DESIGN AND FABRICATION OF 2D PHONONIC CRTSTALS IN SURFACE ACOUSTIC WAVE MICRO DEVICES

K.-B. Gu[1] , *C.-L. Chang*[2], *J.-C. Shieh*[1], *W.-P. Shih*[3]

[1] Department of Bio-industrial Mechatronics Engineering, National Taiwan University, Taipei, Taiwan

[2]NEMS Platform Research Department, Canon Research Center, Canon Inc., Japan

[3]Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

ABSTRACT

In this paper, we present the design and fabrication of innovative phononic crystals integrated with two sets of interdigital (IDT) electrodes for frequency band selection of surface acoustic waves (SAW). The potential applications of this device include performance improvement of SAW micro-sensors, front-end components in RF circuitries, and directional receptions of high frequency acoustic waves. Analogous to the band-gap generated by photonic crystals, the phononic crystals, two dimensional repetitive structures composed of two different elastic materials, can prohibit the propagation of elastic waves with either specific incident angles or certain bandwidth. In this paper, the prohibited bandwidth has been verified by fabricating the phononic crystals between a micromachined SAW resonator and a receiver. Both the resonator and receiver are composed of IDT electrodes deposited and patterned on a thin piezoelectric layer. To confine the prohibited bandwidth on the order of hundred MHz, the diameter of the circular pores in phononic crystals is designed to be 6 micron and the aspect ratio of each pore is 3:1. To maximize the power transduction from IDT electrodes to SAW, the spacing between two inter-digits is one-fourth the wavelength of SAW. Specifically, the spacing ranges from 3.4 microns to 9.0 microns, depending on the central frequency. Both surface and bulk micromachining are employed and integrated to fabricate the crystals as well as SAW resonator and receiver altogether. Firstly, a 1.5-micron zinc oxide, which provides well-defined central frequency, is sputtered and patterned onto silicon substrate. Second, the IDT electrodes are evaporated and patterned by lift-off technique. Then the exposed silicon substrate is etched using DRIE to generate two dimensional phononic crystals. To tune the prohibited SAW bandwidth, the crystal pores are filled with copper or nickel by electroless plating. The insertion loss of the fabricated devices is characterized and is found to agree with simulation results.

1. INTRODUCTION

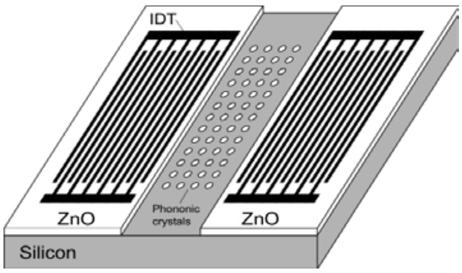
There has been a growing attention for studying periodic dielectric composite structures during the past two decades. The transparent dielectric periodic arrays are capable of inducing stop bands within some frequency range, i.e., photonic crystals. In recent years, the application of photonic crystals is an exciting topic for line defect waveguides [1], sharp bending of light [2], etc. In the 1990s, it was discovered that there are considerable analogy between electromagnetic waves and elastic vibrations [3-5]. The repetitive structures made up of different materials can prevent elastic waves from passing by at some specific angles or in certain frequency bands, and are called phononic crystals.

In the recent years there are literatures aimed at studying the phononic structures both experimentally and theoretically [6-7]. However, the smallest scale of the phononic crystals considered in the existing literatures was in the millimeter scale, and the frequency was all limited in the MHz range. In order to investigate the stop band of surface acoustic waves in a 2-D phononic structure with lattice size in the micron scale and frequency in the couple hundred MHz, The design of the experiment of the 2-D phononic crystals is expected to integrate with microfabrication. Therefore, we choose silicon wafer as the substrate. In order to generate surface acoustic wave in the silicon substrate, piezoelectric thin film is sputtered on top of the wafer. Moreover, the 2-D phononic crystals is fabricated by ICP etching (inductively coupled plasma-reactive ion etching) process.

