Improved alignment is a significant challenge in RF MEMS resonators. It results in asymmetry in the ultra-symmetric radial contour mode disk resonators and reduces their performance by increasing the insertion loss and decreasing their quality factors ($Q$). Self-alignment method seems to be a good solution for misalignment problem, but it cannot be directly applied on high-performance ring-shaped anchored resonators. This paper discusses misalignment effects for ring-shaped anchored resonators and proposes a method for reconfiguring its anchor to be compatible with self-alignment process. Simulation results validate that the crossed ring anchor structure has the same resonance characteristics with the complete ring shape anchored resonator.

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Introduction

Nowadays, Micro-Electro-Mechanical-Systems (MEMS) have extended applications from environmental sensing and actuating to high frequency transceivers [1]. One of the most important applications of MEMS devices is frequency control in electronic systems [2,3]. MEMS resonators and filters have been designed with the ability to work in the frequency range spans from MF (Medium Frequency) [4] to HF (High Frequency) [5–7] to VHF (Very High Frequency) [8–11] and recently UHF (Ultra High Frequency) [12–14] with more than thousands of quality factors ($Q$). Hence, according to their small sizes and the ability to integration alongside with transistor circuits, MEMS resonators are excellent alternatives for off-chip and bulky SAW and ceramic filters.

Due to the demands of wireless communication systems for resonators in UHF frequencies and high quality factors, extremely high stiff disk resonators with the ability to work in GHz frequencies and with high $Q$, achieve great deals of interest in this area [15–19]. But unfortunately, like other MEMS devices, disk resonators suffer from some non-idealities such as reliability, strong spurious modes near the desired mode and misalignment.

Ring shape anchored contour mode disk resonator [2] is able to alleviate the reliability problems in addition to work in UHF frequencies with relatively large size. Spurious modes of this structure are also suppressed by both electrical and
mechanical techniques [20–22]. Also, low velocity coupling method could be employed for constructing narrow band mechanical filters for direct channel selection filters [23]. Another important challenge in all MEMS devices, especially in RF MEMS resonators due to their symmetric resonance features, is misalignment of different layers and parts in the fabrication process. The most important misalignment, which can be occurred for the ring shape anchored device, is anchor misalignment. Anchor misalignment can be a source of strong deviatory stresses in RF MEMS resonators which causes the insertion loss and therefore lowers the $Q$ and raises reliability problems.

In this paper, we model the misalignment and study the deviatory stresses of the structure. Also, we propose a method for preventing the misalignment problem for the ring shape anchored resonator. Finite element validation is also covered.

**Methodology**

**Device design and modeling**

Fig. 1 presents the perspective view schematic of the ring shape anchored disk resonator, identifying key dimensions and indicating two port bias and excitation schemes. The resonator consists of a hollow disk suspended 1 μm above the substrate with a ring shaped anchor at the nodal ring. Plated metal input electrodes surrounding both the inside and outside perimeters of the resonator. The inside and outside electrodes are connected using metal bridges suspended over the structure. A DC bias voltage, $V_P$, is applied to the anchor for polarization for distinction between negative and positive signals and for biasing the variable electrodes to resonator capacitance for producing an output current during the resonating of the device. AC input signal is applied to the input electrode resulting a time varying electrostatic force acting radially on the disk.

Fig. 2 illustrates lumped model simplification of the structure. The vibration function of the structure for the described mode is given by Baghelani and Ghavifekr [2]:

$$u_r(r, t) = R(r)e^{jω_0t}$$

where $ω_0$ is the resonance frequency in (rad/s), $t$ is the time and $R(r)$ is the resonance behavior as a function of radius and could be calculated by solving the following differential equation:

$$r^2 \frac{d^2 R(r)}{dr^2} + rv \frac{dR(r)}{dr} + (k_r^2 r^2 - v)R(r) = 0$$

where $v$ is the Poisson’s constant and $k_r$ is a constant given by Baghelani and Ghavifekr [2]:

