DAMPING DIRECTLY IMPACTS FLICKER FREQUENCY NOISE OF PIEZOELECTRIC ALUMINUM NITRIDE RESONATORS

Hoe Joon Kim, Jeronimo Segovia-Fernandez, and Gianluca Piazza
Carnegie Mellon University, Pittsburgh, USA

ABSTRACT

This paper presents an analysis on the effect of damping on flicker frequency (1/f) noise of 1.1 GHz aluminum nitride (AlN) contour mode resonators (CMR). A total of 52 different AlN-CMRs are systemically designed and fabricated to give quality factors (*Q*) ranging from 300 to 3500, allowing the study of how two major damping mechanisms in AlN-CMRs, 1) anchor losses and 2) thermoelastic damping (TED), affect the resonator 1/f noise. In total, we have measured 104 CMRs and the results confirm that 1/f noise shows a clear power law dependence that is close to $1/Q^3$, independently of the main nature of the damping mechanism. Understanding and accounting for the effect of damping on 1/f noise is crucial for building ultra-low noise Microelectromechanical systems (MEMS) resonators for sensing, timing, and frequency applications.

INTRODUCTION

Flicker frequency (1/f) noise in resonators is an important noise mechanism since it determines the floor of the Allan variance of an oscillator or other resonant sensors (such as inertial, gravimetric, magnetic, etc.) [1]. Measuring the inherent frequency stability of resonators and understanding the source of 1/f noise have been of particular interest for building low-noise and high performance oscillators. Many studies on 1/f noise of quartz crystal resonators have revealed that damping in resonator (or *Q*) directly affects the resonator 1/f noise [2-5]. However, different power law dependencies of 1/f noise on *Q* have been identified and there is a lack of publications on the analysis of 1/f noise in standalone MEMS resonators. This work is the first that systematically looks at how different mechanisms of damping, anchor losses [6] and TED in the electrodes [7], impact 1/f noise in piezoelectric AlN resonators.

Previously reported sources of the 1/f noise in quartz crystal resonators include the impurity migration inside the crystal lattice, transformation of surface waves, energy dissipation in the electrodes, and electro migration across the electrodes and quartz film [2-5]. Regardless of the type of noise sources, it is found that the resonator *Q* directly impacts 1/f noise of the device. One of the most widely accepted theory is that the 1/f noise is induced by the fluctuation of the relaxation time associated with the phonon scattering inside the resonator. In this case, the 1/f noise exhibits a power law dependence of about $1/Q^4$ [2]. Subsequent studies on 1/f noise in quartz crystal resonators have reported power law dependencies that range from $1/Q^3$ to $1/Q^5$ [2-5]. Although there is a clear trend between the 1/f noise and the resonator *Q*, most of previous studies are limited to quartz crystal resonators and the origin of 1/f noise still remains a matter of debate.

AlN-CMRs are part of a promising class of RF MEMS technologies that enable the single chip integration of multi frequency devices while exhibiting a low motional resistance of about 50 Ω and a lithographically definable resonant frequency of up to several GHz [8]. Extensive studies on improving the resonator *Q* have revealed that the two main damping mechanisms for AlN-CMRs are 1) anchor losses, which is the mechanical energy loss through the anchor that connects the resonator to the substrate [6], and 2) TED inside the top and bottom electrodes [7]. Since each damping mechanism can be modeled and accounted for at the resonator design level, AlN-CMRs allow a systemic study on how different damping mechanisms impact the resonator 1/f noise.

This paper reports on the design and the noise measurement of 1.1 GHz AlN-CMRs. The homodyne detection setup allows rapid and precise measurement of the resonator 1/f noise. The results show that the damping directly impacts the 1/f noise of AlN-CMRs.

ALN CMR DESIGN

Figure 1(a) shows the cross-section of an AlN-CMR consisting of an AlN piezoelectric layer (1-µm-thick) sandwiched between patterned Al top electrodes and a Pt bottom electrode (each 100-nm-thick). Interdigitated arrays of top electrodes generate electric field lines across the AlN layer, confined by the floating bottom electrode, and thus inducing a lateral mode of vibration. The pitch of the top electrode is 4 µm for the devices of this work, setting the resonant frequency at approximately 1.1 GHz. The number of top electrodes is fixed at 21. More details on the resonator design, fabrication, and characterization are reported elsewhere [8].

