Vibrating RF MEMS for Timing and Frequency References

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Abstract — This paper presents recent progresses on making vibrating RF MEMS oscillators for timing and frequency reference applications. Starting from the performance requirements of an oscillator in various systems, the key aspects of MEMS oscillators, including resonator design, oscillator performances, temperature compensation, packaging and integrations, are reviewed. Future directions of the research are listed at the end of the paper.

Index Terms — RF MEMS, micromechanical resonators, oscillators.

I. INTRODUCTION

Over the past several years, researchers have been using Microelectromechanical Systems (MEMS) technologies to develop miniaturized, integratable, high quality factor ($Q$) frequency selection devices to replace those currently large, off-chip, and CMOS incompatible components in wireless communication systems or consumer electronic systems. Among these MEMS devices, vibrating MEMS oscillators are generating a wave of impacts on the oscillator markets due to their advantages of small size, easy integration with circuits, and low cost of manufacturing. Although vibrating MEMS oscillator research seems to be more of a commercial activity right now, there are still many remaining issues to be solved.

This paper starts with the reviews on vibrating RF MEMS with the focus on various resonator designs for applications at different frequencies. After resonator, some start-of-art research results on MEMS oscillator will be presented in section III from the angles of phase noise performance, temperature compensation, packaging and integration, and finally aging reliability. From all the above aspects, the MEMS oscillators no doubt show promising future in multiple large volume applications. Moreover, in order to permeate MEMS oscillators into all the applications, future research directions are provided in the last section.

II. VIBRATING RF MEMS

Vibrating RF MEMS can be defined as a micromachined mechanical structure that vibrates at its natural resonance frequency due to external excitations. One mechanical structure could be excited into different vibration modes at different frequencies. The external excitations of micromechanical resonators could be electro- static, piezoelectric, laser, mechanical vibrations, and magnetic field. But regardless the resonators and the excitations mechanism, for oscillator applications, the resonator should be excited to a specific mode with highest quality factor, lowest motional impedance, and highest power before resonator peaks go to non-linear region.

Table I shows variety of micromechanical resonators that can be used for oscillators ranging from low kHz to GHz in frequency. As shown, folded-beam comb-drive resonators that resonate at 32.768kHz can be used for real-time clock (RTC) in electronic systems or in a watch. The challenges to make commercial grade kHz oscillators are low voltage for electrostatic transducer bias, and low current for the oscillator circuits. The state-of-art RTC oscillator is presented in [1], where the resonator can be operated at 1.5V and the IC only consumes less than 1µA of current.

The folded beam comb-drive resonator structure may not be scaled to achieve tens of MHz in frequency due to its large mass. Instead, as shown in Table I, a simple flexural clamped-clamped beam exhibited good $Q$ as high as 8,000 at 9.8MHz [2]. However, while the clamped-clamped beam is scaled to higher frequency such as 50MHz, its $Q$ degraded to less than 500 due to anchor dissipation. As a result, another type of flexural beam with free-free boundary condition was designed to minimize the energy lost through the supporting structures, four support beams with quarter wavelength in this case. The free-free beam resonators showed $Q$ as high as 7.4k at 92MHz.

Other than flexural type of resonator, bulk acoustic mode resonators came into play after researchers figured out a process to form a lateral nanometer gap between electrodes and resonators for efficient electrostatic actuations [3]. The resonators include disk resonator operating in radial mode [4], wine-glass mode [5] and the square resonator in extensional mode [6]. Wineglass mode resonator has demonstrated quality factor as high as 98k in vacuum, and 70k in air, which is very good for oscillator applications.

Both of surfaced micromachined AlN resonators [7] and AlN based FBAR resonators also show good potential on oscillator applications [8] [9]. Compared to silicon resonators, the AlN resonators are in relatively early stage for oscillator applications.
In this section, oscillators with different types of MEMS resonators are compared in terms of key aspects. The aspects include phase noise, temperature compensation, packaging and integration, and aging reliability.

