Fabrication and Characterization of 3D Square Spiral Photonic Crystals

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ABSTRACT

Photonic crystals have demonstrated potential for application in many fields and devices. We demonstrate practical fabrication of three-dimensional photonic crystals using the glancing angle deposition thin film fabrication technique. Optical characterization provides strong evidence for the existence of a complete photonic band gap in three dimensions, centered at 1.6 μm. We also investigate the fabrication of a two- and three-dimensional photonic crystal heterostructure with potential for application in low-loss waveguiding.

Keywords: Photonic Crystal, Photonic Bandgap, Glancing Angle Deposition.

1 INTRODUCTION

Photonic crystals are dielectric materials with a spatial periodicity on the optical wavelength scale. Certain geometries facilitate multiple interference between scattered waves that cause a photonic band gap (PBG) to exist, prohibiting a range of electromagnetic frequencies from propagating inside the crystal [1, 2]. Consequently, photons can be confined to defect states, enabling control over the flow of light in profound ways. The ability to localize light makes PBG materials promising candidates for many applications, including integrated optical networks constructed from a variety of passive optical circuitry and active photonic devices [3]. Furthermore, localization of light using PBG materials is predicted to provide unprecedented microscopic control over the creation of light by means of spontaneous emission.

Economic fabrication of three-dimensional crystals exhibiting a robust PBG has proven to be a difficult feat. Many structures, including the wood-pile configuration [4] and Yablonovite [5], require significant processing effort. Others, including the inverse opal configuration [6] and the 2D slab structure [7], yield weak or leaky PBGs.

The square spiral PBG architecture proposed by O. Toader and S. John [8] holds promise for overcoming many of the obstacles impeding the development of practical PBG crystal fabrication. Robust PBGs as large as 16% and 24% have been predicted for the silicon square spiral architecture and the inverted structure composed of air spirals in silicon, respectively [9].

Utilizing the glancing angle deposition (GLAD) thin film fabrication technique, silicon square spiral PBG crystals have previously been fabricated [10] and optically characterized [11]. Reflectance spectra provided evidence of a PBG centered at 2.7 μm, although confirmation of a *complete* band gap in all directions was not provided.

Toward the application of integrated optical networks, A. Chutinan and S. John recently proposed a waveguiding architecture that utilizes a unique 2D-3D PBG heterostructure [12]. The heterostructure is constructed of three vertically stacked layers. The middle layer, in which the waveguide is created, is a two-dimensional PBG crystal made up of vertically-aligned cylindrical posts, similar to other 2D PBG structures [13] used in electromagnetic waveguiding. The bottom and top layers are square spiral 3D PBG structures previously proposed by O. Toader and S. John, later fabricated and optically characterized by S. Kennedy [10, 11].

In this paper, we investigate scaling down the dimensions of the square spiral structure to produce a PBG near the coveted telecommunications wavelengths (1.3 μm and 1.5 μm) and provide a rigorous optical analysis of films produced using the GLAD fabrication technique. We also investigate the fabrication of a 2D-3D PBG heterostructure as a step toward creation of the proposed optical microchip architecture.

2 GLANCING ANGLE DEPOSITION

Glancing angle deposition is a thin film fabrication technique that utilizes computer-controlled substrate motion to produce highly porous thin films with an engineered architecture [14]. Thin films deposited via physical vapour deposition (PVD) lose their inherent uniformity and begin to take on a columnar structure when the incident flux angle is tilted towards oblique angles. The use of oblique angle deposition was first reported for optical applications in 1959, with the fabrication of optically active thin films [15]. As an extension of oblique angle deposition, the GLAD technique utilizes highly oblique flux and substrate motion to fabricate very porous structures, enabling the manipulation of several fascinating thin film properties.

The thin films characteristic of GLAD are achieved when the deposition angle α, with respect to the substrate normal, exceeds values of roughly 80°, at which point the film consists of isolated independent columns. If a second degree of freedom is permitted in the motion of the substrate, a variety of thin film structures can be fabricated apart from the simple slanted post structure. A typical GLAD apparatus will employ motion about two principal axes. The first allows for control over the incident flux angle α, while the second allows for control over the substrate rotational angle denoted ϕ, as depicted in Fig. 1.

