GHZ CONTOUR EXTENSIONAL MODE ALUMINUM NITRIDE MEMS RESONATORS

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ABSTRACT

This work presents higher-order contour mode piezoelectric AlN MEMS resonators with lithographically defined GHz operating frequencies. By selectively patterning the transduction electrodes and routing the electrical excitation waveform, the resonant frequency of the device is uncoupled from the overall dimensions of the AlN plate and spurious electrical responses are suppressed over a wide frequency range. Resonators employing either parallel or coplanar ground and signal electrode pairs have been developed. The design has been validated by demonstrating a 1.28 GHz resonator with a 231 Ω motional resistance and a *Q* factor over 1,400 when tested in air.

INTRODUCTION

The demand for highly-integrated analog filtering and frequency reference elements has spurred rapid innovation in the area of vibrating RF MEMS [1]. To date, however, no single technology has emerged that can simultaneously deliver monolithic, post-CMOS integration of IF and RF components that can readily interface with 50 Ω RF systems. Surface acoustic wave (SAW) devices are ubiquitous in communication and other electronic applications, but their reliance on exotic crystalline substrates inherently precludes integration with conventional circuitry. Thickness-extensional film bulk acoustic resonators (FBARs) have proven the technical feasibility and commercial viability of thin film piezoelectric aluminum nitride (AlN) based processing technology for RF applications [2], but the mode of operation results in a single frequency per AlN deposition and is not scaleable to IF. Contour mode electrostatic polysilicon resonators with air or solid dielectric gaps do not suffer either of the aforementioned limitations, but despite monumental improvements have yet to demonstrate low motional resistance, fundamental mode resonators suitable for RF filter synthesis [3, 4]. AlN contour mode MEMS resonators have emerged as the premier technology for realizing multi-frequency per silicon chip, CMOS-compatible, low-loss filters, but heretofore have been unable to reach GHz frequencies [5, 6].

The current work presents higher-order contour mode piezoelectric MEMS resonators that effectively uncouple the resonant frequency of the devices from their overall dimensions by selectively patterning the transduction electrodes and routing the electrical excitation waveform. Two electrode configurations have been investigated: thickness field excitation (TFE) employing parallel top and bottom electrode pairs and lateral field excitation (LFE) with coplanar signal and ground electrodes on top of the structural AlN layer (see Figure 1).

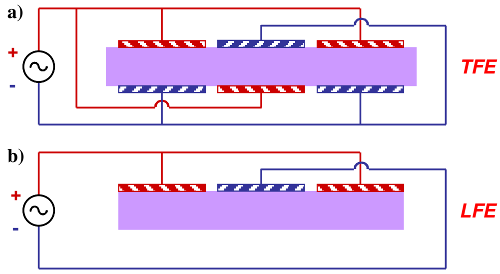

Figure 1: Cross-sectional schematics of higher-order contour mode resonators transduced using (a) thickness field excitation (TFE) between parallel electrodes and (b) lateral field excitation (LFE) between coplanar electrodes.

The ability to scale the lateral dimensions of the structural material allows for more mechanically robust devices that are capable of attaining higher fundamental resonant frequencies (1.28 GHz) with reduced motional resistances (232 Ω), high *Q* (1,420) in air and relaxed fabrication tolerances (AlN plate measures 1.5x40x100 μm). The electrode configuration also suppresses the appearance of any spurious modes in the electrical response of the device over a wide frequency range.

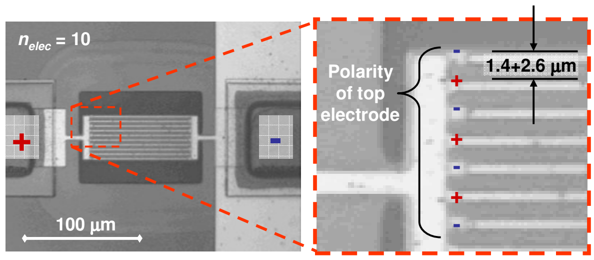

Figure 2: Optical micrographs of higher-order contour mode resonator showing alternating polarity between adjacent electrode pairs. The natural frequency of the device is proportional to the Al electrode line/space period (4 μm) while the motional resistance is proportional to the number of electrode pairs (10 in this case) and the overall width of the AlN plate (100 μm).

THEORY

Piezoelectric and electrostatic contour mode (laterally vibrating) MEMS resonators based on rectangular or annular plates offer the ability to prescribe frequency and motional resistance independently within a limited design space, but have to date been precluded from reaching GHz fundamental modes by the need to define half-wavelength features (on the order of several microns) in whatever structural material is being used [3, 7]. Theoretical designs for low motional resistance, GHz rectangular or annular plate resonators are marked by extreme length to width or average radius to annular width ratios, respectively, which in practice result in unacceptable mechanical compliance, inefficient use of layout area, and the need for exacting fabrication tolerances. While GHz overtones have been reported in contour mode resonators before, the devices exhibit dominant fundamental modes at approximately one-third the frequency.

