Charge-Drift Elimination in Resonant Electrostatic MEMS

Gaurav Bahl[1], James Salvia[1], Igor Bargatin[1], Shingo Yoneoka[1], Renata Melamud[1 #], Bongsang Kim[1 *], Saurabh Chandorkar[1], Matthew A. Hopcroft[1 *], Rajendar Bahl[2], Roger T. Howe[1], and Thomas W. Kenny[1]
[1] Stanford University, California, USA
[2] Indian Institute of Technology Delhi, New Delhi, India

ABSTRACT

We present a biasing technique and a novel oscillator architecture for the elimination of frequency drifts in resonant electrostatic MEMS that are caused by the motion of charge present within dielectrics. We demonstrate more than two orders of magnitude improvement in stability for a test device operating as a frequency reference at 1.077 MHz, reducing frequency drift from more than 100 Hz over 3 hours using traditional actuation, down to less than 1.5 Hz variation over 40 hours using the new technique.

INTRODUCTION

Dielectrics such as silicon nitride and silicon dioxide are common structural materials in microsystems. However, it is known that dielectrics are susceptible to charging and charge migration both in their bulk and on their free surfaces [1]. When dielectric charges change in the proximity of an electrostatic MEMS device, the electric fields in that neighborhood can change as well. This is particularly important for bi-stable RF capacitive switches where failures are noted due to charge-induced stiction. In CMOS-MEMS processes [2] where mechanical structures are built in the metal-dielectric stack above the substrate, biasing of electrodes can lead to electric fields that encourage the movement of dielectric charge. Any resonant gyroscopes or frequency references built in such a process can potentially have stability issues.

Oxide-coated silicon resonators (Fig.1) have enormous potential as high stability frequency references due to their low temperature coefficient of frequency [3]. Some of these devices have been used in frequency references [4, 5] and temperature characterization experiments [6]. However, charge-induced drift of the resonance frequency in a small percentage of these resonators has been reported even under low field conditions [7]. In commercial processes, characterization for identification and filtering of devices that exhibit drift behavior can add significant time and cost. Having an actuation technique that completely avoids the drift issue could potentially have high impact for commercial and academic applications.

** Currently at University of California, Berkeley, CA, USA*
 # Currently at SiTime Corporation, CA, USA

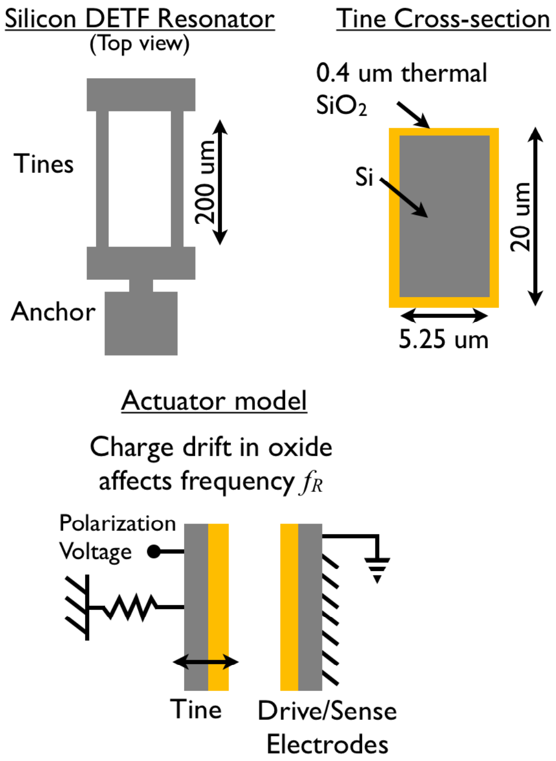

Figure 1: Double-ended tuning fork resonators coated with steam-grown thermal oxide for passive temperature compensation. Drift of charge within the oxide affects the resonance frequency f_R.

BIAS MODULATION

DC voltage sources are typically used to polarize a resonant device in order to reduce the motional impedance. In the specific case of resonators, it has been reported that dielectric charge can drift under an applied field (from this polarization voltage), with time constants greater than seconds, in turn causing drifts in resonance frequency over time [7] (Fig.2).

