A LOW-PHASE NOISE OSCILLATOR EMPLOYING CONTOUR-MODE LITHIUM TANTALATE RESONATORS WITH HIGH TURNOVER TEMPERATURE

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ABSTRACT

This work reports on a low phase noise micro-electromechanical system (MEMS) oscillator, leveraging a combination of high quality factor (*Q*) and low loss achieved by a contour mode X-Cut Lithium Tantalate (LT) resonator. These resonators, once oriented in certain crystalline directions of LT, could offer a turnover temperature exceeding 90°C, making them ideal for implementation of oven-controlled oscillators for ultra-stable clock applications. The resonator used for building the oscillator of this work is oriented along 35° off Y axis, operates at 283 MHz, has an unloaded *Q* of 1920, and an insertion loss of 7 dB, leading to oscillator phase noise levels of -102.59 dBc/Hz and -164.58 dBc/Hz at 1 kHz and 1 MHz offsets, respectively. This class of resonators could open up the possibility of implementing ovenized ultra-stable clocks in single crystal LT platform.

KEYWORDS

Contour-mode; Lateral-field-Excited; MEMS Oscillators; Temperature Coefficient of Frequency (TCF); Thin-film Lithium Tantalate (LT) Resonators; Turnover Temperature.

INTRODUCTION

Precise timing is crucial in a wide range of applications, such as high-speed digital circuits, radar systems, satellite communications, wireless networks, and global positioning systems (GPS). For decades, quartz crystal oscillators have served as a frequency reference component due to their relatively compact size, high quality factor (*Q*), and high temperature stability. With technological advancements, micro-electromechanical system (MEMS) oscillators have emerged as highly promising alternatives, offering advantages such as miniaturization, batch fabrication, and integration capabilities [1]. However, a significant drawback of most MEMS resonators is their poor temperature stability as common materials have substantial temperature coefficient of elasticity (TCE) which contributes to significant frequency variations induced by changing the operating temperature [2]. To mitigate frequency drift caused by temperature variations, various active and passive compensation techniques have been developed for MEMS resonators. Passive approaches involve material engineering and design techniques to achieve resonators with lower or near-zero temperature coefficient of frequency (TCF). These include composite structures incorporating materials with opposing temperature coefficients (e.g., silicon-silicon dioxide), heavy doping techniques (e.g., degenerate boron or phosphorus doping in silicon), and geometric modifications to introduce compensating stresses. Active compensation methods include micro-oven control, where the resonator is placed in a precisely temperature-regulated enclosure, typically at the turnover temperature where the TCF is minimized. By combining passive techniques to design near-zero TCF resonators with the active micro-oven control method to keep the temperature at such near-zero TCF points, MEMS oscillators can attain exceptional frequency stability in a wide temperature range [3,4].

The need for reliable oven-controlled stabilization has highlighted the importance of resonators with zero TCF that ideally occurs outside of their operational temperature range. As such, designing resonators with a high turnover temperature (>85°C) has been the focus of numerous research studies. For instance, highly n-type doped silicon could exhibit a turnover temperature for some modes of vibration which can be adjusted by manipulating factors such as its doping concentration and crystalline orientation as experimentally demonstrated for thin-film piezoelectric-on-silicon (TPoS) resonators [5]. In this regard, quasi-thickness-Lamé (QTL) mode TPoS resonators have shown turnover temperatures more than 80°C [6,7]. However, TPoS resonators (especially the ones based on aluminum nitride) typically exhibit limited electromechanical coupling efficiency (k_t^2 < 0.1%), hindering their use in very low power applications.

Single crystal lithium tantalate (LT) offers significant advantages over other common piezoelectric materials. Notably, it exhibits a turnover temperature at certain crystalline cuts/orientations; it demonstrates at least an order of magnitude larger electromechanical coupling efficiency, and it benefits from extremely low material loss. Combination of these characteristics renders LT ideal for low phase noise oven-controlled oscillators. With its efficient energy conversion and high Q, LT ensures minimal loss and enables precise frequency control, which is indispensable for ultra-stable clock applications. Previous work by our group has shown that the geometric design and the crystalline orientation of the LT contour mode resonators plays a crucial role in achieving a zero TCF and the desired turnover temperature value, however, the open-loop measurements and presence of spurious modes added to the uncertainty of the measurements, demanding further investigations [8].

