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2.2 MHz piezoresistive MEMS oscillator operating in air

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Abstract

This paper describes a MEMS oscillator capable of operation at atmospheric pressure, based on a square-extensional mode single crystal silicon resonator. The resonator is actuated by differential capacitive driving and the motion of the structure is transduced piezoresistively. This transduction scheme successfully mitigates the effects of capacitive feedthrough and enhances the motional signal at micron scale transduction gaps. The oscillator demonstrates an Allan deviation of close to 1 ppm at an integration time of 200 seconds for an output power level of 0 dBm.

Keywords: MEMS oscillator; bulk mode; piezoresistive sensing

1. Introduction

Oscillators based on microfabricated silicon resonators can be viewed as building blocks for timing references and sensors. However, it is not trivial to incorporate electrically addressed silicon microfabricated resonators into conventional oscillator architectures due to their relatively high motional resistances and the capacitive parasitics intrinsic to the hybrid integration of MEMS with electronics. Reducing the motional resistance of capacitively transduced micromechanical resonators usually requires (1) the fabrication of sub-micron transduction gaps and (2) vacuum packaging to enhance the quality factor. This in turn increases the manufacturing complexity of the resonators and limits their range of application.

Piezoresistive sensing method has been shown to substantially enhance the motional signal relative to capacitive feedthrough in air [1], and oscillators built using electrostatic-to-piezoresistive transduction methods have also been reported to operate in moderate vacuum [2], however, the enhancement in motional signal was not sufficiently enough for the oscillator operation in atmospheric pressure. In this work, we combine feedthrough rejection techniques in addition to piezoresistive enhancement of the motional signal, to further reduce the effect of capacitive feedthrough allowing for a large motional to feedthrough current ratio at micron-scale transduction gaps for a given operating frequency. This combination of design enhancements enables oscillator operation at atmospheric pressure

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and room temperature. Experimental characterization of a 2.201 MHz MEMS oscillator operating in air, based on a square-extensional mode single crystal silicon resonator [3] fabricated in a foundry SOI process, is presented.

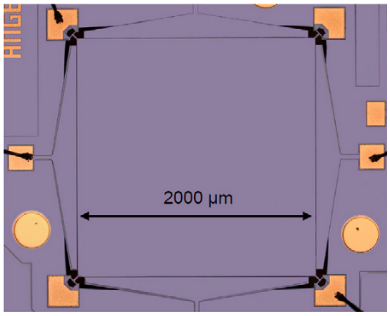
2. Resonator structure and operation

The resonant device is a 2.201 MHz single crystal silicon square plate operated in the square-extensional mode, wherein the square plate undergoes an extension and contraction symmetrically on each side of the square. The suspended square is anchored to the substrate via a T-shape connecting stem located on four corners of the square plate, with one lateral electrode on each side of the square plate for capacitive actuation of the resonator. Electrical connections to the anchors of the square plate are also provided for piezoresistive sensing, as shown in figure 1a. The resonator is fabricated in a commercial SOI foundry process (MEMSCAP), and the resonator parameters are summarized in Table 1.

The transduction of the square-extensional mode resonator using piezoresistive sensing method has been recently shown in [4], with various feedthrough rejection methods documented and compared. In this previous study, harmonic actuation in combination with piezoresistive sensing was reported to demonstrate excellent enhancement of the motional signal, however, this requires the implementation of a nonlinear frequency divider element in the oscillator feedback loop thereby complicating the design. Here, we used differential capacitive driving technique for feedthrough mitigation [5], thereby retaining the same operating frequency throughout the oscillator loop. Two 180° out-of-phase AC signals are applied to one half of the resonator electrode for differential capacitive actuation of the resonator, allowing the effect of feedthrough to be cancelled. Since the electrostatic force depends on the polarity and phase of the applied DC and AC voltages, opposite polarities of the DC bias is required together with out-of-phase AC signals to generate equal actuation force for the excitation of the square-extensional mode. The mechanical response is sensed by passing a drain current between two opposite corners of the square plate to readout the resulting variation in the electrical resistance of the vibrating structure due to the piezoresistive effect. The details of the transduction principle are described in [4].