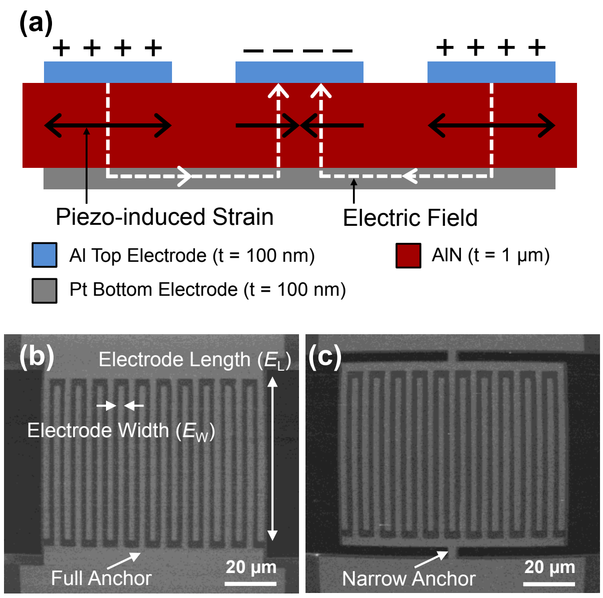

Figure 1: (a) Cross-section of a AlN-CMR. SEM images of fabricated 1.1 GHz AlN-CMRs with (b) full anchor and (c) narrow anchor designs.

Table 1: Parameters of the studied AlN-CMRs. 52 different CMRs each from two different chips (total of 104 CMRs) are tested for the noise analysis.

E_L (μm)	E_W (μm)	Anchor Design
28, 52, 76, 100, 148	0.8, 1.6, 2.4, 3.2	Full anchor Narrow anchor

To analyze the effect of two major damping mechanisms of anchors losses and TED on the resonator 1/f noise, 52 different AlN-CMRs were fabricated with varying device parameters, as shown in Table 1. Device parameters were systemically designed by means of finite element analysis and analytical methods to attain a broad range of *Q*s. Figure 1(b-c) show SEM micrographs of the fabricated AlN-CMRs with an identical electrode layout with different anchor types. To vary anchor losses, we controlled the length of the electrodes (E_L) and fabricated devices with different anchor types, labelled as full anchor and narrow anchor devices. For TED control, we varied the width of the top electrodes (E_W) to change the electrode coverage area of CMRs.

