A NOVEL TRANSDUCER DESIGN TO ENABLE HIGH-PERFORMANCE PIEZOELECTRIC MEMS RESONATORS AND OSCILLATORS

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ABSTRACT

A novel mechanism to drive pure single crystal silicon (SCS) micromechanical structure into resonance using piezoelectric transducer uniquely positioned at its support/anchor location is being reported for the first time with exceptional performance. The resonator was fabricated using MEMSCAP's PiezoMUMPs platform. This innovative method makes use of the excellent piezoelectric property of the Aluminum Nitride (AlN) thin film along with low crystal defect property of SCS, thus ensuring a very low motional impedance and high-quality factor (Q) performance. A differential drive/sense method was employed to reduce the feedthrough and eliminate spurious modes close to wine-glass (desired) mode of the SCS resonator. As a result, the designed wine-glass mode resonator operating at 21 MHz is successfully demonstrated with a motional resistance (R_m) of 1.8 kΩ and a loaded Q of 8,054 in air at 0 dBm driving power. Connecting the resonator to a lock-in amplifier with phase locked loop (PLL), a phase noise of -106 dBc/Hz at 100 Hz offset and -125 dBc/Hz at 1 kHz offset for a carrier frequency of 20.936 MHz was recorded.

INTRODUCTION

Efficient and stable clock has been the keystone for the realization of Internet of Things (IoT) systems. To satisfy the stringent requirement, it is of great importance to realize a resonator having a high quality factor, low insertion loss, and good power handling. Even though capacitive MEMS resonators operating in bulk mode provide a high quality factor, they suffer from very high insertion loss and low power handling [1], [2]. Pure piezoelectric MEMS resonators on the other hand lag in the quality factor and have an average power handling ability [3], [4]. In the face of these limitation posed by aforementioned exclusive domains, the Thin Piezo on Substrate (TPoS) emerges as a clear winner. TPoS ably combines the high quality factor, lower insertion loss and efficient power handling features [5], [6].

The quest to combine the low motional resistance (R_m) owing to the impeccable piezoelectric coefficient of AlN along with the high Q of the bulk mode SCS has been of great interest to MEMS resonator designers. The wine-glass mode has been attempted to realize high Q by various groups [7], [8]. However, due to the presence of the metal and piezoelectric film on the main resonating body, the overall performance deteriorates. Other high performance bulk mode such as Lamé mode has also been a subject of study using piezoelectric excitation. However, due to the fact that net strain is zero for it, the charge generated during resonance gets cancelled making it nearly impossible to excite such modes efficiently [8].

In this work, we propose a unique method to make use of both of the aforementioned features by essentially decoupling the high-Q mechanical resonator (SCS) and mechanically lossy transducers (due to material loss and interfacial loss) made up of the SCS, AlN, and Aluminum (Al) stack. MEMSCAP Inc.'s PiezoMUMPS platform is used to realize this concept. Here a common bulk resonance mode, the wine-glass mode is realized using the above stated decoupling principle. The resonator shows extremely high overall performance, making it a suitable building block for RF communication systems.

Traditionally piezoelectric resonators use Pierce or Colpitts oscillator instead of transimpedance amplifier (TIA) due to low- R_m of TPoS resonators and Q degradation [9]. Additionally, the low R_m would severely limit the noise performance of TIA. To obtain a low power oscillator, the parasitic capacitance (C_P) at input and output

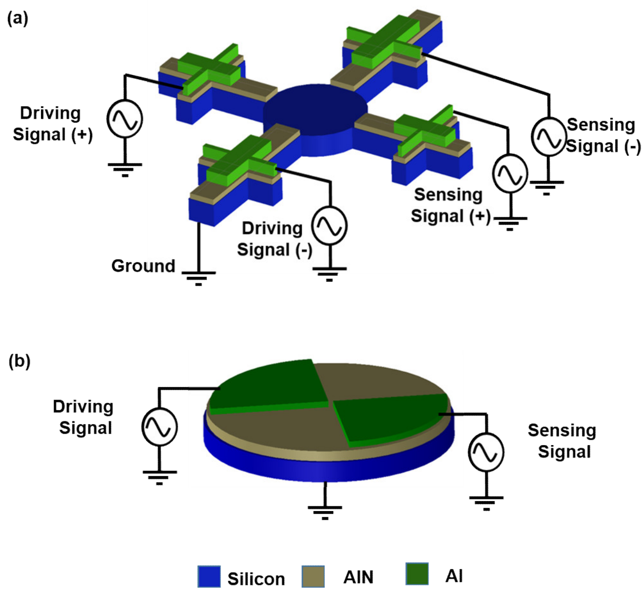

Figure 1: Schematic description of (a) the proposed support drive/sense piezo-MEMS wine-glass resonator, and (b) traditional piezo-MEMS wine-glass resonator.

