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Research Issues in MEMS Resonators

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ABSTRACT: *MEMS resonators have started replacing the quartz crystals and SAW resonators in RF transceivers because of their inherent advantages like high quality factor, small size, robustness and easy integrability with supporting electronics. The paper presents the developments that have taken place in MEMS resonators. Some of the issues in the design and development of electrostatically transduced MEMS resonators have been identified through the literature survey. Applications of MEMS resonators and few of the commercially available MEMS resonators are discussed.*

KEYWORDS: *MEMS Resonators, optimization, resonance frequency, quality factor, motional impedance*

I. INTRODUCTION

MEMS (Micro Electro Mechanical Systems) are micron sized devices that combine mechanical and electrical components. The devices can act as either a sensor, wherein a change in physical property creates an electrical signal, or as an actuator wherein a physical effect can be created by the application of electrical signal. MEMS devices are showing many potential applications in field of communication, industrial automation, biotechnology, military, automotive engineering, consumer electronics etc. This is because of the inherent advantages of the MEMS like low cost, low power consumption, easy integration with electronics, high resistance to vibration, shock and radiation, high reliability, high precision and low cost batch fabrication.

One of the fields in which the MEMS devices are showing high potential applications is the field of RF communication. The MEMS resonators are becoming the most preferred choices for sensing and high frequency applications like oscillators, filters and mixers because of the inherent advantages associated with MEMS. MEMS resonators have started replacing quartz crystal technology whose main drawbacks are large size which ultimately affects the miniaturization, high cost and non-compatibility with integrated circuit technology[1][2].

A. Resonance

Resonance is a phenomenon where a system shows selective response at specific frequencies. The resonance occurs when the system is capable of storing energy and also capable of transferring energy from one mode to another. Depending upon the principle of operation the resonance may occur in different domain like mechanical, electrical, electromagnetic, optical, acoustic etc. For example, in mechanical domain the system may vibrate with greater amplitude at some frequencies than the other. The frequency at which the system oscillates with greater amplitude is known as resonant frequency[1]. In electrical domain a circuit comprising of capacitor, inductor and resistor, connected in series or parallel, acts as a resonator. The two modes of storing energy are the electrical field when the capacitor is charged and the magnetic field when the current flows through the inductor. The system oscillates when the energy is transferred continuously between the two. When the resonance occurs the impedances of capacitor and inductor are equal but opposite hence they cancel each other. Thus at resonance the circuit will have minimum impedance and the frequency at which this phenomenon occurs is known as resonant frequency.

The paper is organized as follows. Section 2 describes the resonator's working principle, modes and parameters. It also covers and modeling of MEMS resonators. In section 3 the literature review is presented. Section 4 identifies the challenges and issues in the design and development of MEMS resonators. Section 5 lists some applications of MEMS resonators.

II. MICRO ELECTRO MECHANICAL RESONATORS

Resonators where in the resonance happens in mechanical domain but sensing and actuation in electrical domain are known as electromechanical resonators. These resonator consist of vibrating mechanical structure, input transducer for converting from electrical domain to mechanical domain and an output transducer for converting back from mechanical to electrical domain[2] as shown in Fig.1. The phenomenon that results in resonance is the formation of one or more standing waves within the mechanical structure. The characteristics of the resonance such as frequency , amplitude and phase depend on the geometry of the device and material property of the device.

Some of the electromechanical resonators that are most commonly used in RF communication area as frequency reference circuits are quartz crystal resonators and surface acoustic wave(SAW) resonators. All though these techniques have demonstrated very large quality factor and excellent thermal stability , there are some drawbacks associated with the two technologies. Some of them are, they cannot be miniaturized beyond certain limit, they cannot be readily integrated with conventional ICs and their manufacturing process is expensive. This poses a challenge in overall system size reduction.