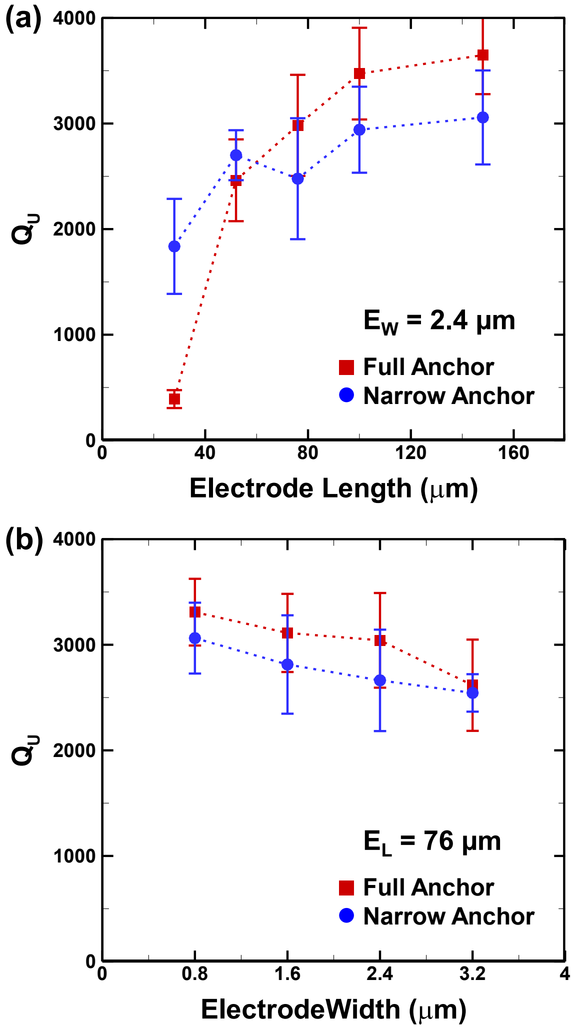

Figure 2: Unloaded quality factor (Q_U) as functions of (a) electrode length (E_L) and (b) electrode width (E_W). A wide range of Q_U, from 300 to 3500, is achieved.

Figure 2 shows the *Q*s obtained over our entire design space by the resonators that are used to understand the fundamental origin of the 1/f noise. For the analysis, we use the unloaded quality factor (Q_U) of a resonator to eliminate the impact of electrical losses in the signal routing and metal electrodes. On average, Q_U is higher than the measured *Q* by about 5%; this is because the electrical resistances of the signal routing and metal electrodes are small compared to the motional resistance of the resonator. Figure 2(a) shows that Q_U increases with E_L, indicating that the effect of anchor losses decreases as E_L increases. It also shows that Q_U is higher for the narrow anchor devices than the full anchor devices E_L is less than 52 μm. However, the change in Q_U becomes small for longer devices because the acoustic wavelength (λ = 8 μm) becomes small compared to E_L and TED dominates the resonator damping. Figure 2(b) shows that Q_U decreases when E_W increases. This is because TED increases with the amount of metal [7]. By systemically designing AlN-CMRs with different parameters, we have successfully fabricated a set of devices with Q_U ranging from 300 to 3500, where a broad range of Q_U is clearly affected by anchor losses for shorter devices (E_L < 52 μm) and by both anchor losses and TED for longer devices ($E_L \geq$ 52 μm) .

HOMODYNE DETECTION OF NOISE

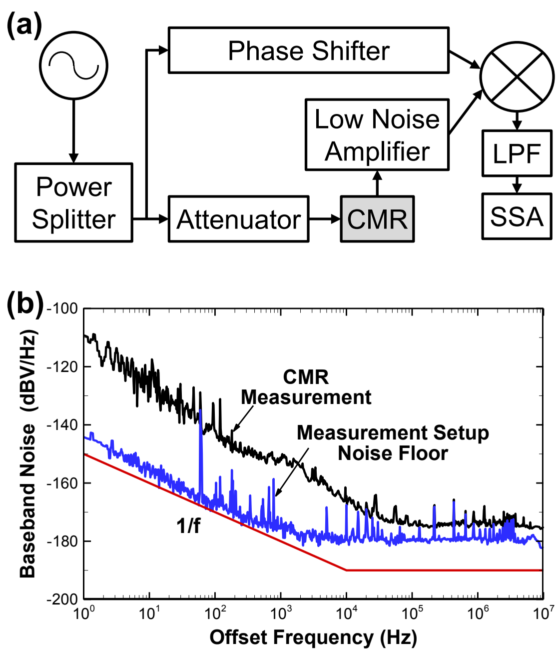

Figure 3: (a) A schematic of the homodyne setup that is used to measure the baseband noise of AlN-CMRs. (b) Measured baseband noise of the test setup and a CMR, which clearly follow the 1/f trend.

Figure 3(a) illustrates the homodyne test setup that is used to directly measure the 1/f noise of AlN-CMRs. This setup can make additive noise measurements on active and passive microwave devices [9]. Frist, a signal from the source is split into a phase shifter and a CMR. To operate the CMRs in the linear regime, an attenuator is used to keep the input power lower than -5 dBm. The output signal from a CMR is then amplified and input into the RF port of the mixer. Another split signal passes through the phase shifter and the delay is adjusted so that the two mixer inputs are in quadrature, giving the output to be proportional to the phase difference between the two signals. The output from the mixer is then filtered through a low pass filter and the resulting baseband noise is measured using a signal source analyzer (Agilent E5052B). This approach cancels the close-in flicker frequency noise from the voltage source and therefore allows a precise and rapid measurement of the resonator 1/f noise. The noise floor of the setup is excellent, as shown in figure 3(b).

