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Nanofabrication of photonic crystal slabs with sealed airholes for optofluidic applications

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ABSTRACT

Suspended 2D Si photonic crystal (PhC) slabs with a 260 nm triangular lattice and 160 nm-diameter airholes were fabricated on a silicon-on-oxide (SOI) substrate using optimized nanolithography and etching processes. Precise PhC pattern transfer from a negative e-beam resist to Ni by liftoff and to Si by plasma etching was achieved. Subsequent wet etch of the underlying SiO_2 led to the formation of suspended PhC slabs. The PhC slab was further capped with a SiO_2 layer deposited by a two-step glancing angle deposition (GLAD) process. Inverted nanotips were formed during GLAD with an exponentially varying flux angle, and coalesced into a continuous film at a thickness of ~260 nm, completely sealing the PhC airholes. The fabricated PhC slabs may be used as the building block for various integrated optofluidics and photonics with enhanced capability for light detection or emission.

1. Introduction

Photonic crystals (PhCs) have many unique optical properties which open up a new way for manipulation and control of light in both passive and active photonic devices [1–14]. For example, the photonic band gaps of PhCs prohibit the propagation of light with photon energies within the band gaps, leading to efficient optical confinement or waveguilding [3,4]. PhCs can change the density of states (DOS) of radiative modes, and thus modify the spontaneous emission properties of light-emitting sources [5–7]. Defects in PhCs are natural resonators with a high quality factor and a small mode volume, serving as nanocavities which may be used to develop ultralow-threshold lasers and high-sensitivity sensors [8–12]. Two-dimensional (2D) PhC slabs with a finite thickness in the vertical direction retain many of these desirable properties of 3D PhCs, but can be more easily fabricated using existing nanofabrication techniques. Therefore, they have been proposed to form the basic platform of many novel integrated optical devices [7–14]. In particular, integrating PhCs or PhC nanocavities with microfluidics would form unique optofluidics, which combine the advantages of microfluidics and nanophotonics [15], and provide an enabling technology for biomolecule analysis, sensing and imaging [12].

To integrate PhCs with a microfluidic channel, the PhC airholes must be sealed to prevent perturbation to the PhCs by fluids. A PhC structure with embedded airholes was recently constructed by lateral epitaxial overgrowth of a capping layer [14]. However, the technique can only be applied to some special materials like (0001) GaN whose growth proceeds much faster in the lateral direction than that in the vertical direction. Deposition of such a capping layer using a generally applicable microfabrication technique would be desirable but has not been reported. Here we propose a unique approach to seal the PhC airholes, i.e., using a thin dielectric capping film formed by glancing angle deposition (GLAD). GLAD has mainly been used to grow porous materials with lower refractive indicies than bulk materials [16–19]. The porous growth is enabled by the self-shadowing effect magnified by the oblique flux angle used during the deposition process. Initial nucleation on surface features with larger heights produces a shadow region that the incident vapor flux cannot reach and a non-shadow region where material deposits preferentially, therefore creating isolated nanopillars which form a film with a high porosity and a low refractive index. It has been proven that a wide range of variations of film microstructure, porosity, and refractive index can be achieved by tailoring the nanopillar shape and dimensions [16,17]. If the nanopillars are deposited atop the PhC slab and tailored to have a gradually increasing diameter, they may eventually merge into a continuous capping layer.

In this work, 2D PhCs are fabricated in a Si-on-oxide (SOI) substrate using optimized nanolithography and pattern transfer techniques. Subsequent wet etch of SiO_2 is conducted to produce suspended 2D PhC slabs. The PhC airholes are then sealed with a SiO_2 layer deposited by a modified two-step GLAD process. Such a capped PhC slab can be integrated with microfluidic channels

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to form integrated optofluidics for various biochemical applications.

2. Material and methods

The fabrication of SiO_2-capped PhC slabs was divided into two major steps: PhC fabrication and SiO_2 cap deposition. The process flow is schematically shown in Fig.1. In the first step, 2D PhCs with a triangular array of airholes were fabricated on a commercial SOI wafer which had a 260 nm top Si (100) layer and a 1 μm buried SiO_2 layer. A triangular PhC lattice pattern with a lattice constant of ~260 nm and an airhole diameter of 160 nm was first created in a thin resist layer by lithography on a JEOL scanning electron microscope equipped with a Nabity e-beam lithography system. The pattern was then transferred to an evaporation-deposited Ni hard mask using etch back or lift-off. For etch back, a positive polymethyl methacrylate (PMMA) resist was spin-coated atop the Ni layer, whereas in the case of lift-off, a negative ma-N 2403 resist was spin-coated and patterned before Ni depsoition. The PhC pattern was further transferred from the Ni mask into the SOI substrate using CF_4/O_2 plasma etching of Si. Finally, suspended PhC slabs with a size of 20×100 μm were formed by etching the underlying SiO_2 layer using diluted HF through the airholes. PhC nanocavity slabs can be fabricated using similar process procedure with small modifications. For example, in this work, we also fabricated a H1 defect nanocavity by creating a triangular lattice pattern with one enlarged airhole in the initial e-beam lithography step.

