Optical and Acoustical Methods in Science and Technology

# Zinc Oxide Semiconductor for Photonics Structures Applications

P. Struk[a,*], T. Pustelny[a], B. Pustelny[a], K. Gołaszewska[b], E. Kamińska[b], A. Piotrowska[b], M. Borysiewicz[b] and M. Ekielski[b]

[a]Department of Optoelectronics at Faculty of Electrical Engineering, Silesian University of Technology Akademicka 2A, Gliwice, Poland

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

The paper presents investigations concerning the analysis of photonic structures with grating couplers. In the paper basic theoretically information on photonic structures with grating couplers is presented. The results of numerical investigations on photonic structures with grating couplers are discussed, too. Investigations show an essential influence of the geometrical parameters of grating couplers on the effectiveness of the input and output of optic power into and out of this photonic structure. In the paper the selected results of experimental realizations of photonic structures with grating couplers based on zinc oxide ZnO are presented.

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## 1. Introduction

The technical development is inspired to a large extent by the development of semiconducting materials and their application in electronic, telecommunication, optoelectronic devices and sensors [1–8]. The present paper is focussed on the analysis of grating couplers in photonic structures. The interest in photonic structures with grating couplers is due to their possibilities of application in photonic elements and systems [3, 4, 9, 10]. These structures may be used as input-output systems in planar waveguides and also as sensor structures sensitive on changes of external conditions of light propagation [3, 10, 11]. Introducing the optical power to a planar waveguide structure realized by prism couplers is popular; however prism couplers do not provide the large-scale integration of optical structures [12, 13].

## 2. Practical remarks on grating couplers

The interest in optical structures with grating couplers is due to the numerous possibilities of their application in photonic structures and optical sensors [4, 14, 15]. On the one hand, a photonic structure with a grating coupler may be an attractive technical solution, permitting to introduce or receive an electromagnetic wave from the visible and near infrared range in optical structure, whose thickness amounts to few hundreds nm [4, 16]. On the other hand, grating couplers can also be used as active elements in sensor structures [17].

In planar optical waveguides, the grating couplers are constructed in the form of periodical disturbances of the refractive index with given geometrical parameters, such as the so-called spatial period of the grating $\Lambda$, the period depth of the grating coupler $d_{\mathrm{s}}$, their shape and filling factor $k_{\mathrm{w}}$ [14, 15]. Such structure may be considered as a set of layers characterised by distribution and value of the refractive index of light in respective layers, viz. the waveguide layer $n_{\mathrm{w}}$, the substrate layer $n_{\mathrm{s}}$, and the environmental layer $n_{\mathrm{c}}$. An advantage of grating couplers on prism couplers belongs on the possibility of using grating couplers as integral parts of the photonic systems. Thanks to this, the scale of integration and miniaturization of the completed structure can be enlarged. The scheme of a grating coupler produced in optical waveguides has been presented in Fig. 1.

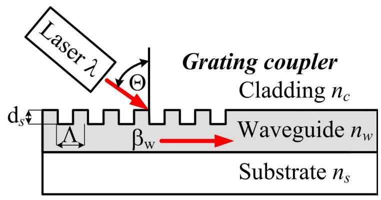


Fig. 1. Photonic structure with a grating coupler.

A photonic structure with a grating coupler, as has already been mentioned above, can be applied as a light input-output system and as elements of optical sensor

* corresponding author; e-mail: Przemyslaw.Struk@polsl.pl

systems [3, 4].

