TEMPERATURE-STABLE THIN-FILM LITHIUM TANTALITE-ON-SILICON RESONATORS

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ABSTRACT

In this paper, a novel passive temperature compensation method is introduced for the first time that could potentially result in canceling both the first and the second order temperature coefficients of frequency (TCF) in silicon-based resonators. The main idea of this work is to construct the resonator body from a thin film of X-cut Lithium Tantalite (LT) bonded to a degenerately n-type doped silicon film aligned to the [100] crystalline orientation. The two films individually exhibit quadratic TCF curves in opposing directions, hence the combined heterostructure is expected to result in a near-perfect compensation of the temperature variation of frequency. This idea is implemented with a 1.8 µm LT film bonded to an SOI wafer, and an overall frequency drift as low as 72 ppm has been observed over the temperature range of 0 ˚C to 90 ˚C at 96 MHz operation frequency for the fabricated contour-mode resonators which is a significant reduction compared to conventional silicon-based resonators and comparable to what is achievable in quartz resonators.

KEYWORDS

Frequency drift, stable resonators, X-Cut LT, highly doped silicon, TCF.

INTRODUCTION

Some of the main requirements for radio-frequency acoustic wave devices are to attain high temperature stability, and high - quality factor. It is due to such demands, that quartz crystal oscillators have been used in most electronic platforms. However, integration of quartz resonators with microelectronics and scaling their frequency is a challenge that has fueled research in seeking alternatives.

Recently, micro electro-mechanical (MEMs) resonators have gained popularity as a replacement for quartz resonators in some application due to their smaller size, lower power consumption, and the potential for CMOS compatibility. Nevertheless, the persistent deficiency of micro-electro-mechanical resonators compared to their Quartz counterparts is their relatively large frequency drift over temperature [1-3]. For example, in lightly-doped conventional silicon and lithium niobate (LN) MEMS resonators, the temperature coefficient of frequency (TCF) is approximately -30 ppm/°C and -80 ppm/°C, respectively, resulting in substantial frequency drifts (several thousand ppm) over the -40 °C-80 °C temperature range [3,4]. To address this deficiency, several active and passive compensation techniques have been developed to improve the temperature-frequency performance of silicon-based resonators [5].

The active compensation can be implemented through a myriad of techniques including electrostatic tuning, capacitive frequency pulling and oven-controlled frequency stabilization [5]. In all the aforementioned methods additional circuitry is involved which increases the power consumption and adds more system-level complexity.

On the other hand, the passive compensation techniques mainly focus on designing the intrinsic properties of the utilized materials to reduce the frequency drift due to the temperature change. Most of the successful passive temperature compensation approaches are based on degenerate doping of the silicon device layer [2] or using a composite structure that contains silicon dioxide (with positive TCE) to partly compensate for the negative frequency drift of silicon and piezoelectric materials, such as AlN and LN in MEMS resonators. However, the resulting overall temperature stability is usually not comparable to quartz due to the quadratic nature of the resulting TCF curve. In addition, silicon dioxide compensation layer unavoidably degrades quality factor and limits the achieved temperature range [3].

Unlike pure silicon and most typical piezoelectric material, the resonance frequency of thickness-shear mode devices built on X-cut lithium tantalite (LT) is approximately an upward quadratic function of the temperature, exhibiting a zero TCF, also known as a turnover temperature [6,7]. In this paper, we exploit a novel passive compensation method to achieve temperature-stability in LT-on-SOI resonators through precise alignment of the crystalline orientations in silicon and LT. The S0 lamb wave in these resonators is excited by a lateral electric field through a single interdigitated transducer (IDT), that enables integration of multi-frequency devices on a single chip.

THEORY AND DESIGN

In our recent report [8], we demonstrated that in contour mode resonators fabricated on an X-cut plate of LT and rotated with respect to the -Y-axis (Figure 1(a)) a turnover temperature is observed and the frequency vs. temperature plot is an upward quadratic function. Figure 1(b) depicts the simulated frequency drift versus temperature for rotated X-cut LT at θ =36, θ=40 and 44 deg as well as n-type doped (n ~ 6.6×10^{19} cm^{-3}) [100]-aligned silicon lateral-extensional resonators respectively [3,8].

