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Fabrication of porous silicon based tunable distributed Bragg reflectors by anodic etching of irradiated silicon

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ABSTRACT

We report a study on the fabrication of tunable distributed Bragg reflectors (DBRs) by gamma/ion irradiation of Si and subsequent formation of porous silicon multilayers. Porous Si multilayers with 50 bilayers were designed to achieve high intensity of reflection. The reflection spectra appear to have a broad continuous band between 400 and 800 nm with a distinct central wavelength corresponding to different wave reflectors. The central wavelength and the width of the stop band are found to decrease with increase in irradiation fluence. The Si samples irradiated with highest fluence of 2×10^{13} ions/cm^2 (100 MeV Ag ions) and 60 kGy (gamma) showed a central reflection at $\lambda = 476$ nm and 544 nm respectively, in contrast to un-irradiated sample, where $\lambda = 635$ nm. The observed changes are attributed to the density of defects generated by gamma and ion irradiation in c-Si. These results suggest that the gamma irradiation is a convenient and alternative method to tune the central wavelength of reflection without creating high density of defects by high energy ion implantation. This study is expected to provide useful information for fabricating tunable wave reflectors for optical communication and other device applications.

1. Introduction

Nanostructured porous silicon is an efficient material to fulfill the requirement of silicon based industry to integrate many opto-electronic functions on a single chip. Porous silicon (pSi) has been investigated extensively as a possible candidate for developing waveguides, light emitting diodes and distributed Bragg reflectors (DBR) etc. [1–5]. There are various methods to synthesize porous silicon (pSi), particularly electrochemical etching is a relatively easy and convenient method to prepare homogeneous nanostructured layers [6]. In electrochemical etching, an aqueous HF solution combined with ethyl alcohol is used to etch the silicon [6]. The structural properties such as size, shape of pores, porosity and thickness of porous Si layer critically depend on the etching parameters such as resistivity of the sample, HF concentration in electrolyte, sample orientation, current density and etching time [7,8]. Among these, the etching current density is a critical parameter to control the formation of porous silicon [9,10]. This property can influence the electrical and optical properties of porous silicon [11].

Porous silicon multilayers can be prepared by a stack of alternate pSi layers that are etched with different current densities. Porous silicon multilayer structures are frequently used as thin film filters such as long wave pass filters, short wave pass filters, or just simple high reflectance mirrors [12–14]. In particular, pSi multilayers attained much attention for the fabrication of DBR structures because the refractive index and thickness of the layers can be altered by changing the etching parameters during etching process [15]. The refractive index of the etched layer mainly depends on its porosity, i.e. number of voids present in the surface and pSi layer thickness. When visible light is incident on the surface of a DBR, wavelengths are reflected at successive boundaries throughout the assembly and reappear at the surface all in phase, as described in Fig. 1. A porous Si based DBR structure can reflect a range of wavelengths $\Delta\lambda$ that is designed on the basis of reflected central wavelength λ. The combination of layer thickness d and refractive index n of each layer within the stack gives an optical thickness nd which should be equal to $\lambda/4$. By controlling the thickness and refractive index of each layer, it is possible to design DBR structures with different central resonant wavelengths [15].

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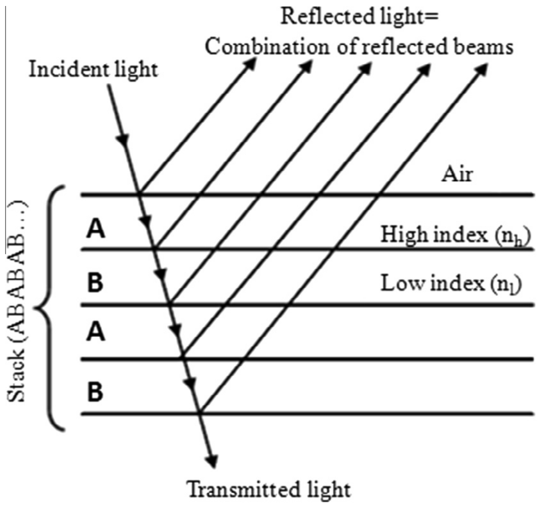

Fig. 1. Porous silicon multilayers having successive high and low refractive indices.

The reflectivity (R) can be estimated mathematically by using transfer matrix approach [16], and is given by

$$R = \left[\frac{\left(\frac{n_h}{n_l}\right)^{2N} - 1}{\left(\frac{n_h}{n_l}\right)^{2N} + 1} \right]^2 \quad (1)$$

where n_h, n_l are high and lower refractive index of the bilayers (layers A and B as shown in Fig. 1) respectively and N is the total number of bilayers with high–low refractive indies.

