ABSTRACT

A “capacitive-piezo” transducer that combines the strengths of capacitive and piezoelectric mechanisms to achieve an impedance and Q simultaneously lower and higher, respectively, than otherwise attainable by either mechanism separately, has allowed demonstration of a 1.2-GHz contour-mode AlN ring resonator with a motional resistance of 889 Ω and Q=3,073 higher than so far measured for any other d_{31}-transduced piezoelectric resonator at this frequency. Here, the key innovation is to separate the piezoelectric resonator from its metal electrodes by tiny gaps to eliminate metal material and metal-to-piezoelectric interface losses thought to limit thin-film piezoelectric resonator Q’s, while also maintaining high electric field strength to preserve a strong piezoelectric effect. In addition, this capacitive-piezo transducer concept does not require dc-bias voltages and allows for much thicker electrodes that then lower series resistance without mass loading the resonant structure. The latter is especially important as resonators and their supports continue to scale towards even higher frequencies.

INTRODUCTION

The ever-increasing appetite for wireless interconnectivity is beginning to drive new functions, like frequency gating spectrum analyzers. Indeed, plenty of researchers have sought to raise the Q’s of polysilicon resonators on the order of 20 times larger than that of sputtered AlN resonators at similar frequencies. Interestingly, material loss theory predicts that the product limit due to phonon-phonon interactions in the AlN material itself is only four times lower than that of silicon. This suggests that the AlN material itself might not be the principal culprit among Q-limiting losses, but rather the metal electrodes or the electrode-to-resonator interface strain might be more responsible. In fact, experimental data show that as the thickness of a piezoelectric resonator’s electrode increases, both the resonance frequency and Q of the resonator drop due to mass loading and electrode loss, respectively [13]. Electrode-derived energy loss perhaps also contributes to the lower Q’s measured in d_{31}-transduced resonators, where the electrodes often cover locations with the maximum strain, versus the Q’s of d_{33}-transduced thickness-mode resonators, where electrodes are placed very close to the nodes of the acoustic standing waves. Of course, despite their lower Q’s, d_{33}-transduced resonators are arguably more attractive than d_{31}, since their frequencies are set by CAD-definable lateral dimensions, so are more suitable for on-chip integration of multiple frequencies.

Whether a resonator uses d_{31} or d_{33}, both share the common problem that Q gets worse as dimensions scale to achieve larger coupling and/or higher frequencies. In particular, while a piezoelectric structure can be scaled, its electrode thickness often cannot scale as aggressively, since doing so incurs excessive electrical loss derived from increased electrode and interconnect electrical resistance. If a designer attempts to compensate for this by using thinner, but wider, metal traces, then the beams supporting the resonator would need to be wider to accommodate the wider metal traces, and wider beams incur more energy loss through supports.

RAISING PIEZOELECTRIC RESONATOR Q

Indeed, plenty of researchers have sought to raise the Q’s of thin-film piezoelectric resonators, with approaches that span from reducing electrode roughness [6], to optimizing the electrode material [7], to carefully balancing the AlN-to-electrode thickness ratio [8], to use of a Bragg reflector to prevent energy loss [9]. Unfortunately, none of the above methods raises the Q’s of on-chip piezoelectric resonators anywhere near the >30,000 values needed for RF channel-selection and frequency gating spectrum analyzers.

Yet, polysilicon resonators easily achieve such Q values (but with higher than-desired impedances). To date, the measured Q’s of polysilicon resonators are on the order of 20 times larger than that of sputtered AlN resonators at similar frequencies. Interestingly, material loss theory predicts that the product limit due to (dominant) phonon-phonon interactions in the AlN material itself is only four times lower than that of silicon. This suggests that the AlN material itself might not be the principal culprit among Q-limiting losses, but rather the metal electrodes or the electrode-to-resonator interface strain might be more responsible. In fact, experimental data show that as the thickness of a piezoelectric resonator’s electrode increases, both the resonance frequency and Q of the resonator drop due to mass loading and electrode loss, respectively [13]. Electrode-derived energy loss perhaps also contributes to the lower Q’s measured in d_{31}-transduced resonators, where the electrodes often cover locations with the maximum strain, versus the Q’s of d_{33}-transduced thickness-mode resonators, where electrodes are placed very close to the nodes of the acoustic standing waves. Of course, despite their lower Q’s, d_{33}-transduced resonators are arguably more attractive than d_{31}, since their frequencies are set by CAD-definable lateral dimensions, so are more suitable for on-chip integration of multiple frequencies.