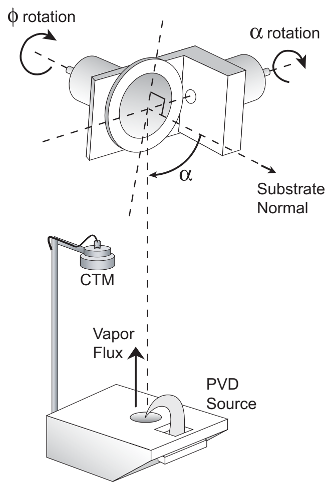


Figure 1: Schematic illustration of the glancing angle deposition apparatus utilizing substrate rotation about two axes.

2.1 Periodic GLAD

Essential for fabrication of materials that exhibit a complete PBG is three-dimensional periodicity. While periodicity in one dimension can be introduced into GLAD films during the deposition process, the randomness of nucleation precludes the realization of three-dimensional spatial ordering. The growth of periodic micro-structures in obliquely deposited thin films [16, 17] has been previously investigated for application as photonic crystals [16, 17] and magnetic microstructures [18, 19]. By providing a pre-patterned topography on the surface of the substrate, the nucleation of incident vapour flux can be confined to specific locations on the substrate [19]. The relief-structure elevation causes regions of the substrate surface to be shadowed from the incident vapour flux and left bare. The growth of individual, isolated columns on each substrate seed can be achieved by matching the planar fill factor of the seeds to the equilibrium volume fill factor of the thin film [17].

3 SUBSTRATE PATTERNING

The geometry and spacing of the underlying seed pattern is a critical component of PBG fabrication using the GLAD technique. A variety of techniques have demonstrated the ability to pattern sub-micrometer seed structures, including laser interferometric lithography [20], embossing techniques [21], electron-beam lithography (EBL) [22], and conventional photolithography. Photolithography presents the distinct economical advantage of high-throughput, inexpensive patterning and has been successfully used for photonic crystal fabrication [10]. However, direct-write lithography provides the significant advantage of easy parameter modification, since no master is required. Laser direct-write lithography (LDL) and electron-beam lithography (EBL) offer distinct advantages over other lithographic techniques [17], and were chosen for this experiment.

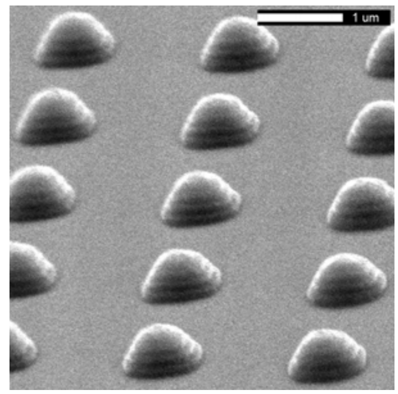


Figure 2: Tetragonal array of substrate seeds fabricated using laser direct-write lithography.

Laser direct-write lithography was performed using a Heidelberg Instruments DWL 200 Direct Write Lithography System, equipped with a 413 nm wavelength krypton ion laser, and with a specified minimum feature size of 0.6 μm. Optimization of the system enabled fabrication of seeds using Clariant AZ-1518 resist with resolutions better than 250 nm over areas as large as 40 mm^2 [17]. Figure 2 shows a scanning electron microscopy (SEM) image of a tetragonal array of resist seeds fabricated with LDL.

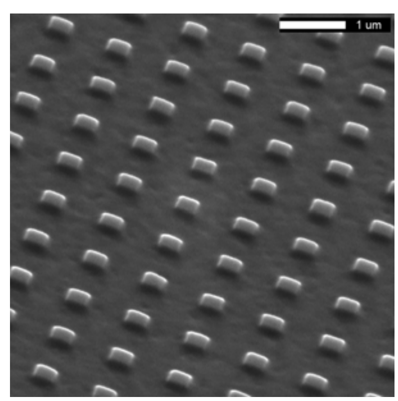


Figure 3: Tetragonal array of substrate seeds fabricated using electron-beam lithography.