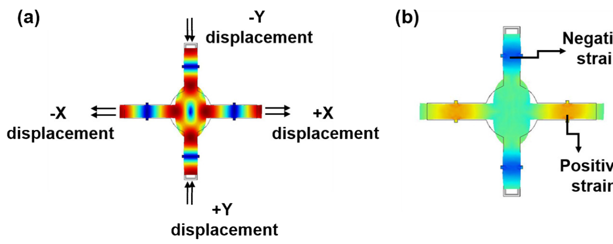

Figure 2: FEM plots of (a) displacement and (b) strain distribution for support drive/sense wine-glass resonator.

is of paramount importance [10]. In our proposed design, we reduce, not only the C_P as the electrode covers only the maximum strain region but also the feedthrough capacitance (C_f) as input and output are isolated.

The paper is organized into three sections. First, the conceptual design of the resonator with anchor transduction is covered along with Finite Element Method (FEM) simulations. Then we discuss measurement results and comparison with prior state of art works. Lastly, we summarize the mechanism and resonator performance.

RESONATOR DESIGN

The central vibrating body made of low crystal defect material is driven into resonance by suitably connecting its high velocity section to the high velocity portion of the resonance mode of the support. Here, to illustrate the working principle, a wine-glass mode is used as a prototype.

Figure 1(a) shows the schematic of the proposed drive/sense mechanism in a piezoelectric MEMS resonator to drive the central SCS structure into resonance. The transducer beam is designed to operate in the length-extension mode. The four high velocity corners of the wine-glass mode are connected with four beams. Here the beams are designed for half wavelength. Anchoring the transducer beam at pseudo nodal point combined with a pure SCS vibrating body operating in wine-glass mode boosts the overall performance of the system. The diametrically opposite transducer beams will undergo similar strain polarity changes at the resonance mode. In this method, there is practically no charge cancellation in the electrodes as the driving and sensing electrodes are completely isolated from the net-zero strain central resonating body. This ensures that a lower insertion loss can be achieved despite lower metal coverage. The central bulk portion is fabricated from high Q material solely. The pseudo nodal anchor ensures Q enhancement. Figure 1(b)

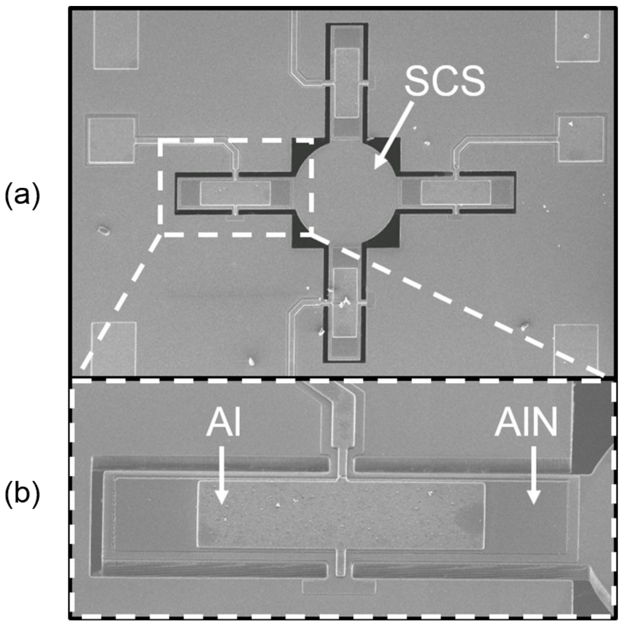

Figure 3: (a) SEM image of 21 MHz wine-glass mode resonator. (b) Zoom-in view of one transducer beam.

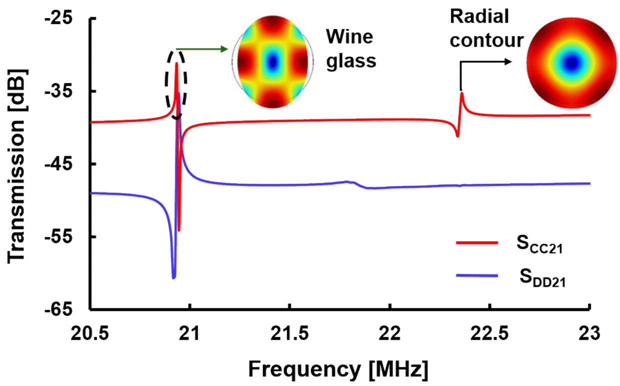

Figure 4: Wide span measurement of differential (blue) and common mode (red) drive and sense scheme showing suppression of radial contour mode for differential configuration. Inset indicates the mode shapes for wine-glass and radial contour modes.

shows the traditional electrode and piezoelectric thin film placement for exciting the wine-glass mode. In such approaches, the resonator suffers from a relatively higher motional impedance and low quality factor due to charge cancellation and interfacial loss across material stack respectively. Simulations were done using COMSOL to verify the concept. Figure 2(a) and (b) show the Finite Element Method (FEM) plots of displacement and strain distribution at resonance respectively. Electrode pairs having opposite strain polarity were used for the driving and sensing functions.

