Double-etch geometry for millimeter-wave photonic band-gap crystals

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We have designed and developed a new double-etch technique for fabricating three-dimensional millimeter-wave photonic band-gap crystals. This technique doubles the band-gap frequency obtainable from silicon wafers. By introducing overetching, the double-etch geometry allows one-way tuning of the midgap frequency. We have experimentally demonstrated this property by fabricating and testing structures with different overetch ratios. Terahertz spectroscopy techniques were used to measure photonic band-gap crystals with midgap frequencies ranging from 340 to 375 GHz.

The coherent scattering and interference of electromagnetic waves in three-dimensional ordered structures lead to formation of forbidden bands in which the propagation of photons is not allowed. These three-dimensional structures, known as photonic band-gap (PBG) crystals, have recently received both theoretical and experimental attention.[1–3] As implied by the name, the early research in the field has concentrated on photonics applications that take advantage of reduced spontaneous emission at optical wavelengths such as thresholdless semiconductor lasers and single-mode light-emitting diodes. Also, applications at millimeter and submillimeter wave regimes like efficient antennas, sources, waveguides, and other components that take advantage of the unique properties of PBG materials were proposed.[4] However, until recently the difficulties associated with the fabrication of smaller scale PBG structures (even at millimeter wave frequencies) had restricted the experimental demonstration of the basic PBG crystals to microwave frequencies (12–15 GHz).[5]

Our recent efforts to alleviate this scaling problem proved to be successful. We have designed a new three-dimensional structure (that consisted of stacked dielectric rods) which exhibited a sizable and robust PBG over a range of structural parameters.[6] Using a large scale model made of cylindrical alumina rods, we have confirmed the existence of a full PBG at *Ku*-band frequencies (12–14 GHz).[7] To scale the PBG to higher frequencies, we developed a semiconductor micromachining technique for patterning silicon wafers. By stacking these wafers to form photonic crystals, we have achieved full photonic PBGs at millimeter-wave frequencies.[8,9] In this letter, we report a new double-etch design, where the spatial pattern is etched on both sides of the wafer. For a given wafer thickness, the PBG frequency is increased to approximately twice that using a single-etched wafer. The double-etch design also allows the PBG to be tuned (in one direction) by overetching.

The crystal reported in Ref. 8 was fabricated by means of etching one side of the silicon (110) wafers (single etching). Although this is a simple one-step fabrication technique, it has a number of drawbacks. First, the resulting structure has a fixed band-gap frequency that cannot be changed once the etch is completed. Second, the dielectric rods have a large aspect ratio (300 μm wide, 3 cm long for the crystal in Ref. 8) and are supported only at the ends, making them susceptible to breakage. These problems can be alleviated by developing a double-etch approach that comes at a cost of increased processing time.

Our double-etch approach takes advantage of the well-known anisotropic etching properties of silicon in aqueous solutions.[10] By lithographically defining stripes (with a center to center spacing of a that are parallel to (111) crystal planes of both surfaces of a silicon (110) wafer, we can simultaneously etch both surfaces of the silicon wafer. This geometry is shown in Fig. 1(a), where the rods on the top and bottom surfaces are at an angle of 70.5° [the angle between two different (111) crystal planes]. These double-etched wafers can be used to form a crystal that is also de-

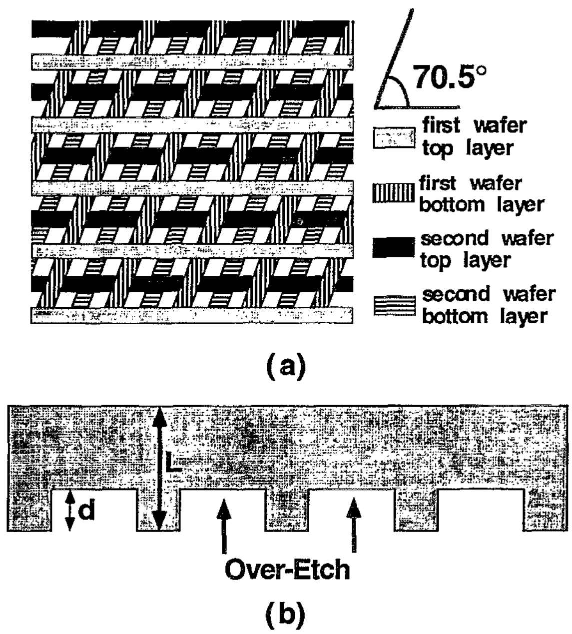

FIG. 1. (a) A schematic depicting the basic structure of the new PBG crystal. The rods at the neighboring layers are at an angle of 70.5°, and the structure repeats every four layers in the stacking direction. (b) Cross section of a rod after overetching. The ratio of the overetched amount, to the thickness of the rod, L, defines the overetch ratio of the structure.

