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LiTaO$_3$/Silicon composite wafers for the fabrication of low loss low TCF high coupling resonators for filter applications

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Abstract

SAW devices are widely used for radio-frequency (RF) telecommunication filtering and the number of SAW filters, resonators or duplexers is still increasing in RF stage of cellular phones. Therefore, a strong effort is still dedicated to reduce as much as possible their sensitivity to environmental parameter and more specifically to temperature. Bounding processes have been developed at FEMTO-ST and CEA-LETI using either Au/Au or direct bonding techniques for the fabrication of composite wafers combining materials with very different thermoelastic properties, yielding innovative solutions for about-zero temperature coefficient of frequency (TCF) bulk acoustic wave devices. In the present work, this approach has been applied to (YX$^l$/42$^l$) lithium tantalate plates, bounded onto (100) silicon wafers and thinned down to 25 $\mu$m. The leading idea already explored by other groups as mentioned in introduction consists in impeding the thermal expansion of the piezoelectric material using silicon limited expansion. 2 GHz resonators have been built on such plates and tested electrically and thermally, first by tip probing. A dramatic reduction of the TCF is observed for all the tested devices, allowing to reduce the thermal drift of the resonators down to a few ppm.K$^{-1}$ within the standard temperature range. We then propose an analysis of the frequency-temperature behavior of the device to improve the resonator design to use these wafers for industrial applications.

Keywords:
1. Introduction

Surface acoustic wave (SAW) devices still are the very standard for radio-frequency (RF) telecommunication filtering such as used in cell phones and mobile systems. Due to the evolution of RF standard specification, reducing the sensitivity of SAW filters to environmental parameters and more specifically to temperature is demanding continuous efforts. Several approaches have been implemented in that purpose, based on thick Silica passivation of thin film waveguide on thermal compensated substrates like quartz. Composite wafers combining several materials also consists of an effective way to compensate the natural thermal drift of leaky surface acoustic waves (LSAW) on lithium niobate and lithium tantalate [1]. For all the proposed technologies, solidly bounding heterogeneous materials is a quite complicated issue as thermal budget must be limited to avoid irreversible damage of the wafers. In this work, Au/Au bounding processes have been developed at FEMTO-ST [2] and CEA-LETI [3] for the fabrication of composite wafers combining materials with very different thermoelectric properties. This approach has been applied here to (YX)/42° Lithium Tantalate plates, bonded onto (100) Silicon wafers and thinned down to about 25 μm. The central idea already explored by other groups consists in impeding the thermal expansion of the piezoelectric material using silicon thermal expansion limited to a few ppm per Kelvin. Along this approach, 2 GHz resonators have been built on such plates and tested electrically and thermally. The devices have been tested first on trench, and then diced and bonded in standard ceramic package to allow for test in climatic chamber. In both cases, TCF remarkably smaller than the one of LSAW on single crystal have measured, almost answering the demand. Although exhibiting limited Q factors with electromechanical coupling factor of only 4%, the devices were found suited for thermal tests, yielding numerous TCF measurements near 2 GHz. Experimental results are reported for on-trench devices as well as packaged test vehicles. TCF absolute values smaller than 10 ppm.K⁻¹ have been systematically observed and some devices even were found temperature-compensated near room conditions. A first analysis attempt is proposed to conclude the paper

2. Wafer manufacturing

The manufacturing process exploited in that work has been described several time (see for example [2]), therefore only a very brief recalled is reported here. LiTaO₃ and Silicon wafers are cleaned first and a Cr/Au layer is deposited on one side of both wafers by sputtering. The two wafers then are bonded together through the compression of the two metallic sides in regard, used as a diffusion layer. This bounding is achieved using either an EVG wafer bounding machine or a Suss Microtech CL200 megasonic cleaner. The bounding is then reinforced by applying homogeneously a high pressure on the bonded wafers, yielding an almost perfect adhesion between both materials, as checked by FIB. The LiTaO₃ side then is lapped down to the expected thickness and polished to allow for top surface processing. Although the roughness could not be obtained lower than a few nm all over the wafer, it was estimated sufficient for our objective.

3. Fabrication and characterization of SAW resonator test vehicles

The fabrication of LSAW devices on the manufactured trenches has been achieved using a stepper-based process, yielding a first evidence of industrial compliance of the LiTaO₃/Si substrates, although local defects already pointed in the previous section did limit the manufacture yield. Actually the wafer was accepted both by our stepper (Nikon Body-9 set-up) and by our CD-SEM (Hitachi S9220), two equipments very sensitive to manufacturing defects and shape irregularities. A template has been generated to fabricate SAW devices (single-port resonators) with various technological parameters (metal ratio, IDT aperture, number of electrodes in the gratings). All periods were fixed to 1 μm, all devices were synchronous to allow for an easy post-processing of the measured electrical responses.

