CHANNEL-SELECT MICROMECHANICAL FILTERS USING HIGH-K DIELECTRICALLY TRANSDUCED MEMS RESONATORS

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ABSTRACT

This paper demonstrates electrically and mechanically coupled channel-select filters comprised of dielectrically transduced thickness shear mode resonators. The filters are fabricated on the 3.2 μm thick device layer of a heavily doped SOI wafer with a 30 nm thick hafnium dioxide film sandwiched between the polysilicon electrodes and the silicon device layer. An 809 MHz half-wave thickness shear resonator is demonstrated with a quality factor (Q) of 7,800 in air and a motional impedance (R_X) of 59 Ω. An array of such resonators is coupled electrically and mechanically to form dielectrically transduced MEMS filters. Electrically coupled channel-select filters with 814 MHz center frequency, 600 kHz bandwidth, -4 dB insertion loss (IL) and < 1dB pass-band ripple are presented. In addition, a mechanically coupled 804 MHz center frequency filter is demonstrated exhibiting -34 dB stop-band rejection and a 20 dB shape factor of 1.28.

1. INTRODUCTION

Numerous applications in cellular transceivers and sensor networks have driven the development of on-chip, high-Q MEMS resonators and filters to replace existing off-chip SAW and ceramic resonator technologies. Receivers operating in the ISM band (902 – 928 MHz) have narrow channels and are susceptible to nearby strong interferers. Channel-select filtering requires small bandwidth, good stop-band rejection, and excellent shape factor to filter out unwanted frequencies. MEMS resonators with high Q, high resonant frequency, and low R_X can be coupled either electrically or mechanically to form a channel-select filter that operates in the ISM band.

The desired filter characteristics are determined by the MEMS resonators comprising the filter. Low insertion loss is achieved by reducing R_X while shape factor is defined by the resonators' quality factor. Previously, the high frequencies necessary to operate near the ISM band were achieved by reducing the air gap and increasing the transducer area of bulk-mode bar resonators [1]. Despite their high frequency, the large R_X of these resonators would result in a high insertion loss filter. An attempt to reduce R_X by filling the air gap of a wine-glass disk resonator with silicon nitride is presented in [2], resulting in a resonant frequency of 165 MHz with a Q of 21,400 and an R_X of 8.5 kΩ. Alternatively, contour-mode aluminum nitride piezoelectric resonators with 656 MHz resonant frequency and an R_X of 170 Ω have been reported. However, the ladder filter comprised of these low Q piezoelectric resonators exhibited a 20 dB shape factor of 2.7 [3].

As demonstrated in [4], the quarter-wave thickness shear mode bar resonator achieved 723 MHz resonant frequency with a Q of 4,400 and an R_X of 2.4 kΩ using silicon nitride dielectric transduction. However, the higher Q half-wave thickness shear mode (Figure 1) of a fully-released bar resonator could not be measured because the motional impedance of the vibration mode was much larger than the feedthrough capacitance between the drive and sense electrodes.

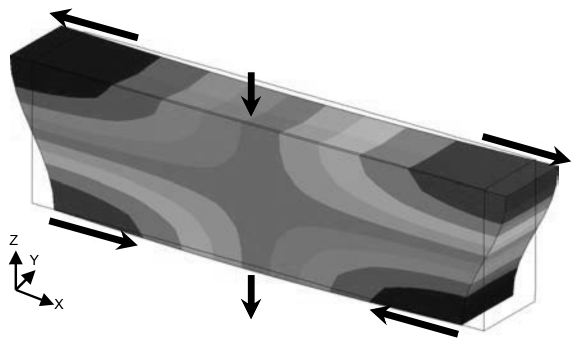


Figure 1: ANSYS contour plot of the symmetric half-wave thickness shear mode. This mode causes the tether suspension at the nodal plane to move along the Z-axis, as indicated by the down arrows.