MEMSCAP Inc. provides an AlN on SOI (Silicon-on-Insulator) platform which consists of a 5 mask process. The stack consists of a thick silicon handling wafer and on top of which there is a 200nm thermal oxide. The resonant body is composed of 10µm Si device layer followed by a 500nm thick Aluminum Nitride layer and an e-beam evaporated stack of 20nm Chromium and 1µm Aluminum which is further patterned using lift-off technique. Back side etch is used to remove the handle wafer underneath the vibrating structure.

An SEM image of the wine-glass resonator operating at 21 MHz is shown in Figure 3(a). A zoom-in view of one of the pseudo-anchor half-wavelength beam is presented in Figure 3(b). It can be seen that the circular geometry is comprised of pure Silicon and the Silicon/AlN/Al stack is present at the transducer beam. The top metal is designed such that it just covers the maximum strain generation region thus ensuring lower R_m and high-Q.

MEASUREMENT RESULTS

Resonator Measurement

The device characterization was conducted in air using Agilent 5071C Network Analyzer with 0 dBm driving power. The resonator was wire-bonded on to a Printed Circuit Board (PCB). Figure 4 presents a wide span sweep for the wine-glass mode using the pseudo-anchor drive/sense methodology. In the common mode excitation method, the similar strain polarity transducers are combined. It is observed that the common mode drive/sense configuration excites both the wine-glass and

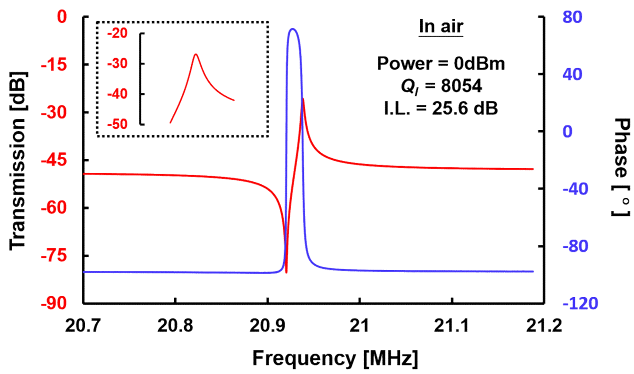

Figure 5: Magnitude and phase transmission plot for differential drive and sense measurement of a wine-glass support drive/sense resonator. Inset image shows the transmission for 5 dBm drive power. No nonlinearity behavior was observed.

the radial modes and has a high feed-through floor. Presence of non-desired mode close to the target mode diminishes the performance of the desired mode. On the other hand, driving the resonator in differential mode not only reduces the feedthrough level of the resonator but also eliminates the radial contour mode due to the strain polarity cancellation at the excitation and sensing ports. The four-port configuration of the design provides more degree of freedom from the measurement perspective. For the differential drive and differential sense, splitter/combiner was used.

Figure 5 presents a magnitude and phase plot for the S_{DD21}. The splitter contributes a loss of 3.44dB at the target frequency range. Compensating for the splitter loss at the resonance frequency of 20.936 MHz for the wine-glass mode, an insertion loss (I.L.) of 25.6 dB corresponding to R_m = 1800 Ω and a loaded Q = 8,054 was recorded. To explore the power handling ability of the device, a higher input power was given to the device. The TPoS resonator was driven up to 5 dBm. No nonlinearity, i.e., no hardening or softening of the peak was observed during the power sweep. The inset image of Figure 5 shows the resonance peak of the resonator at 5 dBm. The presence of the silicon layer beneath the thin film piezoelectric layer enhances the overall performance thereby enabling the device to showcase stable performance at higher power levels.

$$R_m = 2 * Z_o * (10^{I.L/20} - 1) \quad (1)$$

$$FOM = f_r * Q \quad (2)$$

Table 1 provides the performance metric indicating that the salient feature of the proposed support drive/sense piezo-MEMS wine-glass resonator is superior to the reported piezo-MEMS wine-glass resonators. [7] is realized using a traditional two-port measurement whereas [8] uses a differential drive/sense configuration. The advantage of this pseudo anchor drive and sense can be seen as it showcases much higher figure of merit (FOM).

