Micromachined millimeter-wave photonic band-gap crystals

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We have developed a new technique for fabricating three-dimensional photonic band-gap crystals. Our method utilizes an orderly stacking of micromachined (110) silicon wafers to build the periodic structure. A structure with a full three-dimensional photonic band gap centered near 100 GHz was measured, with experimental results in good agreement with theoretical predictions. This basic approach described should be extendable to build structures with photonic band-gap frequencies ranging from 30 GHz to 3 THz.

In analogy to electrons in a crystal, electromagnetic waves propagating in a structure with a periodically modulated dielectric constant are also organized into "photonic bands" separated by gaps in which propagating states are forbidden. Photonic band-gap crystals are periodic dielectric structures which possess a frequency gap in which all optical modes are forbidden, analogous to the electronic band gap in the case of semiconductors.[1,2] In such crystals, spontaneous emission is suppressed for photons with frequencies in the forbidden region.[3] Already, there have been a number of proposals for photonic band-gap based devices with operating frequencies ranging from the microwave to optical, including zero-threshold lasers, novel resonators and cavities, and efficient microwave antennas.[2] Most of these applications rely on the availability of structures with full three-dimensional photonic band gaps. The first structure which exhibited a genuine photonic band gap was the diamond structure predicted from theoretical calculations by Ho, Chan, and Soukoulis.[4,5] Shortly after this discovery, the first experimental photonic crystal was fabricated by Yablonovitch *et al.* on a related structure.[6] The fabrication of Yablonovitch's crystal had an appealing simplicity—the structure was made by drilling three sets of parallel cylinders into the top surface of a block of dielectric material, with each set angled 35° from normal and spread 120° on the azimuth. In making the microwave frequency crystal described in their work, Yablonovitch *et al.* simply bored the holes into a block of dielectric material with a drill press. They went on to suggest that "three cylinder" structures with band gaps at much higher frequencies might be made using reactive ion beam etching to drill the sets of cylinders into semiconductors like Si or GaAs. However, one of the primary challenges in the use of plasma etching techniques will be in maintaining the shape of the cylinders as they are bored deeper and begin to intersect with each other. Any spread or wander in the etch beam will destroy the periodicity of the structure and rapidly degrade the properties of the photonic band gap. To date, there has been no report of a three-cylinder photonic lattice with a band gap above 20 GHz.

Recently Ho *et al.* proposed a new dielectric structure that has a full three-dimensional photonic band gap and which may lift some of the roadblocks towards fabricating crystals with higher frequency photonic band gaps.[7] The new photonic crystal (Fig. 1) is assembled by stacking together layers of dielectric rods, with each layer consisting of parallel rods with a center to center separation of a. The rods are rotated by 90° in each successive layer. Starting at any reference layer, the rods of every second neighboring layer are parallel to the reference layer but shifted by a distance of $0.5a$ perpendicular to the rod axes. This results in a stacking sequence along the z axis that repeats every four layers. This lattice has face centered tetragonal lattice symmetry with a basis of two rods. The symmetry of this crystal is such that the electromagnetic (EM) wave propagation along the z axis is degenerate for both polarizations. However for propagation along the rods, the propagation for the polarization vector $\mathbf{e}$ in the plane of rod layers in nondegenerate with $\mathbf{e}$ along the z axis. The new structure has a sizable and robust photonic band gap over a range of structural parameters. Recently Özbay *et al.* fabricated this structure by stacking layers of alumina rods and confirmed the existence of a full photonic band gap at Ku-band frequencies (12–14 GHz).[8]

In this letter we demonstrate the scalability of this new structure to higher photonic band-gap frequencies in the 100 GHz range using semiconductor micromachining techniques. Our method utilizes the anisotropic etching of silicon by aqueous potassium hydroxide (KOH), which etches the {110} planes of silicon very rapidly while leaving the {111} planes relatively untouched.[9,10] Thus, using (110)-oriented silicon, it is possible to etch arrays of parallel rods into wafers, and the patterned wafers can then be stacked in the correct manner to make the photonic band-gap crystal.

The (110) silicon wafers used in this work were each 3 in. in diameter and 390 μm thick. We chose relatively high-resistivity wafers (180 Ω cm) in order to minimize absorption losses in the silicon. The fabrication is carried out in batches of 20 wafers at a time. The first step in the process is the growth of silicon dioxide on the front and back surfaces of the wafers. The oxide must serve as a mask during the anisotropic etching step, and we found that a 2.0 μm thick oxide was sufficient to provide the necessary protection. After oxidation, the front-surface oxide was patterned by conventional photolithography and buffered hydrofluoric acid etching. The pattern consists of 23 parallel stripes, each 340 μm wide and separated by 935-μm-wide gaps. These stripe dimensions and the wafer thickness determine the center of the forbidden photonic gap—calculated to be 94 GHz in this case. The stripes are aligned parallel to the {111} plane of the silicon, as defined by the major flat of the wafer. The stripes are 3.0 cm long so that the 23 stripes form a square 3.0 cm×3.0 cm pattern. A 1.15-cm-wide border around the stripe array is protected by photoresist, with the outer regions of the wafer left exposed so that a square wafer will be left after etching. Within the border region are four small rectangular openings that will serve as guide holes for the stacking process. A layer of photoresist protects the back surface oxide during patterning of the front surface.

