Simulations of the Anchor Losses in MEM Disk Resonators

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ABSTRACT

MEM *(Micro Electro Mechanical)* resonators have been proposed as fundamental components in RF transmission systems. The quality factor is a fundamental parameter to evaluate the performance of a MEM resonator and consequently it is very important to understand the physical mechanisms, which limit the quality factor. In this paper we concentrate on one loss mechanism in bulk mode disk resonators, namely anchor losses and use finite element methods to get an estimation for these losses. We introduce a simulation strategy implemented in a commercial FEM tool and we compare this technique with other methods and experimental data presented in the literature. The effect of some geometrical parameters of the disk is analyzed, such as the dimensions of the anchor. Simulations show the great importance of the anchor sizes in order to reduce anchor losses. Furthermore the presence of an optimum anchor dimension was found by simulations, so that our results indicate a possible way to reach high quality factor by a proper design of the structure. To our knowledge this optimum has never been found in previous works.

Keywords: anchor losses, disk resonators, quality factor.

1 INTRODUCTION

MEM resonators represent a great opportunity for RF transmission systems, because not only can they improve the performances of exiting architectures, but also allow new possible architectures [1]. MEM resonators can be used as fundamental components in band pass filters, local oscillators and mixers [1]. With respect to the other kinds of MEMS resonators presented in the literature, bulk mode resonators allow to obtain high resonance frequencies (as high as 1GHz [3]) combined with high quality factors (in the range from 1,000-100,000 [2, 3]).

An important parameter for the evaluation of MEM resonator device performance is the quality factor: a higher quality factor means a better selectivity in a filter architecture and lower phase noise in an oscillator architecture [2]. Therefore in order to maximize the quality factor, it is fundamental to understand the physical mechanisms, which limit the quality factor. While at atmospheric pressure the air damping (generally squeeze or slide film damping) has been identified as the main loss mechanism for several different kinds of resonators [4, 5], in vacuum, thermoelastic damping [6, 7] and especially the so called *anchor losses* [7, 8, 9] have been proposed as dominating mechanisms. Anchor losses are basically due to the energy coupling between the resonator and the substrate.

In this paper we address the mechanisms responsible for anchor losses in bulk mode disk resonators (Figure 1). While it is possible to find an analytical approximation for the anchor losses in flexural beam resonators [7], currently only numerical approaches seem reliable for bulk resonators [9]. The problem with numerical approaches is that the substrate is much too large to be simulated entirely; therefore some models or approximations are needed to mimic the complete absorption of energy in a much smaller domain. One way to achieve this is by using a perfectly matched layer (PML) as presented in [9], an element generally used in FEM electromagnetic simulation, whose acoustic counterpart was presented in [10]. To our knowledge this is the only previous paper, which uses this approach. In this paper we present an alterative method to mimic a semi-infinite space with a finite domain in FEM simulation, based on a classic structural element whose viscoelastic damping properties are properly modified; this solution was implemented in FEMLAB [11]. The advantage of this second approach is that it allows an easy implementation in a commercial well established FEM software while the simulation strategy based on PML as described in [9] requires a dedicated software, and consequently a longer development time. The analysis in [9] focuses on the influence of the disk thickness on the anchor losses in a bulk disk resonator. We extend this analysis by simulating the effect of a change in anchor geometries. Results from our simulations show the great importance of anchor dimensioning in order to minimize anchor losses and indicates a possible strategy to minimize these by layout.

2 DEVICE DESCRIPTION

A schematic view of a MEM disk resonator is presented in Figure 1a. The resonating structure is a disk which is connected to the bulk by a cylindrical anchor or *stem*, whose axis coincides with the symmetry axis of the disk. In this paper we consider the stem and the disk as made of the same material. In the following when we talk about “disk material”, we assume the same material also for the stem.

