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Fabrication of Tetragonal Square Spiral Photonic Crystals

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ABSTRACT

We present a simple, versatile technique for the fabrication of large, three-dimensional gap photonic crystals using glancing angle deposition (GLAD). A tetragonal lattice suitable for a large photonic band gap (PBG) can be synthesized by a regular array of square spiral structures grown from a simple, prepatterned substrate using physical vapor deposition and advanced substrate motion. Tetragonal square spiral crystals with a predicted PBG of up to 15% for a silicon structure can be produced in the visible, NIR, and IR spectrum. These PBG's exhibit good stability for large areas of parameter space that can be readily mapped out by the GLAD process through the variation of deposition parameters.

Photonic crystals are optical materials renowned for their ability to restrict the propagation of certain wavelengths of light that fall within the "photonic band gap" (PBG) of the structure.[1,2] PBG materials were first proposed in the context of light localization[1] and inhibited spontaneous emission,[2] where applications include high-efficiency lasers, all-optical microtransistors and optical microcircuitry.[3] The common difficulty with three-dimensional band gap structures, however, is that fabrication is extremely difficult and traditionally involves numerous microelectronic and/or lithographic processing steps and techniques. We present a technique that circumvents these complications, in which fabrication of photonic crystals is virtually reduced to a single-step process and results in an optimal crystal structure.

The diamond lattice structure has traditionally been considered an ideal candidate for a large PBG opening between the second and third photon dispersion bands (fundamental gap).[4] However, its complexity has meant that traditional techniques make successful production of such a crystal even more difficult than for those of the more standard and already complex bcc and fcc lattices. This has motivated efforts to mimic the diamond lattice using woodpile structures[5] and criss-crossing pore structures,[6] which are nevertheless problematic to fabricate on a large scale. Observation of the helical atomic arrangement in the diamond unit cell motivated Chutinan and Noda to consider circular spiral post structures,[7] yet these circular spiral posts exhibit a phase shift between adjacent posts, rendering them impractical for microfabrication.

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Recently, Toader and John have introduced a new blueprint with a large three-dimensional PBG opening between the fourth and fifth photonic bands that is distinct from previous PBG structures based on the diamond lattice.[8] This blueprint, which can be related to a distortion of nonstandard diamond helices, is a tetragonal lattice consisting of square spiral posts and does not involve any phase shift between adjacent unit cells. When the posts are made of silicon, this structure is predicted to have a PBG of up to 15% of the gap center frequency. The corresponding inverse structure (spiral air posts in silicon) exhibits a PBG of 24% of the center frequency. The glancing angle deposition (GLAD) technique is ideally suited to fabricate a tetragonal lattice of helical posts in a single step on a large scale.[9,10,11] The GLAD technique is used in a modified manner to create the stepped helices resulting in a tetragonal square spiral structure.

The GLAD process provides a simple, versatile means of producing large, three-dimensional band gap photonic crystals in a single processing step on a wide variety of elementary, prepatterned wafers. The principle of this technique lies in the deposition of highly porous films at extreme incidence angles (Figure 1). At these oblique angles, α, self-shadowing occurs in the initial nucleation stage where only the higher regions are seen by incoming flux, and further growth is prevented from occurring in other areas. The orientation of the substrate is controlled by two stepper motors and implemented by computer software in conjunction with deposition rate feedback from a crystal thickness monitor. By rotating the substrate appropriately, it is possible to control the growth and shape of the individual structures as they "reach" toward the incoming flux.

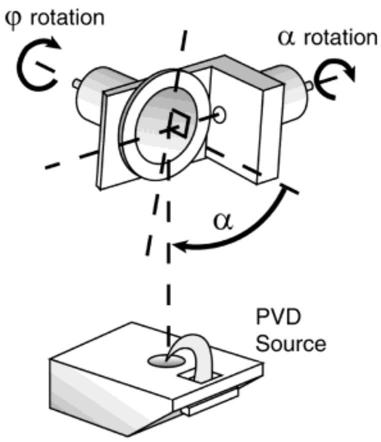

Figure 1. Schematic of the glancing angle deposition system used in vacuo to create tetragonal square spiral structures.

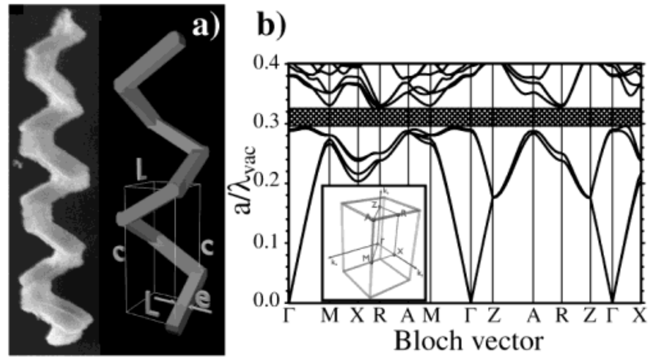

Figure 2. (a) Theoretical computer generated square spiral compared with actual structure produced using GLAD where the two spirals are mirror images of each other grown with right- and left-handed turns, respectively, and (b) theoretical band structure for the crystal with $[L,c,e] = [0.7,1.3,0.44]$.