The computation of the mode properties using FEA/BIM [3] provides mixed-matrix parameters that can be compared to the experimental data (Table 1). We suspect that the use of an inappropriate Al electrode thickness to minimize propagation losses yields rather modest figures of merit. Also the surface quality is expected to affect the quality factor. Finally, the presence of the metal layer at the interface between both plates may impact the mode
properties. Once again, the objective was not to obtain perfect resonators but devices sufficiently operational for TCF characterization and these resonators was found exploitable in that purpose.

A first attempt to measure the TCF of such devices has been first by varying the temperature of the tip-prober chuck from room temperature to 75°C. This first experiment allowed for evidencing the reduction of the resonance frequency dependence versus temperature. As a consequence, systematic measurements have been performed for the different resonator structures to quantitatively characterize their TCF. Although metal thickness of the electrode is assumed to impact the effective resonator TCF, it was assumed of second order here and only the device architecture has been considered here as a main differentiation factor.

Table 1. Comparison between experimental and theoretical resonator characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FEA/BIM</th>
<th>Experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency (MHz)</td>
<td>2014.69</td>
<td>2012.76</td>
</tr>
<tr>
<td>Stop band width (MHz)</td>
<td>84.5</td>
<td>82</td>
</tr>
<tr>
<td>Quality factor, resonance</td>
<td>1500</td>
<td>350</td>
</tr>
<tr>
<td>Quality factor, anti-resonance</td>
<td>3000</td>
<td>900</td>
</tr>
<tr>
<td>Electromechanical coupling (%)</td>
<td>7.5</td>
<td>3.95</td>
</tr>
</tbody>
</table>

Figure 1 Resistance measured in the range 30-80°C for one of the tested resonator (50 electrode pairs in the IDT, 20 electrode in the mirrors) TCF found equal to -18 ppm.K⁻¹

TCF measurements have been made for on-trench resonators from 30 to 80°C with a 5° step, allowing for an easy monitoring of the resonance. It turns out that the resonance was found almost stable for all the tested devices, yielding sometimes difficulties for a clear derivation of a TCF actually representative of the device behavior. Therefore, antiresonance also has been considered to try and assess the TCF values obtained for almost all type of resonator in the range -7 to -5 ppm.K⁻¹. Temperature coefficient of frequency was found larger and easier to monitor. Almost all types of devices did exhibit a TCF of the antiresonance in the -20 to -12 ppm.K⁻¹ range.

Further experiments had to be achieved to confirm the general trends observed for these on-trench tests. Therefore, several devices have been packaged and tested in climatic chambers and temperature controlled oven. Although the dices were much larger than needed, the experiments were assumed representative of the actual industrial implementation of the devices. Results of the packaged devices at FEMTO demonstrate the positive effect of the compound wafer on the global thermal sensitivity of the tested devices but TCF values were found somehow different from the on-trench tests, with positive TCF potentially exceeding 10 ppm.K⁻¹. Very dispersed measurements however did not allow for a definitive conclusion on the actual device TCF using these packaged dices but clearly the resonance frequency remained rather stable versus temperature from -20 to +120°C.
4. First order analysis – discussion

The calculation of the phase velocity coefficient of temperature can be easily computed without thermal expansion correction. In the case of LSAW on single-crystal LiTaO₃ (YX)/42°, the computation indicates a TCV of only -9.0 ppm.K⁻¹, whereas the TCF which accounts for the material thermal expansion is estimated at -25 ppm.K⁻¹. This means a part of the TCF due to thermal expansion of more than 60%, which partly explains the results of the on-trench measurements, considering a Si thermal expansion of 2 to 3 ppm.K⁻¹ which yields TCF in the -12 ppm.K⁻¹ range. One can therefore consider that even for a 25 μm Lithium Tantalate layer, Silicon imposes its in-plane thermal expansion and actually allows for reducing the TCF.
5. Conclusion

In this work, compound wafers combining Lithium Tantalate and Silicon have been manufactured to fabricate LSAW-based resonators exhibiting absolute TCF smaller than 10 ppm. K\(^{-1}\). 2 GHz resonators have been built on these plates and tested electrically and thermally. A dramatic reduction of the TCF is observed for all on-trench tested devices, allowing for a significant reduction of the thermal drift of the tested resonators to a few ppm. K\(^{-1}\) within the standard temperature range.

References


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