Optik 125 (2014) 828–831

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Simulation and fabrication study of porous silicon photonic crystal

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ARTICLE INFO

Article history:
Received 12 March 2013
Accepted 10 July 2013

Keywords:
Porous silicon
Distributed Bragg reflector
Reflective interferometric Fourier transform spectroscopy
Electrochemical etching
Transfer matrix method

ABSTRACT

The present work reports design and fabrication of porous silicon based one-dimensional (1D) photonic crystal. Distributed Bragg reflector (DBR) is a 1D photonic crystal composed of multilayer stack of high and low refractive index layers. Design of porous silicon DBR is a complex one and requires appropriate control in optical parameters of its constituent layers. In order to design DBR, two porous silicon single layer samples were fabricated using current density of 10 and 50 mA/cm^2. Optical characterization of single layer samples showed series of interference fringes. Reflective interferometric Fourier transform spectroscopy (RIFTS) method was employed to determine optical constants of porous silicon single layers. DBR simulation was carried out based on transfer matrix method. DBR was then fabricated using optical parameters obtained from RIFTS method. Reflection bandwidth of prepared DBR was found to be 216 nm, which is comparable to the simulated value of 203 nm.

1. Introduction

Porous silicon (PSi) is fabricated by the electrochemical anodization of crystalline silicon in hydrofluoric acid solution [1]. It showed a tremendous potential for use in microelectronics [2], optoelectronics [3], chemical [4] and biological sensors [5], and in drug delivery applications [6]. Different types of PSi multilayer structures like distributed Bragg reflector (DBR) [7], microcavity [8], rugate filter [9], etc. can be formed easily by controlling anodization parameters.

Distributed Bragg reflectors (DBRs) are one dimensional (1D) photonic crystals consisting of a stack of discrete layers of two different refractive indices. The DBR allows rejection of a wide range of wavelengths of light in a specific region called photonic bandgap (PBG) of the structure. Design of DBR requires that each layer should have optical thickness (i.e. nL, where n and L are the refractive index and thickness of a layer, respectively) of one quarter of design wavelength and the constituent layers must be phase-matched [10]. Therefore, simple and accurate method is required to determine optical constants of PSi layers.

Different techniques, such as spectroscopic ellipsometry [11], gravimetry [12], and reflective interferometric Fourier transform spectroscopy (RIFTS) [13,14] are available to determine optical constants of PSi layers. In recent years, RIFTS technique has been successfully employed to extract refractive index and thickness of the PSi layers as well as in PSi based sensors [15–17]. RIFTS is a simple and faster technique based on the Fourier transform of the reflectance spectrum. In the present work, we studied the design and fabrication of PSi based 1D photonic crystal by transfer matrix and RIFTS method. Simulation code based on transfer matrix method was developed to calculate reflectance spectra of a DBR before its fabrication.

2. Experimental

The PSi samples were electrochemically etched from a boron-doped p$^+$ type (1 0 0) silicon wafer with a resistivity of 0.01–0.02 Ω cm. An aqueous 40% hydrofluoric acid (HF) and ethanol in a ratio of 1:2 (v/v) was used for the electrochemical anodization of silicon substrate. An electrochemical etching cell made of Teflon was used with an effective electrode area of 2 cm^2 [18]. Platinum loop was placed on the top of anodization cell as cathode and a strip of aluminium foil was placed on the backside of the silicon wafer as anode. The current was supplied by a programmable power source (Tektronix, PWS4305, M/s. Optimized Solutions Ltd., Ahmedabad, India). Immediately before etching, the silicon substrates were dipped in piranha solution to remove the organic residues present on the silicon surface. After anodization, samples were rinsed in ethanol and then dried under a stream of nitrogen.

The DBR was prepared by using the same ethanolic HF solution and by repetitions of 20 cycles of a periodic wave current between 10 mA/cm^2 for 10.9 s and 50 mA/cm^2 for 5.16 s. Interferometric reflectance spectra of the prepared samples were collected using a fibre optic spectrometer with charge-coupled device (CCD) detector (Maya2000 Pro, M/s. Sinsil International, Mumbai, India) and deuterium tungsten halogen lamp light source (DH-2000-BAL,

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http://dx.doi.org/10.1016/j.ijleo.2013.07.062

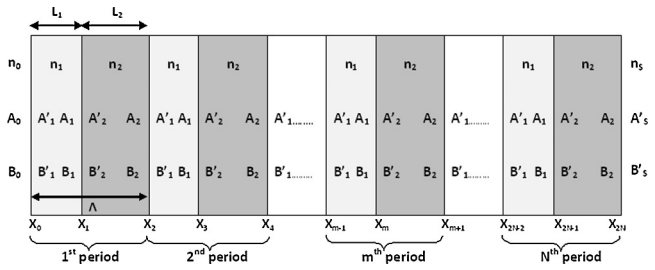

Fig. 1. Schematic diagram of DBR. The thickness and refractive index of each layer is L_m, and n_m respectively.

M/s. Sinsil International, Mumbai, India). The cross-sectional and plan-view images of the DBR were obtained by using a field emission gun scanning electron microscope (JSM-7600F, JEOL). Sputter coating of the DBR sample with thin layer of gold was employed to increase surface image quality.

