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Fish Scale-shaped Acoustic Reflector Array for Quality Factor Enhancement of AlN-on-Silicon MEMS Resonator

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Abstract**—This paper presents a strategy for quality factor (*Q*) enhancement of MEMS (micro-electro-mechanical systems) resonator, based on reducing anchor loss. *Q* is an extremely important property, which affects the practical application of MEMS resonator in many fields. The important measure to improve *Q* is to reduce anchor loss that is the dominant energy loss of thin-film piezoelectric-on-silicon (TPoS) MEMS resonators. So, we propose a fish scale-shaped acoustic reflector array to reflect the leaked acoustic wave and it thus significantly reduce the anchor loss. Compared with the traditional single reflector, the proposed reflector array can more effect suppress the energy dissipation. Moreover, we integrate the reflector array inside resonant body rather than the traditional design that place reflector at the behind of tethers, which can observably enhance the *Q* without increasing the occupied area. The *Q* of the proposed structure is obtained by using finite-element-analysis (FEA) simulation, which achieved a 3.5-fold improvement (i.e. Q_u=17, 414) compared with the traditional design (i.e. Q_u=4, 913).**

Keywords—MEMS, resonator, quality factor, anchor loss

I. Introduction

Micro-electro-mechanical system (MEMS) technology has shown a promising prospects in many fields, due to the advantages of miniaturization and integration, including timing reference, frequency control and sensors [1]-[5]. In these applications, MEMS resonator is necessary and critical. Among different kinds of MEMS resonators, the thin-film piezoelectric-on-silicon (TPoS) MEMS resonators have attracted a significant attention because of the high *Q*, high power handling capability and sufficient electromechanical coupling efficiency. Moreover, the resonant frequency is defined by the center-to-center distance between two adjacent electrodes, which can realize the multiple-frequency solution on a single chip [6], [7], [8]. However, compared with quartz crystal resonators and capacitive MEMS resonators (*Q* usually larger than 100,000), the practical application of TPoS resonator is limited by low *Q* (generally around 1, 000). Because high *Q* can reduce the phase noise of oscillator, increase the noise rejection of filter and improve the signal-to-noise ratio of sensor. So, it is very important to study the strategy for *Q* enhancement of TPoS resonator [9]-[12].

TPoS resonator is an electromechanical device in which electrical and mechanical energies are reciprocally converted to each other. *Q* is the quantitative indicator of energy loss during the conversion process. The main energy loss of TPoS resonator is anchor loss, which is generated because the acoustic energy leaks from resonant to substrate via tethers [13], [14], [15]. There are many approaches to reduce anchor loss, such as using the in-plane acoustic reflectors to reflect the leaked acoustic waves from the anchoring substrate to the resonant body [16], designing the biconvex structure to confine the acoustic energy in the center of resonator thereby reducing acoustic energy leakage [17] and adding a suspended frame structure or phononic crystals (PnC) at tethers to suppress the energy dissipation [18], [19]. However, most of these approaches rely on incorporating additional structures in the periphery of resonator, which not only increase the area of device, but can't suppress the acoustic energy leaked out via tethers. Given this, we proposed a strategy that integrated fish scale-shaped acoustic reflector array on resonator to trap acoustic energy in the center of resonant body and thus reduce anchor loss significantly.

II. Resonator Design And Finite Element Analysis

Fig. 1 shows the proposed TPoS resonator that work in fifth-order width-extensional mode. The resonant frequency is determined by the width of resonant body in *y* direction (W_r) or the center-to-center distance between two interdigital electrodes (W_p) [20]:

$$f_r = \frac{n}{2W_r}\sqrt{\frac{E}{\rho}} = \frac{1}{2W_P}\sqrt{\frac{E}{\rho}} \quad (1)$$

Where *n* is the order of vibration mode, *E* is the Young's modulus and ρ is the density of silicon. Compared with the traditional resonator, the fish scale-shaped acoustic reflector array is integrated inside resonant body by reducing the length of electrodes in *x* direction, as shown in Fig. 1(a). The resonant body comprises a thin-film piezoelectric layer (0.5 μm thick aluminum nitride, AlN) sandwiched by the upper metallic electrodes (1 μm thick aluminum, Al) and the bottom substrate (10 μm thick silicon, Si). It is noteworthy that the bottom substrate is designed as ground electrodes by using anisotropic doped silicon and there is a Silicon-on-Insulator (SOI) substrate, as shown in Fig. 1(b).

