

Optical Sensing of Ethanol using Porous Silicon Photonic Bandgap Microcavity Structure

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Abstract: The present paper reports the feasibility and study of one dimension porous silicon (PS) based photonic bandgap (PBG) microcavity structure for an optical sensing of ethanol. 1D-PSPBG microcavity was fabricated by electrochemical etching process. The reflectance measurement of the 1D-PSPBG microcavity was performed for different concentrations of ethanol. The photonic resonance wavelength of microcavity shows the significant red shift after capillary adsorption because the structure refractive index changes after infiltration of the pores of the microcavity structure. The resonance wavelength shift showed a linear relationship with the different concentrations of ethanol. Also, we observe the ability of reversible sensing by 1D-PSPBG microcavity structures.

Keywords: Photonic Band gap Structures; Porous silicon; Microcavity; Ethanol Sensor; Anodization

1. Introduction

Photonic bandgap (PBG) structures are periodic dielectric structures that control the propagation of electromagnetic wave through the photonic crystal. In recent years, PS is emerged as a promising nano PBG structure due to tremendous advantages. 1D-PSPBG is fabricated from crystalline material silicon. 1D-PSPBG consists of nanometer to micron-sized columnar pores in a silicon matrix. Due to the unique electrical and optical characteristics, 1D-PSPBG has attracted great attention of scientists in the recent years^{1, 2}. PS is an easily fabricated device that has extremely high surface area to volume ratio, making it an ideal platform for optical devices and sensing applications.

Many groups all over the world have been working in the research to develop nano-optical devices and sensors using 1D-PSPBG for the future applications because its optical properties (PL, transmittance and reflectance) are highly sensitive³ to the presence of chemical and biological species inside the pores. Several groups have reported the applications of 1D-PSPBG nanostructures in the optical devices and sensing applications like, chemical, biochemical, solar cell, humidity, different gases, DNA biosensor and other emerging and future nanotechnology applications³⁻⁹.

In the present work, we proposed the feasibility of 1D-PSPBG microcavity structure to use it in potential sensing applications. In section 2, the experimental details for the fabrication of 1D-PSPBG microcavity samples are presented. In section 3, sensing of ethanol for the different concentration by wavelength shift in the reflectance spectra for the prepared samples is analyzed and discussed.

2. Experimental

1D- PSPBG microcavity structure was fabricated by electrochemical etching of p-type (boron doped) Si wafer (<100>, 0.01- 0.02 ohm-cm, 275 μm , 20 cm^2). The schematic diagram of the electrochemical etching cell is shown in Fig.1.

Before electrochemical etching, silicon substrate was cleaned by piranha cleaning method to remove the organic compounds and other contaminations of the wafer surface. The rough surface of silicon wafer was used as anode and platinum grid was used as anode. For electrochemical etching, solution of 40% aqueous HF and 99% aqueous ethanol in the ratio of 1:2 was used. The silicon wafer was then immersed in Teflon bath containing etching solution. A constant current mode was used for anodization process as it is beneficial in terms of regulation. For this purpose DC power supply (PWS 4305, Tektronix) of the rating 0-5 Amp, 0-30 V DC was used. The cathode was immersed in the electrolyte solution and the distance between anode and cathode was kept about 4.5 cm. Experimental conditions for the anodic etching were varied in the range of current density 5-140 mA/cm^2 . After electrochemical etching, the 1D-PSPBG microcavity samples were rinsed in DI water for 10 minutes and then dried at room temperature. The reflectance spectra of the prepared samples were measured before and after exposure to different concentrations of ethanol using an Ocean Optics MayaPro-2000 spectrometer. All measurements were done in air and the polished silicon wafer was used as reference.

