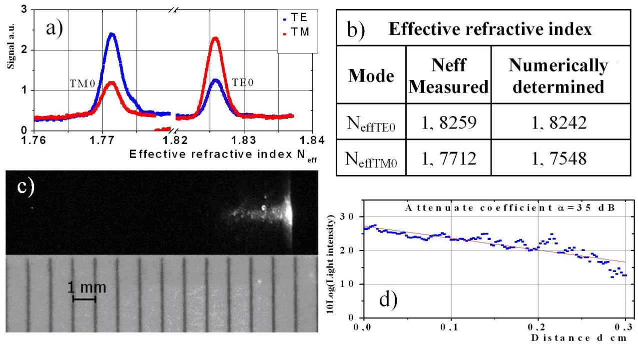

Fig. 4. Modal characteristic of ZnO waveguide #1 excited by means of the prism method (a), table presents also the effective refractive index (b), propagation of light in a ZnO waveguide (c), attenuation coefficient $\alpha = 35$ dB/cm (d).

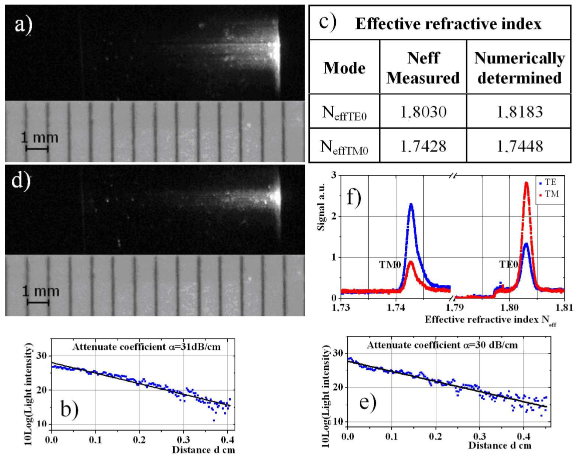

Fig. 5. Propagation of light in a ZnO waveguide #2: (a) TE0, (d) TM0, (f) modal characteristic of the ZnO waveguide; attenuation coefficient: (b) TE0 $\alpha = 30$ dB, (e) TM0 $\alpha = 31$ dB; (c) table includes effective refractive index.

distance of the light propagation in the waveguide structure.

4.2. Multimode layers

In the case of unsoaked ZnO waveguide layers #4 the distance of light propagation amounts to about $d \approx 3$ mm. Also in unsoaked ZnO layers with greater thickness constituting multimode structures, the attenuation coefficient was of considerable importance, e.g. concerning the mode TE it amounts to about $\alpha_{TE0} = 38$ dB/cm, whereas in the case of the TM0 mode it is $\alpha_{TM0} = 40$ dB/cm (Fig. 7).

Figure 8 presents the results of investigations concerning the ZnO layer #5, which was soaked for 10 min in N_2 atmosphere at a temperature of 400°C, and next for 10 min in an O_2 atmosphere at a temperature of 500°C. The attenuation coefficient in this layer amounted to $\alpha_{TE0} \approx 30$ dB/cm (Fig. 8 and Table II).

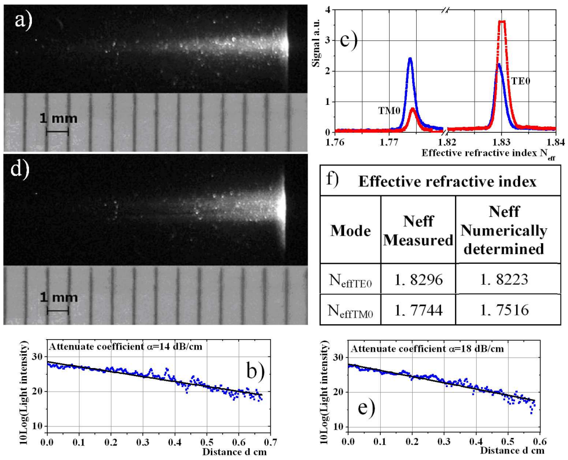

Fig. 6. Propagation of light in a ZnO waveguide #3: (a) TE0, (d) TM0, (c) modal characteristic of the ZnO waveguide; attenuation coefficient: (b) TE0 $\alpha = 14$ dB, (e) TM0 $\alpha = 18$ dB; (f) table includes effective refractive index.

