AN AGING COMPENSATED ALSCN-ON-SI BULK ACOUSTIC WAVE OSCILLATOR TOWARDS TACTICAL-GRADE CLOCK GENERATION

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ABSTRACT

The long-term stability of temperature-stable crystal oscillators is several orders of magnitude lower compared to atomic clocks, due to the large aging rate of mechanical resonators. Here, we demonstrate a compensation approach that reduces the effective aging rate in an AlScN-on-Si bulk acoustic wave (BAW) oscillator to less than 0.15 ppb per day. This is 3-5 orders of magnitude improvement compared to the state-of-the-art quartz and MEMS counterparts. The presented oscillator is based on an AlScN-on-Si BAW resonator operating in a temperature-insensitive shear mode at 64.4MHz, with a Q of 65K and turn-over point of 54.5°C. The aging compensation is achieved by tailoring the residual stress in AlScN transducer to induce a relaxation rate opposing that of mass exchange, as well as inducing transient zero mass-exchange periods by intermittent increase in oscillator drive amplitude. These result in a zero frequency drift after ~15 days and an effective aging rate of 142 ppt per day over 35 days of operation.

KEYWORDS

Silicon bulk acoustic wave resonator, temperature-stable oscillator, aging compensation, tactical-grade clock.

INTRODUCTION

Precise time-keeping in GPS-denied environments is essential for various applications such as wireless communication and navigation. Current hand-held systems rely on temperature-stable quartz and silicon (Si) MEMS oscillators during hold-over periods (*i.e.*, operation between consecutive clock synchronization with GPS), since they provide small size, weight and power consumption (SWaP). Despite their superior SWaP, the hold-over of these clocks is substantially lower compared to atomic clocks. This is due to the poor long-term stability of mechanical clocks, which corresponds to the large aging rates in mechanical resonators. The time-error of mechanical clocks relates to the resonator aging through:

$$t_{error}(t) = \int_0^t \frac{\Delta f_{aging}}{f_0}(t)dt = A_{effective}\frac{t^2}{2} \qquad (1).$$

Here, $A_{effective}$ is the linear effective aging rate with a value reported over 10 ppb/day to 1 ppm/day in state-of-the-art crystal and MEMS oven-controlled oscillators [1-3]. These values are 4-6 orders of magnitude higher than what needed to achieve tactical grade operation that corresponds to a time-error of less than 1µsec over 1 week of operation (translating to $A_{effective}$ of sub-1 ppt/day).

The large aging rate in mechanical resonators is a result of two distinctive processes. First, the residual stress within the resonator body or at its boundary (during packaging) tends to relax over time. The resulting variation translates to resonator frequency drift through elastic nonlinearities. Second, the residual mass within package transfers to resonator surface and induces a frequency drift corresponding to the mass exchange dynamics.

Achieving the effective aging rates needed for extended standby period, as needed for emerging wireless standards besides tactical applications, requires suppression of both stress-relaxation and mass-exchange processes. While this may be practicable for

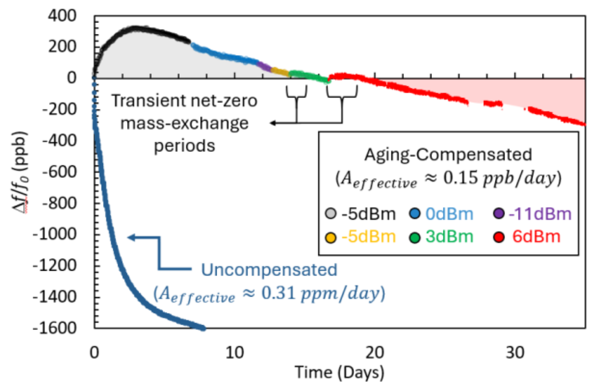

Figure. 1: *Measured frequency drift of AlScN-on-Si BAW oscillators, with and without aging compensation. Tailoring residual stress in AlScN along with intermittent dilution of mass exchange by increasing drive amplitude enables 5 orders of magnitude improvement in effective aging rate.*

stress-relaxation, through pre-aging of clock over extended time and at elevated temperatures, it is not physically possible to suppress mass exchange within limitations of fabrication and packaging processes that are used in quartz and MEMS clocks.