The resonator was characterized using an Agilent 4396B network analyzer and a transimpedance preamplifier to obtain its open loop frequency response. Figure 1b shows a comparison between the open-loop frequency response for the same resonator using the two-port capacitive measurement, driven with a 0 dBm power source and ±40 V DC bias, and the differential capacitive actuation and piezoresistive sensing method, with the same actuation voltages and a drain current of 6 mA. A clear enhancement in the measured magnitude response can be seen using the differential capacitive drive and piezoresistive sensing readout, as the method allows for substantial rejection of capacitive feedthrough at the resonant frequency enabling the oscillation condition to be set by the motional element. The resonant frequency was measured to be 2.201 MHz with a quality factor of 7337 in air.

(a)



(b)

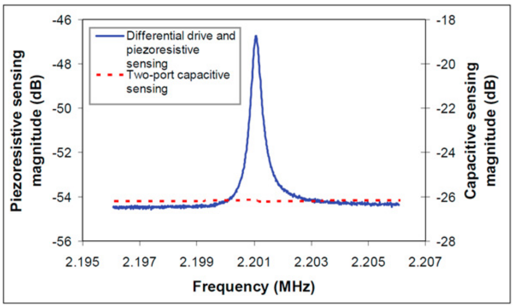


Fig. 1. (a) Optical micrograph of the fabricated resonator; (b) Comparison of the frequency response of the SE mode resonator using two-port capacitive sensing (red) and differential drive with piezoresistive sensing (blue), for the same DC bias of ±40V.

3. Oscillator implementation

The oscillator circuit senses the output current of the square plate resonator and applies an appropriate force feedback to the resonator to sustain oscillation. The condition for oscillator design is that the phase shift of the loop at the oscillation frequency should be zero, and the loop gain at that frequency should be greater than unity. Figure 2 shows a block diagram of the oscillator circuit, similar to that reported in [6]. The first stage is a transimpedance amplifier that converts the resonator motional current to a voltage signal, followed by further signal amplification in a second gain stage. A bandpass filter then removes the unwanted oscillator modes, and the filtered signal is then fed into a comparator. The comparator is a hard voltage limiter, which allows for control over the actuation signal amplitude. The output of the comparator is applied to a single-ended-to-differential drive amplifier, which produces two 180° out-of-phase AC signals for differential capacitive actuation of the resonator. The phase shift in the loop can be tuned in the amplifier cascade, and the feedback gain is controlled using a voltage divider at the comparator output. The oscillator output is a square wave at primary frequency of 2.201 MHz with 2nd harmonic distortion of -32 dB. The output spectrum is shown in Fig. 3a, and the time domain signal as observed on the oscilloscope is shown in Fig. 3b.

The oscillator peak amplitude at various resonator DC bias voltages and drain current is plotted in Fig. 4a, showing that the comparator is fully triggered by the oscillation when the applied DC bias is higher than ±40 V, and for drain currents larger than 4 mA. Successive frequency measurements are taken using the Agilent frequency counter (Agilent 53132A) and the Allan deviation measurement for the MEMS oscillator at a DC bias of ±50 V and drain current of 6 mA is shown in Fig. 4b. The trend in the plot of Allan deviation as a function of integration time indicates that the response is limited by electronic noise. The data points for the Allan deviation measurements were collected continuously over 50 minutes with a sampling time of 0.2 s.

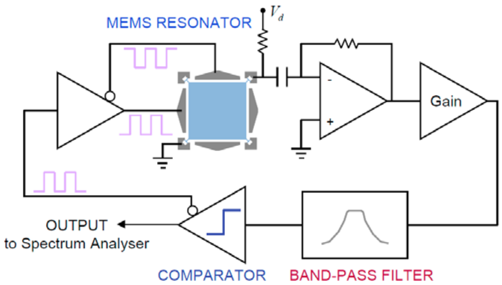
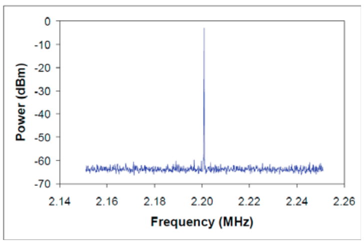


Fig. 2. Block diagram of the oscillator circuit with the SE mode resonator. The differential driving method reduces the effects of capacitive parasitic feedthrough.