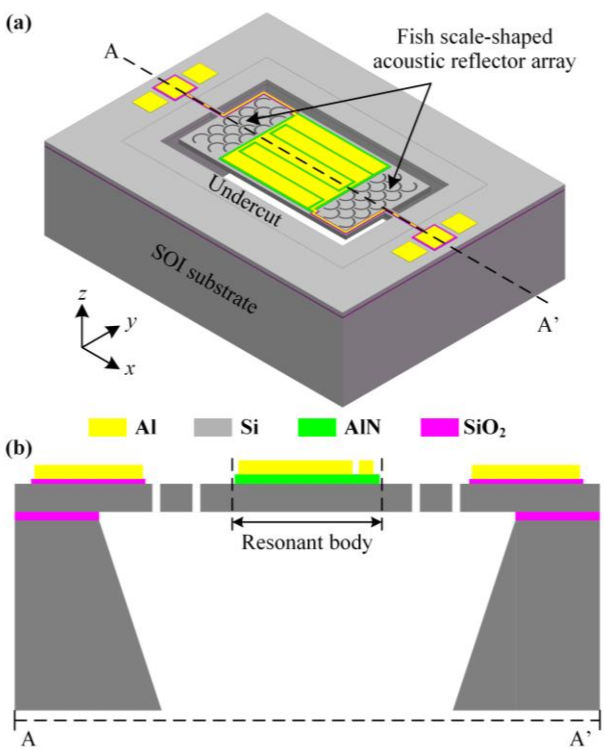

Fig. 1. Illustration of the proposed aluminum nitride-on-silicon (AlN-on-Si) MEMS resonators. (a) 3D schematic view of the proposed configuration that integrats fish scale-shaped acoustic reflector array inside resonant body. (b) Transverse view schematic taken along the dashed line (A-A')

The elasticity value of the silicon used in FEA simulation is defined as [21]:

$$\begin{aligned} &E_x = E_y = 169 \text{ GPa} \quad E_z = 130 \text{ GPa} \quad \rho\text{=}2330 \text{ kg/m}^3 \\ &\sigma_{yz} = 0.36 \quad \sigma_{zx} = 0.28 \quad \sigma_{xy} = 0.0064 \\ &G_{yz} = G_{zx} = 79.6 \text{ GPa} \quad G_{xy} = 50.9 \text{ GPa} \end{aligned} \quad (2)$$

where σ is the Poisson's ratio and *G* is the Shear Modulus.

TPoS resonators exhibit a strong electromechanical coupling, but unlike the capacitive resonators that tend to show a very high *Q*. Because there is massive energy loss and *Q* is the quantitative indicator of energy loss that can be expressed as:

$$Q\text{=}2\pi\times\frac{E_{\text{stored}}}{E_{\text{dissipated}}} \quad (3)$$

where E_{stored} is the energy stored in resonator and $E_{\text{dissipated}}$ is the energy dissipated per cycle of vibration. Different energy loss mechanisms have been studied, including anchor loss, interface loss, thermoelastic damping (TED), material damping, and other losses. Among different energy loss, anchor loss is the main energy dissipation source, so we simplify the total *Q* (Q_{total}) is contributed by anchor loss (Q_{anchor}) and other losses (Q_{other}).

$$\frac{1}{Q_{\text{total}}} = \frac{1}{Q_{\text{anchor}}} + \frac{1}{Q_{\text{other}}} \quad (4)$$

In order to significantly improve the *Q* of TPoS resonator, we designed a fish scale-shaped acoustic reflector array to reduce the anchor loss. Moreover, we integrate the reflector array inside resonant body rather than the traditional design that place reflector at the behind of tethers. So, we can reflect more leaked acoustic waves to the center of resonant body and thus significantly suppressing the energy dissipation.

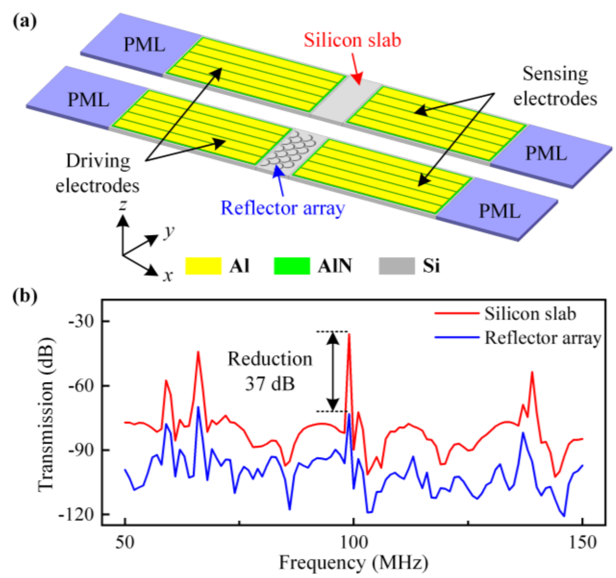

Fig. 2. The systematically study of transmission characteristic for the fish scale-shaped acoustic reflector array. (a) Simulation models of delay line with different mediums between driving and sensing electrodes. (b) Transmission spectra of two delay lines that indicating a 37dB reduction at the resonant frequency.

We well designed the delay line model to demonstrate the proposed reflector array can prevent the propagation of acoustic wave, as shown in Fig. 2. The method of constructing the delay line model is shown in Fig. 2(a). There are different mediums between driving and sensing electrodes for two delay lines. Driving electrodes are used to simulate the vibration of resonator and sensing electrodes are used to detect the output displacement.

