

Theoretical-Experimental Investigation of a Surface Acoustic Wave Sensor Based on Dual Substrates

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Summary:

To monitor air pollution, an innovative cascade impactor integrating Surface Acoustic Wave (SAW) sensors has been developed within our team. Conventional impaction plates are replaced by SAW sensors to measure PM10 and PM2.5, i.e., particles with aerodynamic diameters below 10 μm and 2.5 μm [1]. These sensors are typically based on bulk piezoelectric materials such as AT-cut quartz, which offers excellent thermal stability but low electromechanical coupling, limiting performance. The study investigates alternative substrates, comparing bulk lithium tantalate with a piezoelectric-on-insulator (POI) configuration in terms of performance. Numerical simulations and experiments demonstrate that the POI substrate provides enhanced sensitivity and improved thermal stability. These results highlight its potential for more efficient particulate matter detection.

Keywords: SAW sensors, Bulk substrate, POI substrate, sensitivity analysis, air monitoring.

Background, Motivation and Objective

Air pollution monitoring requires accurate, real-time detection of particulate matter (PM), which poses serious health risks due to deep respiratory penetration. SAW devices exhibit high gravimetric sensitivity and have been investigated by our team as microbalances for particle detection [1]. These sensors must combine high sensitivity at low concentrations with robustness under varying environmental conditions. Two key parameters are therefore considered: the electromechanical coupling coefficient (k^2), governing wave-surface interaction, and the temperature coefficient of frequency (TCF), affecting stability. Initial sensors based on quartz substrates supporting Love waves exhibited $k^2 = 0.14\%$ and $\text{TCF} = -0.035 \text{ ppm}/^\circ\text{C}$ at 125 MHz [1]. To improve performance, quartz is replaced by a composite Piezoelectric-on-Insulator (POI) substrate, investigated and compared with its bulk counterpart.

Description of the Substrates Used

The substrates investigated in this study are, in accordance with IEEE standard, Lithium Tantalate (YXI)/42° in bulk form, referred to as LT42, and in piezoelectric-on-insulator form, referred to as LTOI42, as shown in Fig. 1. The bulk substrate consists of a single LiTaO₃ layer, whereas the POI structure is composed of a thin LiTaO₃ layer bonded onto a SiO₂ layer and supported by a silicon substrate.

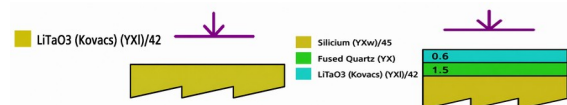


Fig. 1. Bulk and POI lithium tantalate substrates (thickness in μm) used for simulations

Simulation

A numerical tool based on Green's function formalism was used to evaluate the acoustic properties of the substrates. It allows the calculation of key parameters such as the electromechanical coupling coefficient (k^2) and phase velocity [2]. Simulations at 500 MHz show that LTOI42 exhibits higher k^2 (10.984%) and near-zero $\text{TCF} = 4.103 \text{ ppm}/^\circ\text{C}$ compared to LT42 ($k^2 = 5.282\%$, $\text{TCF} = -26.538 \text{ ppm}/^\circ\text{C}$), indicating improved sensitivity and thermal stability. To further assess the impact on mass sensitivity, particle deposition is simulated by introducing a gold layer on top of the substrates. Sauerbrey's equation is then used and adapted accordingly:

$$S_g = \frac{\Delta v}{v_0} \cdot \frac{A}{\Delta m} \quad (1)$$

where S_g is the gravimetric sensitivity (cm^2/g), $\Delta v/v_0$ is the normalized phase velocity variation, A is the active sensing area, and Δm is the deposited mass related to the density and thickness of the gold layer. The simulations evaluate the phase velocity and as a function of gold layer thickness from which the gravimetric

sensitivity is estimated. As shown in Fig. 2, and using $\Delta m = d_e \cdot \rho \cdot A$, where d_e is the thickness of gold layer, the thickness range (0.01–0.2 μm) corresponds to 1.5–29.9 μg for LTOI42 and 2.15–43.0 μg for LT42. In this low-mass region, LTOI42 shows higher sensitivity than LT42. This indicates better performance of LTOI42 for thin deposited layers.