To produce square spiral photonic crystal structures, physical vapor deposition is used in a high vacuum chamber with an electron beam source. Structures can be made from a wide range of materials; however, because of the requirement for a material with a large index of refraction, pure silicon with its favorable optical and deposition properties is most commonly chosen. Alternatively, silica may be used to create a template for an inverse square spiral photonic crystal. The substrate is mounted relative to the source, as shown in the schematic of Figure 1, where the throw distance between the source and substrate is greater than 30 cm so that flux reaching the substrate is collimated.

In traditional GLAD on a planar substrate, the location of growths is random, as determined by the impingement of initial flux and subsequent nucleation on the substrate. The result is not considered a periodic arrangement and as such it is necessary to seed the substrate and confine growths to predetermined, regular locations. To meet this requirement, shadowing is used by forming a regular array of areas on the substrate that are higher than surrounding regions.[12] The substrate is held at a constant angle of incidence of 80−90° from the normal, and at these angles only the regions with higher relief are seen by the incoming flux. Growth is restricted to these locations and self-shadowing of the structures maintains the restriction on growth throughout the deposition.[13]

Many techniques may be used to produce the required patterning of the wafer, depending on the size scale required and the application of the device. Techniques such as photolithography, electron beam lithography, plastic embossing,[14] and laser interference lithography may be used to produce a rectangular array of dots made from various materials. It is important to note that the relief structures are not required to be perfect with vertical sides and sharp corners; rather it is more significant that they have a reasonable aspect ratio. Seeds with a wide variety of cross-sections may be used, implying that the minimum feature sizes of the processing techniques can be probed without worries about the ideality of the structures. The center-to-center spacing of the growth seeds on the substrate is the distance that determines the characteristic length of the crystal basis and is the first means of controlling the structure of the resulting crystal. The period of the seeds is defined as equal to a, and all other lattice parameters are subsequently based on this length scale.

The square spiral structure typical of these unique photonic crystals is created by the rotation of the substrate at regular, fixed intervals during the growth process. Because the growth tracks the direction of incoming vapor flux, it is possible to create abrupt right angle bends in the slanted columnar structure by rotating the substrate by 90° at appropriate times during growth. If we define the pitch as c, equal to the vertical distance between each successive complete helical turn, we find that we are able to tailor this dimension by simply increasing or decreasing the interval between each quarter turn of the substrate. This represents the second parameter that may be varied in this process and can be used to tune the properties of the resulting crystal.

The third parameter that allows accurate control of the crystal structure is the deposition angle, which is responsible for the growth angle of the helices and is held constant throughout the deposition. Following Tait's rule for deposition at highly oblique angles,[15] in the typical incidence angle range of 80°−90° the growth angle can be varied from approximately 55° to 60°. This defines the characteristic horizontal length L, as a function of pitch c determined by the deposition angle. Incidence angles must be kept at values larger than 80°, as films produced at lesser angles have greatly increased density due to the lessening of shadow effects.

A final characteristic dimension of the square spiral photonic crystal is that of the cross-section of the spiral structures. When the square spiral posts have a circular cross-section, a significant photonic band gap is predicted.[8] However, the GLAD deposition process in its most basic and nonoptimized form is much more suited to a square cross-section, as seen in Figure 2. Instead of column radius r, we now define the characteristic size of the spiral cross-section by the length of the side of the square, e. Calculations have shown similar large three-dimensional gaps for symmetrical square cross-sections, as shown in the example of Figure 2b where the nonoptimized crystal has a theoretical

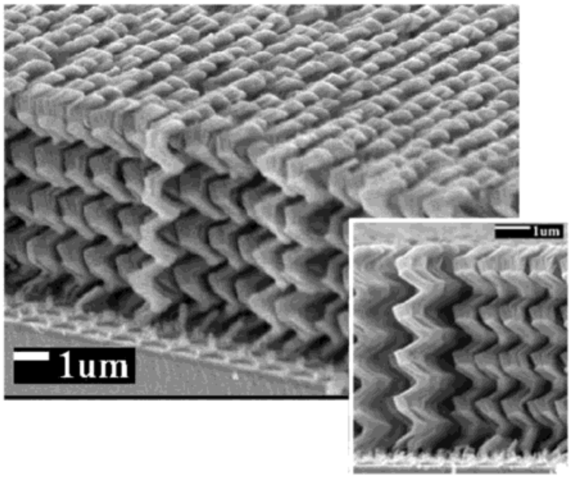

Figure 3. Oblique and edge views of a tetragonal square spiral structure grown using the GLAD process.

relative gap of 9.3%. Control of the square side length in the fabrication process is a function of both incidence angle and structure-to-structure or seed spacing. Since the areal density of the film structure deposited at highly oblique angles is fixed by the incidence angle, smaller seeds spaced closer together result in a structure that is finer with smaller square side length.