In order to compare the obtained noise values to meaningful data reported in the literature for oscillators, we converted 1/f noise into the equivalent closed loop phase noise, *L*(f), that an oscillator would exhibit if it were to be built with such a resonator. The measured baseband noise, S_V(f), is the voltage power spectral density (PSD) due to phase fluctuation introduced by the resonator frequency fluctuations. The PSD of resonator frequency fluctuations, $S_{\varphi(f)}$(f) can be then calculated as:

$$S_{\varphi(f)}(f) = \frac{S_V(f)}{2K^2G^2}\left[\frac{f_0}{2Q}\right]^2 \quad (1)$$

where *K* is the mixer gain constant, *G* is the gain applied to the baseband signal prior to measurement by the signal source analyzer, and f_0 is the resonant frequency of the device. The PSD of the resonator frequency fluctuation can then be converted to the PSD of a closed loop phase noise, *L*(f), as below [10]:

$$L(f) = S_{\varphi(f)}(f)\left[\frac{1}{f}\right]^2 \quad (2)$$

where *f* is the offset frequency from the main carrier. The predicted *L*(f) of a resonator using the homodyne method matches well with the phase noise measurement of an oscillator containing the same resonator (difference is less than 5 dB). Furthermore, the *L*(f) of the setup noise floor is predicted to be -120 dBc/Hz at 1 kHz offset, which is significantly lower than the measured *L*(f) of 1 GHz AlN-CMRs, which is in the range of -60 dBc/Hz to -90 dBc/Hz. In this work, we report *L*(f) values at 1 kHz offset from the carrier frequency because it is an important metric in many wireless systems. All measurements are made at atmospheric pressure and at a temperature of 20 °C.

RESULTS AND DISCUSSION

Using the homodyne noise detection setup, we have measured the 1/f noise of a total of 104 AlN-CMRs (52 CMRs each from two different chips). Figure 4 shows the predicted *L*(f) at 1 kHz carrier frequency offset as a function of Q_U. It is clear that *L*(f) decreases as Q_U increases. Overall, the resonator 1/f noise follows the power law dependence of $1/Q_U^{2.74}$ with a relatively strong correlation (R^2 = 0.67), as shown in figure 4(c). CMRs exhibit similar *L*(f) for a given Q_U regardless of the anchor types, indicating that the resonator 1/f noise depends on the intrinsic Q_U of the device. For this study, the lowest *L*(f) is measured to be -91 dBc/Hz at 1 kHz carrier frequency offset for a resonator with Q_U of about 3300. This *L*(f) value is very close to the previously reported *L*(f) values of 1 GHz AlN-CMRs with Q_U of about 3000 [11].

