Effects of release holes on microscale solid–solid phononic crystals


1Department of Electrical and Computer Engineering, University of New Mexico, Albuquerque, New Mexico 87131, USA
2Department of Mechanical Engineering, University of New Mexico, Albuquerque, New Mexico 87131, USA
3Department of Photonics Microsystems Technologies, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA
4Department of Advanced MEMS, Sandia National Laboratories, Albuquerque, New Mexico 87185, USA

(Received 18 March 2010; accepted 9 July 2010; published online 25 August 2010)

Solid–solid phononic crystals exhibit wider band gaps than those observed with air–solid phononic crystals. For micromachined phononic crystal devices it is advantageous to release the phononic crystal to avoid propagation losses. In a solid–solid phononic crystal operating in the low megahertz range, due to the large lattice constant, it is necessary to place release holes in the center of the inclusions to release devices from the substrate while minimizing the effect the release hole has on the band gap. In this report, we investigate the effect of release holes on phononic band gaps and highlight the need for careful design. It was determined that release holes of radius $r_{\text{air hole}}/r_{\text{inclusion}} = 0.26$ can reliably release a phononic crystal membrane composed of W inclusions in SiO$_2$ without significantly compromising the phononic band gap. © 2010 American Institute of Physics. [doi:10.1063/1.3476354]

Phononic crystals (PnCs) are composite structures where inclusions are periodically placed in a host medium (matrix) in the path of an elastic wave with the effect of modifying the propagation. The periodicity of the structure creates coherent scattering of the incident waves, resulting in a frequency range over which transmission is tremendously reduced, called a phononic band gap (PnBG). With rejection of up to 30 dB over a large frequency range, the PnBG can be manipulated to allow only desired signals to transmit in a controlled filtering process useful for communications. Furthermore, PnCs have been used in liquid sensing, where peak shifts in the transmission of waves can be correlated with the acoustic properties of the material, leading to the identification of the liquid. Other PnC based devices such as waveguides, structures for acoustic collimation, focusing, and negative refraction, have also been demonstrated.

Solid–solid (SS) PnCs (solid inclusions in a solid matrix) exhibit wider PnBGs (Ref. 1) compared to air–solid (AS) PnCs (Ref. 9) (air inclusions in a solid matrix). In a SS-PnC operating in the low megahertz range, it is necessary to place release holes in the PnC membrane to suspend the devices from the substrate to avoid propagation losses. The release holes are placed in the center of the inclusion so that the effect of the hole on the propagating wave is minimized, as the solid inclusion partially masks the release hole. Releasing SS-PnCs is more difficult than AS-PnCs because in the SS case the inclusion is filled with the solid material preventing the undercutting etchant from reaching the sacrificial layer. Because a large hole radius is needed to create a wide PnBG in AS-PnCs, the etchant can travel through the void inclusions to remove the sacrificial layer. Release holes in SS-PnCs have the same function of allowing the etchant to reach the sacrificial layer and suspend the PnC membrane. However, placing release holes in the center of the inclusions in a SS-PnC can interfere with a propagating wave, which partially penetrates through the inclusion and is scattered again at the inclusion–air interface, causing a disruption to the observed PnBG as compared with a PnC having no release holes. In this report, we study the effects of introducing release holes on the propagation of elastic waves through PnCs made of cylindrical tungsten (W) inclusions arrayed in a simple cubic arrangement in a SiO$_2$ host medium. Specifically, we investigate the maximum release hole size one can introduce in a PnC membrane without disturbing the PnBG as well as maintaining a reasonable release time during the fabrication process.

In our device, the distance in the plane of periodicity between the centers of horizontally or vertically adjacent W rods (the lattice pitch $a$) is 45 $\mu$m and the radius ($r$) of the W rods is 14.4 $\mu$m resulting in a $r/a$ ratio of 0.32, which was shown to produce the optimum PnBG in this choice of materials. Figure 1 shows a scanning electron microscope (SEM) image of a PnC with release holes in the center of the W inclusions. Aluminum nitride transducers are used to launch and receive a longitudinal elastic wave through the PnC. Due to the inherent narrow-band behavior of these

![FIG. 1. SEM of a W-in-SiO$_2$ PnC with $a=45$ $\mu$m and $r/a=0.32$.](image-url)
transducers, we use 12 different couplers for each crystal to cover the frequency range of interest.\textsuperscript{9}

