Evidence of the existence of complete phononic band gaps in phononic crystal plates

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Abstract: **We show, by measuring the transmission through a phononic crystal (PC) plate (slab), the evidence of the existence of large phononic band gaps (PBGs) in two-dimensional PCs made by a hexagonal (honeycomb) array of holes etched through a free standing plate of silicon (Si). A CMOS compatible fabrication process is used on a Si on insulator (SOI) substrate to realize the devices. More than 30dB attenuation is observed for eight periods of the hexagonal lattice a very high frequency (VHF) region that matches very well with the theoretical predicted complete PBG using plane wave expansion (PWE) method. This result opens a new direction in the implementation of high frequency practical PC structures with a possible superior performance over the conventional micromechanical devices used in a variety of applications especially in wireless communication devices, and sensing systems.**

***Index Terms* — acoustic devices, filtering, phononic crystals, micromachining, phonons**

1 INTRODUCTION

Phononic crystals (PnCs) [1], [2] are special types of inhomogeneous materials with periodical variations in their elastic properties. PCs to phonons are as photonic crystals are to photons and as semiconductors are to electrons. One of the most interesting phenomena that can be obtained in the PC structure is the existence of frequency ranges in which elastic waves are prohibited from propagation. The existence of these frequency ranges, called phononic band gaps (PBGs), is very important as it can be used to realize fundamental functionalities like mirroring, guiding, entrapment, and filtering for acoustic/elastic waves by creating defects in the PC structure [3]-[5], as in the case of photonic crystals. Possibility of implementation of these functionalities in the PC structures can lead to integrated acoustic devices with superior performance over the conventional electromechanical devices used in wireless communication and sensing systems.

PCs can be categorized as one dimensional (1D), two dimensional (2D), and three dimensional (3D) based on the number of dimensions in which periodicity applies. While 1D PCs provide limited capability to control the elastic waves, 3D PCs are normally found to be difficult or impractical to fabricate. 2D PC structures, however, can provide moderate ability to control the elastic energy while being relatively easier to fabricate. Most of the studies on 2D PCs have been dedicated to the structures that are infinite, or very large in the third dimension, but such structures are not practical to be used in off-the-shelf integrated devices due to their large sizes, and are mostly designed to work at low frequencies (<5MHz).

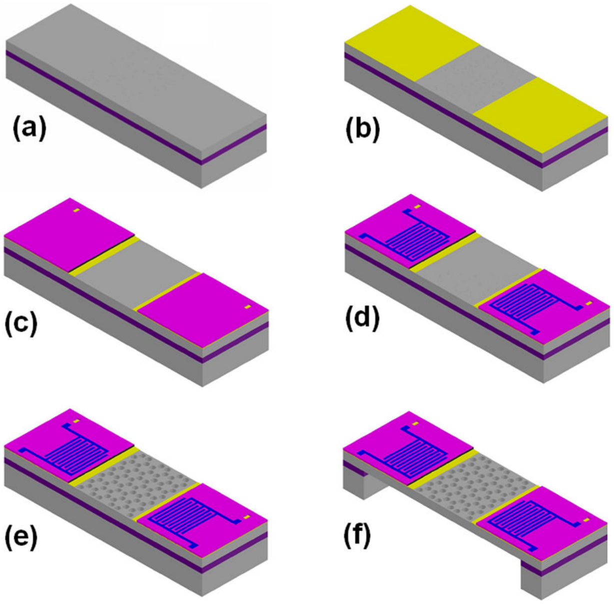

Figure 1. Fabrication steps for Si PC plate characterization, (a) original SOI substrate, (b) lower metal is patterned (c) ZnO layer is deposited and patterned (d) top layer of metal is patterned (e) holes are etched through the device layer (f) lower substrate and the insulator layers are etched by the use of a backside etching technique.

