Design of novel mechanical coupling for contour mode piezoelectric RF MEMS filters

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Abstract. Two novel mechanical coupling methods for synthesizing highly-integrated contour mode piezoelectric aluminum nitride (AlN) filters are introduced. While the underlying resonator technology remains the most viable candidate for realizing arrays of post-CMOS compatible filters at arbitrary frequencies with on-chip matching to 50Ω, previously demonstrated mechanical coupling topologies do not scale well beyond 100 MHz. The current work focuses on design and fabrication techniques intended to extend the numerous inherent advantages of the AlN contour mode resonator technology to filters that are capable of higher center frequencies. The first design involves a series of alternating high and low acoustic impedance quarter wavelength sections that regulate the strength of the elastic coupling between resonators. The second approach relies on elastic coupling elements that are defined in the relatively compliant bottom metal electrode layer rather than the structural AlN film used by the actual resonators.

1. Introduction
Recent advances in MEMS design and fabrication have enabled the creation of contour mode piezoelectric AlN resonators spanning a frequency range from tens to hundreds of MHz on a single substrate [1]. Moreover, the stronger electromechanical coupling of thin film piezoelectric films relative to electrostatic transduction results in filters with lower insertion losses allowing for on-chip realizable termination values. These devices and functionally equivalent ones realized using traditional fabrication techniques are widely used to create electrically or mechanically coupled bandpass filters for a myriad of applications. The fractional bandwidth of filters based on electrically cascaded L-networks of AlN contour mode resonators is fundamentally limited to approximately 2% by intrinsic material properties [2]. In contrast, the use of quarter wavelength long length-extensional bar coupling elements between adjacent width-extensional mode plate resonators effectively allows both frequency and bandwidth to be specified at the CAD layout level [3].

Figure 1 shows an optical micrograph of a coupled array of 64 width-extensional plate resonators. The mechanical connection of eight resonators in series provides the desired multi-pole filter response, while the electrical arrangement of eight parallel branches improves the insertion loss and reduces

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ripple [4]. The resulting fractional bandwidth is proportional to the coupling element to resonator equivalent stiffness ratio [5].

Figure 1: Array of 64 contour mode plate resonator filters with mechanical series connections for multi-pole bandpass response and electrical parallel connections for reduced I.L.

In practice, synthesizing AlN filters at frequencies greater than 300 MHz becomes impractical using this topology because accurately defining sufficiently compliant elastic coupling elements requires sub-micron lithography and etching. Figures 2 and 3 introduce two novel approaches to overcome this limitation. The former approach uses a series of laterally alternating high and low acoustical impedance quarter wavelength reflectors to couple the resonators. In contrast to the quarter wave reflector stacks for existing solidly mounted BAW resonators that require multiple depositions [6], the reflector array in the present implementation is realized in the same lithographic masks as the top and bottom transduction electrodes. The latter design employs the bottom Pt electrode (which for a given lateral dimension is an order of magnitude more compliant than the AlN structural layer) as the coupler between adjacent resonators.
Figure 2: Electrically parallel array of half wavelength resonators coupled by laterally alternating high- and low- acoustical impedance quarter wavelength reflectors

Figure 3: Schematic of two plate, Pt bottom electrode coupled filter
2. Analysis

The fractional bandwidth of the mechanically coupled filter topologies depicted in figures 1 and 3 is a function of the relative equivalent mechanical stiffnesses of the resonator and coupling element. To first order, the relation for an $n$ resonator filter is

$$f_n - f_1 = \sqrt{1 + 2\left(1 - n^{-1}\right)} k_{\text{coup}} / k_{\text{res}} - 1$$

where $f_1$ and $f_n$ are the frequencies of the lowest and highest natural modes in the filter passband, and $k_{\text{res}}$ and $k_{\text{coup}}$ are the mechanical stiffnesses of the resonator and coupler, respectively [4]. The electrically parallel arrangement of multiple mechanically series resonator chains in Figure 1 allows the designer to reduce the filter insertion loss without resorting to high length to width aspect ratio plates, which tend to provide less efficient transduction and greater susceptibility to spurious modes. However, the technique becomes impractical for frequencies greater than 300 MHz because sub-micron lithography and etching is required to accurately defining coupling elements with sufficiently small $k_{\text{coup}}$.

