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A Novel Tuning Method for Repeatability Problem Solving of RF MEMS Disk Resonators

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Abstract: Despite of their very high quality factors, RF MEMS resonators suffer from repeatability problems which preventing them to be commercialized. This paper proposes a method for enabling RF MEMS resonators to become repeatable. The proposed method, utilizes recently demonstrated ring shape anchored contour mode disk resonator constructing from an AlN layer sandwiched between two thin polysilicon layers. The anchor is configured from the continuum ring to crossed ring providing distinct electrodes for applying controlling DC voltages. By such a method, process variations in 0.18 μm technology and below, can be compensated and one of the most significant bottlenecks in the way of commercializing RF MEMS resonators is vanished. *Copyright © 2012 IFSA.*

Keywords: RF MEMS resonators, Tuning, Repeatability, Ring shape anchored, Contour mode disk.

1. Introduction

High quality factor (Q), low power passive resonators utilizing micro-electro-mechanical systems (MEMS) technology are widely interested now a days by RF designers and scientists due to their integrability alongside transistor circuits on a single chip [1]. In this case, disk resonators are much considered because the ability to work in UHF frequencies with thousands of Q [2-4] which is not accessible by on-chip LC filters and resonators.

Although surface acoustic wave resonator (SAW) and ceramic resonators are attained in GHz frequencies with the same Q's [5] but their integration on a single chip alongside CMOS transistors is a challenging problem yet and their large sizes and being bulky is the bottleneck of the designing of a transceiver on a chip. Also, bulk acoustic wave resonators (BAW) can be designed to work in UHF frequencies and can be fabricated alongside transistors, but unfortunately their resonance frequencies are pre-determined by their thickness which is very difficult parameter to be controlled precisely and is not compatible with the state- of- the art CMOS technology [6]. Hence, MEMS resonators are excellent candidates for todays and future transceiver - on- a chip systems.

Recently demonstrated ring shape anchored contour mode disk resonator [7] with large anchor area on the nodal ring, surmounts the reliability and lifetime concerning of such devices. This resonator works in its second resonance mode and hence can resonate in higher frequencies with the same size to its counterparts [8]. Also, according to its special electrode engineering introduced in [9], it's not suffers from spurious modes. Therefore, another challenging problem involved with MEM resonators is suppressed [10].

One of the most important bottlenecks of MEM resonators is frequency tuning. Frequency tuning is a controllable changing in the resonance frequency after fabrication and also during work. Frequency tuning is a very useful characteristic of resonators. For example, when a resonator used as a tank of a voltage- controlled oscillator (VCO), its center frequency determines the oscillation frequency and therefore for changing the output frequency, the resonance frequency of the tank must changes.

Another important aim of frequency tuning is repeatability, which means two devices fabricated by the same process technologies have the same properties e.g. resonance frequency in the resonators case. Since the center frequency of MEM resonators is previously determined by the radius of the disk [11], the process variations can cause very small but still important changes in their radius and therefore their resonance frequency. The importance arises when one considers the very high Q MEM resonator working in GHz frequencies with very narrow band.

In this paper, a novel tuning method for the ring shape anchored contour mode disk resonator with the aim of repeatability is introduced. The proposed method is based on piezoelectric effect and special configuration of the resonator's anchor, which results a small but enough controllable changes on the resonance frequency. The proposed method is reconfiguring the anchor from a continuous ring to a crossed ring for being able to apply a controlling voltage in both up and down sides of the resonator without any additional external electrodes.

The paper is organized as follows; importance of repeatability and its requirements are discussed in section 2. The structure of introduced device and its operation are described in section 3. Results are given in section 4 followed by a conclusion in section 5.

2. Importance and Requirements of Repeatability

As mentioned before, repeatability is an important bottleneck of MEM resonators especially in GHz frequencies which prohibits commercializing them. Due to process variations these devices can be unrepeatable. Although these variations may not be taken into account in most transistor circuits and other MEMS devices, but could strongly affect the operation of RF MEM resonators. For example, assume a resonator with Q=1000 and f_r=1 GHz, then the 3 dB bandwidth of such a resonator is about 1 MHz. But when a resonator is used as a front-end filter in a transceiver, 3 dB bandwidth is not a good criterion because most of standards need at least 40 dB of out of band rejection and less than one dB of in-band loss. Since the insertion loss of the front-end filter directly adds to the noise figure characteristics of the transceiver, 3 dB loss may degrade the overall performance of the system. Then one should consider a narrower bandwidth of a resonator when used a transceiver's front-end filter, e.g. 200 KHz. 0.5 % of process variation causes about 50 KHz of resonance frequency of such a resonator which is completely comparable with resonator's bandwidth and even could make it useless.

