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Simultaneous interrogation of high-Q modes in a piezoelectric-on-silicon micromechanical resonator

Abhinav Prasad [a,*], Jérôme Charmet [b], Ashwin A. Seshia [a]

[a] Nanoscience Centre, Department of Engineering, University of Cambridge, Cambridge, CB3 0FF UK
[b] Department of Chemistry, University of Cambridge, Cambridge, CB2 1EW UK

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ABSTRACT

A piezoelectric-on-silicon micromachined square plate resonator for the simultaneous excitation of three bulk acoustic wave modes lying within a frequency span of 2.84–3.2 MHz is reported. Three resonant modes are electrically interrogated in this frequency span, with two bulk acoustic wave mode types (Square-extensional and Lamé) well-established for this system while the third is a higher frequency mode which has not been addressed before via capacitive or piezoelectric actuation schemes. This mode was found to have a high quality factor, similar temperature co-efficient of frequency and a comparable thin-film mass sensitivity as compared to the other modes. An electrode/transducer configuration to enable selective actuation and/or suppression of the actuated in-plane modes is also reported.

1. Introduction

Micro- and nanomechanical resonators have found applications in frequency and timing references [1], inertial [2] and gravimetric sensing [3] with benefits associated with miniaturization and compatibility with semiconductor manufacturing. Among several topologies studied, silicon bulk acoustic wave (BAW) resonators are particularly interesting for applications where a high operating frequency (due to higher bulk moduli) and high quality factors (due to smaller internal losses) are desired. Piezoelectric transduction of such devices is often favourable as it demonstrates a higher electromechanical coupling efficiency as compared to capacitive and thermal/piezoresistive techniques [4]. While selective excitation and detection of specific in-plane modes has been previously studied [5–7], simultaneous transduction of multiple in-plane modes within a single device may be of interest in several instances. Accessing different in-plane resonant frequencies of differing temperature dependencies can enable the implementation of temperature compensation schemes [8] and can be extended to reject other environmental effects [9]. Monitoring multiple resonant frequencies with different mass sensitivities have been extensively implemented in the case of affinity sensors like the Quartz Crystal Microbalance [10] and microcantilevers [11]. Difference in the spatial sensitivities of different flexural resonant modes has recently been used in cantilever resonators characterize both the mass as well as the position of attachment of the target analyte mass [12]. Also, simultaneous transduction of multiple modes within a single device is of interest for applications in micromechanical filters [13] where in order to tailor filter response several multi-mode resonators are coupled together while rejecting the response of spurious modes.

In this paper, a suspended 1400 μm side-length square micromechanical resonator with a patterned stack of Aluminium (Al)/Aluminium Nitride (AlN) on single-crystal silicon (SCS) is reported. This particular topology allows for simultaneous excitation of three in-plane modes viz. Lamé at ~2.84 MHz, Square-extensional (SE) at ~3.15 MHz and a third-mode at ~3.2 MHz. The third mode, not previously reported, is termed as the Butterfly mode (BF) due to its characteristic mode shape. In the characterization studies, the BF mode was found to have higher quality factors (~3282 in air) as compared to the more commonly studied SE mode (~1914 in air). Temperature coefficients of frequency (TCF) for all the modes were also extracted for a temperature variation of 40 K above room temperature. A higher thin-film mass sensitivity for the BF mode as compared to the SE mode was also observed. Also, due to the axial symmetry of the mode shapes, it was possible to actuate and suppress the modes by selecting different electrode configurations. Finally, the modes were optically characterized using a Laser

* Corresponding author.
E-mail address: abhinav.prsd@gmail.com (A. Prasad).

