# Design and Analysis of a Torsional Mode MEMS Disk Resonator for RF Applications

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***Abstract*— In some Radio Frequency (RF) systems, including transmitters and receivers, resonators play a key role in system performance. In RF resonator design, it's important to achieve precise operating frequency and high Quality (Q) factors. Q is an important property of microelectromechanical resonators which is the amount of energy stored per energy loss in each cycle. Improvement of the Q factor makes it possible to design low phase noise resonators and thus enables us to improve the performance of the resonance system. In this paper, a high Q disk resonator is introduced which resonates in torsional resonance mode. It could be a good candidate for implementation of RF transmitters. Among different types of resonators, disk resonators have small energy loss and high Q values. In most other published papers, axial and bending modes have been considered in RF disk resonators. In this paper, we investigated the torsional mode for a polycrystalline silicon disk resonator with two beams on both sides. The resonator is actuated by electrostatic mechanism with 200nm air gaps in torsional mode of frequency 1.421 MHz. The calculated f-Q value at the resonance frequency is 1.8× $10^8$ which is desired for RF resonators.**

***Keywords*— *Microresonator; RF MEMS; Microelectromechanical devices; Torsional mode; Disk resonator.***

## I. INTRODUCTION

In recent years, the implementation of Microelectromechanical (MEMS) resonators in RF wireless communication systems has been grown tremendously. These systems are in high demand in the fields of RF applications like filters, duplexers, sensors, tunable tanks, resonance oscillators and mixers. RF MEMS resonators, due to their micron or submicron dimensions, have low manufacturing and power consumption as well as access to high frequencies in the kHz-MHz range leading to high quality in specific vibration modes for advanced electronic applications. On the other hand, RF MEMS technology is compatible with complementary Metal-Oxide-Semiconductor (CMOS) fabrication technology. MEMS and CMOS integrated circuits are interested in wireless communications systems. Therefore, recent studies in the field of RF MEMS resonators have become an important research topic.

Quality factor and resonant frequencies parameters are two performance metrics for micro resonators. The resonant frequencies for micro devices are typically in the range of kHz to MHz but can be in the GHz range for well-designed devices. For micro resonator, Q varies from a few to several million depending on the operating conditions and design of the device. Applications of resonators in the field of RF depend on the resonant frequency and quality factor of the resonator. Capacitive electrostatic resonators are available in various forms, including membrane disc capacitors, interdigital resonators and disk resonators. Contour mode disk resonators with central hinges and capacitive gaps within a few hundred nanometers that fluctuate sideways provided relatively high resonant frequency and quality factors [1]. This type of resonator poses challenges, for example, any shift from the ideal center mode results in high anchor losses, which can adversely affect the performance of the resonators. Therefore, hollow resonators with ring anchors were introduced to reduce the loss of anchors [2]. The torsional resonators usually include a pair of beams that support the main part of the resonator as the resonator twists and flips around these beams. Since torsional mode resonators have high resonance frequencies, they can be used as high-frequency resonators. In these resonators, which oscillate in the torsional mode, the predominant stress is shear stress and rotational displacement has occurred. To investigate the torsional frequencies, Yang and his colleagues provided instructions for designing resonant sensors capable of operating in harsh environmental conditions. In this study, the nano crystal diamond platform was used to make torsional multi-resonance frequencies at the High Frequency (HF) band [3]. Recently, Kan and his colleagues used a multi-electrode mode in their study of disc resonators based on Whispering Gallery Modes (WGMs) with multiple-frequency outputs that simplify the communication system and reduce the power consumption of a digital system [4]. The dynamics behavior of electrostatic MEMS resonators has also been studied recently using a model that can simulate the mechanical behavior of micro disks for general conditions and a wider range of electrical loads [5]. It presented plans and a useful tool that can be applied to improve and optimize disk-shape resonators. Also, a kind of disk-plate resonator in wine glass mode resonance was investigated by Lee et al. that provides higher f-Q than some other resonant modes [6]. It was a single crystal silicon resonator made by SOI micromachining technology. The resonance frequency stability of disk resonators was systematically studied by Chen et al. for 3D encapsulated VHF MEMS resonator [7]. The long-term frequency stability results of the resonance frequency variations were ±1 ppm and ±0.95 ppm, respectively.

Briefly, in disk resonators, the torsional resonance modes may make high f-Q in the order of several hundred million. In this paper, a torsional disk resonator is presented and the torsional resonance mode in proposed disk resonators is simulated. High f-Q product of about $10^8$ is achievable based on simulation results.

## II. PROPOSED RESONATOR STRUCTURE

As mentioned, MEMS resonators play an important role in RF wireless communication. The basis of the work of resonators is the continuous conversion of kinetic energies and potentials into one another. There are a variety of energy conversion mechanisms in MEMS devices such as piezoelectric, thermal, piezo resistive and electrostatic capacitive. Among all, the electrostatic capacitive mechanism is simpler to fabricate and operate. Except for high electrical conductivity for the plates, there is no specific feature for material selection. Depending on the functional modes, resonators also are divided into several types including torsional, flexural and bulk modes. In resonators that oscillate in torsional mode, the stress is in the form of shear and displacement is torsional [8].