For a given lateral dimension, an elastic coupling element that is defined in the bottom Pt electrode rather than the AlN structural layer results in approximately an order of magnitude reduction in $k_{\text{coup}}$, thereby greatly reducing the lithographic accuracy required for a given frequency and fractional bandwidth. The device shown in Figure 3 employs this mechanical coupling topology to extend the attainable range of filter center frequencies.

Figures 2 and 4 represent the contour mode analogue of the familiar thickness extensional BAW solidly mounted resonator (SMR) [6]. In the current implementation, two half wavelength resonators are coupled by alternating high and low acoustic impedance quarter wavelength reflectors (QWR). The high and low impedance regions are defined by the presence or absence, respectively, of patterned Pt from the top and bottom electrode layers. In contrast to the quarter wave reflector stacks for existing thickness extensional SMR’s that require multiple depositions, the contour reflector array is realized in the same lithographic masks as the top and bottom transduction electrodes.

![Figure 4: Schematic of coupled two plate filter with six alternating high/low acoustic impedance quarter-wave reflectors](image)

The strength of the coupling between the resonators, and hence the resulting filter fractional bandwidth, is determined by the number of reflectors and the magnitude of the acoustic mismatch between successive high and low impedance regions.
3. Fabrication Process

The filters under investigation are fabricated using a variation of a previously published four-mask, potentially low-temperature process [1, 2]. The devices consist of a thin film piezoelectric AlN structural layer sandwiched between Pt bottom and top electrodes. The structure is released by dry-etching a pit in the underlying Si wafer and is tied to mechanical ground by tethers defined in the same AlN film as the resonator body. The tethers also serve as conduits for electrical signal routing to and from the electrodes. A cross-sectional schematic of the fabrication process is shown in Figure 6.

4. Experimental Results

The fabricated MEMS filters are tested in a Janis RF probe station with micro-manipulated ground-signal-ground (GSG) probes from Picoprobe. All testing is performed in air at atmospheric pressure and ambient temperature. The scattering parameters, $S_{ij}$, of the devices are extracted directly using an Agilent E5071B vector network analyzer with 0 dBm of signal power following a two-port short-
open-load-thru (SOLT) calibration on a ceramic reference substrate. The reported termination values are simulated by the network analyzer and are the same for both ports.

Figure 7 shows the experimentally measured bandpass response of the eight by eight array of mechanically coupled plate resonators seen in Figure 1. Each resonator measures 40 x 60 μm and is mechanically coupled to adjacent resonators by 20 x 6 μm couplers defined in the AlN structural layer. Successive resonators in each series branch are electrically isolated.

The fabricated QWR-coupled filter seen in Figure 2 consists of twelve parallel plate resonator pairs. Each half wavelength resonator measures 20 x 40 μm and is coupled by a series of six 20 x 20 μm QWR pairs. Its transmission response with termination is reproduced below in Figure 8.

The fabricated electrode-coupled filter consists of ten parallel plate resonator pairs, where each resonator measures 12 x 44 μm and is mechanically paired by a 12 x 3 μm coupler defined in the bottom Pt electrode layer. The corresponding transmission response plot is reported below in Figure 9.
5. Conclusions
Recent advances in MEMS design and fabrication have enabled the creation of contour mode piezoelectric AlN resonators spanning a frequency range from tens to hundreds of MHz on a single substrate. Mechanically coupling such resonators allows filters to be synthesized that have both their center frequency and bandwidth specified at the CAD layout level. A coupled array of 64 width-extensional plate resonators with eight resonators in series mechanically to provide the desired multipole filter response and eight branches in parallel electrically to improve the insertion loss and passband ripple has been demonstrated. The device has a 99 MHz center frequency and 2% fractional bandwidth.

This work introduces two novel coupling techniques to overcome the practical limits to accurately defining sufficiently compliant elastic coupling elements filters that occur at frequencies greater than 300 MHz. The former approach uses a series of laterally alternating high and low acoustical impedance quarter wavelength reflectors QWR to couple the resonators. In contrast to its thickness extensional analogue (the SMR) that requires multiple depositions, the reflector array in the present implementation is realized in the same lithographic masks as the top and bottom transduction electrodes by the selective presence or absence of metal. This device exhibited a 169 MHz center frequency and 0.9% fractional bandwidth. The latter technique employs the bottom Pt electrode (which for a given lateral dimension is about an order of magnitude more compliant than the AlN structural layer) as the coupler between adjacent resonators. The electrode-coupled filter has a 292 MHz center frequency and 1.7% fractional bandwidth.

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