If, however, the polarity of the applied polarization field is toggled at a rate at which charge carriers

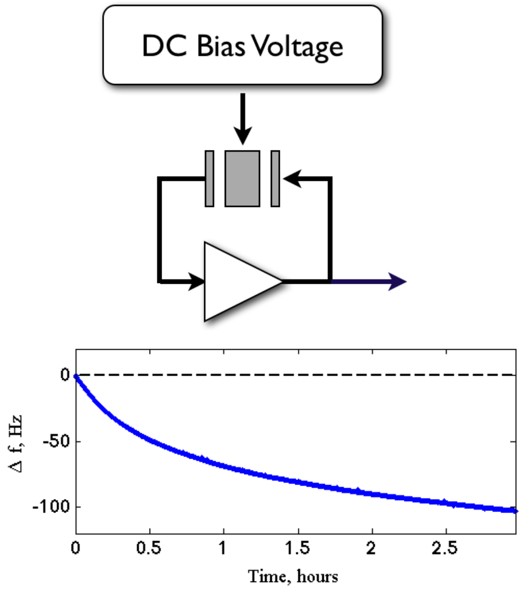

Figure 2: Frequency drift due to motion of charge in an oxide-coated silicon resonator under DC polarization (+15 V) with traditional oscillator architecture (positive feedback amplifier configuration). Oscillator loop generates signal at the resonator frequency f_R and shows significant drift over time.

cannot respond, the charge will not drift. This observation motivates the use of a purely AC polarization voltage (instead of the traditional DC bias) to excite a resonator. Since the charging time constants are of the order of several seconds, or significantly longer, any rate higher than a few hundred Hertz would be suitable. When actuated in this manner, the resonator produces two response peaks, which are above and below the actual resonance frequency f_R (Fig.3).

As an aside, mixed signal excitation of resonators is a standard interrogation technique [8], but typically uses additional DC voltage to reduce the motional impedance of the resonator. The nonlinear technique of driving at half the resonator's natural frequency also requires DC to extract the resonance signal [9]. In contrast, the absence of DC fields is crucial for obtaining drift free operation as we show in this work. By using a low frequency large signal polarization source, devices can still be actuated without the need for additional DC voltage.

OSCILLATOR ARCHITECTURE

When the polarization is a zero-DC-offset AC signal (frequency f_B), the resonator (resonance frequency f_R)

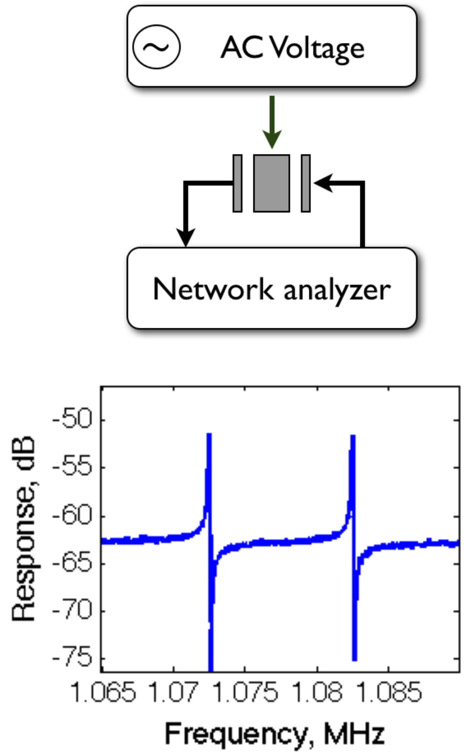

Figure 3: AC polarization voltage at frequency f_B yields two resonances at $f_R + f_B$ and $f_R - f_B$ when observed with a network analyzer. Here f_R is about 1.077 MHz and resonance peaks are $2f_B$ apart (10 kHz).

is excited when driven at $f_R + f_B$ or at $f_R - f_B$ (Fig.3), or at both frequencies simultaneously. Although the electrical excitation now happens away from the resonance frequency f_R the resonator still primarily vibrates at its resonance frequency f_R. Some frequency modulation is expected due to bias amplitude variation in the sinusoidal case, but it can be shown to be a minor effect and is ignored for this discussion. Once the resonator is vibrating, the electrical polarization signal at f_B then mixes with the motion at f_R to generate output current at frequencies $f_R + f_B$ and at $f_R - f_B$ simultaneously.

In an oscillator, this output signal is returned to the resonator with positive feedback. If f_B is small compared to f_R the gain and phase condition of the oscillator loop is satisfied for both output frequencies. Thus when configured in an oscillator circuit (Fig.4), electrical output is generated at both frequencies simultaneously (Fig.5A) and is free of charge-induced drift. Only minor design changes are needed at the input stage of the amplifier to reduce the bias feed-through signal.