Recently, there has been a growing interest in 2D PC structures that are semi-infinite in the third dimension, and the periodic lattice is used to modify the propagation of surface acoustic waves (SAWs) localized near the free surface of the structure [6]-[8]. Such a structure is interesting as it can be fabricated by the available micromachining technology; however, SAW PC devices are prone to suffer from loss in the form of coupling to the bulk waves in the semi-infinite region [10], [11]. To solve this problem, 2D PC plate (slab) structure was recently introduced [12], in which the third dimension of the structure is limited by two parallel free-standing surfaces, and it was proved that large PBGs are possible to obtain in such structure, though very different from the PBGs of the infinite 2D PC. The structure proposed in Reference [12], however is a solid/solid PC structure, and suffers from fabrication difficulties as high frequency structures with low loss is of interest. In Reference [13] it was shown that it is possible to achieve very large complete PBGs in hexagonal (honeycomb) lattice of perforated holes in a silicon (Si) plate. In this paper we show that such devices are realizable by the use of a CMOS compatible process, and can operate in very high frequencies (VHF), and beyond, and verify the existence of large PBGs previously predicted in Reference [13]. We use interdigital transducers (IDTs) to scan a large frequency range to measure the transmission of elastic waves through the PC structure. A large sharp drop in the transmission through the PC in the range of the predicted PBG is detected. Excellent agreement between theory and experiment is observed.

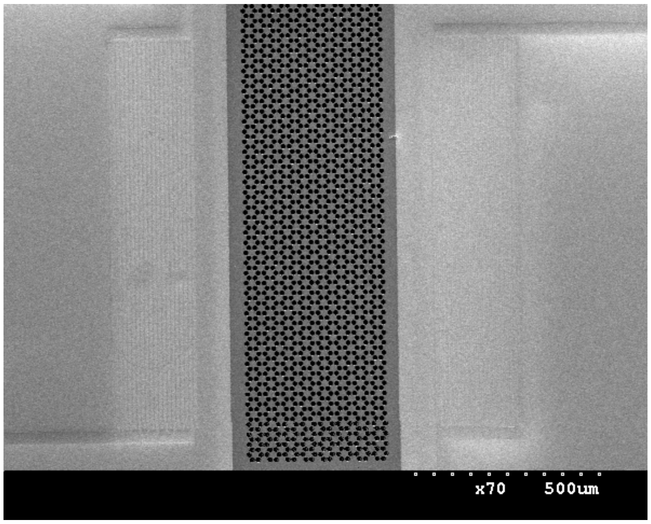

Figure 2. Top view of a sample fabricated device with PC region in the middle, and the transducer electrodes on each side.

2 DEVICE STRUCTURE AND THE FABRICATION PROCESS

The micromachining fabrication steps for devices used in this PnC characterization setup are shown in Figures 1(a)-(f). The process starts with a silicon on insulator (SOI) substrate as shown in Figure 1(a) with the Si layer thickness being 15μm, and a thin layer of metal (~100nm) is deposited and patterned on the Si layer followed by the radio frequency (RF) sputtering and patterning of a piezoelectric zinc oxide (ZnO) layer. Then a second layer of metal is patterned to form the excitation and detection transducers. The fabrication continues by etching the PC holes through the Si layer using a deep plasma etching technique, and finally the lowest substrate and the insulator layers are etched away to form the PC structure with the appropriate acoustic wave transmitters and receivers on the sides.

Scanning electron microscope (SEM) images of the top view, and cross sectional view of a typical device are shown in Figures 2, and 3 respectively. The PC is composed of eight periods of the hexagonal structure with its closest holes 15μm apart (a = 15μm), and the diameter of the holes is approximately 12.8μm as shown in Figure 3(a).

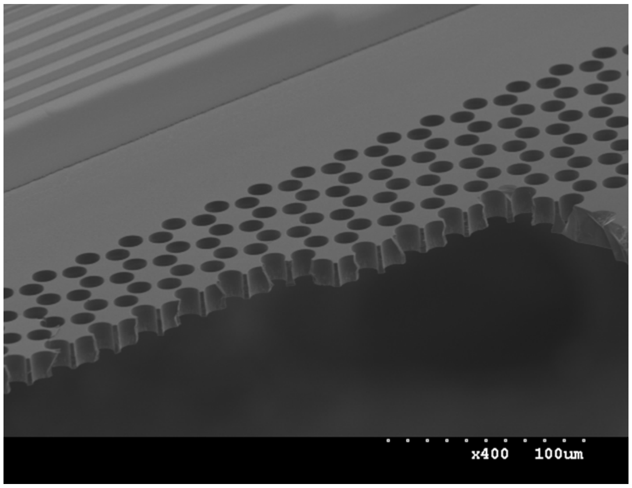

Figure 3. Cross sectional view of the fabricated structure.

Based on these geometrical values, and using the plane wave expansion (PWE) technique discussed in Reference [13] the band structure of the hexagonal Si PC is calculated and shown in Figure 4(c), while Figure 4(b) shows the irreducible part of the Brillouin zone. It can be inferred from Figure 4(c) that the full PBG predicted extends in the frequency range of 115MHz to 151MHz.