In the second step, the samples were loaded into a BJD2000 TEMESCAL e-beam evaporation system, where a SiO_2 capping layer was deposited by GLAD. The system is equipped with a specialized sample mounting fixture designed for GLAD and attached to the regular planetary substrate holder. The fixture has a 150 mm single substrate holder and a PC-controlled stepper motor which precisely controls the substrate rotation. SiO_2 was deposited from a SiO_2 source by oxygen ion beam assisted deposition at a pressure of $\sim 1.5 \times 10^{-4}$ Torr. The oxygen flow was set at 20 sccm and the ion source current was 1.3 A. The incident flux angle θ, defined as the angle between the normal to the wafer surface and incident vapor flux was varied from 0 to ~80°. Critical processing parameters, including the flux angle, deposition rate, and substrate rotating speed, were systematically tuned to achieve a thin uniform capping layer which completely seals the PhC airholes. At different stages of the fabrication process, the top view and/or cross-sectional view of the PhC slabs were examined by scanning electron microscopy (SEM).

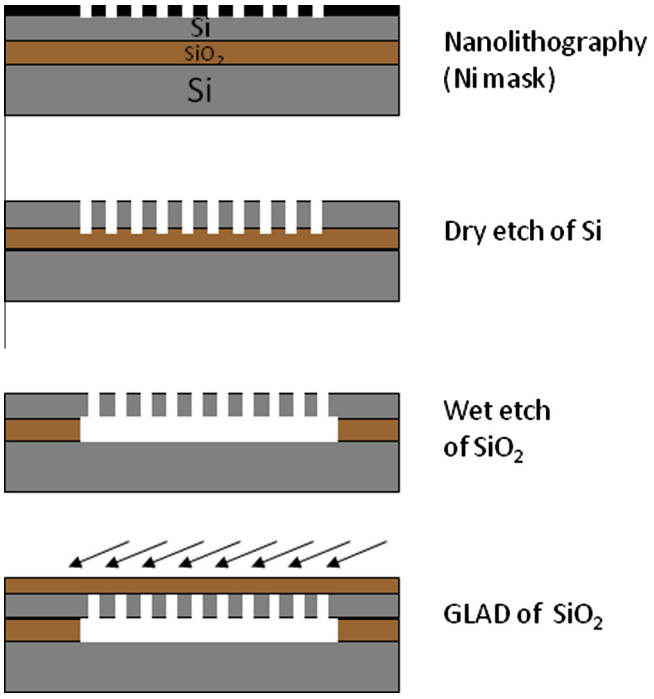

Fig. 1. Process flow of nanofabrication of a SiO_2-capped 2D Si PhC slab on a SOI substrate.

3. Results and discussion

The hard mask plays a critical role in PhC fabrication as it determines the quality of the nanoscale pattern transfer. Compared to dielectric materials such as SiO_2 and SiN_x, metals like Ni and Cr have a much higher resistance to typical Si etching chemistries. Ni has proven to be a better hard mask because it does not cause sputtering as Cr does during plasma etching of Si. Under a typical etching condition in CF_4/O_2 plasma, the Si/Ni etch selectivity was found to be ~50:1. Thus, a 6 nm Ni hard mask can be used to etch ~260 nm-deep Si holes. However, due to the poor selectivity of PMMA over Ni under both chlorine plasma etching and Ar plasma bombardment, pattern transfer from the PMMA resist into a thin Ni layer using the etch back technique was found to be a significant challenge. Pattern transfer using a negative e-beam resist and metal lift-off was then developed. Fig. 2(a) shows the image of a PhC pattern comprising a nano-post array formed in a ~90 nm ma-N 2401 resist. Fig. 2(b) illustrates the top view of a Si PhC nanocavity structure fabricated using this pattern transfer process, which is further described as follows. After e-beam writing of the PhC nanocavity pattern which has a lattice constant of 260 nm, an airhole diameter of 160 nm, and a defect size of 275, ~30 nm Ni was deposited at a rate of 0.2 Å/s using e-beam evaporation. The wafer was then dip into acetone for lift-off, leaving patterned Ni on the Si surface, which acted as a mask during the subsequent etching. The PhC pattern was further transferred into Si by inductively-coupled plasma (ICP) etching using a CF_4/O_2 gas mixture with 18/2 sccm flow rates, 10 mTorr pressure, 400 W ICP power, and 150 W chuck power. The Si etch rate was ~50 Å/s. Airholes with nearly vertical sidewalls penetrating the top Si layer were created. Finally, the remaining Ni mask was removed by wet etching in a Ni etchant solution. The sizes of the airholes and defect were found to be within ±5% of the target values. To form suspended PhC slabs, the sample was merged in a diluted HF solution for 30 s to remove SiO_2 underneath. The image of one resulting suspended PhC slab is illustrated in Fig. 2(c).

The goal of the GLAD step is to deposit a uniform and stable SiO_2 capping layer which completely seals the PhC airholes while minimizing the amount of material deposited inside the airholes. Simulations showed that even a small amount of material extending into the airholes represents a perturbation and has an influence on the photonic band structure of the PhC slab. During typical GLAD with a constant flux angle θ under conditions of limited adatom diffusion, oblique angle flux incidence enhances atomic shadowing and the material is deposited preferentially in non-shadow regions, therefore creating a columnar structure with nanopillars inclined toward the vapor source. By rotating the substrate at a constant speed ω about the axis perpendicular to its surface, vertical nanopillars can be grown as rotation eliminates in-plane anisotropy [17]. However, these regular GLAD processes will not produce a continuous capping layer on top of PhC structures.

To seal the PhC airholes, the nanopillar array must evolve into a continuous film. This is possible if we can tailor the shape and size of the nanopillars on a nanometer scale and convert them into