The plane-wave-expansion (PWE) and finite-difference-time-domain (FDTD) methods were utilized to model elastic wave propagation in our device. Throughout this letter, branches in the band structure have been separated into longitudinal and in-plane transverse modes. While comparing the results obtained using the PWE method to experimental results as well as FDTD results, the in-plane transverse branches were ignored. Ignoring such modes is consistent with the fact that experimental results obtained using a network analyzer show only longitudinal modes, due to the lack of transduction for in-plane and out-of-plane transverse modes inherent in our slanted transducer designs. This effect was included in our FDTD model, which is capable of exciting and detecting all acoustic wave types, by preferentially exciting only longitudinal modes. It is acknowledged that scattering can couple a launched mode with displacement in the longitudinal direction to an in-plane transverse mode. However, since the receivers in both the experimental and FDTD data only detect longitudinal and flexural modes, this coupling manifests as a loss factor that is insignificant relative to the propagating longitudinal signal due to the short transmission length of the device. For this reason, only the longitudinal branches of the band structure obtained using the two-dimensional (infinite thickness) PWE model for propagation in the $\Gamma X$ direction of the first Brillouin zone were used to compare with the experimental and three-dimensional FDTD results. Figure 2 shows the PWE results of elastic transmission through a crystal with release hole radii of 0, 2.5, 3.75, 5, 6.25, and 7.5 $\mu$m. The PnBG appears in the case with no release holes between 37 and 78 MHz. Introducing a release hole of radius 2.5 $\mu$m leads to a modification of the PnBG, resulting in a slightly smaller bandwidth, namely, between 37 and 70 MHz. With a 3.75 $\mu$m release hole, a second PnBG appears creating two distinct PnBGs; one between 65 and 80 MHz and the other between 37 and 60 MHz, with a longitudinal mode appearing between 60 and 65 MHz. Figures 2(d)–2(f) further show the longitudinal branch progressively appearing at lower frequencies between the PnBGs as the release hole size is increased. The longitudinal branch which causes the closure of the lower PnBG is flat, especially on the edges of the first Brillouin zone, which means that its group velocity is extremely small and the density of phononic states is very large, allowing the mode to interfere strongly with the PnBG.

The W–SiO$_2$ PnC with the aforementioned dimensions is fabricated using the process reported by Soliman \textit{et al.}\textsuperscript{10} and the design is similar with the variation that 12 different slanted Al couplers are used to actuate the AIN film at small frequency intervals instead of a single slanted coupler used previously. It is clear from Fig. 2 that eliminating the release holes yields the widest PnBG. Such devices are challenging to undercut using only release pits on either side of the PnC membrane because the structures are large (around 500 $\mu$m$\times$500 $\mu$m) which necessitates the use of release holes with a corresponding smaller PnBG. PnCs with 2.5, 3.75, and 7.5 $\mu$m release hole radii were fabricated to compare with the theoretical results. The release hole of radius 2.5 $\mu$m was not large enough to easily release the PnC membrane as reported in Soliman \textit{et al.}\textsuperscript{10}

Figure 3 shows a comparison between FDTD, PWE, and the experimental results for PnCs with release hole radii of (a) 3.75 $\mu$m and (b) 7.5 $\mu$m. The plots of the branches in the band structure are rotated 90 degree for comparison. Good agreement is achieved between the PWE band structure and the PnBG shown experimentally. FDTD shows the PnBG extending over a slightly larger frequency range as compared to the experimental and the PWE results. While this $\sim$5% discrepancy is reasonably small, it can be attributed to the weak scattering of the longitudinal modes into flexural modes of the membrane. Such modes are detected by the network analyzer, albeit inefficiently compared with longitudinal modes, but were ignored in the FDTD simulation and the two-dimensional PWE calculation. The difference in the depth of the PnBG can be attributed to material losses which are not accounted for in the FDTD simulation. The PnBG is continuous with no splitting or reduction in both the experimental and theoretical results shown.

Figure 3(b) further shows the excellent agreement in predicting the location of the PnBG between the band structure and experimental results for devices with release holes of radius 7.5 $\mu$m. Comparing Figs. 3(a) and 3(b), a mode is observed between 40 and 50 MHz for the device with the
7.5 μm release holes. A second PnBG appears above the original PnBG when the size of the release hole becomes comparable to the wavelength and thus is large enough to be resolved by the elastic wave. Once the air hole is large enough to scatter the propagating waves, second-order scattering takes place at the W–air interface, which creates the second PnBG and reduces the bandwidth of the first, lower frequency PnBG.

Figure 4 shows a theoretical comparison among devices with various release hole sizes in the center of the W rods using FDTD. Again, it can be observed that a splitting of the PnBG compromises the width of the PnBG when a large enough air hole is introduced in the center of the W rods. The mode separating the two PnBGs shifts to lower frequencies as the air hole size becomes greater, which is consistent with the results obtained with PWE. The case with no release hole was calculated theoretically but is impractical to fabricate with the current technology because of release difficulty previously discussed. Indeed, introducing release holes in the center of the W rods has a profound effect on the PnBG when they are large enough; therefore, these holes must be carefully designed to prevent adverse effects on the transmission through the PnCs.

In summary, we reported the effects of release holes, necessary to suspend PnCs to avoid losses to the substrate, on the transmission of elastic waves in PnCs. Release holes are only necessary in the case of SS-PnCs operating in the low-megahertz regime. PnBG splitting occurs when release holes are introduced, with a reduction in the bandwidth of the resulting PnBGs as the release hole size increases. The PnBG corresponding to the 3.75 μm release hole radius was not significantly disrupted by the release hole, although the PnBG splits when the release hole radius is increased to 7.5 μm. Therefore, for reliable fabrication of SS-PnCs, careful design of the release holes is required to avoid compromising the PnBG.

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.