### A. Phase Noise

Both flexural clamped-clamped beams and free-free beams have been demonstrated for low phase noise oscillators [10][11]. An oscillator with a widened clamp-clamped beam resonator showed $-95\text{dBc/Hz}$ at $1\text{kHz}$ away from $10\text{MHz}$ oscillator carrier. On the other hand, an oscillator with a free-free beam resonator has shown $-117\text{dBc/Hz}$ phase noise at $1\text{kHz}$ away from $70\text{MHz}$ carrier, which is equal to $-132\text{dBc/Hz}$ if we convert the carrier to $13\text{MHz}$ GSM reference frequency.

![Image of MEMS resonator](image)

<table>
<thead>
<tr>
<th>Resonator Structure</th>
<th>Freq. Range</th>
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<tr>
<td>Comb-drive</td>
<td>1kHz to 1MHz</td>
<td>Real Time Clock</td>
<td>Res: $Q\approx80k$ $TCF\approx2.5\text{ppm/°C}$ [1] Osc: 32kHz [1], 78kHz Ni osc, 1M poly-Si osc. Pkg: Wafer-level vacuum</td>
<td>Temp. Stability Cost of vacuum pkg. Cost of trimming</td>
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<td>CC-beam</td>
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<tr>
<td>FF-beam</td>
<td>10MHz to 100MHz</td>
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<td>Res: $Q&gt;10k$ for $f&lt;100\text{MHz}$. Osc: 70MHz, met GSM P.N. spec. [11] Pkg: Wafer-level vacuum</td>
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<td>Motional impedance Temp. Stability Aging Cost of trimming</td>
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<td>100MHz to 5GHz</td>
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<td>Res: $Q\approx2k$ from 200MHz to 656MHz with low impedance [8]. Low temp process → can be fabricated on IC</td>
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<td>Res: $Q\approx2k$ @ 1.9GHz [9] Osc: 1,978GHz, P.N. −112dBc/Hz, 10kHz away from carrier</td>
<td>Temp. Stability Aging Cost of trimming</td>
</tr>
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</table>
Temperature compensation by trading off phase noise to consumption by trading off phase noise to 1.9GHz CMOS FBAR oscillator showed only 300 µ−oscillator with an FBAR resonator exhibits phase noise of potential for oscillator applications. A 1.985GHz bipolar requires 80V of bias voltage to reach this performance [6].

13MHz oscillator carrier. However, due to the process limit, it requires 80V of bias voltage to reach this performance [9].

AlN film bulk acoustic resonators (FBAR) also showed the potential for oscillator applications. A 1.985GHz bipolar oscillator with an FBAR resonator exhibits phase noise of −112dBc/Hz 10kHz away from the carrier [8]. Meanwhile, a 1.9GHz CMOS FBAR oscillator showed only 300uW power consumption by trading off phase noise to −100dBc/Hz, 10kHz away from the carrier [9].

B. Temperature Compensation

Silicon based micromechanical resonators exhibit temperature coefficient of frequency (TC) around −20ppm/C due to the temperature dependence of Young’s modulus of the resonator material. The TC is however very linear across wide temperature from −196°C to +150°C. On the other hand, AlN based resonator showed TC of −40ppm/C. Compared these TC’ s to that of the quartz crystals, as shown in Figure 1, temperature compensation is required for vibrating MEMS resonators in oscillator applications.

The basic frequency equation resonator can be expressed as

\[ f = \sqrt{\frac{k_m - k_e}{m}} = \sqrt{\frac{k_m - (V_p^2 \epsilon_o A / d_o^3)}{m}} \] (1)

where \( f \) is the resonator frequency, \( k_m \) and \( m \) are the mechanical spring constant and mass of the resonator, respectively; \( k_e \) is the electric spring constant that is related to the interaction of the electric field between resonator and drive electrode and the resonator movement; \( A \) is the electrode area and \( d_o \) is the air gap between the electrode and the resonator. \( k_m \) is a function of temperature. The TC of the clamped-clamped beam resonator can be expressed as

\[ TC_f = \frac{\alpha_e - \alpha_{material}}{2} \] (2)

where \( \alpha_e \) and \( \alpha_{material} \) are the temperature coefficient of Young’s modulus and the thermal expansion coefficient of the resonator material, respectively.