In this paper, the motional impedance of the half-wave thickness shear bar resonator is substantially reduced by replacing silicon nitride (κ ~ 9) with hafnium dioxide (κ ~ 28), reducing dielectric thickness, and increasing the electrode area. The high Q and low R_X of this resonator enables the design of high quality channel-select filters.

2. HALF-WAVE THICKNESS SHEAR MODE RESONATOR

A 1-D quarter-wave thickness shear mode model was derived for an unreleased silicon bar transduced by a thin dielectric film in [4]. To induce the half-wave mode, the buried oxide layer is fully etched, leaving a free displacement boundary condition on the bottom face of the bar. The dielectric film deposited on top of the bar is sandwiched between the silicon device layer and the conducting top electrodes (Figure 2). A small alternating voltage is applied to the drive electrode while a 5 V bias is applied to the silicon resonator. This time-varying voltage causes a squeezing force on the dielectric thin film. Due to the Poisson effect, the dielectric layer experiences a lateral strain. As the strain distributes through the silicon bar, the half-wave thickness shear mode is excited.

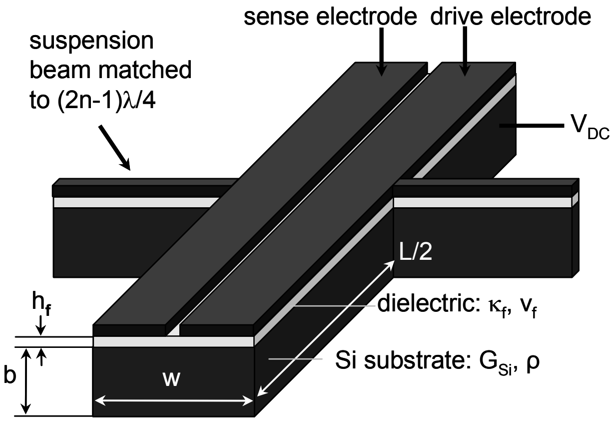


Figure 2: Schematic of a fully released half-wave thickness shear bar resonator.

The first-order motional impedance of the half-wave thickness shear bar resonator is

$$R_X = \frac{8\sqrt{G\rho}}{Q\pi} \frac{(1-\nu_f)}{(V_{DC}\nu_f \kappa_f \varepsilon_0)^2} \frac{h_f^3 b}{wL} . \quad (1)$$

As expected, the motional impedance decreases with area *wL* of the resonator. In addition, the cubic dependence of R_X on dielectric film thickness h_f and its inverse square dependence on dielectric constant κ_f improve motional impedance to values close to 50 Ω.

Pure thickness shear mode resonance of a bar depends only on thickness *b*, with frequency

$$f = \frac{1}{2b}\sqrt{\frac{G}{\rho}} \quad (2)$$

where *G* and ρ are the shear modulus and mass density of the silicon resonator, respectively. In reality, the resonator exhibits a small-amplitude flexure mode coupled to the shear mode. This coupling can be observed in the ANSYS modal analysis in Figure 1. The Southwell-Dunkerley formula [5] approximates the combined shear-flexure frequency as

$$\frac{1}{f_{total}^2} = \frac{1}{f_{shear}^2} + \frac{1}{f_{flexure}^2} . \quad (3)$$

Therefore, the silicon bar's lateral dimensions affect the resonant frequency, giving layout design flexibility covering a 30 MHz range below 840 MHz. Figure 3 shows the bar's simulated resonant frequency as a function of the bar length. This property is exploited to fabricate multiple frequency resonators and filters on the same chip.

Fabrication Process

The resonator is fabricated in a 4-mask SOI process similar to [4]. The silicon nitride layer is replaced with a 30 nm hafnium dioxide film ($\kappa \sim 28$, $\nu_{acoustic} \sim 8{,}500$ m/s) on a low resistivity SOI wafer with a 3.2 µm thick SCS device layer. An SEM of the resonator is shown in Figure 4(a).