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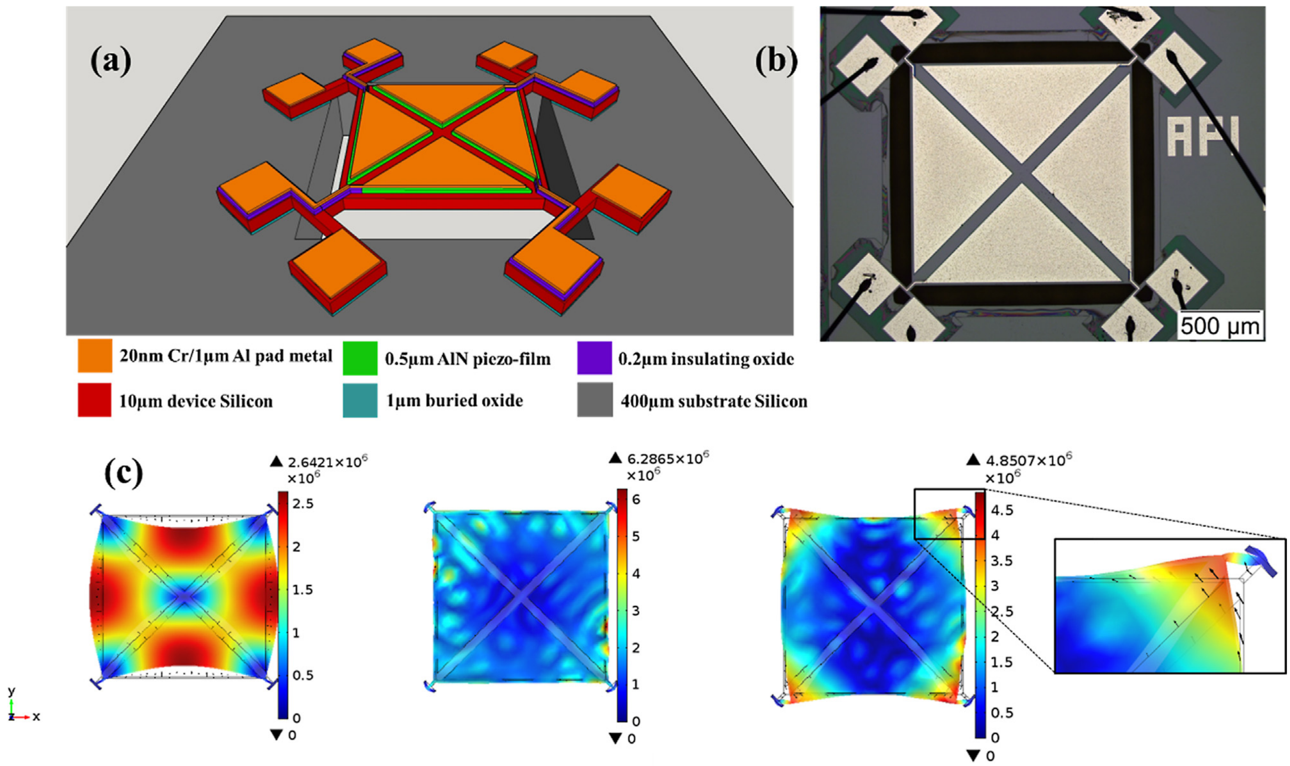

Fig. 1. (a) Isometric view of the square piezoelectric-on-silicon resonator; individual stack layers are illustrated with different colours, (b) Top view of the wire bonded resonator, (c) COMSOL simulations of total displacement for Lamé, Square-extensional and Butterfly mode along with their normalized displacement scale bars. Also shown is a zoomed-in image of displacement near one of the anchors for the butterfly mode; black arrows represent the displacement vectors.

Doppler vibrometer enabling selective identification of the mode shapes and verification of device response.

2. Device design

2.1. Fabrication

The square-resonators are fabricated using silicon-on-insulator (SOI) wafers via a five-mask modified industrial Multi-user MEMS Process (MUMPs) by MEMSCAP, Inc. The process involves reactive sputtering of 0.5 μm thin AlN layer, deposition of 1 μm Cr/Al metal electrodes and subsequent release of the structure using deep-reactive ion etching process. A more detailed discussion on the fabrication is provided in the supplementary material. Fig. 1a shows the schematic of the square resonator with an isometric view of each layer. COMSOL structural simulations of the square device are shown in Fig. 1c. Lamé [6] and SE [5] modes have distinct mode shapes, though with an increased out-of-plane displacements, possibly, as a result of the AlN and Cr/Al layers and Poisson contraction. BF mode is represented by a large minimum displacement (or nodal) area in the centre and synchronous in-plane inward bending of the four vertices towards *X*- or *Y*-axis.

2.2. Design of electrodes

In the current study, the actuation and sensing of the different modes is done through piezoelectric effect by applying and measuring an alternating voltage/current signal on the selected electrodes as shown in Fig. 2 . Governing equations for such transducers can be found elsewhere [14]. Electrodes can be specifically designed to supress the spurious modes and selectively excite the intended modes [15]. However, a more generic design that can excite multiple modes with only slight compromise on the transduction efficiency is aimed in the present work. By patterning triangular electrodes, overlapping each quarter of the square structure, selective excitation/suppression of the BF and the SE mode can be achieved. The Lamé mode was transduced but had relatively much smaller amplitude. This could be due to relatively smaller net strain in the electrode overlap area (refer the supplementary material).

3. Electrical characterization

3.1. Two-port transduction

Piezoelectric resonators can be transduced in a one port or multi-port configuration. The one port configuration results in a large feedthrough capacitance distorting the measured electrical response. In comparison, two-port transduction (*i.e.* actuating from one set of electrodes and sensing from another set of electrodes) limits the effect of the parallel feedthrough capacitance and, hence, was employed in this work. The resonator body was also grounded to minimize feedthrough and eliminate the effects of an unknown node potential across the piezoelectric film which could lead to inaccurate extraction of resonance parameters. In order to demonstrate selective actuation and suppression of multiple modes, each electrode piece can be either-(i) left in the 'open' position, (ii) connected to the in-phase actuating signal, (iii) connected to the out-of-phase actuating signal, and (iv) used for extracting the 'sensed' signal as shown in Fig. 2. An AD8131 amplifier was used in the unity gain configuration to generate the required in-phase and out-of-phase signal while the transmission parameters were obtained through a Network Analyser (4396B) while the circuit (resonator plus electrical components) was being operated in the open-loop scheme. The measurements were performed at atmospheric pressure and under vacuum at 30mTorr.