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Layered SAW Resonators with Near-Zero TCF at Both Resonance and Anti-resonance

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***Abstract*—A layered SAW configuration consisting of a thin piezoelectric layer bonded onto a support substrate has been drawing attention for its superior performances—a higher quality factor (Q), higher electromechanical coupling factor (k^2) and better temperature coefficient of frequency (TCF)—than conventional SAW technologies. However, one of the biggest challenges on the layered SAW is a much worse ΔTCF than conventional acoustic resonator technologies such as $LiTaO_3$ (LT) SAW, temperature compensated (TC) SAW with SiO_2 over coat and BAW, where ΔTCF is defined as TCF at anti-resonance (TCF_p) minus TCF at resonance (TCF_s). The worse ΔTCF causes a serious return loss/VSWR degradation as well as a significant impedance shift of the filters with temperature change. First, this paper analyzes the cause of ΔTCF degradation on layered SAW considering linear and nonlinear effects. Based on the analyses, a new cut of quartz substrate allowing a near-zero ΔTCF as well as near-zero TCF_s and TCF_p is proposed. The bonded wafer with thin LT on the new quartz substrate is fabricated and resonator performances on the new layered SAW substrate are evaluated. Both TCF_s and TCF_p are measured near 0 ppm/°C. The ΔTCF is only –2 ppm/°C, which is the best ΔTCF of all the conventional SAW/BAW technologies. In addition, the experimental results confirm a very high Q of over 5,000 and high k^2 of 8.8% at 1 GHz. Moreover, a spurious free out-of-band response is achieved.**

Keywords—TCF, delta TCF, layered SAW, bonded wafer

I. Introduction

With the continuous advances in mobile communication technologies including carrier aggregation (CA) and 5G, acoustic filters are required to have higher performance such as lower insertion loss, wider bandwidth and increased temperature stability as well as clean out-of-band response. To address these requirements, a layered SAW configuration consisting of a thin piezoelectric layer bonded onto a support substrate has been actively studied in recent years [1–5]. Compared to conventional SAW technologies, the layered SAW exhibits superior performances like a higher quality factor (Q), higher electromechanical coupling factor (k^2) and better temperature coefficient of frequency (TCF). However, one of the biggest challenges on the layered SAW is that the resonance and anti-resonance frequencies shift differently with temperature. In other words, k^2 significantly changes over temperature. ΔTCF, defined as the difference between TCF at anti-resonance (TCF_p) and TCF at resonance (TCF_s), is much larger (in absolute value) than for other acoustic resonator technologies. Table I compares typical ΔTCF for various types of acoustic resonators including solidly mounted resonator (SMR) type BAW, temperature compensated (TC) SAW with SiO_2 over coat, regular $LiTaO_3$ (LT) SAW and previously proposed layered SAW configurations. The layered SAW generally has 2 to 8 times worse ΔTCF than the other SAW or BAW technologies, which causes a serious return loss/voltage standing wave ratio (VSWR) degradation as well as a significant impedance shift of the filters with temperature change.

TABLE I. Typical ΔTCF for Acoustic Resonators

Technology		ΔTCF (ppm/°C) (TCF_p – TCF_s)
SMR-BAW		–4
TC-SAW (SiO_2/128°YX LN)		+6
Regular LT		–8
Layered SAW	LT/sapphire	–20
	LT/quartz	–20
	LT/(SiO2)/Si	–20 to –30

Figure 1 shows simulation results of VSWR variations over temperature for a typical ladder filter assuming ΔTCF of resonators is –10, –20 and –30 ppm/°C. The simulation was done by scaling the resonance frequency (f_r) and k^2 of all the resonators accordingly. The worse ΔTCF (more negative ΔTCF) results in larger variation in VSWR and the variations for ΔTCF of –30 or –20 ppm/°C are not quite acceptable from the viewpoint of matching with power amplifiers (PA). Therefore, ΔTCF for layered SAW must be improved for practical use.

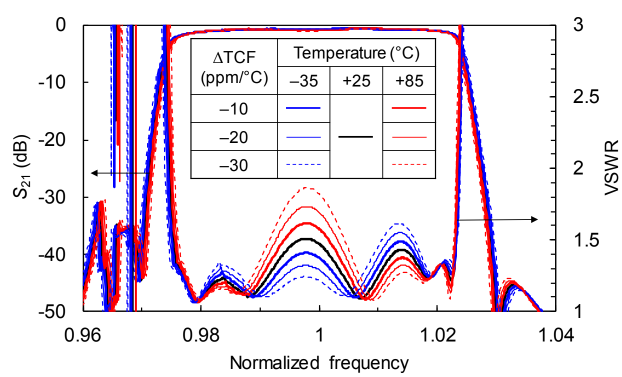

Fig. 1. Simulation results of VSWR variations over temperature.

