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The impact of electrode materials on 1/f noise in piezoelectric AlN contour mode resonators

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This paper presents a detailed analysis on the impact of electrode materials and dimensions on flicker frequency (1/*f*) noise in piezoelectric aluminum nitride (AlN) contour mode resonators (CMRs). Flicker frequency noise is a fundamental noise mechanism present in any vibrating mechanical structure, whose sources are not generally well understood. 1 GHz AlN CMRs with three different top electrode materials (Al, Au, and Pt) along with various electrode lengths and widths are fabricated to control the overall damping acting on the device. Specifically, the use of different electrode materials allows control of thermoelastic damping (TED), which is the dominant damping mechanism for high frequency AlN CMRs and largely depends on the thermal properties (*i.e.* thermal diffusivities and expansion coefficients) of the metal electrode rather than the piezoelectric film. We have measured Q and 1/*f* noise of 68 resonators and the results show that 1/*f* noise decreases with increasing Q, with a power law dependence that is about $1/Q^4$. Interestingly, the noise level also depends on the type of electrode materials. Devices with Pt top electrode demonstrate the best noise performance. Our results help unveiling some of the sources of 1/*f* noise in these resonators, and indicate that a careful selection of the electrode material and dimensions could reduce 1/*f* noise not only in AlN-CMRs, but also in various classes of resonators, and thus enable ultra-low noise mechanical resonators for sensing and radio frequency applications. https://doi.org/10.1063/1.5024961

Frequency stability is an important parameter that ultimately determines the floor of Allan variance of oscillators, resonant sensors, and RF micro electromechanical systems (MEMS).[1–8] As 1/*f* noise is the major factor that determines the inherent frequency stability of resonators, measuring and understanding the nature of 1/*f* noise have been of particular interest for various types of resonators, such as silicon nanoresonators, quartz crystal acoustic devices, and AlN based bulk acoustic resonators.[4–11] Even though many studies have investigated possible sources of 1/*f* noise in resonators, it is still uncertain what ultimately limits the 1/*f* noise of standalone resonators. Past studies have revealed that 1/*f* noise in a mechanical resonator is directly related to damping (or Q), where the 1/*f* noise decreases with increasing Q. For example, quartz crystal resonators,[1,4,11–15] aluminum nitride (AlN) contour mode resonators (CMR),[9,16] and high-overtone bulk acoustic resonators (HBAR)[8] have shown this dependency. Additional studies analyzed 1/*f* noise as a function of the quality of the piezoelectric material, electrode volume, and device size, operating temperature, resulting in some contradicting findings.[14,17–19] One of the most widely accepted theory is that 1/*f* noise follow the $1/Q^4$ law where the quartz crystal lattice anharmonicities, which induce fluctuations in the phonon relaxation time, are assumed to be the major source of the noise.[12] Interestingly, several studies reported that smaller electrode volume induces lower 1/*f* noise, where quartz-electrode

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interfacial loss and temperature effect within the electrode is hypothesized to be the possible noise sources.[14,17]

AlN CMRs possess many advantages over conventional resonator technologies, such as the ability to attain multiple frequencies on a single chip, a low motional resistance of about 50 Ω, low power consumption, and cover a very wide range of frequencies.[20] However, AlN CMRs still needs to improve its *Q* and noise performance for being considered as an interesting alternative to commercial resonators. The two major damping mechanisms of AlN CMRs are anchor losses and thermos-elastic damping (TED), the latter being dominant in high frequency AlN-CMRs.[21,22] TED is due to the anharmonic coupling of thermal and mechanical phonons arising from mechanical deformation of solids. Since TED originates from the thermodynamics of the metal electrodes[11] not AlN, as metals have much larger thermal diffusivities and expansion coefficients, it is important to analyze the impact of electrode designs on $1/f$ noise of AlN CMRs.