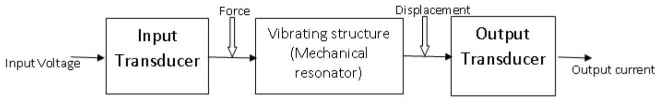


Fig. 1. An Electromechanical resonator

MEMS resonators, the electromechanical structures of micron size, are exhibiting high potential of replacing these conventional electromechanical resonators due to their extremely high miniaturization possibilities, ready integrability with conventional ICs and low manufacturing cost as they can be manufactured using the conventional CMOS IC manufacturing process. Several types of MEMS resonators have been reported till date and a good number of them are also commercially available. MEMS resonators can be classified on the basis of transduction principle involved. The transduction principal refers to the techniques used to actuate and sense the resonance state of resonator. Another way of classifying the MEMS resonator is on the basis of modes of vibration. Various resonator structures have been reported till date based on different transduction principle and on modes of vibration. Some of the resonator structures reported so far are cantilever beam resonator, clamped-clamped beam resonator, free-free beam resonator, comb-drive resonator, disk resonator, ring resonator, square plate resonator, triangular resonator etc.

In this section the different working principles used in MEMS resonators are discussed followed by different modes of vibration, MEMS resonator parameters and modeling of MEMS resonator

A. Principle of Working

Several techniques are used to actuate and detect the resonance state of resonators such as electrostatic, thermal, electromagnetic, electromotive and piezoelectric.

Electrostatic Actuation: The electrostatic actuation and capacitive sensing is the most commonly used transduction principle in MEMS resonators. As the input and output signals are electrical, the resonators can be used in purely electrical environment such as RF transceivers. These resonators comprise of a vibrating mechanical structure and two electrodes, one for actuation and another for sensing. The Fig. 2 shows a electrostatically actuated MEMS cantilever beam resonator. To excite the device a time varying voltage signal is applied to the actuation electrode while maintaining the resonator (mechanical structure) at fixed DC bias. This potential difference between the actuation electrode and beam creates a force between the two. When the frequency of the applied time varying voltage signal approaches beam's natural frequency, the beam begins to vibrate in a direction perpendicular to the substrate.

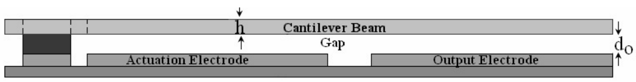


Fig. 2. MEMS Cantilver Beam Resonator

This creates a DC biased time varying capacitor between the beam and the output electrode which in turn results in the production of output motional current at the output electrode[3]. Some of the inherent advantages of electrostatic actuation are simplicity of design, fast response and low power consumption.

Piezoelectric Actuation: The resonators use piezoelectric materials like single-crystalline quartz, Lead-Zirconate-Titanate etc. The piezoelectric resonators works on electromechanical coupling of piezoelectric material. The resonator is actuated by applying alternating voltage to the piezoelectric material placed on the resonator. Even though the electrostatically actuated MEMS resonator are most widely used, their power handling capability is low because of small size and nonlinear effects in the material properties[4]. Compared to electrostatically actuated resonators, the piezoelectric actuated MEMS resonator show better power handling capabilities and provides more linear transduction. Piezoelectric transduction also has the advantage of lower impedance. The piezoelectrically actuated resonators does not require any bias voltage as in case of electrostatically actuated resonators. They also not require any electrode gap. The major drawback of this technique is that most of the piezoelectric materials are not compatible with CMOS technology.

Thermal Actuation: Although electrostatic and piezoelectric actuation are the most commonly used transduction principles, both of the techniques suffer from some limitations. The piezoelectric actuation requires usage of piezoelectric substrate or deposition of piezoelectric thin films. The electrostatic actuation requires the presence of air gap between the structure and the electrodes which may lead to squeezed film damping. The thermal actuation principle is another commonly used actuation mechanism for microscale devices[5] . In thermally actuated resonators heat pads are used on the two sides of the mechanical structure. A combination of AC and DC current passed through the heat pads results in the fluctuating ohmic loses in the structure. Most of the heat is generated in the thin pillers in the middle of the structure. The fluctuating heating power actuates the resonators[6].

Magnetic Actuation: This is contactless technique used for actuation of resonator. A magnetic field is generated around the mechanical structure and an alternating current is made to flow through the structure. The interaction of the magnetic field with eddy current drives the mechanical structure into resonance. The major drawback of this technique is that large magnetic fields are required[7].