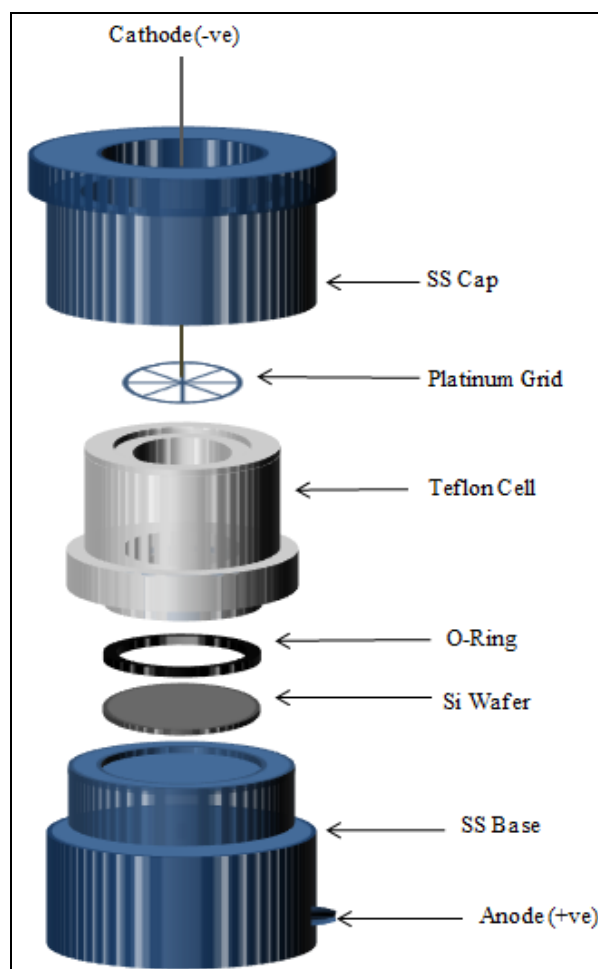


Fig. 1. Schematic Diagram of Electrochemical Etching Cell

3. Results and Discussion

Different samples were prepared with fixed electrolytes concentration. The prepared samples show distinct colour distribution over the entire surface of the structure (Fig. 2). Porous structure in the bulk silicon is strongly responsible for the change in the colour due to the shifting in the band gap energy of bulk silicon.

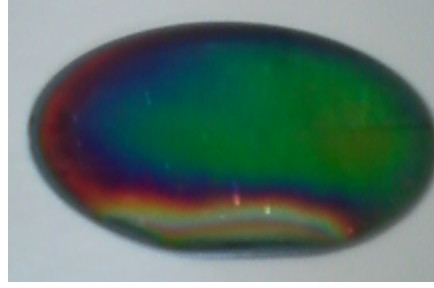


Fig. 2: Fabricated 1D-PSPBG Microcavity

The reflectance spectrum of the fresh 1D-PSPBG Microcavity device (immediately after anodization) shows high reflectance region i.e. a photonic band gap in the region of 650 to 850 nm (Fig. 3), the cavity response of device promoted a low reflectance band situated into the PBG region and centred at 700 nm, this band will be referred as resonance cavity response in the next part of the work. It is important to mention that the effective refractive index of the each layers are composed by silicon and air (pores) composites which could be calculated by the effective medium approximation (EMA) Bruggeman model.

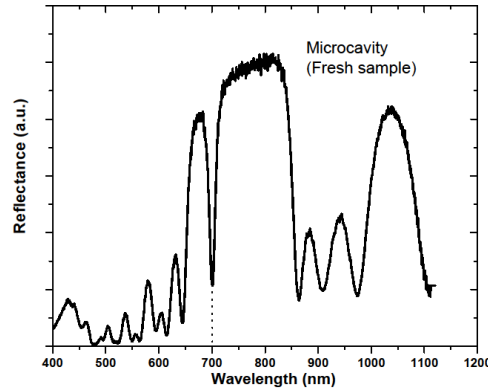


Fig.3. Reflectance Spectra of Fresh Microcavity Sample

We notice the presence of small peaks near 450 nm (Fig. 3); this is due to the refractive index dispersion at high energies. The reason behind this might be the absorption of porous silicon structures at that wavelength since the refractive index is not constant at that energy range⁵.

Variation in the reflectance spectra of the samples during their exposure to different concentrations of ethanol solutions is shown in the Fig. 4.

