Temperature Compensation in SAW Filters by Tri-Layer Wafer Engineering

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Abstract—**Bonded wafer concept is modified by introduction of a third layer that is used for compensation (or even overcompensation) of wafer warping thus increasing the amount of stress at the upper surface of the piezoelectric $LiTaO_3$ layer resulting in significant improvement of temperature coefficient of frequency (TCF), that may become zero or even positive.**

We have successfully demonstrated variants of structure where a third layer with relatively higher coefficient of thermal expansion (CTE) is deposited or bonded on the back surface thus compensating or introducing opposite warping of the combined tri-layer structure. The experimental results and the modeling show that with appropriate choice of supporting substrate materials the unwanted warping can be eliminated and the TCF closer to zero is routinely obtained in $LiTaO_3$/Si/Cu tri-layer structures with thick Al electrodes.

I. Introduction

The "bonded wafer" concept was demonstrated in [1] and further developed in [2], [3] and [4]. It uses a thin layer of piezoelectric single crystal material ($LiTaO_3$ or $LiNbO_3$) that is bonded (with glue or by direct bonding technique) to a low coefficient of thermal expansion (CTE in the range of 0-8 ppm/ºC) supporting substrate (Si, Sapphire, fused silica were demonstrated etc). The effect is based on the properties of particular cuts of $LiTaO_3$ (LT) and $LiNbO_3$ (with average CTE about 16 ppm/ºC) which under CTE mismatch stress acquire lower temperature coefficient of frequency (TCF). This possibility is due to reduction of expansion and to velocity behavior improvement through nonlinear elastic properties (that may be described by third order elastic constants).

Several examples referenced above describe bonded structures with different thickness, Young modulus, and CTE ratios of supporting substrates, however in most cases at the useful thickness of piezoelectric layer the warping of the wafer with temperature change occurs in such direction, that the induced useful stress in the piezoelectric layer near its surface reduces and the TCF does not reach low enough values that could be expected without such warping.

We have successfully demonstrated variants of structure where a third layer with relatively higher CTE (12-16 ppm/ºC or above) is deposited or bonded on the back surface thus compensating or introducing opposite warping of the combined tri-layer structure. The experimental results and the modeling show that with appropriate choice of supporting substrate materials (lowest CTE is the most important feature) not only unwanted warping can be eliminated but the TCF =0 ppm/ºC is routinely obtained in $LiTaO_3$ 42º-YX cut/Si/Cu tri-layer structures with thick Al electrodes (10% of wavelength).

II. Modeling of the Stress in the Bonded Wafer

Commercial software packages like for example ANSYS or Comsol Multiphysics for FEM analysis can be used for modeling the stress distribution in bonded wafers. Most modeling has been made for $LiTaO_3$, however as $LiNbO_3$ has similar averaged CTE and Young modulus (E) values the achievable modeling results are more or less similar.

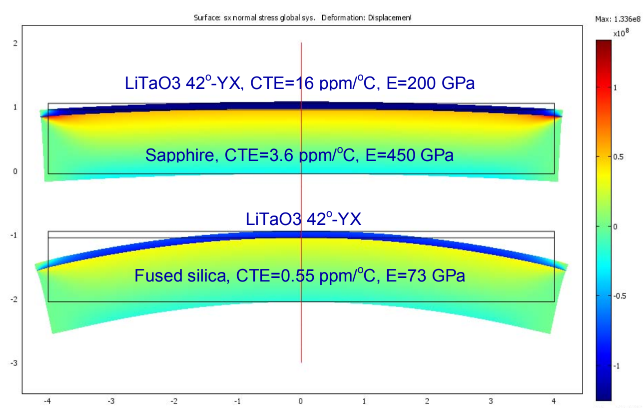

Figure 1. 2D modeling of the stress distribution in common substrate combinations.