B. Resonator Modes

Resonance occurs due to the formation of standing waves in the mechanical structure. The standing waves can be formed in several ways and hence there will be multiple resonances at different frequencies. These are known as modes of resonator. Based on the mode of operation the resonator can be classified as:

- Flexural mode resonator: This mode represents the formation of transverse standing waves. The dominant stress is the bending stress. The structure vibrates orthogonal to the bending stress. Flexural mode resonators are suitable for low frequency operations. Flexural mode resonators have higher surface to volume ratio and hence are more prone to losses from surface effects.[1]
- Bulk mode resonator: This mode represents formation of longitudinal standing waves. Bulk mode of operation is preferred for high frequency and high Q operations because of their larger structural stiffness.
- Torsional mode resonator: This mode is representation of sheer stress. The displacement produced is rotational in nature. These resonator exhibit lower anchor loses and lower squeeze film damping and hence have a very high Q factor. Panasonic and imec have recently presented a innovative SiGe packaged SOI based MEMS resonator featuring an industry record Q factor of 2,20,000 and a low bias voltage [14].

C. Resonator Parameters

Some of the parameters used for characterization of MEMS resonator are described below.

Resonance frequency: The frequency at which the resonator oscillates with maximum amplitude is known as resonance frequency. The resonance frequency w in terms of mass and the spring constant of the resonator is given by equation (1).

$$w = \sqrt{\frac{k}{m}} \tag{1}$$

where k is the spring constant and m is the mass of the beam.

Quality factor: Another important parameter used to characterize the MEMS resonator is the quality factor Q. The quality factor Q of a resonator is defined as the ratio of stored energy to the dissipated energy in one cycle as given in equation (2). It is a dimensionless number that characterizes the quality of the resonator [3].

$$Q = 2\pi \times \frac{Maximum\ instantaneous\ energy\ stored\ in\ circuit}{energy\ dissipated\ per\ cycle} \tag{2}$$

Frequency Tuning: The frequency tuning is defined as the relative change in the resonance frequency with changes in the applied DC bias voltage. The applied DC bias can reduce the natural frequency of the resonator because of the reduction in the stiffness of the structure.

The effect is known as spring softening. The relation between the applied DC voltage and the natural frequency of the resonator is given by (3).The frequency tuning depends upon the gap between the resonator and the actuation/sensing electrode[8]

$$f_r = f_o \left[1 - \frac{1}{k}\frac{C_o}{d^2}V_{DC}^2\right] \tag{3}$$

where f_r is the resonance frequency, f_o is the natural frequency, k is the elastic constant, C_o is the capacitance when the beam is stationary and V_{DC} is the DC bias voltage. Based on this relation (3), the frequency tuning FT is defined in (4).

$$FT = -\frac{\varepsilon A}{d^3}\frac{1}{k} \tag{4}$$

Motional resistance: Motional resistance refers to the impedance of the resonator. Some time it is also referred as series resistance. The motional resistance depends upon factors such as air gap between the resonator and electrodes, the coupling area, the DC bias voltage and k value. This parameter is of prime importance in RF applications where impedance matching as low as 50Ω is required. Equation (5) gives the motional resistance of capacitively transduced MEMS resonator [32].

$$R = \frac{k\, d^4}{w_n Q V^2 \varepsilon^2 A^2} \tag{5}$$

where k is spring constant, d is the electrode to resonator gap, w_n is the resonance frequency, Q is the quality factor, V represents the bias voltage, ε is the permittivity and A represents the overlap area. A lower motional resistance can be achieved by reducing the gap between the resonator and the electrodes and by having large resonator structures which increases the coupling area. However, there is a limitation imposed by the fabrication process on the gap between resonator and electrodes. Also by increasing the resonator dimension, the resonator becomes more susceptible to collapse.

Collapsing Voltage: This is an important parameter for in-plane resonator with electrostatic excitation. The parameter describes the sticking effect where the mechanical structure sticks to the electrode or substrate. The collapsing voltage is defined as the maximum voltage that can be applied to the resonator to prevent vertical sticking of movable structure. The collapsing voltage is given by equation (6) [33].

$$V_c = \sqrt{\frac{nEt^3d^3}{\varepsilon L^4}} \tag{6}$$

where E is the Young's modulus, t is the thickness of the structure, d is the distance between substrate and the structure, L is the length of the structure and n is the constant that depends on the structure of the resonator.