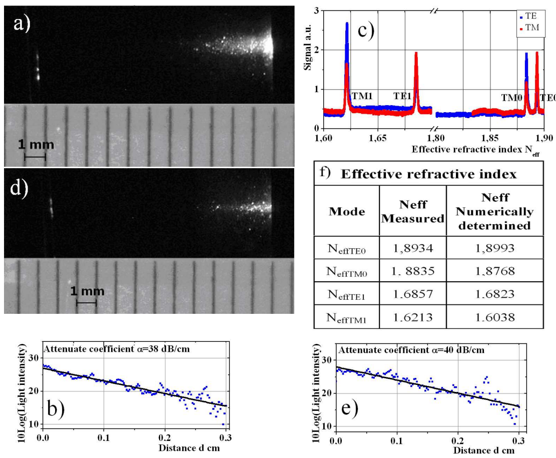

Fig. 7. Propagation of light in a ZnO waveguide #4: (a) TE0, (d) TM0, (c) modal characteristic of the ZnO waveguide; attenuation coefficient: (b) TE0 $\alpha = 38$ dB, (e) TM0 $\alpha = 40$ dB; (f) table provides effective refractive index.

The most favourable optical transmission properties were attained in the case of ZnO layers #6, soaked for 10 min in O_2 atmosphere at a temperature of 500°C, followed by soaking for 10 min in an O_2 atmosphere at a temperature of 600°C. In such a case the attenuation coefficients amounted to: $\alpha_{TE0} = 14$ dB/cm and $\alpha_{TM0} =$ 18 dB/cm (Fig. 9 and Table III).

5. Conclusions

The chief aim of the presented investigations was to find out the possibilities of applying ZnO layers as optical waveguides in integrated optics. The first stage of the investigations permitted to determine the effect of

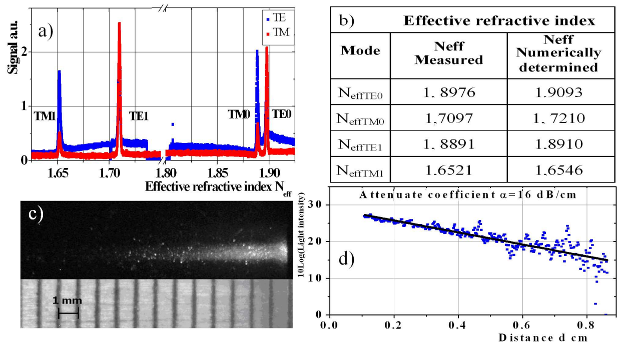

Fig. 8. Modal characteristic of ZnO waveguide #5 (a); table quotes the effective refractive index (b); propagation of light in a ZnO waveguide (c); attenuation coefficient $\alpha = 16$ dB (d).

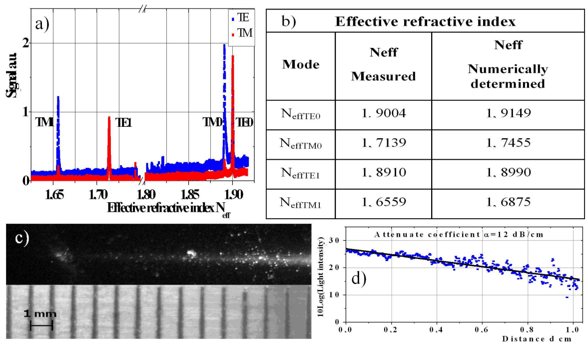

Fig. 9. Modal characteristic of the ZnO waveguide #6 (a); table includes effective refractive index (b); propagation of light in the ZnO waveguide (c); attenuation coefficient $\alpha = 12$ dB (d).

TABLE II

Attenuation coefficients of the investigated optical waveguide structures.

Structure	Soaking	Attenuation of	
		TE0 [dB/cm]	TE0 [dB/cm]
#1	unsoaking	35	–
#2	O_2–500°C/10 min	30	31
#3	O_2–500°C/10 min, O_2–600°C/10 min	14	18

TABLE III

Attenuation coefficient concerning the respective optical waveguide structures.

Structure	Soaking	Attenuation of	
		TE0 [dB/cm]	TE0 [dB/cm]
#4	unsoaking	38	40
#5	O_2–500°C/10 min	16	–
#6	O_2–500°C/10 min, O_2–500°C/10 min	12	–

the technological process of the production of ZnO layers on the optical waveguide properties of such structures. Light attenuation in the waveguides depends both on the internal structure of the materials (their heterogeneity) and the structure of their surfaces. The investigations have proved that in the case of thin waveguide layers the attenuation of the optical signal propagating in them increases rapidly with the roughness of the surface of the rms layer. In order to reduce the attenuation of the optical signal to a minimum, the ZnO layers were subjected to thermal treatment in the RTA process. Layers obtained without soaking were characterized by attenuation on the level of 35–40 dB/cm. The soaking of ZnO layers permitted to decrease the attenuation coefficient to about 10 dB/cm. Adequately performed thermal treatment may cause a reconstruction of the structure of the materials and reduce the roughness of the layer surfaces, and thus improve their optical properties.

Acknowledgments

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