Journal of Energy Challenges and Mechanics
http://www.nscj.co.uk/JECM/
PREPRINT
Volume 1 (2015) issue ?, article ?

Near-Zero Power Wake Up System Enabled by Ultra High Q-Factor Array of MEMS Resonators

Yusheng Wang and Andrei M. Shkel

MicroSystems Laboratory, University of California, Irvine, CA, 92697, USA

yushengw, andrei.shkel@uci.edu

Accepted for publication in August 2015

Abstract - **This paper discusses an approach for continuous and low-power sensing of infrequent, high consequence events. The envisioned sub-10 nW power consumption architecture includes an RF detector, an array of MEMS resonators, and an IC detector. This paper focuses on the MEMS resonator array. We show that MEMS resonators with the Quality factor on the order of 1M can solve the challenging problem of passive detection, converting the 4 µV peak-to-peak voltages from low-power RF detector to an above Brownian noise detection signal by the MEMS resonator. Wafer-scale glassblowing technology is developed, demonstrating devices with the Q-factor of 1.1M, and thus potentially meeting one of the requirements. We also discuss high aspect ratio structures with nm level electrostatic gaps, essential for an efficient capacitive transduction. We propose several design architectures, including "collapsed electrode" and "sacrificial layer" methods, all projected to provide nm-size capacitive gaps.**

Keywords - **MEMS; resonators; high Q-factor; glassblowing; wake up system.**

I. Introduction

Unattended Ground Sensors (UGS) are often deployed to detect and communicate infrequent, but time critical events [1]. The vision of UGS is to deploy many low-cost, self-powered sensors to acquire and process data automatically. In a straight forward implementation, sensors have to be actively powered with correspondingly high power consumption to monitor the events continuously. Therefore, power consumption is a critical parameter for UGS [2], especially in operations that require small batteries, low maintenance costs, and where the sensors are difficult to place or access. Therefore, many solutions, such as power-efficient detection [3], low energy signaling and networking [4] have been studied.

The core idea is to use a system capable of activating a conventional sensor, when an event of interest is detected and confirmed. In our approach, the system is based on the recent breakthrough innovations utilizing the synergistic use of resonant electrostatic MEMS structures with a unique low power RF detector architecture to passively amplify the voltage at Lower Frequency by more than 50 dB. When MEMS structures in series are added to zero bias RF detector and followed by sensitive CMOS voltage detectors, sub-10 nW power dissipation can be achieved. Resonant MEMS structure will build up the input signal level from RF detector to the minimal detectable level in under 10 seconds, such that the output signal is above the Brownian noise and is sufficient to activate the CMOS comparator to complete the detection process.

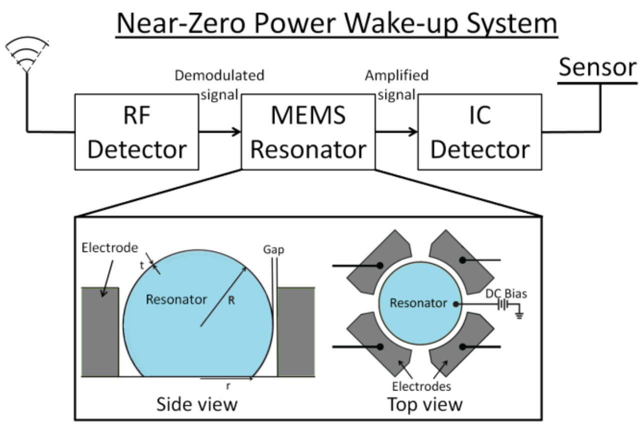

Fig. 1, System architecture a for wake-up system.

In this paper, we focus our discussion on the efficient design of MEMS resonators. The fabrication of the MEMS devices is based on the wafer-scale micro-glassblowing of low internal loss materials, such as fused silica and ultra low expansion titania silicate glass (ULE TSG) [5]. Due to an efficient design of MEMS resonators, AC voltages from RF detectors on the level of 4 µV can be passively amplified above the fundamental noise. We show that MEMS resonators with the Quality factor on the order of 1M can solve the challenging problem of detection with sub-10 nW power consumption. High-aspect-ratio structures with nm level electrostatic gaps can be used to detect the AC voltages due to larger driving force and higher sensitivity of detection.