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Fig. 1: (a) Conventional piezoelectric transducers employing electrodes that directly contact the piezoelectric structure; and (b) working principals behind a capacitive-piezo resonator for which electrodes are separated from the piezoelectric structure via tiny air gaps.
and anchors, hence lower $Q$. If the width of the support beams are decreased in order to lower anchor losses and raise $Q$, the width of the metal traces must also be decreased, which then increases their resistance, again, lowering $Q$ and negating the gains.

**CAPACITIVE-PIEZO TRANSUDICERS**

From the above discussion, it seems that $Q$ degradation cannot be avoided as long as the electrode is in physical contact with the piezoelectric structure (which generates loss through strain coupling) and as long as the piezoelectric structure governs the size and thickness of the electrode (which governs electrical loss). Interestingly, all of these issues can be circumvented by mechanically decoupling the electrodes from the resonating body by simply separating the electrodes from the vibrating structure so that they are no longer in contact, as shown in Fig.1(b). The resulting transducer, dubbed the “capacitive-piezo” transducer, should not only raise the $Q$ of the piezoelectric film, but should also allow much thicker (and thus much less resistive) electrodes without the electrode loss and mass loading penalties that would otherwise result if the electrode is contacted as in Fig.1(a). Thicker electrodes should also further increase the $Q$, since the electrode parasitic series resistance would be smaller.

Although not a well known technique, the use of contactless electrodes on piezoelectric resonators is actually not new. This strategy had in fact been demonstrated on 5- and 10-MHz quartz crystal resonators, called BVA resonators, as far back as 1977 [14]. Since the piezoelectric-to-electrode thickness ratio of these devices was on the order of 100µm-to-100nm, or 1000, separating the electrode from the piezoelectric did little to increase the $Q$ of the device. It did, however, allow for a more stable device against drift, since it eliminates electrode-to-resonator stress variations. This was the main reason for investigating such devices in the past.

For micromechanical resonators, on the other hand, the piezoelectric-to-electrode thickness ratio is much smaller, on the order of 10. Thus, the case for using a “capacitive-piezo” transducer is much stronger on the micro-scale. In addition, the ease with which tiny electrode-to-resonator gaps can be achieved via MEMS technologies further encourages the use of contactless electrodes. In effect, capacitive-piezo transducers stand to improve the $Q$ and drift stability of micro-scale thin-film piezoelectric resonators with very little increase in fabrication cost.

**ANALYTICAL MODELING**

Electrical models for AlN contour-mode resonators with contacting electrodes, such as described in [1], are abundant in the literature. The present approach to modeling the capacitive-piezo resonator focuses on how electrode-to-resonator air gaps influence the electrical model parameters. Pursuant to this, Fig.1(b) presents the cross-section of a contour-mode resonator with capacitive-piezo transducers under a typical excitation configuration. When the input signal is applied across the top and bottom electrodes, mechanical strain, $S_P$, is induced on the AlN film via the reverse piezoelectric effect. The induced strain is linearly proportional to both the piezoelectric stress constant, $e_{31}$ ($e_{31}$~$0.7 \text{ C/m}^2$ for sputtered AlN), and the electric field established within the AlN film, $E_{AlN}$, regardless of the mode shape of the resonator. The gap-AlN-gap stack can be modeled by three capacitors in series, as shown in Fig. 2(a), from which $E_{AlN}$ can be written as

$$E_{AlN} = \frac{V_n}{t + \varepsilon \cdot d_{\text{final}}}$$  \hspace{1cm} (1)

where $\varepsilon$ ($\sim 9$) and $t$ are the relative permittivity in the $c$-axis direction and thickness of AlN, respectively; and $d_{\text{final}}$ is the total gap spacing ($d_{\text{final}}=d_1+d_2$). When the input frequency matches the resonance frequency, the lateral force $F_P$ induced by $E_{AlN}$ via the reverse piezoelectric effect excites the resonator into lateral-mode vibration with an electromechanical coupling coefficient on the drive side given by

$$\eta_{Drive} = \frac{F_P}{V_n} = \eta \cdot e_{31} \cdot \frac{t}{t + \varepsilon \cdot d_{\text{final}}} = \alpha \cdot e_{31} \cdot \gamma(d_{\text{final}})$$  \hspace{1cm} (2)

where the value of $\alpha$ depends on the electrode coverage area and placement, and on the resonator mode shape; and where $\gamma(d_{\text{final}})$ is a function gauging how much the coupling coefficient degrades with increasing air gap spacing. Fig. 3 plots the ($e_{31} \cdot \gamma(d_{\text{final}})$) product for different piezoelectric materials. In general, small gap spacing is preferred to maintain a high coupling coefficient. It should be noted that a large $e_{31}$ than AlN and ZnO, its capacitive-piezo coupling is weaker at most gap spacings due to its much higher relative permittivity.

