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Spider Web-Shaped Phononic Crystals for Quality Factor Improvement of Piezoelectric-on-Silicon MEMS resonators

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***Abstract*—This paper shows the approach to significantly reduce the energy dissipation of thin-film piezoelectric-on-silicon (TPoS) micro-electro-mechanical systems (MEMS) resonator by employing a 2D innovative lightweight spider web-shape phononic crystals (PnC) structure. An AlN-on-Si MEMS resonator, which is working at 40 MHz 5th-order width-extensional (WE) resonant mode, is selected to investigate the energy dissipation reduction by the proposed PnC. According to the simulation results, the proposed PnC structure shows a complete acoustic bandgap from 37 MHz to 44 MHz and can significantly reduce the energy loss. Moreover, the anchor loss (Q_{anc}) of the resonator reached 2,090,000 at 40.03 MHz.**

Keywords—MEMS resonator, Phononic crystals, Quality factor, Anchor loss

I. INTRODUCTION

Thin-film piezoelectric-on-silicon (TPoS) micro-electro-mechanical systems (MEMS) resonators have aroused a tremendous interest in the past decade, due to the great potential applications including sensors [1-2], filters [3] and oscillators [4]. However, to truly affect these practical applications, the quality factor (Q) of MEMS resonators needs to be further improved.

In MEMS resonators, energy losses can be divided into the following items: anchor loss [5-13], thermoelastic damping (TED) loss [14], surface loss, interface loss [15], air damping loss [16] and other losses. Among these items, anchor loss has been considered as one of the most dominating factors causing the reduction of Q.

To reduce anchor loss, approaches including employing trenches as acoustic reflectors [17], using thicker silicon devise layers [18] and modifying resonator structures [19-20] are proposed by many researchers. Moreover, exploiting phononic crystals (PnC) [21-23] as a frequency-selective reflector to reduce the energy leakage out of the resonator, thereby improving Q, has been recognized to be an effective approach recently. Given this, an innovative lightweight spider web-shaped PnC structure was proposed to significantly reduce the anchor loss of MEMS resonators in this work.

II. DESIGN AND MODELING

Q is commonly used to measure the energy dissipations of a resonator as an indicator, which can be defined as:

$$Q = 2\pi \frac{E_{stored}}{E_{lost}} \tag{1}$$

where E_{stored} and E_{lost} refer to the stored energy and energy dissipations of resonators for a unit time, respectively.

As shown in Fig. 1, an AlN-on-Si MEMS resonator (i.e., 10 μm thick Si, 0.5 μm thick AlN and 1 μm thick Al), which is working at 40 MHz 5th-order width-extensional (WE) resonant mode, was designed to investigate the energy dissipation reduction by the proposed PnC. The resonant frequency can be calculated by:

$$f_0 = \frac{n}{2W_r}\sqrt{\frac{E}{\rho}} \tag{2}$$

where W_r is the width between two electrodes, ρ is the density of resonators, E is the Young's moduls in <110> axes and n is the number of resonant mode orders.

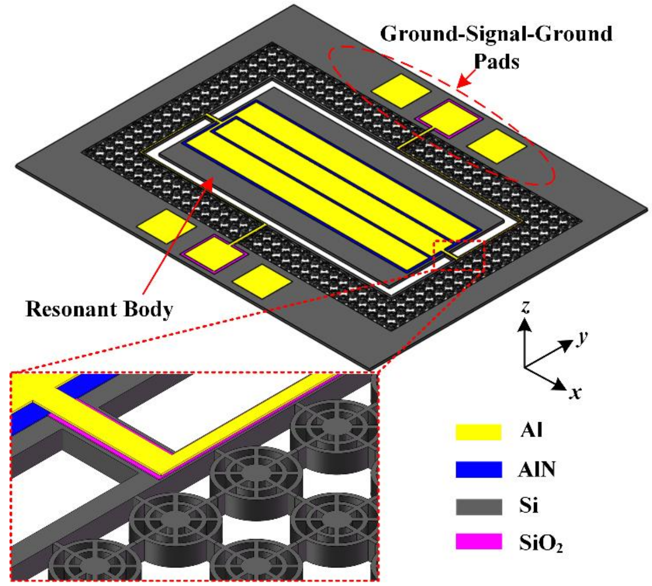

Fig. 1. 3D Illustration of the proposed piezoelectric-on-silicon MEMS resonator with 2D spider web-shaped phononic crystals (PnC) structure.

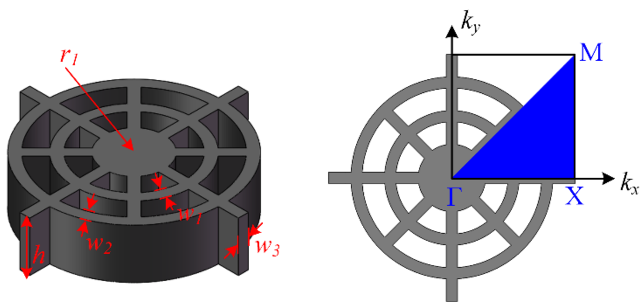

Fig. 2. The schematic view of a PnC unit cell and its Irreducible Brillouin Zone in *k*-space.

