High Overtone Bulk Acoustic Resonators Based on Thinning Single-crystal Piezoelectric Layers

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Abstract— **Bulk acoustic waves excited in thin piezoelectric films have revealed their capabilities for addressing the problem of high frequency RF filters (above 1 GHz). In this paper, we propose an alternative to thin film deposition consisting in single crystal wafers bonded on a substrate (for instance silicon) and thinned, allowing for plate thickness close to 10µm. This has been achieved on 3 inches wafers and allows for an accurate selection of the wave characteristics. More, the properties of the piezoelectric material are found conform with tabulated values, enabling one to reliably design any passive signal processing device.**

I. INTRODUCTION

In the 80s, Lakin & al. have emphasized the capability of High Overtone Bulk Acoustic Resonators (HBAR) to present high quality factors at frequencies in the GHz range. The high overtone bulk acoustic resonator (HBAR) is a key technology for the production of radio frequency (RF) resonators and filters.

HBAR exploit the thickness-extensional vibration mode of thin piezoelectric films with thicknesses of a few microns so that their harmonics resonances frequency is in the GHz range. The necessary piezoelectric thin films are generally deposited by sputtering with their C axis normal to the wafer surface. This fabrication process results in limited Q factors, which in turn sets limitations on their use as resonators for time and frequency applications. In view of improving the Q factor of thin films, it is desirable to use a single-crystal piezoelectric material such as lithium niobate, lithium tantalate, or quartz.

This paper describes fabrication methods to achieve high frequency acoustoelectric resonators. It is well known that the intrinsic losses of single crystal materials are much smaller than those of sputtered thin films. In addition, the material cut can be chosen to optimize such parameters as the coupling factor or the temperature dependence. Single-crystal piezoelectric materials however are not usually available under the form of thin wafers (i.e. with thickness smaller than 100 µm). First, we have developed a process for the fabrication of high quality piezoelectric films of intermediate thickness (between 50 and 10 µm) for bulk acoustic wave (BAW) resonator and filter applications. A piezoelectric wafer first is bonded onto a substrate (silicon) using a thin gold layer using a dedicated facility. It is subsequently thinned by lapping and micro-polishing to control the final thickness. The final resonator thickness ranges between 10 to 20 microns at the end of the process.

Different measurement results are exposed for both approach and the exploitation of these devices for the fabrication of oscillator and filters are shown and discussed.

II. HBAR FABRICATED ON SINGLE-CRYSTAL SUBSTRATE

HBAR springs from the conjugation of the strong coupling coefficient of deposited piezoelectric thin films and of the high intrinsic quality of used substrates. The piezoelectric film and the two electrodes on its both sides are used as a transducer whereas the acoustic energy is mainly trapped in the substrate. The resonant frequency corresponds to a half wavelength in the entire thickness of the device and, in opposition to FBAR and SMR for which only odd harmonics exist, one can utilized both odd and even harmonics which both satisfies the boundary conditions in that case. The fundamental, generally in the vicinity of 10MHz, has no specific interest but $Q.f$ products around 1.1×10^{14} have already been obtained for high overtones using aluminum nitride (AlN) thin films deposited onto sapphire [7]. In order to reinforce the study of HBAR, we propose to electrically characterize a resonator built using $LiNbO_3$ thin films bonded onto silicon plate. Lithium niobate was chosen again because of its strong piezoelectric coupling properties. We start by a gold thin layer deposited by sputtering on both $LiNbO_3$ and Silicon wafers.

The lithium niobate wafer is then bonded onto the silicon substrate using the thin gold layer with a thickness of 200 nanometers into an EVG wafer bonding machine. During the bonding process, we heat the material stack at a temperature of 30°C and we apply a pressure of 65 $N.cm^{-2}$ to the whole contact surface. This process yields an homogeneous and high quality bond as shown in figure 2. It is subsequently thinned by lapping step to an overall thickness of 20 to 30 microns. It is then followed by a micro-polishing step, yielding a final $LiNbO_3$ thickness ranging between 70 to 80 microns. The gold layer becomes the floating electrode and finally, the two topside Aluminum electrodes are deposited on the $LiNbO_3$ to achieve two series-connected resonators for test.