D. Resonator Modeling

Mechanical Modeling: Irrespective of the structure, the resonator can be mechanically modeled using a mass, spring and damper system. as shown in Fig. 3.

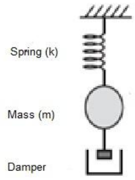


Fig. 3. Mechanical Model of MEMS Resonator

If the mass is subjected to an external force, it oscillates. If the mass is driven at its natural frequency, it vibrates with larger amplitude of displacement. The resonant frequency of the system in terms of spring constant k and mass m is given by equation (7).

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{7}$$

When the system is driven at a frequency above or below the resonant frequency, the amplitude of displacement is smaller. Resonators with higher Q have larger response when driven at resonant frequency. From the equation of resonant frequency, it is obvious that reduction in size which in turn results in the reduction of mass and stiffening of spring leads to increase in the resonant frequency[10].

Electrical Modeling: Traditionally the resonators are electrically modeled using Butterworth- Van Dyke model as shown in Fig 4. The electrical equivalent of the resonator can be represented using a RLC circuit. The resonance behavior of the resonator is modeled by the electrical resonance arising from L_X and C_X . The energy dissipation occurring in the structure through various means is modeled by the electrical dissipation through R_S. C_o represents the feed through capacitance between two terminals and C_{L1} and C_{L2} represents the capacitance between each contact to ground[13].

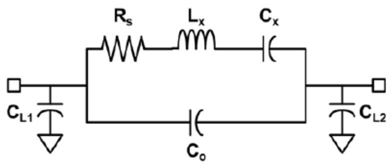


Fig. 4. Butterworth Van Duke Model for Electromechanical Resonator.

Each resonance mode is associated with two types of resonances namely, series resonance and parallel resonance. When series resonance occurs, the device impedance reaches local minimum and hence the current through the device reaches local maximum. During parallel resonance, the device impedance reaches local maximum and hence the current through the device reaches local minimum. Series resonance occurs at a lower frequency than the parallel resonance. The series resonance f_S and parallel resonance f_P are given by equation (8) and (9).

$$f_s = \frac{1}{2\pi}\sqrt{\frac{1}{L_x C_x}} \tag{8}$$

$$f_p = \frac{1}{2\pi}\sqrt{\frac{1}{L_x \frac{C_x C_o}{C_x + C_o}}} \tag{9}$$

III. LITERATURE REVIEW

The first published work on MEMS resonator in 1967 was "Resonant gate transistor" [15]. The literature demonstrates a surface micro machined cantilever beam used as a resonator. The beam was a gold beam of 0.1mm length and 5-10µm thickness. The beam resonated at 5KHz with a quality factor of 500. Since then several versions of MEMS resonators and their applications have been reported. Most of them being capacitively or piezoelectrically transduced. Below is the list of some of the reported MEMS resonators.

One of the earliest resonator structure and most commonly used in MEMS device is the laterally vibrating interdigitated finger comb-drive structure. The structure was developed at University of California, Berkeley, California [16]. In [17] a polycrystalline silicon comb-drive resonator with beam of thickness 2µm, width 2µm and length 185µm is reported. The effective mass of the structure is 5.7×10^{-11} kg and the spring constant is 0.65N/m and the structure exhibits resonant frequency of 17KHz. The resonator has a very high quality factor of nearly 50,000 when operated in vacuum, but the quality factor reduces drastically to 50 when operated in atmospheric conditions. The comb drive structures exhibit large masses and have relatively low spring constants. This limits the resonant frequencies of these structures below 500KHz. Hence the comb-drive structures are suitable for low frequency applications.