(a)


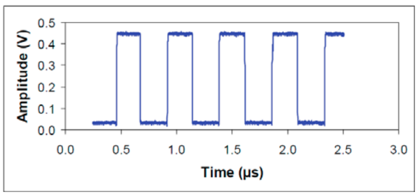
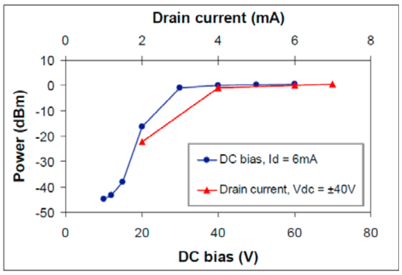
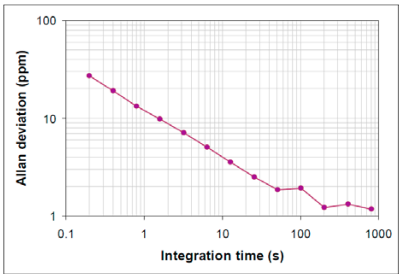
(b)


Fig. 3. (a) Output of the MEMS oscillator in air from the spectrum analyser, showing primary frequency component at 2.201MHz; (b) Time domain output of the MEMS oscillator from the oscilloscope.



(a)



(b)

Fig. 4. (a) Peak magnitude of the MEMS oscillator output for various applied DC bias and drain current; (b) Allan deviation measurements for the MEMS oscillator in air.

Table 1. Resonator parameters

Parameters	Value
Side length	2000 µm
Thickness	25 µm
Transduction gap	2.5 µm
Resonant frequency	2.201 MHz
Measured quality factor	7337

4. Conclusions

We have successfully designed and implemented a HF band MEMS oscillator operating in air. The oscillator is based on a single crystal silicon square plate resonator operated in the bulk extensional mode, with differential capacitive actuation and piezoresistive sensing. The transduction method allows significant enhancement of the motional to feedthrough current ratio at micron-scale transduction gaps. The oscillator output is a square wave at a frequency of 2.201 MHz with a 2nd harmonic distortion of -32 dB. The comparator is fully triggered for an applied resonator DC bias of higher than ±40 V, and for drain currents larger than 4 mA. The oscillator demonstrated an Allan deviation of close to 1 ppm at an integration time of 200 seconds for an output power level of 0 dBm.

References

[1] J. T. M. Van Beek et al., A 10MHz piezoresistive MEMS resonator with high Q, in: Proceedings of the 2006 IEEE International Frequency Control Symposium and Exposition, vols. 1 and 2, 2006, pp. 475–480.

[2] J. J. M. Bontemps et al., “56 MHz Piezoresistive Micromechancial Oscillator”, Tech. Digest Transducers 2009, Denver, pp. 1433-1436.

[3] J. E. Y. Lee et al., "A bulk acoustic mode single-crystal silicon microresonator with a high-quality factor," Journal of Micromechanics and Microengineering, vol. 18, pp. -, Jun 2008.

[4] A. T.-H. Lin et al., “Methods for enhanced electrical transduction and characterization of micromechanical resonators”, Sensors and Actuators A: Physical, vol. 158 (2010), Issue 2, pp. 263-272.

[5] S. A. Bhave et al., "Fully-differential poly-SiC Lame-mode resonator and checkerboard filter," Mems 2005 Miami: Technical Digest, pp. 223-226.

[6] J. E. Y. Lee et al., "A single-crystal-silicon bulk-acoustic-mode microresonator oscillator," IEEE Electron Device Letters, vol. 29, pp. 701-703, Jul 2008.