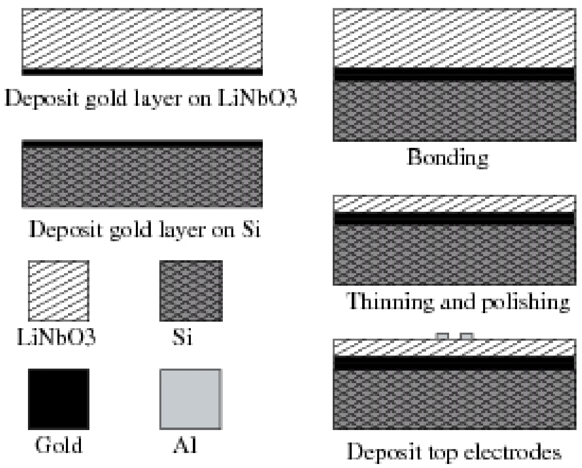


Figure 1. Flowchart of the thinned $LiNbO_3$ based HBAR

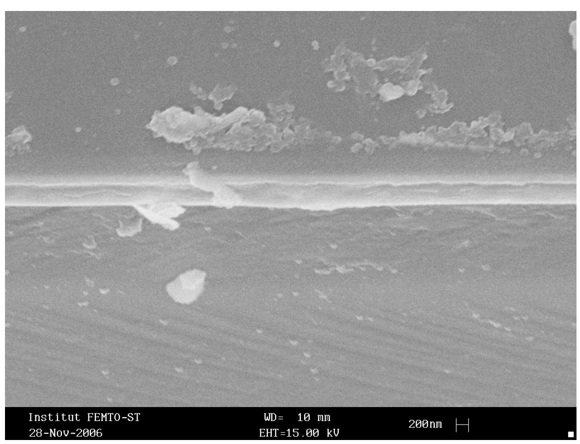


Figure 2. Detail of the gold bond between silicon and lithium niobate

The electrical response of the whole structure has been estimated first thanks to a 2D simulation software based on Fahmy-Adler formulation and a scattering matrix method for multi-layered media [6]. Electrical characterization then is performed with the above-mentioned network analyzer and tip probing bench. Figure 3 compares theoretical and experimental results. In this case, the thickness of the lithium niobate is close to 80 µm and the silicon wafer was 380 µm thick.

