A VHF TEMPERATURE COMPENSATED LITHIUM NIOBATE-ON-OXIDE RESONATOR WITH $Q > 3900$ FOR LOW PHASE NOISE OSCILLATORS

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ABSTRACT

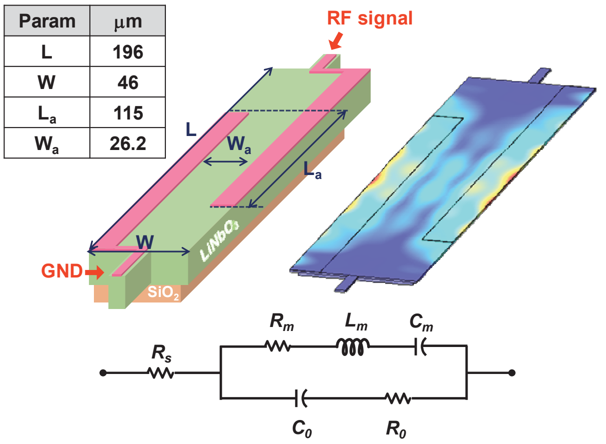
This work reports a 40-MHz lithium niobate-on-oxide (LN/SiO_2) micromechanical resonator which simultaneously features a compensated temperature coefficient of frequency (TC_f) of -13 ppm/°C and a record high $Q > 3{,}900$ in vacuum ($Q > 1{,}600$ in air) for low phase noise oscillators. A high-quality 0.7 µm X-cut LN thin film atop a 2 µm SiO_2 compensation layer was used to form the body of the proposed resonator based on a quasi-fundamental shear horizontal (Q-SH_0) plate wave with acoustic propagation in 170° rotated from the Y-axis. The proposed LN-SiO_2 resonator is suspended through 5-µm narrow-width supporting beams to mitigate the acoustic energy loss to the substrate, thus exhibiting a best-case Q of 3,900 in vacuum with $k_{eff}^2 > 3.8\%$ (FOM = $k_{eff}^2 \times Q > 148$). The closed-loop oscillator was demonstrated with a commercial phase-locked loop (Zurich HF2LI PLL) under a loop bandwidth of 90 kHz. Measured phase noise for the 40-MHz LN-SiO_2 Q-SH_0 wave oscillator at 1 kHz and 10 kHz offsets is -110 dBc/Hz and -123 dBc/Hz, respectively, with a minimal bias instability of only 6.2 ppb.

INTRODUCTION

In recent years, the requirements for the next-generation RF front end systems are fast growing with the boom of Internet of things (IoT) and wireless handsets. High-performance MEMS resonators are needed in order to achieve small size and multiple functionalities in wireless handsets simultaneously.

Phase noise and frequency stability are the key factors for either frequency references or resonant-sensing applications. Single-crystal LN resonators are a prospective candidate for emerging oscillator systems [1] owing to its high electromechanical coupling (k_{eff}^2) for reduced tank loss at high frequencies (VHF to SHF). However, most of the communications systems, like the wireless communications and satellite communications, target systems with temperature coefficient of frequency approaching zero for their frequency reference. This requirement will become the bottleneck for the LN MEMS resonators since it exhibits a rather large TC_f of about -80 ppm/°C.

This work reports the design and fabrication of the LN/SiO_2 MEMS resonators using surface micromachining technology, which delivers a compensated TC_f of -13 ppm/°C. Furthermore, to achieve a higher quality factor (Q), which directly affects the phase noise performance of the implemented oscillators, this work utilizes the narrow supporting design to minimized the anchor loss and have demonstrated higher FOM in comparison with [2].



Param	µm
L	196
W	46
L_a	115
W_a	26.2

Figure 1: Schematic and simulated mode shape for the Q-SH0 wave LN-SiO_2 resonator with its equivalent circuit.

DESIGN CONCEPT

Fig. 1 depicts the resonator design in this work where the device consists of interdigital transducer (IDT) electrodes on top of a LN thin film and a SiO_2 layer, all of which are mechanically suspended. The electric field induced by the IDT electrodes will excite a vibration and the output electrodes will convert the vibration energy back into electrical signal. IDT electrodes take the advantage of increasing the electromechanical coupling coefficient by proper placement and facilitate the resonance frequency definition using the pitch variation realized by the lithographic technique [3]. The proposed resonator is designed to operate in a shear horizontal (SH_0) acoustic plate wave mode. The piezoelectric coupling coefficient K^2 which determines the electromechanical coupling coefficient k_t^2 [4] of SH_0 wave will change with different orientations and cuts of LN. In this work, X-cut LN is selected with a device orientation of 170° to +Y-axis. This specific orientation is chosen as it showcases the highest theoretically predicted electromechanical coupling coefficient [5] for the SH_0 mode. To enhance the quality factor of the device, we engineer the design of the anchor to restrict energy transmission to the substrate.