The next generation of resonators where based on clamped-clamped beam structure. The idea here was to increase the resonant frequency while maintaining a reasonable Q factor of above 1000. The structure comprises of a beam rigidly clamped at both the ends and is driven electrostatically by an electrode placed beneath the beam. In [18] an IC compatible microelectromechanical IF bandpass filter which uses two clamped-clamped beam micromechanical resonators coupled by soft mechanical springs is reported. The bandpass filter was centered at 8.37MHz with a voltage tunable bandwidth. The resonator beams were made of polycrystalline silicon and polysilicon strips underlying each of the resonator served as electrodes. The geometry of the resonators determines the center frequency of the mechanical bandpass filter and the coupling springs determine the bandwidth.

The large stiffness of clamped-clamped beam results in increased anchor dissipation which in turn results in lower Q. The problem is addressed in [19] where a VHF free-free beam high Q micromechanical resonator is demonstrated. The basic flexural mode beam design of the clamped-clamped resonator was retained, however, the anchors where strategically eliminated from the design. This lead to the elimination of anchor associated loses. The free-free-beam are demonstrated with a center frequency of 30MHz to 90MHz and Q's as high as 8400. In [20] an oscillator circuit using clamped-clamped micromechanical resonator is demonstrated. The work describes how the motional resistance of the micromechanical resonator affects the design of the oscillator.

Paper [21] reports how a laterally vibrating free-free beam micromechanical resonator overcomes the limitations associated with vertically vibrating resonators. Also the effect of supports on the Q of the resonator is discussed. Some of the limitations of vertical mode operation listed here are topography induced frequency uncertainty, high energy dissipation through the supporting anchors resulting in lower Q, geometrical inflexibility imposed by vertical mode operation. The laterally vibrating free-free beam resonator overcame these limitations. Based on this two such resonators for resonance frequency of 10MHz and 20MHz where designed and fabricated. The experimental analyses of the resonator shows a resonance frequency of 10.47MHz and 19.553MHz and Q of 10,741 and 7,306 which is significantly higher than the clamped-clamped beam resonator.

The effect of Q and power handling capacity of a resonator on the oscillator performance is discussed in [22]. The three resonators tested for are capacitively transduced 10MHz clamped-clamped beam similar to that used in [20], a clamped-clamped beam with 5 times wider width and a 60MHz wine glass disk resonator. The comparison of the two 10MHZ clamped-clamped resonator with different width shows that as the width of the beam increases, the motional resistance decreases and the power handling capacity increases. Increasing the width results in increased stiffness of the clamped-clamped beam which in turn lowers the effective Q. So a tradeoff exists between Q and motional resistance. The resonance frequency of clamped-clamped beam is practically limited to 30MHz beyond which the Q reduces drastically. Higher resonant frequency and higher Q can be achieved by the micromechanical resonators having disk shapes. Also because of higher stiffness the power handling capacity of the disk resonator will be higher than the clamped-clamped resonator.

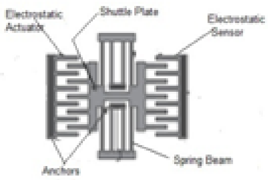
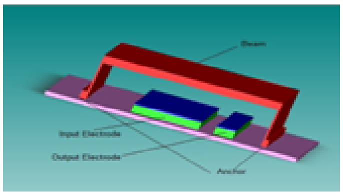
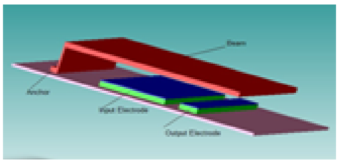
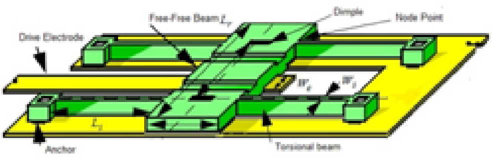
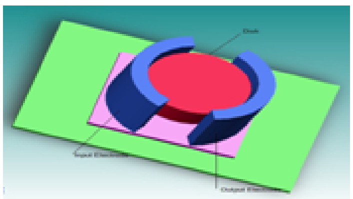
Paper [23] reports self-aligned vibrating radial-mode disk resonator with a record resonance frequency of frequency of 1.14GHz. This was the highest resonance frequency recorded so far with a Q exceeding 1,500. The disk with self aligned stem allows superior balancing which in turn results in high Q at GHz frequency not only in vacuum but also in air. The literature also reports 733MHz resonator with a Q of 7330 and 6100 in vacuum and air respectively. In [24] a hollow disk ring resonator is demonstrated. A radial ring resonator is demonstrated in the work that utilizes a centralized support structure and notching at the support attachment that greatly reduces support loses. Using the design a polysilicon resonator with resonance frequency greater than 1GHz and Q exceeding 10,000 is demonstrated.. Electrodes are used both inside and outside the disk ring structure which allows for larger electrode overlap area. This not only results in higher Q but also provides very low impedances as 282KΩ which is 12 times lower than that of disk resonator of [23].

