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Large Qxf Product for HBAR using Smart Cut™ transfer of LiNbO₃ thin layers onto LiNbO₃ substrate

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Abstract—In this paper, we propose a novel approach for HBAR devices using the Smart Cut™ technology to obtain thin homogeneous X-cut single crystal films of LiNbO₃. Sub-micron layers were successfully transferred onto LiNbO₃ handle wafers. RF characterizations were performed around 1.95 GHz and quality factors in excess of 40 000 are extracted, proving the applicability of layer transfer by Smart Cut™ to acoustic devices. An excellent matching between simulations and experimental data as well as TCF measurements are presented in this paper.

Keywords—Lithium Niobate, X-cut, HBAR, Smart Cut™, Q f product.

I. INTRODUCTION

High overtone Bulk Acoustic Resonators (HBAR) have been investigated for several years as frequency sources and filters because of very high quality factors exhibited at a gigahertz range and above. State of the art Qxf product of 1.1×10^{14} has been obtained by Lakin *et al.* [1]. 3 inches in diameter sapphire substrates of 650 microns thickness were employed with circular aluminium electrodes and AlN films. More recently, Gachon *et al.* [2] have studied Metal/LiNbO₃/Metal/LiNbO₃ HBAR structures. They obtained an excellent Qxf product of 8.1×10^{13} on those structures as well as on niobate-on-sapphire or AlN-on-sapphire. These structures were obtained by wafer bonding via a gold layer, then grinding and polishing the active piezoelectric layer down to 30 microns.

Here, a new approach is proposed using the Smart Cut™ technology [3], well known in the semiconductor industry for making thin silicon layers on SiO₂ for high performances transistor circuits. Such technique has already been applied to a piezoelectric material to obtain Surface Acoustic Wave (SAW) devices [4]. In this paper, we propose a HBAR that uses X-cut thin LiNbO₃ film that is transferred by Smart Cut™ onto an X-cut LiNbO₃ substrate. In this way, 3-inch X-cut LiNbO₃ single-crystals have been successfully placed by this technique onto carrier wafers comprising a metallic electrode. This technique allows us to obtain <1 μm thick homogenous films (that are more suitable for high frequency applications. RF

characterization was performed around 1.95 GHz using a 2 port design, with temperature varying from 30°C up to 100 °C.

In the first section, the realization of the HBAR is described with emphasis on the Smart Cut™ process adapted to piezoelectric layers for acoustic devices. In the second part RF measurements are compared with simulations and excellent matching is shown. The third part deals with temperature stability and the Temperature Coefficient of frequency is extracted from experiments.

II. HBAR REALIZATION USING SMART CUT™

A HBAR device is the combination of a layer exhibiting a high electromechanical coupling factor and a high quality substrate (Fig.1). The piezoelectric layer sandwiched between two electrodes acts as a transducer that generates the acoustic waves. Lithium Niobate is an ideal material for this, and especially the X-cut, with its two shear waves being electromechanically coupled. The substrate is the primary resonant cavity. Indeed, acoustic waves generated in the piezoelectric layer propagate into the substrate: we observe a harmonic spectrum of bulk resonances. Parameters such as acoustic losses, parallelism and roughness are affecting the HBAR quality factor, usually described by the Figure Of Merit Qxf – Product of the quality factor with frequency. LiNbO₃ single crystals are excellent materials for high Qxf HBAR.

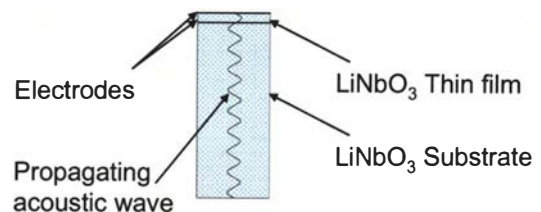


Figure 1. High Overtone Bulk Acoustic Wave Resonator (HBAR) principal with LiNbO₃ thin film and substrate.

