Anchor Losses Dependance on Electrode Material in Contour Mode Resonators

Andrea Lozzi, and Luis Guillermo Villanueva
Advanced NEMS Group
École Polytechnique Fédérale de Lausanne (EPFL)
Lausanne, 1015 Switzerland (CH)
andrea.lozzi@epfl.ch

Ernest Ting-Ta Yen
Kilby Labs
Texas Instruments Inc.
Santa Clara, CA, USA
ernest.ttyen@ti.com

***Abstract*—We here present a study on the influence of metal electrodes on the anchor losses in Contour Mode Resonators (CMRs). Our Finite Element Modelling (FEM) simulation results show that electrode material is key to determine the acoustic losses, and therefore the quality factor. Also, improvement in, quality factor, can be achieved via acoustic matching between the electrodes and the active piezoelectric layer.**

Keywords—Contour Mode Resonators, finite element analysis, acoustic material matching, perfectly matched layer, quality factor, anchor losses.

CMRs are an emerging class of piezoelectric devices particularly appealing for their capability to span a broad range of frequency. However, their impact on market is still limited due to low Figure of Merit (FoM) [1]. The FoM is composed of the two most important parameters for a microelectromechanical resonator: the quality factor, Q, and the electromechanical coupling k_t^2, which both influence the resonator's performances. In particular, a high Q is desirable to limit phase noise in MEMS-based oscillators [2]-[3].

Q is inversely proportional to the energy loss (or damping) per cycle of vibration. Thus, it is important to study the sources of energy loss in CMRs, which in general can be electrical load, gas viscous friction, material damping, and radiation of acoustic energy through the anchors. Air damping can be neglected at high frequencies.. The electrical loading can be minimized and quantified to obtain an unloaded Q [1]. Material damping depends on the properties of the materials themselves, how they are combined and processed, which makes this type of damping difficult to predict. Thus, experimental measurements are required for the estimation of material losses. However, acoustic losses can be and have been modeled by many groups, using FEM, and shown *qualitative* agreement with experiments.

We herein use FEM modeling to obtain quantitative estimate how the Q due to acoustic losses changes as design parameters and electrodes material are varied. Our device is a lateral field excitation (LFE) one port CMR as shown in *Figure 1a*. It is made of top interdigitated (IDT) electrodes that produce an electric field into the active layer (aluminum nitride) inducing a deformation due to the piezoelectric effect. A bottom metal plate acts as a floating potential to confine the electric field. For the particular case discussed here, the thicknesses of the active layer is 1 μm and 100 nm for the metal electrodes [4]-[5], but the conclusions should not be limited to this geometry.

In order to obtain quantitative predictions of anchor losses we use perfectly matched layer (PML) as boundary condition in FEM models, which has in some cases provided predictions with a reasonable accuracy [5]-[7], and we build a 3D model as close as possible to the actual resonator. This point is particularly important as other authors have typically ignored the metal electrodes in their simulations [5] in order to decrease their computational cost (i.e. simulation time). However, our results show that the presence of electrodes greatly affects the simulations and cannot be ignored.

Exploiting the symmetry of the device we model only one quarter of the geometry. We also use a properly dimensioned PML region to avoid creation of spurious reflections at the PML interface (*Fig. 1*). We compute the quality factor of the mode under study solving an Eigen-frequency analysis [8] and taking the ratio between the imaginary and real part of the eigenvalues. We perform these simulations as a function of the anchor width W_a and length L_a. We also change the material of the electrodes. Importantly, the materials are assumed to be perfect, i.e. no material damping is included in the model, so that the only energy loss contribution accounted for in the simulations is that coming from acoustic emission to the substrate.

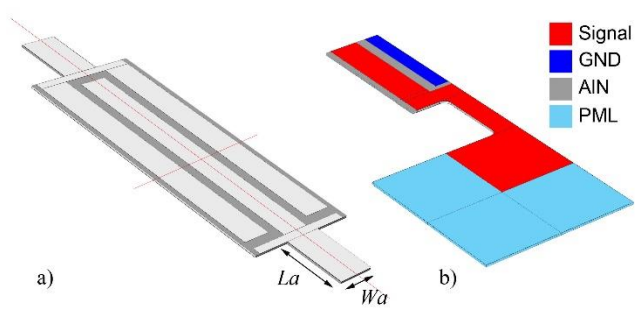

Fig. 1: a) 3D view of the 220 MHz CMR device with axes of symmetry. b) View of the FEM model where ¼ of the device is modeled exploiting symmetry boundary conditions. AlN was used as the piezoelectric material.

The dimensions of the resonator itself remain the same over all our simulations. In CMRs the resonant frequency (f_r) is set by the electrode pitch and the equivalent acoustic

velocity of the stack. As the pitch is maintained (20 µm), the acoustic wavelength ($\lambda \sim 40$ µm) remains almost constant and the frequency is around 220 MHz (*Table 1).*

Our numerical results show that *acoustic* losses depend on the chosen electrode material (material damping is not implemented in the simulation). This can be seen in *Fig. 2* which presents three 2D sweeps of *Wa* and *La*, one for a different set of materials. Much information can be extracted from these plots, but the point to convey here is extracted in *Table 1*, where it can be seen that the introduction of metal electrodes lowers the obtained quality factor by more than one order of magnitude, incidentally proving incorrect those simulations of acoustic losses not including the metal. A decrease in Q due to metal addition to the resonator can be experimentally seen in most cases. However, all of them attribute this increase in losses to material damping in the metal or in the interface between different materials. In our case, it being a numerical experiment with the material damping turned off, it can only be due to a purely acoustic component. We think that this energy loss directly depends on acoustic mismatch between the different materials composing the resonator, but further work is being performed to confirm. Finally, not only the maximum value of Q (Q_{max}) changes depending on the material, but also the optimal W_a and L_a. This is tremendously important as it directly affects the resonator's design rules, which results most important when acoustic losses tend to be the dominating damping mechanism [5].

