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Effect of fabrication tolerances in macroporous silicon photonic crystals

D. Segura*, D. Vega, D. Cardador, A. Rodriguez

Micro and Nanotecnologies research group, Electronic Engineering Department (EEL), Universitat Politècnica de Catalunya (UPC), c/Jordi Girona, 1–3, 08034, Barcelona, Spain

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ABSTRACT

Macroporous silicon photonic crystals show a great potential for a range of applications such as optical sensing or signal processing. These applications require tight fabrication tolerances. In particular, the effect of process variability in 3-d photonic crystals and out of plane propagation has been seldom studied in literature. In this paper we report the effect fabrication imperfections on the spectral response of macroporous silicon photonic crystals. To quantify fabrication disorder and its influence, several 3-d macroporous silicon structures were fabricated consisting of modulated pores arranged in a square lattice. The pore modulation is similar to a stretched sinusoidal waveform. Lattice pitch is 700 nm, pore diameter is in the range from 250 nm to 520 nm, and modulation period is 1.2 μm. The samples were characterized by SEM inspection and the actual etched pore profiles extracted. The statistical analysis of the profiles reveals two main sources of randomness: radius variability and modulation period irregularity. Surface roughness and asymmetry do not seem to play a major role. Several FDTD simulations have been performed based on the statistical parameters extracted, and the results are compared to actual FT-IR measurements of the fabricated samples. The obtained results show that, in general, the dispersion in *z* period has the most severe effect in the structure's optical response.

1. Introduction

Photonic crystals (PhCs) are periodical structures which offer unique optical features [1]. PhCs can be used in a broad range of applications such high quality factor (Q-factor) optical filters [2], signal guiding and routing [3], lasers [4], bio sensing [5], waveguides [6] or gas sensors [7]. The periodic arrangement of high and low refractive index materials in a PhC forbids light at certain wavelengths from propagating through the photonic structure, thus giving rise to photonic bandgaps (PBG). The photonic structure therefore will have a characteristic optical spectrum which can be engineered to meet the application needs.

For optical applications, tight tolerances are necessary in order to achieve good photonic response of the devices. In particular, disorder in the dielectric spatial disposition will break the propagating light's coherence, scattering light and smoothing the optical response of the structure. This results in a loss of performance as light will leak at undesired wavelengths.

PhCs may be in one-, two- or three-dimensional (1-, 2-, 3-d) in regards to the spatial dielectric arrangement [8]. For each of these types there are different fabrication methods which introduce variability in certain ways. In particular, this work is concerned about 3-d PhCs made of macroporous silicon (MPS) fabricated using the electrochemical etching (EE) technique. Using this method, silicon can be locally dissolved to create holes or pillars. Furthermore, the EE of silicon allows controlling the shape of the pores by changing the etching parameters such as current or potential. The process has been described in detail elsewhere [9–11]. Fabrication of macroporous silicon PhCs with EE present the advantages of repeatability, reduced costs and high throughput. In this work the fabricated structures consist in pores of circular cross-section and modulated with a stretched sinusoidal waveform.

Most of the works studying the effect of fabrication tolerances on light propagation in PhCs deals with 1-d and 2-d structures. For example, scattering losses due to disorder have been extensively studied for PhC waveguides [12–14]. More general studies looking into propagation of 2-d PhCs are those by Asatryan [15,16], Wang [17], and the review by Melati [18]. Also the effect of disorder in defect cavity resonators, such as Q-factor or wavelength shift, has

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* Corresponding author.
E-mail addresses: daniel.segura.garcia@upc.edu (D. Segura), didac.vega@upc.edu (D. Vega), david.cardador@upc.edu (D. Cardador), angel.rodriguez@upc.edu (A. Rodriguez).

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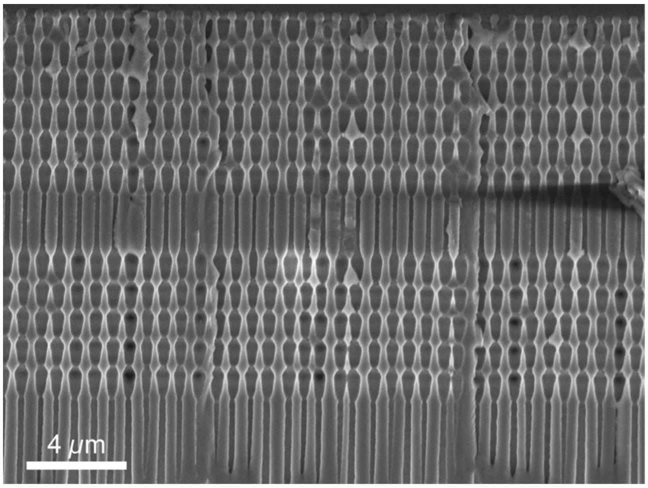

Fig. 1. SEM view of a section of a fabricated MPS silicon structure. The PhC consist of modulated pores with a defect in the middle. Some shape irregularities due to fabrication imperfections can be seen with the naked eye.

also been examined [17,19,20]. However, for 3-d PhCs, research in disorder effect is scarcer. For example in [21], the effect of fabrication tolerance is qualitatively commented. In [22] the control of disorder in self-assembled colloidal PhCs is assessed. Finally in [23] the fabrication deviations from a perfect spherical shape to other "spherical shapes" is investigated in electrochemically etched MPS. However, the authors do not analyse the consequences of period fluctuations. The general consensus is that PhCs tolerate a small amount of perturbation, but it is very application specific how large it can be.

