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Enhancing quality factor by etch holes in piezoelectric-on-silicon lateral mode resonators

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ABSTRACT

We report a unique method of using etch-holes to greatly improve the unloaded quality factor (Q_u) of VHF-band low impedance laterally vibrating AlN Thin-film Piezoelectric-on-silicon (TPoS) MEMS resonators. We have validated the proposed method experimentally by applying it to fabricated devices operating at their 5th order modes with resonant frequencies of 105 MHz. The largest improvement in Q_u resulting from adding holes was found to be 5.7 times on average using the proposed method. The experimental results are corroborated by finite-element (FE) simulations which show that the holes re-distribute the strain energy in the resonator body. The re-distribution of strain energy consequently greatly suppresses the axial-direction deformation in the supporting beam tethers and undercut anchoring regions. Having less energy in the supporting tethers and undercut anchoring regions leads to a reduction of anchor loss and thus enhances Q_u particularly when Q_u is limited by anchor loss. It was also found that this effect of enhancing Q_u through the proposed approach remains significant for different supporting tether lengths. Experimental results show that the increase in Q_u going from plain resonators to resonators with holes is consistent regardless of tether lengths variation (i.e. the measured variation in Q_u for different tether lengths is insignificant compared to the increase from adding etch holes). In comparison, no increase in Q_u is observed when driving the same set of devices in their fundamental modes (22 MHz) as the added holes do not suppress axial deformation in the supporting beam tethers and undercut anchoring regions as indicated by FE simulations. As such, the enhancement in Q_u using the proposed approach is specific to the mode, thus offering the benefit of selectivity.

1. Introduction

Thin-film piezoelectric-on-silicon (TPoS) micromechanical resonators have been of great interest as such resonators offer both high quality factor (Q) and low motional resistance. This is because TPoS resonators combine the advantages of piezoelectric transduction using a thin piezoelectric film like Aluminum Nitride (AlN) (which offers strong electromechanical coupling) and a single crystal silicon (SCS) substrate (which provides low intrinsic damping) [1,2]. Due to the low intrinsic damping and high energy density of SCS, the quality factor and power handling capability of TPoS resonators can be enhanced by increasing the thickness ratio of SCS layer to the piezoelectric film as reported in [3]. In addition, the fabrication process of AlN-on-SCS resonators is CMOS-compatible, which makes TPoS resonators highly attractive from the view of potential monolithic integration with CMOS circuitry [4]. So far, the demonstrated applications of TPoS resonators include integrated high-frequency oscillators [5], radio frequency (RF) filters [6] and low power resonant sensors [7]. In all these applications, high Q is desired. In the case of oscillators, Q sets the close-to-carrier phase noise. In RF filters, higher Q reduces insertion loss in filters while narrowing the bandwidth. In the case of resonant sensors, higher Q benefits detection resolution. However, the reported values of Q for TPoS resonators are typically much lower than capacitive silicon resonators at the same frequency range. Although Q of TPoS resonators can be improved by increasing the thickness ratio of SCS layer to the piezoelectric film, it was recently found that the electromechanical coupling efficiency decreases as the ratio of the SCS thickness to acoustic wavelength (λ) increases due to dispersion of the Lamb waves [8]. Thus, other Q-boosting strategies for TPoS resonators are still of great interest. It has been widely perceived that anchor loss is one of the primary sources of energy loss limiting Q in laterally-vibrating piezoelectric resonators [9–11]. Anchor loss

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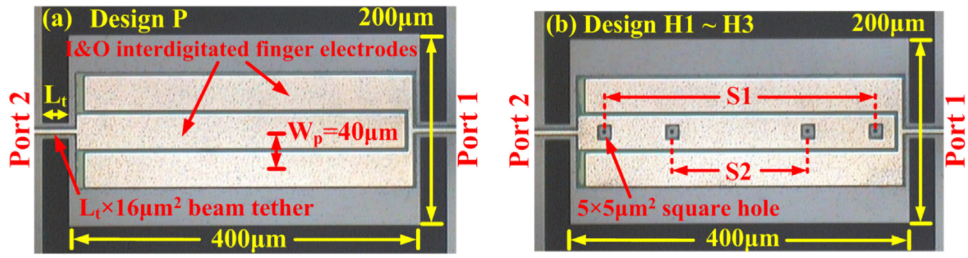

Fig. 1. Optical micrographs of (a) plain AlN-on-SCS resonator (P); (b) three variants of AlN-on-SCS resonators with different hole-spacing: $S1 = 280\,\mu m$, $S2 = 32\,\mu m$ (H1); $S1 = 320\,\mu m$, $S2 = 130\,\mu m$ (H2); $S1 = 320\,\mu m$, $S2 = 160\,\mu m$ (H3).