In the Smart Cut™ process two wafers are bonded, split and a final CMP is possibly performed. Fig.2 shows the usual

Smart Cut™ process as it is applied for microelectronic purposes. This process has been adapted for LiNbO₃ wafers. A metal electrode has been deposited onto an adhesion layer on wafer “A” and silicon oxide is deposited on both substrates “A” and “B”.

- Helium ions are implanted on a 3-inch X-cut LiNbO₃ single-crystal substrate “A” thus creating an implanted zone at a defined depth.
- Molecular bonding is then performed, followed by the splitting at the implanted depth.
- Chemical Mechanical Polishing may then be used in order to remove the damaged top LiNbO₃ layer and adjust the thickness of undamaged transferred layer.
- Finally, platinum is deposited by evaporation and etched with an Argon-assisted Ionic Beam milling (IBE) technique to pattern the top electrode.

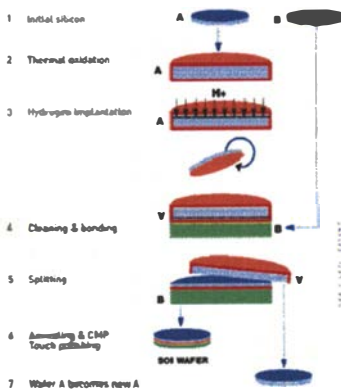


Figure 2. Usual Smart Cut™ technology for Silicon On Insulator wafers.

III. RF CHARACTERIZATION

Samples with two resonators in series via a floating electrode (Fig.3) were characterized using a Vector Network Analyzer and SOLT calibration. Two kinds of measurements were performed:

- In the frequency range 1940 MHz – 1960 MHz at room temperature
- In the same frequency range but with temperature ranging from room temperature up to 100°C. Focusing on the Temperature Coefficient of Frequency (TCF), only one resonance is shown, the one appearing at 1957 MHz at room temperature.

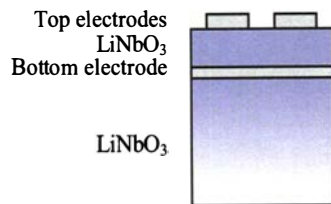


Figure 3. Two resonators in series.

Thickness excitation of the X-cut of LiNbO₃ exhibits strongly coupled shear waves. Indeed the two acoustic shear waves are coupled and propagate in the LiNbO₃ - the slower one is less coupled ($k_t^2 = 20\%$ from material constants [5]) than the faster one ($k_t^2 = 40\%$).

IV. COMPARISON WITH COMPUTATIONS

The approach for data extraction depends on the fitting of experimental measurements with calculations using the scattering matrix method [6]. Adjusting material parameters and losses allows a perfect matching between simulated and experimental data. We observe a clear resonance corresponding to a shear in-plane resonance mode. High Q values and thus large Qxf products are obtained, close to the state of the art [1]. Two different wafers have been characterized and simulated: they are referred as HBAR1 and HBAR2.

A first step is to set thicknesses and elastic constants for the matching of velocities and frequencies which can be done on real parts of admittance.

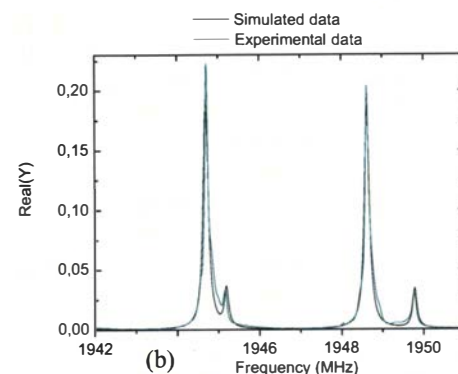
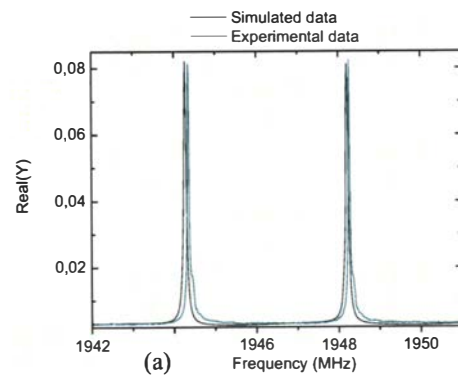


Figure 4. Excellent matching between simulated and experimental real parts of admittance respectively for HBAR 1 (a) and HBAR 2 (b).