The RF applications which require frequencies in the UHF range needs resonator of smaller size and higher stiffness so as to achieve large Q. But as the size of the resonator is reduced, the power handling capacity also decreases. Paper [27] presents a radial-contour mode disk resonator which can attain very high resonance frequency and still can retain relatively larger dimensions. The designed resonator has fundamental frequency of 433MHz with Q exceeding 4000. Also the resonator when operated in second and third modes yields high frequency as high as 829MHz.. Such designs will allow the resonator to be used in UHF range and also provide potential for lower power consumption.

Paper [28] reports a metal micro electromechanical resonator having resonance frequency of nearly 60MHz and Q of 54,507. The literature demonstrates the usage of nickel as a high Q structural material for RF MEMS. A wine-glass disk structure of nickel is surrounded by two pairs of electrodes is used. As the radius of the supporting anchor is reduced a dramatic increase in Q is found. An anchor less disk resonator design which is supported by the solid filled in the gap between disk and the electrodes has shown a Q as high as 54,507.

In [29] a torsional mode silicon triangular beam resonator is demonstrated having a resonance frequency of 20MHz and a high Q of around 2,20,000. The reported resonator uses a very low bias voltage of 1V and shows a motional resistance of 11.9KΩ. The resonator shows a very high Q because of the torsional mode of vibration which has very low anchor loss and lower squeeze film damping compared to flexural mode of vibration. Such high Q resonator can provide higher frequency accuracy and consume very low power. Table 1 lists some of the reported MEMS resonators

Table. 1: List of some reported MEMS Resonator

Type	Schematic	Features
Comb-drive resonator	 Fig. 5. Comb-Drive Resonator[10][25]	• Structure was developed at University of California, Berkeley, California • Comprises of laterally vibrating interdigitated finger comb-drive structure • Structure exhibits large mass and relatively low spring constant • Suitable for low frequency below 500KHz application. • A quality factor as high as 50,000 is reported for the comb-drive structure[25].
Clamped-Clamped beam resonator	 Fig. 6. Clamped-Clamped Beam Resonator[18]	• Structure comprises of a beam rigidly clamped at both the ends • Can be used in flexural as well as lateral mode • Can provide high resonance frequency. • These structures suffer from anchor loss which puts limitation on achievable Q. • A resonance frequency as high as 9.34MHz with Q of 3100 has been reported[22].
Cantilever beam resonator	 Fig. 7. Cantilever Beam Resonator[9]	• The structure comprises of a beam rigidly clamped at one end, while the other end is free. • Simple to design and most widely used structure in MEMS field. • A cantilever beam with resonance frequency of 960KHz is reported [9].
Free-Free beam resonator	 Fig. 8. Free-Free Beam resonator[19]	• The structure comprises of beam supported at flexural nodal point by the quarter wavelength torsional beams. • Since the anchors are strategically eliminated, the structures can achieve high quality factor • Resonance frequency from 30 to 90MHz with Q as high as 8000 have been reported for these structures
Disk Resonator	 Fig. 9. Disk Resonator[23]	• The structure comprises of a circular disk, supported at center by a stem. • The structure operates in two modes namely, radial mode and wine-glass mode. • The structure exhibits high motional resistance. • Resonance frequency of 193MHz with Q as high as 8800 has been reported[23].

A. Commercally Available MEMS Resonators

Discera in 2003 came up with the first MEMS oscillator MRO-100. It was a 19.2 MHz oscillator and was intended for multiband wireless application. The oscillator comprised of 30µm X 8 μm^2 MEMS beam as the resonator. Discere also demonstrated a 1.2GHz tunable oscillator based on MEMS resonators[30].