Although the structure cross-sections presented in this paper are not yet perfect, it will be possible to adapt the deposition process through careful control of parameters and implementation of spin-and-pause advanced substrate motion to fabricate more idealized structures with symmetrical circular cross-sections.[11] In addition to the detrimental effects of nonsymmetric cross sections, microscopic roughness of the spirals is also undesirable and must be avoided to achieve the maximum band gap and reduction in states predicted from theory. It has been shown that postdeposition anneal of GLAD films can substantially change the surface properties while at the same time improving crystallinity of the film.[16] These techniques of optimizing the cross-sections and structure of square spirals can be implemented to ensure a band gap results from the structure and while they represent slight complication of the process, they maintain a relative hands-off approach to a rather simple means of producing large band gap devices.

To produce a square spiral photonic crystal, a wafer patterned with a square array of dots and fabricated by one of the methods described above is placed on the substrate mount. A square array is required to restrict growth to the tetragonal lattice found from theory to be optimal for a large band gap.[8] The parameters of deposition angle and helical pitch are then entered into the control software and the deposition is started with relative deposition rates at the substrate maintained at 6−10 Å/s. For the example shown in Figures 2 and 3, a deposition angle of 85° and helical pitch of 1300 nm were used, as these parameters produced a structure that most easily fit that of the theoretical model given our photolithography-limited size of $a = 1000$ nm on the patterned wafer. A resonant quartz crystal monitors the normal deposition rate and the thickness of the film is calculated with a geometric correction factor by integration of the deposition rate. For this initial and nonoptimized structure, when the appropriate film thickness defined by one-quarter of the helical pitch is reached, the substrate is rotated quickly through 90° by a stepper motor. This motion produces the characteristic bends in the square spirals and can be repeated as many times as is necessary to produce a film with the desired thickness and number of turns. Ideally, the crystal may have many turns so as to obtain optimal optical characteristics, but in the interest of efficiency our sample crystal has been grown with only 4 turns.

The success of this production technique can be seen in both Figures 2 and 3, where in Figure 2a a single helical strand that has broken off during the cleaving process is compared to a computer-generated model utilized for band structure calculations of square spiral photonic crystal structures. The band diagram is shown in Figure 2b where the predicted relative gap of this nonoptimized structure is 9.3%. This film was deposited on a photolithography patterned wafer with structure parameters of $a = 1000$ nm and $[L,c,e] = [0.7,1.3,0.44]$ in units of a. Also note that the two images in the comparison are mirror images of each other, where the fabricated square spiral has been grown with left-handed helical turns as compared to the right-handed spiral of the computer image. This degeneracy is easily varied by the direction of rotation of the stepper motors during deposition. In the final figure is a view of the cleaved edge of a periodic square spiral structure. The cleaving of the wafer has left a slightly uneven edge with some of the individual spirals missing from the front rows; however, the correlation between the dimensions and proportions of this film and the ideal, computer-generated square spiral lattice is excellent from visual inspection of the scanning electron micrographs. This successful preliminary result provides encouragement for the pursuit of more idealized structures through the development of an optimized process.

Finally, as the analogy of optical semiconductors is carried to the production of photonic crystals, we note that a semiconductor is not useful without doping and, likewise, we need to be able to introduce controlled defects in a PBG crystal lattice to increase its functionality. The GLAD technique of producing tetragonal square spiral lattices allows for various methods of introducing waveguides or micro-cavities necessary for the production of optical devices. First, a predeposition technique can be used to either remove or tie together individual spiral structures. This method of microcavity "doping" can be done in the seed production step and is relatively straightforward.[17] Second, intermediate steps can be taken during the fabrication process to create planar defects in the lattice either by changing the deposition parameters for a given period of deposition or by filling the structure with a removable polymer such as a photoresist from which a new layer can be grown with different properties.[18]

In conclusion, we have demonstrated that the GLAD technique provides a simple method for producing tetragonal square spiral structures on a large scale. These unique structures are ideal candidates for large, three-dimensional

PBG crystals that can be tailored to specific applications. The versatility of this fabrication process also allows for tuning of the microstructure within the highly stable regions of parameter space, making this structure less sensitive to minor variations.

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