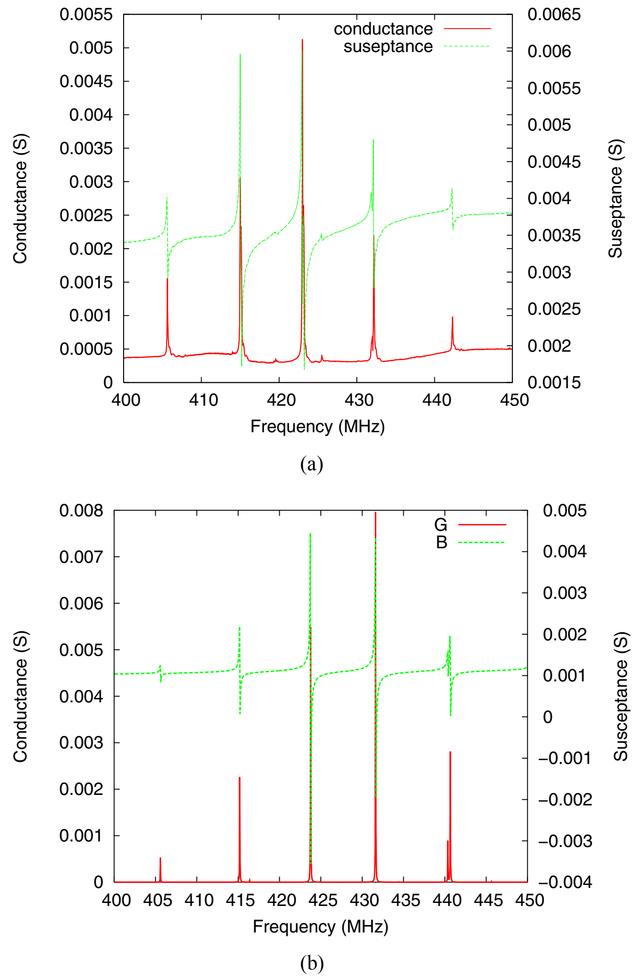


Figure 3. Comparison of an experimental (a) measurement with the theoretical prediction (b) of the electrical response of the resonator

The resonators exhibit Q-factors around 7500 at 430 MHz, yielding Q.f products about $3.2x10^{12}$ and the coupling factor (K_s^2 = 0.16%). The same device was fabricated with lithium niobate thickness close to 40 µm still on 380 µm thick silicon.

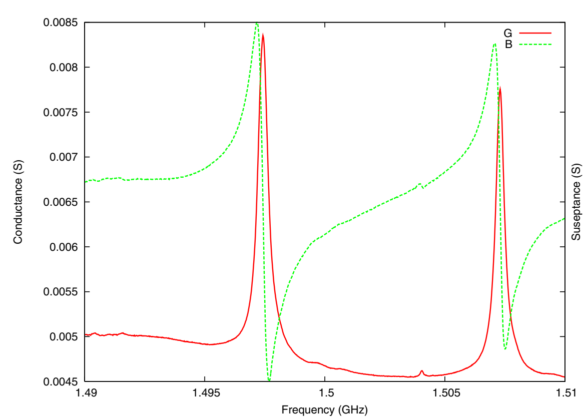
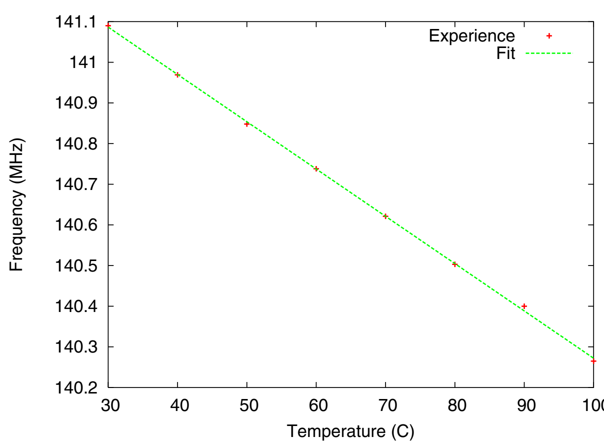


Figure 4. The electrical response of the resonator

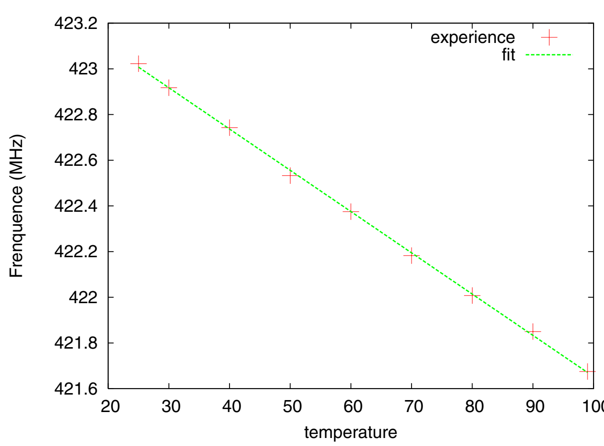
In that case, the resonators exhibit Q-factors around 2800 at 1507 MHz, yielding Q.f products about 4.2x10^{12} and the coupling factor (K_s^2 = 0.08%). Such a limited Q.f figure can be explained by the poor parallelism between the top $LiNbO_3$ surface and the Silicon-Niobate interface, due to a bad control of the lapping process yielding a significant thickness variation across the wafer (thickness variation larger than 30 µm on the 3" wafer surface). Consequently, we can obtain larger Q factors by first improving this control and second by using single resonators instead of 2 serial devices, as discussed in the next section.

