Angular dependence of the optical reflectance in two-dimensional Si-ZnO photonic crystals

J G Murillo1*, V. M. Carrillo-Vázquez1, Víctor Castillo Gallardo2, Miguel Ángel Téllez Villaseñor3, Héctor Pérez Aguilar2, José Antonio Medina-Vázquez1, Evelyn Yamel González Ramírez1, G. Herrera3, and A. Duarte-Moller1

1Centro de Investigación en Materiales Avanzados S.C. Miguel de Cervantes 120, Complejo Industrial Chihuahua, C. P. 31136, Chihuahua, Chih. México
2Facultad de Ciencias Físico Matemáticas, Universidad Michoacana de San Nicolás de Hidalgo, Av. Francisco J. Mújica S/N, C.P. 58030, Michoacán, México.
3 Catedra CONACYT Assigned to Department of Physics of Materials, Centro de Investigación en Materiales Avanzados S. C., Miguel de Cervantes 120, Chihuahua 31136, Chihuahua, Mexico

*E-mail: jose.murillo@cimav.edu.mx

Abstract. In this work, we present an experimental study of the angular dependence of the optical reflectance in two 2-dimensional photonic structures, built on a silicon substrate coated with a ZnO thin film. Photonic structures studied describe a regular square lattice with a lattice constant $a = 1.05 \mu m$ and circular air holes with a radius $r = 0.63a$. Additionally, one of these photonic structures contains a pattern of nine quasi-circular micro-cavities embedded in a regular square lattice photonic crystal, describing a secondary square lattice. A comparison of the optical reflectance of the two photonic structures as a function of the incidence angle for transverse magnetic polarization mode in the visible (Vis) and near-infrared (NIR) ranges of the electromagnetic spectrum was accomplished. Results obtained revealed a strong angular dependence of the reflective optical properties of the two 2-dimensional photonic structures on the illumination incidence angle. The photonic structure with the array of resonant optical cavities presented a very unusual behavior regarding the reflectance of the substrate, this because its reflectance described specific modulations dependent on the incidence angle of illumination.

1. Introduction

The study of photonic crystals (PhC) is an emerging area with great technological potential which can be exploited in diverse daily life requirements. Some of these applications of PhCs have been suited to one dimensional (1D) and two dimensional (2D) PhCs such as antireflective coatings [1], band pass filters [2], electro-optical sensors [3], switches [4], light extraction on LEDs [5] and power splitters [6] just to mention some of them. Two dimensional (2D) photonic crystals and 2D PhC slabs are of particular interest since several fabrication methods are currently available for this kind of structures. New applications based on photonic crystals have played a significant role in new advances to develop the ultimate technology.

In this work we report the optical reflective properties of two 2D PhC fabricated on a silicon (Si) substrate coated with a zinc-oxide (ZnO) thin film of about 240 nm thick. The film of ZnO was
deposited onto a Si substrate to control and prevent excessive damage over the silicon substrate during the irradiation with gallium ions from the FIB system. Nevertheless, it was found that the ZnO thin film added new and interesting optical properties to the hybrid PhC. One of the photonic structures studied called the control sample was defined by a square lattice of circular air columns with lattice constant $a=1.05 \mu m$ and air hole diameter of 0.63$a$. The air columns were milled on the Si-ZnO heterostructures using a focused ion beam (FIB) equipment. The other PhC fabricated included nine circular micro-cavities with a diameter of about 10 $\mu m$ each, embedded in a structure such as the control photonic crystal. This second photonic structure was fabricated with the intention to induce a coupling among the micro-cavities embedded within the photonic crystal square structure. Reflectance measurements at variable incidence angle carried out on this photonic device revealed unusual reflectance modulations dependent on the incidence angle of incident radiation.

2. Experimental details
PhC’s were fabricated on a silicon substrate coated with a ~240 nm thick ZnO thin film deposited by Aerosol Assisted Chemical Vapor Deposition method (AACVD) [7]. PhC’s were milled directly on the Si-ZnO hetero-structure on the area of 84 x 84 $\mu m^2$ using a Focused Ion Beam system. It was necessary to adjust FIB fabrication settings using the spot milling shape to obtain circular patterns since this tool was not enabled for circular geometry for milling. The photonic crystal parameters described above were achieved by setting a dose of 200 nC/$\mu m^2$ and 1000 pA of irradiating current during 15 seconds per single hole using the spot milling shape. The two photonic crystals milled have a lattice constant $a=1.05 \mu m$ and circular air columns of radius $r=0.57a$ that describe a square lattice. A pattern of nine quasi-circular micro-cavities of about 10 $\mu m$ in diameter and a lattice constant of ~20 $\mu m$ was embedded in one of the photonic crystals describing a secondary square lattice. These structures were optically characterized measuring the optical reflectance varying the incidence angle and using diode lasers coupled to an optical fiber with wavelengths between 633-1308 nm. These light sources were used to cover discrete broad spectra on VIS and NIR wavelengths with the aim to identify the optical properties of the hybrid photonic hetero-structures. Furthermore, an additional measurement on one of the hybrid photonic crystals was performed by measuring reflectance levels across the spatial coordinate $x$ of the PhC. This measurement was carried out to identify the contribution of micro-cavities embedded within the regular square lattice on the optical properties of the photonic hetero-structure. Structural characterization was conducted by scanning electron microscopy (SEM) using a JEOL JSM-7401F operated at 2kV.