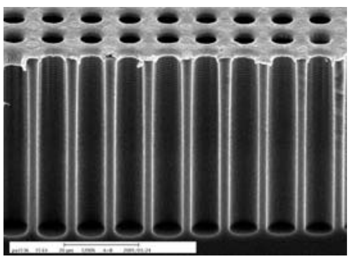
From the experimental results, we observe that the power of the surface wave is diminished when the pass band of the SAW filter is located in the band gap of the phononic structure. On the contrary, as the pass band of the SAW filter is not within the band gap, most of the SAW power can be received by the receiving IDT.

2. DESIGN

Figure 1 shows the schematic diagram of the 2D phononic crystals in SAW micro devices. Silicon substrate is used because it can be easily patterned to form high-aspect-ratio crystals. Zinc oxide is used as the piezoelectric layer for its simple fabrication process of deposition and wet etching. Aluminum is the electrode material because its small density generates negligible mass loading effect, and hence the central frequency will not be shifted. Analogous to the band-gap generated by photonic crystals, the phononic crystals, two dimensional repetitive structures composed of two different elastic materials, can prohibit the propagation of elastic waves with either specific incident angles or certain bandwidth. As a result, the photonic crystals will be filled with, respectively, copper and nickel for the comparison of band-selection efficiency.



(a)



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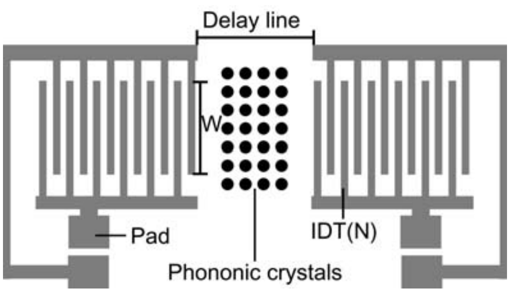

(c)

Figure 1: (a) Schematics of 2D phononic crystals in SAW micro devices. (b) SEM image of fabricated phononic crystals. (c) Dimensions of SAW device and phononic crystals.

Table I lists the design parameters. The spacing between two inter-digits is one-fourth the wavelength of SAW. In periodic phononic crystal array design, the diameter of crystal pores is 6.0μm and the spacing between adjacent pores is 10.0 μm. So the filling fraction equals $(\pi r^2)/a^2$. In this case, we choose the filling fraction as 0.283 (r/a=0.3) [8]. It should be noted that the energy of surface acoustic waves is mostly confined to a depth of two wavelengths. It means the depth of each pore should be at least twice the wave length (λ). Based on the simulation result, the band gap of copper/silicon is located within 152.46MHz to 182.20MHz.

Table I: Design parameters of layered SAW device and phononic crystals.

Configuration	**Parameter**		
Electrode	Aluminum		
λ (μm)	28.0	24.8	21.6
IDT pairs	40		
IDT aperture (μm)	100λ		
Delay line (μm)	10λ		
IDT thickness (Å)	2000		
Diameter of crystal pores, 2r (μm)	6		
spacing of pores, a (μm)	10		
Depth of pores (μm)	more than twice λ		
Thickness of ZnO (μm)	1.5		

The phase velocity (V) on excited layered zinc oxide piezoelectric thin film is chosen to be 4300 m/s. According to $V=f\ \lambda$, the central frequency depend on the designed wavelength will fall into the band gap when the range of λ between 23.8 to 28.0 μm. In addition, each IDT transducer has a 100λ aperture length, and the distance between the input and output transducers is 10λ. The distance (d) between the input and output transducers should be an integer multiple of wavelength. When d decreases, significant electromagnetic feedthrough might occur. When d increases, great propagation loss of SAW could be induced. As a result, d = 10λ is a suitable choice. The number of the finger pairs is 40. Aluminum is chosen to be the IDT material with the thickness of 2000Å. If the electrode is too thin, large resistance, increased insertion loss, and low Q-factor are inevitable. In the contrast, the electrodes with very large thickness will result in obvious mass-loading effect and finger-reflection effect. Typically, when the IDT thickness divided by λ is less than 1%, the finger reflection effect can be neglected. Finally, the thickness of zinc oxide thin film is about 1.5μm. This thickness is sufficient to provide good piezoelectric property in this study and avoid large shift of the measured central frequency.