3. Simulation of DBR

Transfer matrix method (TMM) was used to develop a simulation code for the design of DBR. TMM is broadly used for the mathematical study of wave transmission in 1D structure [19]. DBRs are 1D photonic crystals consisting of a stack of discrete layers of two different refractive indices (n_1, n_2) and thicknesses (L_1, L_2). These layers are coupled to a homogeneous medium with refractive index n_0 at initial medium and n_s at final medium. The schematic of DBR is shown in Fig. 1, where Λ is the period of the 1D structure, $A(x)$ and $B(x)$ correspond to the amplitudes of the right-travelling wave and left-travelling wave, respectively. The A_m and B_m amplitudes are presented as column vectors and plane waves can be correlated by:

$$\begin{pmatrix} A_{m-1} \\ B_{m-1} \end{pmatrix} = D_{m-1}^{-1} D_m \begin{pmatrix} A'_m \\ B'_m \end{pmatrix} = D_{m-1}^{-1} D_m P_m \begin{pmatrix} A_m \\ B_m \end{pmatrix} \quad (1)$$

where $m = 1, 2, \ldots, 2N+1$ and matrices D_m are the dynamical matrices presented as

$$D_m = \begin{cases} \begin{pmatrix} 1 & 1 \\ n_m \cos\theta_m & -n_m \cos\theta_m \end{pmatrix} & \text{for TE wave,} \\ \begin{pmatrix} \cos\theta_m & \cos\theta_m \\ n_m & -n_m \end{pmatrix} & \text{for TM wave,} \end{cases} \quad (2)$$

and P_m is the propagation matrix, that can be presented as

$$P_m = \begin{pmatrix} e^{ik_{mx}h_m} & 0 \\ 0 & e^{-ik_{mx}h_m} \end{pmatrix} \quad (3)$$

The relation between A_0, B_0 and A'_s, B'_s can be obtained as

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = D_0^{-1} \left[D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1} \right]^N D_s = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \begin{pmatrix} A'_s \\ B'_s \end{pmatrix} \quad (4)$$

where N is the number of periods in the structure.

The reflectance of DBR structure is calculated from the matrix elements. If the light is incident from lossless medium n_0, then the reflection coefficient is defined as

$$r = \left(\frac{B_0}{A_0} \right)_{B_s=0} \quad (5)$$

From Eqs. (4) and (5), we obtain following relation,

$$r = \frac{M_{21}}{M_{11}} \quad (6)$$

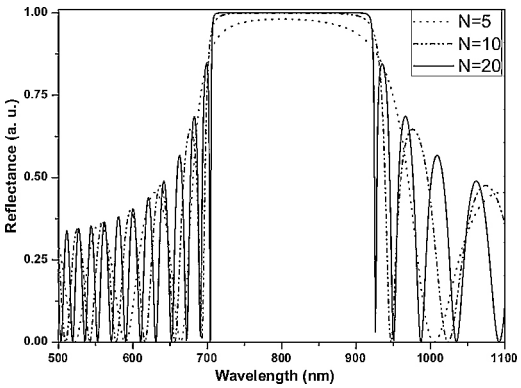

Fig. 2. Simulated reflectance spectra of DBR with $n_H = 2.34$, $n_L = 1.56$ and periods of 5, 10, and 20.

Then, reflectance is specified as

$$R = \left| r^2 \right| = \left| \frac{M_{21}}{M_{11}} \right|^2 \quad (7)$$

Based on this method, simulation code in MATLAB was developed to study the reflectance of a DBR before its fabrication. This simulation code requires following parameters: (i) refractive index of ambient medium; (ii) refractive index of substrate; (iii) refractive indices of high and low index layers; (iv) central wavelength (nm); (v) number of bilayers; (vi) angle of incidence (degree); (vii) lower wavelength limit (nm), and higher wavelength limit (nm).

Fig. 2 shows the effect of number of periods on the reflectance spectra of the DBR. These spectra were simulated with high and low refractive indices of 2.34 and 1.56, respectively. It can be seen from Fig. 2 that with increase in number of periods, PBG edges become sharper and reflectance within bandgap increases.

4. Results and discussion

4.1. Design of DBR

The DBR consists of discrete layers of two different refractive indices (n_1, n_2) and thicknesses (L_1, L_2). It shows the broader spectral peak, also called photonic bandgap when the Bragg condition [20] is satisfied, as following:

$$\frac{\lambda}{4} = n_1 L_1 = n_2 L_2 \quad (8)$$

where λ is the Bragg wavelength corresponding to centre of the photonic bandgap region. Eq. (8) shows that each Bragg layer has to be one quarter of Bragg wavelength and optical thickness (i.e. nL) of each layer should be same for optimal design.

4.2. Optical characterization of single layer PSi

In order to design a DBR, two PSi single layer samples were prepared using 10 and 50 mA/cm^2 for 3 min. The reflectance spectra of single layer samples are shown in Fig. 3. Both spectra show significant series of interference fringes and this type of Fabry-Perot fringe pattern results from the constructive and destructive interference of light reflected from the PSi-medium and PSi-crystalline silicon interfaces. The maxima in the fringe pattern occur at λ_{max} and are related to the physical properties of PSi through following equation [5]:

$$m\lambda_{max} = 2nL \quad (9)$$

where m is the spectral order, L is the thickness of the PSi layer, n is the average refractive index of the layer and term $2nL$ is also referred to as the effective optical thickness.