FABRICATION AND MEASUREMENT OF AN IC-COMPATIBLE GHZ-RANGE PIEZOELECTRIC LONGITUDINAL BAR RESONATOR

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ABSTRACT

We report on the fabrication and measurement of a piezoelectrically-actuated, longitudinal-mode acoustic MEMS resonator designed to operate in air with high Q and low impedance in the ~ 50 MHz – 2 GHz frequency range. Since the longitudinal-mode frequency is set lithographically by the lateral bar dimensions, a wide range of resonator frequencies can be created on a single chip. Device processing is IC compatible, offering the potential for integration in transceiver applications.

This first set of fabricated devices had resonator lengths ranging from 3 to 30 microns, corresponding to frequencies from 100 MHz to 1.3 GHz, on a single wafer. We discuss the fabrication process for these aluminum nitride (AlN) devices and present measurements on resonators with frequencies ranging from ~ 100 -700 MHz.

INTRODUCTION

Radio-frequency transceivers used today rely on off-chip components for highly frequency selective resonant elements. The ability to integrate extremely small, high quality factor (Q) resonators will significantly impact size and performance in existing transceivers [1]. In addition, new system architectures will take advantage of ultra-dense arrays of resonators to make chip-scale filter banks and frequency synthesizers, enabling a new generation of small, universal transceivers.

Towards these goals, relevant performance metrics of the resonators include small size, high Q , frequency scalability over 0.3-3 GHz, RF integrated circuit process compatibility, RF impedance compatibility, linearity, and power handling. On all fronts, the thin-film resonator (TFR) technology, which uses piezoelectric actuation, is particularly advanced. Resonators at 0.8-3 GHz with Q 's ranging from 450-2000 and impedance levels in the range of 50 Ohms are reported [2,3,4]. Quartz resonators have been demonstrated with Q 's above 13,000 at 590 MHz [5]. Several capacitively actuated resonator designs that are easily scalable have also demonstrated impressive Q 's. In [6], a disk-mode resonator at 1.14 GHz produced $Q=1500$ in air. Capacitively actuated designs are challenged however by high impedance levels (in the range of 10k Ω) and process compatibility.

The Draper piezoelectric longitudinal bar (L-Bar) resonator design strategically addresses key requirements for RF applications. In the following sections, we review the resonator design and several of its merits. The fabrication process is next described in detail. Finally, we present results from initial device measurements.

RESONATOR DESIGN

The L-Bar resonator physically resembles a suspended capacitor. Figure 1 shows a solid model of the center bar suspended above a silicon substrate via tethers. The bar is metalized on top and bottom. These electrodes apply a field

through the thickness of the AlN. At most frequencies, the device response is that of a capacitor. At the mechanical resonance, however, the electrical impedance drops by orders of magnitude, depending on the device Q .

The choice of a piezoelectrically actuated, in-plane longitudinal mode MEMS device is unique and the design addresses important application metrics. The frequencies of in-plane longitudinal modes are lithographically scalable over ~ 50 MHz – 2 GHz, allowing arrays on a single chip. These modes are also robust to package (thermal) stress. The piezoelectric actuation allows for impedance matching. The suspended bar structure and materials choices enable extremely high Q designs. In addition, the use of aluminum nitride (AlN) as a structural and transduction material has multiple advantages. AlN can be deposited at temperatures well below 400°C for process compatibility, it has a low dielectric loss tangent, the dielectric breakdown is $\sim 10^6$ V/cm (allowing for high power handling), and the response is extremely linear. Finally, the electrode geometry enables a self-aligned, manufacturable process and minimizes spurious modes so that additional mode selection filters are not necessary.

Figure 1. Schematic of the L-bar device. The suspended resonator is made of piezoelectric aluminum nitride sandwiched between metal layers. The resonant structure is suspended over a gap by tethers. Nominal dimensions for an 800MHz resonator are 5 μ m long x 3 μ m wide with a 1.5 μ m wide tether.