Electron beam lithography was performed using a RAITH150 EBL system, equipped with a laser interferometer stage with nanometer scale write-field stitching accuracies, and MicroChem SU-8 2000.1 epoxy novolak negative tone resist. Feature sizes of less than 50 nm have been demonstrated using SU-8 as a negative EBL resist [23]. Figure 3 shows an SEM image of a tetragonal array of resist seeds fabricated with EBL.

4 OPTICAL PROPERTIES

Following the substrate topography patterning, silicon dies were mounted in an electron-beam evaporation chamber at an angle of $\alpha = 85°$ and undoped silicon metal (99.999%, Cerac) was evaporated at rates between 1.0 nm/s and 1.5 nm/s. The evaporation chamber was evacuated to a base pressure of approximately 8×10^{-5} Pa and the deposition pressure did not exceed 3×10^{-4} Pa. The rotational motor controlling the incident flux angle α was held constant throughout the entire deposition, while the rotational motor controlling the azimuthal angle ϕ was rotated through a series of abrupt 90° turns to form the square spiral structure. An SEM image of a square spiral film fabricated using this procedure is shown in Fig. 4.

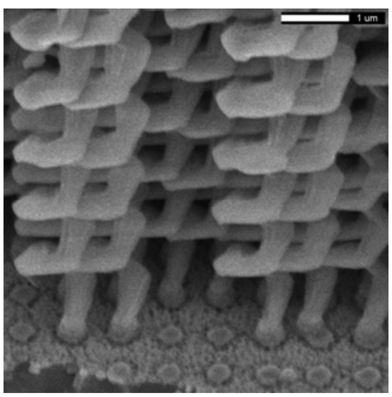
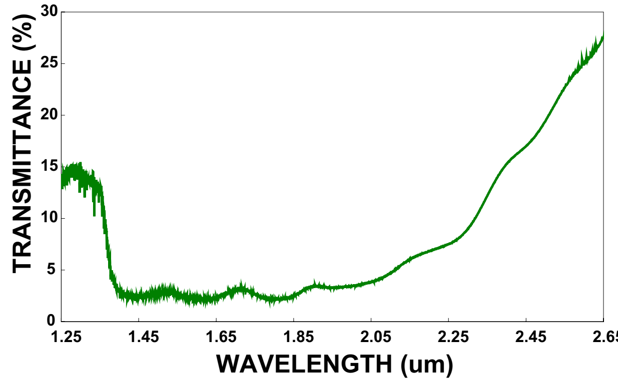


Figure 4: Square spiral film deposited using the glancing angle deposition technique at an incident flux angle of α=85°.

The existence of a complete three-dimensional PBG was investigated using Fourier transform infrared (FTIR) spectroscopy. Reflectance spectra at various angles of incidence and transmittance spectra were obtained with a Thermo Nicolet Nexus 670 FTIR spectrometer, exhibiting a resolution of 1 nm and a beam spot size of approximately 1 mm. Further, the possibility of optical phenomena arising from alternate means, such as the substrate, the seed topography, or the composition material, was investigated using additional reflectance spectra. This investigation included analyzing each constituent material in bulk as well as in various configurations. No evidence was found to support the possibility that any constituent component could account for high reflectance bands in the silicon square spiral GLAD films.



Evidence of a PBG is provided via the transmission spectrum of the square spiral GLAD previously shown in Fig. 5. The spectrum, depicted in Fig. 5, exhibits a low transmittance band over the wavelength range from 1.4 µm to 2.1 µm. This spectral feature was only observed for the periodic, tetragonally arranged silicon square spirals, supporting the supposition of a PBG.

Figure 5: Transmission spectrum of a PBG square spiral thin film.