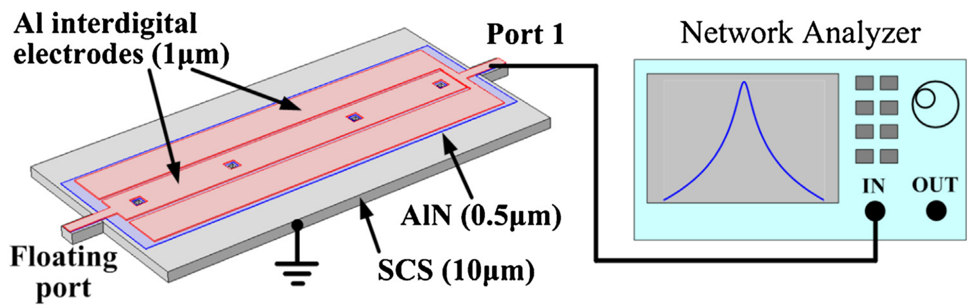

Fig. 2. Perspective-view schematic of the AlN-on-SCS resonator with four etch holes. Thickness for each composite layer is given in the bracket. One-port electrical characterization setup is also shown which is applied to all the devices.

occurs when elastic waves propagate out from the resonator to the surrounding substrate through the supporting structures (e.g. beam tether). A general guideline to minimize anchor loss is to locate the supporting tether at the nodal points of the resonator and reduce the cross-sectional dimensions of the tether [12]. However, there are limitations for the smallest feature size practically feasible for the tether. Another approach to reduce anchor loss in TPoS resonators is to place acoustic reflectors around the resonator with the aim to reflect a portion of the radiated elastic waves back to the resonator. A number of ad-hoc structures have been proposed to form such acoustic reflectors. Harrington et al. [13] demonstrated Q enhancement by over 5 times in a 110 MHz AlN-on-SCS resonator by placing arc-shaped acoustic reflectors at a chosen distance away from supporting tethers. Another approach proposed by Zhu et al. used two-dimensional phononic crystal arrays with engineered acoustic band-stop characteristics [14] to form acoustic reflectors and achieve a twofold enhancement of Q in 142 MHz AlN-on-SCS resonators. It was also reported that 1D phononic-crystal ring arrays which serve as acoustic reflectors can be used directly as supporting structures [15]. The drawback of these methods is that they increase the net device area. It should be noted that the beam tether with length of a quarter acoustic wavelength ($\lambda/4$) has also been used as an effective acoustic reflector for resonators fabricated only of silicon (i.e. homogeneous structure) [12]. However, reports by [13,16] have demonstrated that this $\lambda/4$ wave reflection theory does not apply to TPoS resonators. More recently, we demonstrated a more compact solution to boost Q via using biconvex design to confine the acoustic energy to the center of the resonator [16]. Another approach to reduce anchor has been to use etched slots to improve Q slightly by 50%, demonstrated for a 220 MHz AlN body contour mode resonator [17]. The etched slots also behave as acoustic reflectors placed within the resonator plate but in close proximity to the supporting tethers in order to reduce the energy transmitted to the handling substrate via the tethers.

This work explores another compact Q-boosting approach via strategic placement of etch holes in the resonator body. It should be noted that etch holes are common perforation features used in fabricating silicon-on-insulator (SOI) micromechanical resonators to realize free standing structures. We have previously found that uniformly distributed etch holes drastically reduce Q in SOI square-plate resonators by increasing thermoelastic damping (TED) [18]. In contrast, we have also found that when placed strategically, holes can be used to significantly enhance Q in a fundamental mode 14 MHz capacitively-transduced silicon bulk acoustic resonator as a result of reducing anchor loss [19]. In this work, we extend the etch-hole-assisted Q-boosting approach to a 105 MHz AlN-on-SCS resonator which leverages the strong electromechanical coupling of the piezoelectric AlN. Preliminary results of this approach demonstrating a proof of concept were reported in [20]. In this paper, we also consider the effects of the supporting beam tethers. Besides, we consider the mode selectivity of the proposed approach by comparing its effectiveness between the fundamental mode and intended 5th order mode of vibration. The working mechanism of our proposed method of using etch holes to reduce anchor loss is different from the use of etched slots reported previously by [17]. In our proposed approach, the holes serve to re-distribute the strain energy in the resonator body with the ultimate result of reducing anchor loss. These holes do not have to be close to the supporting tethers. The slots used by [17] on the other hand as acoustic reflectors and as such have to be placed close to the tethers. Our proposed approach is thus presented as an alternative mechanism to reduce anchor loss by adopting etched features into the resonator body, for which we demonstrate significant improvements in the quality factor by margins much greater than reported by [17].

2. Resonator design and simulation

2.1. Resonator dimensions and vibration modes

We designed a series of four AlN-on-SCS rectangular-plate resonators (referred to as Design P, H1, H2, and H3) of the same plate size ($400\,\mu m \times 200\,\mu m$). As shown in Fig. 1, design P (where the letter "P" stands for "plain") is a conventional width-extensional (WE) mode resonator with no holes. Designs H1–H3 (where the letter "H" stands for "holes") contain four $5\,\mu m \times 5\,\mu m$ square holes