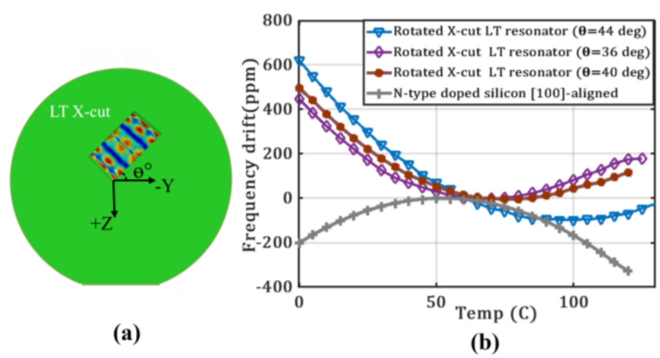

Figure 1:(a) The orientation of contour-mode resonators fabricated on LT substrate. (b) Simulated frequency drift versus temperature for rotated LT and degenerately n-type-doped silicon resonators [8].

As seen, LT resonators have the opposite TCF trend compared to highly n-type doped silicon. Observing this unique property has sparked the idea that by bonding thin-film LT on highly doped silicon, we could nullify both first and second-order terms of the TCF to achieve highly stable micro-machined resonators. To test this hypothesis, the proposed resonators were modeled and simulated in COMSOL Multiphysics by combining the slab of LT on n-type doped Si aligned to [100] using eigenfrequency analysis to examine and verify the hypothesis discussed above. The simulated stress profile of a one-port 7th order resonator as well as the cross-sectional view of the resonator's displacement are shown in Figure 2. with the design parameters of Table 1. The electrodes are placed on the top of the LT at mechanical antinodes to form the excitation lateral electric field.

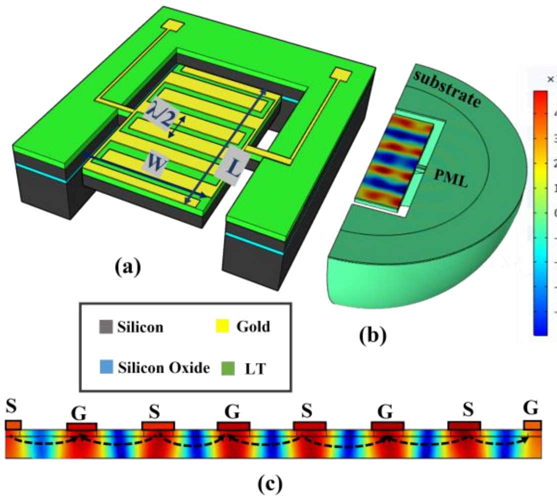

Figure 2:(a) The schematic view of a 7th-order harmonic contour-mode LT-on-Silicon resonator(b) simulated stress field of half of the resonator in y direction (c) displacement of resonator with electrodes placed at anti-nodes.

Table 1: The dimensions of the simulated resonator

Parameter	*Value*
Plate length *(L)*	238 µm
Plate Width *(W)*	154 µm
Silicon slab thickness	5 µm
LT slab thickness	1.5 µm
Wavelength (λ)	68 µm
Target resonant frequency	100 MHz

Two main factors that affect the temperature-induced frequency variations are change in effective Young's modulus, which depends on elastic constants, and thermal expansion. In our simulation, we neglect the thermal expansion since the change in elasticity is deemed to be the dominant effect. In the simulation the elasticity matrix of both LT and highly-doped silicon resonators is varied with temperature to find the frequency drift. The elasticity constants for LT and silicon were borrowed from [7] and [9], respectively.

Several series of simulations have been performed to study the effect of Si/LT thickness ratio as well as LT orientation with respect to the -Y-axis on the frequency vs temperature (Figures 3 and 4). As seen, for lower thickness ratios in a device (with rotation angle of 36-44 deg), the TCF behavior expectedly resembles that of the highly doped Si resonators and for higher ratios, it is similar to LT resonators. At a thickness ratio of ~0.3 a minimum frequency variation is achieved (Figure 3).

The simulation results of the composite structure with a thickness ratio of 0.3 are plotted in Figure 4 for different rotation angles of LT with respect to -Y-axis. A minimum frequency drift of 70 ppm between 0 C to 80 ˚C has been accomplished at θ=36 deg, confirming the initial hypothesis (Figure 4).