In this study, the presence of the zero TCF in lateral-field-excited contour mode resonators based on thin-film X-cut LT is further investigated and a low phase noise oscillator is designed and implemented to enable closed-loop and more reliable TCF measurements. Theoretical analysis reveals that by rotating the device 35 degrees relative to the Y-axis and optimizing its dimensions (Fig. 1), a turnover temperature of approximately 90°C is attainable. This is experimentally proven by a low phase noise high-performance oscillator circuit. Phase noise values of -102.59 dBc/Hz and -164.58 dBc/Hz at 1 kHz and 1 MHz offsets, respectively, from a 283 MHz carrier with power consumption of 8.2 mW is demonstrated. This passive temperature compensation approach could provide a stable frequency reference for clock application once integrated in a micro-oven-controlled oscillator.

DESIGN & FABRICATION OF RESONATOR

Design

As mentioned in the previous part, high turnover temperature, high electromechanical coupling, and low insertion loss are the key elements for resonators used in oven-controlled MEMS oscillators. In lithium tantalate, like other crystalline structure, these elements depend on its crystallographic orientation. Therefore, the effect of crystallographic orientation of the LT resonator on its performance with focusing on achieving high turnover temperature, high electromechanical coupling coefficient and low acoustic loss has been explored, using COMSOL Multiphysics finite element analysis (FEA). The design was based on exciting contour mode by applying lateral field through interdigital electrodes (IDT) made of

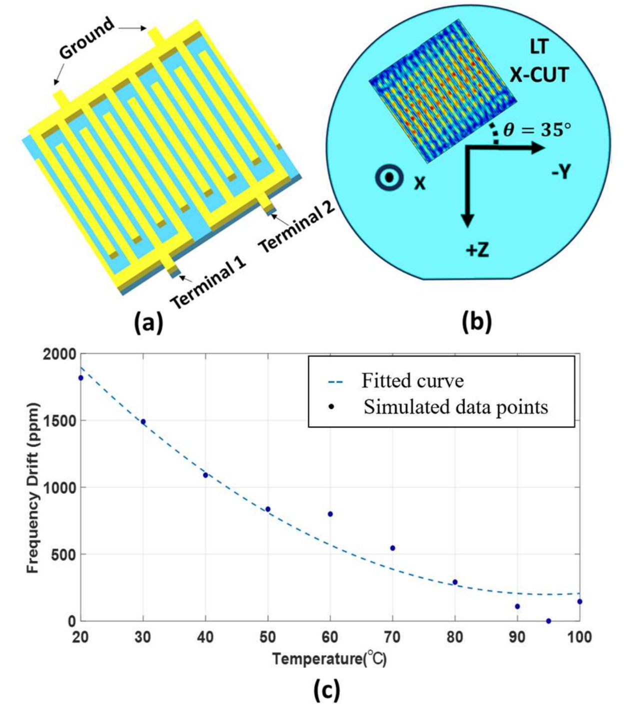

Figure 1. (a) Conceptual schematic of the device structure; (b) The orientation of contour-mode resonators on LT substrate including displacement profile of a 15th order resonator; and (c) simulated TCF of the resonator.

gold (Au) on the surface of 1.3 µm X-cut LT. FEA was performed on LT slab (Figure 1. (a)), while varying in-plane rotation angles (θ) and optimizing its dimension to achieve a combination of high turnover temperature, high electromechanical coupling, high Q, and low number of spurious modes. An optimal design based on a 15th order resonator at the frequency of 283 MHz was achieved and used for implementation of the oscillator as detailed in the experimental results section. The schematic viewgraph, and the orientation of the 15th order contour-mode resonator on LT substrate used in this work are shown in Fig. 1 (a), and (b), respectively. The simulations further considered the temperature dependency of LT's elasticity matrix and Au's Young's modulus to assess the frequency drifts due to TCE variations. The temperature dependent elasticity constants for LT and Au are reported in [9] and [10], respectively. As previously noted, the orientation and geometrical design of the LT resonator is important in attaining a zero TCF and determining the turnover temperature. As such, the in-plane orientation and dimension of the resonators were tailored to achieve a high-turnover temperature and high electromechanical coupling coefficient. The resonator was ultimately optimized with a 35-degree in-plane orientation and engineered dimensions. The simulated frequency drift of the designed device is plotted in Fig. 1(c) indicating the presence of the high turnover temperature at ~95°.