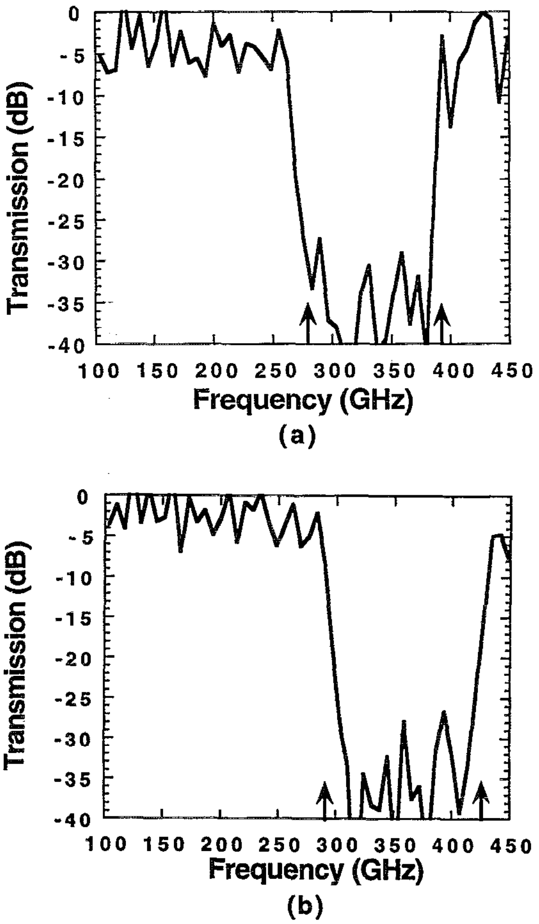

FIG. 2. (a) em wave transmission through the micromachined crystal made of regular (no overetch) double-etched silicon wafers, (b) em wave transmission through the micromachined crystal made of 20% overetched silicon wafers. The arrows indicate calculated band-edge frequencies.

picted in Fig. 1(a). In this crystal, the wafers are stacked such that the rods of the neighboring wafer are parallel to the rods of the first wafer, 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 two wafers.

In this geometry, the rods on the top surface of the double-etched wafer are interconnected to the rods on the bottom surface resulting in a more robust structure. The double-etch geometry makes it also possible to tune the PBG properties of the new structure by overetching. If the wafers are kept in the etch solution longer than the time it takes to etch the wafer from both sides, the rods will be etched from the back. The resulting change on the cross section of the rods is depicted in Fig. 1(b). The ratio of the additional amount etched, d, to the total thickness of the bar, L, is defined as the overetch ratio for this structure. This overetch removes material from the backsurfaces of the rods, effectively changing the filling ratio (the ratio of the dielectric volume to the overall volume), which also changes and increases the midgap frequency. This can be used as a new tool for tuning the midgap frequency in the following manner. Once the wafers are etched and stacked, the PBG frequency of the stack can be measured by a transmission experiment. If the measurement does not result in the desired band-gap frequencies (if the measured value is less than the desired value), the wafers can be put back into the etch solution for more overetching. After the overetch, they can be restacked and measured again. This process can be repeated until the desired PBG characteristics are obtained.

In order to assemble this crystal structure from the stacking process, we have to align the patterns on both sides of the silicon wafer. We achieve this alignment by using trapezoidal-shape alignment holes, that are etched through the whole wafer during the first lithography step. Now that the holes can be seen on both surfaces, the alignment of both surfaces can be easily done.

In our process, we used 3-in.-diam, 250-μm-thick, high-resistivity ($>100\ \Omega$ cm), (110) silicon wafers. Fabrication starts with the growth of a 2.0-μm-thick oxide layer that is thick enough to protect the wafers through the whole process. Oxidation is followed by the first lithography step, where the trapezoidal-shape alignment holes are transferred to the front surface by conventional photolithography and buffered hydrofluoric acid etching. The wafers are then put into 40% KOH (potassium hydroxide) solution at 75 °C, where it takes around 90 min to etch the alignment holes through the silicon wafer. After the etching of the alignment marks, the front-surface oxide was patterned into 80 parallel stripes, each 90 μm wide and separated by 290-μm-wide gaps. The stripes are parallel to the (111) plane of the front surface. These stripe dimensions and the wafer thickness determine the center of the forbidden photonic gap—calculated to be 375 GHz in this case. The stripes are 3.0 cm long so that the 80 stripes form a square 3.0×3.0 cm pattern. A 1.0-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.