3. FABRICATION

Figure 2 shows total fabrication process. Firstly, a 1.5-micron zinc oxide, which provides well-defined central frequency, is sputtered on the silicon substrate. This piezoelectric layer is then patterned with H_3PO_4/HAc/DI water (1:1:10) solution. The etch rate is about 50nm/sec. Then the exposed silicon substrate is etched using DRIE to generate two dimensional phononic crystals. To tune the prohibited SAW bandwidth, the crystal pores are filled with copper by thermal evaporation of the seed layer, followed by the electroplating. It should be noted that two different plating electrolytes are used in this study. The basic electrolyte, as listed in Table II [9], include 0.25 mol/L CuSO4 and 1.8 mol/L H_2SO_4 to which a combination of 1.0×10^{-3} mol/L NaCl (Cl). In the other electrolyte, 8.8×10^{-5} mol/L $H(OCH_2CH_2)_{55}OH$ (PEG, average molar mass ~ 3400 g/mol) is added. The purpose of the PEG addition is to achieve the superfilling in the deep silicon pores. A comparison of the plating results with the PEG additives is shown in Fig. 3. After using copper etchant ($HAc+H_2O_2$+DI water =1:1:20) to remove the superfluous copper above silicon substrate, the copper residues attached to the photoresist above the silicon substrate is removed by acetone. Finally, the IDT is deposited using e-beam evaporation and patterned by lift-off techniques. The fabricated devices are shown in Fig. 4.

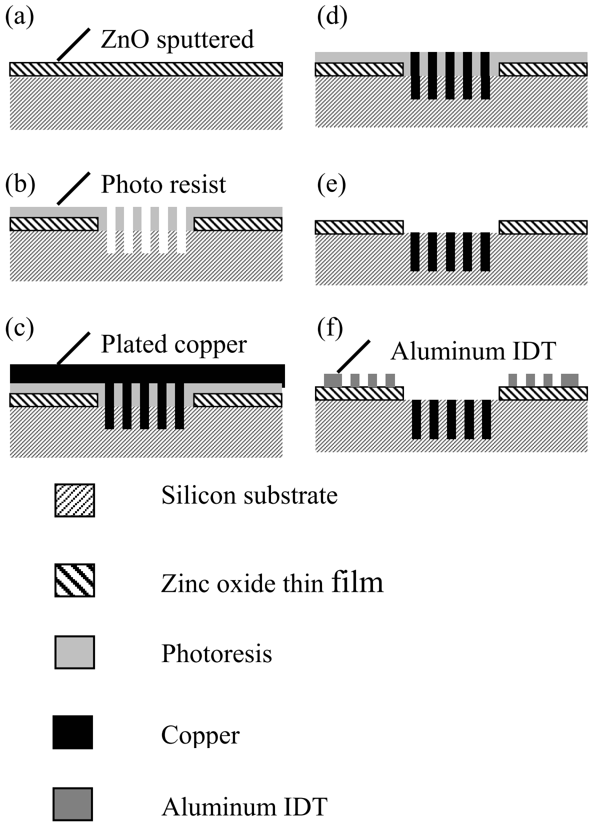

Figure 2. Process flow of 2D phononic crystals in SAW micro devices. (a) A 1.5-micron zinc oxide is sputtered and patterned onto silicon substrate. (b) The exposed silicon substrate is etched using DRIE to generate two dimensional phononic crystals. (c) Copper seed layer is evaporated. To tune the prohibited SAW bandwidth, the crystal pores are filled with copper by electro plating. (d) The overplated copper is removed by acetic acid. (e) Photolithography is performed for the lift-off proce4ss. (f) Aluminum is deposited and patterned as the IDT structure by lift-off method.

4. DISCUSSION AND CONCLUSION

This study focuses on the propagation of high frequency SAW in 2-D phononic structures with micrometer scales. We constructed the copper/silicon pore arrays which are designed to investigate the phenomenon of the phononic band gap and to verify our simulation. The pore arrays can be filled with various materials to study the influence on the frequency band gap. The energy of surface acoustic waves has obviously vanished with great attenuation when the central frequency is in the range of 152.46MHz to 182.20MHz. The simulation results are in good agreements with the experimental measured results. It is worth noting that this is a first try on integrating surface micromachining and bulk-micromachining techniques to fabricated 2-D phononic crystals instead of drilling holes in a solid substrate and the results may find potential applications in MEMS applications.