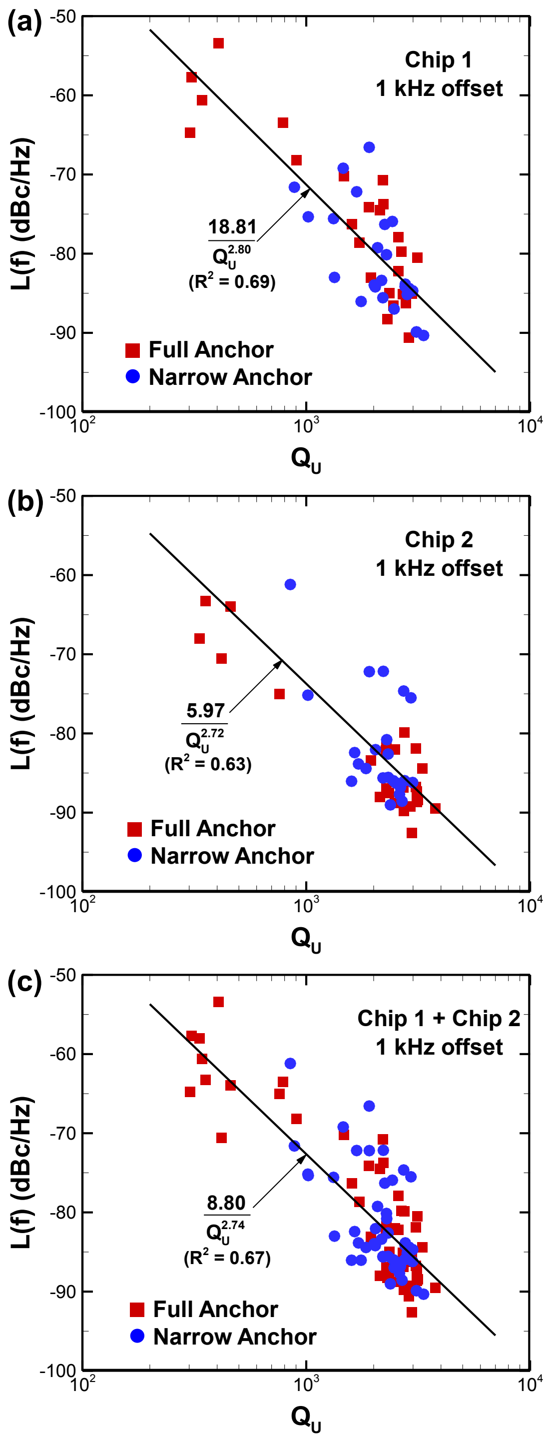

Figure 4: (a-b) L(f) of all measured CMRs from two different chips. (c) Least square power law fitting of L(f) for CMRs from chip 1. L(f) shows a clear power law dependence that is close to $1/Q_U^3$.

We have analyzed the relationship between *L*(f) and Q_U for the varying resonator parameters. Figure 5 shows *L*(f) and Q_U as functions of E_L and E_W. Each data point represents averaged *L*(f) and Q_U values with a standard error of four different CMRs with identical device parameters from both chips. For both cases, *L*(f) is lower for higher Q_U, indicating that both anchor losses and TED indeed affects the resonator 1/f noise. Although we have controlled the major mode of damping for each resonator by varying certain resonator parameters, it is unclear which damping mechanism fundamentally limits $L(f)$ of AlN-CMRs. Despite the nature of damping and therefore the mechanism of the 1/f noise, the absolute value of the noise is inversely proportional to Q_U^3.

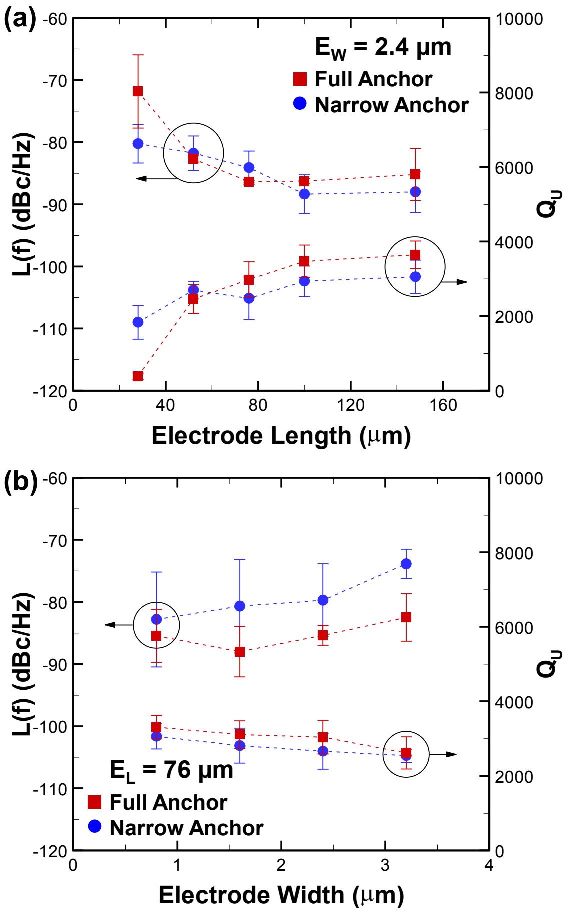

Figure 5: L(f) and Q_U as functions of (a) E_L and (b) E_W. For both cases, the L(f) of CMR decreases as Q_U increases. Each data point represents averaged L(f) and Q_U values with a standard error of four different CMRs with identical device parameters from both chips 1 and 2.