Fig. 2 shows the 3D model of the proposed PnC and the Irreducible Brillouin Zone for its unit cell. The thickness (h) of the PnC structure is defined as 10 µm, equal to that of the silicon substrate of the resonator. Besides, for other designed dimensions, the lattice constant (a) and radius (r_1) of circle are 44 µm, 6 µm, respectively, while width of two rings (w_1, w_2) and narrow beams (w_3) are equally set as 2 µm.

III. SIMULATION AND RESULTS

Simulated transmission S21 of delay line and solid line were performed in this work to further verify the existence of complete bandgap, which can be calculated in decibels as:

$$S21 = 20\log_{10}\left(\frac{P_{out}}{P_{in}}\right) \tag{3}$$

where P_{in} refers to the value of input power in the delay line and solid line, which is set as 0 dBm, while P_{out} is that of output power. As shown in Fig.3(a) and (b), the delay line is the model with PnC array as the transmission medium between drive and sense electrodes while the solid line employes a solid strip.

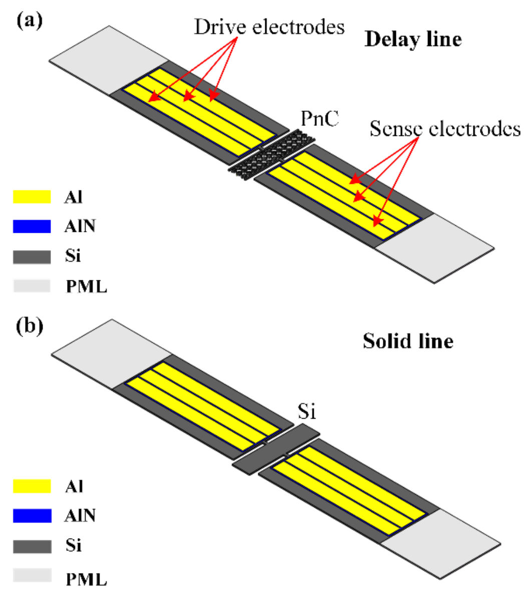

Fig. 3. The schematic view of (a) a delay line with PnC structure and (b) a solid line with solid strip.

In addition, Perfectly Matched Layers (PMLs) were used in all the models to absorb the acoustic waves to avoid the reflected waves stimulating unexpected spurious peaks. According to the Bloch-Floquet thearom, the periodic boundary condition was applied to simulate the dispersion relation of the proposed PnC by finite-element-analysis (FEA) simulation in COMSOL. The left side in Fig.4(b) shows a complete bandgap in the frequency range from 37 to 44 MHz, which include the resonant frequency. Meanwhile, transmission spectra of acoustic waves through a finite PnC array shows the significant attenuation, which are highly consistent with the acoustic bandgaps. Fig. 4 proves that a bandgap can truely inhibit the propagation of acoustic waves, thereby reducing the energy loss, which is up to 19.4 dB at 39.9 MHz.

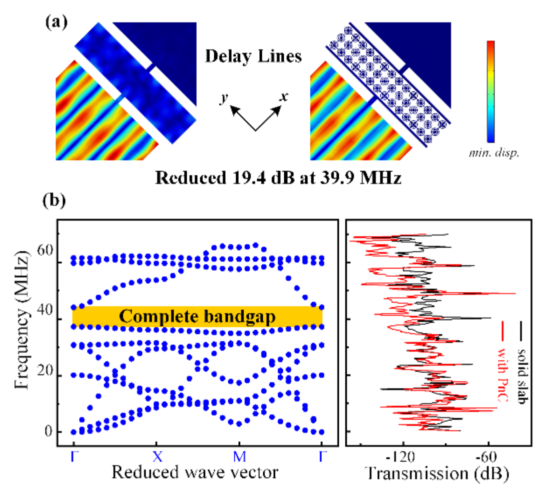

Fig. 4. (a) The mode shapes of delay line and solid line. (b) Dispersion relation of the proposed PnC showing one complete bandgap in the frequency range from 37 to 44 MHz. Meanwhile, transmission spectra of acoustic waves through a finite PnC array showing the significant attenuation, which are highly consistent with the acoustic bandgaps.

In this research, anchor loss (Q_{anc}) is the only one being considered to determine Q as one of the major energy losses, which can be calculated by:

$$Q_{anc} = \frac{\mathrm{Re}(\omega)}{2\,\mathrm{Im}(\omega)} \tag{4}$$

where $\mathrm{Re}(\omega)$ and $\mathrm{Im}(\omega)$ are the real part and imagery part of eigenfrequency of resonators, respectively. Simulations reveal that the Q of 5th-order WE mode MEMS resonators without PnC is 35,790 while that of resonators with PnC is 2,090,000 at 40.03MHz, which indicates the spider web-shaped PnC can effectively reduce the anchor loss.

IV. CONCLUSIONS

In this work, a 2D spider web-shaped PnC structure was proposed as a frequency-selective reflector to reduce the energy leakage out of the 5th-order WE mode MEMS resonator. FEA simulation was employed to systematically investigate the proposed PnC. In comparison with the resonator without PnC, the Q of resonator with spider web-shaped PnC reached up to 2,090,000 at 40.03 MHz, indicating an enhancement by 58.4 times. These results reveal that PnC has great potential in the applications of MEMS devices.

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