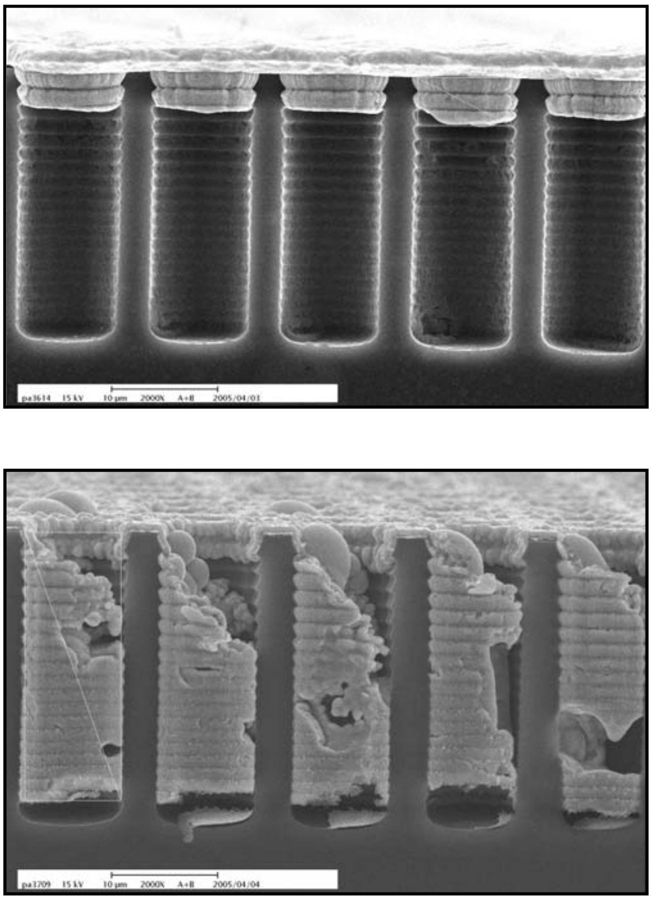

Figure 3. Cross-sectional SEM pictures show the effect of bottom void (a) without and (b) with PEG additives in the plating electrolytes.

5. ACKNOWLEDGMENTS

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Table II. Electrolyte composition (mole/L)

	Basic electrolyte
$H_2SO_4 \cdot 5H_2O$	0.25
H_2SO_4	1.8
Cl^-	1×10^{-3}
PEG (3400 Mw)	0
pH	1.2~1.7
Current density (A/m^2)	300

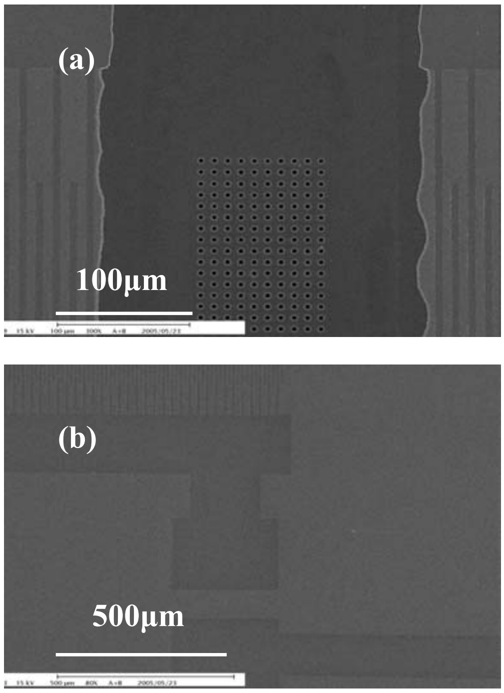

Figure 4. (a) SEM picture of 2D phononic crystals in SAW micro devices. (b) SEM picture of aluminum pad of IDT.