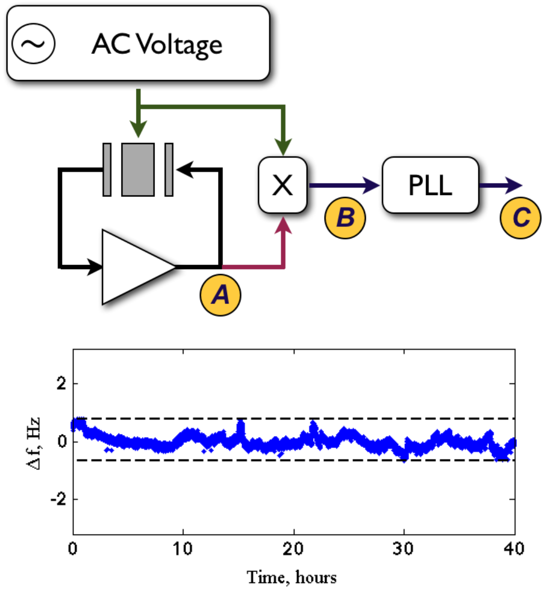

Figure 4: Elimination of drift due to charge with modified oscillator architecture using AC polarization source at frequency f_B and PLL acting as a narrow-band filter. Test performed on same device as Fig. 2. Output only has 1.5 Hz variation about the average frequency. Polarization of 18 Vpp applied at f_B = 9kHz.

SIGNAL CONDITIONING

An oscillator that produces two output frequencies may have some practical applications, though it is of limited use as a frequency reference. Additionally, the dependence of the oscillation frequencies on the bias at f_B is unacceptable for frequency references since this would require an additional high precision reference for the polarization source. To eliminate this dependence on f_B the oscillator output signal is mixed (or multiplied) with the polarization source signal. This results in a dominant spectral peak at f_R that is, at least in theory, independent of the bias frequency (Fig.5B). Selectively filtering this peak will yield the required single-tone reference signal.

In our case, a phase-locked loop (PLL) consisting of a phase detector, filter and voltage controlled oscillator (VCO) is then used to generate a new signal by locking frequency with the highest power signal present in the conditioned spectrum. If the loop filter is designed with small bandwidth it should significantly attenuate any sidebands or spurs present (Fig.5C). The end result from this system is a VCO-generated square wave at frequency f_R that can be used as a drift-free high stability frequency reference.

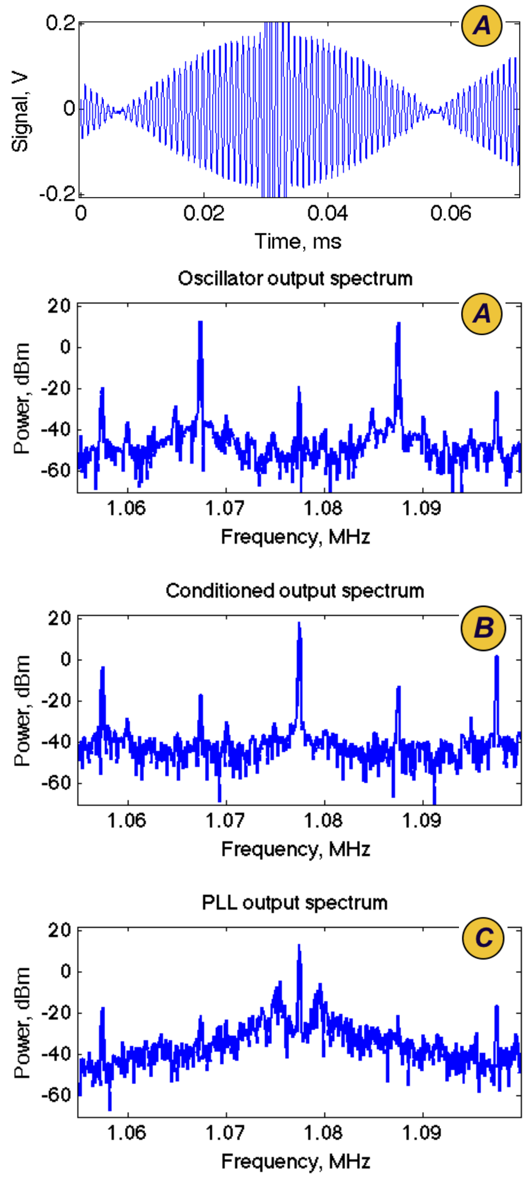

Figure 5: Output of new oscillator (at point A) is the sum of two sinusoids at frequency $f_R + f_B$ and $f_R - f_B$. To use the resonator as a frequency reference, dependence on f_B must be eliminated. Oscillator signal is mixed with f_B to regenerate peak at f_R at point B. This peak is now independent of f_B and can be locked-in by the PLL. The end result is a square wave at f_R from the VCO at point C.