This work is mainly concerned about the effect of fabrication tolerances in the PBG of 3-d PhCs fabricated using the EE method. In particular, the variance in the profile modulation period and amplitude along the pore depth is studied. The considered photonic structures are intended to be used as optical filters or selective thermal emitters for gas sensing applications [9,24]. We are mainly interested in the change of the PBG, the shift in the cavity resonant frequency and Q-factor. In this paper MPS samples have been fabricated and characterized to obtain the fabrication tolerances; the statistical models built are used to quantify the introduced error by comparison of simulations to FTIR measurements of the built samples. Here we report on our findings on the effect of fluctuations in modulation period.

2. Fabrication

Several macroporous silicon samples dedicated to gas sensing applications were fabricated. These structures are to be used with light incident at normal or shallow angles, that is, with light parallel to the pores' axis. Therefore, the created PhC needs to be modulated in depth, resulting in a 3-d crystal [9,24]. To fabricate such structures EE is one of the most versatile methods to obtain three dimensional MPS. This method is thoroughly described elsewhere [10,11] and a brief summary will be given here. The substrates used where n-type, 100 oriented silicon wafers of the appropriate resistivity (about 0.3 Ω cm). Etched pores are arranged in an ordered fashion. For this, the initial pore pattern, a square lattice with a 700 nm pitch, is transferred by nanoimprint lithography (NIL) to the substrate. Afterwards, the nucleation points for pores are created by an alkaline anisotropic etch of silicon. With the samples so prepared, they are etched by EE. This method uses hydrofluoric (HF) acid to dissolve silicon, for which holes are needed. Following the method described in [10], the substrate is illuminated from the backside to generate the desired hole current. By modulating the photocurrent, it is possible to change the pore diameter along its depth, and thus fabricate 3-d PhCs. Applied potential and temperature may also be adjusted to achieve fine-grained control of the etching process. The etched pores have cylindrical or quasi-cylindrical cross-section.

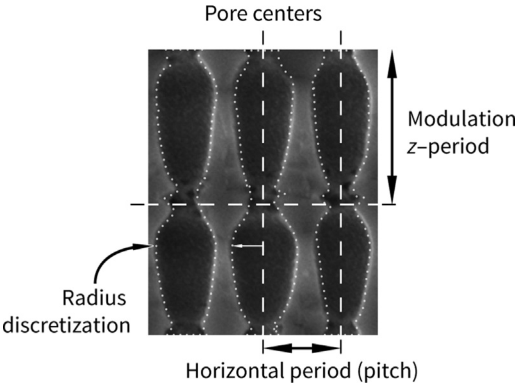

Fig. 2. Scheme of the studied geometrical properties of the modulations.

The fabricated samples consist of modulated pores with a stretched sinusoidal profile with a z period of 1.2 μm, and pore radius between 250 nm and 520 nm. There are a total of 11 modulations in the defined pore profile. The structures furthermore have an embedded defect in the PhC to create a resonant state. This defect consists on a span of a constant diameter inserted at the middle of the crystal. The radius of the defect is of 250 nm and the length is of 2.4 μm. After the modulated profile, a further straight section of several microns in length is also added for structural reasons. An example of the fabricated MPS structures is shown in Fig. 1.

An additional sample of only five modulations with the same profile as above (ending before the defect) was fabricated under the same etching conditions. This sample was used to validate the extracted statistical parameters and model.

2.1. Causes of sample variability

In the electrochemical etching of silicon several sources of error can be found to cause deviations of the desired shape during the fabrication process. In one hand, there are the intrinsic uncertainties due to the material and the etching solution. For instance, the silicon substrate may show certain doping level variation from wafer to wafer even for wafers cut from the same ingot. This effect is also present in a smaller scale, such that doping concentration gradients may be found on a same wafer. This irregularity of doping level will cause local changes in etching speed as detailed in [25]. Other intrinsic causes due to the material are the presence of impurities or crystalline defects that may act as recombination centres [26]. These centres will affect the carrier current flow, therefore diminishing the number of holes that reach the electrolyte-silicon interface locally at certain spots. This reduction in current will alter the radius of the affected pores making them narrower. This local unbalance may cause a pore to end prematurely (pore death) or the adjacent pores to grow wider (current crowding). These factors are difficult to control, and to the best of our knowledge, the only solution is to use better quality (usually more expensive) wafers. Regarding the electrolyte, the fluoride concentration $\left[F^-\right]$ and other species in the solution may vary due to aging (volume of silicon etched, storage time, evaporation, etc.) which will affect the etching speed. Also the presence of contaminants can also alter the rate of oxidation of the semiconductor. However, silicon dissolution is not so sensitive to changes in $\left[F^-\right]$. Employed solutions are to renew the etching bath after a certain number of days orcertain volume of etched silicon, and bubbling the electrolyte with N_2.