In this work, for the first time we demonstrate an approach for aging-compensation based on using stress-relaxation to effectively reduce mass-exchange drifts over long periods of operation time. Additionally, we demonstrate transient suppression of mass transfer through deriving the resonator at increased drive amplitudes to lower the aging rate. This results in a record-low effective aging rate of ~142 ppt/day after 35 days of operation, which is 3-5 orders of magnitude lower compared to state-of-art quartz and MEMS. Figure 1 shows effectiveness of the presented approach by comparing long term frequency drift of AlScN-on-Si BAW oscillators with and without aging compensation.

RESONATOR DETAILS AND AGING PHYSICS

Our mechanical resonator is created from 600nm-thick piezoelectric AlScN transducer grown atop a 50µm-thick doped

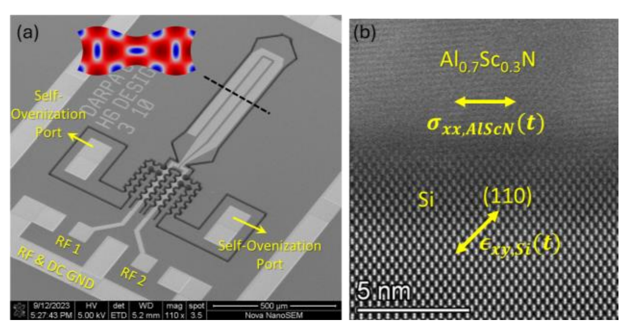

Figure. 2: *(a) SEM and (b) X- TEM images of AlScN-on-Si X-Lamé resonator. Residual stress in AlScN transducer induces a time varying strain in Si that contributes to frequency drift through elastic nonlinearities. the inset shows cross-sectional mode-shape.*

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silicon layer. The device operates in cross-sectional Lamé (X-Lamé) mode with high Q and parabolic temperature characteristic. Figure 2 shows the SEM image of the resonator, as well as cross-sectional TEM highlighting the AlScN-Si interface.

The frequency of X-Lamé resonator relates to acoustic properties, dimensions (considering W = 3H$_{Si}$), residual stress and mass exchange through:

$$f_{X-Lamé}(t) = \frac{1}{W\sqrt{2}}\sqrt{\frac{G_{110}^{(0)} + G_{110}^{(1)}\frac{\sigma_{AlScN}(t)H_{AlScN}}{2H_{Si}E_{100}^{(0)}}}{\rho_{AlScN-Si} + \rho_{transfer}(t)}} \quad (2).$$

Here, $G_{110}^{(0)}$ and $G_{110}^{(1)}$ are second- and third-order shear moduli in (110) crystal direction and $E_{100}^{(0)}$ is the second-order extensional modulus in (100) direction of Si. H_{AlScN} and σ_{AlScN} are the thickness and residual stress of AlScN transducer, respectively. $\rho_{AlScN-Si}$ is the corrected density of AlScN-on-Si resonator, and $\rho_{transfer}$ represents the effect of mass exchange. To compensate the aging of X-Lamé resonator, σ_{AlScN} can be tailored to oppose the impact of $\rho_{transfer}$. Considering $\rho_{transfer}$ is positive (mass adsorption at resonator surface), tensile residual stress is induced in AlScN by controlling nitrogen gas flow during growth. Figure 3 compares the stress on two wafers, before and after tailoring, showing wide range of control and the resulting tensile stress in the wafer used for aging compensation. Comparing the resonators implemented in these two substrates, it is evident that in the resonator with compressive AlScN, a large stress-relaxation aging is added to the mass exchange rate, inducing a descending trend. On the other hand, for the sample with tensile AlScN, an initial ascending trend in frequency is evident that is compensating mass exchange rate. As a result, after ~15 days of operation a net-zero drift is noted in frequency.