Most of the MEMS LN resonators suffer from a large TC_f of about -80 ppm/°C. This study makes use of the idea of TC_f compensation between the LN and oxide. The positive temperature coefficient of Young's modulus of SiO_2 films is used to compensate for the huge negative TC_f of LN thin film. The thickness of the LN is 0.7µm while the SiO_2 underneath it is 2µm.

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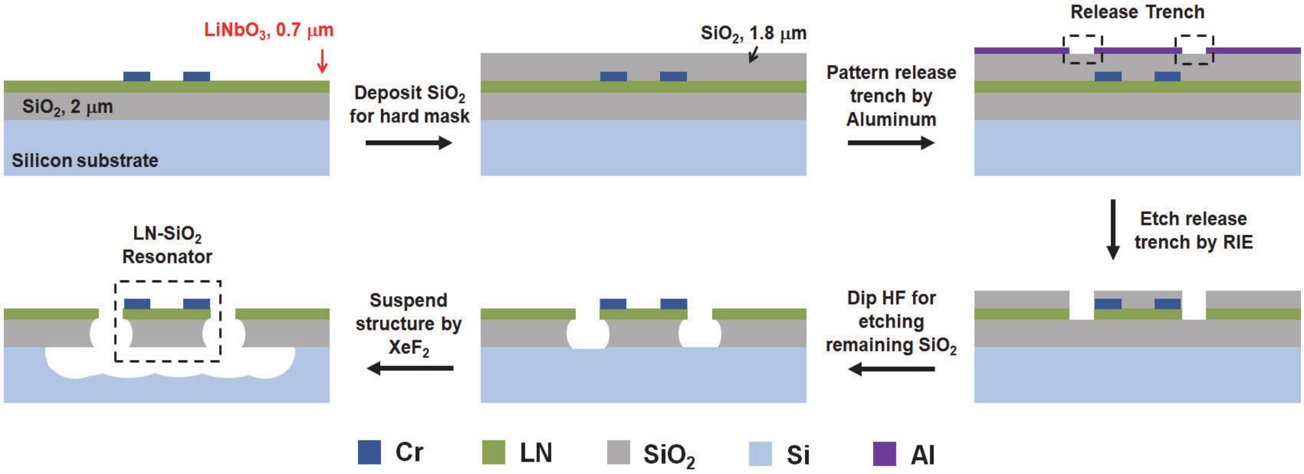


Figure 2: Detailed fabrication process for the LN-SiO$_2$ resonator. The underneath SiO$_2$ would be slightly smaller than the LN plate due to the time-controlled wet HF etching.

FABRICATION AND RESULT

The devices are fabricated using a 2-mask in-house process. The process flows can be divided into three parts where the first part defines the electrodes; the second part is the etching process of the hard mask and LN thin film by RIE dry etching; the third part is to release the device and enable the resonators to vibrate freely.

Fig. 2 presents the detailed fabrication process for the LN/SiO$_2$ resonators, which starts with a commercially available X-cut LN-SiO$_2$-Si wafer from NANOLN which is composed of a 0.7μm LN thin film and 2μm thick oxide stack on top of a 400μm thick silicon substrate. The process starts with the deposition of a 0.1μm Chromium (Cr) on top the LN thin film by RF sputtering. Cr was patterned by the first mask using wet etching process to form the IDT electrodes. For the next step, SiO$_2$ serves as hard mask and it is deposited by plasma-enhanced chemical vapor deposition (PECVD). In addition to it, a 0.1μm thick aluminum (Al) is deposited on top of oxide, which will serve as the hard mask for defining the SiO$_2$ release window. Al is deposited by thermal evaporation coater then patterned by the second mask to form the release window using wet etching. After that, the release window is patterned on the SiO$_2$ layer using RIE by CHF$_3$ gas at 1.33 Pa on a SAMCO Dielectric RIE-10NR system. During this process, Al layer protects the SiO$_2$ layer outside the release window region. A mixture of Cl$_2$/BCl$_3$ based gas at 1.33 Pa on a SAMCO Metal RIE-200L is then applied to dry etch the 0.7μm LN thin film and the SiO$_2$ layer serves as the hard mask during the patterning of the LN thin film. Once the resonator dimensions are defined, the final step is to release the structure. Here Xenon Difluoride (XeF$_2$) -based dry etching is used as compared to the Hydrofluoric (HF) wet etch releasing step in previous work [6]. The releasing process starts by dipping the die in HF to facilitate the etching of SiO$_2$ under the release window region until the Si substrate is exposed. This however preserves the SiO$_2$ layer underneath the LN thin film for temperature compensation purpose. Finally XeF$_2$ gas is used for the final release step by dry etching the Si substrate to achieve the fully suspended LN/SiO$_2$ resonators. This releasing method eliminates the possibility of stiction, which commonly occurs in wet etch release process.