In the present design, the frequency determining dimension is effectively uncoupled from the overall dimensions of the AlN plate by patterning the transduction electrodes such that the polarity of the excitation electric field alternates at half-wavelength intervals in the direction of wave propagation. As seen in Figure 3, the polarity of the electrodes uniquely matches that of the strain field for a specific bulk mode of vibration of the plate. This feature strongly suppresses the appearance of spurious electrical responses over a wide frequency range. Moreover, the number of half-wavelength electrodes can be scaled to engineer a proportional decrease in motional resistance (the motional resistance also depends on the width and thickness of the plate).

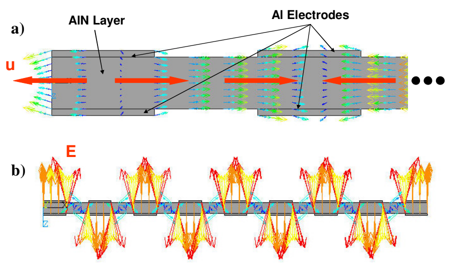

Figure 3: Cross-sectional view of multiphysics 3D FEM simulation results for TFE higher-order contour mode resonator showing (a) mechanical displacement and (b) electric field vectors at resonance.

The practical implication of the design is that half-wavelength features need only be defined in the thin metal electrodes, and the feasibility of fabricating such features in a production environment has essentially been proven by SAW device manufacturers (in fact SAW devices have more demanding fabrication requirements due to their lower acoustic wavespeed). As with SAW devices, the nominal frequency of the resonator depends not only on the absolute dimensions but also the periodicity of the electrodes.

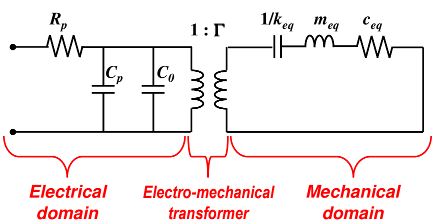

Figure 4: Equivalent lumped parameter model for a 1-port electro-mechanical resonator based on the direct (or current) analogy that maps voltage to force and current to velocity.

Figure 4 shows the equivalent lumped parameter model for a 1-port, single mode, electro-mechanical resonator. The transduction factor used to calculate the equivalent electrical parameters for TFE transduced piezoelectric higher order contour mode resonators is given by Eq. 1, which represents a generalization of the derivation given by [8].

$$\Gamma^{TFE} = n_{elec}^{1/2} e_{31} \frac{w_{elec}^{2}}{w_{res}} \sin\left(\frac{\pi}{2} L_{elec} / L_{res}\right) \qquad \textit{Eq. 1}$$

The series resonant frequency of the partially electroded device is approximated by Eq. 2.

$$f_s \approx \frac{\sqrt{E_{AlN}/\rho_{AlN}}}{2 L_{res} \Phi} \qquad \textit{Eq. 2}$$

$$\Phi = 1 + \frac{L_{unelec}}{L_{elec}} \sqrt{\frac{1 + \frac{t_{Al}\rho_{Al}}{t_{AlN}\rho_{AlN}}}{1 + \frac{t_{Al}E_{Al}}{t_{AlN}E_{AlN}}}}$$

FABRICATION PROCESS

The resonators under investigation are fabricated using a variation of a previously published four mask, low-temperature process [9]. Each device consists of a thin film piezoelectric AlN structural layer with either parallel top and bottom or coplanar top Al transduction electrodes (the approximate thicknesses of the AlN and each Al layer are 1.5 μm and 150 nm, respectively). For the TFE transduced devices, a Nb liftoff step has been added to provide an etch stop where vias through the AlN layer are required to expose the bottom Al electrode. A gently sloped etch profile permits these vias to be used for routing signal traces between the top and bottom metal layers.

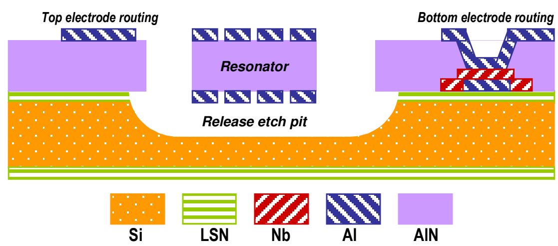

Figure 5: Cross-sectional view of fabrication process showing resonator with 4 top and bottom electrode pairs for TFE. The tethers anchoring the released resonator to the surrounding AlN layer are not shown in this cross-section.

