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Photonic band gap and defects modes in inorganic/organic photonic crystal based on Si and HMDSO layers deposited by sputtering and PECVD

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ABSTRACT

Hybrid inorganic/organic one dimensional photonic crystal based on alternating layers of Si/HMDSO is elaborated. The inorganic silicon is deposited by radiofrequency magnetron sputtering and the organic HMDSO is deposited by PECVD technique. As the Si refractive index is n = 3.4, and the refractive index of HMDSO layer depend on the deposition conditions, to get a photonic crystal with high and low refractive index presenting a good contrast, we have varied the radiofrequency power of PECVD process to obtain HMDSO layer with low refractive index (n = 1.45). Photonic band gap of this hybrid structure is obtained from the transmission and reflection spectra and appears after 9 alternative layers of Si/HMDSO. The introduction of defects in our photonic crystal leads to the emergence of localized modes within the photonic band gap. Our results are interpreted by using a theoretical model based on transfer matrix.

1. Introduction

Photonic crystals (PCs) are artificial structure formed by two materials having different refractive indexes arranged periodically in space. This periodicity varies in one, two, three dimension [1,2] and can induce the appearance of frequency range for which the propagation of the light is prohibited and commonly called photonic band gap (PBG) [3,4]. This PBG is similar to the electronic band gap in crystalline semiconductors and this is due to the analogy of the propagation of photons and electrons respectively in the photonic structure and the semiconductors which are governed by Shrödinger and Maxwell equations [5]. Photonic crystal have been from 1987 the subject of intensive research because their attractivity in many applications which require special localisation of light such as waveguides, multiplexers… [6] and can initiate new research field, as plasma [7,8] and superconductor photonic crystals [9], metamaterial devices. The introduction of defect in a photonic crystal breaks the periodicity for the dielectric constant and allows the appearance of a transmission band in the PBG. This defect is the basis of many applications in different fields as the control of spontaneous emission and the realization of large scale optical integrated circuit… [10–12]. PC can be fabricated with various techniques in one, two or three dimensions. The one-dimensional photonic crystal is elaborated by depositing alternatively layers of low- and high-refractive index in Bragg mirror structure with several techniques as sputtering, PECVD, evaporation [13,14]. This structure is attractive since its production is relatively easy and can its modelised by simple analytical and numerical calculations. The two-dimensional crystal are essentially designed by drilling holes in an appropriate dielectric material. For the three-dimensional structure the crystal is obtained by stacking spheres in the dielectric medium . Conventional one dimensional photonic crystals are formed mostly with staked layers of inorganic dielectric materials such as Si/SiO_2 [15–17]. Recently we have developed new types of photonic crystals elaborated by PECVD technique from the same gas mixture under different conditions. One from a unique gas mixture of (HMDSO+O_2), which gives, by varying the flow of oxygen an hybrid photonic crystal formed with alternative layers of high and low refractive indexes, corresponding to HMDSO and SiO_2

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materials, respectively [18] and the other from using a mixture of ($HMDSO + N_2$) which gives by the variation of the RF power an hybrid photonic crystal with alternative layers corresponding to $SiC_xN_yO_zH$ and α-Si_3N_4 with a good refractive index contrast [19]. These new generations of hybrid photonic crystals could have potential applications in many fields such as telecommunication, optoelectronics with low cost and easily elaboration covering a wide variety of initial mixed gaz.

In this work we are interested to the elaboration of an hybrid one-dimensional photonic crystal based from an inorganic material the silicon and the pure organic compound (hexamethyldisiloxane: HMDSO) deposited alternatively by sputtering and PECVD with high and low refractive index of 3.4 and 1.4 for respectively Si and HMDSO.

Silicon is the most dominant material in the technology of microelectronic and optoelectronic components, due to its purity, electronic properties, and the relative good control of its layers deposition on various substrates (glass, plastic …) on very large surface, which allows the design of potential devices as flat screen, photovoltaic cells, sensors, LEDS ... [20]. It's layer deposition by RFMS technique consists in a collision between radicals generated in plasma and the target of the Si material. The atoms of target are then sputtered and condensed on the glass substrate. A pure argon plasma (Ar) is produced with an RF of 300 W and a total pressure of 10^{-6}Pa, in order to obtain homogeneous layers [15].