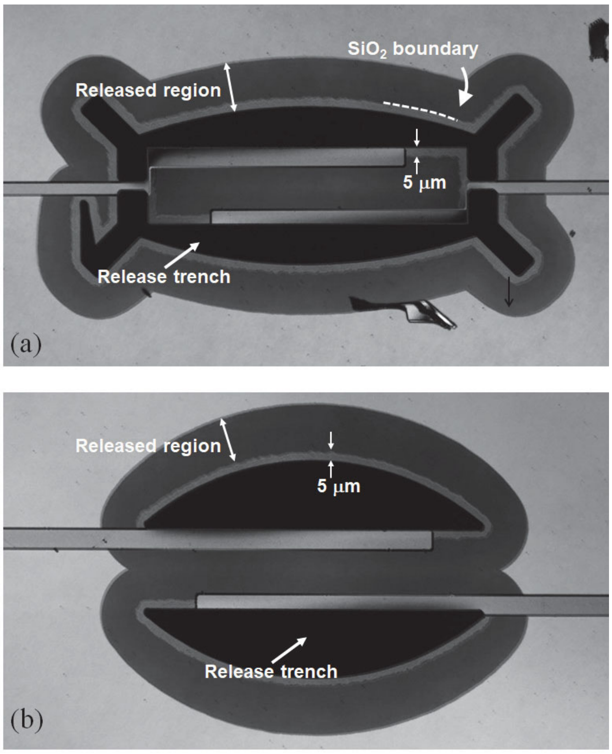


Figure 3: Confocal microscopy view for the proposed (a) Narrow support and (b) Full-width support resonator. The oxide boundary recessed about 5μm can be observed.

A photo for the fabricated device captured using a confocal microscope) is shown in Fig. 3 with key features labeled. The oxide boundary is recessed about 5μm from the edge of the release trench due to the time-controlled HF wet etching (i.e., the fifth step in Fig. 2). The edge of the release window is designed to mimic a curved structure rather than making it straight so as to improve the management of thin film stress. Aggregated residual stress can cause device fracture after releasing the LN thin film [7]. The release window designed in rectangle will tend to have cracks due to the sharp corner.

MEASUREMENT RESULTS

Resonator Measurement

The fabricated LN- SiO_2 devices were characterized in a cryogenic vacuum Lakeshore probe station. The piezoelectric MEMS resonator was driven using the Network Analyzer (Agilent E5071C). The RF ground-signal-ground (GSG) probe was employed in the measurement to prevent the large parasitic capacitance since the proposed resonators is operated in the very high frequency (VHF) range.

Fig. 4(a) shows the admittance plot for the proposed resonator measured under different pressure. The device has Q of 1,626 and R_m of 10.8 kΩ in air, while it records Q of 3,409 and R_m of 5.5 kΩ in vacuum. To take the device characterization study one step forward, temperature dependency study for the resonator was carried out. Fig. 4(b) shows the admittance plot measured in 107°C for a traditional full-width support device [8] with Q_{FW} = 197, which is significantly lower than the proposed narrow-beam-supported resonator which shows Q_{NW} = 3,900, while k_{eff}^2 = 3.8% is extracted for both cases. The high Q performance of the proposed narrow-beam supported resonator is due to the lower acoustic energy loss from the anchor to the surrounding support substrate.

The TC_f characterization presented in Fig. 5(a) reveals a compensated TC_f of -13 ppm/°C which is 5 times lower than uncompensated SH0 resonator in [8]. The temperature dependence of the Q-factor (TC_Q) was also recorded during temperature ramp, as shown in Fig. 5(b). Note that Q in vacuum is increased around 20% for a 80°C temperature difference, showing a potential to be used in oven-controlled MEMS oscillators.