To characterize $1/f$ noise as a function of electrode designs of AlN CMRs, we designed and fabricated CMRs with different electrode dimensions and materials followed by a $1/f$ noise measurement using a custom-built homodyne detection setup. The results show that the electrode design directly affects the $1/f$ noise of resonators, and suggest that not only the electrode dimensions, but also the type electrode materials should be carefully selected to enhance the noise performance of AlN CMRs.

For the study, a set of AlN CMRs with different dimensions and top electrode materials are fabricated using a previously reported process.[20] Each resonator consists of a 1-µm-thick AlN piezoelectric film, and 100-nm-thick Pt bottom electrodes and 100-nm-thick top electrodes, as shown in figure 1(a). For this study, only the top electrode materials varied since the Pt bottom electrode is used to facilitate the deposition of highly oriented AlN films. All the materials forming each resonator and the fabrication steps are identical except for the top metal deposition, *i.e.* all devices come from the same wafer. Electrical fields generated between the voltage source and ground top electrodes induce

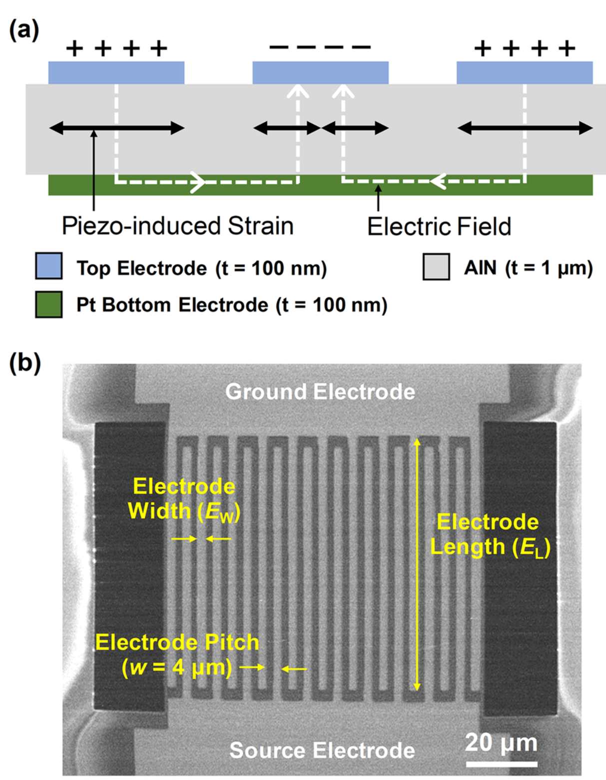

FIG. 1. (a) A cross-sectional view of an AlN contour mode resonator (CMR). Electrical fields generated between the top source and ground electrodes induce vibrations in lateral direction. (b) A scanning electron microscope (SEM) micrograph of a 1 GHz AlN CMR.

TABLE I. Parameters of fabricated AlN CMRs.

Electrode length, E_L (µm)	28, 52, 76, 100, 148
Electrode width, E_W (µm)	0.8, 1.6, 2.4, 3.2
Top electrode material	Au, Al or Pt

a vibration in the lateral direction, as shown in Fig. 1(a). The pitch (w) of the top electrodes and the mechanical properties of the resonator stack determine the resonant frequency ($f_0 = 1/2w\sqrt{E_{eq}/\rho_{eq}}$) of the device, where E_{eq} and ρ_{eq} are equivalent Young's modulus and density of the resonator stack, respectively. For this study, we used a pitch of 4 µm, which gives a resonant frequency of about 1 GHz. Figure 1(b) shows a SEM micrograph of the fabricated 1GHz AlN CMR.

Table I presents the parameters of the top electrodes of the fabricated AlN CMRs. All devices have anchors as wide as the resonator width and the bottom-floating electrode covers the area where the voltage source and ground top electrodes overlap. The top electrode length (E_L) ultimately sets the resonator length that affects anchor losses, while the top electrode width (E_W) determines the metal coverage rates, thus affecting TED. For the damping analysis, we measured the Q of each resonator and de-embedded the electrical loading from the electrical routings to extract the unloaded quality factor (Q_U) of the resonator.