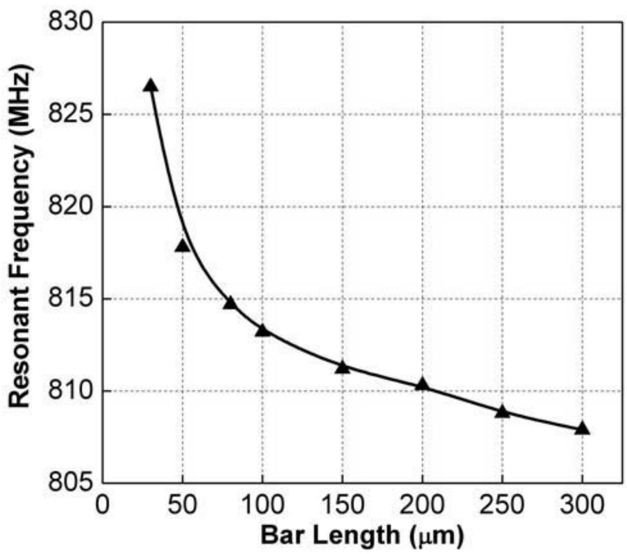


Figure 3: ANSYS simulation of length (L) vs resonant frequency of the 3.2 µm thick half-wave shear mode resonator. The pure shear mode resonant frequency of the bar is 844 MHz.

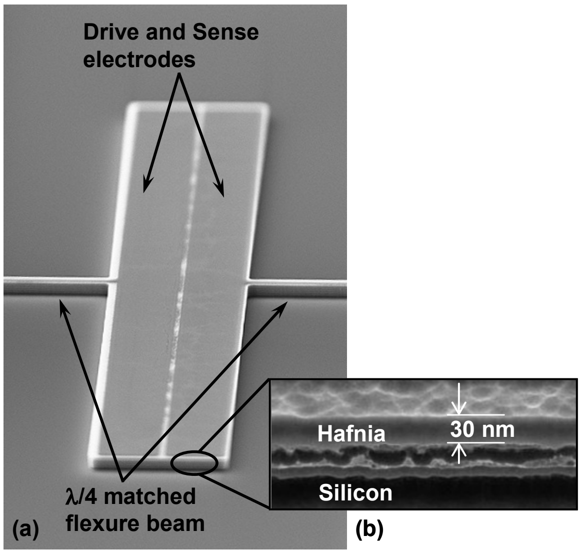


Figure 4: (a) SEM of a hafnium dioxide-on-silicon fully released bar resonator. (b) SEM of the 30 nm hafnium dioxide layer on the top of the silicon resonator.

A high-resolution SEM revealing the 30 nm hafnium dioxide layer is shown in Figure 4(b).

Experimental Results

A 100 µm × 40 µm bar resonator was tested in a DesertCryo microwave probe station at room temperature and pressure. To simplify the microwave frequency measurement, the resonator device layer was grounded and both drive and sense electrodes were biased to 5 V using bias-Ts. SLOT (short-load-open-through) characterization and transmission measurements were performed using an Agilent 8720ES network analyzer and the Q and insertion loss were determined from the measured S21 response. The half-wave thickness shear mode of the released silicon resonator was measured with a resonant frequency of 809 MHz, a Q of 7,800 and an R_X of 59 Ω in air (Figure 5).

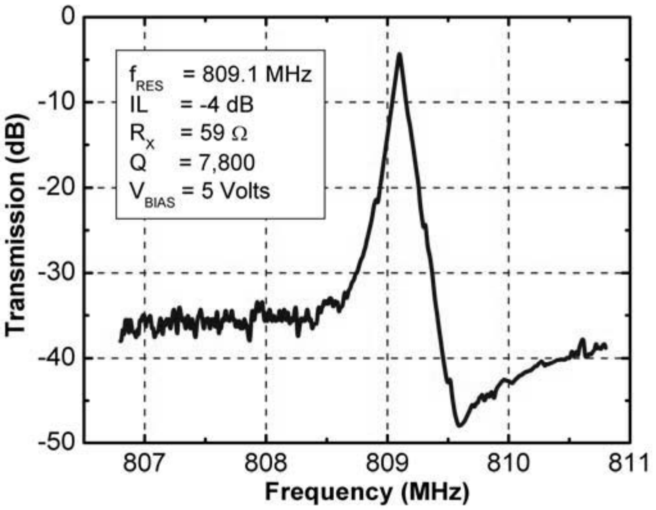


Figure 5: Measured transmission response of a half-wave thickness shear mode resonator in air. The f·Q product of the resonator is 6.2x10[12] Hz.