In Figure 1 the result of heating to 80 ºC of the wafers bonded at 20 ºC is shown with exaggerated amount of deformation. This helps to understand the reasons why the level of TCF compensation was much lower than that expected in some early experiments [2]. In fact due to warping of the bi-layer the stress on the surface of the piezoelectric is released. The deformation in graphs is highly exaggerated for clarity.

If the structure was prevented from warping the stress level could be higher and should obey the simplest equations describing two mechanically joined springs with different hardness. The stress profile across the centers of the dies shown in Figure 1 is presented in Figure 2.

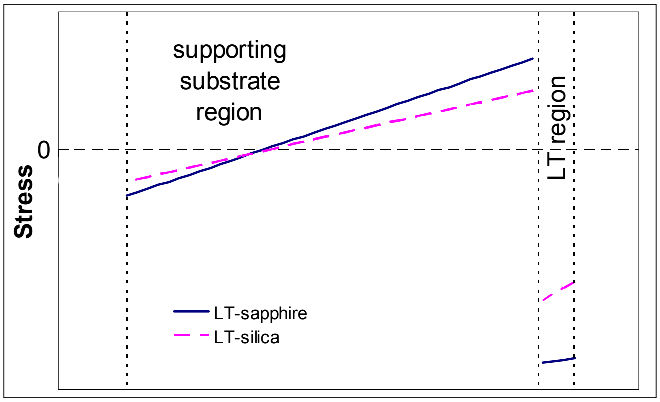

Figure 2. Stress profile for $LiTaO_3$ thickness equal to 10% of the supporting substrate thickness.

Even very rigid sapphire substrate suffers from warping and substantially releases the achievable amount of stress level introduced into the $LiTaO_3$ layer. However the final level of stress remains in relatively useful limits to ensure efficient reduction of TCF to 17 ppm/ºC for series resonance. The stress release in warped fused silica supporting substrate is excessive, and the resulting stress level in $LiTaO_3$ layer does not provide useful values of TCF. The improvement in TCF is almost negligible following our early experiments.

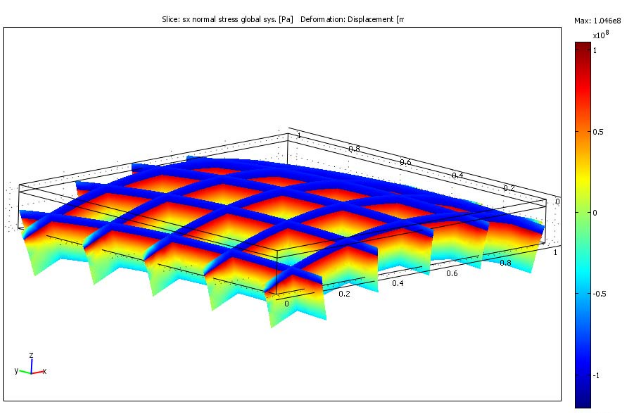

Figure 3. Example of 3D modeling with anisotropic materials.

2D modeling gives a clear descriptive picture of the stress distribution however real structures are three-dimensional. The validity of the modeling results can be confirmed in 3D runs with such structures, where anisotropy of the substrates can be taken into account.

In Figure 3 the $LiTaO_3$ 42º-YX /alumina is modeled in 3D. Anisotropy of the $LiTaO_3$ 42º-YX layer clearly results in warping with non-spherical and almost cylindrical shape. For this cut, 2D modeling of warping seems to be quite adequate, while in isotropic case the shape is spherical, and some difference in the actual stress near the surface and in its distribution profile can be expected in 2D and in 3D.

III. STRAIGHTENING OF WARPED WAFER

If the lower boundary of the supporting substrate could be fixed against movement in vertical direction the warping of the wafer with temperature should not occur and the amount of stress release in this case would be low. Modeling this arrangement shows that this assumption is true. Our experiments with a $LiTaO_3$ 42º-YX layer on Si have shown that when the wafer was fixed on a temperature controlled flat stage by vacuum, especially under heating conditions, the warping was not observable while the TCF improved greatly in comparison to the same measurement without fixing.