In order to fit the measured peaks, acoustic and dielectric losses in the substrate are considered as imaginary parts of the elastic and dielectric constants, respectively. Imaginary part of the elastic constant can be evaluated in a first approximation as the elastic constant divided by the measured quality factor.

Concerning dielectric losses – imaginary part of dielectric constants – tables such as the Landolt-Bornstein [7] provide standard values of $\tan(\delta)$ for LiNbO_3 of 0.0011. Those two loss factors are then adjusted to fit perfectly the peaks of experimental data (Fig.5).

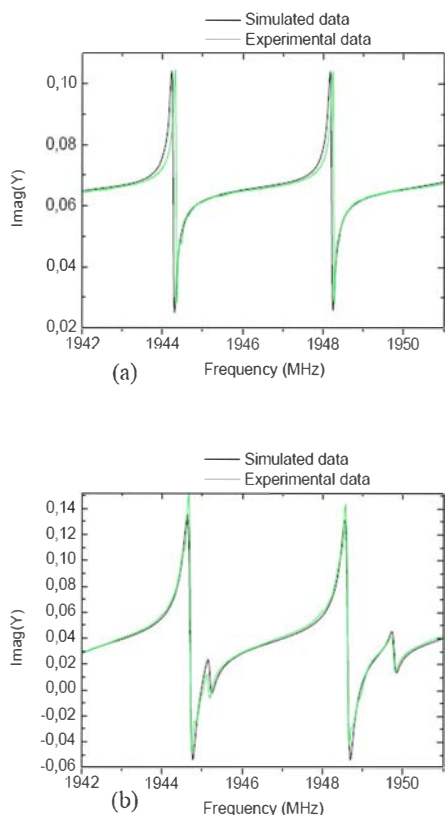


Figure 5. Excellent matching between simulated and experimental imaginary parts of admittance respectively for HBAR1 (a) and HBAR2 (b).

As seen in Fig.4 and Fig.5, we achieved an excellent matching between experimental data and simulations on both the real part and the imaginary part of admittance. Elastic, dielectric or piezoelectric constants and their associated losses have been adjusted.

From Figures 4(a) and 4(b) quality factors of respectively 40400 and 19800 are extracted which lead to Qxf products of 7.9×10^{13} and 3.8×10^{13} . Especially for HBAR1, Qxf product is close to the state of the art $1.1 \cdot 10^{14}$ obtained by Lakin *et al.*[1] with AlN deposited on a sapphire substrate. These results are excellent considering that HBAR designs were not optimized.

Although the matching errors are cumulative on the modulus of admittance – with the combination of the errors on both real part and imaginary part – the agreement is still excellent, as can be seen on Fig.6 where both fast and slow shear waves are shown.

