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Synthesis and characterization of porous silicon layers for 1D photonic crystal application

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ABSTRACT

In this paper, we studied the optical and physical properties of electrochemically prepared porous silicon layers. The atomic force microscopy analysis showed that the etching depth, pore diameter and surface roughness increase as the etching time increased from 30 to 50 mA/cm^2. By tuning two current densities J_1 = 50 mA/cm^2 and J_2 = 30 mA/cm^2, two samples of 1D porous silicon photonic crystals were fabricated. The layered structure of 1D photonic crystals has been confirmed by scanning electron microscopy measurement which showed white and black strips of two distinct refractive index layers. Finally, the measured reflectance spectra of 1D porous silicon photonic crystals were compared with simulated results.

1. Introduction

Porous silicon is a material which has new aspects for photonic devices fabrication and it is compatible with established standard microelectronics technology that enables advances in silicon-based devices [1]. The morphology and size-scale of porous silicon features are highly dependent on the process parameters. Porous silicon is described as a network of void spaces within a nanostructured silicon matrix which has the capability to modify the optical properties of silicon in order to overcome the limitations of the intrinsic indirect silicon electronic band gap. Porous silicon has been produced by a variety of approaches, but it is most commonly prepared by electrochemical etching in HF based solutions [2]. The precise control of layer porosity and thickness allows the tailoring of optical properties of porous silicon and has opened the door to a multitude of applications in advanced optoelectronics technology such as photonic crystals [3], microcavities, waveguides [4], photodetectors [5], and biosensors [6].

Presently, photonic crystals have shown the potential to change the whole scenario of light propagation and became a key subject of today's engineering and technological research [7–9]. By forbidding light propagation of specific wavelength range, controlling the propagation in certain directions and confining the light in desired areas, the photonic crystals are proved to be a promising candidate to realize all optical functionalities for advanced optical components. One-dimensional (1D) photonic crystals can be easily prepared by the periodic variation of the electrochemical etching parameters which lead to periodic variations of the refractive index and thickness of each layers [10]. By adding optical functionality to the well-established silicon manufacturing infrastructure an enhanced performance of both existing microelectronic and developing photonic devices can be achieved. Hence, silicon based photonics technology is fully capable to integrate electrical and optical components on a single chip.

In this paper, various samples of monolayers and multilayers porous silicon have been electrochemically fabricated and characterized to study its optical and physical properties. In Section 2, the experimental details of porous silicon layers have been presented. The characterized results are summarized in Section 3. Finally, Section 4 concludes the paper.

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2. Experimental details

Boron doped p-type silicon substrate of ⟨1 0 0⟩ orientation was used as starting material. Before synthesis, the wafers were rinsed in de-ionized water after heating, separately in trichloroethylene, methanol and acetone for 5 min. The cleaned silicon wafers were dried in the presence of nitrogen. Various samples were prepared using single tank electrochemical system at different anodization parameters in electrolyte solution consists of hydrofluoric acid (48%), de-ionized water and ethanol in a proportion of 1:1:2 respectively. These electrochemically prepared monolayers and multilayers of porous silicon were studied by atomic force microscopy (Nanoscope (NSE)) in contact mode, scanning electron microscopy (Leica Cambridge 440 Microscope) and UV–vis spectrophotometer (Shimadzu UV-1601).

3. Results and discussion

The study of various samples of monolayers prepared at different anodization parameters point out that the refractive index of porous silicon layers decreases as the current density and etching time are increased. However, the thickness of porous silicon layer increases with current density and etching time. The atomic force microscopy (AFM) images of porous silicon monolayers prepared at 30 mA/cm^2 (sample S1) and 50 mA/cm^2 (sample S2) under 2 min etching time are depicted in Fig. 1(a) and (b). In both AFM images, the inhomogeneous and irregular shaped pores can be clearly observed which are distributed over the entire surface. Samples S1 and S2 show the good uniformity and homogeneity of porous silicon layers. The measured refractive indices and thicknesses of samples S1 and S2 are 1.15 and 1.06 and 151 nm and 167 nm respectively. However, the surface roughness with irregular upright structure of silicon crystallites was measured to be 5.784 nm and 6.912 nm corresponding to the samples S1 and S2.

