Applied Surface Science 264 (2013) 1–6

Contents lists available at SciVerse ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Hybrid structure for efficiency enhancement of photodetectors

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ARTICLE INFO

Article history:
Received 10 November 2011
Received in revised form 11 August 2012
Accepted 11 August 2012
Available online 12 September 2012

Keywords:
Photonic crystal
Porous Si
Solar cells
Interference lithography
Photodetectors

ABSTRACT

A nanoporous tapered silicon (Si) photonic crystal (PC) is realized. The PCs with this structure, which may be called hybrid PC-porous can significantly reduce the surface reflection over the broad wavelength range of 400–2000 nm. Moreover, the absorption enhances in this structure significantly. The PCs are fabricated by interference lithography and then nanoporous structure is applied on it using metal assisted chemical etching. The measured reflectance and absorption across a spectral range of 400–2000 nm are, approximately 3% and 96%, respectively. The improvement on the reflectance and absorption are about 90% and 70% compared to bare Si respectively; which is promising in the utilization of this structure for various applications.

1. Introduction

For many investigators, efficiency enhancement in photovoltaic devices (e.g. solar cells and photodetectors) is an intriguing subject [1–6]. One method for the efficiency enhancement of these devices is reflection reduction of incident light. This method is especially important for silicon (Si)-based devices which have high indices of refraction and thus high reflectance [7,8].

Another way to increase the efficiency of these devices is to increase their absorption via enhancement of the light–matter interaction time [9,10]. The enhancement of the absorption coefficient may also be achieved by fabrication of nanostructures due to creation of new absorption bands [11–14].

Several methods have been used to decrease the reflectance or to increase the absorption of silicon-based devices such as manufacturing antireflection single layer [15] or multiple layers [6]. In an antireflection single layer the efficiency enhancement occurs in a narrow spectral range whereas in multiple antireflection layers, choosing suitable material is limited in order to obtain large spectral line width.

Another method for reflectance reduction is utilizing pores to produce intermediate antireflection layers with suitable refractive index matching between air and substrate [16–20]. In addition, the use of porous structures in the absorbing layer increases the light propagation length and light confinement. Hence, the total absorption increases. Furthermore, the existence of nanostructure in porous areas can create new absorption bands and therefore increase the absorption even below the band gap [11–13].

On the other hand, photonic crystals (PCs) are extensively used to increase the efficiency of photovoltaic devices as upside antireflection or downside total reflection layer [3,21–28]. Also PCs have been used to enhance coupling efficiency at leaky modes [23]. Several groups have used this effect to enhance the efficiency of the photodetectors, although it occurs in a narrow bandwidth [24–27]. Also, array of tapered rods in sub-wavelength period called moth-eye structure, has been used in silicon solar cells to enhance efficiency across a broad bandwidth [29–31].

In this work we develop a technique to enhance the efficiency of photovoltaic devices based on the combination of PCs with tapered holes and low-depth nanoporous structures. This technique can realize gradual increase of effective refractive index in three low-thickness index matching layers. This good index matching can be used to achieve suitable broadband antireflection layer. The resultant hybrid PC-porous samples have low fragility and low non-uniformity in comparison to high-depth porous area. Moreover, it seems that low depth porosity can cause better refractive index matching due to the existence of more conical-shaped pores and more random depth distribution. However this highly textured structure could increase surface recombination of generated carriers in photovoltaic devices. On the other hand, the nanoscale pores

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http://dx.doi.org/10.1016/j.apsusc.2012.08.037

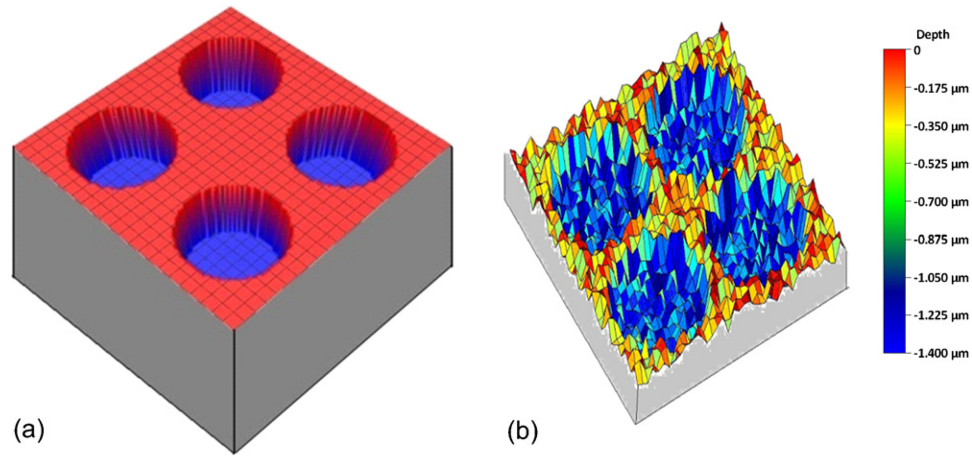

Fig. 1. The schematic of the sample (a) PC (b) PC-porous profile.

on the surface can cause a new absorption band that enhances the absorption coefficient.