Figure 2(a) shows Q_U as a function of an E_L with a fixed E_W at 2.4 µm. For all electrode materials of Al, Au, and Pt, Q_U increases with E_L, as the effect of anchor losses becomes smaller

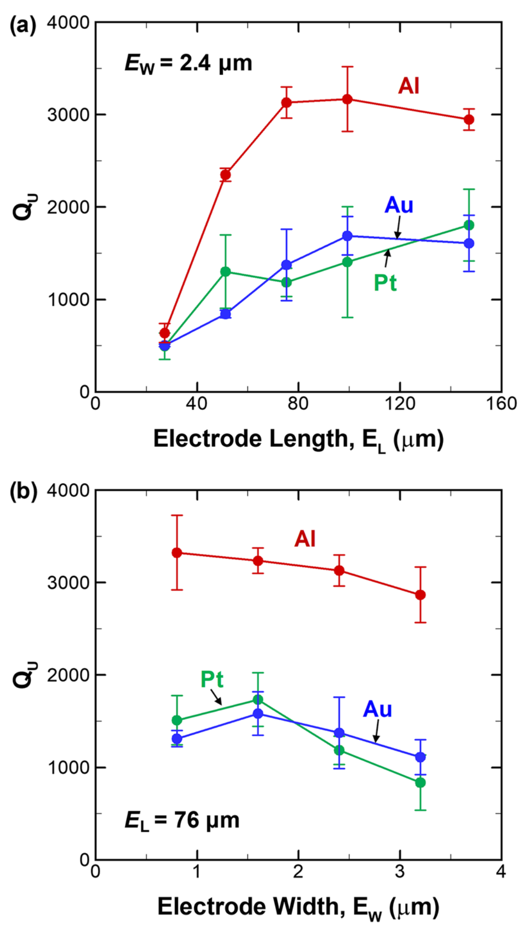

FIG. 2. Unloaded Q (Q_U) as a function of electrode length (E_L) and width (E_W). Electrode dimensions affect the amount of thermoelastic damping (TED), and thus directly impact Q_U of CMRs. Out of different top electrode materials, Al gives the highest Q_U.

for longer devices. Q_U ultimately saturates as E_L reaches above 76 μm, and this is because TED becomes dominant instead of anchor losses. In this work, we excluded those resonators, whose Qs are heavily affected by anchor losses, hence we only considered the resonators with $E_L \geq 76$ μm for the different metal study. Figure 2(b) shows Q_U decreases as E_W increases, when E_L is 76 μm. Since TED is dominant in metal electrodes compared to AlN, larger metal coverages results in lower Q. Interestingly, resonators with either Au or Pt top electrode resulted in much lower Q_U compared to Al; this result reasonably matches with previously reported values for 1 GHz CMRs with either Al, Au, or Pt top electrode.[22]

A previously reported homodyne noise measurement system[9] measured the baseband noise of AlN CMRs. In brief, figure 3(a) shows the measurement setup. A source signal is split between a CMR and a phase shifter. By adjusting the delay in the phase shifter so that the two mixer inputs are in quadrature, we can measure the phase difference between the two signals. Such approach cancels the inherent 1/f noise from the voltage source, thus allowing a precise measurement of the 1/f noise of a standalone resonator. The presented homodyne detection method provides a much lower noise floor compared to CMRs, as shown in figure 3(b). To predict the phase noise of an oscillator built with a CMR, the measured baseband noise is converted into the equivalent closed loop phase noise, L(f), using the conversion process reported in Ref. 8. For the purpose of comparing the performance of various resonators, we report the L(f) values at 1 kHz offset from the carrier frequency.

Figure 4(a–c) shows the predicted phase noise, L(f), of 34 CMRs with Al top electrode, 15 CMRs with Au top electrode, and 15 CMRs with Pt top electrode as a function of Q_U, respectively. In addition to the measured noise data, the power-law best fitting curve is applied to each metal type. For all cases, L(f) exhibits a power law dependence ranging from $1/Q^{3.2}$ to $1/Q^{3.8}$, which follows the similar trend compared to the previously reported results of flicker noise studies on AlN CMRs[8] and quartz crystal resonators.[9] It is clear that for all types of top electrode materials, the phase noise decreases as Q_U increases, showing that the noise performance of CMRs could further improve by mitigating damping.