Hexamethyldisiloxane ($C_6H_{18}OSi_2$ - HMDSO) is often used in the plasma polymerization because its higher organic character and high vapor pressure, it's sufficiently volatile near the room temperature, relatively non-toxic and non-flammable, cheap and available from commercial resources. Due to these interesting properties, HMDSO has been used for a variety of applications in the last few years. It can be used as a precursor deposited in thin layer by the PECVD technique [21–23] which combines physical and chemical processes in the plasma phase as and in the plasma-solid interface. These process are based on the molecule dissociation in the gas phase by impact of energetic electrons and atoms in metastable states followed by chemical reactions of gas radicals. This methods enable the preparation of thin layers with intimate adhesion to diverse substrates, and good mechanical, optical or electrical properties. Compared with classical chemical methods, PECVD has several advantages as low substrate temperature, and production of layers with various properties by changing simply some deposition parameters leading to many promising applications in optoelectronic field [24,25].

We used as substrate a glass slide ($1 \times 2\,cm^2$) cleaned in successive ultrasonic baths of acetone, ethanol and distilled water, and then dried with compressed air. Before the layers deposition, the substrates are etched with argon plasma in order to remove any surface residual contaminants. The layers are deposited on the substrate temperature at room temperature, using a pure gas of HMDSO, by varying the RF power from 20 to 200 W and maintaining constant the flow of this gaz at 20 sccm with a total pressure of 7×10^{-3} Torr.

After optimizing the thickness layers of Si and HMDSO, with respect to Bragg mirror law and wavelength reference, we have determined experimentally by transmission and reflection measurement the minimal period numbers which leads of large and well structured photonic band gap. In addition, we have incorporated two defects within this structure which gives rise to a localized modes into the PBG corresponding to the 1.55 μm and 1.33 μm telecommunications wavelengths . All our experimental results are in good agreement with our developed theoretical model based on transfer matrix.

2. Experimental details

2.1. Measurement of the refractive index of layers

2.1.1. Refractive index of Si

Thin layers of silicon (Si) are deposited by sputtering during a time deposition of 5 min. We have measure transmission and reflection spectra of the deposited layers with a double beam UV–Visible–NIR 5E Varian spectrophotometer in the wavelength range of 400–2500 nm. The analysis of these spectra by a numerical commercial software code allows the determination of the variation of refractive index (n) as a function of the wavelength. We have reported this variation in the Fig. 1 where we obtain for the high wavelength according with the optical Cauchy law [26] a refractive index for the silicon layer $n_{Si} = 3.4$. We also determined by the same code the variation of absorption coefficient with the wavelength as shown in Fig. 2, we note that the absorption for the Si is almost zero for wavelength higher.

2.1.2. Refractive index of HMDSO

Thin layers of HMDSO are deposited by PECVD, with fixed flow rate at 20 sccm., and varied RF power (20–200 W) at a same deposition time of 5 min for all the layers. We then measured for each layer the transmission and reflection spectra with the Varian spectrophotometer . And we have analyzed these spectra by using a commercial software code, which permit the determination of the refractive index layers for different RF power. The value of this refractive index are reported in Fig. 3.

This figure indicated that the refractive index increases with the RF power, and varies from 1.45 to 1.9 respectively to RF power for 20 W and 200 W. It is noted that the films deposited at 20 W have an index of 1.45 which corresponds to a typical value of the polymer films. From a power of 100 W, relatively high index values are obtained, which corresponds more to the index of disordered carbonaceous materials. At 200 W the index has a value of the order of 1.9 which is similar to a highly disordered carbon compound. The variation of the refractive index can be associated with the variation in the density of the material. Thus the increase in refractive index may reflect a densification of our layers when the energy supplied to the monomer during the deposition is increased.

Finally, the silicon which refractive index is 3.4 will be considered as the high index material, we will choose as low material index the HMDSO layer obtained for RF power 20 W and corresponding to an index to 1.45. The photonic crystal will consist of an alternating Si/HMDSO layers with best a refractive index contrast $\Delta n = 1.95$.

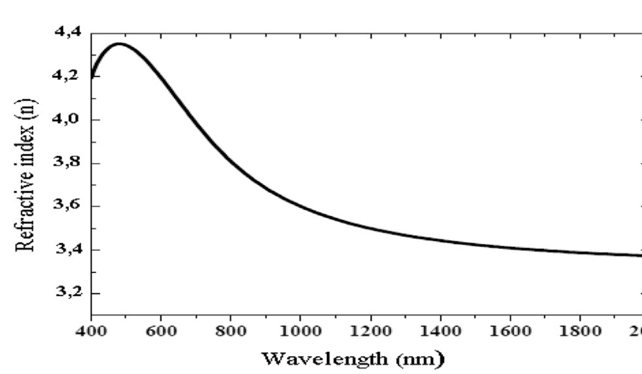

Fig. 1. Variation of the refractive index as a function of wavelength obtained for the Si layer.