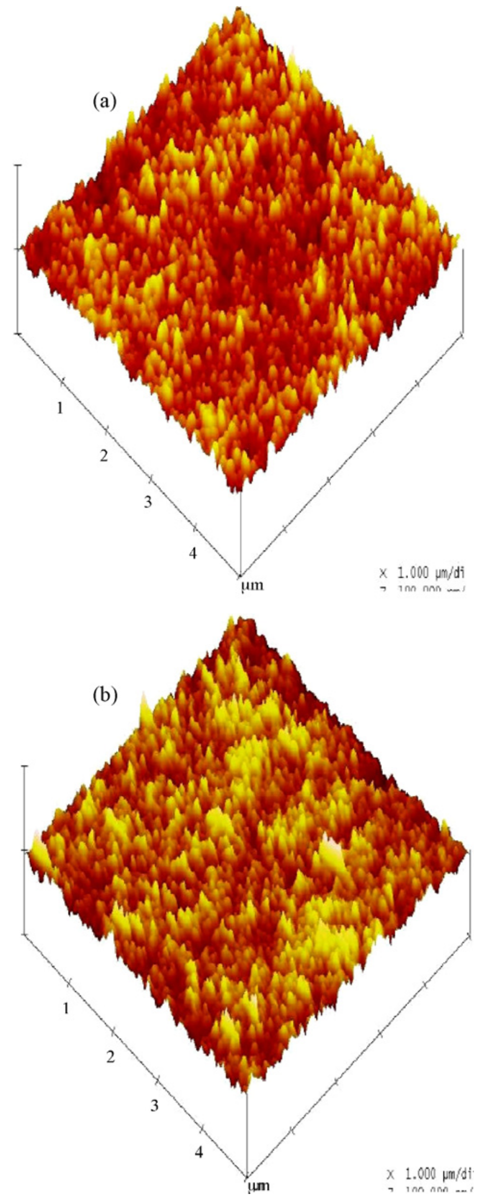

Fig. 1. Atomic force microscopy of porous silicon monolayers anodized at 30 mA/cm^2 (a) and 50 mA/cm^2 (b) for 2 min etching time respectively.

If the current density changes alternately the one-dimensional photonic crystal with sinusoidal refractive index profile can be formed. The result of this process forms columns normal to the surface of the silicon substrate. Higher charge densities produce a slightly different structure because the positive charge density is sufficient to begin etching immediately, long before the charge has time to travel to the surface and congregate at a surface minimum. Any new charge externally injected into the substrate only needs to reach the charge filled silicon–electrolyte interface. This induced the anodization process and because of this action, pores can form laterally as well as normal to the substrate. The pores are smaller also because the holes do not have the time to congregate before the etching occurs and the result is a sponge-like system. Fig. 2(a) and (b) shows the AFM images of samples S3 and S4 which consist of four layers (two periods) and six layers (three periods) of high and low refractive index of porous silicon respectively. As compared to the sample S3 more hillocks like structure with high etching depth and roughness can be observed in sample S4. The estimated surface roughnesses of samples S3 and S4 are 6.3 nm and 8.9 nm.

Using the same anodization parameters to prepare the samples S3 and S4 we have again prepared multilayer structures of porous silicon but for increased periods. This multilayer structure is nothing but the 1D porous silicon photonic crystal which is composed of six periods of high and low refractive index respectively. Fig. 3(a) shows the cross-sectional SEM image of 1D porous silicon photonic crystal (sample S5) in which the different layers can be observed by white and black strips corresponding to the refractive index $n_1 = 2.14$ and $n_2 = 1.88$ respectively. The average thicknesses of first and second layer are 1.36 µm and 0.56 µm prepared at current density 50 and 30 mA/cm^2 under 2 min etching time respectively. The homogeneity and uniformity of porous layers observed in sample S5 are poor.

Similarly, we have prepared another sample of 1D porous silicon photonic crystal (S6) at slightly reduced etching time (1 min). Fig. 3(b) shows the cross-sectional SEM image of sample S6 in which the different layers of high and low refractive index can be clearly seen. The average thicknesses of the first and second layer etched under 1 min etching time are 1.84 µm and 0.72 µm prepared at current density 50 and 30 mA/cm^2 respectively. The refractive indices of first and second layer measured by ellipsometer are 1.42 and 2.65 respectively. If we compare Fig. 3(a) with (b) we will find that the SEM of Fig. 3(a) shows the non-uniform layers prepared under 2 min etching time. However, as the etching time reduces to 1 min the structure becomes more uniform with good homogeneity as depicted in Fig. 3(b). In addition, the refractive index contrast (n_2/n_1) of sample S6 is large as compared to sample S5 prepared at 2 min etching time. The SEM images shown in Fig. 3 are synthesized for six periods of high and low refractive index layers. However, the intermixing of porous layers can be seen in both SEM