There is a possibility to fix the supporting substrate to a thick, rigid base with low CTE and this is a possible solution to the warping problem. However the package materials rarely have all required properties while die fixing is often made with soft glue and more importantly the trend to packageless structures requires reduction of the total thickness of the SAW device.

Another possibility to overcome the problem is to apply a compensating layer that eliminates warping or even overcompensates to give reversal of the warping direction, so that instead of getting released, the stress on the top surface gets enhanced. Figure 4 shows the modeling results of an example where a $LiTaO_3$ layer is formed on the top surface of a supporting alumina wafer and a Cu compensating layer is formed at the bottom surface.

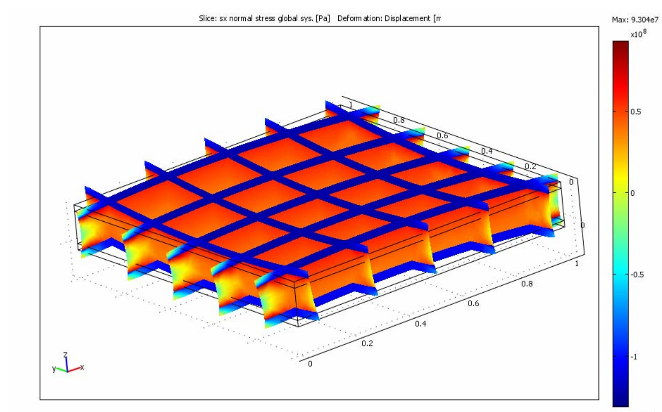

Figure 4. 3D modeling of warping compensation by a Cu compensating layer

The warping is greatly reduced but it is not completely eliminated and the structure has a saddle-like shape. Both top $LiTaO_3$ and bottom Cu layers acquire compressive stress due to CTE mismatch.

Again, for clarity of conceptual presentation we return to 2D modeling, while the 3D is always available for verification of quantitative results.

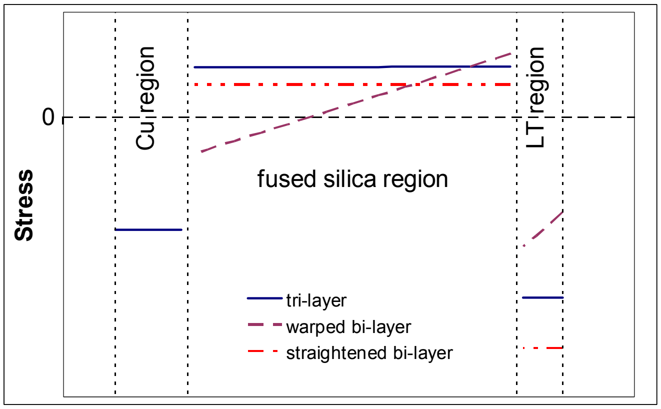

Figure 5. Stress profile for warped and straightened bi-layer structures and for a structure compensated by a Cu third layer.

Figure 5 shows that the compensating layer provides lower stress value in $LiTaO_3$ layer than one gets by wafer straightening, for example, by fixing on a vacuum wafer holder. The stress reduction is due to the increase of averaged CTE of the complete layered structure by addition of a layer that has relatively high CTE. In fact very good experimental values of TCF were obtained after fixing the wafers on substrate holder and thus eliminating the warping while no restriction to lateral movement was introduced. But such conditions are not easy to implement on a die, so tri-layer approach still looks quite useful.

IV. PROPERTIES OF DIFFERENT TRI-LAYER STRUCTURES

The choice of the supporting substrate and of compensating layer materials is not unique; the palette of useful materials is relatively large.