These variations can't be controlled or prevented and have stochastic behavior. Generally, fabrication of repeatable devices is only possible if full control over the mechanical properties of the materials and the size of the devices has been accomplished [6], which is impossible unless expensive lithographical processes such as electron-beam or X-ray lithography's utilized which are make the device to be too costly to be commercialized in ordinary applications. Various methods have been proposed for frequency adjustment and trimming, which are categorized into two major sections; passive and active methods. Passive frequency adjustment is a permanent change in the resonator's center frequency and can adjust the frequency between 20 to 800 ppm. Some of these methods are grinding a major surface, grinding a minor surface, edge grinding, sand blasting, drilling and laser trimming.

In contrast with passive frequency adjustment, active tuning is a non-permanent change in resonance frequency and is based on changing the internal stresses and modification the modules of the resonating material. These changes can be taken placed by methods such as thermal annealing, electrostatic tuning and etc.

Although passive and active methods introduced in literatures could considerably change the resonance frequency, these methods are just applicable to low frequency resonators such as comb-drive and beam, but not to the disk resonators for some reasons: disk resonators must be symmetric and any asymmetry cause deviation in resonance characteristics and drastically decrease the Q, then passive methods can't be used. Also disk resonators have extremely high resonance energies in so far as the energy of electrostatic force which tries to change the resonance frequency is not comparable with it. Hence, electrostatic method couldn't change the resonance frequency of disks. In addition, thermal methods are not applicable on integrated circuits and even if be applicable, can't change the resonance frequency substantially.

Here, we want to discuss on the amount of requiring frequency change for repeatability. Assume the ring shape anchored contour mode disk resonator designed to work in 1 GHz. According to TSMC© technical data [12], the maximum process variation which can be occurred during fabrication is 0.458 % for 0.18 μm CMOS technology. By finite element simulation of the disk, one can see that this is equal with 822.6 pm change in device radius. One can apply this variation in different ways. The maximum frequency shift is about 11 KHz. Therefore, the tuning for repeatability method must be able to compensate this error.

3. Device Structure and Operation

The anchor of recently demonstrated ring shape anchored hollow disk resonator [7] is configured to carry out tuning for repeatability. The structural material is changed from polysilicon to aluminum nitride (AlN) piezoelectric which can be deposited alongside its C-axis [13].

Resonance behavior of the ring shape anchored disk resonator, shown in Fig. 1, described by the following equation [7]:

$$r^2 \frac{d^2 R(r)}{d r^2} + r \nu \frac{d R(r)}{d r} + \left(k_r^2 r^2 - \nu\right) R(r) = 0 \tag{1}$$

which is a Bessel type differential equation, where υ is the Poisson's constant and k_r is a constant given by:

$$k_r = 2\pi f_r \sqrt{\frac{\rho_0 \left(1-\nu^2\right)}{E}} , \tag{2}$$

where f_r is the resonance frequency, ρ_0 is the density of the structural material, and E is the Young modulus. The design procedure is as follows; given a specific center frequency and inner radius of the disk (r_{in}), k_r can be calculated for the defined material from equation (1), then for calculated k_r the equation (1) can be solved for the below boundary conditions

$$R(r_{in}) = R_0 \quad and \quad \left.\frac{d\,R(r)}{d\,r}\right|_{r=rin} = 0 \,, \tag{3}$$

where R_0 is the maximum of $R(r)$ adjusted on a desired value (e.g. 10 nm).

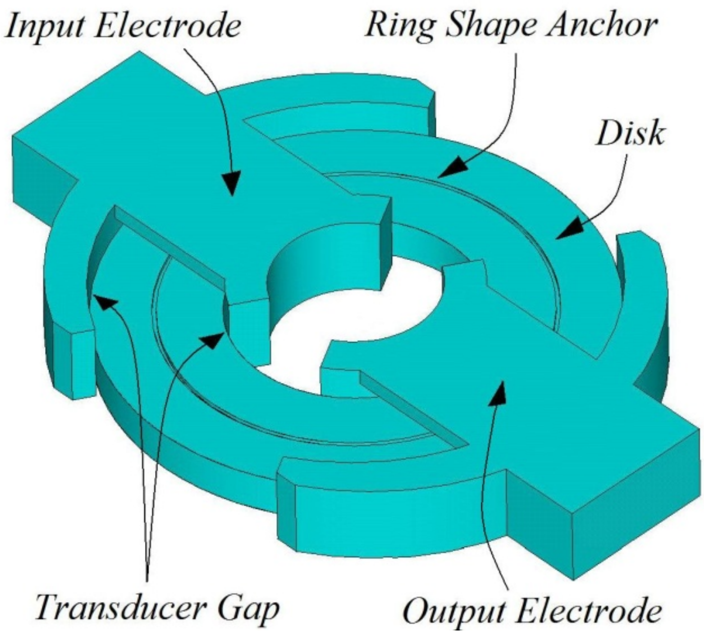

Fig. 1. Perspective view of the proposed microelectromechanical radial contour mode disk resonator with ring shaped anchor.