II. Parametric Design

2.1. Linear model

For the purpose of analysis, we consider a nodal motion of a hemispherical shell resonator vibrating in n=2 mode, which can be simplified by a one degree of freedom system with an equivalent mass, stiffness, and damping coefficient (Fig. 2). Assuming the thickness of the shell is uniform, the effective mass is calculated to be above 0.191 times the total mass [6]. In the process of glassblowing, the total mass of fused silica does not change, and the mass can be estimated based on dimensions of wafers before glassblowing as

$$m_{eff} = 0.191 \times \pi r^2 t \rho, \tag{1}$$

where m_{eff} is an effective mass of the equivalent system, r is the radius of pre-etched cavity, t is the thickness of the device layer before glassblowing, and ρ is the density of fused silica (see Fig. 1). Effective stiffness can be calculated based on resonant frequency and effective mass as

$$k_{eff} = 4\pi^2 f^2 m_{eff}, \tag{2}$$

where f is the resonant frequency of the resonator in Hz. Damping coefficient can be calculated based on effective mass, stiffness, and the quality factor as

$$c = \frac{\sqrt{k_{eff} m_{eff}}}{Q}, \tag{3}$$

where Q is the quality factor of the resonator. When an excitation force is at the resonant frequency of the structure, the amplitude of the resonator will be proportional to the quality factor. If the input signal remains the same, the Q-factor becomes a mechanical amplification gain of the device.

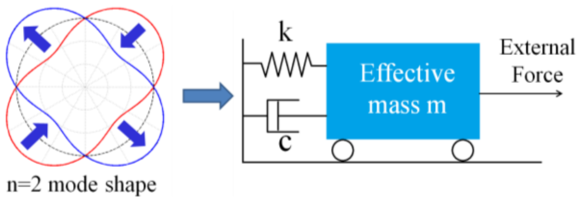

Fig. 2, Nodal motion of n=2 mode shape of a shell is approximated by a linear 1-DOF mass-spring-damper model.

However, the quality factor has to be limited to ensure that the resonator can response quickly to an input signal. Settling time of the resonator is defined by Q/f ratio, representing the time that the system needs to start from rest to reach the maximum amplitude of response. Settling time in our system is set to be 10 s.

In our simulation, the following numerical parameters were used: m = 1.25e-8 kg, k = 4.93e3 N/m, and c = 7.85e-9 N/(m/s) corresponding to the shell geometry with R = 1.12 mm, r = 0.58 mm, t = 50 um, E = 71.7 GPa, ν = 0.17, Fig. 1. Based on identified properties of test devices, these parameters correspond to the shell with the n=2 resonant frequency of f=100 kHz and the quality factor of Q=1 million. The input signal is assumed to be 4 μV peak-to-peak voltages and 10 nm electrostatic gaps. The time response of the shell is shown in Fig. 3. The results show that the amplitude of vibration reaches maximum in 10 seconds and the maximum displacement is about 3.2e-6 um.

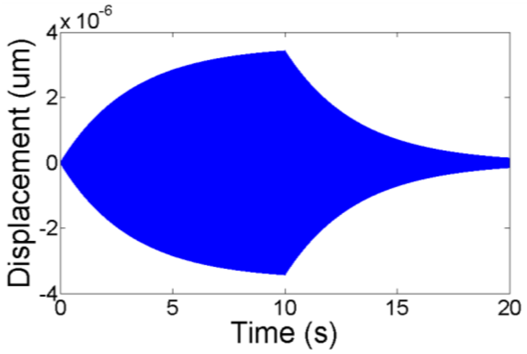

Fig. 3, Time response of the resonator, when driven at resonance, after 10 seconds of transition time.

2.2. Electrostatic gaps

There are mainly two considerations when deciding on electrostatic gaps for actuation and detection. One consideration is that the driving signal level should be higher than forcing introduced by Brownian motion. This requires the gaps for driving electrodes to be small, such that the driving force is larger than the force introduced by Brownian motion. The other consideration is that the output signal should be larger than the noise level of an IC detector. It means that the gaps for sensing electrodes should be also small to obtain a large enough motional current from the vibration.