The stop band ($\Delta\lambda$) and central resonant wavelength (λ) of DBR structure are related to the layer's refractive indices [17] used and are given by

$$\frac{\Delta\lambda}{\lambda} \approx \frac{2}{\pi}\frac{\Delta n}{n_a} \quad (2)$$

where, $n_a = \frac{(n_h+n_l)}{2}$, $\Delta n = n_h - n_l$

The intensity of reflected light and the width of the stop band can be altered by varying the number of periods and the ratio of layer refractive indices within the stack. As the ratio of refractive indices of the bilayers (n_h/n_l) increases, the stop band width can increase. By extending this, one can fabricate an optical microcavity by simply sandwiching a spacer layer (where the optical thickness $nd = \lambda/2$ or λ) between two DBRs. The introduction of this spacer layer will simply allow narrow transmission at λ while reflecting all other wavelengths [18]. This design could be used for light propagation with a mono energetic wavelength for optical communications.

Ion/gamma irradiation and subsequent anodization of silicon can be a very efficient method to fabricate tunable distributed Bragg reflectors without changing the layer parameters [4,18]. In particular, by ion irradiation one can achieve spatial selectivity and accuracy that could be used to change the structural and optical properties of the material [19,20]. However, the importance of gamma irradiation is to create low density of defects throughout the sample, which is distinctly different from high density of localized defects produced by ion irradiation. These defects can collectively increase the total resistivity of the sample. The resistivity change induced by gamma irradiation is more prominent as compared to that induced by single energy ion irradiation of equivalent fluence. These changes can reduce the flow rate of electric holes through the irradiated regions during anodic etching [21–24]. Hence, it results in the change in structural and optical properties of the pSi layers.

Table 1
Estimated refractive index (n) and surface roughness (RMS) of pSi prepared at different etching current densities.

Layer label	Etching current density J (mA/cm^2)	Estimated etching rate (nm/min)	Estimated refractive index (n) [4]	Estimated RMS roughness (nm)
A	5	420	2.75 (n_h)	0.781
B	45	1320	1.65 (n_l)	1.992

Table 2
Gamma irradiation induced atomic displacements in Si and its equivalent ion fluence.

Gamma irradiation dose (kGy)	Estimated No. of displacements/cm^2	Equivalent ion fluence Ag$^+$/cm^2
1	8.04×10^{10}	1.78×10^{7}
6	4.82×10^{11}	1.06×10^{8}
12	9.65×10^{11}	2.14×10^{8}
24	1.93×10^{12}	4.28×10^{8}
48	3.86×10^{12}	8.57×10^{8}
60	4.82×10^{12}	1.07×10^{9}

Table 3
Ion irradiation induced atomic displacements on Si and its equivalent absorption dose (gamma).

Ion irradiation fluence Ag$^+$/cm^2	Estimated No. of displacements/cm^2 within the DBR region (up to ~6 μm)	Equivalent absorption dose (kGy)
2×10^{11}	9.01×10^{14}	1.12×10^{4}
1×10^{12}	4.51×10^{15}	5.60×10^{4}
2×10^{12}	9.01×10^{15}	1.12×10^{5}
1×10^{13}	4.51×10^{16}	5.60×10^{5}
2×10^{13}	9.01×10^{16}	1.12×10^{6}

This paper presents a detailed comparative study on the effects of gamma and ion radiation induced defects in silicon on the subsequent formation of porous silicon based DBRs. To the best of our knowledge, there are no previous reports on the gamma irradiation of Si and subsequent formation of porous silicon based DBRs. This study provides useful information for fabricating tunable wave reflectors for optical communication and other device applications.

2. Experimental

Porous silicon multilayers have been synthesized to design distributed Bragg reflectors. p-type, mirror-polished (boron doped), 2×2 cm^2 Si (100) samples with resistivity <0.005 Ω-cm were anodically etched with two alternate current densities viz. 5 and 45 mA/cm^2 to fabricate variable refractive index layers, labeled as A & B in Fig. 1 and Table 1. The electrolytic solution for the anodization was made with volumetric ratio of 1:1:2::HF:H_2O:Ethanol. The mixing of ethanol in electrolyte is helpful to improve the lateral homogeneity and the uniformity of the porous silicon layer by promoting the hydrogen bubble formation. The thickness d of a single porous silicon layer can be obtained by using the optical thickness and wavelength relation, which is given by [18]

$$n_h d_h = \frac{\lambda}{4} = n_l d_l \quad (3)$$

$$d_h = \frac{\lambda}{4n_h}, \quad d_l = \frac{\lambda}{4n_l} \quad (4)$$

By using estimated thickness (d) of the layer and with the knowledge of etching rate, one can determine the required etching time (t) as follows