Fabrication

The fabrication procedure of the designed resonator proceeded through five stages. Fig. 2 (a-e) shows the fabrication steps and Fig. 2 (f) depicts the AA1 cross-section of the fabricated device. Initially, a 4-inch LT X-Cut wafer was bonded to a 500 µm silicon handle wafer. This bonding process was performed by NGK insulators. Following that, the LT film was polished down to a thickness of 1.3 um. Next, a bilayer of chromium (Cr) and gold (Au) (30 nm/120 nm) was deposited using an Electron Beam (Ebeam) evaporator and patterned using a lift-off process to establish the electrodes, with Cr serving as the adhesion layer. The next stage involved defining the boundaries of the resonators through etching LT. This was accomplished by using PECVD-deposited silicon dioxide (SiO_2) as a hard mask. The SiO_2 was then patterned using CHF_3 plasma within an inductively coupled plasma reactive ion etching (ICP RIE) chamber, followed by the etching of the underlying LT film using argon (Ar) plasma in the same chamber. Finally, the handle wafer, bonded to the LT film, was etched from the backside using the Bosch process within an ICP RIE chamber.

EXPERIMENTAL RESULTS

The frequency response (one port admittance) of the fabricated resonator used for implementing the oscillator is shown in Fig. 3, using a network analyzer (Rohde & Schwarz ZNB8). A loaded *Q* of ~1100 with a motional impedance of 134 Ω is measured, resulting in an unloaded *Q* of 1920.

To provide a low phase noise oscillator, a two-stage circuit including a feedback loop and a buffer was designed using Advanced Design System software, as depicted in Fig. 4 (a). The feedback loop incorporates a gain stage that utilizes an NPN bipolar junction transistor (BJT), AT-41486 (Avago Technologies co.), known for its excellent high-frequency performance in terms of gain and noise figure, with a gain bandwidth product of 8 GHz. This gain stage, operating in a common emitter configuration, acts as a sustaining amplifier within the oscillator feedback loop and was biased at 3.3 V with a 2.5 mA bias current. To ensure circuit performance in high oven temperature environments and protect against thermal runaway, a degeneration resistor (RE1) was employed in the emitter, along with voltage divider bias at the base. The resonator served as the feedback element for this gain stage. Both Terminal 1 and Terminal 2 of the resonator in Fig. 1 (a) were

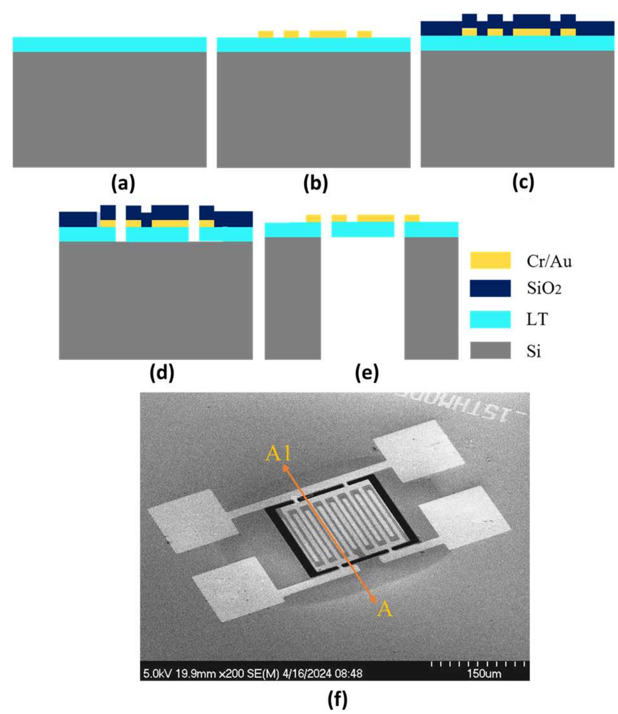

Figure 2. The contour mode resonator fabrication process flow: (a) Lithium Tantalate (LT) bonded on Silicon (Si) substrate; (b) Patterned electrodes; (c) Oxide mask deposition; (d) LT etching using oxide mask; (e) Released resonator; (f) Scanning electron microscopy (SEM) of the resonator.