The perfectly matched layer (PML) is applied to both ends of the delay line to reduce the reflection of acoustic wave that would introduce spurious peaks in the transmission spectra. Fig. 2(b) shows the effect of the proposed reflector array, from which we can see that there is a 37dB reduction at the resonant frequency.

We investigated the effect of proposed fish scale-shaped acoustic reflector array for reducing anchor loss by finite-element analysis (FEA) simulation, as shown in Fig. 3. In order to simplify the simulation model, we use the PML boundary conditions to replace the 400 μm thick SOI substrate and the width of PML is 3-fold wavelength (3λ). The simulation model in COMSOL Multiphysics is shown in Fig. 3(a), there is a quarter section of the resonator due to the conditions. Q_{anc} is obtained by FEA simulation, which can be calculated by applying PML boundary conditions [22]:

$$Q_{anc} = \frac{\mathrm{Re}(\omega)}{2 \times \mathrm{Im}(\omega)} \tag{5}$$

where ω is the eigen-frequency of the resonant frequency, $\mathrm{Re}(\omega)$ and $\mathrm{Im}(\omega)$ represent the real and imaginary parts, respectively. Fig. 3(b) shows the simulation results, from which we can see that the proposed reflector array can significantly prevent the spread of acoustic wave from the resonant body to substrate and thus reduce the anchor loss. The energy is trapped in the center of resonant body by investigating the distribution of strain.

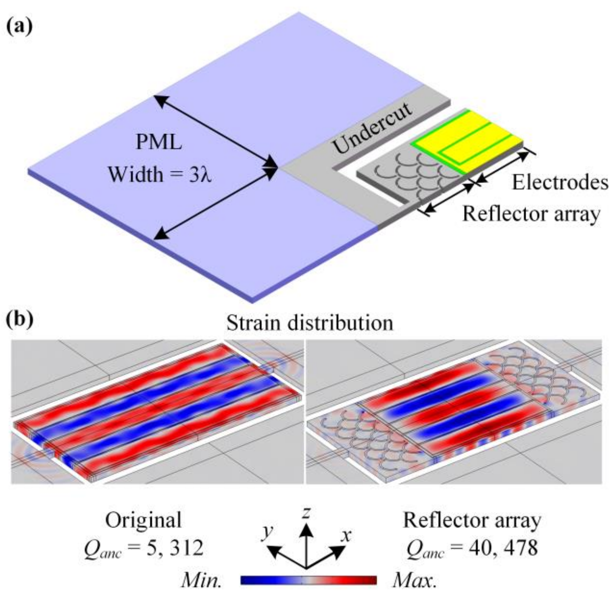

Fig. 3. Investigation of the effect of fish scale-shaped acoustic reflector array for reducing anchor loss by finite-element analysis (FEA) simulation. (a) The simulation model with perfectly matched layers (PMLs, '3λ' means 3-fold wavelength) boundary conditions. It requires only a quarter section of the resonator due to the symmetric. (b) Investigation of the Q enhancement mechanisms by comparing the distribution of strain.

III. Result and Discussions

Fig. 4 shows the S21 parameters of the resonators with and without reflector array. The Q of the resonator with the proposed reflector array gained a 3.5-fold improvement (i.e. Q_u=17, 414) compared with the conventional one (i.e. Q_u=4, 913). In addition, it can be determined the proposed reflector array can trap acoustic energy in the center of resonant body and thus reduce anchor loss by comparing the maximum displacement of vibration mode. The change of resonant frequency is due to the hole of reflector changed the equivalent Young's modulus and density of resonator.

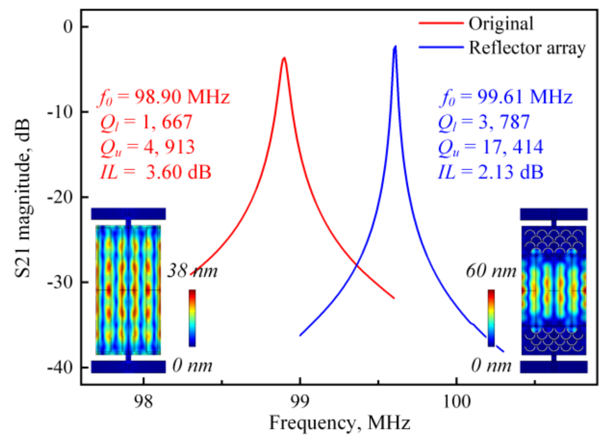

Fig. 4. S21 parameters of the resonators with and without reflector array that revealing a 3.5-fold enhancement of Q.

IV. Conclusions

In this paper, we propose a fish scale-shaped acoustic reflector arrays and integrated it inside the resonant body at a chosen distance away from the center electrodes. The AlN-on-Silicon MEMS resonator in fifth-order width-extensional mode is selected to estimate the efficacy of the proposed strategy by using finite-element-analysis (FEA) simulation in COMSOL Multiphysics. The strategy we proposed can enhance the confinement of acoustic energy and consequently minimize the anchor loss. Moreover, the Q is significantly improved without increasing the area of the resonator.

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