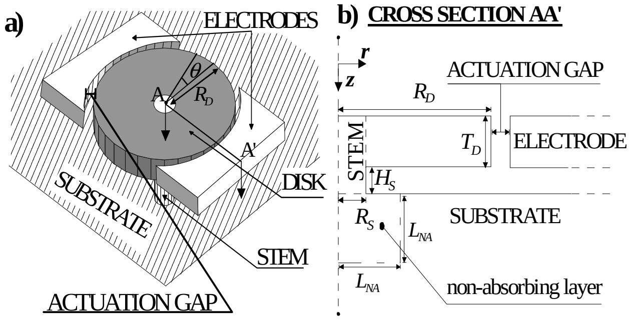

Figure 1: Schematic view of a disk resonator: a) 3D view; b) radial cross section (R_D is the disk radius, T_D the disk thickness, R_S the stem radius and H_S the stem height); also the optional non-absorbing layer is indicated, with dimensions L_{NA}xL_{NA}

The disk is electrostatically actuated in bulk contour mode, by applying a voltage between the disk and actuation electrodes, which are placed around the perimeter. The electrodes are properly shaped to stimulate only the so called *contour modes*, i.e. resonance modes where only radial extension and compression of the disk are allowed. The modes are axisymmetric, i.e. their deflected shape at resonance does not depend on the rotation angle θ around the symmetry axis of the disk and the stem. The resonance frequencies of the disk contour mode resonator are [3]:

$$f_n = \frac{1}{2\pi}\frac{\lambda_n}{R_D}\sqrt{\frac{E}{\rho(1-\nu^2)}} \qquad (1)$$

where R_D is the disk radius, and E, ρ, ν, are respectively the Young's modulus, mass density and Poisson ratio of the disk material; λ_n (n=1,2,3,...) is the eigenvalue for the nth resonance mode and it can be calculated by solving the following equation:

$$\lambda_n \frac{J_0(\lambda_n)}{J_1(\lambda_n)} = 1-\nu\,. \qquad (2)$$

where J_0 and J_1 are Bessel functions of the first kind of zero and first order, respectively; if $\nu=0.226$ the eigenvalues for the first and the second mode are $\lambda_1=2.002$ and $\lambda_2=3.832$, respectively. The stem effect on the resonance frequency is not taken into account in (1).

3 ANCHOR LOSSES SIMULATIONS

The anchor losses occur because each cycle an amount of energy flows from the resonator to the substrate, through a propagating acoustic wave. Since the substrate is much larger than the resonator, this energy can be assumed to be lost, unless some discontinuity causes a reflection. The substrate behaves like a semi-infinite space, or better an energy sink, where all the propagating energy is absorbed.

We performed FEM simulations of the anchor losses via the stem into the substrate. From these simulations the anchor loss dependent quality factor Q_{al} was extracted. The Q_{al} underestimates the overall quality factor Q:

$$\frac{1}{Q} = \frac{1}{Q_{al}} + \sum_{i=1}^{N}\frac{1}{Q_i} \qquad (3)$$

where the Q_i are the quality factors due to other damping sources, like air damping and thermoelastic losses. If $Q_{al}<<Q_i$, for any i, the overall quality factor is practically determined by anchor losses ($Q\approx Q_{al}$). This is the typical condition for resonator operating in vacuum [3, 5]. We implemented a finite element model of the disk resonator. Only the disk, stem and substrate were modeled. The disk and stem are modeled as undamped structural elements, whereas the substrate is modeled as a perfectly absorbing domain. We used two different approaches to model the total energy absorption in the substrate. The first approach has been introduced in [9], where the substrate was modeled as a perfectly matched layer (PML) [10]. In [9] simulations were performed with a dedicated software called HiQLab. As an alternative way to the method used in [9] for mimicking the energy absorption by the substrate, we introduce a viscoelastic Rayleigh damping in a traditional structural element. The damping was chosen artificially high so that all incoming energy is absorbed. The advantage of this method is that the structural element with Rayleigh damping can be implemented in traditional FEM tools whereas the PML approach needs dedicated support from the tool. The two substrate models are implemented in two different FEM tools, the PML model in HiQLab [10], whereas the Rayleigh damped substrate is modeled in FEMLAB[11].