Besides tailoring the stress, we benefited from intermittent increase in oscillator drive amplitude. When increasing drive amplitude, added mass on resonator surface is desorbed by kinetic energy that overcome van der Waals adhesion. This results in a transient period with net-zero mass exchange. Once the system reaches steady-state, mass exchange continues at the same rate governed by package pressure and volume, and surface energy.

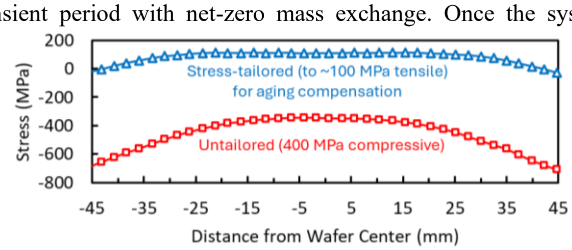

Figure. 3: *Measured residual stress in piezo transducer, across 100mm wafers, for samples with and without process optimization. For aging-compensation, ~100 MPa tensile stress is induced.*

OSCILLATOR CHARACTERISTICS & TEST SETUP

The resonators are mounted on a PCB board and inserted in a vacuum chamber with a volume of ~5 liters. The chamber pressure is reduced to 10mTorr. Figure 4 shows the measured frequency response of the AlScN-on-Di BAW resonator. A Q of 65K is measured for the X-Lamé mode at 64.4 MHz. Figure 5 shows the measured temperature characteristics of the resonator.

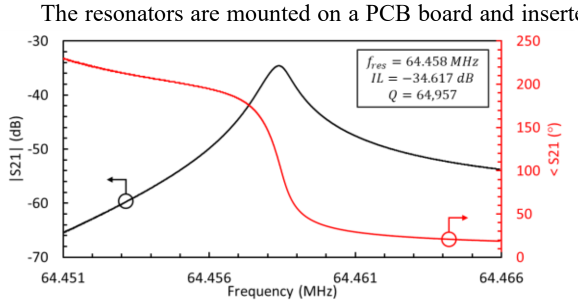

Figure. 4: *Measured response of the aging-compensated resonator.*

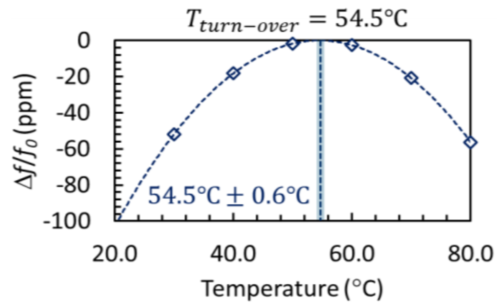

Figure. 5: *Measured temperature characteristics of the resonator.*

The resonator is connected to a Zurich UHFLI lock-in amplifier to create the oscillator. The temperature of the oscillator is controlled within ±0.6°C around turn-over temperature (*i.e.*, 54.5°C) using an environmental chamber. The effect of temperature fluctuations, with a period of ~2 hours, is evident in the zoomed-in frequency-drift plot (Figure. 6).

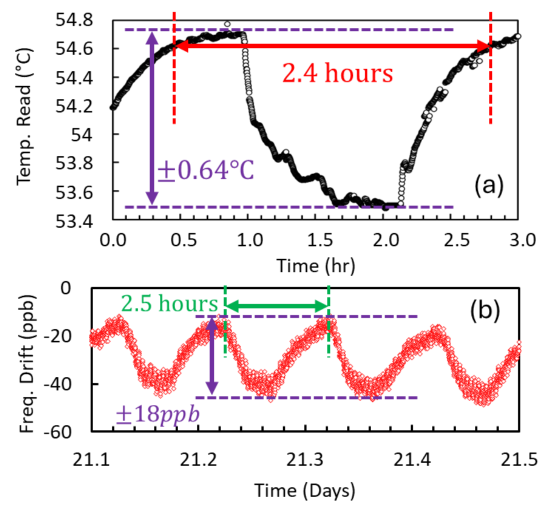

Figure. 6: *(a) Measured chamber temperature. (b) Zoomed-in oscillator drift, showing the effect of temperature fluctuations.*

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