Using the condition of matching the parameters of a grating coupler to the light wavelength [3, 4] one can get the dependence on the angle $\Theta$ of the entrance or departure of the light to- and from- the structure as a function of its material and geometrical properties. The angle $\Theta$ depends, among others, on changes of the refractive index of the ambient medium $n_c$ and changes of the effective refractive index $N_{\text{eff}}$ as well as on the spatial period of the grating $\Lambda$ and the order of diffraction $m$. The angle may serve as a measure of changes of the physical properties of the ambient medium

$$\Theta = \arcsin \frac{1}{n_c}\left(N_{\text{eff}} - m\frac{\pi}{\Lambda}\right). \tag{1}$$

In the course of designing the photonic structure can be considered to be a layered structure, consisting of the waveguide layer with the refracting index $n_w$ embedded in a substrate with the refractive index $n_s$. The structure is placed in the ambient layer with the refractive index of the environment $n_c$. An important problem in the course of designing and the realisation of photonic structures with grating couplers is, therefore, besides the choice of the geometrical parameters also the choice of adequate materials for the respective layers, particularly the waveguide layer. Of essential importance is also the technology of its realisation. A very attractive group of materials with potential possibilities of applying them in photonic structures with grating couplers as waveguide layers and active layers of sensor structures are transparent metal oxides — semiconductors materials with wide band gaps.

The refractive index of ZnO is of a high value, viz. $n > 2$ [13, 14]. The high values of the refractive index are especially required in sensor structures, both those making use of spectroscopy of the fading field and those with grating couplers. In the case of the latter a high sensitivity is achieved for structures with a high sensitivity on changes of external conditions of light propagation on the values of refractive index and narrow angular characteristics of the optical excitation of the structures as well as narrow spectral characteristics of light coupling by the grating couplers [8, 14]. Planar waveguides constructed with the application of ZnO, presented in literatures [14, 15] are characterized by a relatively high attenuation, above $\alpha > 3$ dB/cm. The refractive index $n_w$ of the zinc oxide layers performed by us is characterized by strong dispersion of refractive indices varied in the range from $n_w \approx 2.2$ at the wavelength $\lambda = 400$ nm to $n_w \approx 1.95$ at $\lambda = 1000$ nm [14, 15].

## 3. Numerical investigations of optical structures with grating couplers

In modal analyses it was assumed that the refractive index of the waveguide layer amounts to $n_w = 2.00$, the refractive index of the optical substrate to $n_s = 1.45$ (quartz) or $n_s = 1.51$ (BK7 glass) and of the environment to $n_c = 1.00$ and the wavelength (in vacuum) of $\lambda = 677$ nm.

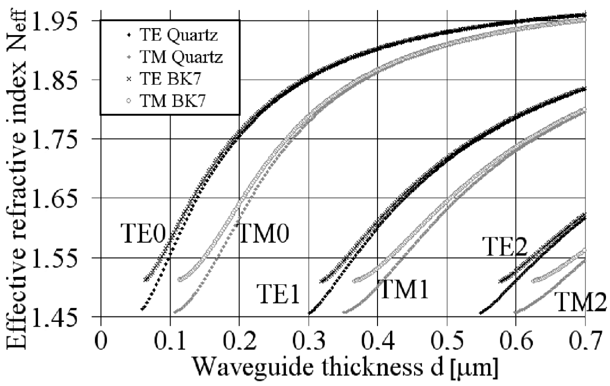


Fig. 2. The effective refractive index as a function of the thickness $d_w$ of the waveguide layer for BK7 or quartz substrate.

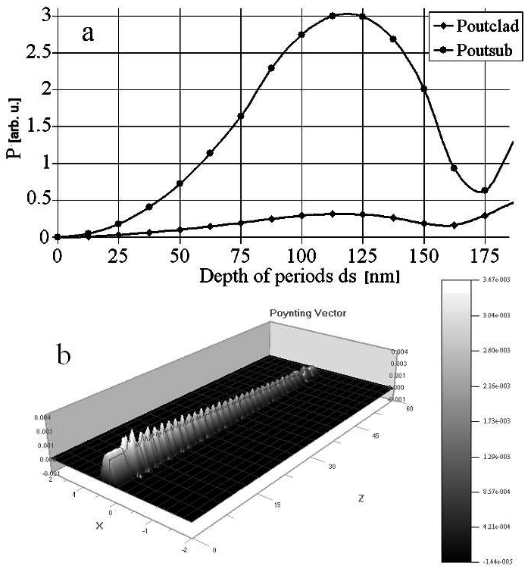


Fig. 3. Optical power into the waveguide layer with the grating coupler: (a) in cladding $P_{\text{outclad}}$ and in substrate $P_{\text{outsub}}$ for the mode TE0; (b) Poynting's vector for the depth of the periods $d_s = 112.5$ nm.