Mechanical thermal noise, also called the Brownian motion, is evaluated by the root-mean-square of the force caused by molecular agitation

$$\sqrt{\overline{F_n^2}} = \sqrt{4ck_BT} = \sqrt{\frac{8\pi k_B T m_{eff}}{\tau}}, \tag{4}$$

where c is a damping coefficient, k_B is the Boltzmann constant, T is environmental temperature, τ is a settling time of the resonator. The driving force is created by electrostatic actuation is calculated by

$$F_e = \frac{1}{2}\varepsilon\frac{A}{h^2}V^2, \tag{5}$$

where ε is permittivity of vacuum, A is the effective area of capacitor, h is the gap of capacitor, and V is the voltage applied between electrodes and the shell. Fig. 4 presents the relationship between the electrostatic driving force and the gap for 100 kHz resonator under 4 μV peak-to-peak voltages. The blue line shows that the driving force increases with decreasing the electrostatic gaps. The red, blue, and green dashed lines are the noise levels corresponding to the quality factor of 1e5, 1e6, and 5e6, respectively. The noise level is decreased with the quality factor. However, the quality factor should not be higher than 1e6 for 100 kHz device to make sure the settling time is less than 10 s. Fig. 4 shows that 10 nm gaps can guarantee the Signal-to-Noise ratio (SNR) higher than 10. Since the shell is a linear system, the displacements caused by driving force and noise are proportional to force levels.

Motional current is the current created through sensing capacitors due to capacitance variations. It has to be large enough for an IC detector to produce the signal above the noise level, and is inversely proportional to the gap squared

$$I_m = \varepsilon U \frac{A}{h^2} x\omega, \qquad (6)$$

where U is the DC bias voltage applied to the resonator, x is the vibration amplitude, and ω is the angular frequency of vibration in [rad/sec]. If the device is driven at resonance, the amplitude of vibration will be the displacement due to static force of same value multiplied by a quality factor. Fig. 5 shows the relationship between motional current and electrode gaps. DC bias is assumed to be 3 V. It should be noticed that biasing does not drain current and therefore allowing to have a low power consumption. Fig. 5 shows that devices with 1 million quality factor and 10 nm gaps can create 3 uA motional current, when driven at resonance.

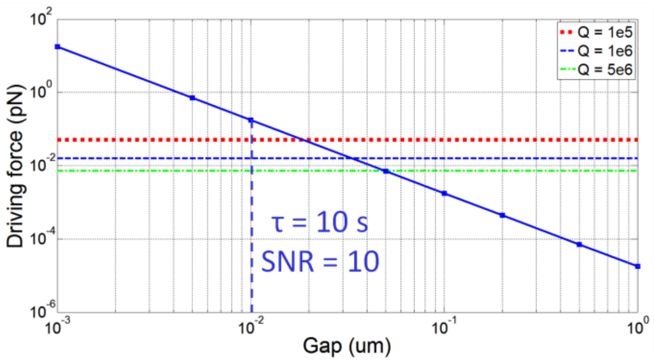

Fig. 4, Relationship between actuation force and electrostatic gaps, compared with the force caused by mechanical thermal noise.

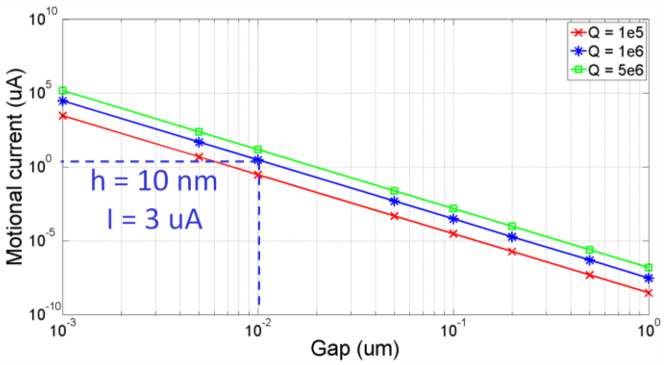

Fig. 5, Relationship between motional current and electrostatic gaps.