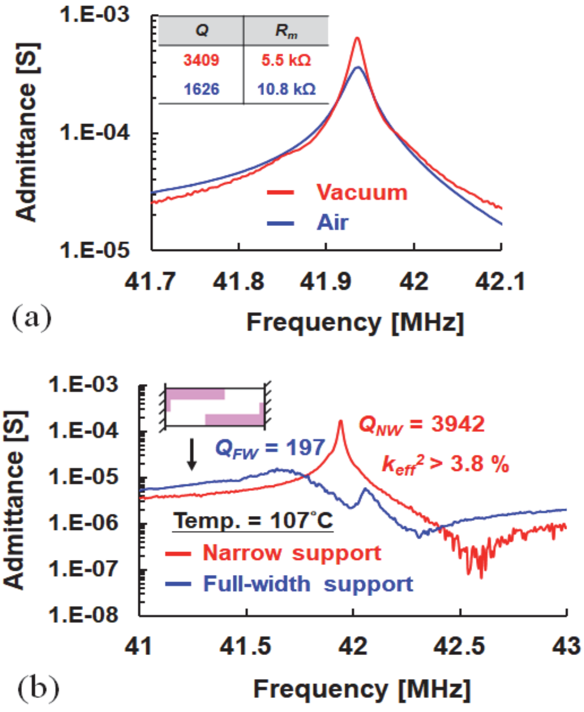


Figure 4: Admittance plots for the Q-SH0 wave LN-SiO$_2$ resonator: (a) Q-comparison under different pressure, and (b) Q-comparison in vacuum with different supporting design (measured at elevated temperature of 107°C).

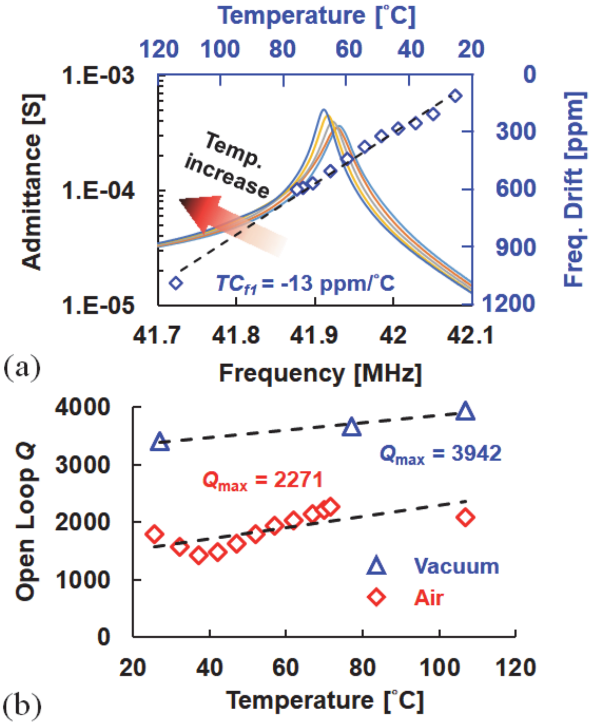
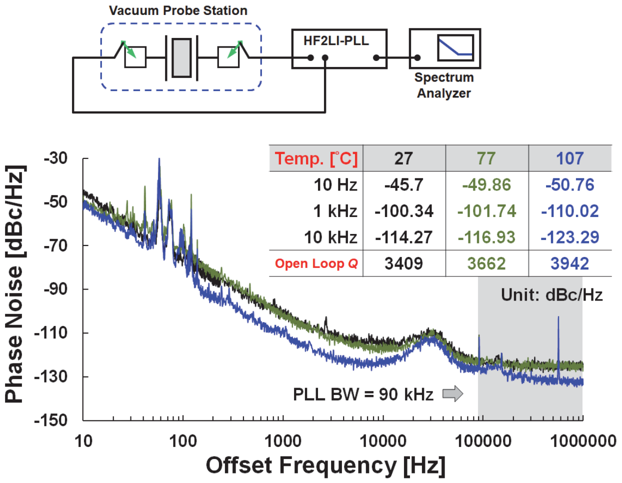


Figure 5: Measured (a) temperature dependence of the frequency (TC_f), and (b) temperature dependence of the Q-factor.