The investigations were devoted to model analyses of the planar structures made with ZnO determining the influence of the thickness of the waveguide layers $d_w$ on the number of propagating waveguide modes. Thus it became possible to define the thickness $d_w$ of the ZnO waveguide layer in order to get single-mode structure to the value $d_w < 300$ nm for quartz substrate or value $d_w < 320$ nm for BK7 substrate. The waveguide layer with the thickness above $d_w > 300$ nm are multimodal for quartz substrate or $d_w > 320$ nm for BK7 substrate. The situation is presented in Fig. 2.

The next stage comprised model analyses of photonic structures with grating couplers with a period of the grating $\Lambda = 1.6$ $\mu$m and thickness of the waveguide layer $d_w = 500$ nm. In the numerical analyses the finite difference time domain (FDTD) method was applied [11, 14]. This method permits to perform model investigations of optoelectronic structures with grating couplers [14, 15]. The numerical investigations were carried out for optimizing the effectiveness of input and output of the optical power into- and out- of the photonic structure by means of grating couplers (Fig. 3).

The quoted investigations have been proved that an increase of the depths of grooves $d_s$ of the grating coupler periods involves an increase of the optical power propagated both into the cladding layer $P_{outclad}$ and the substrate layer $P_{outsub}$ until the maximum value has been reached. In the case of the mode TE0 the optical depth of the periods, at which respectively occurs the maximum of the power emitted from the output structure to the cladding medium (to the environment) and into the substrate is contained within the range: 113 nm $< d_s <$ 125 nm (Fig. 3a). The presented value of Poynting's vector for the groove depth of the periods of the grating coupler amounts to $d_s = 113$ nm (Fig. 3b). The performed numerical analyses permit to perform such technological processes to obtain structures with optimal parameters.

## 4. Results of experimental investigations

Further on, the results of experimental investigations are presented, first concerning structures of planar waveguides, and next photonic structures with grating couplers with a spatial period of the grating: $\Lambda = 1.6$ $\mu$m, realized on the basis of zinc oxide ZnO.

The realization of optoelectronic structures with grating couplers is a complex technological process [15]. It is started with the depositing of the waveguide layer on the substrate, e.g. on glass BK7 or quartz, making use of the technology of physical vapour deposition (PVD), and applying reactive cathode sputtering.

Presented below results referred to the ZnO layers produced by means of reactive sputtering technology in the RF mode, making use the ceramic target of ZnO (99.99). The elaborated technology makes it possible to obtain layer with the required thickness.

Grating periodical structures in the waveguide layers are achieved thanks to the application of the technology of photolithography and etching of the ZnO layer in inductively coupled plasma (ICP) [15]. This technology permits to construct a periodic structure with a relatively well determined depth of the periods $d_s$. Investigations of photonic structures with grating couplers produced on the ZnO layer were started with investigations concerning the optical and waveguide properties of manufacturing structures.

Presented below results concern the optical waveguide layer with above $d_w > 630$ nm thickness. For such thickness, it was a multimode structure, in which three modes can be excited by prism coupling: the zero, first and second order for the polarization TE or/and TM. Figure 4 illustrates the mode characteristics of the analyzed waveguide as a function of the effective refractive index $N_{eff}$.

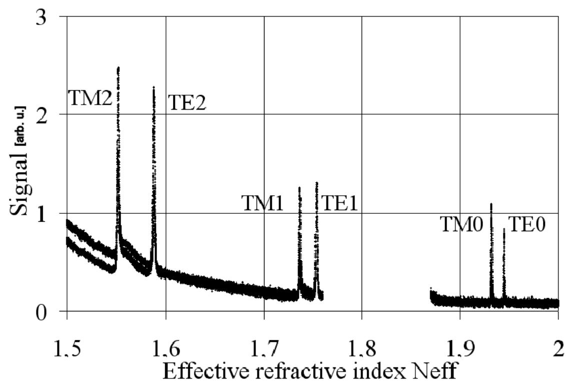


Fig. 4. Mode spectrum of the optical waveguide structures ZnO.