PROCESS OVERVIEW

Figure 2 shows an overview of the process flow for the resonator. The starting point is the following materials stack on a silicon wafer: a release layer (0.5 – 1 μ m thick) of thermally-grown SiO₂, a thin (~ 200 Å), “seed” layer of AlN, 1500Å of Mo, and 5000Å of polycrystalline, c-axis-oriented, piezoelectric AlN. Approximately 2000Å of Ni is then patterned by evaporation and liftoff.

The patterned nickel serves as an etch mask for wet etching of AlN, which serves as an etch mask for RIE of the Mo bottom metal and a further wet etch of the seed AlN. At this point the mechanical form of the resonator, support tethers, and probe pads has been defined into the stack. Figure 3 shows a scanning-electron micrograph of an etched stack test structure.

Figure 2. Schematic of L-bar process flow. Mechanical form of resonator, including critical alignments, is defined in first mask level. Each layer in the device film stack serves as a self-aligned etch mask for subsequent layers. Several etch steps pattern the electrical circuit. The release etch is self aligned.

Figure 3. Scanning-electron micrograph of etched stack structure. Nickel, patterned by liftoff, serves as an etch mask for the underlying AlN, which is wet etched in AZ400k photoresist developer. The Ni and AlN serve as etch masks for RIE of the molybdenum bottom metal in CF₄ plasma.

The next sequence of steps forms the proper electrical circuit. To minimize parasitic capacitances (*i.e.* top/bottom metal overlap other than on the resonator), breaks are etched into the tether Mo and Ni on opposite sides of the resonator. Then the Ni and AlN are removed by wet etching on the probe pad opposite the bottom metal break to allow electrical access to the Mo for testing. To complete the electrical circuit, isolated top and bottom metal islands on the tethers are shorted to appropriate pads by liftoff of a platinum “patch.”

The device is released by etching the underlying SiO₂ in BHF. Figure 4 shows scanning-electron micrographs of two released resonator devices.

Figure 4. Scanning-electron micrographs of released resonator structures. TOP: 5 μm long x 3 μm wide resonator. BOTTOM: 10 μm long x 6 μm wide resonator. Tethers are approximately 1 μm wide for both devices.

FABRICATION DETAILS

CRITICAL ALIGNMENTS: The small device size requires precise alignments in the structure. For example, the resonator should be centered on the tethers to minimize sensing of non-longitudinal modes, and the resonator and tethers should be centered on the support structure to allow minimization of acoustic wave propagation into the supports through tether-length “tuning.” This process incorporates all of these alignments into the first mask level, which patterns the nickel. Since the nickel serves as an etch mask for the entire stack, the device definition is self-aligned. Additionally, the patterned device structure serves as a self-aligned etch mask for its own release.

MATERIAL/PROCESS CHOICES: Tradeoffs among device electrical characteristics, IC-compatible processing, and piezoelectric film growth requirements dictated materials selection.

Our AlN films were deposited by a commercial vendor [7]. Their best-quality process, which typically yielded an x-ray rocking curve FWHM of ~1.5 degrees, dictated the bottom of the piezoelectric stack (seed AlN/Mo/AlN). Nickel was chosen as the top metal for its suitability as an etch mask for both wet etching and Cl-based dry etching [8] of AlN, as well as for a ratio of density to electrical conductivity comparable to that of molybdenum.

The choice of molybdenum, aluminum nitride, and nickel required a unique set of selective etch chemistries, shown in Table 1.

rate/ notes	20:1:1 DI:HF:H ₂ O ₂	AZ400k developer	CF ₄ /O ₂ RIE [9]	XeF ₂	BHF
Ni	~1000Å/min	x	x	x	x
AlN	x	self- limiting (see text)	x	x	x
Mo	x	x	anisotropic ~133Å/min	isotropic, undercut	x
SiO ₂	not exposed	x	not exposed	x	re- lease

Table1. Etch chemistries used to fabricate resonator.

The Mo/AlN stack is deposited by sputtering/reactive sputtering at 400°C or below. No high-temperature steps are used in the subsequent processing of the device, making this process IC-compatible.