SiTime was established in the year 2004 with a mission to incorporate MEMS timing reference devices inside standard silicon electronic chips and thus eliminate the need for quartz crystals. The first range of products introduced by SiTime was SiT8002 series programmable oscillators and SiT1 series of fixed frequency oscillators. These oscillator series used a 4-beam MEMS resonator. The SiTime also offers a MEMS resonator SiT0100 which operates as 5.1MHz as a separate part. The SiTime MEMS resonator are available in the form of die which can be easily embedded with other die inside a plastic semiconductor package [31].

In year 2010 Panasonic Imec presented a SiGe thin film packaged MEMS resonator at international electron devices meeting in San Fransisco featuring industry standard Q factor of 2,20,000 with low bias voltage. The resonator operates in torsional mode and is vacuum encapsulated in a thin film package which results in lower squeeze film damping.

IV. ISSUES IDENTIFIED

The key issues in the design and development of MEMS resonator in the field of RF communication are attainable resonant frequency, quality factor, thermal stability and motional impedance.

With the advancement in wireless technology, the need for resonators that work in the higher VHF and UHF range is growing. Many of the application today require frequency references in GHz range. Thus designing resonators with resonance frequency in GHz range is the need of hour. The resonance frequency is the function of material properties and geometry of the resonator. Another most important performance parameter of the resonator is the quality factor Q. The quality factor is the dimensionless number that characterizes the energy storing capability of the resonator. Q factor describes the mechanical energy damping. Higher the Q, better is the resonator. High Q provides higher signal to noise ratio, higher resolution and low power consumption. Factors that influence the quality factor are thermo elastic damping, squeezed film damping, air damping and anchor losses. Thermo elastic damping is a type of intrinsic loss and depends on the type of the material. Air damping refers the loss of energy to the gas molecules surrounding the resonator structure and is a major source of loss. The third major source of loss is the anchor loss also known as clamping loss. This is the most dominant loss for low frequency resonators and depicts the energy dissipation to the substrate through the anchor. Anchor loss is design dependent and can be minimized by appropriate selection of the stem design that connects the vibrating mechanical structure to the anchor. An optimized stem structure can significantly reduce the energy dissipation to the substrate and thereby can provide a better quality factor.

The frequency-quality factor product of the resonator is considered as the prime performance criteria. The requirement today is the resonators with frequency in VHF and UHF range and very high quality factor. The resonance frequency is inversely proportional to the mass of the resonator. In order to achieve higher resonance frequency we need to scale down the resonator dimension so that the resonator has smaller mass. But this decreases the power handling capability of the resonator. The quality factor also decreases.

The Motional impedance of the resonator is another important performance measure for MEMS resonator, particularly in the field of RF MEMS. The parameter is of prime importance for resonators used in oscillator and filters of RF communication where impedance as low as 50Ω is required. The motional impedance governs the relation between the input voltage and output current at resonance. The motional resistance also depicts the power handling capability of the resonator. The motional impedance depends on electrode to resonator gap, resonance frequency, the quality factor, the bias voltage and the overlap area. Motional resistance can be reduced by increasing the bias voltage and reducing the electrode to resonator gap. There is a limit on reducing the gap between the electrode and resonator as it decides the maximum displacement amplitude which in turn decides the maximum carrier amplitude. Another way of reducing the motional resistance is by increasing the overlap area between the resonator and electrode. This can be achieved by having wider resonator structure. But wider structure results in increased stiffness, which in turn reduces the quality factor Q. So a tradeoff exists between the motional resistance and the quality [20][22][35].

The thermal stability of the resonator defines the shift in the resonance frequency with changes in temperature. This drift in the frequency is due to the dependence of the Young's modulus of material used for the resonator structure on the temperature. Frequency drift in typical silicon MEMS resonator is of the order of 10 ppm/^{o}C to 20 ppm/^{o}C. Several techniques have been reported for providing the temperature compensation.