$$k_r = \frac{2πf_r}{\sqrt{\frac{\rho_0(1 - v^2)}{E}}}$$

where $f_r$ is the resonance frequency, $\rho_0$ is the density of the structural material (e.g. polysilicon) and $E$ is the Young modulus. The design procedure is as follows, given a specific frequency and inner radius of the disk ($r_{in}$), $k_r$ can be calculated for a defined material and frequency from (3) and then for calculated $k_r$, the Eq. (2) could be solved with below boundary conditions:

$$R(r_{in}) = R_0 \text{ and } \frac{dR(r)}{dr} \bigg|_{r=r_{in}} = 0$$

where $R_0$ is the maximum value of $R(r)$ and could be adjusted on a desired value which usually defined by the technological constraints (e.g. 10 nm). It is important to mention that, in the radial contour mode disk resonator described by Wang et al. [1], the center of the disk is under very strong stresses.
in normal direction, but there are no stresses over the anchor of the presented resonator, see Fig. 3.

**Modeling and effects of misalignment**

As mentioned before, misalignment occurs during deposition of structural material after anchor deposition due to small variations which are usual in fabrication process. Fig. 4 depicts modal analysis of the structure without any misalignment and with 50 nm, 100 nm and 200 nm misalignments of the anchor for the structure designed for 940 MHz GSM applications. The anchor width is 250 nm, hence the maximum acceptable mask misalignment is 94 nm [24] in the standard CMOS technology.

As illustrated in Fig. 4, misalignment in small values does not affect the resonating performance of the structure. This is because of extremely large stiffness of disk resonators in their contour mode. When the structure is excited in contour mode resonance frequency, a strong mechanical wave is produced radially which causes a great deflection of the anchor. Hence, although the structure is resonating in its normal contour mode, the anchor is under a great amount of stresses (because it is not placed at its nodal area). This effect causes strong insertion losses and drastically lowers the $Q$. Fig. 5 shows the anchor tension for different misalignment values.

Another effect of misalignment is frequency shifting. We cannot use a lumped model, like that in Fig. 2, for considering the misalignment because the resonance frequency is more related to shape mode and structure width than that of anchor location. By solving the Eq. (2) with the related boundary conditions, the curve depicted in Fig. 6 is achieved. In the figure, one can assume the misalignment effect as forcing the curve to zero at non-ideal anchor location. This can cause non-symmetric resonating characteristics, but does not change the location of points with maximum resonance amplitude which placed at inner and outer radiuses. Fig. 7 shows a contextual lumped model of the resonator with exaggerated misalignment. Here again, anchor splits the resonator into two distinct resonators. In the case of misalignment, these resonators have different effective masses and stiffness and therefore have different resonance frequencies. Note that, those mentioned resonators comprise of a one coupled system which resonates at a single frequency, and therefore, are forced to resonate at a same frequency. It is obvious that, the mentioned frequency is not the natural frequency of those virtual resonators (at least for one of them), therefore the larger part tends to decrease its effective mass to compensate decreasing its stiffness (according to its larger length) by decreasing its resonance amplitude. The same phenomenon happens for the smaller part, but in the opposite manner. Therefore, the resonance profile of the whole resonator becomes non-symmetric, i.e. non-radial resonances and subsequently energy loss. Note that, the resonance frequency is a predefined parameter and outer radius is calculated upon that. But due to nonlinear effects, which decrease the effective width of the structure, the mechanical wavelength is decreased and therefore the resonance frequency is increased due to below equation [25]:

$$f_0 = \frac{\pi}{r} \sqrt{\frac{E}{\rho}}$$  \hspace{1cm} (5)

where $r$ is the disk radius and $\pi$ is a parameter depends on Poisson ratio of the structural material and mode shape. As mentioned before, effect of misalignment on the resonance...
frequency can be considered as a very slightly decreasing in the effective radius of the resonator. Fig. 8 describes this effect in another way. The middle curve is related to ideal anchor placement and defines the location of inner and outer radiuses of the resonator. The upper curve considers the misalignment effect for the left part of the lumped model of Fig. 7 (highlighted by a dashed red circle). Here, the points on inner radius of the resonator should resonate with more amplitude than the outer radius points. This phenomenon changes the ideal anchor location and tends to bend the anchor through that point, as indicated in Fig. 8. A same procedure happens for the right hand side of Fig. 7 and lower curve of Fig. 8, but on the opposite manner.