Researchers have demonstrated reduced TC’s of micromechanical resonators by making the parameters in equation (1) temperature dependent in order to counter act the negative TC, of the resonator. A very obvious approach is to apply a temperature dependent tensile stress on the resonator beam to counteract on the negative TC, of the resonator [14][15]. As a result, the TC’s of the resonators showed 7x reduction.

Another approach is to create a temperature dependent \( k_e \) to compensate the frequency. From equation (1), a temperature dependent \( V_p \) can be created through IC circuits, but this approach increases the variation of motional resistance \( R \), across the temperature so the open loop gain of the oscillator needs to be adjusted based on the temperature. Also if one electrode is constructed by a material that has a different thermal expansion coefficient, a temperature dependent \( d_o \) can be created to change the \( k_e \) [16]. This approach exhibited −0.24ppm/C on 10MHz clamped-clamped beam resonators. However, when the resonator frequency moves to higher range, the km becomes a lot larger than \( k_e \). Therefore, using the effect of \( k_e \) to compensate \( k_m \) may not be practical.

Both of the \( k_m \) and \( k_e \) temperature compensation may suffer manufacturing variations. Recent approach is to use fractional-N synthesizer and an on-chip temperature sensor to correct the frequency variation of MEMS reference oscillator [17]. The oscillator shows overall 8ppm frequency variation from −40°C to 85°C. In this case, although the phase noise is now dominated by VCO phase noise so the oscillator may not suitable for RF applications, the oscillator shown in this paper meets most the jitter requirements of clock oscillators.

Temperature compensation on micromachined AlN resonators has not been seen in publications. However, the efforts of compensating the FBAR oscillators are actively ongoing [18].

C. Package and Integration

Since the size of the resonator is as small as 100µm by 100µm, the resonator frequency and quality factor is impacted
by the vacuum level in which the resonator is operated. Low frequency resonators in fact require higher vacuum level. As shown in Figure 2, two different resonators show different requirements for vacuum packaging. The 32kHz resonator requires close to 1mTorr of packaging while the 19MHz resonator only requires 1Torr.

The integration of vibrating MEMS and integrated circuits has been the major incentive that drives the development of the oscillators as well as other MEMS systems. With all good integration processes that have been proposed, the integration would still be the best under the following conditions: (1) the size of the MEMS matches with IC, (2) the yield is high for both MEMS and IC, and (3) the cost of implementing the MEMS is low. If the above three conditions do not apply to the oscillator design, one may just use hybrid approach from cost point of view. Current great progresses on wafer level chip scale packaging (WLCSP) have made MEMS assembly on whole IC wafers possible.

D. Aging Reliability

One of the major concerns of using any mechanical devices in a system is aging. Quartz crystal, which is one of the mechanical devices in electronic systems, had established knowledge on aging over the past 30 years. In fact, some of the techniques have been applied to the micromechanical resonators to against mechanical aging such as reliable vacuum packaging, packaging mechanical and thermal isolations. Some aging data of micromechanical resonators taken in a controlled environment has been presented. Although the resonator is not on real product format, it shows good aging around 2ppm per year. If the packaging and IC integration is designed correctly, based on the initial data taken at elevated temperature, the overall aging of the whole integrated oscillators is expected to be better than 2ppm the first year and better than 5ppm over the 10 years.

IV. CONCLUSIONS

Vibrating MEMS oscillators have demonstrated all the individual requirements for timing and frequency reference applications. However, in order to make MEMS oscillators as products in the highly competitive market, all those specifications need to be met at the same time. At this moment, given the fact that phase noise performance is traded for digital temperature compensation for MEMS oscillator, vibrating MEMS oscillators are only good for clock and timing applications, although that is a huge market. To achieve the specifications for RF application, one of the future research focuses should be on making temperature compensation without sacrificing the phase noise performance.

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REFERENCES