After the oxide layer has been patterned, the wafers are dipped into an aqueous KOH etching solution. A typical etch performed in a 20% KOH solution at a temperature of 85 °C takes approximately 4 h to etch entirely through the wafer. Once the etch is completed, the remaining oxide is removed from both surfaces. A photograph of a single etched silicon wafer is shown in Fig. 2.

The individual wafers were stacked to form the photonic crystal using a holder having pins that align to the guide holes that were etched into the wafers. The guide holes are not symmetric with respect to the stripe patterns, but instead are offset slightly in the direction perpendicular to the rods. The separation between the edge of the rod patten and the guide holes on one side is larger than the corresponding separation on the other side by one-half the rod-to-rod spacing. Thus if one wafer is rotated by 180° with respect to a second wafer while keeping the guide holes aligned, the rods of the first wafer will be translated by one-half the rod spacing with respect to the rods of the second wafer. The photonic crystal is then easily assembled by stacking the patterned silicon wafers one by one on the holder, with a rotation of the holder by 90° before each wafer is put in place. This results in a stacking sequence that repeats every four layers, as shown in Fig. 1. A photograph of the completed silicon photonic crystal is shown in Fig. 2.

Once the fabrication was completed, the transmission properties of the crystal were measured with a W-band (75–110 GHz) measurement arrangement. A Ku-band frequency synthesizer was used to generate a signal that was first amplified and then multiplied in frequency by six times to reach the W band. The high-frequency signal was radiated by a standard-gain horn antenna (aperture size of 1.17 cm×1.45 cm) with a photonic crystal in the path of the beam, and the transmitted radiation was collected by a second horn antenna. The amplitude of the received signal was measured using a harmonic mixer and a network analyzer. The setup was calibrated for power measurements of the EM wave transmitted from the source antenna. In order to improve the sensitivity of the test setup, EM absorbing pads were stacked around the test set to create a pseudoanechoic environment. The resulting sensitivity was about 60 dB throughout the W-band.

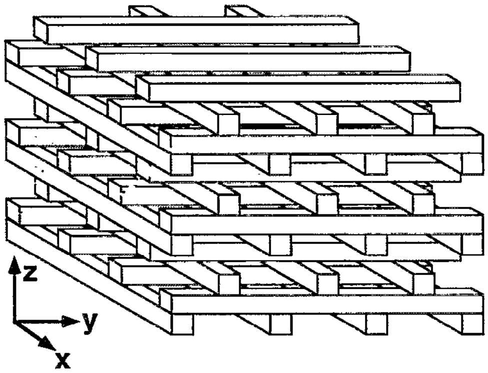

FIG. 1. A schematic depicting the basic structure of the new photonic band-gap crystal. The structure repeats every four layers in the stacking direction.

Figure 3 shows the transmission measurement for propagation along the z axis (which is degenerate for both polarizations along the rods) of a crystal which has 28 stacked wafers (7 unit cells). The drop off in transmitted power, corresponding to the valence band edge for the crystal, starts at 81 GHz, which matches the calculated value exactly. The upper band edge for this orientation, predicted to be at 120 GHz, was beyond the upper measuring limit of the W-band test set and so does not appear in Fig. 3(a). In the forbidden band, the average attenuation was 50 dB, a limit which was

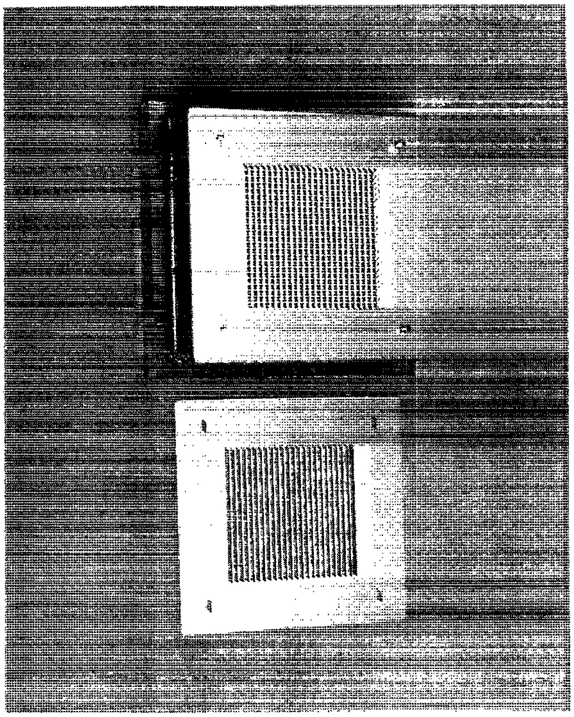

FIG. 2. Photographs of a single etched wafer and the completed photonic crystal consisting of a stack of wafers on the alignment jig.