First, this paper analyzes the cause of ΔTCF degradation on layered SAW considering linear and nonlinear effects. In the linear analysis, TCF simulations are conducted by using a finite element method/boundary element method (FEM/BEM) to figure out the main factors to degrade ΔTCF. The nonlinear analysis reveals that the thermal stress in the piezoelectric layer degrades ΔTCF. Based on these analyses, a new cut of quartz substrate allowing a near-zero ΔTCF as well as near-zero TCF_s and TCF_p is proposed. The bonded wafer with thin LT on the new quartz substrate is fabricated and resonator performances on the new layered SAW substrate are evaluated. The measured performance confirms near-zero TCF_s, TCF_p and ΔTCF as well as a very high Q, high k^2 and a spurious free out-of-band response.

II. Analysis for ΔTCF Degradation

A. Linear analysis

First, linear TCF simulations for LT SAW and layered SAW are conducted by using a FEM/BEM to figure out the main factors causing the ΔTCF degradation. The influences of the temperature coefficients of the elastic (Tc), piezoelectric (Te) and dielectric ($T\varepsilon$) constants for the electrodes, the LT and the support substrate are separately evaluated.

Figure 2 shows the TCF simulation model and results for LT SAW. The 2D periodic model includes a 42°YX LT substrate and 7.5%λ-thick Al electrodes (λ: wavelength). In the linear TCF simulation, only Tc, Te and $T\varepsilon$ for each material were separately considered. The geometrical changes, i.e. coefficient of thermal expansion (CTE) and temperature coefficient of density (Td), were not considered. The nonlinear analysis in the next section will include the effect of geometrical changes. The linear TCF simulation results shown in Fig. 2 indicates that Tc, Te and $T\varepsilon$ for only LT play a role to change ΔTCF. In LT, the impacts on ΔTCF is positive for Tc and negative for Te and $T\varepsilon$. The impact of Tc for Al on ΔTCF is very small. When all the temperature coefficients are considered, ΔTCF for LT SAW were simulated as –13.8 ppm/°C which is a little overestimated compared to the measured value of –8 ppm/°C.

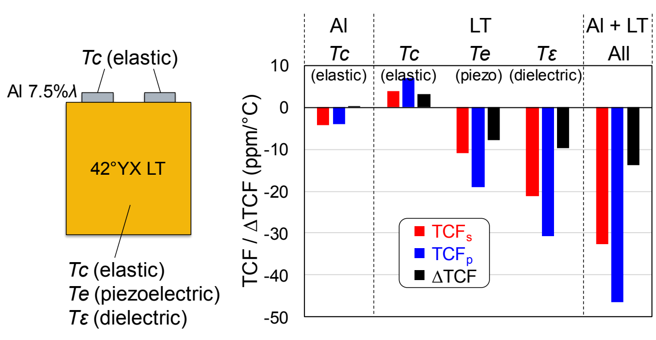

Fig. 2. Linear TCF simulation results for LT SAW.

Figure 3 shows the TCF simulation model and results for LT/quartz layered SAW. The 2D periodic model includes 15%λ-thick 42°YX LT and 7.5%λ-thick Al electrodes. The support substrate is Z-propagation quartz which we proposed in [6]. In this linear TCF simulation, only Tc, Te and $T\varepsilon$ for the quartz substrate were separately considered. To understand the impacts of the support substrate on TCF/ΔTCF, no temperature coefficients for Al or LT were considered. The geometrical changes were also not considered. The linear TCF simulation results shown in Fig. 3 indicates that only Tc for quartz has a large impact on TCF/ΔTCF and the impacts of Te and $T\varepsilon$ for quartz are very small. Therefore, one of the important parameters determining ΔTCF as well as TCF is the temperature coefficient of elastic constant (Tc) for the support substrate. Tc for Z-prop. quartz degrades ΔTCF by about –5 ppm/°C which is one reason for worse ΔTCF for LT/Z-prop. quartz layered SAW.