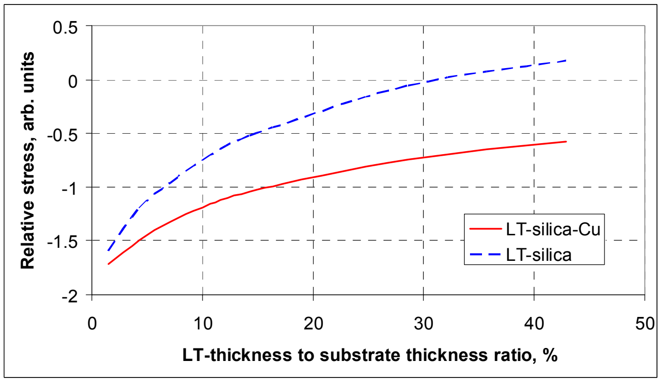

Figure 6. Comparison of stress on the top of the $LiTaO_3$ layer for bi-layer structure and warping compensated tri-layer structure.

First of all, one looks into the CTE and secondly into Young modulus data. Both properties can be anisotropic. The materials with low CTE (0-0.5 ppm/ºC) such as fused quartz (or silica) and low CTE glasses are relatively soft; diamond substrates are simultaneously rigid and have CTE in the range of 2 ppm/ºC, but are not yet in common use; expensive sapphire is rigid and has the CTE below 4 ppm/ºC, same as cheaper Si, that is 3 times less rigid. Other materials, like alumina are rigid enough, while they have slightly higher CTE.

The stress level on the top surface of the $LiTaO_3$ layer obtained from 2D isotropic modeling against the thickness of the $LiTaO_3$ layer is shown in Figures 6 and 7. Bi-layer structure (LT42-silica) and tri-layer structure (LT42-silica-Cu) are compared on Figure 6. The thickness of the warping compensating Cu layer is chosen to be 150% of $LiTaO_3$ thickness. This choice reflects mainly the average Young modulus ratio of these materials (about 200 GPa for $LiTaO_3$ and about 110 GPa for Cu) while also reflecting slightly higher CTE of Cu.

In uncompensated structures the warping due to relatively thick $LiTaO_3$ layers may be so serious that the stress near the $LiTaO_3$ upper surface may even change the sign, as shown by the curve for LT-silica. Positive stress means that such layered structure has even worse TCF than a usual $LiTaO_3$ substrate. However, when $LiTaO_3$ thickness gets below 3-5% of the substrate thickness the amount of stress in $LiTaO_3$ approaches the values obtained in compensated structures, because the warping becomes small. Nevertheless even in this situation controlled formation of warping eliminating layers is still beneficial, as the stress still may be increased, while remaining warping may be further reduced. Also realization of small ratio of layer thickness requires very thin layer of $LiTaO_3$ or excessively thick supporting substrate. In the first case, the $LiTaO_3$ layer becomes too fragile and moreover SAW properties may noticeably get altered, in the second case SAW device becomes bulky due to larger thickness of combined substrate.

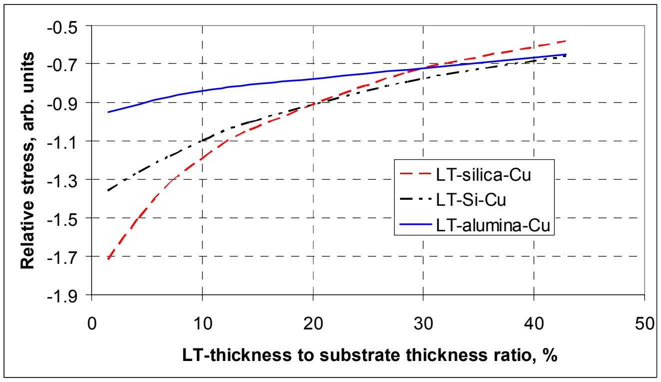

Figure 7. Comparison of stress on the top surface of the $LiTaO_3$ layer in a warping compensated tri-layer structure with different supporting substrates.

