INTERNAL ELECTROSTATIC TRANSDUCTION FOR BULK-MODE MEMS RESONATORS

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ABSTRACT

This paper demonstrates a new approach to electrostatic drive and detection of bulk acoustic resonators in which the electrode-gaps are filled with a high dielectric constant material. *Internal electrostatic transduction* has much higher efficiency than air-gap electrostatic transduction for bulk-mode resonators, which results in improved electrical performance. As a proof-of-concept, we demonstrate this phenomenon by electrostatic actuation of a 1.9GHz AlN (κ ~ 9) film bulk acoustic resonator (FBAR).

INTRODUCTION

Surface micromachining technology supports fabrication of multi-frequency, electrostatically transduced lateral bulk resonators. A single mask can include multi-frequency filters, oscillators and mixers. However, lateral bulk acoustic resonators have very large motional resistance due to reduced transducer area [**1**] and inefficient air-gap electrostatic transduction (compared to piezoelectric transduction [**2**]). Creative approaches to increasing transducer area include forming a coupled array of resonators [**3**] and large diameter bulk annular ring resonators [**4**]. However, to reach motional resistances on the order of 50Ω, we would need a coupled array of 100 resonators or a 400µm diameter ring resonator. The signal routing challenges for these structures will be daunting at GHz frequencies and the chip area occupied by these resonator designs will be larger than an FBAR (which has motional resistance of 2Ω).

The electrostatic force and motional current for a parallel-plate electrostatic transducer are:

$$f = V_{DC} \cdot \frac{\varepsilon_0 \cdot A}{g^2} \cdot v_{in} \quad ; \quad i = V_{DC} \cdot \frac{\varepsilon_0 \cdot A}{g^2} \cdot \omega \cdot x$$

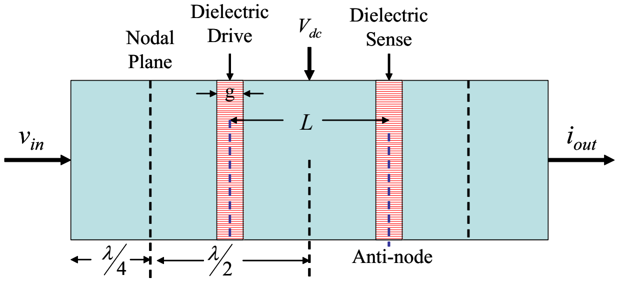
Both terms are proportional to the permittivity of capacitor dielectric (ε_0 for air or vacuum). We propose to fill the electrode gaps of the bulk acoustic resonators with a dielectric material having much higher permittivity than air. The high-κ dielectric will enhance both the force density of the electrostatic actuator as well as the sense capacitance, thereby reducing the motional resistance of these resonators by κ^2.

Bouwstra *et al* demonstrated that audio-frequency cantilever beams can be driven and sensed using silicon nitride dielectric capacitors embedded in a silicon resonator [**5**]. The resonator made use of Poisson's ratio to convert applied strain perpendicular to the beam's thickness into strain along the beam, which coupled into the fundamental bending mode. The approach was deemed inefficient because air-gap capacitive transduction provided larger displacement, the preferred performance metric at that time.

BULK-MODE INTERNAL ELECTROSTATIC TRANSDUCTION

Bulk-mode resonators have significantly different design requirements compared to flexural resonators. These resonators typically have displacements on the order of a few nanometers. In principle, we can enhance the transduction efficiency of bulk resonators by filling the air-gaps with a low Young's modulus, high-κ dielectric material. A more practical approach would be to find a dielectric with similar acoustic velocity as the resonator material and 'build-in' an internal electrostatic transducer at the maximum strain 'anti-nodes' rather than the maximum displacement nodes. This approach would minimize bulk energy losses due to acoustic velocity mismatch and optimize transduction efficiency of the resonator. TiO_2 with relative permittivity κ ~ 80 and bulk acoustic velocity 7900m/s is an attractive material for this purpose.

In order to benchmark the performance of the internal electrostatic transducer, we evaluate its performance in a 3rd overtone lateral bulk acoustic resonator. This class of resonators has been demonstrated with air-gap electrostatic [**1,4**] and piezoelectric transduction [**2**]. The 3rd overtone can be excited and detected by introducing layers of TiO_2 at the two anti-nodal planes, as shown in Figure 1.



E = Young's modulus
A = Cross-section area
Q = Quality factor
ω = Resonant frequency
L = Half wavelength
g = Length of transducer element
V_{DC} = Bias voltage
$\varepsilon_{TiO_2} = \kappa_{TiO_2} \cdot \varepsilon_0$ = Permittivity of TiO_2

Figure 1. *Schematic of electrostatically transduced 3rd overtone bulk acoustic resonator*

The motional resistance of this resonator is

$$\frac{1}{R_{electrostatic}} \approx \frac{V_{DC}^2 \cdot \kappa_{TiO_2}^2 \cdot \varepsilon_0^2 \cdot A^2}{g^4} \cdot \frac{\omega \cdot Q}{E \cdot A/L}$$

By replacing the electrode-gap with TiO_2 at the antinodes, we can reduce the motional resistance by $\kappa^2 = 6{,}400$.

A 14MHz bulk acoustic resonator with 1µm air-gap electrostatic transducers has a motional resistance of 590kΩ [**1**]. The 3rd harmonic of an identical resonator with TiO_2 dielectric transduction would have a motional resistance of 275Ω. Similarly, the motional resistance of the 1.2GHz 3rd harmonic ring resonator [**4**] would scale down from 282kΩ to 44Ω.