Lock-in Measurement

In order to characterize the performance of the piezoelectric resonator for frequency reference, the piezoelectric resonator was placed in a vacuum chamber and the oscillator was implemented by using a commercially available phase-locked loop (Zurich HF2LI PLL) with a loop bandwidth of 90 kHz. Selected loop bandwidth is far beyond the cutoff frequency of the MEMS device ($f_o/(2Q)$ = 5 kHz) to set a fair basis for making



Temp. [˚C]	27	77	107
10 Hz	-45.7	-49.86	-50.76
1 kHz	-100.34	-101.74	-110.02
10 kHz	-114.27	-116.93	-123.29
Open Loop Q	3409	3662	3942

Figure 6: Measured phase noise plot for the PLL-based oscillator at 3 temperature points.

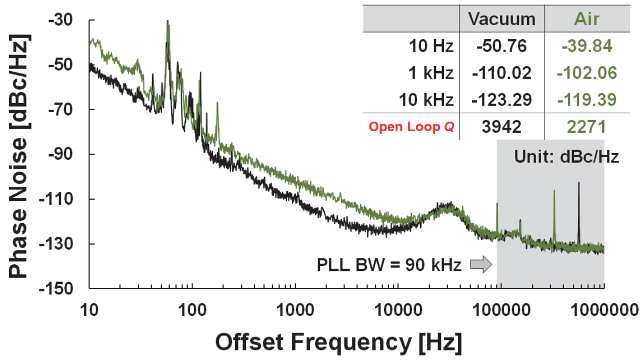


Figure 7: Measured phase noise plot for the PLL-based oscillator under different environmental pressure.

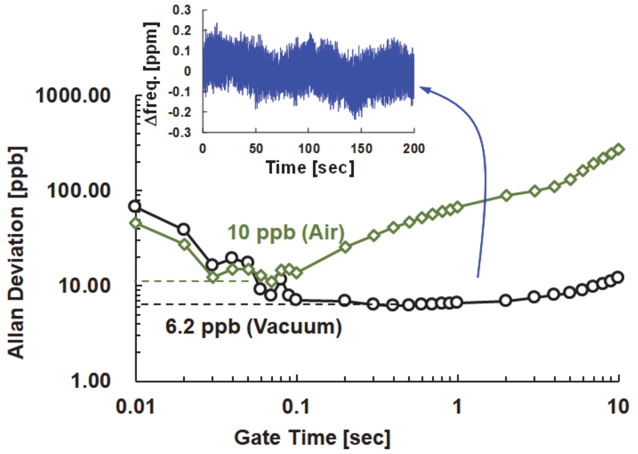


Figure 8: Measured Allan deviation for the PLL-based oscillator under different environmental pressure. The frequency stability is greatly improved as operated in vacuum.

comparison with other oscillators. The measurement setup of the oscillator is depicted in Fig. 6 and the phase noise was measured using the Keysight Spectrum Analyzer. The phase noise at different temperature is shown in Fig. 6, presenting a best-case phase noise of -110 dBc/Hz at 1-kHz and -123 dBc/Hz at 10-kHz offset ($T = 107°C$) with carrier frequency of 41.9 MHz. The phase noise results of Fig. 6 indicate that Q enhances with the increase in operation temperature and it in turn improves the phase noise as well. Fig. 7 shows the phase noise measured in air and vacuum respectively. Fig. 8 further shows the Allan deviation measured under different pressure. In this case, the ultimate bias instability for the oscillator is calculated to be 10 ppb in air and 6.2 ppb in vacuum. As a result, the proposed low-TC_f VHF LN/SiO$_2$ Q-SH0 wave resonator (FOM > 148 at 107°C) oscillator exhibits a very competitive performance to the prior arts [1][9] at similar frequency range thanks to the exceptional $Q > 3,900$.

CONCLUSION

This work successfully establishes the process flow using dry etching to release the resonator structure to implement the single crystal 0.7μm X-cut thin film atop a 2μm SiO$_2$ compensation layer to form the MEMS resonators. Furthermore, two different anchor designs (Narrow support and Full-width support) have been employed and successfully fabricated to verify the anchor loss effect. The fabricated LN/SiO$_2$ MEMS resonators operating at 40 MHz based on a shear horizontal mode simultaneously show a compensated temperature coefficient of frequency (TC_f) of -13 ppm/°C and a best-case Q of 3,900 in vacuum at 107°C with $k_{eff}^2 > 3.8\%$ (FOM = $k_{eff}^2 \times Q > 148$). Phase noise of -110 dBc/Hz and -123 dBc/Hz were recorded at 1 kHz and 10 kHz offsets respectively, with an extremely low minimal bias instability of 6.2 ppb.

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