2.3. Weak coupling of resonators

Fabrication imperfections are inevitable and may cause a shift in resonant frequency. For high quality factor devices, a small frequency mismatch between driving signal and resonant frequency may lead to a great reduction in vibration amplitude.

Our approach to address this problem is based on a dynamic weak coupling of resonators. We use the effect of manufacturing imperfections to our advantage by fabricating an array of identical resonators [7]. Due to variations in the fabrication process, the resonators will have slightly different central frequencies, and the weak coupling will allow the peaks of the system to merge and form a broad bandwidth frequency response, illustrated in Fig. 6.

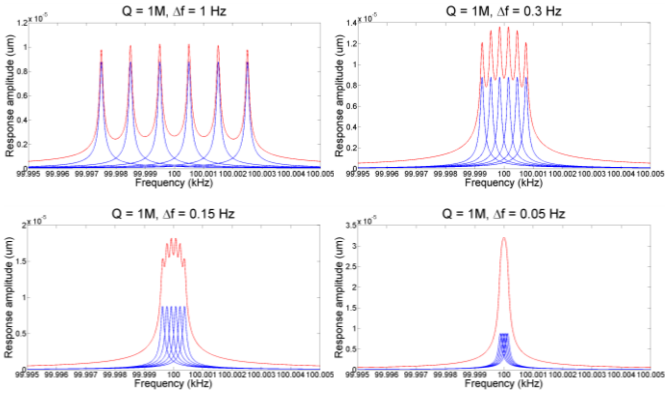

Fig. 6, The illustration of weak coupling of resonators.

Fig. 6 shows the frequency response of an array of six resonators with the same quality factor (1 million) and resonant frequencies evenly separated by 1 Hz, 0.3 Hz, 0.15 Hz, and 0.05 Hz, respectively. It illustrates that if the frequency mismatch is small enough (0.05 Hz in this case), the peaks will merge into one, which would give the largest bandwidth of the array and therefore immunity to environmental variations. The precision of glassblowing provides the required frequency separation. The weak coupling between resonators can be used to even the motion of each resonator at different driving frequencies. All individual responses would be effectively added up, producing a relatively flat peak at the resonant frequency. The quality factor of the flat region is influenced, but insignificantly, while the bandwidth is substantially increased. A conceptual illustration and an example of possible implementation are shown in Fig. 7. Illustrated is an array of resonators, excited by central electrode and detected by an outer electrode (not shown). The weak coupling between resonators is provided by the substrate and a parasitic capacitance between resonators.

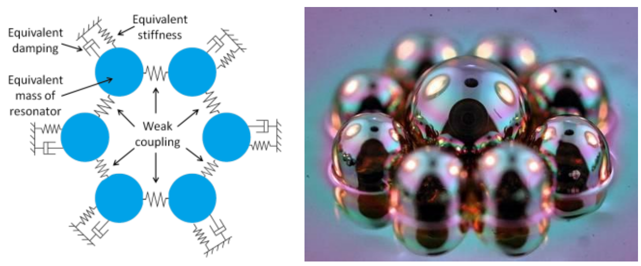

Fig. 7, A conceptual illustration of an array of resonators.

III. Fabrication Process

3.1. Micro-glassblowing

Micro-glassblowing is a fabrication process that takes advantage of a plastic deformation driven by gas pressure and surface tension forces (glassblowing), allowing to build atomically smooth, symmetric 3-D wineglass and spherical shell structures [5]. Surface tension driven glassblowing provides a better surface roughness than conventional etching-based fabrication process. During glassblowing, the viscosity of the glass decreases with increasing temperature and the pressure difference causes plastic deformation of the glass wafer. Glassblowing is also a batch fabrication process, during which arrays of glass shells can be shaped simultaneously on top of a silicon wafer [8].