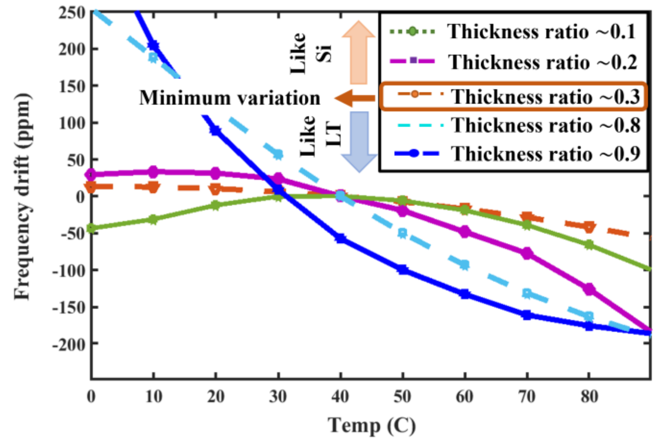

Figure 3: The simulated frequency drift versus temperature for different thickness ratios of LT/Si for the structure depicted in Figure 2.

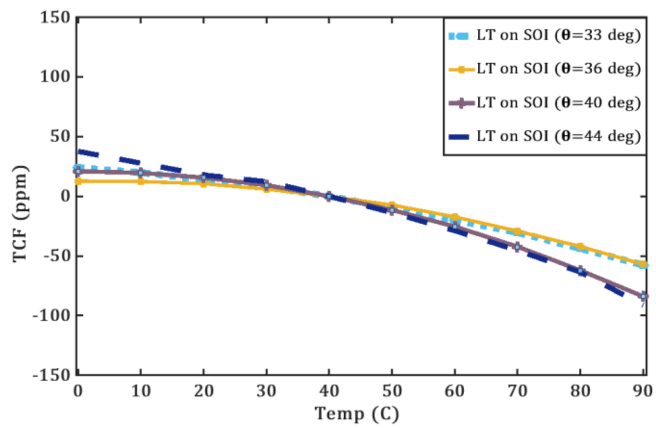

Figure 4: The simulated frequency drift versus temperature of the proposed resonator at different angles for the structure depicted in Figure 2.

DEVICE FABRICATION

The fabrication of the device summarized in Figure 5, starts with bonding a 4-inch lithium tantalate X-Cut substrate onto an SOI wafer and thinning it to the targeted thickness (e.g. 1.8µm). This step is outsourced and is accomplished by our industrial partner, "NGK Insulators". The SOI device and handle layer silicon thicknesses are 5 and 450 µm, respectively. To form the interdigitated electrodes on LT, Cr/gold (30nm/120nm) is deposited by an Ebeam evaporator and patterned through the lift-off process. In the next step, the boundary of the resonator is defined by plasma etching the full stack of the material (LT and silicon substrate) down to the SOI buried oxide (BOX) layer. LT is etched physically in an inductively-coupled argon plasma, while Si is etched in a deep reactive ion etching chamber (Bosch process). Finally, the backside of the substrate is etched to the BOX layer by Bosch process and the device is released by etching the BOX layer in the buffered oxide solution. The scanning electron micrographs (SEM) of one of the fabricated devices is shown in Figure 6.

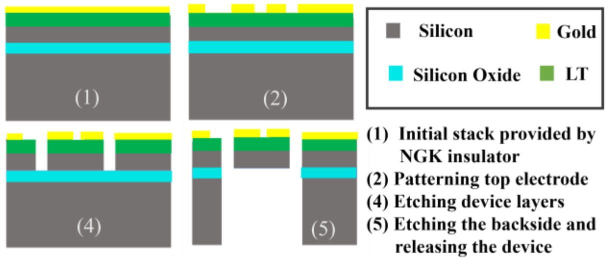

Figure. 5: The Process flow of fabrication resonators.

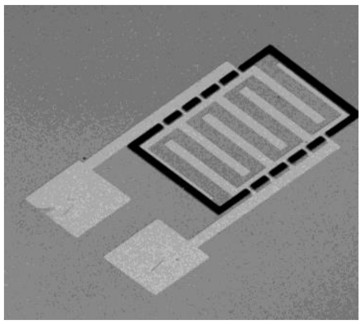

Figure. 6: The SEM of the resonator

EXPERIMENTAL RESULTS

The measured admittance response of a one-port resonator operating at 96 MHz is shown in Figure 7. The equivalent Butterworth-Van Dyke (BVD) model is used to extract the for Q, electromechanical coupling coefficient (K_t^2), motional components (C_m, L_m, R_m), and static capacitance (C_0). The K_t^2 and Q are calculated to be approximately 6.5 K and .04 % respectively.