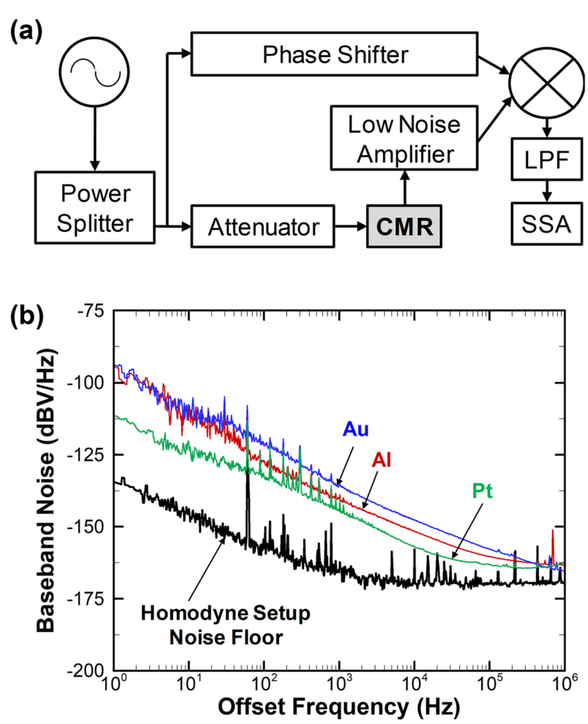

FIG. 3. (a) Block diagram of the homodyne test setup for CMR noise measurements. (b) Measured open loop baseband noise of the setup (black) and CMRs each with different top electrode materials. The noise floor of the setup is much lower than the device noise, thus allowing an accurate measurement of baseband noise over a wide range of offset frequency.