3 EXPERIMENTAL RESULTS

On the other hand, several transducers with different geometries are designed and fabricated to scan a wide frequency range around the expected PBG region. A different set of devices with the same frequency coverage, but without the PC holes etched were fabricated to act as a reference. A network analyzer is used to excite the structure by applying a high frequency electrical signal between the first and the second layer of metals producing a strong electric field across the ZnO layer. As the ZnO layer is sputtered by setting appropriate parameters to give highly oriented crystalline nano grains to show proper piezoelectric properties, the elastic energy is induced in the structure, and couples into a wide range of modes in the structure. Based on the spacing distances between the upper layer metal electrode fingers, the frequency of the excited modes would change. A wide range of electrode finger spacing distances is used to make sure various plate modes with frequencies within the PBG are excited. The signals transmitted through the PC structure are collected at each scanned frequency and normalized to the signal transmitted through an intact plate to get the frequency response of the PC structure. The normalized transmission response is shown in Figure 5. As it can be seen in Figure 5, more than 30dB drop in the transmission with a very sharp transition region is apparent in the 119MHz – 150MHz frequency range which is in excellent agreement with the results predicted by theory.

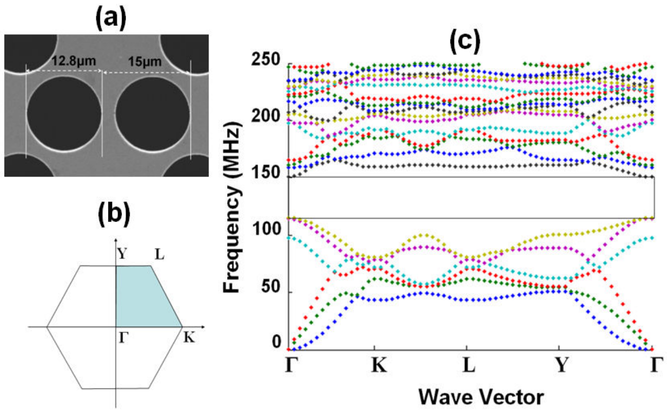

Figure 4. (a) Close SEM image of the PC structure indicating the lattice parameters, a = 15μm, and diameter of 12.8μm (r = 6.4μm). (b) Irreducible part of the Brillouin zone for hexagonal lattice in Si (c) Band structure of the hexagonal PC plate with $a = d$ = 15μm, and r = 12.8μm.

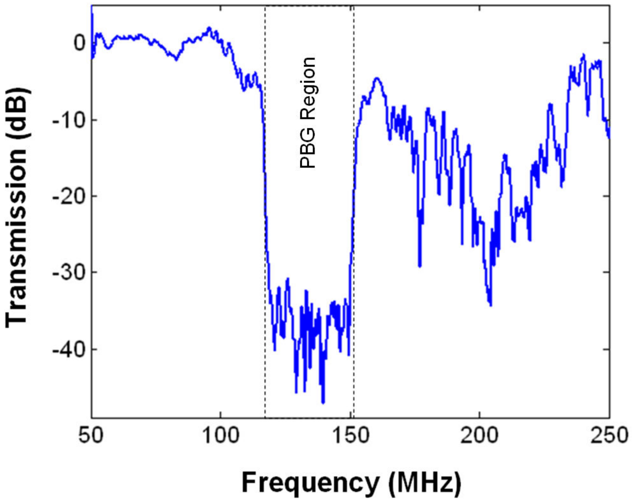

Figure 5. Average transmission through the PC structure as a function of frequency.

IV. CONCLUSION

We verified, by measuring the transmission through a PC plate made by etching eight layers of a hexagonal lattice of air filled holes through a free standing plate of Si, the existence of large PBGs in PC plates made of perforations through a solid plate. A CMOS compatible fabrication process is developed and used on a SOI substrate to realize the PC structure, and the appropriate transmission and receiving transducers. More than 30dB sharp attenuation is obtained within a frequency region that matches very well with the complete PBG region predicted by the PWE method. This result verifies the validity of the theoretical predictions of the existence of large complete PBGs in single crystalline PC plates. This result opens a new direction in the implementation of high-frequency, and high quality PC structures with a variety of applications especially in wireless communication devices and sensing systems.

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