RESULTS

Testing of the new oscillator topology was performed with an oxide-coated device that was known to show significant drifts with the conventional biasing scheme and architecture (Fig.2). In a verification test we noted a >100 Hz drift over 3 hours at constant temperature and biasing where the resonance frequency is 1.077 MHz. Note that even after 3 hours the frequency had not stabilized.

Following this drift verification test, the device was allowed to rest without bias for several hours at the same temperature in order to restore the charge to its previous state.

The AC polarization test was subsequently performed to see the effectiveness of the new technique (Fig.4). We noted significant improvement in drift performance. The output frequency of the PLL, monitored using a frequency counter, showed variation of only 1.5 Hz and no obvious drift behavior in 40 hours of testing.

The enhanced frequency stability persisted through several additional repetitions of the above tests, in some of which we reversed the order of AC and DC polarization measurements. Thus, we verified that the observed enhanced stability was indeed due to the polarization technique and not artificially induced by initially stabilizing the drift in the device with the DC polarization test.

CONCLUSIONS

We have proposed an alternative actuation technique for resonant MEMS that eliminates the frequency drift caused by dielectric charging or ionic impurities in the resonator environment. In addition, we have demonstrated an oscillator architecture that can generate a stable reference frequency in spite of using a resonator that exhibits significant charge drifts under DC polarization.

To demonstrate the drift elimination capability of this technique, we have applied it to a device from our library that was known to exhibit the largest drifts that we have seen till date. As a result, the frequency stability improved significantly, indeed approaching that of the best silicon-only drift-free resonators available to us.

ACKNOWLEDGEMENT

This work was supported by DARPA CIEMS, Bosch, Epson, HP, Agilent, Boeing, Qualcomm, DARPA HERMIT, and the National Nanofabrication Users Network facilities funded by the National Science Foundation. The authors would like to thank Prof. A. Seshia, H. Lee, G. Yama, Prof. C. Nguyen, Dr. A. Partridge, M. Lutz, and Dr. E. Perozziello for their guidance and support. Additional financial support was provided in part by a National Science Foundation Graduate Fellowship for J. Salvia, and in part by a Stanford Graduate Fellowship for R. Melamud.

Corresponding author: Gaurav Bahl, Stanford University, 440 Escondido Mall, Building 530 Room 224, Stanford, CA, 94305
E-mail: bahlg@stanford.edu

REFERENCES

[1] W. Shockley *et al*, “Mobile electric charges on insulating oxides with application to oxide covered silicon p-n junctions,” Surface Science 2, pp. 277-287, 1964
[2] H. Xie *et al*, “Post-CMOS processing for high-aspect-ratio integrated silicon microstructures,” JMEMS, vol. 11, no. 2, pp. 93-101, April 2002
[3] R. Melamud *et al*, “Temperature-insensitive composite micromechanical resonators,” JMEMS, vol. 18, no. 6, pp. 1409-1419, Dec 2009
[4] J. Salvia *et al*, “Phase lock loop based temperature compensation for MEMS oscillators,” Proc. IEEE MEMS 2009, pp. 661-664, Sorrento, Italy, 25-29 Jan. 2009
[5] H. Lee *et al*, “Electrostatic-tuning of hermetically encapsulated composite resonator,” Solid-State Sensors, Actuators, and Microsystems Workshop, pp. 48-51, 1-5 June 2008
[6] H. Lee *et al*, “A novel characterization method for temperature compensation of high stability composite resonators,” Proc. IEEE MEMS 2010, Hong Kong, China, Jan 2010
[7] G. Bahl *et al*, “Observations of fixed and mobile charge in composite MEMS resonators,” Solid-State Sensors, Actuators, and Microsystems Workshop, pp. 102-105, 1-5 June 2008
[8] A.C. Wong *et al*, “Micromechanical mixer-filters (“Mixlers”),” JMEMS, vol. 13, no. 1, pp. 100-112, Feb 2004
[9] B. Bahreyni *et al*, “Oscillator and frequency-shift measurement circuit topologies for micromachined resonant devices”, S&A:A, vol. 137, no. 1, pp. 74-80, 2007