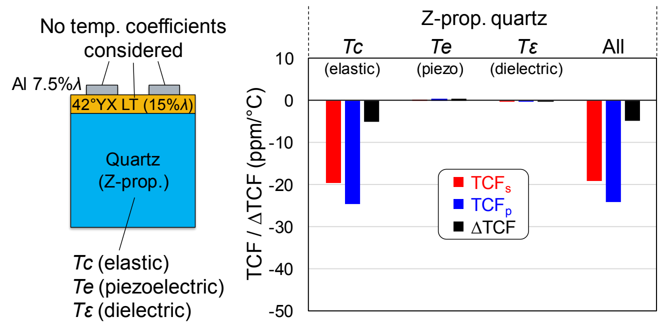

Fig. 3. Linear TCF simulation results for LT/Z-prop. quartz.

B. Nonlinear analysis

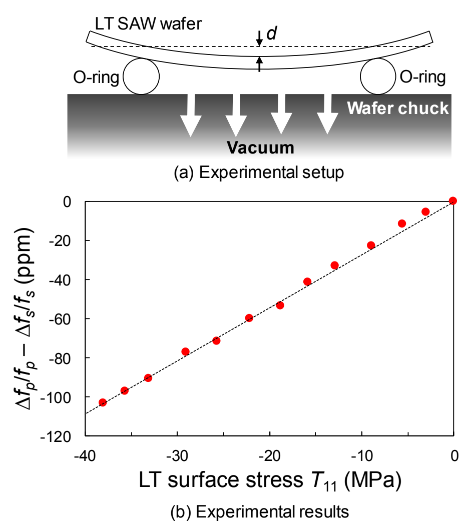

Fig. 4. Experiments for nonlinear effect.

The support substrates of layered SAW generally have smaller CTE than that of piezoelectric layer to compensate TCF. Therefore, due to CTE mismatch, the piezoelectric layer is submitted to thermal stress when the temperature changes which may affect ΔTCF if any nonlinear effects are present. The influence of this thermal stress in the piezoelectric layer on ΔTCF was experimentally investigated. The experimental setup is shown in Fig. 4(a). A LT SAW wafer was placed on a wafer chuck interposing an O-ring and the vacuum level for the wafer chuck was controlled to adjust the wafer deflection (i.e. stress in LT). SAW resonators near the wafer center were probed to measure S-parameters with changing the wafer deflection. Each time S-parameter was acquired, the wafer deflection d was optically measured. Figure 4(b) shows the experimental results. The x-axis is the surface stress T_{11} in LT along the SAW propagation direction converted from the deflection d based on

FEM simulation, and the y-axis is the difference in frequency shift between anti-resonance ($\Delta f_p/f_p$) and resonance ($\Delta f_s/f_s$) due to the deflection/stress. The experiment revealed a linear relationship which suggests that the stress in LT induces a change in the k^2 of SAW resonators.

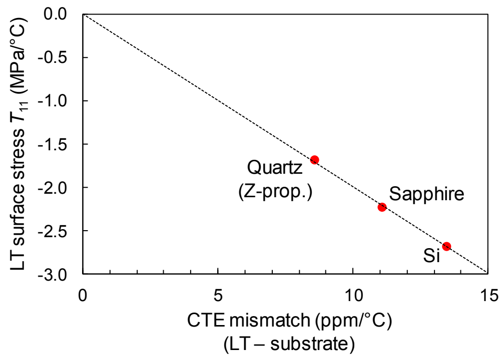

Fig. 5. FEM simulation results for thermal stress vs. CTE mismatch.

Next objective is to estimate how much the thermal stress in LT due to CTE mismatch in layered SAW degrades ΔTCF from the experimental results shown in Fig. 4(b). First, the correlation between CTE mismatch in layered SAW and thermal stress in LT was derived by using FEM simulation. Bonded wafers were modeled using FEM simulation and the thermal stress T_{11} in LT was extracted. Figure 5 shows the simulation results where the x-axis is CTE mismatch between LT and the substrate (CTE for LT minus CTE for substrate), and the y-axis is simulated surface stress T_{11}. Silicon, sapphire and Z-prop. quartz were used as a substrate and the substrate thickness was set thick enough compared to LT to converge T_{11}. The extracted 3 points are linearly aligned and the linear approximation for these 3 points yields the linear relationship between T_{11} and CTE mismatch. The x-axis of the plot in Fig. 4(b) can be converted to CTE mismatch using the linear relationship extracted from Fig. 5, and then the y-axis of the plot in Fig. 4(b) is equivalent to ΔTCF change. Eventually, the plot in Fig. 4(b) can be converted to the plot in Fig. 6 where the measured points are deleted and only the linear regression is displayed with the dashed line. Equation (1) is obtained from the linear regression in Fig. 6:

$$\Delta\text{TCF change (ppm/°C)} = -0.54 \times \text{CTE mismatch (ppm/°C)}. \tag{1}$$