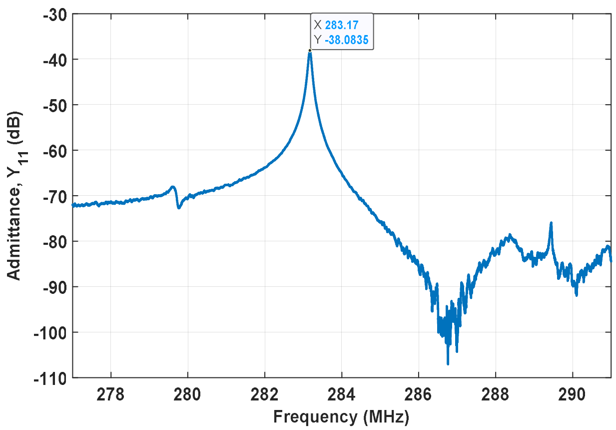

Figure 3. The frequency response of the resonator.

connected to the collector of the transistor, while the ground port was connected to the base of the transistor. In future implementations, the second port can be leveraged for additional frequency tuning and correction through the piezoelectric stiffening effect. This could further enhance the frequency control and stability.

For the buffer stage, an additional AT-41486 transistor was utilized to establish a connection between the oscillator circuit and a 50 Ω termination device, such as an oscilloscope or a phase noise analyzer. In this study, we used RTO 1024 oscilloscope and Rohde & Schwarz FSUP signal analyzer.

The output waveform of the oscillator is depicted in Fig. 4 (b). The measured oscillation frequency of the circuit was 283.3 MHz, exhibiting a peak-to-peak amplitude of ~2 V. Moreover, the phase noise characteristics and output signal power of the oscillator are shown in Fig. 4 (c). The measured phase noise at 1 kHz and 1 MHz offset from the carrier is approximately -102.59 dBc/Hz and -164.58 dBc/Hz, respectively. Notably, the spectrum analysis reveals the absence of neighboring peaks within a range of at least 20 MHz.

To characterize the frequency versus temperature behavior of the LT based oscillator, the oscillator PCB was placed in a vacuum chamber, and was heated while maintaining a partial vacuum. The measuring setup and the obtained TCF of the oscillator is illustrated in Fig. 5 (a) and (b), respectively. The results show a turnover temperature of ~90°C, with a frequency drift of 350 ppm from 30°C to 90°C. Therefore, the high turnover temperature exhibited by this LT-based oscillator makes it promising for implementing oven-controlled, highly stable oscillators for precision timing applications.

The performance of this oscillator is compared with several state-of-the-art piezoelectric MEMS oscillators in Table 1. For better comparison, the reported phase noise values are normalized to the oscillation frequency of 283 MHz. Compared to other oscillators, the LT-based oscillator reported in this work exhibits excellent phase noise performance, while also offering a turnover temperature. This positions the LT-based MEMS oscillator as a competitive solution for ultra-stable oven-controlled clock applications.

CONCUSION

This work has demonstrated a low phase noise MEMS oscillator employing a contour-mode lateral-field-excited LT resonator. The designed resonator, optimized for a 35-degree orientation off the Y-axis of the X-cut wafer, exhibits a turnover temperature above 90°C, enabled by the geometric design and inherent material properties of LT. The fabricated ~283 MHz