III. Discussion

A very important point for the fabrication of stable resonator is the very strong thermal drift of the frequency versus temperature on $LiNbO_3$. We have characterized the temperature sensitivity of the fundamental mode of (YXl)/36° $LiNbO_3$ FBARs (thickness 25 µm, fundamental at 140 MHz). We found a thermal drift around –85 ppm/K (see Figure 5), in coherence with the data published on longitudinal bulk waves in lithium niobate [8].



(a)



(b)

Figure 5. Comparison of the thermal drift between $LiNbO_3$ FBAR fundamental mode (–85 ppm/K) (a) and $LiNbO_3$-on-silicon HBAR, harmonic #42 (–41 ppm/K) (b)

This rather strong drift encourages to find solutions for compensating temperature effects, as it is a main feature for practical filter applications. Let us finally note that the higher harmonic mode follows the same frequency-temperature law as the fundamental mode. In the case of $LiNbO_3$/Silicon HBAR, we can significantly reduce this drift thanks to the differential thermoelastic behavior of both material, yielding a reduced temperature coefficient of frequency (TCF) as found experimentally (fig.5b). The TCF reduction is more than a factor of 2, encouraging us to check for the optimal volume fraction allowing for a possible compensation. The predicted value of TCF was found rather in the -50 ppm/K, using our 1D model with no account for thermal differential stress. As we observed significant deformation of the wafer during the TCF characterization procedure, we assume that the 10 ppm/K discrepancy between theory and experiment should find its origin in these thermal differential stress effects. More work (both experimental and theoretical) must be achieved to definitely conclude on that issue.

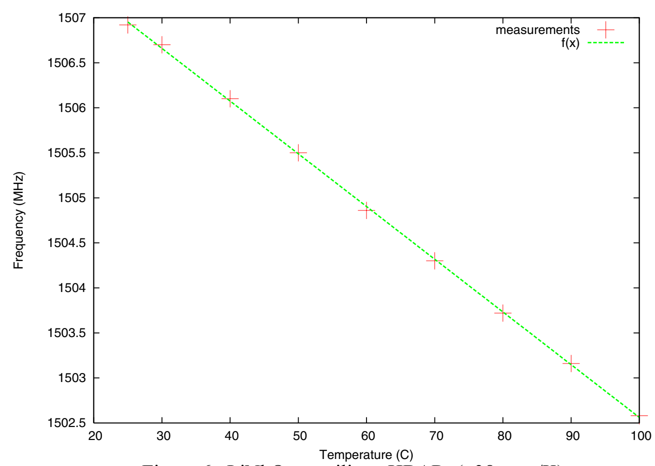


Figure 6. $LiNbO_3$-on-silicon HBAR, (–38 ppm/K)

IV. CONCLUSION

This paper has presented new design aspects and fabrication approaches for single-crystal-based Film Bulk Acoustic Resonators used for filtering applications. Lithium niobate was used for its remarkable acousto-electric properties. $LiNbO_3$/Si HBAR have been successfully tested, providing well-defined resonance together with coupling coefficient comparable or even larger to those generally obtained on quartz. We also have inspected the difference between probing one resonator and two series-connected resonators in terms of Q factor. We found that using very simple equivalent model, it was possible to demonstrate that single resonators provide better Q-factor and larger K_s^2 than two devices in series. This issue will be considered for our next developments. Finally, temperature sensitivity was also found favorable for thermal drift reduction of $LiNbO_3$-based resonators. Further developments will be devoted to better controlling the spectral purity of our resonators and to thin down the layer toward a few microns. Also the coupling factor is expected to be improved by optimizing the HBAR structure.

ACKNOWLEDGMENT

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