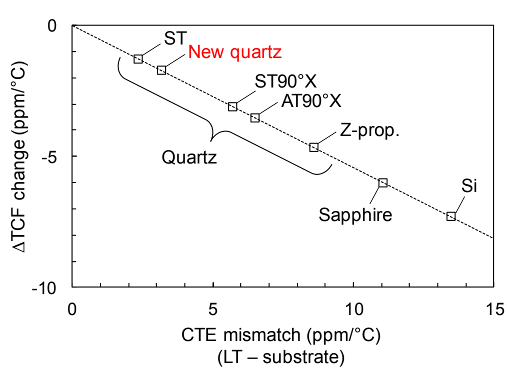

Fig. 6. Estimated ΔTCF change vs. CTE mismatch due to thermal stress.

Figure 6 is also overlaid with several squares corresponding to layered SAW substrates using silicon, sapphire and various orientations of quartz. Because silicon has small CTE and large CTE mismatch with LT, the thermal stress in LT is large and ΔTCF change due to thermal stress is as large as –7.3 ppm/°C. This explains why silicon based layered SAW has the worst ΔTCF as shown in table I. This analysis suggests that a choosing a support substrate having a small CTE mismatch with LT help to have a better ΔTCF. Eventually, ΔTCF of layered SAW would be the summation of ΔTCFs estimated in the linear and nonlinear analysis sections.

III. New Substrate with Near-Zero ΔTCF and TCF

A. *Proposal and simulations*

Based on the analyses in the previous section, a new support substrate for layered SAW allowing a near-zero ΔTCF as well as near-zero TCF_s and TCF_p is proposed in this section. The linear and nonlinear analyses revealed that the important parameters determining ΔTCF are the temperature coefficient of elastic constant (*Tc*) for the support substrate and the CTE mismatch between LT and the support substrate. Quartz was chosen as a support substrate and a better cut/orientation having both a better *Tc* and less CTE mismatch with LT was selected in order to improve ΔTCF and TCF.

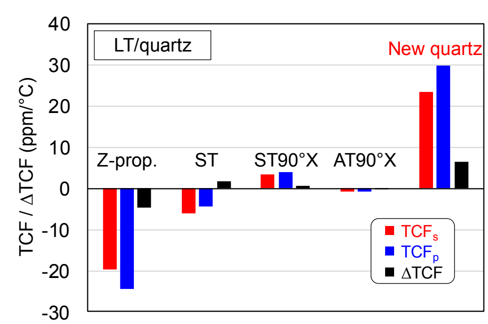

Fig. 7. Simulated impacts of different orientation of quartz on TCF/ΔTCF.

Figure 7 compares the linear TCF/ΔTCF simulation results for LT/quartz layered SAW with different cut/orientation of quartz. The simulation model is the same as the one shown in Fig. 3 and the temperature coefficients only for quartz (*Tc*, *Te* and *Tε*) were considered to see the impacts of the support substrate. Figure 7 includes not only Z-prop. quartz which we proposed in [6], but also ST [3], ST90°X [3], AT90°X [2] and a new cut of quartz we discovered. The new quartz has +6.5 ppm/°C of ΔTCF which is the largest (best) of all quartz orientations here, and also has the largest positive TCF_s and TCF_p of all. Therefore, better ΔTCF and better TCF are expected with the new quartz from the linear simulations.

The CTE mismatch of the new quartz with LT is as small as 3.2 ppm/°C so that ΔTCF change due to CTE mismatch (thermal stress) is estimated as small as –1.7 ppm/°C as shown in Fig. 6. Because the estimated ΔTCF change for the new quartz in Fig.6 is much smaller than that for our previous cut (Z-prop.), a better ΔTCF is expected with the new quartz orientation from the perspective of the nonlinear effect as well. The TCF improvement by wafer bonding with the new quartz would be smaller due to smaller CTE mismatch, but the large positive TCF improvement due to *Tc* shown in Fig. 7 should compensate this disadvantage. Figure 8 compares the simulated thermal stress T_{11} in LT at –35°C between (a) LT/Si and (b) LT/new quartz bonded wafers. Both models have 0.6 µm-thick LT on 20 µm-thick substrate assuming LT and substrate are bonded at 20°C. Obviously, the thermal stress in LT on the new quartz is much smaller than in the Si case that leads to a better ΔTCF.

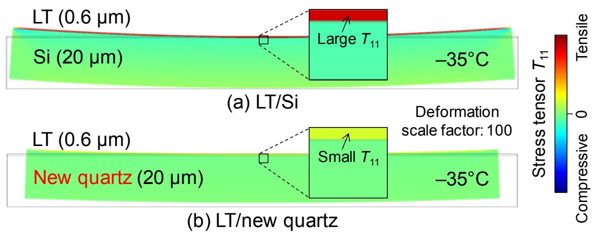

Fig. 8. Comparison of simulated thermal stress in LT (Si vs. new quartz).