The process flow for fabrication of spherical resonator with integrated electrodes is shown in Fig. 8, [9]. First, 1 mm thick silicon wafer is patterned by AZ4620 photoresist. Then, circular cavity is etched by Deep Reactive Ion Etching (DRIE). The volume of the cavity defines the dimensions, and thus resonant frequency of the spherical resonator. Glass wafer and silicon-on-insulator (SOI) wafer are anodically bonded and serve as a device layer and an electrode layer, respectively. Ambient air at atmospheric pressure is trapped in the cavity between the silicon wafer and Pyrex wafer. After the top layer of SOI wafer is patterned and etched, the whole wafer stack is submerged into hydrofluoric acid to remove exposed oxide layer in SOI wafer, defining discontinuity between two silicon parts of the SOI wafer. Then, the bottom layer of SOI is etched by DRIE using the same mask as in the previous step, so that all electrodes are electrically isolated. The glassblowing process is carried out in a high temperature furnace. The viscosity of glass decreases and the pressure of the air trapped in the cavity increases with the temperature increase, which results in deformation of the glass layer into a spherical shape. The surface tension of glass will guarantee that the surface can reach an atomic smoothness and extreme symmetry (0.23 nm Sa, [5]). The time of glassblowing process is controlled, such that the shell is allowed to touch electrodes. After glassblowing, XeF_2 etchant is used to etch the silicon electrodes to form an air gap between the shell and electrodes. Finally, Titanium is deposited by sputtering to form capacitors between the shell resonator and electrodes [9].

3.2. GAP DEFINITION

The electrostatic gaps required for a wake-up system at sub-10 nW power consumption are technologically very aggressive for most conventional micro-fabrication processes. Typical minimum features for lithography-base fabrication of MEMS are on the order of 3-5µm, while we are projecting the requirement of 0.01-0.5µm. One possible way to fabricate a gap of these dimensions is to use a "sacrificial layer" process. The thickness of a sacrificial layer can be controlled down to 10nm, which would satisfy our needs. A version of sacrificial layer method was described in [10], demonstrating a gap of 65nm on SOI wafers.

In this paper we propose to develop a new approach of "collapsed electrodes", combined with a "sacrificial layer" process. The idea is to glassblow a shell until it collapses to the high aspect ratio electrode structure coated with sacrificial layer, for example metal Titanium, thus forming a near-zero gap. Subsequently, the sacrificial layer is etched to form a narrow gap and the gap will be defined exactly the same as the thickness of the sacrificial layer.

This approach is compatible with the glassblowing fabrication flow. Metal Titanium is selected as the sacrificial layer for mainly two reasons. First, the melting temperature for Titanium is 1668 °C and it is higher than the glassblowing temperature which is about 1500 °C. Second, both dry etching and wet etching can be used to remove Titanium. Dry etching is used, so that metal on the sidewall can be protected while metal on the Pyrex is removed. Wet etching can be used to completely remove Titanium after glassblowing (Fig. 8, step h). After the Pyrex wafer is released (Fig. 8, step i), Titanium is deposited on the wafer of the desired thickness. Then, metal on the wafer is removed by DRIE, while metal on sidewalls remains. Titanium sacrificial layer is removed by hydrochloric acid (HCl) after glassblowing.

Thermal expansion mismatch is utilized to accelerate the sacrificial layer etching process. Thermal expansion coefficient of Pyrex (3.25 ppm/K) is larger than that of silicon (2.6 ppm/K). As there is a temperature drop of more than 800 °C after the glassblowing process, the Pyrex shell will contract more than silicon electrodes. The gaps due to thermal expansion mismatch will facilitate HCl solution to etch sacrificial layer and thus reduce the time needed for etching.