ELECTROSTATIC EXCITATION OF AN FBAR

We used Agilent Technologies' AlN FBAR [**6**] to demonstrate internal electrostatic transduction. AlN has a relative permittivity of κ ~ 9 and the resonator has a mechanical quality factor Q ~ 1350

Travel support has been generously provided by the Transducers Research Foundation and by the DARPA MEMS and DARPA BioFlips programs.

at a resonant frequency of f_0 = 1.92GHz. Electrostatic force is quadratic; therefore we can actuate the FBAR with an input signal at half the resonant frequency (Figure 2). This ensures that there is no piezoelectric actuation of the resonator. A low-pass-filter was added to prevent any harmonics from the RF synthesizer from reaching the input electrode.

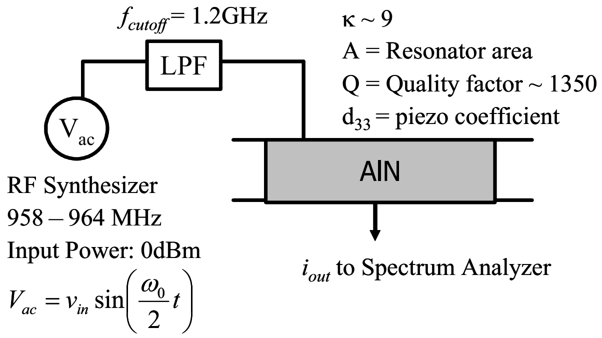


Figure 2. *Test equipment setup for half-frequency measurement. The Spectrum Analyzer is set to MAX_HOLD as the synthesizer frequency is swept near half-resonance frequency.*

Electrostatic actuation will generate stress in the resonator at the resonant frequency:

$$T_{electrostatic}(f_0) = \frac{1}{4}\cdot\kappa_{AlN}\cdot\varepsilon_0\cdot\frac{v_{in}^2}{t^2}$$

This electrostatic stress generates dielectric displacement and results in piezoelectric displacement current:

$$i_{out,piezo}(f_0) = \omega_0\cdot A\cdot Q\cdot d_{33}\cdot\frac{1}{4}\cdot\kappa_{AlN}\cdot\varepsilon_0\cdot\frac{v_{in}^2}{t^2}$$

The output current also has an electrostatic component due to the quadratic electrostatic force. However, this component is extremely small compared to the piezo component due to the relatively large resonator thickness.

By sweeping the RF synthesizer frequency from 958MHz to 964MHz and using the MAX_HOLD function [7] on the 8562EC Spectrum Analyzer, we were able to construct the mechanical transfer function and extract Q of the FBAR (Figure 3).

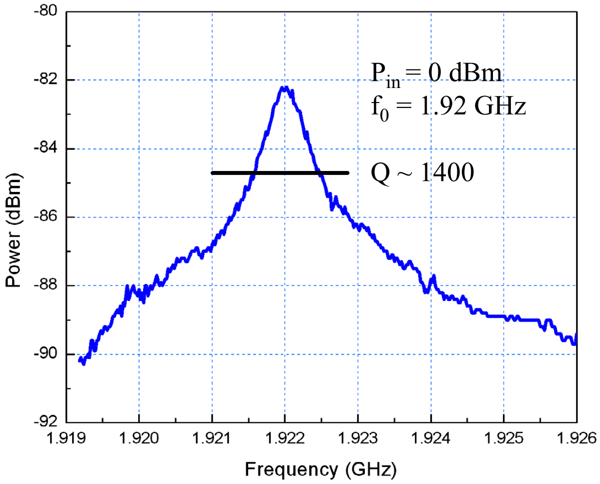


Figure 3. *FBAR transmission spectrum obtained using half-resonance electrostatic actuation. Q ~ 1400 was extracted from the shape of the transfer function.*

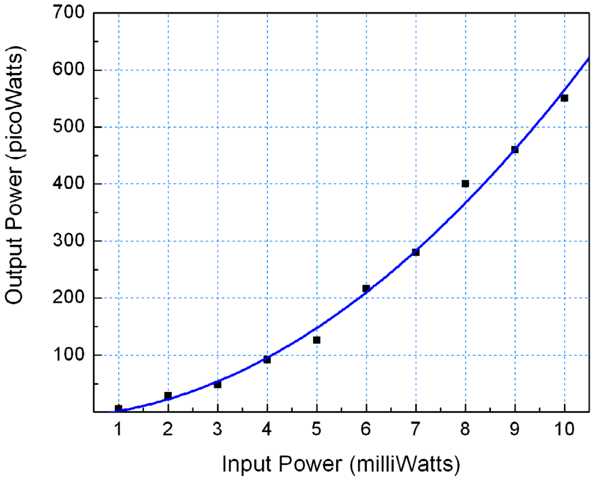


Figure 4. *Output power is proportional to the square of the input power, verifying internal electrostatic actuation of the FBAR.*

While the output current is due to piezoelectric effect, the mechanical motion of the FBAR is due to electrostatic stress. Hence, both the mechanical motion and output power are proportional to square of the input power (Figure 4).

The FBAR is a one-port device and hence is not suitable for electrostatic transduction. However, these two measurements provide preliminary experimental verification of internal electrostatic drive for bulk-mode resonators.

CONCLUSION

Internal electrostatic transducers using high-κ dielectrics can achieve κ^2 higher efficiency than conventional air-gap transducers. This new approach will enable us to fabricate arrays of small foot-print lateral bulk acoustic resonators with motional resistances <1kΩ. It will also open up the opportunity to design microwave frequency resonators with reasonable motional resistances. As a proof-of-concept, we excited an FBAR at 1.92GHz with internal electrostatic actuation.

ACKNOWLEDGMENT

The authors wish to thank Dr. Dan Radack and the DARPA NMASP program, whose generous grant (#N66001-00-1-8955) has made this research possible.

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