Solution of equation (1) for a given f_r and boundary conditions results a schema like the one sketched in Fig. 2.

The new tunable structure is based on the energy of the piezoelectric effect which can works against high resonance energy of the disk in its contour mode. For this aim, the structural material is AlN which can be deposited in its C-axis and therefore can support radial resonance without any considerable defect. If a DC voltage vertically applied between its surfaces, as shown schematically in Fig. 3, an electrical field produces which, due to piezoelectric effect, cause an expansion/contraction of the disk. This phenomenon changes the resonance frequency of the disk by two mechanisms; creation radial stresses inside the resonator and changing the radius of the resonator as the result of piezoelectric effect, which the last one is more important.

Fig. 4 shows the simulation results of this phenomenon by Finite Element Analysis (FEA). Applying the DC voltage between two surfaces of the disk needs for electrodes which may attach to the disk externally. This attachment should perform mechanically and hence affect the mechanical performance of the resonator and obviously increases the insertion loss and hence decreases the quality factor of the resonator. For preventing these losses the abilities of the ring shaped anchor are utilized. The structure of the anchor configured from the continued form to the crossed ring as shown in Fig. 5.

All anchor pieces are used for applying DC biases in alternation, one for connecting the bottom surface to the electrical ground and another for applying the desired DC voltage.

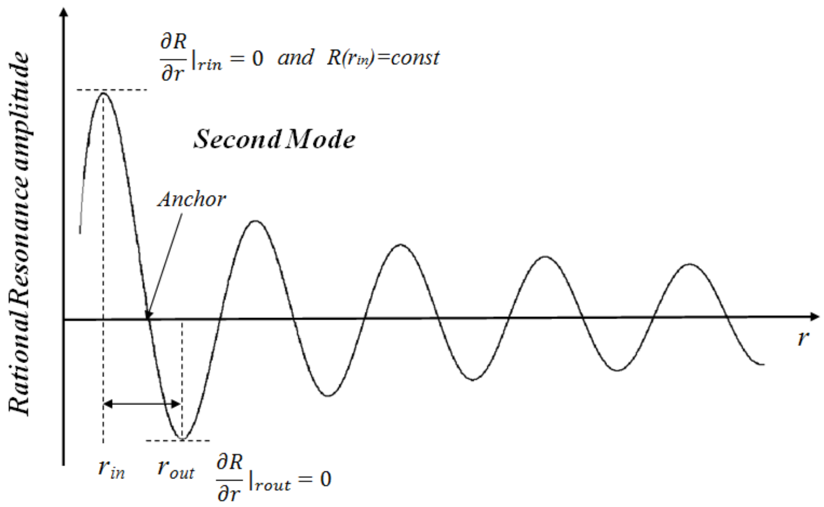

Fig. 2. The solution of equation (1) for a given frequency and boundary conditions.

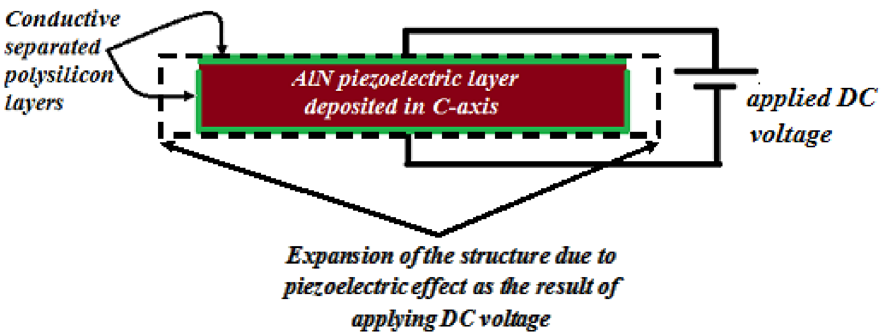

Fig. 3. The procedure of applying DC voltage on the resonator.

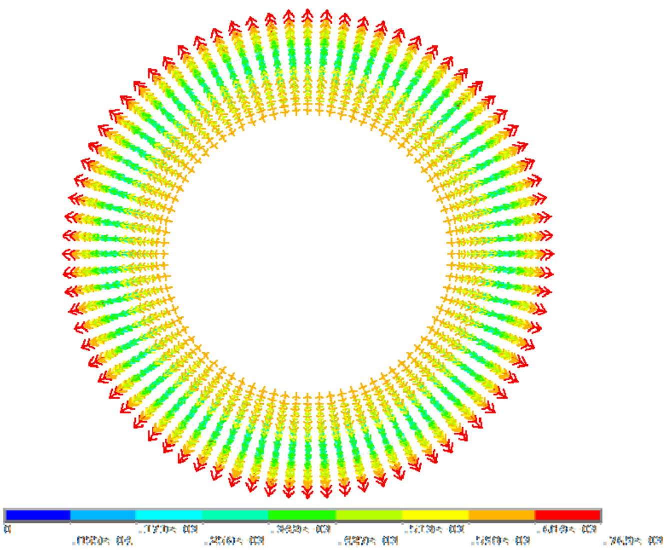

Fig. 4. Vector plot of the displacement of the AlN ring shape anchored resonator built based on the schema of Fig. 3.