We also investigated the effect of introducing a portion of substrate beneath the anchor, without energy dissipation (*non-absorbing layer*) as in [9] (Figure 1b). This could be reasonable to obtain a more realistic low-damping region where the highest substrate deformations are expected; but on the other hand it also introduces an artificial interface inside the substrate, which can lead to spurious reflections. In Section 4 simulations including the non-absorbing layer are compared with simulations of structures without non-absorbing layer, i.e. all the substrate dissipates energy.

Simulations of contour mode disk resonators can be simplified because contour modes deformed shapes are axisymmetric, thus we can reduce a 3D problem in a 2D axisymmetric problem, finding the deformations in a radial section like the one in Figure 1b.

For the two different substrate models, we extract the Q_{al} in different ways, depending on the two different simulation tools. In the HiQLab model, the introduction of the PML leads to complex eigenvalues λ_n found by solving the eigenvalue equation:

$$Det\left(\left[K\left(\lambda_n\right)\right]-\lambda_n^2\left[M\left(\lambda_n\right)\right]\right)=0 \qquad (4)$$

where $[M(\lambda_n)]$ and $[K(\lambda_n)]$ are the mass and stiffness matrix, respectively. The quality factor for the n^th mode $Q_{al}^{(n)}$ can be extracted by:

$$Q_{al}^{(n)} = \frac{\mathrm{Re}(\lambda_n)}{2\,\mathrm{Im}(\lambda_n)}. \tag{5}$$

To extract the $Q_{al}^{(n)}$ in the model with the Rayleigh damped substrate, we first perform a static simulation, applying a constant load in radial direction, to find the static displacement G_0 in radial direction of one point of the resonator. Next harmonic simulations are carried out. Harmonic loads of the same amplitude of the static load are applied, in order to find the displacement G_n in radial direction of the same point at the n^th resonance frequency. If we suppose the device behaves as a second order system, the ratio between the amplitude of displacement at the resonance and the static displacement gives the quality factor of the n^th mode of the structure:

$$Q_{al}^{(n)} = \frac{G_n}{G_0}. \tag{6}$$

4 RESULTS AND DISCUSSION

All the presented results are about the anchor losses dependent quality factor $Q_{al}^{(1)}$ for the first contour mode of a disk resonator. In the following we indicate $Q_{al}^{(1)}$ with Q_{al}.

The two different substrate models give very similar results, as seen in Figure 2, which shows the dependence of the quality factor Q_{al}, only due to anchor losses, versus the stem radius R_S for the first contour mode of a polysilicon disk resonator (resonance frequency about 184MHz). The curve $Q_{al}(R_S)$ shows some interesting behavior: both a minimum and a maximum exist for reasonable values of the stem radius, while it is generally assumed [3] that an increase of stem radius causes a monotonic decrease of Q_{al} because it increases the area through which energy can be lost. Figure 2 shows also a great sensitivity of Q_{al} to the stem radius and this implies that it is very important to have a good dimensional control over the stem radius. On the other hand the presence of a maximum for reasonable values of the stem radius in the curve $Q_{al}(R_S)$ can be very important for the design of these structures: the only two geometrical dimensions, which can be fixed by layout are the disk radius R_D and the stem radius R_S, while the goals in designing MEMS resonators are to fix resonance frequency and to maximize the quality factor. The first target can be obtained by properly choosing R_D, as indicated by Eq. (1). Secondly the quality factor can be maximized for the chosen disk radius by analyzing the curve $Q_{al}(R_S)$, and choosing the optimum R_S. Changing R_S does not affect too much the resonance frequency of a contour mode.