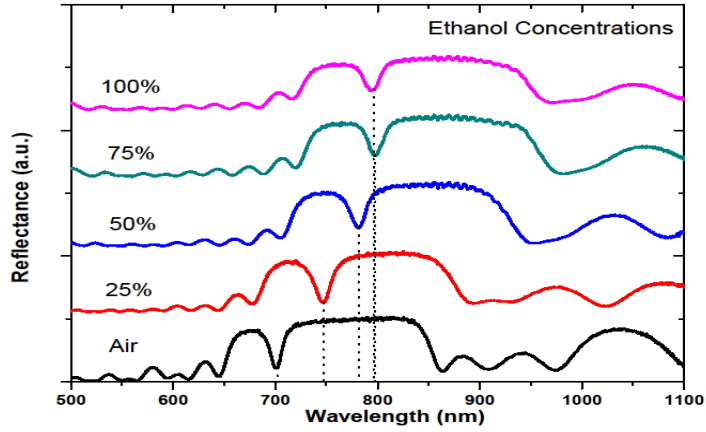


Fig. 4. Wavelength Shift in the Reflectance Spectra Microcavity Sample before and after Ethanol Adsorption

During this exposure, the PBG and resonant cavity band were shifted toward the low energy region. This can be explained as the substitution of the air in the pores by the ethanol leads to increase of effective refractive index of layers and consequently increasing optical thickness. As the thickness of each porous silicon layer is fixed, the shift in the reflectance of spectra can only be due to changes in the average refractive indices of the porous silicon layer. This effect promotes the red shift of resonant cavity band (Fig. 4). The strength of the red-shift effect would be depended on the concentration value of the ethanol which is listed in Table 1 from the reflectance spectra.

Table 1: Red Shift in Reflectance Spectra for different Concentration of Ethanol

Ethanol Concentration	Wavelength Shift $\Delta\lambda$ (nm)
25%	46
50%	80
75%	98
100%	98

The sensor response of the device was evaluated throughout the change of the wavelength shift, this parameter showed to be a good indicator for sensing measurement in the 1D-PSPBG devices. Figure 5 and Table 1 presents the relationship between ethanol concentration and the position of the wavelength shift.

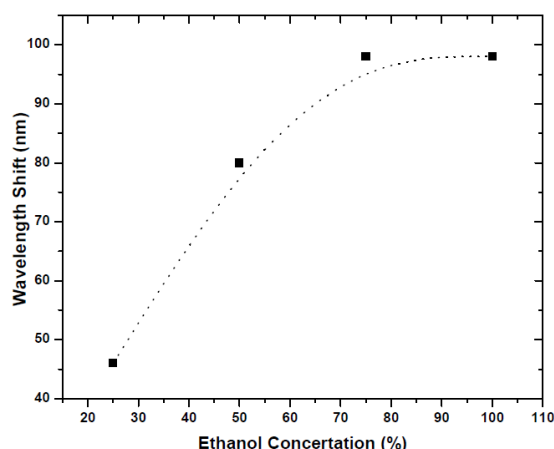


Fig. 5. Wavelength Shift vs. Ethanol Concentration

The Fig.5 showed the good linear fitting of the wavelength shift versus ethanol concentration values up to 75% concentration. This is due to the change in the refractive index of the ethanol for the different concentration and hence the variations in the effective refractive index of the porous structure with change in the concentration. We observed that, as the ethanol concentration increases, above 75% the wavelength shift in the reflectance is constant. The reason behind this may be that at the higher concentration the effective refractive index of the ethanol is almost same and due to that the effective refractive index change in the porous structure is constant which results in the constant wavelength shift at higher concentration.

It is important to mention that the 1D-PSPBG microcavity device showed reproducible behaviour for various measurements cycle. It is also observed that, after the removal of the ethanol by natural evaporation, the reflectance spectra of the sample promptly returned to their original state. This implies that the change in reflectance spectra is indicative of the presence or absence of ethanol in the pores and that the change in the spectra of the 1D-PSPBG structure is temporary. These results are due to chemical stability of surface area of the PS layers in the device. These results are very much useful for the development of effective reversible 1D-PSPBG based organic solvent sensors.

4. Conclusion

A 1D-PSPBG microcavity structure was fabricated by electrochemical etching process. It is shown that microcavity structure can be used as a chemical sensor for detecting different concentrations of ethanol. The reflectance spectra and resonance cavity band of this structure showed to be

suitable for organic chemical detection as their shift is directly in relation with the varied ethanol concentration. Also, we observe the ability of reversible sensing by 1D-PSPBG microvity structures.

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