Torsional mode resonators have high resonance frequency. They can be used to reduce the loss and better efficiency of the resonance system. In this study, the torsional resonance mode for a disk resonator is investigated with the specific structure shown in Fig. 1. Studies have shown that silicon has excellent mechanical properties and enables high mechanical quality factors to be achieved in resonance systems. Hence the model studied consists of polycrystalline silicon components whose properties are presented in Table 1 and the dimensions of the components in Table 2. As can be seen in Fig. 1 (a), to reduce loss, the support is in the form of a stem that is $500\ nm$ away from the substrate and suspends the resonator from the frame. In Fig. 1 (b), two 200 nm air gaps are seen around the beams, which is the distance between the electrodes and the beams, the lateral capacitors.

*TABLE 1. Material properties for Polycrystalline silicon*

| *Density* *[kg/m^3]* | *Young's Modulus* *[Pa]* | *Thermal Conductivity* *[W/(mK)]* | *Poisson's Ratio* | *Relative Permittivity* | *Heat Capacity* *[J/(kg*K)]* |
|---|---|---|---|---|---|
| 2320 | 160E9 | 34 | 0.22 | 4.5 | 678 |

*TABLE 2. The dimension of resonator components*

| *Disk* | *Beam* | *Anchor* | *Gaps* | *Substrate* |
|---|---|---|---|---|
| Radius: 16.8µm<br>Thickness: 2µm | Width: 8µm<br>Height: 2µm<br>Thickness: 2µm | Radius: 0.5µm<br>Thickness: 2.5µm | 0.2µm | Radius: 20µm<br>Thickness:500µm |

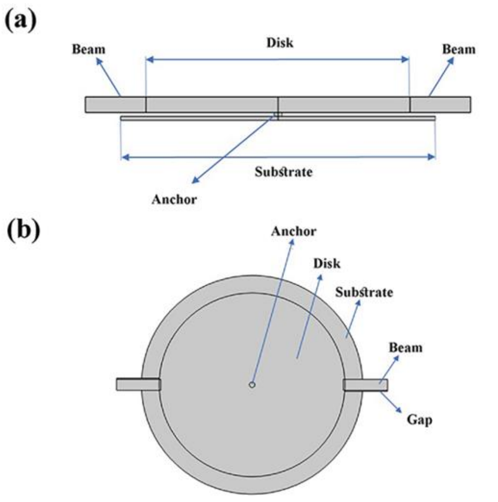


Fig. 1. *Schematics summary of torsional mode disk resonator **(a)** YZ cross-section view and **(b)** XY cross-section view*

## III. SIMULATION RESULTS

The design of the structure is evaluated in COMSOL Multiphysics and the simulation results are analyzed. It should be noted that the simulation results are for a 1-atmosphere pressure air environment. These micromechanical resonators also can be tested in a vacuum environment to reduce the effects of viscous damping and to achieve high-quality factors.

A combination of DC-bias voltage and AC excitation voltage is applied across the electrode gap to the resonator, applying force to the plate and generating resonance in different modes. Fig. 2 shows the resonant modes obtained by applying voltage for different resonant frequencies. According to Fig. 2 (c), the torsional mode is obtained at a frequency of 1.421MHz in which the resonator rotates around the disk anchor by applying bias voltage and excitation voltage.

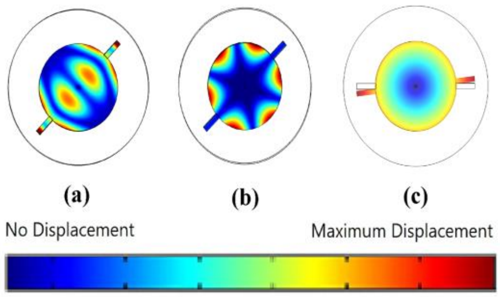


Fig. 2. *Total displacement for each resonance mode at the (a) Frequency 60.34MHz (b) Frequency 13.24MHz and (c) Frequency 1.421MHz*

The disk resonator with the proposed structure introduced in the preceding section has torsional mode frequency at 1.421MHz based on simulation results and evaluating the obtained Eigen frequencies. Fig. 3 (a) shows the transducer for this resonator, which is driven by 8V DC bias voltage. As shown in Fig.3 (a), the displacement diagram contains a peak and anti-peak that represent the minimum energy loss at this frequency. The transfer function ( $i_{out}$ / $V_{in}$ ) of the resonator as the results of harmonic analysis is illustrated in Fig.3 (b). As shown, the resonator has a very sharp frequency response, with sideband rejection of about 39 dB, which is a large value.