Tri-layer structures with a warping compensating Cu layer based on different supporting substrates are compared in Figure 7. It shows that the dependence of stress induced into a $LiTaO_3$ layer in warping compensated conditions is nonlinear and that it depends more on the CTE difference at low $LiTaO_3$ thickness and more on the Young modulus values of the supporting substrate at larger $LiTaO_3$ thickness. The example with alumina supporting substrate shows that the achievable stress level is not as large as that with Si or silica. This fact means that the amount of TCF compensation should be lower, and achievable TCF values should be worse.

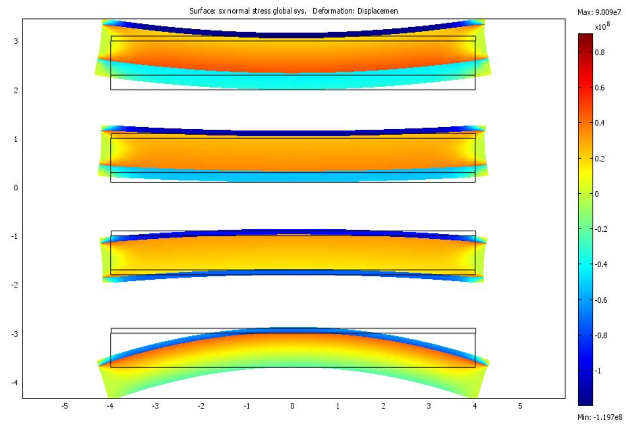

Figure 8. Compensation and overcompensation by Cu plating

As it is easy to deposit Cu or Ni by electroplating, they may become a good choice for economically viable route in forming the third layer. About the same stress behavior is obtained in modeling with Cu and Ni.

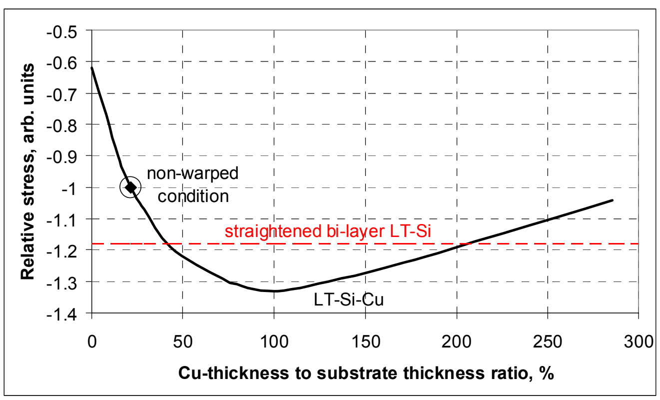

Figure 9. Stress on the top surface of the $LiTaO_3$ layer for tri-layer structure with different degree of warpig compensation or overcompensation.

In Figure 8 the following layer combinations are modeled from top to bottom: $LiTaO_3$-Si-Cu (3 times thicker than $LiTaO_3$), $LiTaO_3$-Si-Cu (2 times thicker than $LiTaO_3$), $LiTaO_3$-Si-Cu (same thickness as $LiTaO_3$), $LiTaO_3$-Si, where $LiTaO_3$ is 7 times thinner than the supporting Si substrate. This figure shows that by using a thick Cu layer one can obtain inverse warping. Such warping produces improvement of TCF, but increasing of thickness of Cu layer increases the averaged CTE of the layered structure that finally results in worsening of TCF.

The stress level on the top surface of the $LiTaO_3$ layer for the LT-Si-Cu structure against the thickness of the Cu layer is shown in Figure 9. $LiTaO_3$ is 7 times thinner than the supporting Si substrate as in Figure 8. Zero thickness of the Cu layer corresponds to a usual bi-layer structure. Also, the stress level on the top surface of the $LiTaO_3$ layer for straightened bi-layer structure is included into the graph for comparison. As one can see in Figure 9 the absolute value of the stress increases with Cu layer thickness until it is thinner than the Si layer. Maximum absolute value of stress is reached in inverse warping conditions when Cu layer thickness is about 5 times larger than that in non-warped conditions. This value of stress is about 2 times larger than the one for warped bi-layer structure, it is about 30% larger than that for non-warped tri-layer, and it is even slightly larger (about 10%) than one for straightened bi-layer structure. Although numerical relations are different for other materials and for other thicknesses ratios of $LiTaO_3$ layer to supporting layer, the present results show that using of quite thick third layer for obtaining inverse warping can give more improvement in TCF.