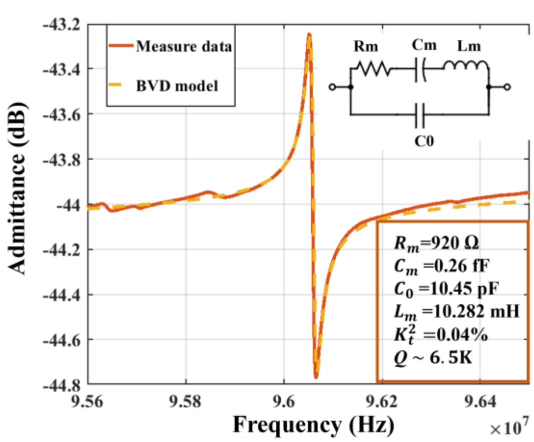

Figure 7: The simulated and measured frequency response of the resonator along with the extracted BVD model in the inset.

The frequency drift measurement is conducted in a cryogenic vacuum probe station (Figure 8). The sample holder is cooled by liquid nitrogen and heated with a resistive heater and the temperature is controlled by a PID controller within ±0.05°C. The frequency drift of the resonators at θ=36, θ=40 and θ=44 deg rotation angle between 0 ◦C to 90 ◦C have been measured and plotted in Figure 9.

A minimum frequency drift of around 72, 92 ppm have been obtained for the devices with rotation angles of θ=36 and θ=44 degrees. These values are significantly lower than conventional silicon-based MEMS resonators, AlN-based resonators [6] and Lithium Niobate (LN) resonators [4].

The observed increase in the temperature-induced frequency drift of the resonator roated at θ=40 deg (~500 ppm) confirms the simulations results indicating that the frequency variation strongly depends on the orientation.

The discrepancies between the trend of the measured and simulated frequency drift versus temperature could stem from the tolerance of the silicon doping, and rotation angle of LT which all cause change in frequency behavior of LT and Si. For example, in simulation, the doping of the slab of silicon is assumed to have a constant value of 6.6×10^{19} cm^{-3}, while the actual doping of Si is somewhere between 5×10^{19} to 6.6×10^{19} cm^{-3}. We predict that superior results could be achieved by improving the fabrication process and optimizing the thickness ratio of silicon and LT substrate as well as rotation angle of LT.

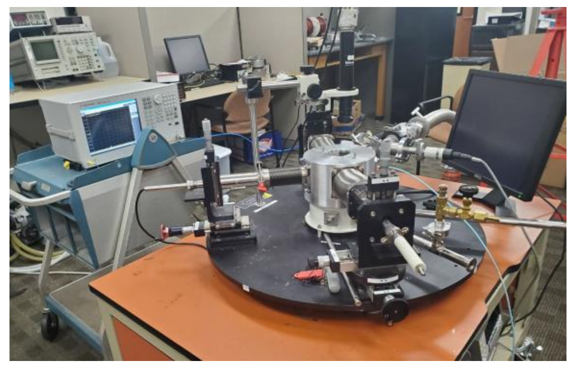

Figure 8: TCF measurement setup

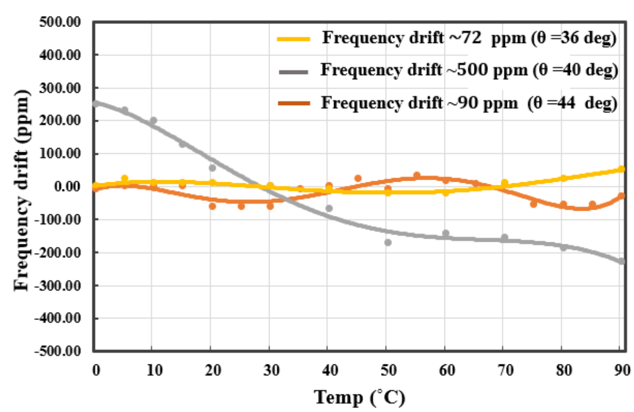

Figure 9: Measured frequency drift of the resonators versus temperature.

CONCLUSION

In this work a novel passive temperature-compensation technique based on an engineered substrate is presented in silicon micro-resonators, which addresses the important demands of most communication systems, including stability and high-quality factor. A thin layer of LT (1.8 µm thickness) has been overlayed on a 5 µm thickness n-type doped silicon to compensate for both the first and second order coefficients of frequency-temperature variation in silicon.

The proposed resonators operating at 96 MHz are shown to offer high quality factor (>6.5 K) and low frequency drift of 72 ppm between 0 to 90 ˚C, which is a great improvement compared to conventional silicon resonators. These lateral-field excited contour mode resonators have the potential to be one of the best candidates for extremely stable time-keeping applications.

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