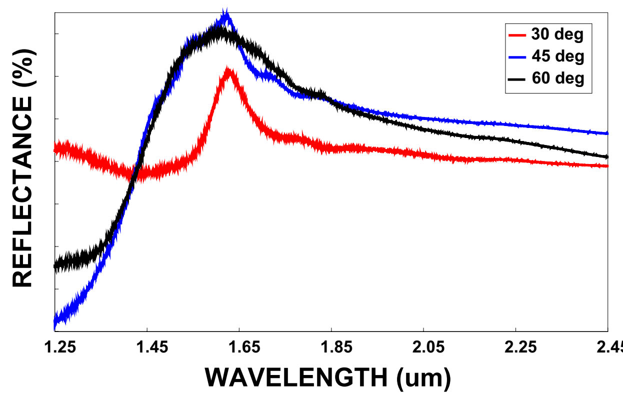


Figure 6: Reflectance spectrum of a PBG square spiral thin film obtained at multiple light-incidence directions.

Evidence of a PBG is further provided via reflectance measurements at various angles of light incidence, as well as various polarizations. Figure 6 depicts the corresponding reflectance spectra obtained from the same square spiral GLAD film, measured at incident light angles of 30°, 45°, and 60°, measured from the substrate normal. Relative reflectance values greater than 100% appear on account of a lower reflectance exhibited by the aperiodic GLAD square spiral film used as a reference.

5 PBG HETEROSTRUCTURES

Fabrication of the 2D-3D PBG heterostructure involved sequential deposition of three layers. Silicon dies were prepared using the same method described in Sec. 3 and deposited under the same conditions described in Sec. 4.

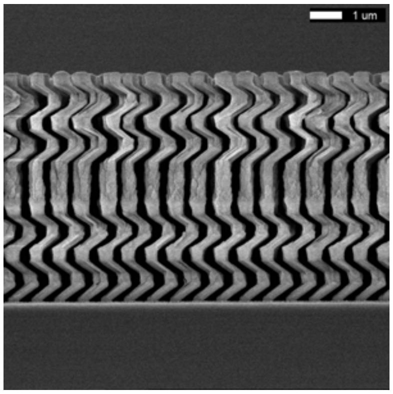


Figure 7: Photonic band gap heterostructure with a 2D photonic crystal layer between to 3D photonic crystal layers.

The bottom and top square spiral layers were fabricated using the recently published PhiSweep method described in Ref. [24], which utilizes periodic oscillations of the ϕ-motor. The PhiSweep method is essential for fabrication of this multi-layer structure to reduce the drastic effects of column broadening and bifurcation. The incident vapour angle, controlled by the α-motor, was held constant at a value of 85° during the entire deposition process. The mid-layer of the heterostructure was fabricated by simply rotating the ϕ-motor at a constant rate such that the columnar structure was prohibited from growing in any particular lateral direction. The individual layers of the fabricated films are distinctly visible, as seen in Fig. 7.

6 CONCLUSIONS

We demonstrated fabrication of a three-dimensional square spiral photonic band gap crystal using the glancing angle deposition technique. We presented and described the use of laser direct-write lithography and electron beam lithography for creating periodically patterned substrates inherent periodicity in the porous, columnar evaporated thin films. The techniques described include laser direct-write lithography and electron beam lithography.

We presented a rigorous optical characterization of the square spiral PBG thin films using Fourier transform infrared spectroscopy. Our investigation included transmittance measurements as well as reflectance measurements at variable angle of incidence and with various polarizations of light. The results obtained provide strong evidence for a complete, three-dimensional photonic band gap centered at approximately 1.6 μm.

Finally, we demonstrate fabrication of a 2D-3D PBG heterostructure as a step toward creation of high-bandwidth optical microchip architectures. The multi-layer heterostructure consists of a vertical post 2D PBG region sandwiched between two square spiral 3D PBG regions. Fabrication of the square spiral section was achieved via the PhiSweep technique, which helps alleviate common problems such as broadening and bifurcation in obliquely deposited thin films.

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