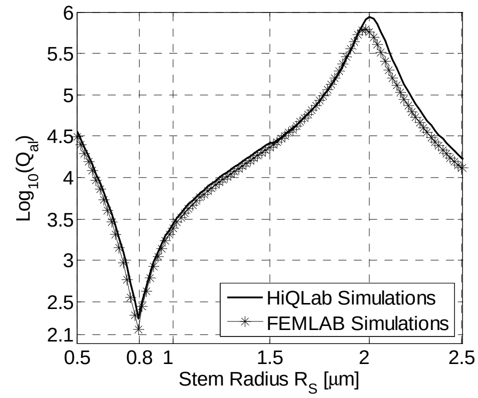

Figure 2: Dependence of quality factor Q_{al} of the first contour mode on stem radius: comparison between FEMLAB and HiQLab (including non-absorbing layer with L_{NA}=6µm, R_D=15µm, T_D = 3µm, H_S = 0.5µm, material polySi (E = 160GPa, ρ = 2230 ν=0.226); resonance frequency approximately 184MHz).

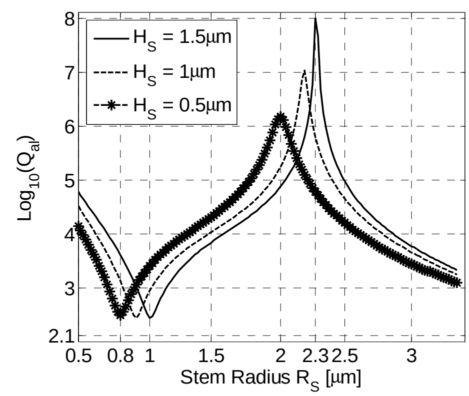

Figure 3: Dependence of quality factor Q_{al} of the first contour mode on stem radius with parametric stem height including non-absorbing layer (L_{NA}=8µm R_D=15µm, T_D = 3µm, material PolySi (E = 160GPa, ρ = 2230 ν=0.226); simulated resonance frequency approximately 184MHz). Simulator HiQLab.

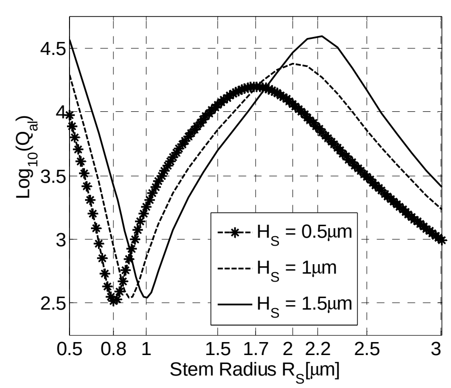

Figure 4: Dependence of quality factor Q_{al} of the first contour mode on stem radius with parametric stem height without non-absorbing layer (R_D=15µm, T_D = 3µm, material PolySi (E = 160GPa, ρ = 2230 ν=0.226); resonance frequency approximately 184MHz). Simulator FEMLAB.

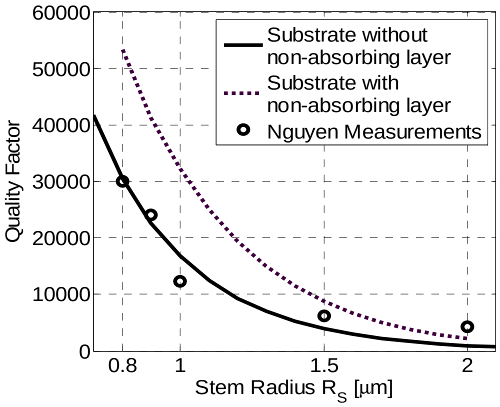

Figure 5: Comparison between simulations and Nguyen measurements (R_D=18μm, T_D = 2.1μm, H_S = 0.35μm, material polySi (E = 150GPa, ρ = 2300 ν=0.226); measured resonance frequency nearly 150MHz [3]. Simulations includes only anchor losses while the measured quality factor is determined by all the damping sources operating on the device.

Modal simulations performed with FEMLAB show that the resonance frequency of the first contour mode slightly raises if the stem radius increases, but only a variation of less than 1% occurs in the range 0.5μm< R_S<2.5μm for all the simulated structures.