3. Results and Discussion
The two PhC tailored by FIB milling method on a Si-ZnO hetero-structure using the fabrication parameters described above are shown in Fig. 1. Fig. 1(a) shows the control PhC sample “PhC Ctrl-Si-Sqr” describing a square lattice structure with a lattice constant $a=1.05 \mu m$ and circular air columns with a diameter of ~600 nm. Fig. 1(b) shows a PhC “PhC 9Cav-Sqr-Si” with an array of nine circular micro-cavities of about 10 $\mu m$ in diameter and a lattice constant of ~20 $\mu m$ embedded in a regular square lattice of air columns describing a secondary square lattice. Optical characterization of the hetero-structures was completed by measuring the optical reflectance for TM (transverse magnetic) polarization mode varying the incidence angle from 25° to 75° at 632.8, 785 nm, 852 nm and 1308 nm wavelengths. These measurements showed a notorious deviation of the reflectance behavior in PhC’s as a function of the incidence angle radiation respect to the optical reflectance behavior known for the component materials of the substrate. As shown in figure 2, the optical reflectance of both PhC’s shows some modulations dependent on the incidence angle of radiation not present in the optical reflectance of the substrate. Clearly, the set of circular micro-cavities present in the sample "PhC 9Cav-Sqr-Si" has a noticeable effect on the reflectance and induces on it a non-classical behavior as a function of the incidence angle of the incident radiation.
Figure 1. SEM micrographs of hybrid 2D photonic crystal structures milled on a Si-ZnO substrate using the FIB fabrication technique. (a) “PhC Ctrl-Si-Sqr” square lattice control structure with a lattice constant $a=1.05$ μm and circular air columns with a diameter of ~600 nm. (b) “PhC 9Cav-Sqr-Si” hybrid photonic crystal describing a regular square lattice of circular air columns similar to the control sample PhC Ctrl-Si-Sqr, with nine embedded quasi-circular micro-cavities of ~10 μm in diameter and a lattice constant of ~20 μm in a square array.

It is known that the nonlinear changes in the angle-dependence of the reflectance are strongly influenced by the dispersion properties of the photonic band structure associated with a particular PhC. In order to obtain the intrinsic properties of one of the two 2D PhC’s considered in this research, we have calculated its photonic band structure. Figure 3 shows the theoretical photonic band structure of the “PhC 9Cav-Sqr-Si” photonic crystal calculated using the “PWE band solver” of the software package “optiFDTD.” Additionally, in figure 3 it has been included some points, denoted by solid red circles, corresponding to the experimental photonic band structure of the “PhC 9Cav-Sqr-Si” sample obtained from its reflectance measurements as a function of the incidence angle $\theta$ of the incident radiation. This angle $\theta$ determines the in-plane photon wave vector $k = (\omega/c) \sin(\theta)$ defined by the angular speed $\omega$ and the speed of light $c$ in free space. In this way from the experimental reflectivity measurements, it was possible to estimate some representative points of the photonic band structure of the PhC considered. Although, only there was included a few experimental points due to only were used a few light beams of different wavelength to measure the reflectivity of the “PhC 9Cav-Sqr-Si” sample.
Figure 2. Comparison of the optical reflectance of the two photonic structures “PhC Ctrl-Si-Sqr” and “PhC 9 Cav-Sqr-Si” measured as a function of the incidence angle of the incident radiation for TM polarization mode using the wavelengths of 633, 785, 852 and 1308 nm. The solid lines represent the reflectance of the substrate component materials Si-ZnO calculated with TFCalc (Thin film design software).

Figure 3. Theoretical photonic band structure calculated for TM polarization mode for the photonic structure “PhC 9 Cav-Sqr-Si”. The solid red circles represent experimental points of the photonic band structure obtained from the reflectivity measurements along the Γ–X line corresponding to the incident radiation with a wavelength of 1308 nm. The inset shows the corresponding 2D first Brillouin zone and the high symmetry lattice points.
4. Conclusions
Results obtained in this research revealed a strong dependence of the optical reflectance on the incidence angle of the incident radiation in both PhC’s studied. It was found a notorious deviation of the optical reflectance behavior as a function of the incidence angle of radiation for the wavelengths of light used regarding the reflectance of the substrate component materials. The optical reflectance of the PhC’s showed modulations dependent on the incidence angle of radiation which are not present in the substrate reflectance. The behavior of the optical reflectance as a function of the incidence angle of radiation in each of the PhC studied was different. The array of circular micro-cavities in one of the samples “PhC 9Cav-Sqr-Si” investigated induced a non-classical behavior of the optical reflectance as a function of the incidence angle of radiation, which is more evident as the wavelength increases. This strong angular dependence of the reflectivity properties of the PhC’s investigated opening up the possibility of being used in applications in nonlinear optical devices, including wavelength conversion, optical limiting, tunable and adaptive filtering and in general in optical communications systems.

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