One of them is to make the resonant frequency dependent on the bias voltage, so that any temperature dependent drift in the frequency can be compensated for by adjusting the bias voltage[37]. Another way to minimize frequency drift is to operate the resonator in a temperature controlled environment. The challenge here will be to provide an optimum temperature control with quick settling time[38].

A. Objectives Derived

Some of the objectives derived from the issues identified are listed here:

- Resonator topologies that have resonance frequency in UHF range and which can provide high quality factor are required.
- Scaling down the dimensions of the resonator can increase the resonance frequency. There are certain limitations imposed by the fabrication technology on the scaling of the device. Also scaling down can affect the power handling capability of the resonator and hence can have an adverse effect on quality factor. An investigation on factors that influence the quality factor and resonance frequency is essential to evolve a resonator topology that can provide high resonance frequency and quality factor product.
- There exist a trade-off between the quality factor and the motional resistance of the resonator. An optimized design of resonator that significantly reduces motional resistance by giving up as much small as possible quality factor is essential.
- To make the MEMS resonators suitable for RF applications another important factor to be considered is their thermal stability. An investigation of temperature compensation techniques that can provide long term thermal stability is required

V. APPLICATIONS OF MEMS RESONATORS

MEMS resonators have found applications in several diverse fields like mass sensing, bio-chemical sensing, motion sensing, communication etc. This section presents some selected applications of MEMS resonator.

A. MEMS Resonators for Bio-Chemical and Mass Sensing :

The resonance frequency dependence of the resonator on the mass of the structure makes the resonators suitable for mass sensing applications particularly in bio-chemical field. Exposure of the resonator to an environment consisting some bio-chemical species can make the the species get attached(absorbed or adsorbed) to the resonator. This in turn results in change in the spring constant and mass of the structure, which ultimately causes a shift in the resonant frequency of the resonator. The shift in the resonant frequency will be proportional to the mass of the attached species and hence can be used to determine the mass of the species [33][34].

In [33] a MEMS resonator based mass sensor to measure the mass changes of evaporating micro droplets is presented. The resonator based sensor has uniform mass sensitivity and uses electromagnetic actuation and laser detection.

B. MEMS Resonators for Motion Sensing :

The most common application of MEMS resonators in the field of motion sensing can be found in gyroscopes used for measuring or maintaining the orientation based on the principle of angular momentum. The gyroscopes have a wide applications in the field of avionics, automotive, handheld consumer appliances, industrial robotics etc.The resonators of different shapes are used in a class of gyroscopes known as Coriolis Vibratory Gyroscope. The basic principle used here is that a vibrating structure will tend to vibrate in the same plane even when its supports rotate. In [36] a laterally driven symmetric microresonator with self tuning capability is presented. The resonator structures which are inherently symmetric such as disks and hemispheres are preferred choices for gyroscopic applications. Another most widely used application of MEMS resonator is in accelerometers.

C. MEMS Resonators Based Oscillators :

One of the most exciting application of the MEMS resonator is that they act as time-base generators in MEMS based oscillators. The MEMS resonators can be easily integrated with the supporting electronic circuitry and PLL on the same silicon substrate to act as an oscillator.Paper [25] reports 32KHz MEMS based oscillator for low power applications which uses a comb drive flexural mode resonator of single crystal silicon with 500 fingers of finger length 10µm and finger overlap of 4µm. The resonant frequency was 32KHz and the resonator demonstrated a quality factor of 50000. The described oscillator operates over a wide range of operating voltage of 1.5V to 3.6V and temperature of -40 to 125^{o}C. The power consumption of the oscillator is less than 1µW similar to quartz crystal based oscillator. In [26] a first ever fully differential RF MEMS resonator made of silicon carbide is reported. The resonant frequency was 173MHz and the resonator demonstrated a quality factor of 9300.

VI. CONCLUSION

The MEMS resonators have high potential of replacing conventional frequency reference devices like quartz crystal and SAW resonators. Particularly in wireless applications, where miniaturization and portability are two essential requirements, the MEMS resonators can play a major role as frequency references. The need of the hour is to achieve frequencies in UHF range and high quality factor. Research is required in this regard to design and develop MEMS resonators having high resonance frequency and quality factor product.

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