Figure 5. Scanning-electron micrograph of progress of AlN wet etch in AZ400k photoresist developer. The top Ni etch mask protects the underlying AlN film, which is on a Mo bottom layer. The surface of the exposed AlN quickly roughens into conical-shaped structures that slowly etch to the underlying Mo. TOP: 1:30 etch. MIDDLE: 2:30 etch. BOTTOM: 10:00 etch. The AlN etch is self-limited at the sidewall angle shown (~50x overetching showed no change in the structure).

WET ETCHING OF AlN: For our AlN films, wet etching in AZ400k photoresist developer was self-limiting at a fixed sidewall angle of approximately 55°. Figure 5 shows scanning-electron micrographs of a time sequence of the AlN etch. In unprotected regions, the etch produces conical structures. As the etch progresses, these cones shrink in size, eventually disappearing. Note that in the protected areas the film is dense, *i.e.* no etchant infiltrates from the sides.

The self-limiting nature of this etch is quite high; ~50x overetching showed no change in the structure. Previous literature on etching of AlN in AZ400k does not mention film roughening,

conical structures, or self-limited etching [10, 11]. This effect is beneficial to our process, but not well understood at this time.

UNDERCUT ETCHING OF Mo: Minimizing stray capacitance required a break to be patterned in the top and bottom tether metal. For the top metal, this was a rather straightforward wet etch with a photoresist mask, but for the Mo bottom metal, an undercut etch was required.

To execute this etch, a resist window was opened in the area around the bottom metal break, and a XeF₂ etch [12, 13] was used to etch the Mo. XeF₂ gave high selectivity to all other materials in the structure, and was a highly isotropic etch.

DEVICE MEASUREMENTS

Resonator testing was conducted at the wafer level, in air, at room temperature, using GGB Industries probe tips on a Cascade Microtech probe station and an Agilent 8753 Network Analyzer. The device is wired in a series configuration for two-port measurements.

Figure 6. S21 measurement of a 10- μm x 5- μm L-bar resonator. Two longitudinal-mode resonances are evident, corresponding to the length and width modes of the device.

Figure 7. S21 data from a different 10- μm x 5- μm device, along with fit to a BVD model. This model gives a Q of 125. Q values as high as 550 at 700 MHz have been measured on these devices.

Figure 6 shows an S21 measurement of a 10 μm long x 5 μm wide resonator over a wide frequency sweep. Two longitudinal-mode resonances are evident, corresponding to the length and width modes, at approximately 350 and 700 MHz, respectively. The spurious feature at 120 MHz, which is currently not well understood, is present in all devices as well as non-resonant calibration structures.

Figure 7 shows a fit to a 5 μm width mode from a different resonator. The fit uses a Butterworth van Dyke (BVD) model [14] for the mechanical resonance. Parasitics were modeled as port capacitance and resistance. The BVD circuit parameters were $R=35\text{ k}\Omega$, $L=1\text{ mH}$, $C=0.047\text{ fF}$, and $C_0=2.7\text{ fF}$. This corresponds to a Q of 135. Q values as high as 550 at 700 MHz have been measured on fabricated devices.

Figure 8. Closeups of S21 data from two other devices. LEFT: 25 μm length mode. RIGHT: 5 μm width mode.

Figure 8 shows detailed S21 data of resonances from two other devices. Figure 9 shows a plot of frequency vs. inverse length. The slope of 3.7 GHz- μm is consistent with calculations based on the AlN and metal layer mechanical properties for a simple longitudinal mode.

Figure 9. Frequency vs. inverse length for a number of resonators.

CONCLUSIONS

A new RF MEMS resonator has been designed, fabricated, and measured. The design addresses key performance parameters including quality factor, frequency scalability, mode isolation, and impedance matching. The design allows for a self-aligned fabrication process enabling high dimensional precision even as feature sizes are pushed to sub-micron ranges. A unique undercut etch is used to isolate the electrical leads and form the basic overlap capacitor structure. Initial measurements verify that well-isolated longitudinal modes are excited in the devices. Although measured quality factor and electrical admittance are much lower than theoretical limits predict, ongoing work will address electrical parasitics and process improvements. These first experimental results verify that the RF resonator design is widely scalable in

frequency, confirm that the modes are well-isolated, and demonstrate an IC-compatible fabrication process.

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