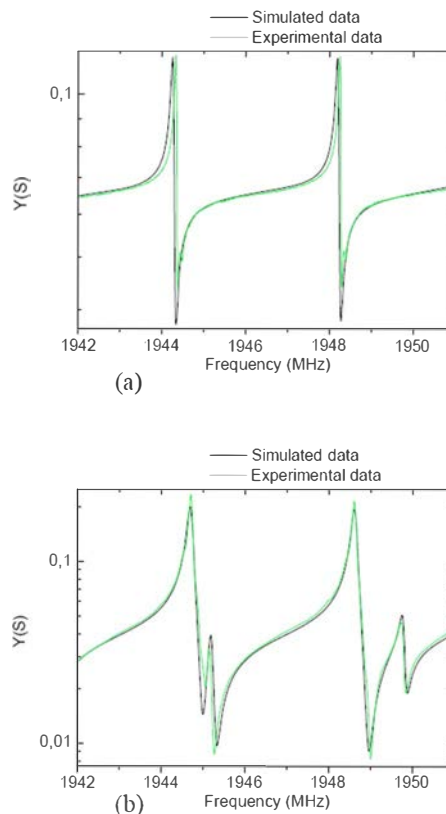


Figure 6. Matching between simulated and experimental data of the modulus of admittance on HBAR 1 (a) and HBAR 2 (b).

The main difference between HBAR1 and HBAR2 is the second shear wave not appearing on Fig.4(a) as it should appear for an X-cut niobate with thickness excitation (fig.4b). This can be explained by the mode conversion occurring between the two shear waves when an angle exists between the transducer – the niobate transferred layer – and the propagating media – the niobate substrate.

V. TEMPERATURE MEASUREMENTS

For an acoustic RF device, the temperature stability is an important value when used in an oscillator circuit or a filter application. Though it was not the aim for these structures, Temperature Coefficient of Frequency (TCF) measurements were performed between 30°C and 90°C and we focused on a particular resonance as temperature was increased to obtain the TCF value.

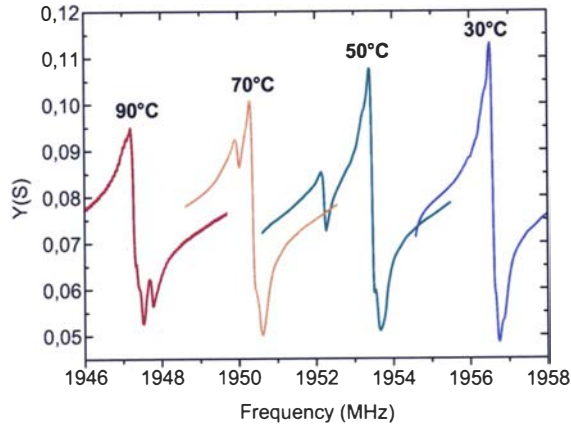


Figure 7. Shift of one resonance as temperature increases.

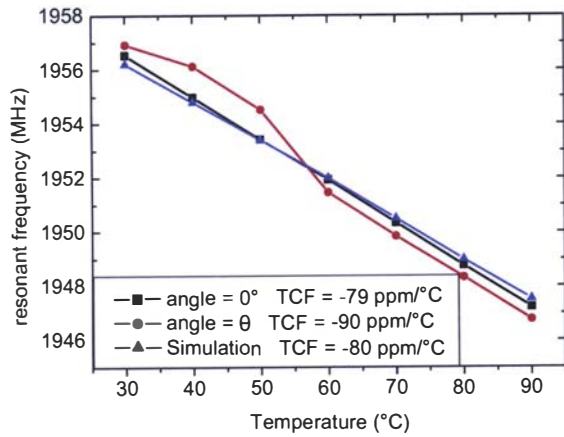


Figure 8. Comparison of the resonance frequency for HBAR1 and HBAR2 as temperature increases.

Fig.7 shows the frequency shift as a function of temperature and as seen in Fig.8, the resulting shift is linear and is about -90 ppm/°C for HBAR1 and -79 ppm/°C for HBAR2. These TCF measurements are in good accordance with the simulations performed with similar structures where extracted TCF is about -80 ppm/°C.

VI. CONCLUSION

HBARs with sub-micron LiNbO₃ layer produced by the Smart Cut™ layer transfer technology have been experimentally demonstrated. Despite a lack of optimization of the HBAR, we still achieved excellent quality factors and Qxf products. An excellent matching between simulated and experimental curves was also obtained. Although the device was not designed to match requirements in terms of temperature shifts, structures were characterized and a large shift was observed as expected. The next step is to prove the feasibility of a self-resonating layer by decoupling the resonator from the substrate effect.

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