Phononic crystals operating in the gigahertz range with extremely wide band gaps

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(Received 5 May 2010; accepted 1 October 2010; published online 8 November 2010)

Phononic crystals have numerous potential applications including use as filters and oscillators in communications systems and as acoustic isolators for resonant sensors such as gyroscopes. These applications are based on the ability of phononic crystals to exhibit elastic band gaps, frequency bands where the propagation of acoustic waves is forbidden. Here, we focus on solid-solid phononic crystals (solid inclusions in a solid matrix), since they typically exhibit wider band gaps than those observed with air-solid phononic crystals (air inclusions in a solid matrix). We present a micromachined solid-solid phononic crystal operating at 1.4 GHz center frequency with an ultrawide 800 MHz band gap. © 2010 American Institute of Physics. [doi:10.1063/1.3504701]

Phononic crystals (PnCs) are inhomogeneous media where inclusions composed of one material are periodically placed in another material. The periodic variations in elastic properties can lead to the existence of phononic band gaps (PnBGs) where devices such as waveguides1 and filters2 can be formed. Integration of PnC devices can lead to compact components with high performance for wireless communications and sensing.

Solid-solid (solid inclusions in a solid medium) PnCs exhibit band gaps over a wider range of topological parameters, and thus generally have a larger minimum feature size for easier fabrication,3 than air-solid PnCs.4 With a band gap desired in the frequency bands used for consumer wireless communication, 400 MHz to 2.4 GHz, the lattice pitch, a, and the radius of the inclusions, r, must be micron scale. Solid elastic materials have higher acoustic velocity and lower acoustic damping than liquids or gases, which is beneficial when scaling to higher frequency. Recently, PnCs in the consumer wireless communication frequency band were reported5 using W rods in a SiO2 medium. However, utilizing Si as the host medium for PnCs offers several advantages. First, Si exhibits lower material loss than SiO2. Second, the elastic speed in Si is higher than in SiO2, which results in higher frequency devices for the same lattice constant. The elastic speed mismatch between W and Si of ~2 allows for the maximum band gap to appear at a near optimum, for ease of fabrication, r/a ratio of 0.26, as compared to that of W–SiO2 (0.32) or air-Si (>0.45). This allows for higher frequency scaling with less stringent lithography requirements. Third, among the previously published PnCs implemented in low loss materials suitable for micromechanical devices, the W–Si PnCs reported here exhibit the highest frequencies and widest band gaps. Finally, recent research has shown that under certain conditions solid-solid PnCs can be less sensitive to the thickness of the PnC membrane than air-Si PnCs.3

In this paper, we show the existence of a PnBG in a solid-solid PnC made of W cylindrical inclusions embedded in a Si membrane operating at a center frequency of 1.4 GHz. To investigate the band gap properties of the W–Si PnC plate, the following complementary metal-oxide semiconductor compatible fabrication process was developed. The process starts with a high-resistivity Si wafer on which a 2.5 μm thick sacrificial oxide is thermally grown, followed by the deposition of the 1.2 μm thick poly-Si device layer [Fig. 1(a)]. A silicon-on-insulator wafer could also be used as long as the device layer thickness uniformity is acceptable. Cylindrical trenches are then etched in the Si film followed by a chemical vapor deposition of W to fill the trenches. The wafer is then polished using chemical mechanical polishing to ensure that W only remains in the trenches and is removed from elsewhere on the wafer [Fig. 1(b)]. A bottom electrode is then deposited and patterned [Fig. 1(c)], followed by the deposition and patterning of an aluminum nitride (AlN) film [Fig. 1(d)]. The devices were patterned in a standard photolithography process using an optical stepper and reactive-ion etching. The piezoelectric characteristics of AlN are used to launch and receive elastic waves through the PnC. A top electrode, which serves to electrically actuate the AlN film, is

![FIG. 1. (Color online) Fabrication process for the W–Si PnC.](image-url)
then deposited and patterned [Fig. 1(e)]. In our case, we designed broadband couplers to excite and detect the elastic waves using interdigitated transducers (IDTs) with different finger widths and spacings, known as chirped couplers. Finally, the sacrificial oxide layer under the PnC membrane is removed using vapor phase hydrofluoric acid (HF) [Fig. 1(f)]. A scanning electron microscope (SEM) image of the fabricated PnC is shown in Fig. 2, where the lattice pitch \( a \) and the radius \( r \) of the W inclusions are 2.5 \( \mu \text{m} \) and 0.65 \( \mu \text{m} \), respectively. The thickness of the Si layer, \( t \), is 1.15 \( \mu \text{m} \) with a thickness-to-lattice-pitch ratio, \( t/a \), of 0.46, since it has been shown that the PnBG is minimally compromised for \( t < a \), or \( r > 10a \).