V. EXPERIMENTAL VERIFICATION

$LiTaO_3$/Si bonded wafers with $LiTaO_3$ thickness equal to about 30 microns and Si thickness equal to 350 microns were subjected to patterning with synchronous resonator layouts. The thickness of Al layer was about 10% of the wavelength that usually results in the series resonance TCF in about -45 ppm/ºC range on a freestanding $LiTaO_3$ 42º-YX wafer. As seen in Figure 10, bonding of $LiTaO_3$ wafer to Si supporting substrate with thickness reduction already provides serious improvement in TCF. For the series resonance the TCF is -14.5 ppm/ºC and for parallel resonance it is -30 ppm/ºC.

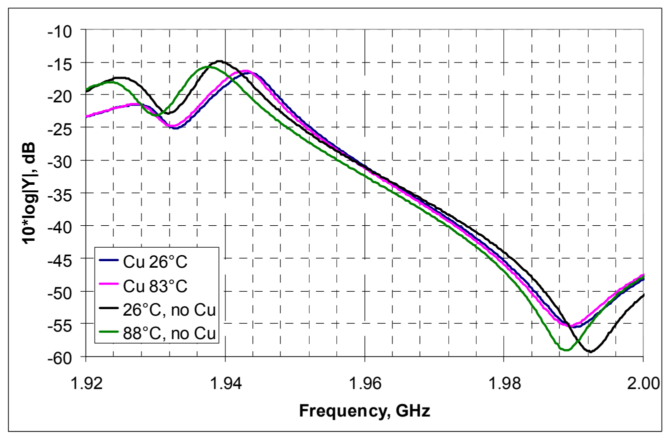

Figure 10. Frequency response of a $LiTaO_3$/Si bonded wafer with 50 microns Cu electroplated on the backside of Si supporting wafer

Deposition of about 50 microns of Cu (as measured in the central region of the wafer) has further improved the TCF; for the series resonance it became close to -5.5 ppm/ºC and for the parallel resonance – about -11 ppm/ºC. In Figure 10 the data from slightly different resonators with and without Cu are presented, and this is the reason for the difference of the curve shapes. Electroplating needs special measures to avoid thicker coating formation closer to the edges of the plating area. In our test sample the Cu thickness near the wafer edges was reaching almost 80 microns, and the resonators measured in this area were showing zero or even positive (up to +5 ppm/ºC) TCF of the series resonance.

The result of glue bonding a 100 microns thick stainless steel foil to the backside $LiTaO_3$/Si bonded wafer is shown in Figure 11. While the CTE of steel is lower than that of Cu (close to 12 ppm/ºC), application of thicker foil still results in warping reduction and even probably in some warping in the opposite sense, so that about the same amount of TCF compensation is achieved. The TCF of the sample shown in Figure 11 in the region of the series resonance is close to zero, while the TCF of the parallel resonance is about -17 ppm/ºC. In experimental data one observes that the compensation works in a slightly different way for the series resonance and for the parallel resonance.