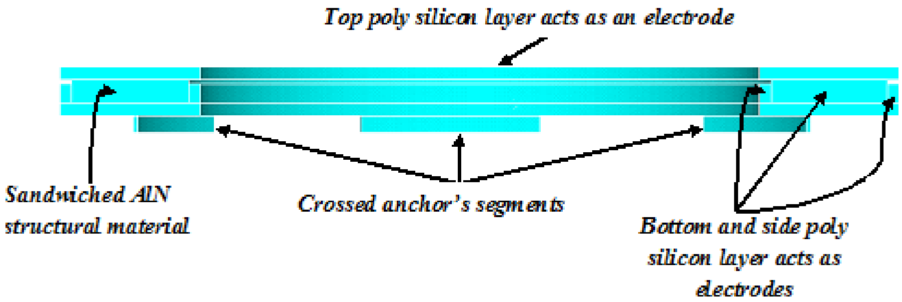

Fig. 5. A simple Cross – section of the proposed tunable crossed anchor resonator.

4. Simulation Results

In this section, the proposed idea for tu*ning for repeatability* is verified. As an example, consider a ring shape anchor resonator designed for 940 MHz (GSM receive band) and fabricated by 0.18 µm standard technology. From TSMC © technical data [12], the maximum fabrication error is less than 822.6 pm for 0.18 µm technology. This maximum technological error translates to 15 kHz variation in center frequency of defined resonator. Due to their very high Qs, any deviation from resonance frequency of MEMS resonators could cause a significant loss. Hence, the center frequency needs to adjust exactly.

Simulation results verify the ability of the proposed method for compensating these errors. Fig. 6 illustrates the diagram of frequency changes versus biasing voltage. As mentioned, the structural material is AlN here. As shown, the proposed method can totally compensates the process variation errors with relatively low biasing voltage. It is needless to say that, the bias voltage of MEMS resonators injects no DC current to the device and therefore its headroom, if not very high, is not a problem.

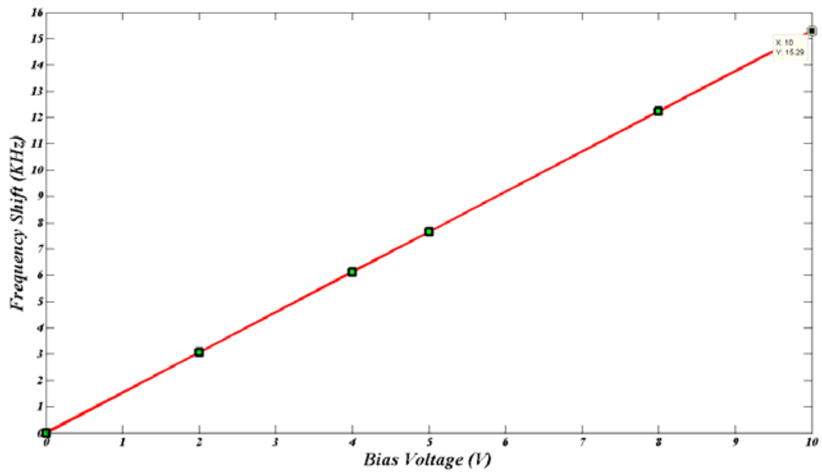

Fig. 6. Frequency change versus bias voltage curve of the proposed resonator. As shown, the attained change is completely sufficient for compensation of the process variations and hence the resulting device is repeatable.

5. Conclusion

A new method for tuning the RF MEMS disk resonators with the aim of repeatability has been introduced and results of the implementation over the ring shape anchored contour mode disk resonator have been provided. This method is based on the piezoelectric effect of a sandwiched AlN piezoelectric layer between two thin polysilicon layers which produce mechanical deformations and stresses that can change the resonance frequency of the ultra stiff contour mode disk resonators. By segmenting the continuum ring anchor, several anchors achieved which can apply different DC voltages to the top and bottom surfaces of the resonator without the need for any external electrodes and also any defects and losses. Simulation results show that the resulting device is repeatable even if the maximum process variations are considered. Therefore an important challenge in RF MEMS resonators is subdued.

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Guide for Contributors

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