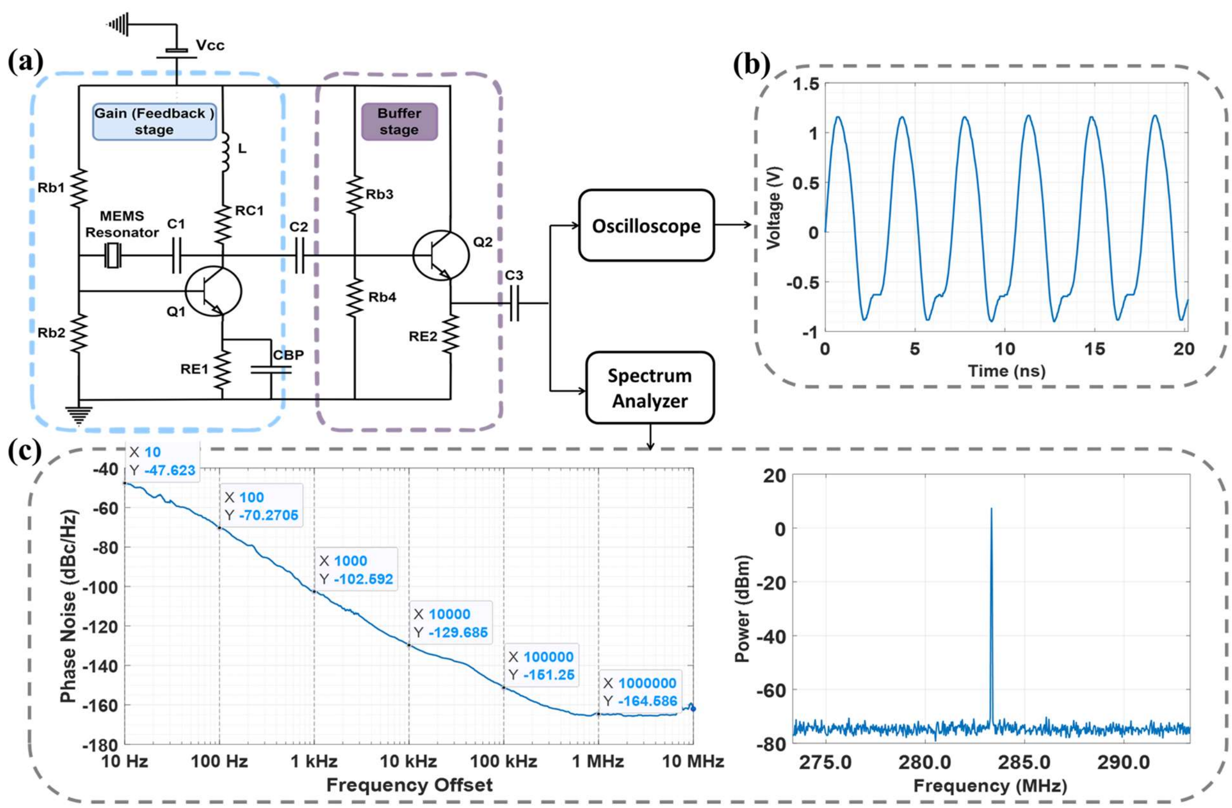

Figure 4. (a) Schematic of the oscillator circuit and measured (b) output waveform, (c) the measured phase noise and output signal power of oscillator.

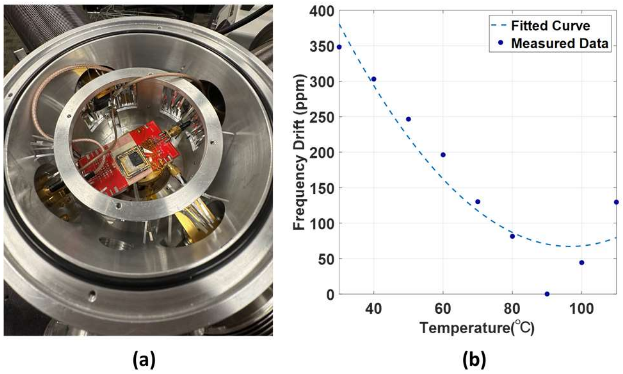

Figure 5. (a) The oscillator circuit inside the vacuum chamber used for measuring the TCF, and (b) the obtained TCF plot.

oscillator circuit achieved a phase noise of -102.59 dBc/Hz and -164.58 dBc/Hz at 1 kHz and 1 MHz offsets, respectively. The oscillator also demonstrated a frequency variation of only 350 ppm from 30°C to 90°C. These results indicate the potential of LT-based contour-mode MEMS resonators for implementing highly stable, low phase noise, and power-efficient oven-controlled oscillators, which are crucial for a wide range of precision timing applications.

Table 1: Oscillators performance summary and comparison.

Piezoelectric MEMS Oscillator	**[11]**	**[7]**	**[12]**	**[13]**	**[14]**	**This Work**
Resonator Type	LiNbO3	AlN /Si	AlN	AlN /Si	AlN	**LT**
Center Frequency (MHz)	150	123	1500	233	204	**283**
P.N. @1KHz[1] (dBc/Hz)	-78	-116	-59	-90	-74	**-102**
P.N. Floor[1] (dBc/Hz)	-140	-155	-165	-136	-117	**-164**
Power (mW)	5	-	6.9	-	0.05	**8.2**

[1]Normalized to 283 MHz; P.N.: Phase Noise

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