We use interference lithography to fabricate PCs as tapered hole arrays in silicon matrix. Then, a metal assisted chemical etching (MaCE) technique is applied to make shallow porous silicon on the PC surface. This fabrication technique is cost-efficient and simple and can be potentially used for large effective-area photodetectors.

2. Simulation

We use the finite difference time domain (FDTD) method to calculate the reflectance (R) (including specular and nonspecular) and the transmission (T) spectra of our samples. The schematic of the samples is shown in Fig. 1. In the simulation, we consider 2D PCs in the form of holes in high-doping density of Si wafers. We use the constant refractive index $n = 3.55$ and the absorption coefficient $\alpha = 40\,\mathrm{cm}^{-1}$ for Si. We also assume the pores in the porous region to be ellipsoid in shape with random depth (in the range of 0–400 nm) as well as random diameter and distribution.

The simulation is conducted for various values of the PC parameters such as period, filling factor (FF), and wall slope as well as for different values of the pores parameters such as size, depth and density. For instance, Fig. 2 shows the reflectance spectra for different values of the wall slope and for a given value of FF = 0.5. This figure reveals that by increasing the slope of the lateral wall up to 20° the reflectance reduces, which is in full agreement with the previous studies [5].

Fig. 3 shows the simulated reflectance spectra for the hybrid PC-porous structures for different values of the pores density (ρ). In these structures, the pore's diameter is considered to be randomly distributed in the range of 0–50 nm. The depth and period of the PC are 1 μm and 1.15 μm respectively. The pore's depth is randomly distributed in the range of 0–400 nm. Also, for comparison, in Fig. 3 the reflectance of the same porous structure with a density of 3000 pores per $(\mu\mathrm{m})^2$ without PC is shown. The comparison of Figs. 3 and 2 reveals that in hybrid PC-porous structures, the reflectance decreases significantly compared to just the PC alone or porous structure alone.

In Fig. 4a the average reflectance (between 900 and 2100 nm) versus pore density is shown for the same hybrid structures. Also in Fig. 4b the average reflectance for the structures with different distribution of the porous diameters is shown. The horizontal axis (d_m) is the maximum diameter of the pores in each sample that randomly distributed in the range between 0 and d_m. From this simulation, we obtain the minimum reflectance of 1.5%, on average, for $d_m = 50$ nm and $\rho = 3000$ pores/$\mu\mathrm{m}^2$.

3. Experiment

In this work, 2D Si PCs are fabricated by interference lithography and reactive ion etching (RIE) techniques. The schematic setup of interference lithography is shown in Fig. 5. For interference lithography, a He–Cd laser of wavelength 325 nm is used. The laser beam is separated by a beam splitter (BS) into two beams of equal intensity and passes through two spatial filters to delete speckles. Then, the beams are directed toward the sample to interfere with each other in the photoresist layer coated on the sample. The period of

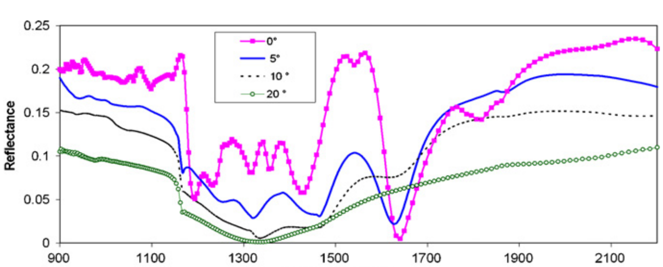

Fig. 2. Reflectance spectra for 1 μm hole depth and 1.15 μm period PCs but with different wall slopes at constant FF of 0.5.

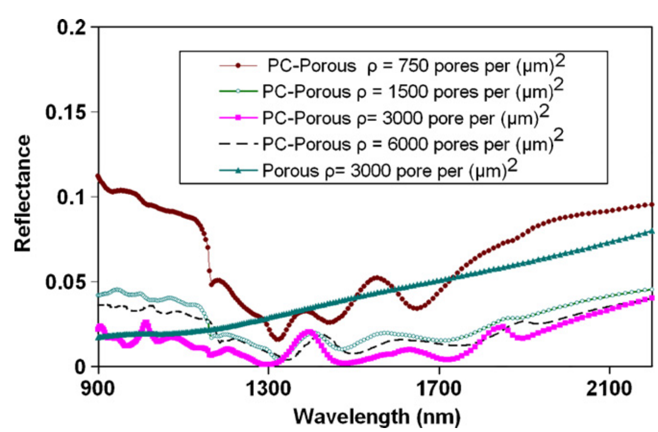

Fig. 3. Reflectance spectra for PC-porous with random depth of $h = 0$–400 nm and constant maximum pores diameter ($d_m = 50$ nm) but different porous density (ρ). PCs hole depth = 1 μm, FF = 0.5 and lateral wall slopes = 5°. (a) $\rho = 750$ pores per $(\mu\mathrm{m})^2$, (b) $\rho = 1500$ pores per $(\mu\mathrm{m})^2$, (c) $\rho = 3000$ pores per $(\mu\mathrm{m})^2$, (d) $\rho = 6000$ pores per $(\mu\mathrm{m})^2$, and (e) same porous structure with $\rho = 3000$ pores per $(\mu\mathrm{m})^2$ but without PC.