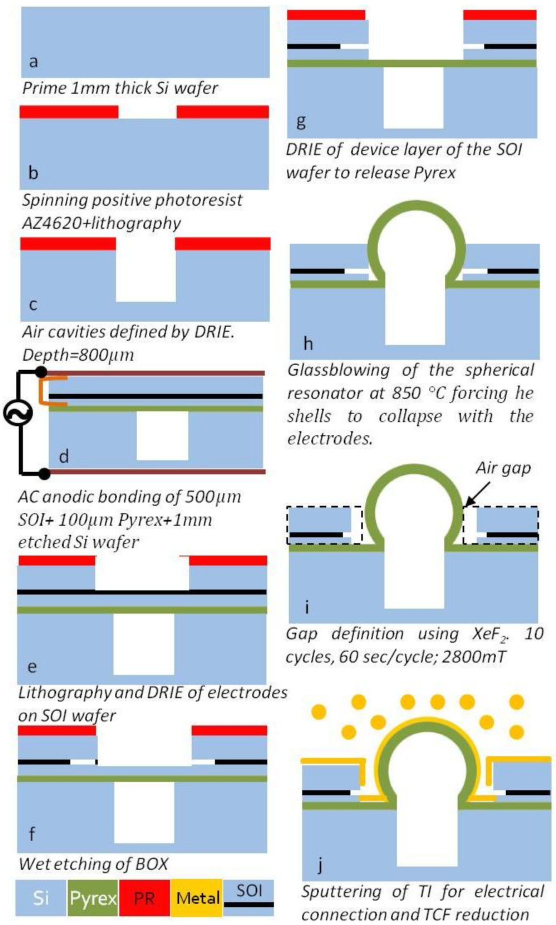

Fig.8, Fabrication flow for glassblowing. Repeated from [9]

3.3. Preliminary Results

The two key parameters of the discussed resonator are the quality factor and the electrostatic gap dimensions. Our preliminary results, [8], [9], and [11], indicate that the required parameters are achievable.

The high quality factor is required for a resonator to achieve the large gain at resonance. The quality factor of a resonator is influenced by many aspects, such as viscous damping, surface losses, anchor losses, and internal material losses. Fused silica wineglass resonators have been fabricated to minimize many of the listed energy lost factors and demonstrated the quality factor of 1.1 million. Frequency sweep of the resonator is shown in Fig. 9, [11].

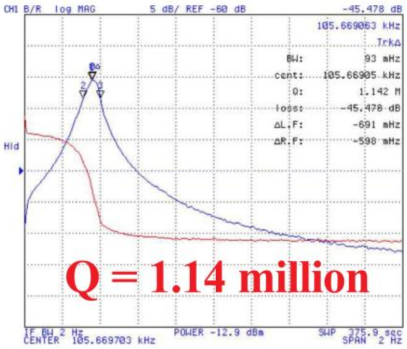

Fig.9, Frequency sweep of the resonator with 1.14 million Q factor. Repeated from [11]

Capacitive gap is another important parameter for actuation and detection of the resonator. Driving force and motional current are both inversely proportional to gap squared. Therefore, the gain of the resonator is inversely proportional to the gaps dimension to the fourth power. Collapsed electrodes method can potentially achieve sub-micron electrostatic gaps. The idea was partially demonstrated in [9], Fig. 10.

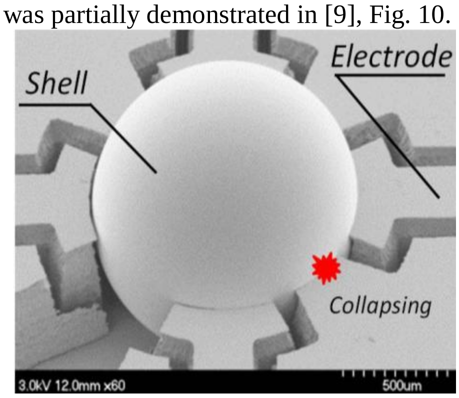

Fig. 10, Demonstration of collapsed electrodes Repeated from [9]

IV. Conclusion

In this paper, an approach to fundamentally break the paradigm of using active power to sense infrequent, high consequence events is discussed. Models are developed to illustrate the performance requirements of MEMS resonators, amplifying the low power RF detected signal to a level detectable by IC comparator. A combination of 1M quality factor resonator array, separated by 0.05 Hz and operated at the central frequency of 100 kHz, and electrostatic gap of 10 nm, enables sub-10 nW wake up system. Modeling and preliminary experimental results show that these requirements are potentially achievable.

V. Acknowledgements

Design, modeling analysis, post-processing, and characterization are performed in UCI MicroSystems Laboratory. The authors would like to thank the INRF cleanroom staff at the University of California, Irvine for their assistance in fabrication. Authors would also like to acknowledge insightful discussions with Drs. Aly Ismail, Frank Carr, and Franco De Flaviis.

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