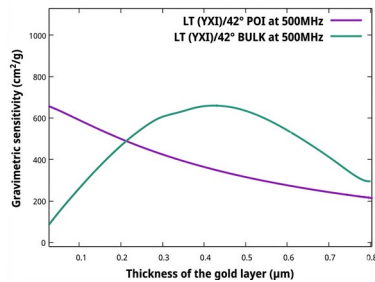


Fig. 2. Gravimetric sensitivity for LTOI42 and LT42

Experiments

Experiments were conducted in a leak-proof chamber where the cascade impactor is placed. Tests were done under a PM2.5* concentration of $250 \pm 5 \mu\text{g}/\text{m}^3$. A Gilian® pump of type Gilair™ Plus is then used to collect the generated particles through the impactor at 3 Lpm flowrate. The sampling conducted until the surface of both devices are saturated as shown in Fig. 3.

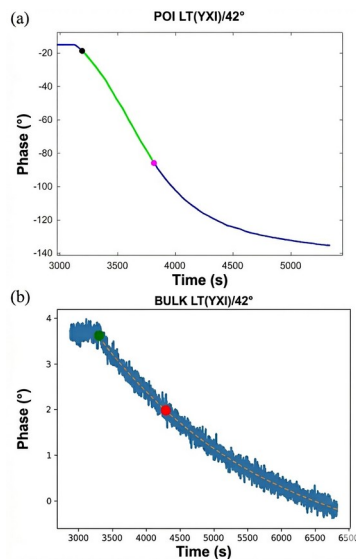


Fig. 3. Phase monitoring upon long term particle collection for (a) LTOI42 and (b) LT42

To relate the simulated gravimetric sensitivity S_g to the experimental sensor sensitivity S_s , a model previously developed within our team is used, based on Sauerbrey's approach [3]. The sensor sensitivity is defined as:

$$S_g = \frac{df}{f_0} \cdot \frac{A}{dm} \quad (2)$$

with dm representing the mass of particles deposited on the sensing area A . By linking the phase variation to the deposited mass and the operating conditions of the impactor, the following relationship is obtained:

$$S_{s,estimated} = S_g \frac{\alpha f_0 Q}{2A} \quad (3)$$

where $\alpha = d\phi/df$, f_0 is the operating frequency, Q the flow rate, and A the sensing area. This formulation enables a direct comparison between experimental and theoretical sensitivities, allowing validation of substrate influence on sensor performance.

Substrate	$S_{s,experimental}$ ($^{\circ} \cdot \text{s}^{-1} \cdot \text{g}^{-1} \cdot \text{m}^3$)	$S_{s,estimated}$ ($^{\circ} \cdot \text{s}^{-1} \cdot \text{g}^{-1} \cdot \text{m}^3$)
LN42	22.02	189.905
LNOI42	266.85	26814.70

Analysis

The comparison between experimental and estimated sensitivities shows a significant difference in absolute values, while preserving the same trend between substrates. This discrepancy has previously been observed for other substrates and is attributed to the absence of a correction factor β in the theoretical model [3]. Indeed, the estimation of sensitivity based on gravimetric simulations does not account for several real phenomena such as particle surface interactions, particle rebound, and non-uniform deposition within the impactor. These effects are incorporated through a correction factor β (< 1), which must be introduced into the model to match experimental observations.

Conclusion

In both experimental and estimated results, the POI-based substrate shows higher sensitivity than the bulk, consistent with the higher electromechanical coupling coefficient (k^2) and confirming the strong influence of substrate properties. Experiments under controlled particle concentrations will be conducted to characterize sensitivity and its evolution with fooling, enabling improved model validation including the β correction factor and determination of the detection limit.

References

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