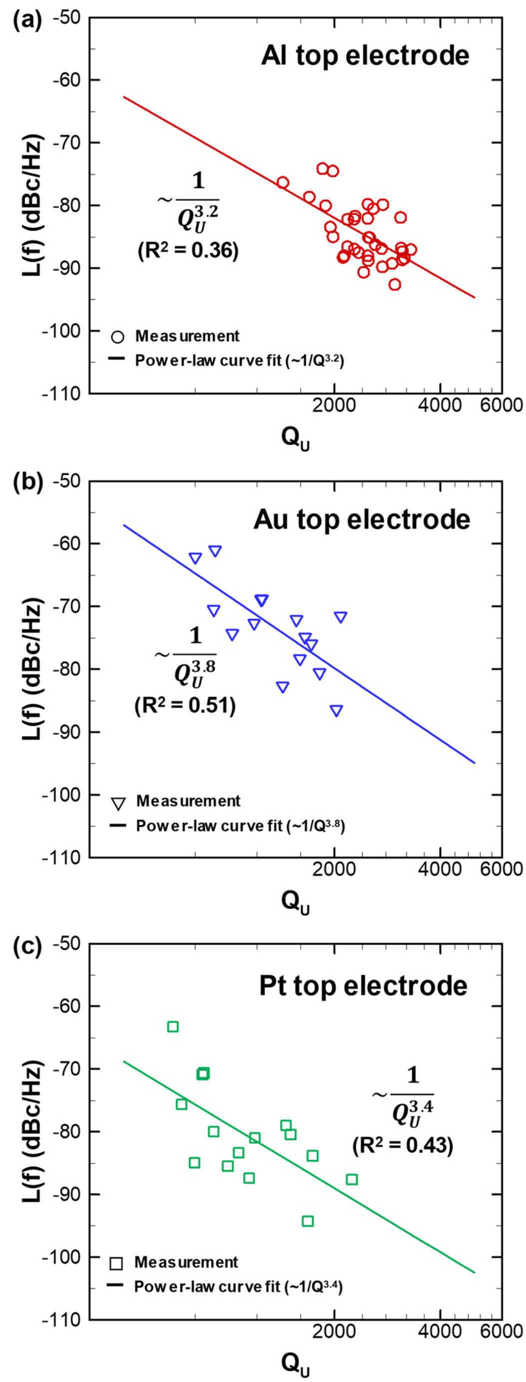

FIG. 4. Predicted closed loop phase noise, L(f), calculated from the measured baseband noise, for different top electrode materials of (a) Al, (b) Au, and (c) Pt. For all electrode materials, L(f) decreases with Q_U indicating that the careful selection of the electrode materials can further lower the flicker noise of CMRs.

Figure 5 shows all measured noise data along with the best power law fitting ($1/Q^n$, where n changes with the type of metal) and a power law fitting to $1/Q^4$, which is the reported $1/f$ noise to Q dependency for quartz crystal resonators. The fit to $1/Q^4$ is not introducing a significant error and permits to make a direct comparison of the $1/f$ noise between different metal types for the top electrode. Interestingly, out of three top electrode materials, Pt exhibits the lowest noise. For example, L(f) for Pt top electrode is lower by nearly 8 dBc/Hz compared to L(f) of Au top electrode devices

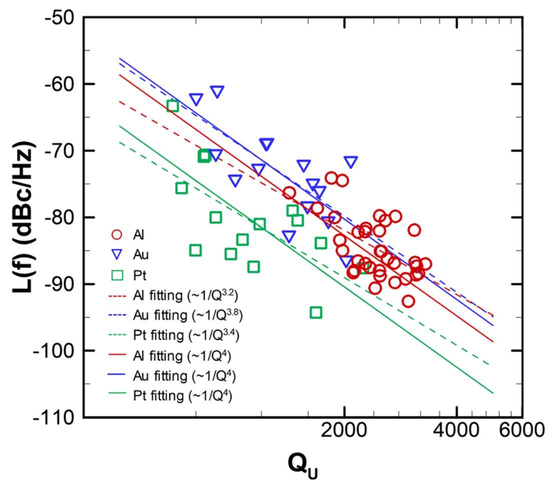

FIG. 5. Combined predicted closed loop phase noise, L(f), with the best power-law curve fit (dashed line) and the$1/Q^4$ power fit (solid line) for Al, Au, and Pt top electrode devices. Among the studied metal types, Pt top electrode results in the lowest noise level.

when Q_U is about 2000. Such trend is apparent over a wide range of Q_U, indicating that a careful selection of electrode material is required to build high Q and low noise AlN CMRs.

Because all the tested CMRs were built through the same exact fabrication steps and the resonator stack composition is the same except for the top electrode, one can conclude that the apparent differences in noise level must be due to the top metal electrode itself. Out of several possible reasons, we exclude the adsorption of contaminant or oxidation of the top electrode, as all the measurements were taken right after the device release. In addition, Au and Pt are both chemically inert, so the oxidation of the electrode surface is highly unlikely. In previous studies on quartz crystal resonators with Au electrodes, such as BAWs and SAWs, the energy loss or the damping due to the stress jump at the metal-quartz crystal interface is assumed to be one of the possible damping sources, and ultimately affecting the flicker noise of the resonator.[2,17] However, a previous study on AlN CMRs has shown that such damping effect is rather small compared to anchor losses or TED for 1 GHz AlN CMRs.[23] Although it is unclear what causes the discrepancy in noise behaviors for different top electrode materials, it is clear that the right choice of electrode material could further enhance the noise performance of AlN CMRs and possibly other classes of piezoelectric resonators.

In conclusion, we report an experimental study on the impact of electrode materials on flicker frequency noise of 1 GHz AlN CMRs. Our results on Au, Al, and Pt top electrode resonators show that the noise decreases as Q_U increases with a power law dependency that is about $1/{Q_U}^4$ regardless of the type of top electrode materials. Interestingly, although not clearly understood, Pt gives the lowest noise level compared to Au and Al.

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