To measure the PnBG of our fabricated PnC, we monitored the transmission in the \( \Gamma X \) direction through a structure with 17 layers of W rods between launching and receiving couplers. We used a network analyzer to excite the structure by applying an electric signal over the frequency range for which a PnBG is predicted by finite-difference time-domain (FDTD) simulations. The electric field between the top and bottom electrodes induces a displacement in the AlN film, which in turn causes longitudinal and flexural displacements in the Si membrane. The displacement field propagates through the PnC, where it induces an electric field between the electrodes placed above and below the AlN film on the opposite side of the device. The received signal is compared with the launched signal to determine the effect of the PnC on propagating elastic waves.

A single IDT, although chirped for broadband transduction, cannot cover the entire PnBG frequency range. Thus 24 couplers were used to cover the frequency range of 0.8–2.2 GHz, which spans the location of the PnBG as predicted by FDTD. The 24 PnC structures were identical except that each IDT was designed to operate at a unique frequency interval such that the overall frequency range of interest is covered.

To isolate the effect of the PnC, we also fabricate an unpatterned matrix, which is the same as Fig. 2 but without the W rods. Normalizing the transmission through the crystal to that through a matrix isolates the effects of the PnC at the output port.

Figure 3(a) shows a comparison between our FDTD model and experimental data for elastic wave transmission through the PnC device. A band gap appears between 1–1.8 GHz in the experimental results which is well predicted by the FDTD modeling. The measured gap to midgap ratio of 57% is extremely high when compared to previously reported values of 25% (Ref. 4) and 44%5, and is wide enough to cover a large variety of communications devices. Note that it appears that a mode can be observed in the experimental transmission plot, Fig. 3(a), at around 1.4 GHz. The mode can be seen in Fig. 3(b) for the matrix response as a dip in transmission at 1.4 GHz but without a corresponding feature in the PnC response. This indicates that such behavior in the normalized transmission plot is artificial, occurring only because of a sharp dip in transmission through the matrix at that specific frequency. The sharp dip in transmission at 1.4 GHz is present for all 24 matrix couplers and corresponds to the thickness mode through the Si/Al/AlN/Al transducer. The noise floor was also measured and plotted in Fig. 3(b) (“isolation” curve), confirming that, although the measured matrix and PnC signals become small, they are well within the dynamic range of the characterization system and the features in the plot are indicative of the actual acoustic behavior of the samples. This isolation measurement was performed by measuring the signal across the same frequency range for a set of input and detection IDTs that were identical, in both

*Fig. 2. (Color online) An SEM image showing the PnC and AlN transducers.*

*Fig. 3. (Color online) (a) Normalized results for transmission through a PnC comparing FDTD and experimental results, (b) the un-normalized experimental crystal and matrix responses.*
size and spacing, to the ones used in PnC and matrix measurements but acoustically isolated from each other.

To better understand the modal behavior of this PnC that gives rise to the PnBG, the structure was simulated using the two-dimensional plane-wave expansion technique. The resulting dispersion diagram is plotted in Fig. 4(a) for the optimal \( \frac{r}{a} \) of 0.26, where a small PnBG for all modes can be observed at a center frequency of 880 MHz. However, to compare these data with the experimental results, two factors must be considered. First, the IDTs fabricated on the samples are unable to excite or detect in-plane transverse modes; this effect was also included in the FDTD simulations, thus those corresponding modes in Fig. 4(a) can be ignored. Second, the out-of-plane transverse (i.e., flexural) modes within the range of 1.2–1.7 GHz exhibit either negatively sloped or very flat dispersion behavior, making it extremely difficult to couple energy into them and highly unlikely that they will transmit energy to the output IDTs. This, combined with the fact that the inherent coupling of the AlN transducers for this geometry is about three times smaller for flexural modes than for longitudinal modes, indicates that the out-of-plane transverse modes shown in Fig. 4(a) can be ignored as well. Thus, both the complete and longitudinal-only band gaps normalized to the center frequency were calculated for \( \frac{r}{a} \) values ranging from 0.1 to 0.48, as shown in Fig. 4(b). This plot agrees well with the FDTD and experimental results, indicating the same optimal \( \frac{r}{a} \) value of 0.26, corresponding to a normalized band gap of 56%. Considering that the measurements were performed for only the \( \Gamma X \) direction, it can be observed from Fig. 4(a) that the indicated longitudinal band gap for \( \Gamma X \) is 0.84–1.73 GHz (indicated by the black arrow at the X point), again showing good agreement with the experimental results and FDTD.

In conclusion, a PnC exhibiting a band gap between 1 and 1.8 GHz has been fabricated and demonstrated. Furthermore, the width of the band gap of 800 MHz is one of the largest absolute band gap widths reported to date, and the gap to midgap ratio of 57% is also among the highest reported.

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia National Laboratories is a multiprogram laboratory operated by the Sandia Corporation, Lockheed Martin Co., for the United States Department of Energy’s National Nuclear Security Administration under Contract No. DE-AC04-94AL85000.