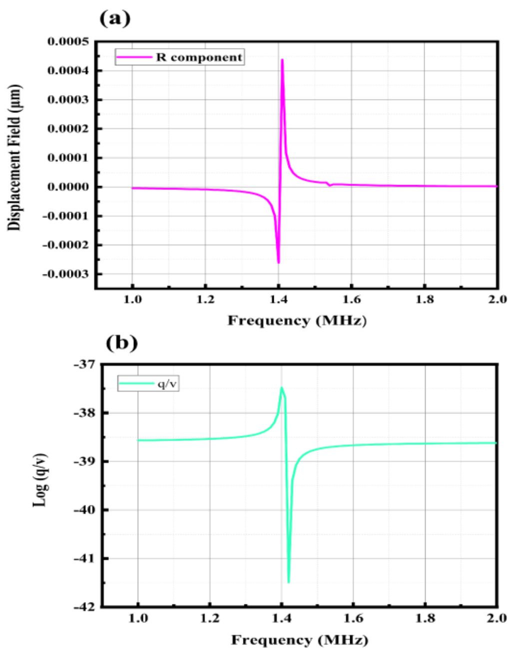


Fig. 3. *(a) Displacement and (b) Transfer function of proposed MEMS torsional mode disk resonator with a centered anchor.*

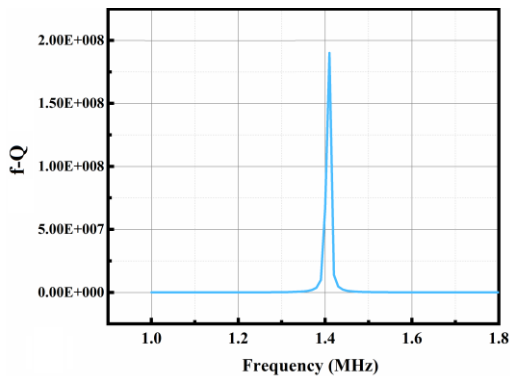


Fig. 4. *The quality factor of the proposed microelectromechanical torsional mode disk resonator with centered.*

The most important feature for resonators used in RF MEMS applications is their quality factor, which indicates better system performance. The f-Q product for this polycrystalline silicon resonator was calculated $1.8 \times 10^8$ at a frequency of 1.421MHz As shown in Fig.4.

## IV. DISCUSSION

High quality-factor, together with a wide tuning range and reduced insertion loss, are some of the key points making MEMS technology an enabling solution for multi-standard RF platforms. Key performance parameters for integrated components are the quality factor and resonant frequency. Higher Q component helps to minimize RF power loss, to reduce noise and to eliminate dc power consumption of RF integrated circuits. Q for resonators is defined as the ratio of energy stored to energy lost per cycle according to the following equation:

$$Q = 2\pi \frac{average\ energy\ stored}{energy\ lost\ per\ cycle} \quad (1)$$

By running a single frequency response measurement, one can estimate the resonant frequency of a micro resonator by locating the peak in the frequency response while the quality factor can be estimated from:

$$Q = \frac{f_0}{\Delta f_{-3dB}} \quad (2)$$

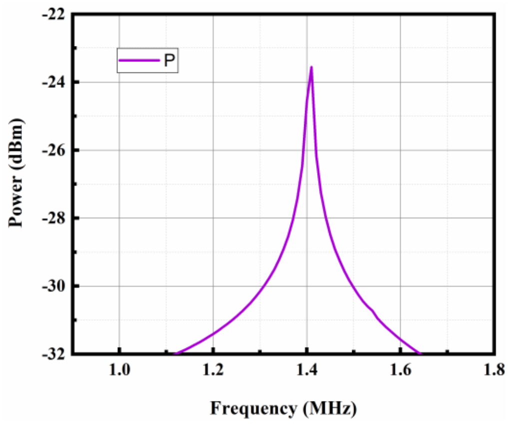


Fig. 5. *Power versus frequency diagram for torsional resonance mode*

Where $f_0$ is the undamped resonant frequency and $\Delta f_{-3dB}$ is the -3dB bandwidth around the resonant frequency [8].

In this paper, at first, the torsional mode resonance of the disk resonator with the central anchor was simulated. The disk resonators with the central anchor have low energy loss. According to equation (2) and using data in fig.4, the f-Q value is almost $1.8 \times 10^8$ in the vacuum which is a high-quality factor for the torsional modes of the disk resonators.

## V. CONCLUSION

The torsional resonance mode for a disk resonator with a central anchor was investigated to propose a RF resonator. The designed resonator has f-Q value in the order of several hundred million which is useful for high-performance resonance systems. This structure was investigated concerning the torsional modes for which they can yield high-performance improvements in the system. These RF-MEMS resonators can be used in a variety of fields of wireless communication with improved performance and low noise and loss.

Further work can also be done on the win-glass modes for this structure, given that this mode of resonance would provide high quality factor for disk resonators.

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