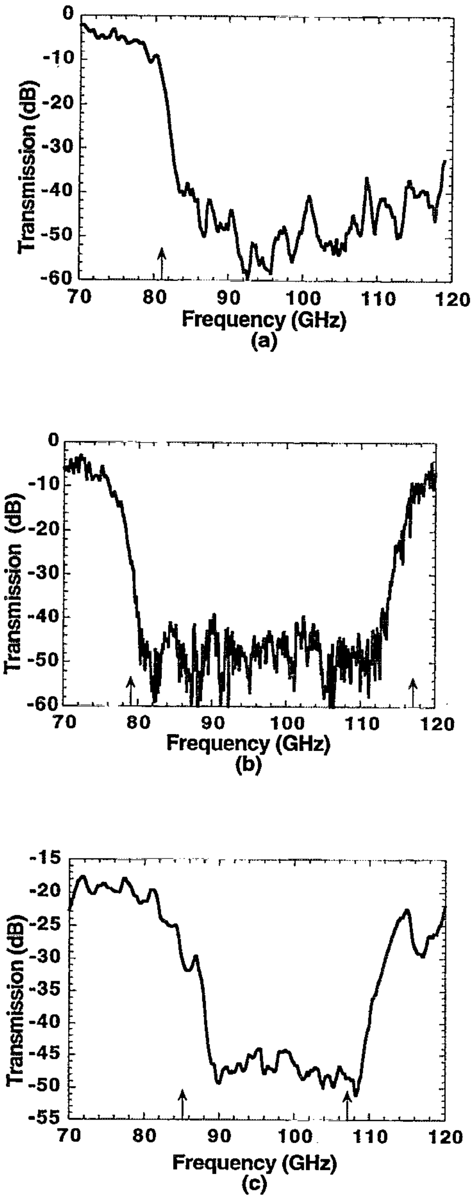

FIG. 3. EM wave transmission through the micromachined crystal in which the wave vector of the incident EM waves is (a) normal to the wafer surfaces, (b) 35° from the normal to the wafer surface, and (c) parallel to the wafer surfaces. The arrows indicate calculated band edge frequencies.

most likely due to leakage of the EM power around the sample, either through surface states of the crystal or through other leakage paths around the crystal. The upper band edge was detected when the crystal was rotated so that the EM wave was incident at an angle of 35° with respect to the wafer surface normal (while the polarization vector **e** kept parallel to the wafer surfaces). Then the complete band gap fell within our measurement range, and both edges of the band gap were well defined, as shown in Fig. 3(b). The valence band edge occurred at 76 GHz, while the conduction band edge was at 116 GHz, values that are in good agreement with the calculated values of 79 and 117 GHz.

For EM propagation in the stacking direction, we also measured the band-gap attenuation as a function of the number of stacked unit cells. The result was an average of 16 dB attenuation per unit cell, close to theoretical expectation of 17 dB per unit cell. This result is especially important for device considerations of these structures since three unit cells (for a total of 12 wafers) will yield a photonic band gap with 45–50 dB attenuation which is large enough for most applications.

Figure 3(c) shows the transmission characteristics for the case when the EM waves are incident on the side surface of a 40 wafer stack, with the polarization vector **e** along the z axis. The lower edge of the gap was near 87 GHz, while the upper edge was near 110 GHz. Again, these values are in reasonably good agreement with the calculated band edges of 85 and 107 GHz. The average attenuation within the band gap was around 45 dB which was again mostly due the leakage of the EM power around the crystal.

Although the structure used in this work was designed to have a photonic band gap near 100 GHz, the frequency can be changed by simply scaling all the dimensions of the structure. Scaling to larger dimensions (lower frequency) is an easy extension of the current process and would be limited by the maximum size of the available silicon wafers. Structures with photonic band-gap frequencies as low as 30 GHz could easily be built using commonly available wafers. On the other hand, scaling down the structure dimensions (going to higher frequencies) will require thinner silicon wafers and finer rod sizes, with attendant difficulties associated with increased fragility. By using special silicon thinning methods and double etching the wafers on both surfaces, the frequency range of this fabrication technology could probably be extended to build structures with photonic band gaps as high as 3 THz.

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