B. Experiments

The bonded wafer with thin LT on the new quartz substrate was fabricated and several SAW resonators with different electrode pitches were made on the same bonded wafer with the same metal thickness. S-parameters for the resonators on the new layered SAW substrate were measured at room temperature and 60°C and TCF_s, TCF_p and ΔTCF were extracted.

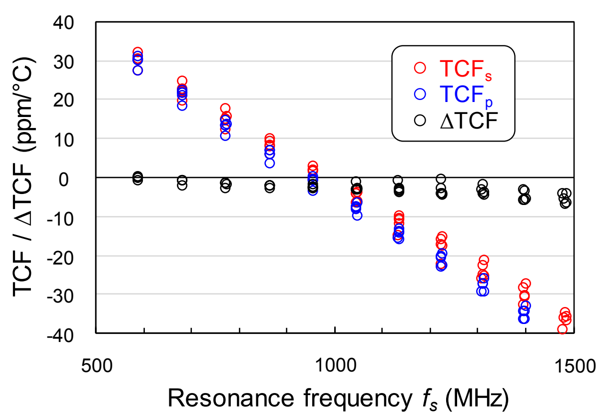

Fig. 9. Measurement results for TCF/ΔTCF for different pich resonators.

Figure 9 shows the extracted TCF_s, TCF_p and ΔTCF variations with the resonance frequency f_s of each device measured. TCF_s and TCF_p strongly depend on f_s (i.e. electrode pitch) because the relative metal thickness and LT thickness to wavelength are different if the pitch is different. When f_s is higher (pitch is smaller), the relative metal and LT thicknesses are thicker and TCF becomes more negative. This is because Al has negative TCF and the positive contribution of the new quartz substrate to TCF shown in Fig. 7 becomes smaller. Both TCF_s and TCF_p were measured near 0 ppm/°C when f_s is 950 MHz. ΔTCF was close to 0 ppm/°C over all frequencies and became slightly more negative for the higher frequency. This is also because the positive contribution of the new quartz substrate to ΔTCF shown in Fig. 7 becomes smaller with higher frequency. Figure 10 shows the correlation between TCF_s and TCF_p obtained from the same experiments shown in Fig. 9. The best point shows $TCF_s = 1.3$ ppm/°C, $TCF_p = –0.8$ ppm/°C and ΔTCF = –2.0 ppm/°C. In addition, the experimental results confirmed a very high Q of over 5,000 and high k^2 of 8.8% at 1 GHz. Moreover, a spurious free out-of-band response was achieved.

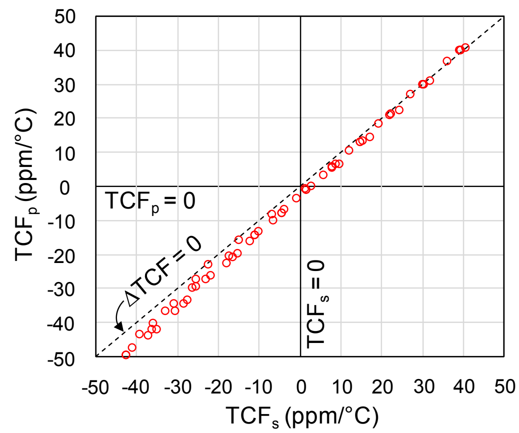

Fig. 10. Correlation between measured TCF_s and TCF_p.

IV. Conclusions

This paper analyzed the cause of ΔTCF degradation on layered SAW considering linear and nonlinear effects. In the linear analysis, it was found that the temperature coefficient of elastic constants Tc for the support substrate affects ΔTCF. The nonlinear analysis revealed the thermal stress in LT degrades ΔTCF. Based on the analyses, a new cut of quartz substrate allowing a near-zero ΔTCF as well as near-zero TCF_s and TCF_p was proposed. The bonded wafer with thin LT on the new quartz substrate was fabricated and resonator performances on the new layered SAW substrate were evaluated. Both TCF_s and TCF_p were measured near 0 ppm/°C. The ΔTCF was only –2 ppm/°C, which is the best ΔTCF of all the conventional SAW/BAW technologies. In addition, the experimental results confirmed a very high Q of over 5,000 and high k^2 of 8.8% at 1 GHz. Moreover, a spurious free out-of-band response was achieved.

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