Our results confirm that damping directly impacts the 1/f noise of AlN-CMRs. However, the exhibited power law dependency of $L(f)$ to Q for AlN-CMRs, which is $1/Q^3$, differs from the previously reported values for quartz crystal resonators of about $1/Q^4$, where it is assumed that the fluctuation in relaxation time associated with the phonon scattering inside the quartz crystal dominates the 1/f noise [2]. This discrepancy might be due to the fundamental difference in quartz crystal resonators and AlN-CMRs, such as the type of piezoelectric or electrode materials, the range of operating frequencies, and the active volume of devices. Thus, perhaps a different model or analysis should be applied to understand the 1/f noise mechanism for AlN-CMRs or other types of MEMS resonators.

For 1.1 GHz AlN-CMRs, TED in the top and bottom electrodes ultimately limits the resonator Q. In contrast, anchor losses can be largely mitigated by fabricating longer CMRs (where $E_L >> \lambda$). Thus, improving the electrode designs to alleviate TED should further enhance the noise performance of AlN CMRs. It has been demonstrated that a stress induced annealing of AlN-CMRs by driving them with high RF power improved Q and decreased the residual noise of the device [11]. This is believed due to the change in grain size of metal electrodes and dislocations of the AlN film. Similarly, an annealing also improved the noise performance of quartz surface acoustic wave (SAW) resonators [12]. Thermal annealing of metals at high temperatures (i.e. 400 °C for Al) induces a grain growth, and thus could be a good way to study the effect of grain size of the metal electrodes on the resonator Q and 1/f noise. This will be the subject of future work.

CONCLUSION

In summary, we report on a detailed study on the effect of two major damping mechanisms (anchors losses and TED) on the 1/f noise of 1.1 GHz AlN-CMRs. Our experiment results show that the 1/f noise follows a clear power law dependence that is close to $1/Q^3$, regardless to the main nature of the damping mechanism. The findings from this work not only pave the way for future ultra-low noise AlN-CMRs, but also provide an insight on what fundamentally limits the 1/f noise in various classes of resonators and what determines the resonator limit of detection when used in inertial, gravimetric or other sensing applications.

ACKNOWLEDGEMENT

This work was supported by the DARPA DEFYS Award # FA86501217264 (PENNTAC).

REFERENCES

[1] A. Hajimiri and T. H. Lee, *IEEE J. Solid-State Circuits*, vol. 33, no. 2, pp. 179–194, Feb. 1998.

[2] J. J. Gagnepain et al., *IEEE Freq. Cont. Symp.*, pp. 476–483, 1981.

[3] T. E. Parker, *Appl. Phys. Lett.*, vol. 46, no. 3, pp. 246–248, Feb. 1985.

[4] F. L. Walls et al., *IEEE Freq. Cont. Symp.*, pp. 327–333, 1992.

[5] M. M. Driscoll and W. P. Hanson, *IEEE Freq. Cont. Symp.*, pp. 186–192, 1993.

[6] J. Segovia-Fernandez et al., *J. Microelectromech. S.*, vol. 24, no. 2, pp. 265–275, Apr. 2015.

[7] J. Segovia-Fernandez and G. Piazza, *IEEE Int. Conf. on MEMS*, pp. 1000–1003, 2015.

[8] G. Piazza et al., *J. Microelectromech. S.*, vol. 15, no. 6, pp. 1406–1418, Dec. 2006.

[9] G. K. Montress et al., *IEEE Freq. Cont. Symp.*, pp. 349–359, 1989.

[10] N. Miller and G. Piazza, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 61, no. 6, pp. 913–919, 2014.

[11] N. Saldhana, U. Zaghloul, and G. Piazza, *IEEE Freq. Cont. Symp.*, pp. 1–4, 2014.

[12] M. J. Loboda et al., *IEEE Ultrasonics Symp.*, pp. 43–46, 1987.

CONTACT

*H.J. Kim, +1-412-268-8013; hoejoonk@andrew.cmu.com