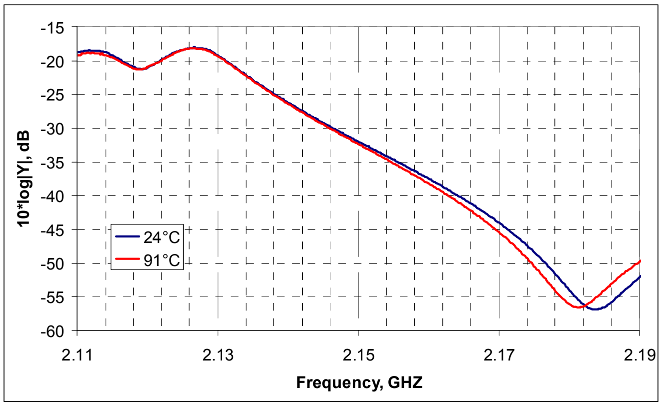

Figure 11. Frequency response of an $LiTaO_3$/Si bonded wafer with 100 microns stainless steel bonded to the backside of Si supporting wafer.

VI. EDGE EFFECTS

When the die size approaches the thickness of the tri-layer substrate structure, edge effects can be expected.

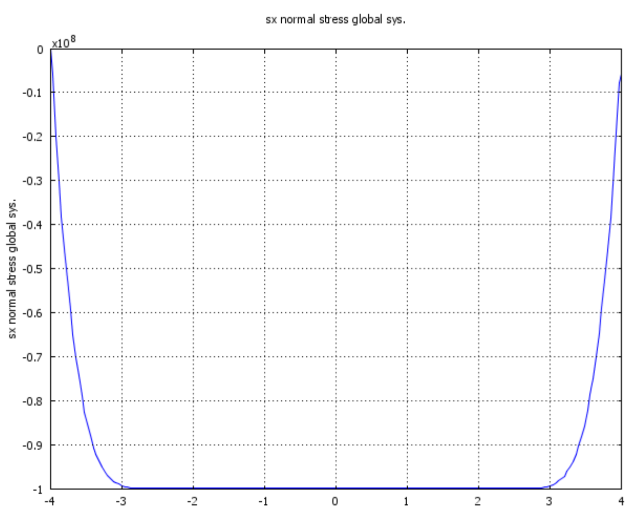

Figure 12. Change of stress (arbitrary units) near the edges of the die area

Figure 12 shows the stress variation along the die area in the middle of the $LiTaO_3$ layer bonded to a Si wafer. In this example the Si thickness is 0.7 units and $LiTaO_3$ thickness is 0.1 units in the graph (14% of thickness of supporting substrate) and it is clearly seen that stress behavior stabilizes at some distance from the edge. This distance depends on the Young modulus and on the thickness ratio of both layers. One has to take it into account when designing filters in a restricted die area. Dicing laminated substrate structures into individual dies is not straightforward. One has to avoid delaminating of layers near the edges and increasing area of released interfacial stress. The damaged region increases the die size in comparison to the useful area of the filter. So far we have reliably tested dicing into enlarged die size 8*8 mm. With back side patterning of the dicing streets on Cu, device level dicing without delamination problem will be possible.

VII. DISCUSSION

While very useful examples of bonded wafer concept have already penetrated the market, the level of TCF compensation may still be improved by engineering substrates with multiple layers, and especially by including the warping compensation layer. Modeling and experimental data show that the compensation of the series resonance TCF may be very successful; one can either obtain zero TCF (compensation) or even inverted temperature behavior – positive TCF in the range of several ppm/ºC (overcompensation). The parallel resonance TCF (negative) has a 10-15 ppm/ºC higher initial magnitude for $LiTaO_3$ 42º-YX based devices, and it is less easy to compensate to zero. It may sometimes be the case, when by choosing slight overcompensation at a series resonance (positive TCF of several ppm/ºC) one can also obtain a relatively low parallel resonance TCF several ppm/ºC but still negative. In this case, the central frequency of a filter will remain temperature stable, while the bandwidth will change. Of course the choice of such properties depends on the device specifications.

VIII. CONCLUSION

The use of multiple layer bonded wafer concept allows to overcome warping problems in device fabrication and to improve the TCF of the devices to almost zero. The choice of useful materials greatly increases, as relatively soft supporting substrates can be used successfully.

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