3. ELECTRICALLY COUPLED CHANNEL-SELECT FILTER

Electrical coupling is achieved by routing the electrical signal from successive resonators in a ladder configuration. The design flexibility afforded by the frequency dependence on lateral dimensions enables the design of series and parallel resonators of the ladder without the need for additional mass-loading or electro-etching steps to reduce the shunt resonator frequency [6,7].

Five electrically coupled ladder filters were designed with 1 MHz separation in center frequency and 3 dB bandwidth of ~ 600 kHz. Figure 6 shows an SEM of two ladder filters. Figures 7(a) and 7(b) provide the frequency characteristics and summarize the filter performance in air.

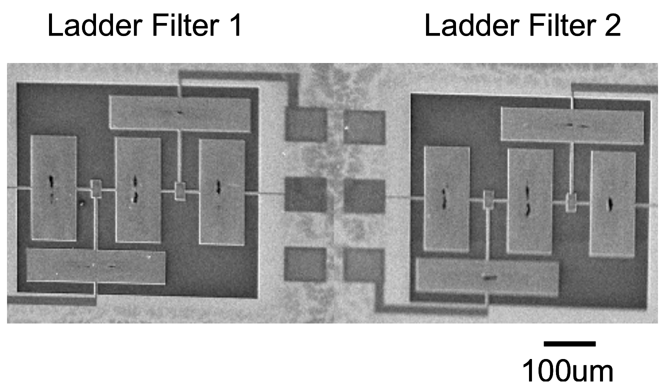
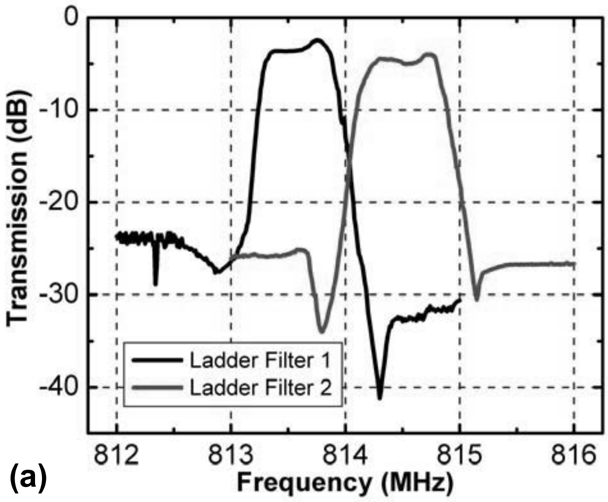


Figure 6: SEM of an array of ladder configuration electrically coupled thickness shear filters. The series resonators are 280μm × 100μm and the shunt resonators are 300 μm × 100μm.



(b)

	Ladder Filter 1	Ladder Filter 2
IL	-3.5 dB	-4 dB
3dB BW	630 kHz	680 kHz
f_{CENTER}	813.6MHz	814.5MHz
ripple	< 1 dB	< 1.1 dB
stop band rejection	-24 dB	-25.2 dB
20 dB Shape factor	1.43	1.5
$R_{TERMINATION}$	712 Ω	750 Ω

Figure 7: (a) Measured filter transmission response showing two 650 kHz channel-select filters. The measured characteristics are summarized in (b).

4. MECHANICALLY COUPLED CHANNEL-SELECT FILTER

A mechanically coupled thickness shear arc filter is shown in Figure 8. The three arc array is implemented instead of one wide shear arc to suppress plate modes in the resonators.