After the patterning of the front surface, the backsurface oxide is also patterned with the same stripe array, except that the stripes are aligned parallel with the other (111) directions at an angle of 70.5° with the front-surface rods. Once both surfaces are patterned, the wafers are dipped into a buffer oxide etch solution to remove the oxide. The wafers are then etched in the same KOH solution (40%, 75 °C) which takes about half of the time (45 min for 250-μm-thick wafers) of the original etch, since etching proceeds from both surfaces. The etching is stopped once the wafers are etched through which can be visually observed. In order to fabricate overetched wafers, we etched a second batch of wafers for 54 min (which corresponds to 20% overetching as the etch rate remains constant).

Both batches of the etched silicon wafers are then stacked using plexiglass jigs. The jigs contain pins that are placed into holes precisely machined to match the pinholes of the etched wafers. Using the regular (no overetch) and 20% overetched wafers, we have constructed two different crystals each containing 14 wafers (corresponding to seven unit cells in z direction). Transmission through the two sets of structures is measured by an all-electron terahertz free-space spectroscopy setup.[11] The dynamic range of the system is around 35–40 dB for frequencies up to 450 GHz. We carry out the free-space spectroscopic measurements of the photonic crystal by placing the structure on the beampath of the radiated signal. Since the pulses are periodic, the frequency domain information is limited to the harmonics of the pulse frequency (6.4 GHz).

Figure 2 shows the transmission characteristics of the regular structure (no overetch). The lower edge of the PBG (along the stacking direction) is at 265 GHz, while the upper edge is at 390 GHz. Both polarizations of the electromagnetic (em) waves are degenerate for this propagation direction. This is in good agreement with the calculated band-gap edges of 276 and 388 GHz. For comparison, a scaling of the single-etched procedure[8] from the previous 390 μm wafers to the present 250 μm wafers would result in band edges of 126 and 190 GHz. Hence more than a factor of 2 improvement in the midgap frequency is possible with the double-etch design.

Figure 2(b) shows the transmission characteristics of the 20% overetched structure along the stacking direction. The band-gap edges for the overetched structures are measured to be 295 and 425 GHz. This is again in good agreement with the theoretical predictions of 290 and 425 GHz. As explained earlier, overetching decreases both the filling ratio and the effective refractive index, hence increasing the midgap frequency. The increase of the gap with overetching is similar to the increase gap in complex multiply connected structures found in previous calculations.[6] This experiment shows that overetching can effectively be used to tune (in one way) the PBG frequency of the photonic crystals.

Measurement of the transmission from the side surface of the crystal would require a crystal that was at least 2 cm thick, corresponding to 80 double-etched wafers that would be too expensive to build. Although it was possible to make transmission measurements along other crystal directions by rotating the crystal, the refraction at the surface of the crystal resulted in a misalignment of the detected signal by steering the beam away from the original path. This misalignment resulted in uncalibrated measurements where we rotated the crystal from its original orientation. This prevented us from measuring the PBG properties of the crystals along other propagation directions.[9] Rather, we rely on our theoretical calculations which predict full band gaps in all directions. In our earlier work, the agreement between theory and experiment was remarkably good. We have used standard photonic band-structure methods[2,6] to model the overetched structure [Fig. 1(b)] as either (i) two silicon rods in the (111) direction with an extra connecting rectangular block connecting these two rods, resulting in three rods, or more easily by (ii) two overlapping rectangular air rods. Both schemes produce equivalent results. Figure 3 shows the dependence of the full PBG as a function of overetch. The midgap frequency of the photonic crystal can be changed (in an increasing manner) from 355 to 425 GHz, which corresponds to a 20% change. This can be advantageously used for PBG applications where tuning of the midgap frequency is needed.

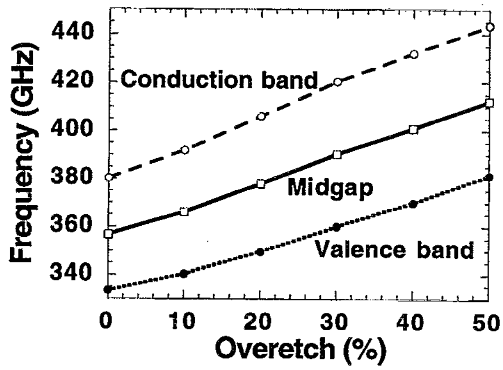

FIG. 3. Theoretical band-gap frequencies of the photonic gap structure as a function of overetch. The conduction band minimum and valence band maximum of the structure define the full PBG of the crystal.

In conclusion, we have developed a new double-etch design for PBG structures that provides a factor of 2 increase in the midgap frequency. The new design is more robust than earlier structures, and by means of overetching the midgap frequency can be tuned in an increasing manner.

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