A cross-sectional schematic of the fabrication process is shown in Figure 5. The entire fabrication process could be rendered CMOS-compatible by replacing the 300 nm low-stress silicon nitride (LSN) layer between the silicon substrate and bottom electrodes with a low-temperature silicon oxide (LTO) or AlN isolation layer. High resistivity silicon substrates are used to reduce deleterious electrical parasitics. The AlN films are deposited by the authors using a single-module Advanced Modular Sputtering (AMS) tool.

EXPERIMENTAL RESULTS

The fabricated MEMS filters are tested in a Janis RF probe station with micro-manipulated ground-signal-ground (GSG) probes. All testing is performed in air at atmospheric pressure and ambient temperature. The S_{11} parameter of the devices is extracted by an Agilent E5071B vector network analyzer (VNA) with 0 dBm of signal power following a short-open-load (SOL) calibration on a precision reference substrate. The admittance transformation is calculated by the network analyzer.

The measured dimensions of the fabricated resonators and typical material parameter values for Al and AlN are summarized in Table 1. Key experimentally determined parameters for the TFE transduced resonator are given in Table 2.

L_{res}	4 μm	n_{elec}	10
L_{elec}	1.4 μm	E_{AlN}	350 GPa
L_{unelec}	2.6 μm	ρ_{AlN}	3200 kg/m^3
w_{res}	100 μm	E_{Al}	70 GPa
w_{elec}	86 μm	ρ_{Al}	2700 kg/m^3
t_{AlN}	1.5 μm	$\varepsilon_{33\ AlN}$	9 (relative)
t_{Al}	150 nm	e_{31}	-0.5 to -0.75 C/m^2

Table 1: Measured dimensions of the fabricated TFE transduced resonator and typical values of material properties. The magnitude of the e_{31} piezoelectric coefficient depends on the quality (crystallinity) of the AlN film.

f_s	1.2836 GHz
f_p	1.2857 GHz
Q	1,420
$C_0 + C_p$	139 fF
R_m	231 Ω
L_m [$= QR_m/\omega_s$]	41 μH
C_m [$= 1/(QR_m\omega_s)$]	0.34 fF
k_t^2 [$= \pi^2/4\ (f_p - f_s)/f_s$]	0.415 %

Table 2: Summary of experimental results obtained for the TFE transduced resonator. The relations used to determine L_m, C_m and k_t^2 appear in brackets; all other quantities are measured directly.

Figure 6 and Figure 7 show the experimentally measured admittance response of a TFE transduced, higher-order contour mode AlN resonator from DC to 4 GHz exhibiting a single dominant peak at 1.28 GHz with 231 Ω motional resistance and Q around 1,400. The resonator exhibits a very strongly attenuated (Q<60) thickness-extensional resonance at 3.37 GHz due to the e_{33} piezoelectric coefficient of AlN. Figure 8 shows the Smith chart from 1,255 to 1,305 MHz for the same TFE transduced resonator.

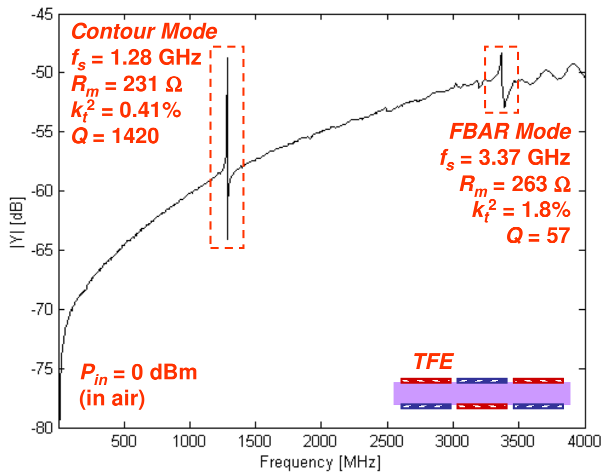

Figure 6: Admittance magnitude plot showing experimental resonator response from DC to 4 GHz. Contour and FBAR modes are excited by TFE acting on the e_{31} and e_{33} piezoelectric coefficients, respectively.