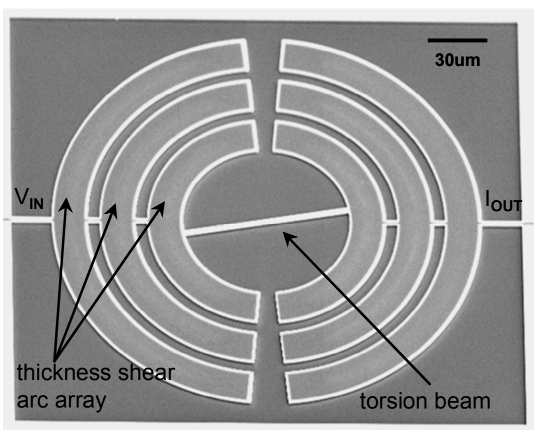
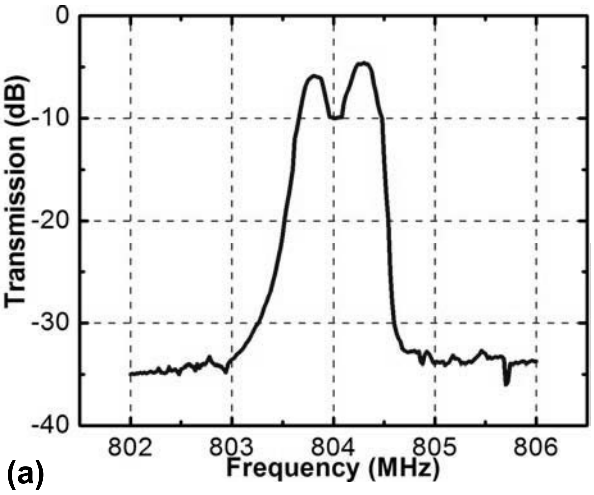


Figure 8: SEM of mechanically coupled shear arc filter.

Two arc arrays are mechanically coupled with a low velocity torsion beam. The arc filter symmetry accesses the full range of the coupling beam's effective stiffness, allowing for easy control of filter bandwidth at the expense of pass-band ripple. In order to access the low velocity coupling point, the three-arc-array filter is coupled near the nodal plane of the resonators. Figures 9(a) and 9(b) present the frequency response and characteristics of the mechanically coupled filter measured in air with a 5 V bias and a termination impedance of 2 kΩ.



(a)

(b)

	Arc Filter
IL	-4.6 dB
3dB BW	800 kHz
f_{CENTER}	804 MHz
ripple	< 5 dB
stop band rejection	-34 dB
20 dB Shape factor	1.27
$R_{TERMINATION}$	1.98 kΩ

Figure 9: (a) Transmission response of the mechanically coupled arc filter. (b) The arc filter characteristics show improved stop-band rejection and 20 dB shape factor compared to the electrically coupled filters.

5. CONCLUSIONS

Half-wave thickness shear mode resonators with frequencies greater than 800 MHz and *Q* > 7,000 have been fabricated. Dielectric transduction by a high-κ hafnium dioxide thin film reduces the motional impedance of the resonators 800 times relative to air-gap electrostatic transduction. Their 59 Ω motional impedance is the lowest reported to date for any silicon-based electrostatic VHF MEMS resonator design.

The frequency dependence on lateral dimensions provides the ability to fabricate resonators of various frequencies on a single chip. An array of ladder filters with 600 kHz bandwidth, < 4 dB insertion loss, and < 1dB pass-band ripple has been demonstrated. The mechanically coupled arc filter has higher insertion loss compared to the electrically coupled ladder filters as the overall electrode area is smaller. However, it demonstrates superior stop-band rejection (-34 dB) and better 20 dB shape factor (1.28) due to the large distance between the drive and sense electrode and high *Q* of the constituent resonators. The pass-band ripple in the mechanically coupled filter can be greatly improved by narrowing the width of the coupling beam and placing it closer to the nodal plane of the resonators.

6. ACKNOWLEDGEMENTS

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