In the case of this structure of the planar waveguide, the image of propagation of the beam of light for the modes TE0 and TE1 are presented in Fig. 5a and b. The reordered images of the beam of light propagation and their analyses have made it possible to determine the attenuation coefficients of the modes in the waveguide layers. In the case of the mode TE0 this coefficient amounted to $\alpha \approx 8.0$ dB/cm, in the mode TM0 to $\alpha \approx 7.6$ dB/cm.

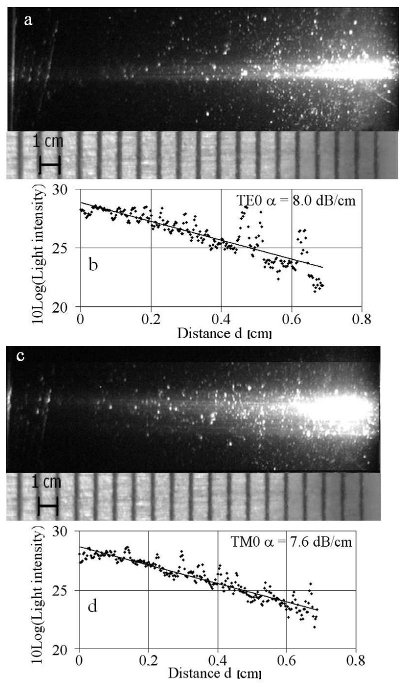


Fig. 5. Propagation of light in the ZnO layer for the modes: (a) TE0, (c) TM0; coefficient of attenuations for the modes: (b) TE0 and (d) TM0.

The existence of waveguide layers based on zinc oxide ZnO with attenuation of the optical signal (below $\alpha = 8$ dB/cm) is one of the elements allowing to develop optoelectronic structures with grating couplers, particularly when such a structure is an element of the input-output system of planar waveguides. The investigated structures with grating couplers were performed applying laser photolithography and etching in inductively coupled plasma ICP in a gaseous medium $BCL_3$. The ICP technology permits to etch the grating couple to the required depth $d_s$ with a precision of several percent.

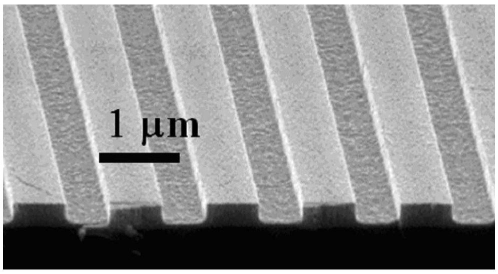


Fig. 6. Optical structure with a grating coupler with a period of $\Lambda = 1.6$ $\mu$m.

Investigations concerning photonic structures with grating couplers first of all concentrated on the analysis of their shapes and regularity of the periods of the grating couplers. These examinations concerned photonic structures with grating couplers for the spatial period of the grating $\Lambda = 1.6$ $\mu$m, making use of scanning electron microscope (SEM). Figure 6 shows the image of the investigated structure. The analysis of the SEM picture indicates that in this structure the periods of the grating coupler are characterized by very regular shapes all over the scanned region, their shape being nearly rectangular.

## 5. Summary

The chief aim of the investigations presented in this paper was to design and to realize photonic structures with grating couplers, constructed basing on ZnO — wide-band semiconductor.

The experimental investigations showed that it is possible to realize photonic structures based on zinc oxide waveguides with grating couplers at a relatively low attenuation of the optical modes (below $\alpha < 8$ dB/cm). The realized investigations exhibited that zinc oxide is an attractive material to be applied in optoelectronics and photonics.

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