Results and discussion

Due to the importance of anchor misalignment effects, described in previous section, it can be a challenging problem in MEMS resonators. A method for self-alignment of the stem
Fig. 9  The mask structure (a) for the center anchored disk resonator, (b) for the ring shape anchored resonator (as it is obvious, this resonator requires two step masking which is not compatible with self-alignment context), (c) for the crossed ring shape anchored resonator (this procedure is completely adapted with self-alignment process).

Fig. 10  (a)The proposed structure with crossed ring anchor, (b) resonance characteristics of proposed structure with crossed ring anchor.

Fig. 11  A comparison of effects for 1 μm self-alignment between (a) center anchored resonator of Wang et al. [1], (b) presented crossed ring shape anchored resonator; as shown, the proposed resonator is less sensitive to misalignment.
shape anchored disk resonators, which prevents misalignment as much as possible, has been proposed by Wang et al. [1]. Some subsequent works used this technique for self-aligning of the anchor for various resonators and prove the abilities of self-aligning method [26–28].

The process is completely described by Wang et al. [1]. The anchor is not the pre-deposited part of the structure here, but the structure is deposited first and the exact location of the anchor is opened at the structure’s mask. After deposition of the structure, the anchor is deposited and its related hole is filled. Using this procedure, the misalignment problem is eliminated.

Unfortunately, the self-alignment process for the ring shape anchored resonator is not possible because it needs one more mask, because of its ring shaped anchor, which increases the cost and also can be a source of more misalignments. Note that, there are no paths for etching acid between inner and outer areas. This causes the etch time of this structure to be problematic and even damaging for the structure during releasing of sacrificial layers.

In order to using self-aligning process without extra masks, we reconfigure the anchor from ring shaped to crossed ring shaped. This approach makes the self-alignment of the anchor to be possible and also facilitates releasing of sacrificial layer because of creating several paths between inner and outer radiiuses through crossed areas. Fig. 9a illustrates the mask shapes for the center anchored resonator. Fig. 9b illustrates the mask for the ring shape anchored resonator, which unfortunately has two completely distinct areas and requires two masking steps which completely is in oppose to self-alignment technique. But, for applying the self-alignment technique on this resonator, the anchor should be reconfigured from a complete continuous ring to a crossed ring. Fig. 9c depicts the mask structure of this resonator which is utterly suitable for self-alignment technique.

Fig. 10a shows the structure with crossed ring anchor. It is obvious that the crossed parts of the anchor are parts of the ring shaped anchor and placed at nodal ring. Fig. 10b illustrates the resonance characteristics of a quarter of the crossed ring anchored structure and shows no defects on resonance characteristics and no stresses on anchor segments. Note that, the crossed ring anchor has smaller area than the complete ring and hence acoustic coupling between substrate and structure is decreased which cause increasing in $Q$.

Fig. 11 shows a comparison between the effects of misalignment over the proposed resonator and center anchored resonator presented by Wang et al. [1]. It can be seen that, as the result of removing the inside area of our resonator, it is much more robust than the center anchored resonator. The resonator is now confident enough to be utilized in wireless applications according to its reliability, spurious modes freeness and preventing misalignment.

Conclusion

Effects of anchor misalignment for resonance characteristics and frequency shift of the ring shape anchored resonator have been discussed. Results shown that, misalignment could drastically degrade the performance of the resonator in both its reliability and $Q$. After that, a new anchor configuration, called crossed ring, has been proposed which made the device to be compatible with the self-alignment process and its effectiveness validated by finite element analysis. Researches on the other problems of RF MEMS resonators such as impedance matching and more increasing in their resonance frequency are ongoing.

Conflict of interest

The authors have declared no conflict of interest.

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