Modeling the substrate with a non-absorbing layer does not affect the position of the minimum Q_{al} with respect to R_S, while the maximum in Q_{al} shifts slightly to higher R_S, and its value increases drastically (Figures 3 and 4), with values reaching from 10^6 and 10^8: this does not mean that actual measurements would yield these high Q_{al} values, but simply that anchor losses are negligible with respect to the other loss mechanisms. We also performed simulations to evaluate the influence of non-absorbing layer size and we verified that the if the layer size L_{NA} is large enough, a further increase in L_{NA} does not affect the simulations results. The slight difference between HiQLab curves $Q_{al}(R_S)$ for H_S = 0.5μm in Figures 2 and 3 is due to different non-absorbing layer dimensions L_{NA}.

The influence of the stem height H_S on the curves $Q_{al}(R_S)$ is presented for both models. In Figures 3 and 4 it is shown that an increase in the stem height H_S produces a shift of both the minimum and the maximum towards greater stem radius R_S. However, the influence of the stem height is much smaller than the influence of the stem radius: this is important because H_S is a parameter which can change due to process induced variations, and this can reduce the quality factor value obtained, even if we design R_S to get the optimum Q_{al} value.

To validate our approach we compared simulations with experimental data for a 150MHz contour mode resonator presented in [3]: there is a good agreement, especially for the case where the substrate is modeled without a non-absorbing layer (Figure 5). The model without the non-absorbing layer shows a better agreement with the experiments and this could mean that the artificial discontinuity introduced in the substrate has a negative effect on the reliability of the model. However our model only takes anchor losses into account, neglecting other damping sources as thermoelastic losses, which have been discovered to be important for flexural beam resonators in [6,7]. Therefore the effect of these losses has to be included in the model before making any conclusion about which is the best model for the substrate.

5 CONCLUSIONS

In this paper we introduced a new way of modeling the total energy absorption in the substrate, by introducing an artificially high Rayleigh damping: a comparison with an existing PML model, shows a good agreement.

Furthermore we evaluated two different ways of modeling the substrate, with and without the non-absorbing layer. We compared both of these with measurements in literature and a good agreement was found, so that we can conclude that the employed approach is well founded. However more experimental data are needed for a rigorous validation and a more accurate investigation is required to decide whether the non-absorbing layer is useful to increase the accuracy of the simulations or not.

Moreover, we demonstrated the importance of the stem radius to maximize the quality factor only due to anchor losses by layout, and we estimated the influence of a change in the stem height.

Finally our simulations predict for the first time a behavior for the dependence of anchor losses quality factor Q_{al} on the stem radius with a minimum and a a maximum, while to our knowledge in all the previous work Q_{al} was assumed as monotonically decreasing with any increase in the stem radius.

REFERENCES

[1] C.T.-C Nguyen, Topical Meeting on Silicon Monolithic Integrated Circuits in RF Systems, pp.23-32, 2001
[2] V. Kaajakari et Al., Transducers 2003, pp.951-954
[3] J. Wang, Z. Ren and C.T.-C Nguyen, IEEE Trans. Ultrason. Ferroelect. Freq. Contr., vol.51, no.12, pp. 1607-1628, 2004
[4] D. Galayko et Al., ESSDERC 2002, pp. 447-450
[5] P. Bruschi, A. Nannini and F. Pieri, Sensors and Actuators A, vol. 114, no. 2, pp. 21-29, 2004.
[6] R. Lifshitz and M. L. Roukes, Physical Review B, vol.61, no.8, pp. 5600-5609, 2000.
[7] Z. Hao, A. Erbil and F.Ayazi, Sensors and Actuators A, vol. 109, pp. 156-164, 2003.
[8] Y.-H. Park and K.C. Park, J. of MEMS, vol. 13, no. 2, pp. 238-247, 2005
[9] D. S. Bindel et Al., IEEE MEMS 2005, pp 133-136, 2005
[10] U. Basu, A. K. Chopra, Comput. Methods Appl. Mech. Engrg., vol. 192, pp. 1337-1375, 2003.
[11] http://www.comsol.com/products/femlab/.