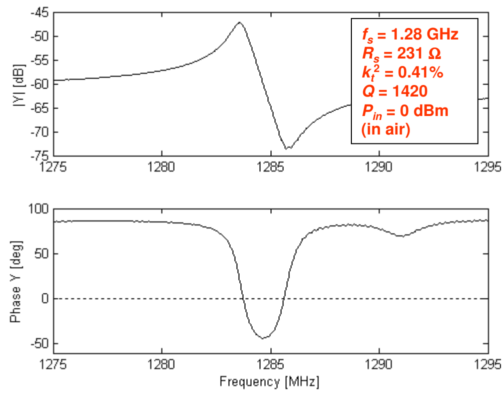

Figure 7: Experimental admittance magnitude and phase plots for the same device as Figure 6 in the vicinity of its series and parallel resonances. The reported data are taken directly from the network analyzer without using any interfacing circuitry or subtracting any parasitics.

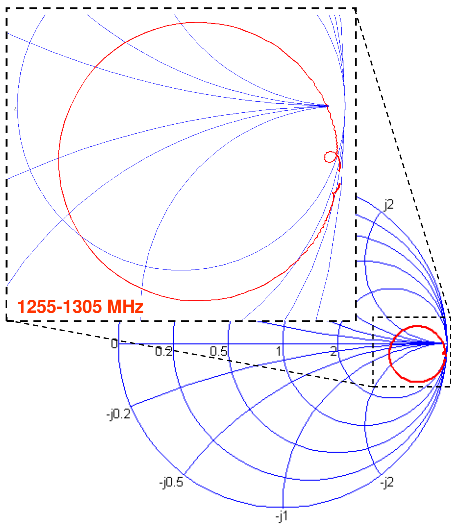

Figure 8: Smith chart showing the Q circle for the TFE transduced 1.28 GHz higher-order contour mode resonator.

The difference between the 2 µm line and 2 µm space electrode pitch drawn on the mask and the 1.4 µm line and 2.6 µm space pitch that was actually achieved during fabrication is believed to have nearly doubled the measured R_m with respect to its expected value (see Eq. 1).

The experimentally measured admittance response of a LFE transduced, higher-order contour mode AlN resonator showing a series resonance at 1.18 GHz with 1.4 kΩ motional resistance and Q of 690 is plotted from 600 to 1,400 MHz in Figure 9. The Q reduction of the LFE resonator vis-à-vis the TFE transduced device could be caused by out of plane flexural vibrations induced by the asymmetric (top electrodes only) layer stack or inferior AlN quality resulting from its deposition directly on bare LSN.

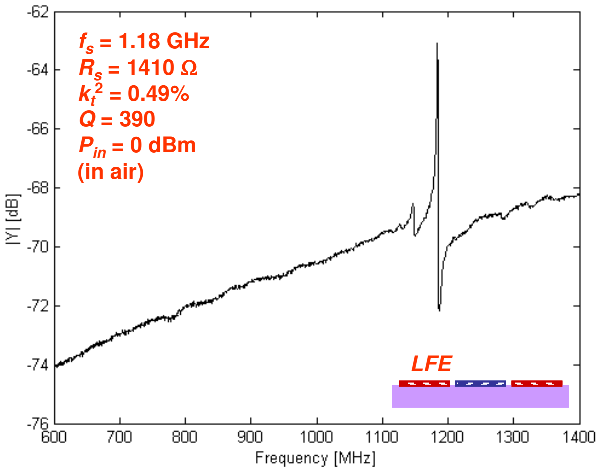

Figure 9: Experimental admittance response of resonator with the same AlN dimensions and top electrode layout as the device in Figure 6 and Figure 7 but without bottom electrodes transduced by LFE.

These are believed to be the highest ever reported fundamental frequencies for contour mode thin film electro-mechanical resonators.

CONCLUSIONS

Higher-order contour mode piezoelectric AlN MEMS resonators have been demonstrated that break the GHz fundamental frequency barrier. The improvement arises from a design for selectively patterning the transduction electrodes and routing the electrical excitation waveform to selectively transduce a specific mode of a rectangular AlN plate. The design uncouples the motional resistance and operating frequency of the resonator, and suppresses spurious resonant responses in the device over a wide range of frequencies. Resonators employing both TFE and LFE have been developed, with the former showing higher Q and lower R_m.

A TFE transduced AlN resonator measuring 1.5x40x100 µm overall with 10 pairs of 4 µm period Al electrodes has been tested at 1.28 GHz with 231 Ω motional resistance and a Q of 1,420 in air with 1 mW input power. All frequency response plots represent 1-port measurements taken directly from a network analyzer following SOL calibration.

With 1 µm minimum feature size lithography (to pattern thin metal films only, minimum structural feature size remains >10 µm), the design is scaleable to nearly 3 GHz with motional resistances below 100 Ω. This technology has the potential to for the first time achieve monolithic integration of post-CMOS compatible, low-loss filters spanning IF to RF that can readily be interfaced with existing 50 Ω RF systems.

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