In essence our findings provide a point of view that had been disregarded up-to-date: the dependence of acoustic losses on the utilized materials. This can have important implications on the design rules of mechanical resonators in general and piezoelectric CMRs in particular.

REFERENCES

[1] R. Ruby, "*Method of Extracting Unloaded Q Applied Across Different Resonator Technologies*", in *2008 IEEE International Ultrasonics Symposium (IUS)*, Beijing, CN, 2008, pp. 1815 - 1818.

[2] C. Enz and A. Kaiser, MEMS-based circuits and systems for wireless communication. New York: Springer, 2013, pp.29–54.

[3] G. Piazza, P. Stephanou and A. Pisano, "Piezoelectric Aluminum Nitride Vibrating Contour-Mode MEMS Resonators", Journal of Microelectromechanical Systems, vol. 15, no. 6, pp. 1406-1418, 2006.

[4] C. Cassella, J. Segovia-Fernandez, G. Piazza, M. Cremonesi, and A. Frangi, "Reduction of anchor losses by etched slots in aluminium nitride contour mode resonators" , 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (Eftf/Ifc), Prague , CZ, 2013, pp. 926-929.

[5] J. Segovia-Fernandez, M. Cremonesi, C. Cassella, A. Frangi and G. Piazza, "Anchor Losses in AlN Contour Mode Resonators", Journal of Microelectromechanical Systems, vol. 24, no. 2, pp. 265-275, 2015.

[6] M. Cremonesi, A. Frangi, C. Cassella and G. Piazza, "Enhancement of the Quality Factor of AlN Contour Mode Resonators by Acoustic Reflection: Numerical Design and Experimental Investigation", Procedia Engineering, vol. 87, pp. 468-471, 2014.

[7] A. Frangi, M. Cremonesi, A. Jaakkola and T. Pensala, "Analysis of anchor and interface losses in piezoelectric MEMS resonators", Sensors and Actuators A: Physical, vol. 190, pp. 127-135, 2013.

[8] A. Frangi, A. Bugada, M. Martello and P. Savadkoohi, "Validation of PML-based models for the evaluation of anchor dissipation in MEMS resonators", European Journal of Mechanics - A/Solids, vol. 37, pp. 256-265, 2013.

[9] J. Segovia-Fernandez, M. Cremonesi, C. Cassella, A. Frangi, and G. Piazza, "Experimental study on the impact of anchor losses on the quality factor of contour mode AlN resonators", Transducers, 10.1109/Transducers.2013.6627307, Barcellona, ES, Jun. 2013

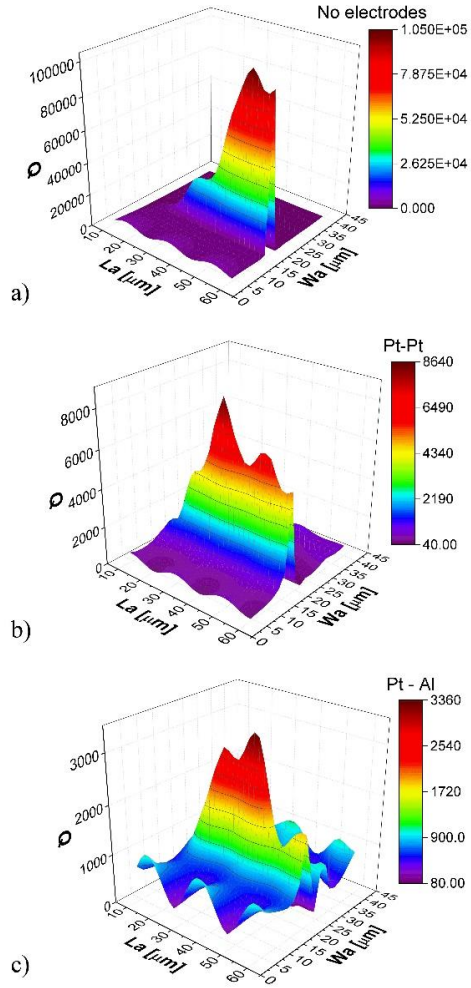

Fig. 2: 2D sweep of La and Wa for three model configurations. a) the electrodes were removed from the model; b) bottom and top metals are Pt; and c) bottom metal is Pt while top metal is Al.

TABLE I

Quality factors vs electrodes material				
Materials: bottom - top	***Wa (λ)***	***La (λ)***	***Q_{max}***	***fr [MHz]***
No electrodes	9/20	5/4*	101000	270
AlN – AlN	8/20	23/20*	59533	277
Pt – Al	11/16	19/20	3357	221
Pt – Pt	9/20	17/20	8626	205
Pt – Au	9/20	16/20	2930	204
Pt – Mo	1/2	18/20	5039	221

λ is set to 40 µm as the electrode pitch is 20 µm.

*in those models the maximum Q as a function of the La was not obvious.