Table I: Comparison of the proposed support drive/sense piezo-MEMS wine-glass resonator with state of the art piezo-MEMS wine-glass resonators.

Parameters	[7]	[8]	This work
Operation Setup	2 Port	Diff. Drive & Sense	Diff. Drive & Sense
Material	ZnO on Ni	AlN on Si	AlN on Si
Resonance Frequency	29.1 MHz	10.5 MHz	21 MHz
Insertion Loss	29.3dB	20.3dB	25.6dB
Loaded Q	546	5220	8054
R_m	3kΩ	1.2kΩ	1.8kΩ
Transducer Area (mm^2)	0.025	0.16	0.023
FOM (f*Q)	16.10^9	55.10^9	169.10^9

Lock-in Measurement

To demonstrate the advantage of the proposed resonator for frequency reference applications, a HF2LI lock-in amplifier with PLL was used to realize an oscillator in a non-controlled environment. The PLL filter bandwidth was set to the maximum value of 100 kHz, thus PLL noise shaping can be observed for frequency above 100 kHz. The Lock-in amplifier was set to drive at 0 dBm. The red curve is the phase noise for the carrier at the resonance frequency. An improved close-to-carrier phase noise is observed due to high Q of the SCS resonant body in addition to the low far from carrier noise of typical piezo-MEMS oscillators. The phase noise at 100 Hz and 1 kHz offsets is -106 dBc/Hz and -125 dBc/Hz respectively. The phase noise at

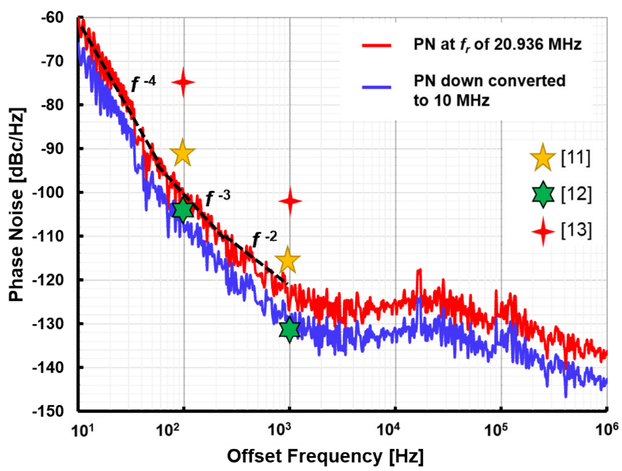

Figure 6: Phase noise plot using HF2LI lock-in amplifier with PLL at resonance frequency (red) and down converted (blue) to 10 MHz for the proposed resonator. After down conversion, phase noise at 100 Hz offset is -109dBc/Hz and at 1 kHz offset is -131 dBc/Hz.

1 kHz and beyond it is limited by the performance of internal clock of the lock-in amplifier.

$$PN(@f_{ref}) = PN(@f) - 20 * \log(\frac{f}{f_{ref}}) \qquad (3)$$

For a fair comparison with prior works, the phase noise is down converted to a carrier of 10 MHz using equation 3. The blue trace in Figure 6 shows the down converted phase noise. The phase noise at 100 Hz and 1 kHz offsets is -109 dBc/Hz and -131 dBc/Hz respectively. The down converted values for state of the art piezo-MEMS oscillators [11], [12] and CMOS-MEMS oscillator [13] are depicted in Figure 6 for ease of comparison.

CONCLUSION

This paper reports an innovative pseudo anchored support transducer to drive central resonant bulk mode into operation using MEMSCAP's PiezoMUMPs platform. The ability to have a high *Q* material as the bulk enhances the overall system metric greatly. By the use of silicon/AlN/Al composite structure as the transducer, it provides a decent electromechanical coupling between the domains. A wine-glass mode resonator using this drive/sense configuration is reported for the first time with exceptional performance. Although 2-support can excite the wine glass mode, a 4-support design was used to provide more combinations of excitation and sensing configuration. Differential drive/sense not only reduces the undesired spurious mode but also lowers the feedthrough level significantly. Finally, a wine-glass mode resonator using a driving power of 0 dBm working at 21 MHz is successfully measured with a motional resistance (R_m) of 1.8 kΩ and a loaded *Q* of 8,054. A Figure of Merit of 169.10^9 was reported. The TPoS displays a very good power handling in air. Closed-loop performance of the device at resonance was studied using a lock-in amplifier with PLL. Phase noise of -106 dBc/Hz at 100 Hz offset and -125 dBc/Hz at 1 kHz offset was recorded which is at par with the state of the art CMOS-MEMS oscillators.

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