On the sense side, vibration-induced strain polarizes the AlN film via the piezoelectric effect, and the resulting electric displacement can be expressed as
**Parameter**

The electromechanical coupling coefficient, $\eta_{sens}$, is also a function of the gap spacing through $\gamma(d_{total})$. Although air gaps degrade $k^2$ by a factor of $\gamma^2$, the higher $Q$ provided by non-contacting electrodes together with sufficiently small gap spacings actually make it possible to achieve higher $Qk^2$ than piezoelectric resonators with contacting electrodes.

Perhaps the best way to compare different transducers is via the filter FOM defined in [4], given by

$$\text{FOM} = \frac{1}{R_c C} \times \frac{\eta_{sens} \eta_{sens}}{m C}$$

where $R_c$ is the filter termination resistor, $C_c$ the physical input capacitance, and $m$ the motional mass of a constituent resonator in the filter. The right most form delineates parameters in the expanded equation most relevant to resonator design.

Fig. 4 compares simulated plots of $(\eta_{sens} \eta_{sens}/m C_c)$ in the filter FOM for three different transducers (i.e. piezoelectric, capacitive-piezo, and capacitive alone) versus gap spacing $d$ at the same frequency. The simulation uses a ring inner radius and thickness of 25.6 $\mu$m and 1.5 $\mu$m, respectively; and ring widths of 5 $\mu$m for AlN and 4.3 $\mu$m for polysilicon, both chosen to achieve a 1.2-GHz resonance frequency for both materials under the same mode shape, neglecting DC bias-induced electrical spring softening inherent to capacitive resonators. In addition, the electrodes for the polysilicon resonator are assumed to be placed both inside and outside the ring, similar to [3]. As expected, the FOM of the capacitive-piezo transducer depends on gap spacing, but not as strongly as one might think, mainly because $C_c$ drops by the same ratio $\gamma$ as the electromechanical coupling coefficient when the gap spacing increases. Even so, a capacitive-piezo transducer with a 200 nm gap spacing achieves a filter FOM of 0.7x10$^{17}$ $\mu$m$^{-2}$ for which a capacitive (alone) transducer would require a much smaller gap spacing of 23 nm. Needles to say, this relaxed gap spacing is a distinct advantage of capacitive-piezo transducers over capacitive.

**FABRICATION**

AlN resonators employing capacitive-piezo transducers were fabricated using a newly-developed 4-mask low-temperature CMOS-compatible process briefly summarized in Fig. 5. Here, aluminum top and Al/Ni bottom electrodes are temporarily separated from the AlN structure by a sputtered molybdenum (Mo) sacrificial material. Molybdenum is used as a sacrificial material instead of the oxide, silicon, or germanium, more commonly used in surface-micromachining processes, mainly to attain better c-axis orientation when sputtering the AlN film. Anchoring for all suspended structures, including the AlN and top electrode, is realized by a single electroplated nickel peg that contacts the top electrode. The device is released via a gaseous XeF$_2$/Ni$_2$ etchant.

Fig. 6(a) presents the wide-view SEM of a completed 1.2-GHz contour-mode $d_{33}$-capacitive-piezo-transduced ring resonator. Fig. 7 presents SEM’s of different parts of the same ring resonator.
It should be noted that the 260 nm gap spacing used in this device is a rather conservative design. In fact, if the gap spacing were reduced from 260 nm to the 100 nm commonly used in capacitive (only) resonators, the impedance could be lowered to 250 Ω.

To evaluate the efficacy of building mechanical circuits using capacitive-piezoelectric transducers, mechanically coupled two-resonator arrays, shown in Fig. 10, were also fabricated and tested. Here, the top electrode on the coupling beam is removed to electrically isolate the output from the input. The measured frequency response, shown in Fig. 11, exhibits much less feedthrough than seen in single-electrode devices. However, the Q is lower for this mechanical circuit than for a single resonator, which might be caused by etch residuals atop the coupling beam formed after dry etching the top electrode. Fixes to this problem are underway.

CONCLUSIONS
This paper demonstrated a 1.2-GHz contour-mode AlN ring resonator with a motional resistance of 889 Ω and Q=3.073, confirming that resonators equipped with “capacitive-piezoelectric” transducers can achieve higher Q than so far measured for any other d33-transduced piezoelectric resonator at this frequency and at the same time maintain high electromechanical coupling. Although the demonstrated Q is higher than other piezoelectric resonators, it is probably far from what is achievable using this technology. In particular, it is not unreasonable to expect that future capacitive-piezoelectric resonators equipped with better defined quarter-wave length supports and stiffer anchors might eventually achieve the Q’s in the tens of thousands predicted by the theory.

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